SOME QUESTIONS OF MODELLING ARC IN SMALL-OIL-VOLUME CIRCUIT-BREAKER

By

G. MADARÁSZ

Institute for Heavy Current Engineering, Technical University, Budapest.

Received October 5, 1979

Presented by Prof. Dr. P. O. GESZTI

Calculating switching processes in electrical network often raises the problem of modelling switching arc in circuit breakers.

In constructing circuit-breakers, a proper arc model is also needed to determine the power or energy of the arc inside the arc quenching chamber.

In respect to the network, the electric arc can be replaced by a resistor, which has a resistance changing from a good conductor to a good insulator.

In Fig. 1, parallel to the resistor there is a spark-gap featured by its breakdown voltage.

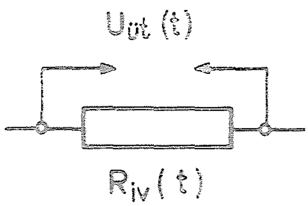

Fig. 1

The main problem is, that the value or change rate of arc resistance not constant, but highly dependent on the arc quenching medium and the construction of the circuit-breaker. Nowadays, knowledge of complicated phenomena related to circuit-breaker arc permits exact, quantitative calculations.

The physical phenomena and the data required for calculations are mainly known for air-blast and sulphur hexafluoride-type circuit-breakers, developed during the last decades.

In the case of oil circuit breaker, for the most part experimentally developed earlier, enough knowledge and data for exact calculations are not available.

Meanwhile some drawbacks of oil circuit breakers such as the restriking phenomenon under interrupting capacitive load have been managed to eliminate. But the oil-circuit breakers have some advantageous features, for example the low price, simplicity, low energy for operation, which are still unique nowadays.

For their further improvement, it is therefore necessary to know and calculate the physical processes.

1. General modelling of the electric arc

The substance of the known various dynamic arc-theories does not much differ. The basic physical effects can be well followed according to the so-called "cybernetic arc-model" [4], [5], [6]. The dynamic model of an arc extinguished by gas flow is seen in Fig. 2. The electrical conductance G and the heat-content Q are related by the temperature profile of the arc.

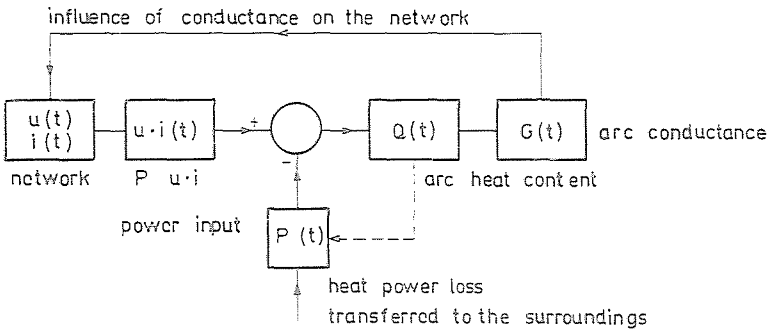

Fig. 2. An arc-model for gas blast circuit-breakers

The rate of change of heat content is proportional to the difference between the input power $u \cdot i$ and the power loss P_l. However, the input power depends not only on the network parameters, but also on the arc resistance. According to Fig. 2, the following equations may be written:

$$\frac{dQ}{dt} = u \cdot i - P_l \tag{1}$$

$$\frac{dG}{dt} = \frac{\partial G(Q)}{\partial Q} \cdot \frac{dQ}{dt} \tag{2}$$

Substituting the energy balance equation (1) into Eq. (2), a general form of the dynamic arc-equation is obtained [1]:

$$\frac{1}{G}\frac{dG}{dt} = \frac{\partial G(Q)}{\partial Q}\frac{1}{G}(u \cdot i - P_l) \tag{3}$$

or in another form:

$$F=\frac{1}{R_a}\cdot\frac{dR_a}{dt}=\frac{1}{\tau}\left(1-\frac{u\cdot i}{P_l}\right) \tag{4}$$

where R_a – arc resistance

$\frac{dR_a}{dt}$ – rate of change of R_a

$\tau=\frac{1}{\frac{\partial G}{\partial Q}\cdot R_a\cdot P_l}$ – a parameter in time units and the so-called thermal arc "time constant".

Using various assumptions the classical arc equations can be derived from Eqs (3) or (4). In the case of a stationary arc, the input power equals the power loss. In the case of transient arc the power loss can be expressed by a suitable stationary arc with the same power loss as that of the transient arc.

Depending on the method of assigning a transient arc to a stationary one, various well-known arc equations arise. If P_l has a constant value, Mayr's equation is derived. In this case, the stationary arc-voltage as a function of current is a hyperbola. Assuming that the transient arc-resistance also corresponds to the stationary arc resistance ($R_a=R_{as}$) Cassie's arc-equation is derived.

$$\frac{1}{R_a}\cdot\frac{dR_a}{dt}=\frac{1}{\tau}\left(1-\frac{\frac{u^2}{R_a}}{\frac{U_s^2}{R_a}}\right)=\frac{1}{\tau}\left(1-\left(\frac{u}{U_s}\right)^2\right) \tag{5}$$

If both the respective stationary and transient power losses, and currents are equal ($i=I_s$), Hochrainer's arc-equation is obtained:

$$F=\frac{1}{R_a}\cdot\frac{dR_a}{dt}=\frac{1}{\tau}\left(1-\frac{u\cdot i}{U_s\cdot i}\right)=\frac{1}{\tau}\left(1-\frac{u}{U_s}\right)$$

or written in the usual form:

$$\frac{dG}{dt}=\frac{G_s-G}{\tau}$$

where $G_s = \dfrac{i}{U_s}$ — stationary arc conductance

$G = \dfrac{i}{u}$ — transient arc conductance.

The model in Fig. 2 and Eq. (4) are valid only if the thermal ionization is predominant in the arc column and the arc is supposed to be in thermal equilibrium.

Measurements showed, that the constants generally used in Eq. 4 (τ and P_l) are in fact not constant, but are better defined as "parameters".

These parameters are usually obtained from current and voltage oscillograms by the relationships

$$F = \frac{1}{u}\cdot\frac{\mathrm{d}u}{\mathrm{d}t} - \frac{1}{i}\cdot\frac{\mathrm{d}i}{\mathrm{d}t}$$

$$P_{in} = u \cdot i \tag{7}$$

For the relationship $F\ (P_{in})$ the classical Mayr's theory would give a sloping straight line, but in reality it is not rectilinear (Fig. 3).

To obtain the parameters in latter case, the derivative of $\dfrac{\mathrm{d}F}{\mathrm{d}P_{in}}$ is also needed.

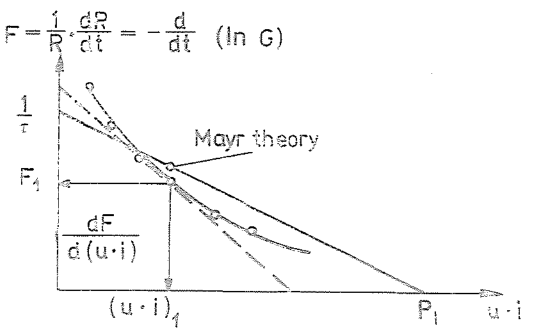

Fig. 3

2. Modelling the dynamic arc of oil circuit-breakers

The arc control device of the oil circuit breaker is the so-called "self-extinguishing" type, that is, the efficiency of arc suppression depends upon the value of breaking current. This advantageous characteristic exists essentially because of a "feed-back mechanism" of the physical processes as it is shown in Fig. 4. While in gas-blast circuit breakers, the velocity of the gas flow primarily depends on outer effects (e.g. reservoire pressure), on the other hand in selfextinguishing type circuit breakers the generated gas volume highly depends on the arc parameters. The power loss of arc generates gases and vapours from the oil. Experience shows the volume of released gases and vapours to be proportional to the arc energy.

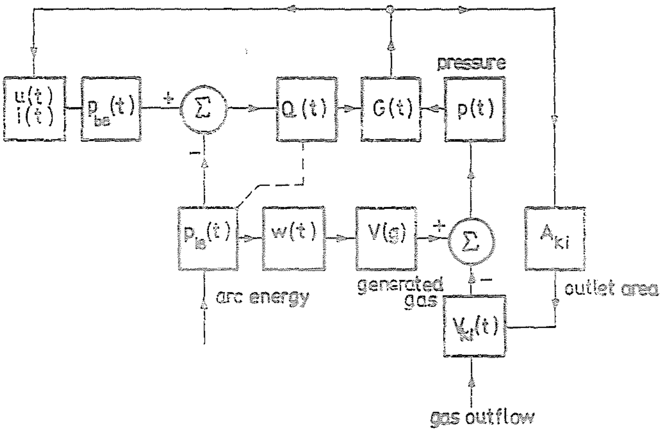

Fig. 4. An arc-model for oil circuit-breakers

The high pressure and the cooling effects due to the gas flow also affect the arc. The effect of pressure upon the arc resistance can be studied by using Saha's equation.

The arc conductivity is described by the equation:

$$\sigma \cong A \frac{T^{\frac{3}{4}}}{p^{\frac{1}{2}}} \cdot e^{-\frac{B}{T}} \tag{8}$$

where T – gas temperature
p – pressure
A and B – constants

The cooling effect of the gas flow can be taken account in the value of power loss P_l.

The arc conductance is proportional, mainly at high current values, to that part of the cross section which has a fairly good electrical conductivity.

The velocity of the flowing particles is maximum in the hot axis of the arc column, at a temperature of 6000 – 15000 °K. On the other hand, in the axis of the arc column the gas density is at a minimum, so that the mass-flow in the axis is negligible. Due to this effect, the effective outlet area of the arc chamber is reducing under arcing, so that the pressure inside the chamber also depends on the arc cross section.

According to the model in Fig. 4 the investigations could be divided into two parts:

a) Investigation of the electrically conducting part of the arc plasma;

b) The investigation of heat transfer, gas flow and pressure conditions

Below, mainly the problems of electrical modelling of arc plasma will be detailed, without penetrating into pressure, flow and heat-transfer problems.

According to Fig. 4 and Eq. 8, the electrical conductance of the arc column G depends on both the heat content of arc plasma Q and the pressure p:

$$G = G(Q, p)$$

The derivative of Eq. 2 with respect to time may therefore be written:

$$\frac{dG}{dt} = \frac{\partial G}{\partial Q} \cdot \frac{dQ}{dt} + \frac{\partial G}{\partial p} \cdot \frac{dp}{dt} . \tag{9}$$

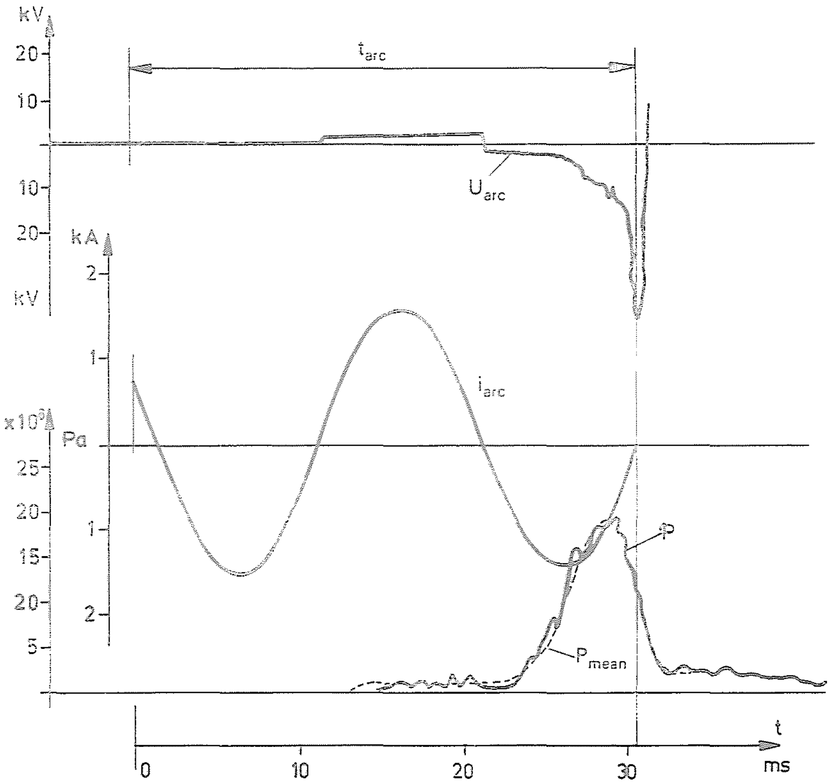

Fig. 5. Current interruption oscillogram $U = 26.25$ kV, $I = 10$ kAmps

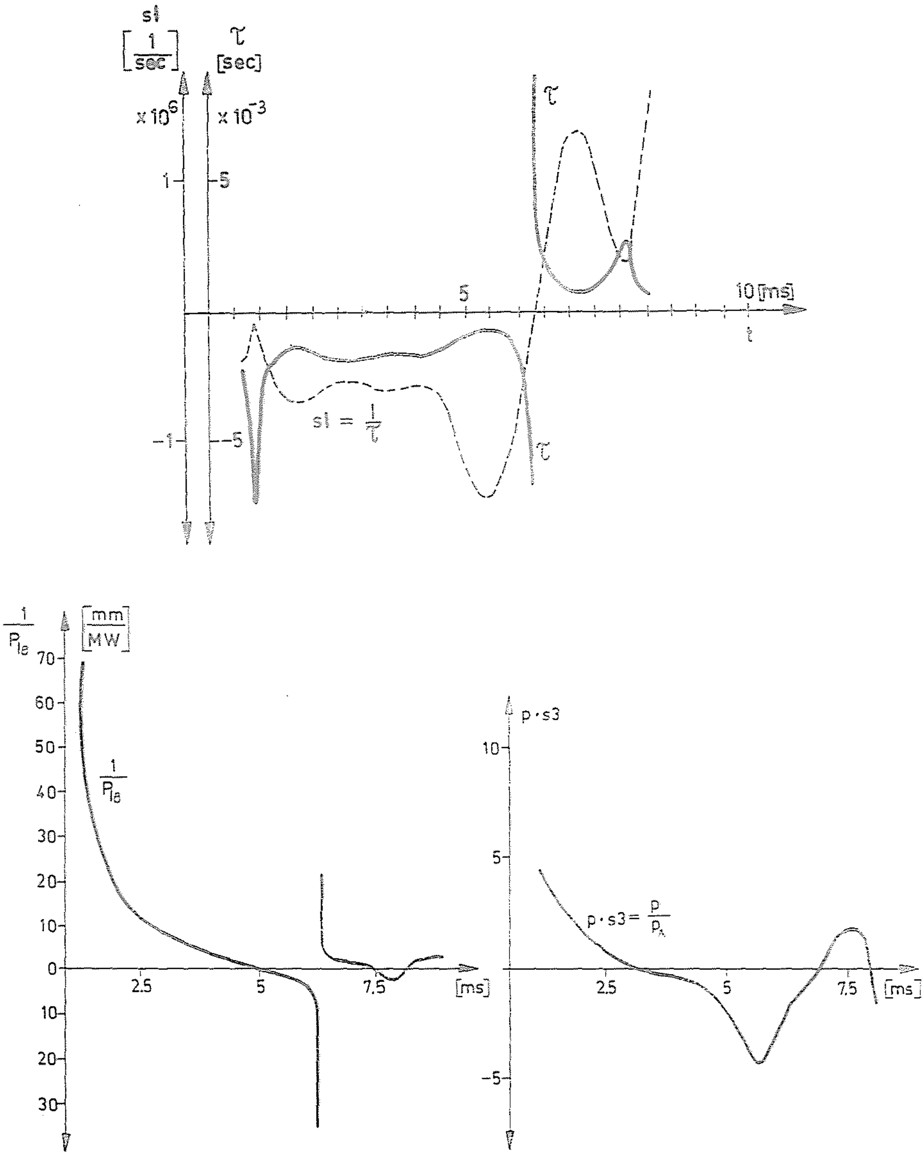

Fig. 6. Evaluation of an arc interrupting 10 kAmps

Substituting Eq. (1) into Eq. (7) and dividing by G yields a dynamic arc equation.

$$\frac{1}{G}\cdot\frac{\mathrm{d}G}{\mathrm{d}t}=\frac{\partial G}{\partial Q}\cdot\frac{1}{G}(u\cdot i-P_l)+\frac{\partial G}{\partial p}\cdot\frac{1}{G}\cdot\frac{\mathrm{d}p}{\mathrm{d}t} \tag{10}$$

or, written in the usual form:

$$F = \frac{1}{R_{\text{arc}}} \cdot \frac{\mathrm{d}R_{\text{arc}}}{\mathrm{d}t} = \frac{1}{\tau}\left(1 - \frac{u \cdot i}{P_l}\right) - \frac{1}{p_a} \cdot \frac{\mathrm{d}p}{\mathrm{d}t} \tag{11}$$

where p_a is a parameter in pressure units.

With varying parameters, Eqs (10) or (11) can be used for describing electrical phenomena in oil circuit-breaker. Compared to other arc control devices, there is such a great change in pressure that must be taken into account. Voltage, current and pressure oscillograms measured in an axially blown type small-oil-volume circuit-breaker is seen in Fig. 5.

The derivative of the pressure is approximated by means of the formula [2]:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{u \cdot i \cdot k_g \cdot T}{273 \cdot V_1} - \frac{pA_{\text{out}} \cdot V_{\text{out}}}{V_1} \tag{12}$$

where p — pressure in arc-chamber
$u \cdot i$ — arc power
k_g — gas volume generated by unit arc energy
T — average gas temperature outside the arc
V_1 — average gas volume at temperature T
A_{out} — effective area of outlet
v — velocity of gas flow in the outlet.

The evaluation of oscillogram data in Fig. 5 is shown in Fig. 6. The last half-period before the interruption was only taken into account for evaluation.

3. Explanation of negative "Time-Constant" in the range of high currents

It is well known [3], that the curves $F(u \cdot i)$ obtained from measured data often greatly differ from the shape of curve represented in Fig. 3. The same refers to test data, measured on oil-circuit-breakers. The deviation is marked out by a positive derivative of curve $F(u \cdot i)$.

In this case, the "arc-time constant" is negative. Until now, there was no sufficient explanation of this phenomenon and the negative time-constant was considered as physically meaningless.

Evaluating test data for oil-circuit-breakers, the value of function $F(u \cdot i)$ was found to be negative but its derivative to be positive during the greater part of the half-period. It seems to be physically reasonable, because the arc resistance is decreasing in the first part of the half-period.

The positive value of the derivative of function $F(u \cdot i)$ was attributed to the negative term from pressure change. But taking the term $\frac{1}{p_A}\frac{dp}{dt}$ into account, a negative value for parameter $\frac{1}{\tau}$ was still found in a part of the investigated period.

For this reason, the "arc-time constant" based on Eqs (4) and (11) or its reciprocal value was investigated in detail.

The time-parameter as a reciprocal value of "time-constant" is defined by Eq. (4).

$$\frac{1}{\tau} = \frac{\partial G}{\partial Q} R_{\text{arc}} \cdot P_l . \tag{13}$$

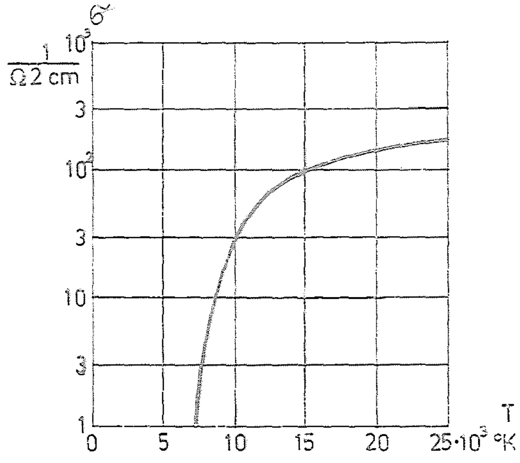

Fig. 7. Electrical conductivity of nitrogen vs. temperature at atmospheric pressure

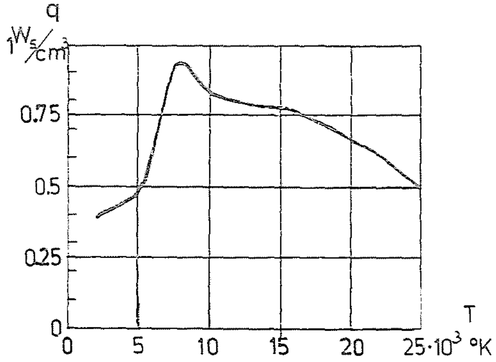

Fig. 8. Internal energy per unit volume of nitrogen vs. temperature at atmospheric pressure

In Eq. (13) R_{arc} and P_l always have positive values. The arc conductance G and heat content (Q) can be expressed by the following equations:

$$G = \int_0^{l_{\text{arc}}} 2\pi \int_0^{r_{\text{arc}}} \sigma(T(r, z)) \cdot r\, \mathrm{d}r \cdot \mathrm{d}z \tag{14}$$

$$Q = \int_0^{l_{\text{arc}}} 2\pi \int_0^{r_{\text{arc}}} q(T(r, z)) \cdot r\, \mathrm{d}r \cdot \mathrm{d}z \tag{15}$$

where r — radial coordinate
z — axial coordinate
T — temperature in °K
r_{arc} — radius of electrically conductive part of the arc plasma (at about 5000 °K)
l_{arc} — arc length
$(T(r, z))$ — arc conductivity (Fig. 7)
q — inner energy per unit volume (Fig. 8)

Since both the conductance G and heat content Q depend upon the temperature T, the derivative from Eq. (13) is:

$$\frac{\partial G}{\partial Q} = \frac{\dfrac{\partial G}{\partial T}}{\dfrac{\partial Q}{\partial T}} = \frac{\displaystyle\int_0^{l_{\text{arc}}}\int_0^{r_{\text{arc}}} \frac{\partial \sigma}{\partial T} r \cdot \mathrm{d}r \cdot \mathrm{d}z}{\displaystyle\int_0^{l_{\text{arc}}}\int_0^{r_{\text{arc}}} \frac{\partial q}{\partial T} r \cdot \mathrm{d}r \cdot \mathrm{d}z} \lessgtr 0 \tag{16}$$

The electrical conductivity (σ) as a function of temperature is represented in Fig. 7. The derivative of electrical conductivity-curve is seen to always be greater than zero. The derivative of inner energy per unit volume $q(T)$ with respect to temperature is seen in Fig. 8 to be positive at low temperature but above a certain temperature it becomes negative.

The curve $q(T)$ in Fig. 8 refers to nitrogen gas, but the shape is similar for other gases. The sloping part of the curve is due to decreasing of density with the increase of temperature (Fig. 9). The density increases with pressure.

The arc-model calculations published until now mainly referred to the current-zero range, where the plasma temperature is relatively low, making negative time-constants to be unfrequent and considered to be irrelevant. One must remember, however, that in the low-current range, additional ionization may arise from a high electric field, which also decreases the value of function F.

Further measurements are needed to justify and refine the model of the described processes.

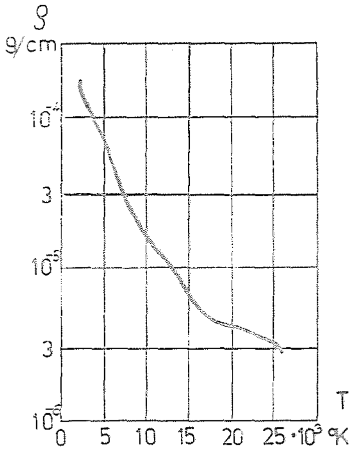

Fig. 9. Mass density of nitrogen vs. temperature at atmospheric pressure

Summary

The circuit-breaker-arc as an element of the network can be described by differential equations. In oil circuit breakers the arc generates gases and vapours which affect the arc itself through a "feedback mechanism". This phenomenon, neglected earlier is discussed in this article. It is well known from several studies that in certain case the arc-time constant evaluated from measurements had a negative value.

Until now, there has not been sufficient explanation for the negative value of time constant. Investigating the arc quenching processes in oil circuit-breakers a possible solution to this problem is given, which can be generalized for arc phenomena in other kinds of circuit breakers.

References

1. Browne, T. E. Jr.: A Study of $A-C$ Arc Behaviour Near Current Zero by Means of Mathematical Models AIEE Trans. Vol. 67. 141—153. 1948.
2. McNeill, W. A.—Crane, P. H. G.: Arc Control Devices, Electrical Review V. 9. Jul. 1954.
3. Rieder, W.: Plasma und Lichtbogen F. Vieweg et Sohn Braunschweig. 1967. 128—129.
4. Grütz, A.: Mathematical Investigation of Circuit Breaker Performance With the Aid of a Generalized Arc Theory, ETZ-A Vol. 92. No. 9. (1971).
5. Hochrainer, A.—Grutz, A.—Schwarz J.—Thiel H. G.: Study of Arcs in Breakers with the Help of a Cybernetic Model and Under the Influence of Turbulence, 'CIGRE Rep. No. 13—10. 1972.
6. Smith, R. K.—Colclaser, R. G. Jr.: A Modified Cybernetic Arc Model Capable of Describing the Energy Balance Phenomena In a Power Circuit Breaker., IEEE PAS. Summer Meeting. Publ. Portland. 1976.

Dr. György Madarász, H-1521 Budapest