IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, no. 5, September/October 1977

# THEORETICAL DESCRIPTION OF THE CURRENT INTERRUPTION IN HV GAS BLAST BREAKERS

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## ABSTRACT

A theoretical model is derived which is able to describe the current interruption in hv gas blast circuit breakers. The model is based on experimental observations of the relevant physical phenomena. The guidelines for establishing the equations were to describe these relevant effects according to present knowledge as good as possible and to keep the model as simple as possible. Two constants describing the intensity of the turbulence were adjusted to get agreement with measured data. The model then describes correctly the dependence of the limiting curves for thermal reignition on current and on pressure. The difference between air and $SF_6$ is also described correctly by changing only the material properties in the model. Besides these results curves for the dependence of the post arc current on pressure and switching current are calculated.

## 1. INTRODUCTION

In ref. |1| experimental investigations were described which revealed a number of observations concerning the physical mechanisms which are important for current interruption in hv gas blast circuit breakers.

The most important findings which form the basis of the theory to be described are shortly summarized with the help of Fig. 1.

Two arc sections with different behaviour have to be distinguished:

a) the 'high pressure arc section' which extends from the stagnation point in the high pressure reservoir up to about the nozzle throat (length $L_a$)

b) the 'turbulent arc section' which extends from about the throat some cm downstream (length $L_b$).

Different physical phenomena prevail in these two sections and it turned out that with respect to current interruption this difference leads to a very effective mutual support of these two sections.

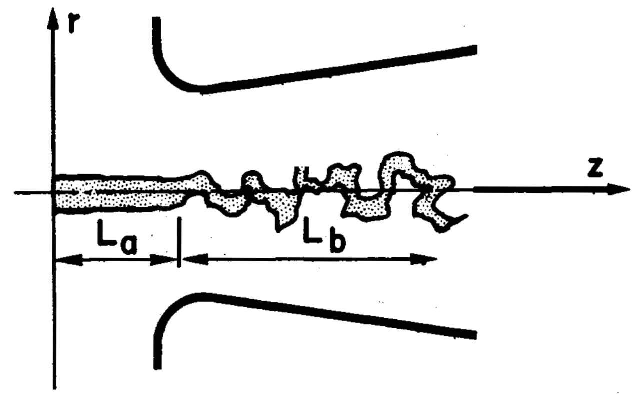


Fig. 1. Arc in the nozzle around current zero. $L_a$ high pressure arc section; $L_b$ turbulent arc section.

In the high pressure arc section (a) radiation and convection play a dominant role in the energy balance. This has the following consequences: This section is dominant in the quasi-stationary arc before current zero, it has the highest field strength in this phase. Approaching current-zero the strong contribution of the convective term results in a very rapid adjustment of the arc diameter. The main merit of section (a) for the current interruption is to produce a very thin (less than 1 mm for typical current slopes of 20 A/μs) arc column around current zero.

In the turbulent arc section (b) this thin arc filament is strongly and effectively attacked by turbulence. This turbulence is produced by an instability of the arc boundary layer and attains its full intensity not before the nozzle throat because of the strong acceleration of the mean flow up to the nozzle throat. Around current zero the turbulent exchange of energy dominates the energy balance. Section (b) is limited in the downstream direction due to a broadening of the arc resulting in a reduction of turbulent exchange.

## 2. THE MAIN APPROXIMATIONS USED IN THE THEORETICAL MODEL

### 2.1. 'Cylindrical One-Section Approximation'

Instead of describing section (a) and (b) by the dominating processes of each and coupling the two sections at a certain position we calculate the behaviour of one hypothetical cylindrical arc section which includes all energy exchange mechanisms of section (a) and (b).

F 77 127-4. A paper recommended and approved by the IEEE Switchgear Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Winter Meeting, New York, N.Y., January 30-February 4, 1977. Manuscript submitted August 26, 1976; made available for printing November 22, 1976.

The following arguments support this approximation:

- Both sections remain essentially cylindrical within the time interval of their major importance i.e. the temperature distribution does not depend on the z-coordinate.
- The upstream section (a) clearly is not influenced by section (b). In the time interval where section (b) dominates the reverse is valid too. (This statement is equivalent to zone (b) being cylindrical).
- The length L of our model can be adjusted to the length of section (b). This is somewhat longer than $L_a$. The fact that L is larger than $L_a$ only increases the stationary arc voltage. This can be considered as an approximation of the contribution of the other arc sections to the arc voltage in the stationary phase.
- The change of importance of the different effects which occurs in reality in space (change from (a) to (b)) and time (some µs before current zero) is produced in the one-section model automatically in time only. The reason for that is, that the turbulent exchange has practically no influence on the hypothetical cylindrical arc section as long as the arc is in the quasistationary regime so that it describes very well section (a). The physical reason is that the energy removal in section (a) is dominated by the convection in the conducting arc region. Around current zero the turbulent exchange with the surrounding gas is of major importance. The convection is of influence only in this surrounding gas. So different effects dominate at different times. The dominating effects have to be described by the parameters of the zone in which they dominate.

## 2.2. Radial Discretisation

As was shown in |2| for the description of the section (a) a two-zone model with an isotherm as zone-boundary is a very good approximation. To describe the turbulent exchange of section (b) 3 zones are regarded as a minimum.

Zone 1 is the conductive arc core with an isotherm as boundary (4000 K for $SF_6$ and 6000 K for $N_2$). Zone 2 is a zone of intermediate temperature which acts as an energy buffer during the decay of the arc. Zone 3 finally is the surrounding cold gas which is important for zone 2 as an energy sink. The boundary between zone 2 and 3 is the 1000 K isotherm.

The calculation is performed by applying the conservation equations for the 3 zones. The independent variables are then zone averages of the different magnitudes. To establish relations between these averages and to derive the exchange terms between the zones from the averages an assumption for the radial temperature profile within the zones is to be made (Fig. 2).

For zone 1 a parabolic profile is assumed and for zone 2 and exponential one.

$$\text{Zone 1: } T(r^2) = T_a - (T_a - T_1)\,\frac{r^2}{r_1^{\,2}} \qquad (1)$$

$$\text{Zone 2: } T(r^2) = T_3 + (T_1 - T_3)\; e^{-\alpha(r^2 - r_1^{\,2})}$$

$$\alpha = \frac{1}{r_2^{\,2} - r_1^{\,2}}\,\ln\frac{T_1 - T_3}{T_2 - T_3} \qquad (2)$$

In the isotherm representation $T_1$, $T_2$ and $T_3$ are fixed values, $T_a$, $r_1$ and $r_2$ are variables.

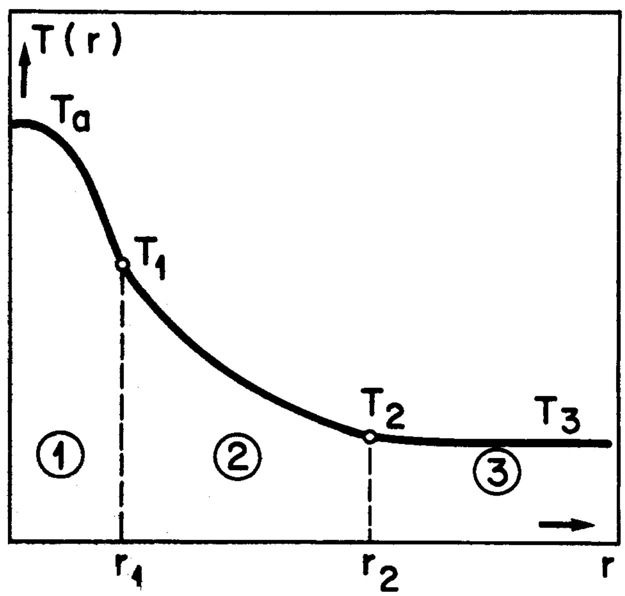


Fig. 2. Radial temperature profile.

## 2.3. Description of the Turbulent Transport

In view of the complicated interaction of the arc and the turbulence (see |1|) any description of this term is necessarily of an approximative nature. We have chosen the following set of equations (see also |3|).

Turbulent viscosity

$$\eta_t = \rho\,\varepsilon \qquad (3)$$

Turbulent heat conductivity

$$\kappa_t = 2\,\rho\,c_p\,\varepsilon \qquad (4)$$

with $\rho$ = mass density
$c_p$ = specific heat

and

$$\varepsilon = 1.5\ 10^{-4}\ L\ c\ f_t. \tag{5}$$

$\varepsilon$ is an exchange coefficient which scales with the product of a characteristic length times velocity. For these two parameters we choose the length of the effective arc section and the velocity of sound at the arc boundary. $f_t$ is an additional empirical factor which is fitted to experimental data as shown below.

### 2.4. Description of the Radiative Transport

Radiative energy exchange is an important effect only in the stationary regime. It decreases in importance approaching current zero. For this effect only rather crude approximations are available. In |4| the temperature-dependent radiative transport in the axis of an arc with rectangular temperature distribution was solved for different arc radii and different pressures.

From these calculations we derive for the integrated radiative balance of zone 1:

$$\bar{u}_1 = u_r(T)\ f_r\ f_p\ C_1. \tag{6}$$

The temperature dependent part $u_r(T)$ is calculated by integrating the radiative balance for the rectangular arc over our parabolic profile. This curve is shown in Fig. 3.

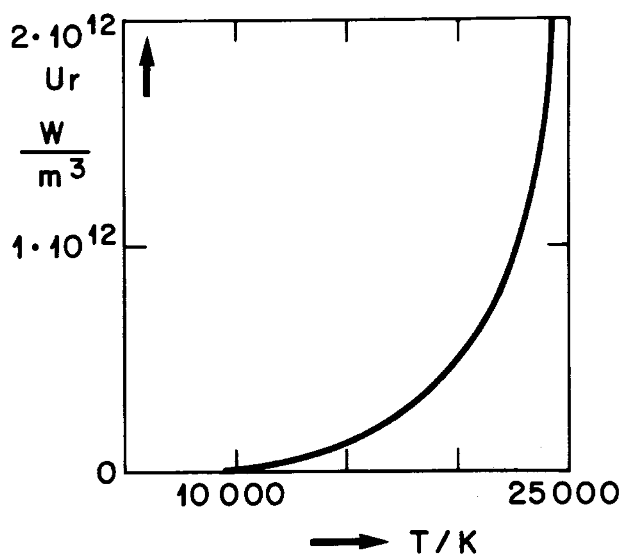


Fig. 3. Temperature dependent part of the radiative balance of zone 1.

The pressure and radius dependence is taken from |4|. These curves are shown in Fig. 4.

$C_1$ is a factor smaller than one which describes the fraction of $u_r$ leaving zone 1. This value was taken from detailed calculations of a 2 kA arc |4| and was held constant during the decay of the arc: $C_1 = 0.35$.

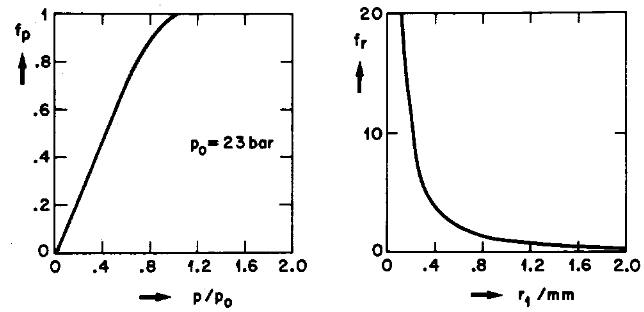


Fig. 4. Pressure and radius dependence of the radiative balance of zone 1.

A part of the emitted radiation from zone 1 is reabsorbed in zone 2. This is approximated by

$$\bar{u}_2 = -\bar{u}_1 \quad 0,7 \cdot \frac{A_1}{A_2}\ . \tag{7}$$

$A_1$ and $A_2$ are the areas of zone 1 and zone 2.

## 3. EQUATIONS

### 3.1. Conservation Equations for Zones 1 and 2

The basic conservation equations for mass, momentum and energy are now derived with the aforementioned approximations. Zone 3 imposes around current zero an axial pressure gradient on the other zones. For the axial pressure distribution

$$\frac{\partial p}{\partial z} = -\ Cz \tag{8}$$

is assumed. C being taken from the high pressure arc section.

In consistence with the assumption of a cylindrical model we get:

$$v_{z1,2} = B_{1,2}\quad z \tag{9}$$

Zone 1 (electrical arc)

Mass conservation

$$\frac{\partial}{\partial t}\ (A_1\bar{\rho}_1) = A_1(\overline{B\rho})_1\ -\ q_1\ \equiv M_1 \tag{10}$$

Momentum conservation

$$\frac{\partial}{\partial t}\ (A_1(\overline{B\rho})_1) = 2A_1(\overline{B^2\rho})_1 - q_1B_1 + A_1C - \frac{2\pi r_1}{z}\ S_1\ \equiv I_1 \tag{11}$$

Energy conservation

$$\frac{\partial}{\partial t}\ (A_1(\overline{\rho h})_1) = -A_1(\overline{\rho h B})_1 - q_1h_1 + A_1(\bar{\sigma}_1E^2 - \bar{u}_1) - 2\pi r_1W_1\ \equiv E_1 \tag{12}$$

Zone 2 (intermediate zone)

Mass conservation

$$\frac{\partial}{\partial t}(A_2\bar{\rho}_2) = -A_2(\overline{B\rho})_2 - q_2 + q_1 \equiv M_2 \tag{13}$$

Momentum conservation

$$\frac{\partial}{\partial t}(A_2(\overline{B\rho})_2) = -2A_2(\overline{B^2\rho})_2 - q_2B_2 + q_1B_1 + A_2C - \frac{2\pi r_2}{z}S_2 + \frac{2\pi r_1}{z}S_1 \equiv I_2 \tag{14}$$

The energy equation of zone 2 can - as was shown in |5| - be replaced by expressions for the radial mass fluxes relative to the isotherms:

$$q_1 = \frac{\pi}{(c_p \frac{\partial T}{\partial r^2})_{r_1}} \left(-u(r_1) + 2\frac{\partial}{\partial r^2}(rW)_{r1}\right) \tag{15}$$

$$q_2 = \frac{2\pi}{(c_p \frac{\partial T}{\partial r^2})_{r_2}} \frac{\partial}{\partial r^2}(rW)_{r2} \tag{16}$$

Besides the usual nomenclature the following expressions were used:

$$S = -(\eta+\eta_t)\frac{\partial v_z}{\partial r} \tag{17}$$

$$W = -(\kappa+\kappa_t)\frac{\partial T}{\partial r} \tag{18}$$

## 3.2. Relations between Averages

There exist relations between the averages (indicated by a bar) in eqs. (10-14). For purely temperature dependent magnitudes these relations can be derived straightforward with the help of the temperature profiles of eqs. (1) and (2).

Relations between averages containing the velocity factor B (eqs. (10-14)) were approximated in the following way:

$$\overline{Bh\rho} = \bar{B}\,\overline{h\rho} \tag{19}$$

$$\overline{B^2\rho} = \bar{B}\,\overline{B\rho} \tag{20}$$

The justification for that is the weak temperature dependence of $h\rho$ and $B\rho$. For the relation between $\overline{B\rho}$ and $\bar{B}$ a parabolic profile of B in zone 1 and an exponential one in zone 2 was assumed similar to the approximations for the temperature profile.

## 3.3. Calculations of Exchange Terms between the 3 Zones

The exchange terms S, W and q (eqs. (15-18)) contain temperature dependent material properties (e.g. $\kappa_t$) and radial gradients (e.g. $\partial T/\partial r$). This results in a complicated interaction of the material properties with the temperature profile. E.g. in a temperature regime with high heat conductivity the profile is flattened and vice versa. As the change of the profile is excluded in our model we approximate this effect by using material property averages over both zones for the calculation of the exchange terms between two zones.

For the calculation of the heat flux from zone 1 into zone 2 we use for instance:

$$W_1 = \frac{1}{2}\left((\overline{\kappa+\kappa_t})_1 \left(\frac{\partial T}{\partial r}\right)_1 + (\overline{\kappa+\kappa_t})_2 \left(\frac{\partial T}{\partial r}\right)_2\right) \tag{21}$$

$(\overline{\kappa+\kappa_t})_1$ means the averaged heat conductivity of zone 1 and $(\partial T/\partial r)_1$ is the temperature gradient in zone 1 at the boundary between zone 1 and 2.

In the same sense the other exchange terms are formed.

## 3.4. Solution of the Equations

The derived set of eqs. is complete for the calculation of the time evolution of the following unknowns: $\bar{T}_1$, $\bar{v}_{z1}$, $A_1$, $\bar{v}_{z2}$, $A_2$, $q_1$, $q_2$.

With the above defined abbreviations for the right hand sides of eqs. (10-14) the eqs. can be solved for the following differentials:

$$\frac{\partial T_1}{\partial t} = \frac{(\overline{h\rho})_1 M_1 - \bar{\rho}_1 E_1}{A_1\left((\overline{\rho h})_1 \frac{\partial\bar{\rho}}{\partial T} - \bar{\rho}_1 \frac{\partial(\overline{\rho h})_1}{\partial T}\right)} \tag{22}$$

$$\frac{\partial A_1}{\partial t} = \frac{\frac{\partial\bar{\rho}_1}{\partial T}E_1 - \frac{\partial(\overline{\rho h})_1}{\partial T}M_1}{(\overline{\rho h})_1 \frac{\partial\bar{\rho}_1}{\partial T} - \bar{\rho}_1 \frac{\partial(\overline{\rho h})_1}{\partial T}} \tag{23}$$

$$\frac{\partial(\overline{B\rho})_1}{\partial t} = \frac{I_1}{A_1} - \frac{1}{A_1}\frac{\partial A_1}{\partial t}(\overline{B\rho})_1 \tag{24}$$

$$\frac{\partial A_2}{\partial t} = \frac{M_2}{\bar{\rho}_2} \tag{25}$$

$$\frac{\partial(\overline{B\rho})_2}{\partial t} = \frac{1}{A_2}\left(I_2 - (\overline{B\rho})_2\frac{M_2}{\bar{\rho}_2}\right) \tag{26}$$

If initial conditions are given and relations between I and U are known from the electrical network the time dependence of the unknown quantities can be calculated.

The initial conditions are provided in the following way: The set of equations is solved with arbitrary initial conditions for a constant current of 1,9 kA. The program then performs a time relaxation towards the stationary state. This then is taken as initial condition for the decaying arc.

In this paper the network interaction is not considered. This problem will be discussed in a future publication.

Instead we impose before current zero a linear current ramp, characterized by the slope di/dt or by the r.m.s. value of a 50 Hz sine wave with the same slope at current zero. After current zero a linear voltage ramp is applied characterized by the slope du/dt.

### 3.5. Input Data

The calculations were made for nitrogen and $SF_6$. Nitrogen is regarded equivalent to air. The material properties for nitrogen were taken from |6|, those for $SF_6$ from |7|.

The length of the effective arc section was chosen according to the experimental observations of the electrical field strength distribution around current zero of |1| Fig. 11 to be L = 3 cm.

The value of C which represents the influence of the geometry was chosen to be $C/p_o$ = 530 $1/m^2$. The turbulence intensity factor $f_t$ in eq. (5) is needed at the two zone boundaries: $f_{t1}$ to describe the exchange between zone 1 and zone 2 and $f_{t2}$ for zone 2 and zone 3.

These intensity factors were varied independently to give the best agreement with measured thermal extinction limiting curves. The result of this fitting was: $f_{t1}$ = 0,8 and $f_{t2}$ = 0,16. These factors were held constant in the following calculations.

## 4. RESULTS

In this section some typical results of our model are given.

In Fig. 5 thermal extinction limiting curves are shown. The geometry factor C was held constant. Only the switching current and the pressure were varied. The change from $SF_6$ to air ($N_2$) was achieved by changing only the material properties.

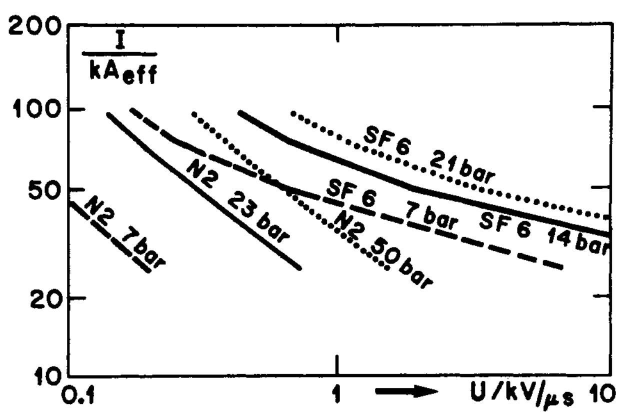


Fig. 5. Thermal extinction limiting curves for air and $SF_6$ at different pressures.

These limiting curves were compared with a number of measurements on model experiments |1,8| and on real circuit breakers. The agreement is very good over the full range. As an example the calculated pressure dependence is compared with measured values of Frind and Rich |8|. For $SF_6$ we calculate at 50 kA and 7 bar a limiting du/dt of 0,67 kV/µs, at 21 bar 3,3 kV/µs. If we apply the empirical law of |8| namely du/dt $\sim p^{1,4}$ we get with the same value at 7 bar 3,1 kV/µs at 21 bar. For air we obtain as calculated values at 50 kA and 7 bar: du/dt = 0,09 kV/µs and at 50 bar du/dt = 0,64 kV/µs. This corresponds exactly to the empirical law du/dt $\sim$ p given in |8| for air.

Other important informations can of course also be derived from the model. In Fig. 6 the post arc current in the vicinity of the limiting curve is plotted. These curves give the possibility to judge the distance to the limit by a measurement of the post arc current. To judge the influence of the post arc current on the damping of the recovering voltage the size of the post arc current on the limiting curve is of importance. These values are shown in Fig. 7 for air and $SF_6$ in dependence on the current for various pressures.

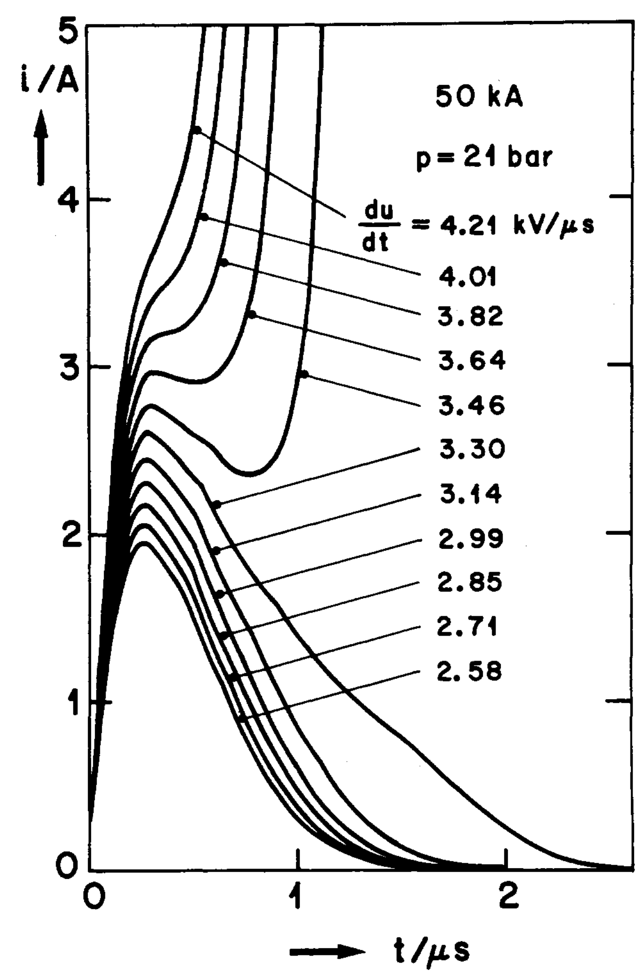


Fig. 6. Post arc current for $SF_6$ 21 bar and $I_{eff}$ = 50 kA for different du/dt values.

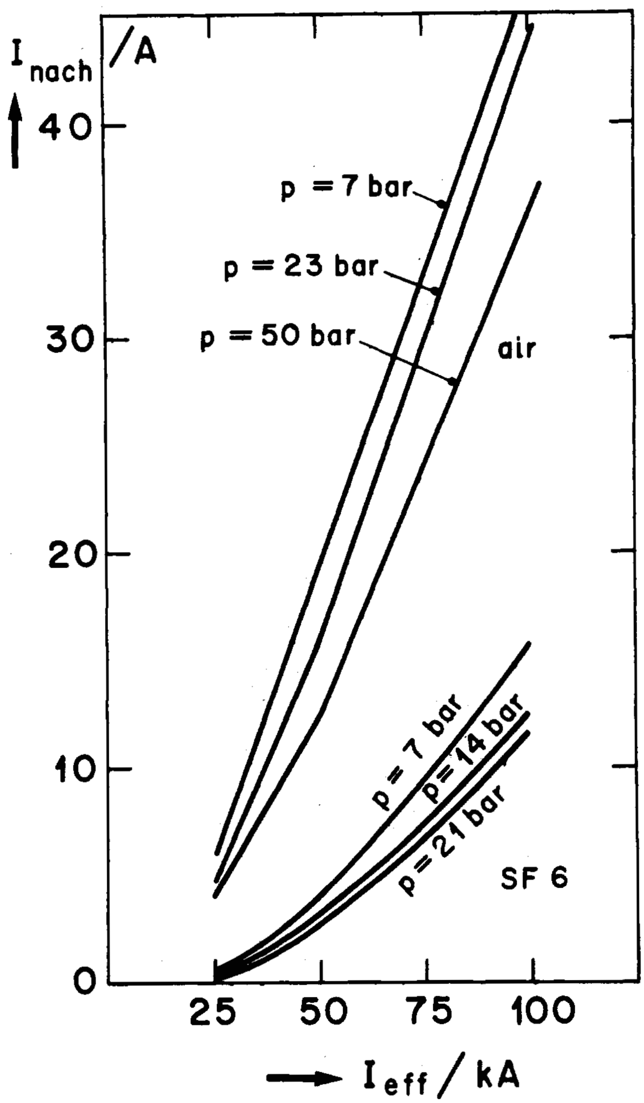


Fig. 7. Maximal post arc current in dependence on switching current for air and $SF_6$ at different pressures.

## 5. DISCUSSION

The correct description of the limiting curves over a wide range of current and pressure is very encouraging. It is for the first time that this is achieved by an arc model. In a recent publication |9| Swanson proposes a model where the z-dependence is taken into account. We feel that this extension could improve our model in so far as the assumption of an effective arc length L would no longer be necessary but would result from the z-dependent calculation. On the other hand we don't need - in contrast to Swanson's model - a current-dependent adjustment of the turbulent exchange. It seems that our radial discretisation and the description of the exchange terms is the reason for that, although arguments for a current-dependent turbulence resulted also from other observations |10|. As a future task it could be fruitful to find out the physical reasons for the different behaviour of these two models in this respect in order to get a better understanding of the physical phenomena.

Further comparisons with experimental data are possible by changing the geometry (factor C) and comparing the calculated with measured post arc currents (see e.g. |11|. Our curves Fig. 6 and 7 indicate that the post arc current is a very sensitive parameter for a check of the model.

Unsatisfactory is the lack of information concerning the turbulent transport. We hope that future experiments can supply information to support the values of $f_t$ we have chosen.

Another encouraging result is that a model taking all relevant physical phenomena into account still is relatively easy to handle on a modern computer. One run of our program takes 1,7 sec on an IBM 370/168. Therefore the interaction of the arc with the network can be treated without problems by adding the network equations to the program. We feel that this makes the use of simplified arc equations obsolete perhaps with the exception of the simplest Mayr-equation which is of great didactic value.

## REFERENCES


|1| W. Hermann, U. Kogelschatz, L. Niemeyer, K. Ragaller, E. Schade, 'Investigation on the physical phenomena around current zero in hv gas blast breakers', IEEE paper F 76 061-2, Winter Power Meeting N.Y.1976.

|2| W. Hermann, U. Kogelschatz, K. Ragaller, E. Schade, 'Investigation of a cylindrical, axially blown, high pressure arc', J. Phys. D: Appl. Phys., vol. 7, pp. 607-619, 1974.

|3| W.Hermann, U. Kogelschatz, L. Niemeyer, K. Ragaller and E. Schade, 'Experimental and theoretical study of a stationary high-current arc in a supersonic nozzle flow', J.Phys.D, vol. 7, 1703-1722, 1974.

|4| W. Hermann, E. Schade, 'Radiative energy balance in cylindrical nitrogen arcs', J.Q.S.R.T., vol. 12, no. 9, pp. 1257-1282, 1972.

|5| W. Hermann, 'Computation of Decaying Wall-Stabilized Arcs', Z. Naturforsch., vol. 28a, pp. 443-453, 1973.

|6| J. M. Yos, Technical Documentary Report No. ASDT DR-729, revised version 1967.

|7| L. S. Frost, R. W. Lieberman, 'Composition and transport properties of $SF_6$ and their use in a simplified enthalpy flow arc model', Proc. IEEE, vol. 59, no. 4, pp. 474-485, 1971.

|8| G. Frind, J. A. Rich, 'Recovery speed of axial flow gas blast interruptor: Dependence on pressure and dI/dt for air and $SF_6$', IEEE paper T74 183-0, Winter Power Meeting, N.Y. 1974.

|9| B. W. Swanson, 'Nozzle arc interruption in supersonic flow', IEEE paper A76 309-5, Summer Power Meeting Portland 1976.

|10| L. Niemeyer, K. Ragaller, 'Development of Turbulence by the Interaction of Gas Flows with Plasmas', Z. Naturforsch., vol. 28a, pp. 1281-1289, 1973.

|11| M. Murano, H. Nishikawa, A. Kobayashi, T. Okazaki, S. Yamashita, 'Current zero measurement for circuit breaker phenomena', IEEE paper T75 070-8, Winter Power Meeting N.Y. 1975.

## Discussion

**T. E. Browne, Jr.** and **L. S. Frost** (Westinghouse R. & D. Center, Pittsburgh, PA): We wish to congratulate the authors on their advanced dynamic arc model, which treats the radial physical relations in a more complete and realistic way than any so far proposed. The elimination of the axial variable z by means of their hypothetical cylindrical cross section including all exchange mechanisms appears to result in less computer time than treatments by others [1-5] which more correctly represent axial variation of arc properties. The promised further development of the model is awaited with much interest. Especially needed, it appears to us, are further comparisons of model solutions with those of other authors for a wider range of nozzle configurations, leading to a promise of future success in optimizing gas-blast nozzle design.

In spite of the recent advances in more nearly complete physical-electrical arc models and the availability of high speed computers for solving them, we are unable to agree with these authors that simplified arc models are thus made obsolete. First, it appears to us that all present models, including that of this paper, depend to some degree on experimental data (Examples appear at the ends of the authors' Sections 2.3 and 3.5.), and so can still serve basically just as means for extrapolation from actual tests. For this purpose the much simpler combined Cassie-Mayr model (not just the Mayr) has been found by us [6-9] to be adequate and greatly enhanced in usefulness for the necessary arc-circuit interaction calculations by its simplicity and the resulting shortness of any required computer time. Second, even the most complete models for the arc column have not considered the disturbing effects of the relatively cool and rapidly vaporizing solid arc terminals which we feel to be responsible for much of the observed [10] disparity between the electrical behavior very near current zero of the models and of actual breaker arcs [11]. Thus, since even the most complete arc models so far devised are still only approximate, we feel that the relatively simple approximate models still have important practical uses as means for extrapolation from test data.

### REFERENCES

[1] Reference 7 of the paper.

[2] D. T. Tums and J. J. Lowke, "Prediction of properties of arcs stabilized by forced convection", *Jour. App. Physics*, Vol. 46, No. 8, pp. 3361-3367, August 1975.

[3] J. J. Lowke and H. C. Ludwig, "A simple model for high-current arcs stabilized by forced convection", *Jour. App. Physics*, Vol. 46, No. 8, pp. 3352-3360, August 1975.

[4] Fathi R. El-Akkari and D. T. Tuma, "Simulation of Transient and Zero Current Behavior of Arcs Stabilized by Forced Convection", paper No. F 77 126-6, presented at the *IEEE Power Eng. Soc.* 1977 Winter Meeting, Jan./Feb. 1977, New York, N.Y.

[5] Reference 9 of the paper, presented by title as paper No. F 77 190-2 at the IEEE Power Eng. Soc. 1977 Winter Meeting, Jan./Feb. 1977, New York, N. Y.

[6] L. S. Frost, "A Practical Dynamic Model of the Resistance-Shunted Arc Near Current Zero", unpublished report to the "Current Zero Club", Pittsburgh, Pa., July 1971.

[7] L. S. Frost, "Dynamic Circuit Breaker Test Analysis and Its Use in the Generalized Specification of Short-Line Fault Performance", *IEEE International Conference on Plasma Science*, Austin, Texas, May 24-26, 1976; Conference Record 76 CH 1083-5-NPS, p. 150 (abstract).

[8] L. S. Frost, "Dynamic Arc Analysis of Short-Line Fault Tests for Accurate Circuit Breaker Performance Specification", submitted for presentation at the *IEEE Power Eng. Soc.* Summer Meeting, July 17-22, 1977, Mexico City, Mexico.

[9] T. E. Browne, Jr., "Practical Modeling of the Circuit Breaker Arc as a Short Line Fault Interrupter", submitted for presentation at the *IEEE Power Eng. Soc.* Summer Meeting, July 17-22, 1977, Mexico City, Mexico.

[10] Reference 11 of the paper.

[11] T. E. Browne, Jr. and L. S. Frost, *Discussion* of Reference 11 of the paper.

Manuscript received February 23, 1977.

**Bruce W. Swanson** (Westinghouse Electric Corporation, Pittsburgh, PA): The authors are to be commended for a very interesting paper that makes a significant contribution to model arc theory. For the first time a dynamic model has been presented that quantitatively explains the difference in the interrupting abilities of air and $SF_6$ and this point merits further discussion. Equations (22) and (23) may be written in the form

$$\frac{\partial \bar{T}_1}{\partial t} = t_1 E_1 + t_2 M_1 \frac{1}{A_1} \tag{D-1}$$

and

$$\frac{\partial A_1}{\partial t} = a_1 E_1 + a_2 M_1 \tag{D-2}$$

where the coefficients $t_1$, $t_2$, $a_1$ and $a_2$ are given by the equations

$$t_1 = \frac{\bar{\rho}_1}{D} \qquad t_2 = -\frac{\overline{(\rho h)}_1}{D} \tag{D-3}$$

$$a_1 = \frac{\left|\frac{\partial \bar{\rho}_1}{\partial T}\right|}{D} \qquad a_2 = \frac{\frac{\partial \overline{(\rho h)}_1}{\partial T}}{D} \tag{D-4}$$

$$D = \overline{(\rho h)}_1 \left|\frac{\partial \bar{\rho}_1}{\partial T}\right| + \bar{\rho}_1 \frac{\partial \overline{(\rho h)}_1}{\partial T} \tag{D-5}$$

These coefficients $t_1$, $t_2$, $a_1$, $a_2$ are functions only of the gas properties and their temperature derivatives for an assumed temperature profile. It is significant that Equations (22) and (23) have been rigorously derived from the integrated continuity and energy equations while the approximate equations of Lowke and Ludwig, (D-1) El-Akkari and Tuma (D-2) and Swanson (9) were derived only from the integrated energy equation.

In the initial steady state the terms $E_1$ and $M_1$ are equal to zero. As the current is ramped to zero, $E_1$ becomes negative and $M_1$ should become positive. This latter statement follows from the fact that $M_1$ is defined by the equation.

$$M_1 = -\frac{\partial}{\partial z} \overline{(\rho V)}_1 A_1 - q_1 \tag{D-6}$$

where initially $\partial/\partial z\ \overline{(\rho V)}_1 A_1$ is positive and $q_1$ is negative. As the current decreases, we would expect $\partial/\partial z\ \overline{(\rho V)}_1 A_1$ to decrease as $A_1$ decreases leaving $M_1$ positive. The coefficients $t_1$, $t_2$, $a_1$, $a_2$ amplify the terms $E_1$ and $M_1$ so that the greater these coefficients, the greater will be the time rates of change of $\bar{T}_1$ and $A_1$. For good interrupting ability, we want $\bar{T}_1$ and $A_1$ to be as small as possible at current zero, which implies that large values of these coefficients favor arc interruption. Furthermore, these coefficients may indicate the relative interrupting abilities of different gases and it is of interest to evaluate them for air and $SF_6$. Figures D-1 and D-2 show the relative values of these coefficients for air and $SF_6$ as functions of temperature. These figures clearly indicate the superiority of $SF_6$ when both gases are compared at the same temperature. Note that Figure D-2 shows that for $SF_6$, $a_2$ is negative which follows from the fact that $\partial \overline{(\rho h)}_1/\partial T$ is negative for $SF_6$ and positive for air over the entire temperature range. Since $a_2$ is negative for $SF_6$ and positive for air, it follows from Equation D-2 that the collapse of arc area is faster in $SF_6$ than it is in air. Therefore, at current zero, we would expect the $SF_6$ arc to be more constricted and to have a smaller cooling time constant which may explain its superior interrupting ability. In view of these remarks, it would be very helpful if the authors would compare the arc areas and arc temperatures of air and $SF_6$ at 2000 A and at current zero as determined from their model calculations. Also of interest would be a comparison of the pre-current zero arc voltages for both gases as determined by their model.

Manuscript received February 25, 1977.

If we assume that $(\overline{\rho h})_1 = \bar{\rho}_1 \bar{h}_1$, then it is easy to show that Equations (D-3) and (D-4) reduce

$$t_1 = \frac{1}{\bar{\rho}_1 \bar{c}_{p_1}} \qquad t_2 = \frac{-\bar{h}_1}{\bar{\rho}_1 \bar{c}_{p_1}} \tag{D-7}$$

and

$$a_1 = \frac{1}{\bar{\rho}_1 \bar{c}_{p_1} \bar{T}_1} \qquad a_2 = \frac{\bar{c}_{p_1} \bar{T}_1 - \bar{h}_1}{\bar{\rho}_1 \bar{c}_{p_1} \bar{T}_1}$$

where $\bar{c}_{p1} \equiv \partial \bar{h}_1 / \partial T$. It thus appears that, as a first order approximation, the product $\rho c_p$, which appears in all the terms above, is that gas property which accounts for its interrupting ability. This conclusion is corroborated by the work of Kinsinger and Noeske (D-3) who showed that the interrupting abilities of various gases can be correlated by a gas property function where

$$\S = \frac{P}{\sigma} \frac{d\sigma}{dF} = \frac{P}{\rho c_p \sigma} \frac{d\sigma}{dT} \tag{D-8}$$

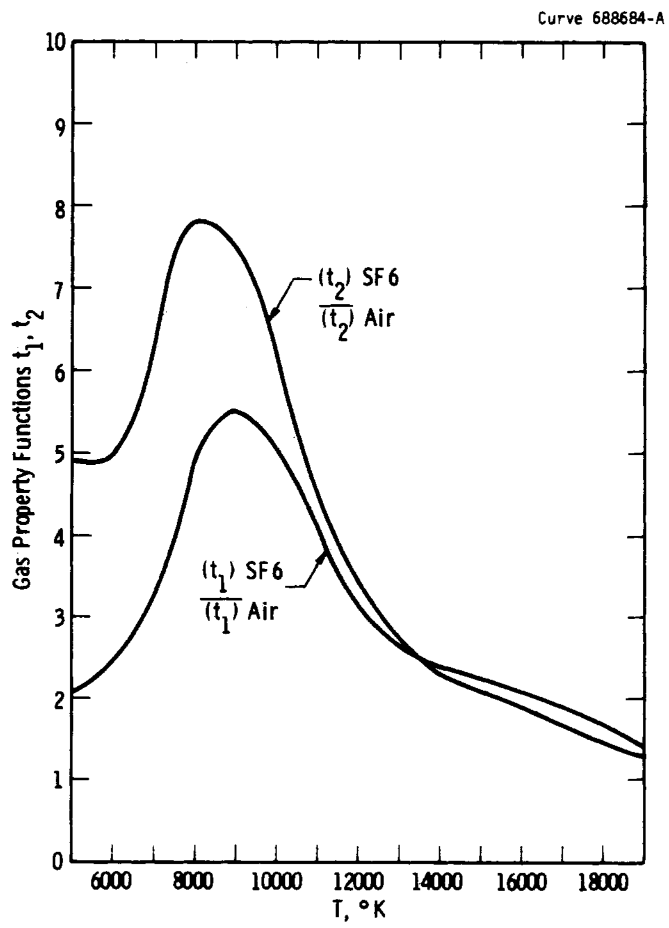


Fig. D-1. Gas property functions versus temperature for air and $SF_6$

However, while the assumption that $\overline{\rho h} = \bar{\rho}\bar{h}$ is a reasonable one for $SF_6$, it does not hold for air. Therefore, more information about a gas is contained in these four coefficients than can be extracted from this simplifying assumption. In summary, the model formulation in Equations (22) and (23) is significant for the following reasons: (a) it explains differences in interrupting ability in terms of differences in gas properties as shown by this discussion; (b) it defines rigorous dynamic equations for arc temperature and arc area; and (c) it raises the possibility of formulating a more general nozzle arc model that accounts for variations in the z direction that is more accurate than the models of Lowke and Ludwig, (D-1) El-Akkari and Tuma (D-2) and Swanson. (9) Such a model is needed to fully investigate the effect of nozzle design on interrupting ability.

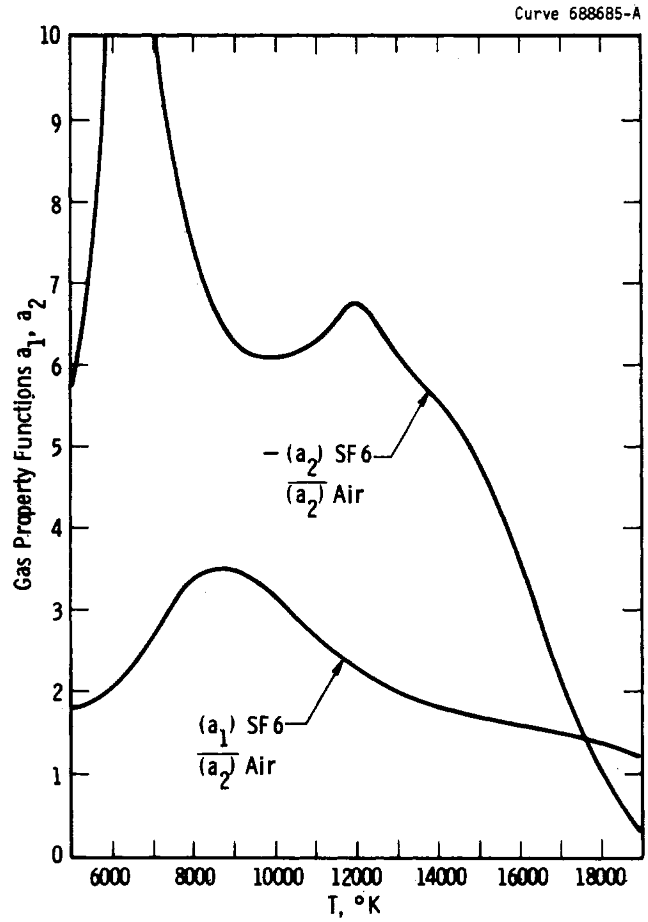


Fig. D-2. Gas property functions versus temperature for air and $SF_6$

## REFERENCES


(D-1) J. J. Lowke and H. C. Ludwig, "A Simple Model for High-current Arcs Stabilized by Forced Convection, Jnl. Appl. Phys., Vol. 46, No. 8, Aug. 1975.

(D-2) F. R. El-Akkari and D. T. Tuma, "Simulation of Transient and Zero Current Behavior of Arcs Stabilized by Forced Convection," IEEE Paper F77126-6, Winter Power Meeting, New York, 1977.

(D-3) R. E. Kinsinger and H. O. Noeske, "Arc Thermal Recovery in Different Gases," EPRI Symposium on New Concepts in Fault Current Limiters and Power Circuit Breakers," Sept. 28-30, 1976 at State University of New York at Buffalo.


**G. Frind** (General Electric Corporate Research and Development, Schenectady, NY): The authors are to be congratulated to another fine paper on the physics of the interruption process in gas blast breakers. I have a few comments and questions to the results presented.

The thermal extinction limiting curves presented in Fig. 5 of the paper show for $SF_6$ a strong variation of the slope m defined by:

$$\frac{dV}{dt} \sim \frac{1}{I^m} \sim \frac{1}{(dI/dt)^m}$$

I extracted from the author's curves for $SF_6$ m values as low as 1.4 (high current, low pressure) and as high as 4.5 (low current, high pressure). In contrast to this strong variation, the m values of the air curves are rather constant over the reported range. Would the authors care to comment on the physical processes or properties which are causing this different behavior of the two gases and particularly the strong variation of m in $SF_6$?

In the paper theoretical results on recovery speed are compared with experimental ones reported earlier (1) and good agreement between the two is found. Again, using the curves of the author's Fig. 5, I repeated the comparison and found indeed good agreement between


Manuscript received February 28, 1977.

theory and experiment with respect to the pressure dependence of RRRV for both air and $SF_6$ and also for the dI/dt dependence of RRRV for $SF_6$. An exception is however the dI/dt dependence of RRRV in air, where the theoretical curves yield approximately m = 1.15 and where the experimental value was close to m = 2. This difference in m is significant both for practical and theoretical reasons and the author's opinion on the reasons for the discrepancy would be appreciated.

Still on the subject of the limiting curves, I would like to ask the authors to which specific experimental result they fitted their theory (by choosing appropriate values for the turbulent intensities). Also, does the shape of the limiting curves in Fig. 5 depend strongly on the fitting process?

The geometrical nozzle factor c of the theory, defined by:

$$\frac{\delta p}{\delta z} = -cz$$

promises to describe effects of nozzle variations on interruption speed. It might for instance be directly useful in describing the effect of nozzle throat diameter D on RRRV. Assuming for instance the use of optimum upstream electrode position for different size but "similar" shaped nozzles, c will vary roughly with $c \sim 1/D$. How strong will c (or D) affect recovery speed and specifically, are smaller nozzles faster than larger ones?

The paper presents in Figs. 6 & 7 some very useful information on the time, current and pressure dependency of post arc currents in $SF_6$ and air. Especially Fig. 6 invites the experimenter to try for a comparison. Such a comparison would be significantly sharpened, if the authors could add to Fig. 6 still some more time dependent information for higher dI/dt values (or for air). Experiments will give the time dependence automatically (as does probably the computer run), and it appears useful to compare theory and experiment with respect to as many easy accessible parameters as possible.

## REFERENCE

[1] G. Frind and J. A. Rich, "Recovery speed of axial flow gas blast interrupter: dependence on pressure and dI/dt for air and $SF_6$", IEEE Transactions, PAS-93, 1675-1684 (1974).

**W. Hermann** and **K. Ragaller**: The authors appreciate the great interest shown in the paper and thank the discussors for their valuable comments. We are pleased that the contributions of Browne and Frost give us the opportunity to comment in greater detail on our short and admittedly somewhat provocative statement regarding arc models. We believe that since the time of Cassie and Mayr, scientific investigations of arc models have to a certain extent followed an inappropriate direction. The models of Cassie and Mayr were derived from physics corresponding to the state of knowledge at that time. The physical description was relatively crude and therefore simple models were the result. One could not expect these models to describe circuit-breaking phenomena with the continuously increasing accuracy demanded by circuit-breaker testing. This was the reason for continuing the development of arc models for which various methods were employed.

One approach (e.g. Hochrainer) was to discontinue the derivation from physics and make a purely mathematical modeling. It is evident that this is in principle possible. If the underlying differential equation is sufficiently complex and a sufficiently large number of parameters can be fitted, an increasingly more exact model of a specific circuit breaker can be obtained. With this method one is clearly limited from the beginning to the extrapolation of measurements.

A second approach was to improve the original models of Cassie and Mayr by means of a more exact description of the underlying physical processes. This approach can basically satisfy all requirements demanded of a circuit-breaker model, such as predicting the circuit-breaking capacity of various gases in various geometries, etc. Our work has followed the second approach, and it must be said that many other authors before us have made valuable contributions in this area. In part, these investigations showed that the authors have intuitively anticipated physical phenomena, which only later were observed experimentally (e.g. the significance and influence of turbulence). This method shows great potential inasmuch as it is possible for the first time to reproduce accurately the limiting curves of the circuit breaker over a wide range. We continue to seek further confirmation of the model (e.g. faithful reproduction of the chopping of small inductive currents) and are convinced that with the methods and knowledge available today one will be able to make with sufficient accuracy the connection between the fundamental physical processes and the interaction of arc and network.

Manuscript received April 4, 1977.

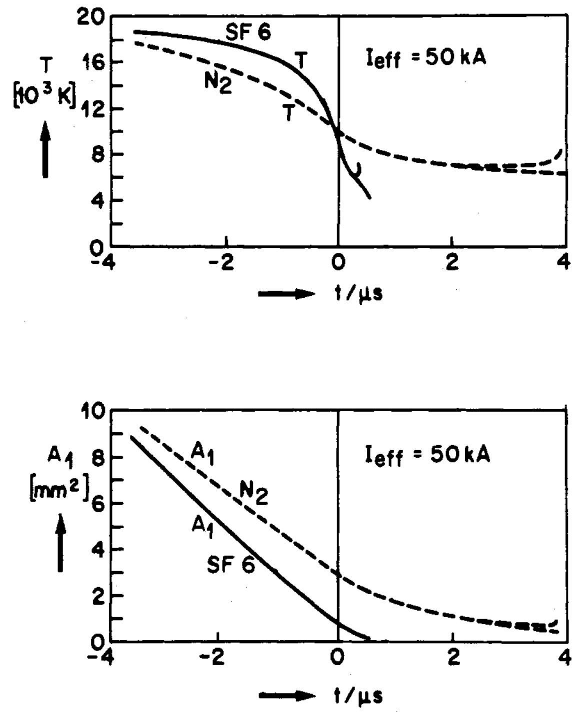


Fig. 1. Computed temperature and area curves for $SF_6$ and air for a current of 50 kA.

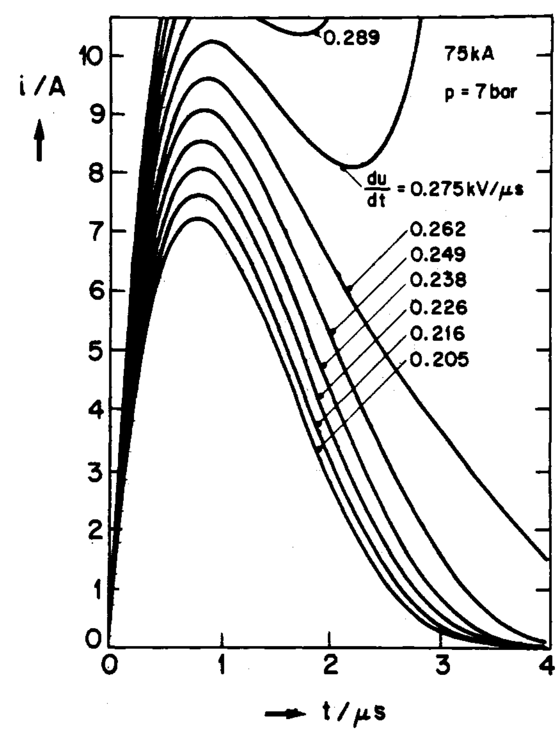


Fig. 2. Post arc current for $SF_6$ 7 bar and $I_{eff}$ = 75 kA for different du/dt values.

Investigations which simply provide the original physical models of Cassie and Mayr with additional terms which have not been derived from quantitative physical understanding but are of a speculative nature and as a result merely provide possibilities for adjusting parameters, are, in our opinion, methodologically unsound and obsolete by present standards of knowledge. This leads to a mixing of the two approaches mentioned for which there is no justification. Naturally it would be ideal to have an arc model as simple as possible. Therefore, the next step would be to see whether our model, which initially describes all observable phenomena as exactly as possible, could be simplified without a significant loss in accuracy. In our opinion this appears to be an undertaking that might possibly yield successful results. The discussion by Swanson is already a step in this direction.

We are certainly willing to accept Swanson's suggestion to discuss the coefficients of $E_1$ and $M_1$ (see equations D-1 and D-2; factor $A_1$ is missing from the left hand side of equation D-1). Up to now, the difference between $SF_6$ and air was sought primarily in variations in the factor $E_1$ which includes the heat flux. As Swanson indicates, the new feature is that even if $E_1$ and $M_1$ are the same, temperature and arc cross section decrease more rapidly in $SF_6$ than in air. The physical explanation for this is that air, in contrast to $SF_6$, recombines within the temperature range 4000 to 6000 K (large $\rho c_p$), and therefore delays a temperature drop. This is certainly an important factor in circuit-breaking phenomena. Fig. 1 shows, as Swanson surmises, that $SF_6$, in contrast to air, has a lower temperature and smaller cross section when approaching current zero.

On the other hand, turbulent heat exchange plays a significant role. In this case again the magnitude of $\rho c_p$ is important, however in the inverse sense, i.e. the greater $\rho c_p$, the better. A decided advantage is that for $SF_6$ the value of $\rho c_p$ below 4000 K is greater than for air, i.e. in the case of $SF_6$ the heat transfer in the arc boundary is greater than for air. The value of $\rho c_p$, therefore, influence the circuit-breaking process in various ways and the dependence over a wide temperature range is of importance. The approach of the limiting curves of $SF_6$ to those of air at higher currents is, for example, caused by the following effect. At higher currents the current zero temperature is higher and therefore the value of $\rho c_p$ in $SF_6$ determining the heat flux is lower.

It has also been suggested by Frind that it might be valuable to investigate the fundamental physical processes and the correlation with the limiting curves. At the present time we are unable to answer concrete questions relating to the differences in curves and the discrepancies between theory and experiment.

It was observed that in regard to the question of sensitivity of the circuit breaker limiting curves for various parameters, that both c as well as $f_t$ excessively influence the limiting rate of rise of the voltage. Both values also influence the shape of the limiting curves.

We gladly provide the post arc current curves for a higher interrupting current, as suggested (see Fig. 2).