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CHANGES TO THE SF_6 OUTFLOW AREA IN THE NOZZLE OF A HIGH VOLTAGE AUTO-PNEUMATIC CIRCUIT BREAKER DURING A SHORT-CIRCUIT CURRENT INTERRUPTION

ABSTRACT *The paper presents a calculation method for the SF_6 outflow area across the critical cross-section of the nozzle in an HV puffer circuit breaker during the interruption of a short-circuit current. The presence of an electrical arc can cause clogging of the nozzle at the moment when the arc cross section is close to the nozzle throat area. The clogging depends on the instantaneous current value and can cause ablation of the nozzle material. In the long term it can result in a change in the nozzle dimensions which adversely affects the interrupting ability of the circuit breaker.*

Keywords: *HV puffer circuit breaker, SF_6, nozzle, ablation, gas flow*
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1. INTRODUCTION

SF_6 circuit breakers are used in low, medium and high voltage networks. At medium voltages they are substituted by vacuum circuit breakers, which are also produced for higher voltages of up to 145 kV. One can expect that in the near future a level of 245 kV will be reached. It seems, however, that it will not be possible to develop a vacuum circuit breaker for higher voltages. Consequently SF_6 circuit breakers will have to be

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produced for 400 kV and higher voltages. There are several publications [1, 2, 3] dealing with the phenomena occurring during the interruption of short circuit currents.

In SF_6 circuit breakers the critical parts are the nozzles (Fig. 1, 2). They are sensitive to short circuit currents, which cause decomposition of the nozzle material. During a current interruption the area of the critical cross section increases due to ablation of this material, and this change influences the future behaviour of the circuit breaker [4].

Special attention should be paid to the so-called clogging effect that appears during current interruption at the limit of the circuit breaker's breaking ability. The arc can cause an increase in the temperature of the nozzle material of up to 3000°K. The nozzle can become overheated, which results in an ablation of the nozzle material. The calculation presented below for a typical SF_6 circuit-breaker takes into account the pressure dependence of the short-circuit arc and a temporary clogging of the nozzle.

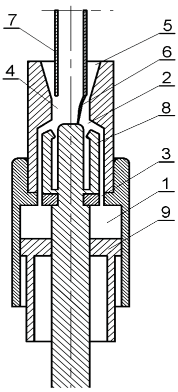

Fig. 1. Circuit breaker pole:
1 - SF6 compression chamber, 2 - nozzle before the throat, 3 - conduit, 4 - nozzle throat, 5 - outflow, 6 – arc, 7 – fixed contact, 8 - movable contact, 9 - piston

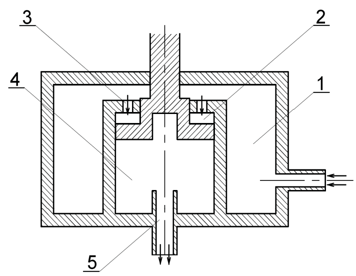

Fig. 2. Pneumatic actuator:
1 – air tank, 2 – working chamber, 3 – air inlet to the working chamber, 4 – dumping chamber, 5 – air outflow

In the calculations a pneumatic actuator was assumed.
Symbols used:

A – area of the gas outflow
A_{cr} – critical cross section of the nozzle
B – area of the piston in the compression chamber
B_w – area of the piston in the working chamber
B_d – area of the piston in the damping chamber
d – arc diameter
c_P – specific heat of SF_6 at a constant pressure
c_V – specific heat of SF_6 at a constant volume
ΔQ – energy change of the gas
ΔU – internal energy change of the gas
ΔW – work done on gas compression
F – total force used

F_a – force of the actuator
F_K – friction force in the compression chamber
F_N – friction force in the actuator
F_S – friction between contacts
g – gravity acceleration
i – instantaneous current value
l – total piston displacement
M – mass of all of the moving parts
m – mass of SF_6 in the compression chamber
m_n – mass of SF_6 in the nozzle before the throat
m_w – mass of the air in the working chamber
m_d – mass of the air in the dumping chamber
m_{out} – mass of SF_6 outflow from the compression chamber
m_{n_in} – mass of SF_6 inflow into the nozzle, $m_{n\_in} = m_{out}$
m_{n_out} – mass of SF_6 outflow from the nozzle
m_{w_in} – mass of air inflow into the working chamber
m_{d_out} – mass of air outflow from the damping chamber
p – pressure in the compression chamber
p_{ext} – pressure in the circuit breaker pole
p_n – pressure in the nozzle before the throat
p_m – air pressure in the tank
p_w – air pressure in the working chamber
p_d – air pressure in the damping chamber
$P(u_a, i_a)$ – power delivered by the arc to the gas in the nozzle
R – SF_6 gas constant
R_{air} – air gas constant
t – time
T – SF_6 temperature in the compression chamber
T_n – SF_6 temperature in the nozzle before the throat
T_m – air temperature in the pressure tank
T_n – air temperature in the working chamber
T_d – air temperature in the damping chamber
U_a – arc voltage
V – volume of the gas in the compression chamber
V_n – volume of the gas in the nozzle before the throat
V_w – volume of the air in the working chamber
V_d – volume of the air in the damping chamber
v_t – piston velocity
x – instantaneous position of the piston
z – distance between the compression chamber and the critical cross section of the nozzle
κ – adiabatic expansion exponent of SF_6
κ_{air} – adiabatic expansion exponent of air
ρ – density of the gas in the compression chamber
ρ_n – density of the gas in the nozzle before the throat
ρ_w – density of the air in the working chamber
ρ_d – density of the air in the damping chamber
ε – ratio of the gas pressure in the pole of the circuit breaker and in the nozzle before the throat
ε_{cr} – critical pressure ratio
ξ – coefficient of the arc power heating the gas in the nozzle

2. METHOD OF CALCULATION

It was assumed that the pressure inside the pole of the circuit breaker does not change during the interruption of a short-circuit current.

First let us consider the outflow of SF_6 through the nozzle throat. The volume considered is the volume of the nozzle between the compression chamber conduit and the nozzle throat.

According to the first thermodynamic law the energy balance equation is as follows:

$$\delta Q = \delta U + \delta W \tag{1}$$

where:

$$\delta Q = c_p \left(T_{n\_in} dm_{n\_in} - T_n dm_{n\_out} \right) + P(u_a, i_a) \tag{2}$$

$$\delta U = c_v d(Tm) = c_v \left(T_{n\_in} dm_{n\_in} - T_n dm_{n\_out} + m_n dT_n \right) \tag{3}$$

$$\delta W = p_n dV_n \tag{4}$$

The ideal gas equation concerning the SF_6 inside the nozzle before the throat:

$$p_n V_n = m_n R T_n \tag{5}$$

In the differential form:

$$dp_n V_n + p_n dV_n = R\left(m_n dt_n + T_n dm_n \right) \tag{6}$$

Taking into account:

$$\kappa = \frac{c_p}{c_v} \qquad\qquad R = c_p - c_v \tag{7}$$

and

$$m_n = \rho_n V_n \tag{8}$$

Substituting equations (2-8) into (1) one can describe the pressure change in the nozzle as:

$$\frac{dp_n}{dt} = \frac{\kappa}{V_n}\left(\frac{1}{\rho_n}\frac{dm_n}{dt} - p_n \frac{dV_n}{dt} \right) + \frac{\kappa - 1}{V_n}\left(P(u_a, i_a) + R\left(T_{n\_in} - T_n \right)\frac{dm_{n\_in}}{dt} \right) \tag{9}$$

The change of SF_6 density in the nozzle before the throat:

$$\frac{d\rho_n}{dt} = \frac{1}{V_n}\left(\frac{dm_n}{dt} - \rho_n \frac{dV_n}{dt}\right) \tag{10}$$

The ratio of the gas pressure in the pole of the circuit-breaker and in the nozzle:

$$\varepsilon = \frac{p_{ext}}{p_n} \tag{11}$$

Critical pressure ratio of the gas in the nozzle at which the SF_6 in the opening between the pole and the nozzle reaches the speed of sound [5] is determined by:

$$\varepsilon_{cr} = \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \tag{12}$$

The intensity of the gas outflow m_{n_out} through the nozzle throat can be calculated according to formulae:

$$\frac{dm_{n\_out}}{dt} = \begin{cases} A\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2(\kappa-1)}}\sqrt{\kappa p_n \rho_n} & for \quad \varepsilon \in <0, \varepsilon_{cr}> \\ A\sqrt{\frac{2\kappa}{\kappa-1} p_n \rho_n \left(\varepsilon^{\frac{2}{\kappa}} - \varepsilon^{\frac{\kappa+1}{\kappa}}\right)} & for \quad \varepsilon \in <\varepsilon_{cr}, 1> \end{cases} \tag{13}$$

In accordance with Lowke and Ludwig [6] the diameter of the arc (in SI units):

$$d_{arc} = 0.004976\sqrt[4]{\frac{z}{p_n}}\sqrt{i} \tag{14}$$

The area of gas outflow through the nozzle:

$$A_n = A_{cr} - \pi\frac{d^2}{4} \tag{15}$$

The power released by the arc in the nozzle is assumed as:

$$P(u_a, i_a) = U_a i_a \xi \tag{16}$$

Bearing in mind that the gas in the compression chamber is not heated by the arc and there is no inflow of gas, the same reasoning for the compression chamber yields the simplified formulae:

$$\frac{dp}{dt}=\frac{\kappa}{V}\left(\frac{T}{\rho}\frac{dm}{dt}-p\frac{dV}{dt}\right)$$
$$\frac{d\rho}{dt}=\frac{1}{V}\left(\frac{dm}{dt}-\rho\frac{dV}{dt}\right) \tag{17}$$

The instantaneous volume of the compression chamber:

$$V=B(l-x) \tag{18}$$

The derivative:

$$\frac{dV}{dt}=-B\frac{dx}{dt}=-Bv_t \tag{19}$$

By combining equations 19 and 20 with equation 18 the pressure change and the gas density can be expressed as:

$$\frac{dp}{dt}=\frac{\kappa v_t p}{l-x}-\frac{\kappa p}{\rho B(l-x)}\frac{dm_{out}}{dt}$$
$$\frac{d\rho}{dt}=-\frac{1}{B(l-x)}\frac{dm_{out}}{dt}+\frac{\rho v_t}{l-x} \tag{20}$$

Similar equations can be derived for the pneumatic drive: the working cylinder receives air from the pressure tank and there is no air outflow; the damping cylinder on the other hand has only an air outflow. The actuator drive force:

$$F_a=B_w p_w-B_d p_d \tag{21}$$

The drive movement depends on the total force ***F*** acting on the contacts of the circuit breaker:

$$F=F_a-F_N-F_K-F_S-Mg-B(p-p_{ext}) \tag{22}$$

Finally, the phenomena in the circuit breaker satisfy the following system of differential equations:

$$\frac{dp}{dt}=\frac{\kappa v_t p}{l-x}-\frac{\kappa p}{\rho B(l-x)}\frac{dm_{out}}{dt}$$
$$\frac{d\rho}{dt}=-\frac{1}{B(l-x)}\frac{dm_{out}}{dt}+\frac{\rho v_t}{l-x} \tag{23}$$

$$\frac{dp_n}{dt} = \frac{\kappa\, p_n}{V_n}\left(\frac{1}{\rho_n}\frac{dm_n}{dt} - \frac{dV_n}{dt}\right) + \frac{\kappa - 1}{V_n}\left(P(u_a, i_a) + R(T_{n\_in} - T_n)\frac{dm_{n\_in}}{dt}\right)$$

$$\frac{d\rho_n}{dt} = \frac{1}{V_n}\left(\frac{dm_{n\_in}}{dt} - \frac{dm_{n\_out}}{dt} - \rho_n \frac{dV_n}{dt}\right)$$

$$\frac{dp_w}{dt} = \frac{\kappa_{air}\, p_w}{V_w}\left(\frac{1}{\rho_w}\frac{dm_w}{dt} - \frac{dV_w}{dt}\right) + \frac{\kappa_{air} - 1}{V_w} R_{air}(T_m - T_w)\frac{dm_{w\_in}}{dt}$$

$$\frac{d\rho_w}{dt} = \frac{1}{V_w}\left(\frac{dm_{w\_in}}{dt} - \rho_w \frac{dV_w}{dt}\right)$$

$$\frac{dp_d}{dt} = \frac{\kappa_{air}\, p_d}{V_d}\left(\frac{1}{\rho_d}\frac{dm_d}{dt} - \frac{dV_d}{dt}\right)$$

$$\frac{d\rho_d}{dt} = -\frac{1}{V_w}\left(\frac{dm_{d\_out}}{dt} + \rho_d \frac{dV_d}{dt}\right)$$

$$\frac{dx}{dt} = v_t$$

$$\frac{dv_t}{dt} = \frac{F}{M}$$

3. CALCULATION RESULTS

Using the formulae derived it is possible to calculate: contact movement, SF_6 pressure in the compression chamber and in the nozzle, the arc diameter in the critical cross section and the change in the gas outflow area through the nozzle, as well as the air pressure in the working and damping chambers of the actuator as functions of time.

During the breaking operation the actuator moves the piston and compresses the gas in the compression chamber. The gas flows through the nozzle and at the final position of the contacts the pressure in the compression chamber reduces to match the value in the circuit-breaker pole. The arc should be extinguished at the time when the pressure and the gas outflow assume their highest values.

At first the contacts are closed and the fixed contact partly closes the critical cross-section of the nozzle. When the contacts separate the arc is initiated and heats the SF_6 gas, which partly “clogs” the critical cross-section of the nozzle. The arc diameter is diminished by the increased pressure in the nozzle and prevents complete clogging of the gas outflow. Finally, when the fixed contact is taken out of the nozzle - the outflow area increases, and the pressure in the nozzle drops.

Figure 3 shows: the contact position and velocity, the pressure in the compression chamber when opening the circuit breaker without current interruption and when switching a short-circuit current of 31.5 kA and the effective cross-section of the nozzle throat. Figure 5 and 7 illustrate the same quantities when switching currents of 40 kA and 50 kA. Figure 4 shows the SF_6 pressure in the compression chamber and in the nozzle.

The temperature in the volume of gas between the compression chamber and the nozzle throat increases due to arc burning. An increase in pressure follows. When the current reaches a certain value the pressure in the nozzle can reach values greater than in the compression chamber. This phenomenon lasts only for a few milliseconds (see Fig. 4). The momentary AC current value decreases and finally the pressure falls to the same value as in the compression chamber. With the increase in the current crest value, the crest value of the pressure and the duration of the pressure rise both increase.

When the nozzle throat leaves the fixed contact only a part of the arc length heats the gas in the nozzle before the throat. For the same momentary current value the gas temperature and pressure is lower. On the other hand the pressure in the compression chamber becomes higher – and there is no longer any difference between the pressure in the compression chamber and in the nozzle.

Figure 6 shows the SF_6 density in the compression chamber and in the nozzle. The interrupted current (31.5 kA, 40 kA and 50 kA) increases the SF_6 temperature and decreases its density.

Figure 8 shows the instantaneous effective outflow area of the nozzle and the diameter of the arc column.

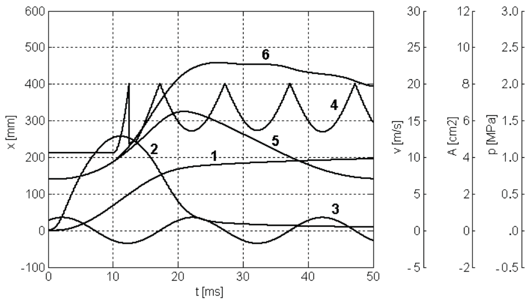

Fig. 3. Switching characteristics for 31.5 kA:
1 – contact position [mm], 2 – contact velocity [m/s], 3 – current form, 4 – free nozzle area [cm^2], 5 – SF_6 pressure in the compression chamber without the presence of a current [MPa], 6 – SF_6 pressure in the compression chamber with a short-circuit current [MPa]

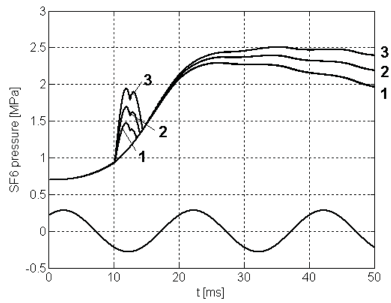

Fig. 4. SF_6 pressure in the compression chamber and in the nozzle before the throat when switching short-circuit currents:
1 – 31.5 kA, 2 – 40 kA, 3 – 50 kA

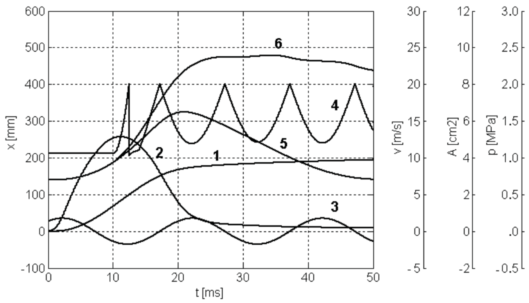

Fig. 5. Switching characteristics for 40 kA. Plot numbering as in Fig. 3

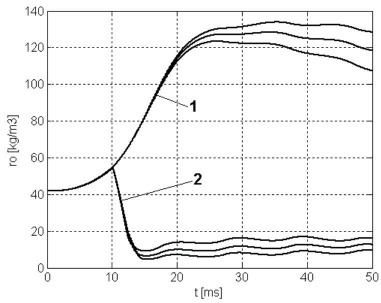

Fig. 6. SF_6 density in the compression chamber (1) and in the nozzle before the throat (2) when switching short-circuit currents 31.5 kA, 40 kA and 50 kA

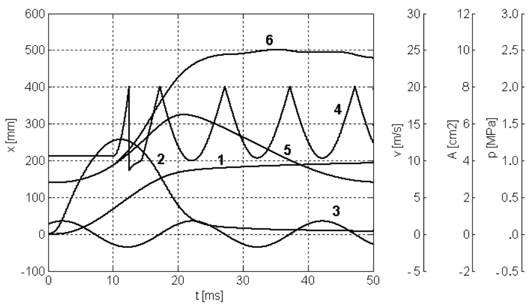

Fig. 7. Switching characteristics for 50 kA. Plot numbering as in Fig. 3

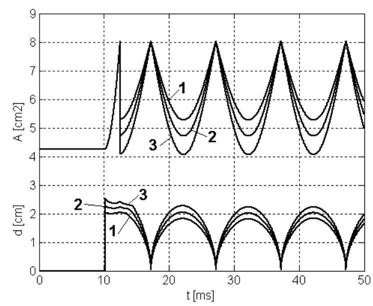

Fig. 8. Effective cross-section area of the nozzle throat and the arc diameter when switching short-circuit currents:
1 – 31.5 kA, 2 – 40 kA, 3 – 50 kA

4. CONCLUSIONS

The calculated gas outflow area is reduced with the rise in the instantaneous current value (see Figs 3, 5 and 7). The clogging effect (Fig. 8) raises the pressure before the throat, as well as in the compression chamber to a much greater value than in the pole of the circuit breaker (Fig. 4). The instantaneous pressure rises also with the rise in the current value (Fig. 4) and can result in an increase in the breaking ability of the circuit breaker. The SF_6 gas temperature in the volume between the compression chamber and the nozzle throat is much higher, than in the compression chamber because the energy of the electrical arc is dissipated in the nozzle.

It can happen after some short-circuit current interruptions, when the arc current diameter is almost equal to the critical cross section of the nozzle, that the high temperature of the arc and the arc radiation cause ablation of the nozzle material, increasing its diameter and adversely affecting the long term interrupting ability of the circuit breaker.

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ZMIANY PRZEKROJU KRYTYCZNEGO DYSZY SF_6 AUTO-PNEUMATYCZNEGO WYSOKONAPIĘCIOWEGO WYŁĄCZNIKA PODCZAS WYŁĄCZANIA PRĄDU ZWARCIOWEGO

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STRESZCZENIE: *W artykule podano sposób obliczania wypływu gazu SF6 w przekroju krytycznym dyszy w wyłącznikach autopneumatycznych. W wyniku działania łuku elektrycznego podczas wyłączania prądu zwarciowego może dochodzić do zatykania dyszy i wzrostu ciśnienia, a po wielokrotnych wyłączeniach w wyniku wysokiej temperatury łuku może wystąpić deformacja dyszy i pogorszenie własności łączeniowych. Do obliczeń przyjęto wyłącznik z napędem pneumatycznym, posiadający komorę roboczą i tłumiącą. Po rozejściu się styków zapala się łuk, który wydłużony do przekroju krytycznego dyszy zatyka częściowo dyszę zwiększając w efekcie ciśnienie w objętości dyszy wskutek wzrostu temperatury gazu. Po wielokrotnych wyłączeniach prądu zwarciowego wysoka temperatura powoduje degradację powierzchni w przekroju krytycznym dyszy i w efekcie powiększenie przekroju dyszy, co może zmienić parametry łączeniowe wyłącznika.*

Słowa kluczowe: *wyłącznik autopneumatyczny SF_6, dysza, ablacja, przepływ gazu*