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The influence of the arc-quenching medium density on the rate of electrical strength recovery of the intercontact gap

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One of the problems in designing new arc-quenching devices for HV AC gas-blast circuit breakers is the choice of an insulating arc-extinguishing medium, since the main insulating medium sulfur hexafluoride (SF_6) is a greenhouse gas. Much attention to insulating gas environments with a low density relative to SF_6 (dry air, N_2, CO_2) is paid. The structure of the gas flow in the arc-quenching device has a significant impact on the rate of electrical strength recovery of the contact gap. In this paper, the interdependence between the generation of turbulence and the processes of electrical strength recovery in the thermal phase of breakdown for gases of different densities (N_2, CO_2, SF_6) in a typical configuration of an arc-quenching device based on supersonic nozzle are studied.

Keywords: switching arc, electrical strength recovery, turbulence, breaking capacity, numerical simulation.

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One of the major problems encountered in increasing the rated parameters per interruption in arc-quenching devices (AQDs) of HV AC gas-blast circuit breakers is the enhancement of breaking capacity. The main insulating and arc-quenching medium in AQDs designed for ultra-high voltages and high rated breaking currents is electronegative gas (SF_6). However, it is a greenhouse gas with a high global warming potential (GWP = 23 500) [1]. Therefore, a rather intensive search for alternative arc-quenching media has been performed in recent decades. Research attention is focused on insulating gas media with a density smaller than that of SF_6 (dry air, N_2, CO_2), gases with a density comparable to or higher than the one of SF_6 (e.g., C_4F_7N, $C_5F_{10}O$), and their mixtures with lighter gases (dry air, N_2, CO_2) [2]. Alternative gas media, such as dry air, CO_2, and N_2, are characterized by a slow (compared to SF_6) recovery of electrical strength of the AQD intercontact gap after zero current. The process of recovery of electrical strength is divided tentatively into four phases [3]. The transition from one phase to another is continuous. The first phase is associated with thermal breakdown and lasts for several microseconds after zero current. It is the thermal phase that plays an important role in the process of electrical strength recovery. The structure of gas flow (the distribution of pressure fields, the presence of shock waves, and the intensification of turbulence of arc-quenching flow) has a significant impact on the rate of recovery of the electrical strength of the intercontact gap in the thermal breakdown phase. Notably, an increase in kinetic energy of turbulent pulsations is observed in experiments prior to current zero (CZ) and in the thermal phase of breakdown [4–6].

In the present study, we analyze the influence of density of arc-quenching gas on the rate of growth of turbulence energy at CZ based on the turbulence energy balance equation. A numerical experiment was performed in order to compare the rate of electrical strength recovery of the intercontact gap in the following gases: N_2, CO_2, and SF_6. Since experimental data for alternative gases with a density higher than the one of SF_6 (e.g., C_4F_7N, $C_5F_{10}O$) are fragmentary and scarce at present, other arc-quenching media were not examined.

As was demonstrated in [7], the kinetic energy of turbulence in unit volume $E_t = \overline{\rho' u'_k u'_k}/2$ (u'_k are projections of the pulsating velocity component on the corresponding axes) increases due to the fact that a generation term proportional to $d\overline{u}/dt$ ($\overline{u}$ is the average velocity value in the direction of axis x) is present in the equation. In the vicinity of CZ, the remaining terms on the right-hand side of the turbulent kinetic energy equation may be neglected. In this case, the equation takes the form

$$\frac{dE_t}{dt} = -\overline{\rho' u'}\frac{d\overline{u}}{dt}, \tag{1}$$

where the bar denotes averaging, fluctuation values are primed, and ρ', u' are the pulsation of density and velocity of the gas medium. In an arbitrary cross section of the channel, the following approximate equality [8] is valid for the averaged values of density and velocity:

$$\overline{\rho}_a \overline{u}_a^2 \cong \overline{\rho}_e \overline{u}_e^2. \tag{2}$$

In Eq. (2), subscript a corresponds to parameters in the core of an arc, while subscript e corresponds to parameters in the cold gas flow. It should be noted that formula (2) is valid for any two points of the section. It was also demonstrated in [7] that

$$\overline{\rho' u'} = Cl^2 \frac{\partial^2 \sqrt{\overline{\rho}}}{\partial r^2}, \tag{3}$$

where $C = \sqrt{\overline{\rho}_e \overline{u}_e} = \text{const}$ and l is the mixing length, which is usually defined in arc problems as the arc radius.

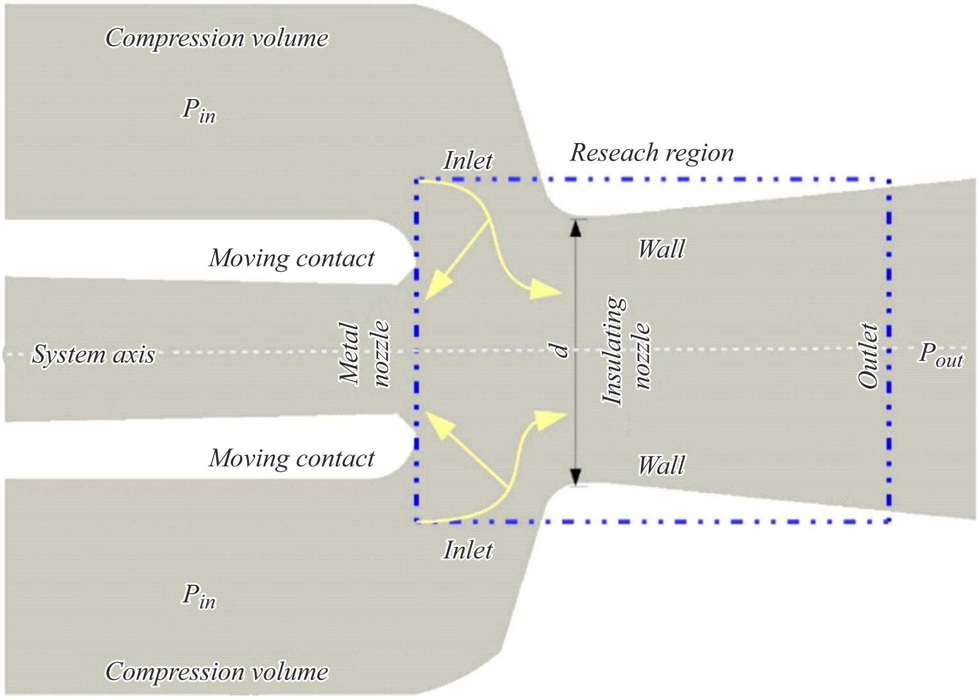

Figure 1. Typical configuration of an AQD based on a supersonic nozzle.

Using Eqs. (2), (3) and the formula for approximate calculation of the second derivative, we may obtain the following expression:

$$\frac{dE_t}{dt} = -C\sqrt{\rho_e}\left(1 - \frac{\sqrt{\rho_{e/2}}}{\sqrt{\rho_e}} + \frac{\sqrt{\rho_a}}{\sqrt{\rho_e}}\right)\frac{d\overline{u}}{dt}$$
$$= -C\sqrt{\overline{\rho}_e}\left(1 - \frac{\sqrt{\overline{\rho}_{e/2}}}{\sqrt{\overline{\rho}_e}} + \frac{\sqrt{\overline{\rho}_a}}{\sqrt{\overline{\rho}_e}}\right)\frac{d}{dt}\left(\sqrt{\frac{\overline{\rho}_e}{\overline{\rho}_a}}\,\overline{u}_e\right), \tag{4}$$

where subscript $e/2$ characterizes the parameters in the mixing layer between the arc core and cold gas. Within the time intervals under consideration, the flow velocity in cold gas in the chosen section changes little compared to the rate of change of density. It may be regarded as a constant within a given period of time. Thus, the rate of change of kinetic energy of turbulence in unit volume depends on the rate of change of density of the arc-quenching medium. With increasing density, the rate of growth of turbulence energy will increase and, consequently, the process of heat removal from the arc will intensify. This should translate into a higher rate of electrical strength recovery of the gap and allow one to improve the AQD breaking capacity.

Figure 1 presents the configuration of an AQD based on a supersonic nozzle, which is typical for most HV AC gas-blast circuit breakers. The calculation domain is highlighted. The direction of gas flow is indicated by yellow arrows. Numerical modeling was carried out on the basis of experimental data [9]: nozzle throat diameter $d = 12\,\mathrm{mm}$ and pressure drop $P_{in} : P_{out} = 3.4 : 1\,\mathrm{atm}$. The temporal variation of current corresponds to a synthetic circuit where the steady-state value is $I_{\max} = 1.5\,\mathrm{kA}$, $dI/dt = -27\,\mathrm{A}/\mu\mathrm{s}$. The examined arc-quenching media were N_2, CO_2, and SF_6. The time-averaged system of magnetohydrodynamic equations supplemented by Ohm's law and a model of turbulent viscosity and radiation transfer [10] was used for numerical modeling of the influence of arc-quenching gases on the rate of electrical strength recovery of the intercontact gap. The model of turbulence at the first stage of the synthetic circuit (current is constant, steady state) included two types of instability: shear instability in the mixing layer between the arc core and cold gas and the Rayleigh–Taylor instability [10]. The theory of „freezing“ of kinematic turbulent viscosity [10] was used to analyze the second stage of the synthetic circuit (current decreases linearly, non-steady state): within the period of current reduction, the kinematic turbulent viscosity is assumed to be constant and equal to its steady-state value. The radiative heat conduction approximation [10] was used to model radiation transfer. Radiation transfer produces a significant contribution to heat transfer at the maximum current value (but not at CZ) and has no effect on the subsequent recovery of the intercontact gap strength in the thermal phase of breakdown.

It is known from experiments [4] that certain regions on the arc axis are characterized by a faster temperature reduction after CZ in the thermal breakdown phase. The electrical strength of gas starts to recover if the temperature at least at two points on the arc axis [11] reaches 3000 K for SF_6 and 4000 K for N_2 and CO_2 [12,13]. The rate of strength recovery depends on the length of the non-conducting section and the pressure within this interval.

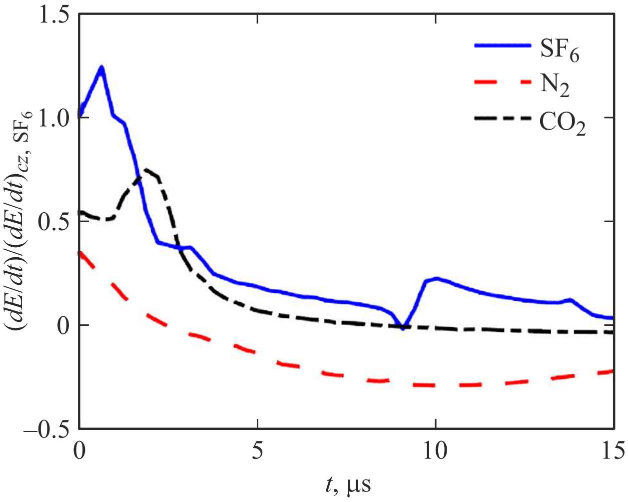

Figure 2. Dependence of the kinetic energy of turbulence on the axis in the insulating nozzle throat on time after CZ.

The results of numerical modeling are presented in Figs. 2–4. Figure 2 shows the relative variation of kinetic energy of turbulence on the axis in the insulating nozzle throat $\frac{dE_t}{dt}/\left(\frac{dE_t}{dt}\right)_{cz,\mathrm{SF}_6}$ calculated using formula (4) as a function of time after zero current (cz) for various arc-quenching gases. The change in turbulence energy at CZ in SF_6 was chosen as the scale value. The curves suggest that the generation of kinetic energy of turbulence in SF_6 is at its peak within the first few microseconds. SF_6 has the highest density of the three gases under consideration and the lowest axial temperature (Fig. 3, a) at zero current in the throat and the first third of the diffuser, where the intercontact gap strength starts to recover. Light gases (N_2 and CO_2) have a similar temperature value in the throat and a plateau near the nozzle throat and in the diffuser. The similarity of temperature curves is attributable to the smallness of the diffuser half-angle and closeness of ratio of specific heats for N_2 and CO_2. It should be noted that the generation of turbulence in nitrogen (Fig. 2) drops to negative values within 2 μs after CZ. Thus, the turbulization intensity does not increase after CZ, and the process of energy removal from the decaying arc becomes less intense. This conclusion is verified by the distribution of average temperature on the axis $T_{axis\,mid}$ at CZ and in the thermal breakdown phase (see Fig. 3, b). The process of strength recovery in the thermal phase of breakdown in N_2 is initiated later than in the other two gases. The rate of growth of the maximum breakdown voltage U determines the rate of recovery of electrical strength of the intercontact gap. Figure 4 illustrates the nature of variation of U as a function of time after CZ and confirms that heat removal grows weaker to the reduction in turbulence generation in N_2. The length of the time interval from CZ crossing to the moment when gas becomes non-conductive at least at two calculated points determines the delay of recovery of electrical strength of the gap. The curve corresponding to N_2 has the maximum delay time and the lowest breakdown voltage U within the entire time interval under study. At the same time, CO_2 and SF_6, which have a close level of turbulence generation, also have similar delays of recovery of electrical strength, which is confirmed by Fig. 4. The comparative analysis of calculated and experimental data [9] in Fig. 4 confirms that the reported findings agree closely with the general concepts regarding the process of electrical strength recovery of the intercontact gap in various arc-quenching gases.

In the present study, the influence of arc-quenching gas density on the rate of growth of turbulence energy at CZ was revealed via statistical analysis. It was found that the growth rate of kinetic energy of turbulence increases with increasing density, which leads to intensification of heat removal from the arc at CZ and in the thermal breakdown phase. The numerical study of the growth rate of ultimate breakdown voltage (recovery of electrical strength of the intercontact gap) in N_2, CO_2, and SF_6 gases confirms this conclusion. The examined effects should be more pronounced in gases with a density higher than that of SF_6, which will be investigated in the future. Thus, one needs to devote certain attention to the study of alternative gases with a density higher than (or comparable to) the SF_6 when designing new AQDs with higher rated parameters.

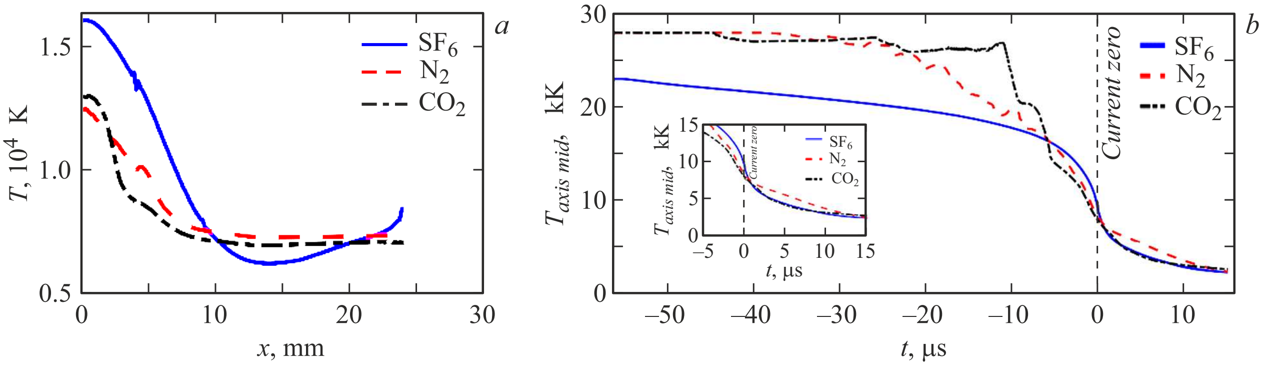

Figure 3. Temperature along the x-axis for different arc-quenching gases: at CZ (a) and in the vicinity of CZ (b).

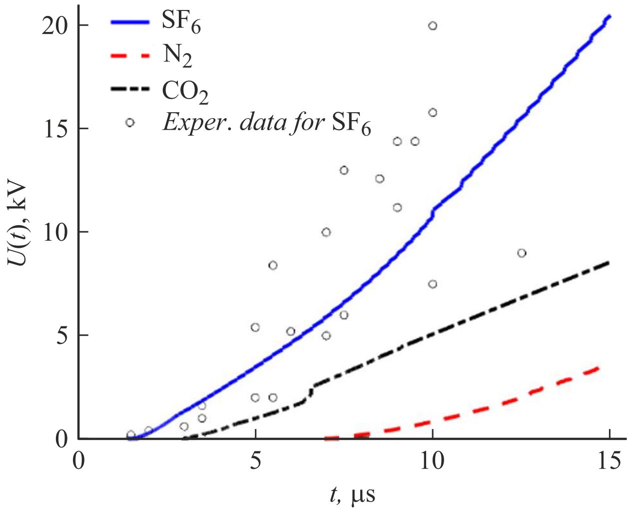

Figure 4. Rate of growth of ultimate breakdown voltage as a function of time after CZ for different arc-quenching gases.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] C.M. Franck, A. Chachereau, J. Pachin, IEEE Electr. Insul. Mag., **37** (1), 7 (2021). DOI: 10.1109/MEI.2021.9290463

[2] L. Zhong, J. Wang, J. Xu, X. Wang, M. Rong, Plasma Chem. Plasma Process., **39**, 1379 (2019). DOI: 10.1007/s11090-019-10015-8

[3] H. Ikeda, T. Ueda, A. Kobayashi, M. Yamamoto, S. Yanabu, IEEE Trans. Power Appar. Syst., **PAS-103** (10), 3038 (1984). DOI: 10.1109/TPAS.1984.318308

[4] K. Ragaller, *Current interruption in high voltage networks* (Plenum Press, N.Y., 1978).

[5] R. Bini, N.T. Basse, M. Seeger, J. Phys. D, **44**, 025203 (2011). DOI: 10.1088/0022-3727/44/2/025203

[6] E.P. Bel'kov, Zh. Tekh. Fiz., **44** (9), 1946 (1974) (in Russian).

[7] S. Averianova, N. Akatnov, E. Tonkonogov, in *XVI Symp. on physics of switching arc* (Brno, Czech Republic, 2005), vol. 1, p. 13–17.

[8] J.D. Yan, K.I. Nuttall, M.T.C. Fang, J. Phys. D, **32**, 1401 (1999). DOI: 10.1088/0022-3727/32/12/317

[9] H.-R. Moll, *Untersuchungen über die dielektrische Verfestigung bei SF-6-Leistungsschaltern*, Diss. Arb. (ETH, Zürich, 1983).

[10] S. Averianova, N. Akatnov, E. Tonkonogov, in *VII Int. Conf. „Plasma physics and plasma technology“* (Minsk, Belarus, 2012), p. 655–658.

[11] S.A. Aver'yanova, *Teoriya gasheniya dugi v elektricheskikh apparatakh. Vzaimodeistvie dugi otklyucheniya s gazovym potokom* (2024) [Electronic source] (in Russian). http://elib.spbstu.ru/dl/2/5480.pdf

[12] B. Chervy, A. Gleizez, M. Razafinimanana, J. Phys. D, **27**, 1193 (1994). DOI: 10.1088/0022-3727/27/6/017

[13] V.S. Engel'sht, A.B. Uryukov, *Nizkotemperaturnaya plazma* (Nauka, Novosibirsk, 1990), Vol. 1 (in Russian).

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