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Controlled pulsed injection for HV gas blast circuit breakers

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Abstract. According to modern trends, the interrupting performance and reliability of HV gas blast circuit breakers should be increased with transition to SF_6-free technologies. Controlled switching is a promising method to reach it. However, high level of failure of the operating mechanism (drives) hinders this goal and would also result in the serious accidents. Some problems of the controlled switching application are discussed in the present study. A method of a short time gas pulse under high pressure – synchronous gas injection – is proposed to achieve the necessary cooling-heating balance in a thermal mode considering benefits and drawbacks of the controlled switching. The controlled pulsed injection should be introduced to the plasma region before current zero to decrease pre-zero arc conductivity and achieve the effective arc-gas interactions immediately after current zero. In the study the performance of the suggested approach is verified by numerical simulation and empirical relationships with a model mono-flow arc quenching device. The research confirms the synchronous gas injection has a wide perspective to increase breaking capacity of realistic circuit breakers in high voltage levels, especially for short-circuit interrupting.

Keywords: HV gas-blast circuit breakers, arc quenching, breaking capacity, controlled switching, synchronous gas injection, numerical simulation

1. Introduction

The use of the controlled switching in HV gas blast circuit breakers (GCB) undoubtedly has considerable promise and is aimed at limiting the transients and overvoltage in the power system, improving the electric power quality, reducing the risks of electrical equipment failure. Conseil International des Grands Réseaux Electriques (CIGRE) prepared several documents on practical use of controlled switching in GCB (WG 13.07, WG A3.07, WG A3.35). To date, typical controlled switching applications include operations for switching capacitive currents and shunt reactors, power transformers, and power transmission lines. But there are problems of the controlled switching use, as shown below.

To implement an effective controlled switching scheme, the behavior of the system is to be predicted and the break time is to be determined accurately the next points of current zero (CZ). Many factors may affect the measurement of the initial parameters of current and voltage necessary for the controlled switching: the asymmetry of the angles between the phases, a nonlinear transient resistance at the site of the short-circuit, external disturbances, etc. The use of the controlled switching in practice is also limited by the reliability and performance of auxiliary drive devices for a fixed command signal before CZ. Such devices should control/change the break time due to the type of an accident. A large share of the GCB failures is associated with drives. An insufficient pressure build-up or small contact distance necessary for effective work of the nozzles, a limited volume of the arc quenching medium at the end of the interruption window due to much loss of extinction pressure can inhibit the use of the controlled switching in modern auto-puffer circuit breakers.

Today, SF_6 is widely used in GCB for high voltage levels commutation. But, under the Kyoto Protocol adopted in 1997, the use of SF6 should be restricted. This is because SF_6 has a high global warming potential (GWP = 23500), and its decomposition products are highly toxic. Many scientific works of recent years are devoted to a search for alternative arc-quenching media [1] such as: dry air, CO_2, $(CF_3)_2CFCN$, known as g^3 (or "green gas for grid") and mixtures of g^3 with nitrogen N_2 and carbon dioxide CO_2. However, they rank below SF_6 in their arc-quenching properties, and different technical solutions will be preferred, or even be operated in parallel.

In this paper the synchronous gas injection (SGI) is proposed as a new controlled switching technique of arc quenching to increase the interruption performance of GCB. The SGI is a controlled short-time pulse of gas under high pressure directed into the remnant arc at the vicinity of CZ. Dry air is considered as the SF_6-free medium.

2. Synchronous gas injection study

The power source of the experimental stand with controlled switching [2] was a Gorev single-frequency oscillatory circuit with a capacitor battery, where the amplitude of the first half-wave was 1200–1400 A at the initial voltage of 10 kV and frequency of 50 Hz. The current and the arc voltage within the half period, the arc current near CZ, the recovery voltage and the pressure in the chamber of the model were measured. Analysis of the results of the experiments [2] confirms the controlled switching efficiency and shows that the arc quenching performance of the mono- and double-flow systems increases when the contacts are opened 1.5–3 msec before CZ: the limiting value of the extinguishing pressure is minimal within the specified interval (see Fig. 1). In the interval up to 1.5 msec, there is a deterioration the interruption ability, since, as we assume, the time of transition of the gas flow to the "stationary" flow mode, i.e. "relaxation" of the flow without shock waves is of considerable importance.

Fig.1 clearly demonstrates the advantage of the mono-flow system. However, as known, the arc-quenching in the double-flow device have significantly better interruption ability (by 1.4–1.5 times). Conflicting results of the research in the experiments [2] reveal the weak points of the design features of the double-flow chamber. For example, the arcing time in the study [3] with similar system design was about 1.5–2 msec. That means a successful commutation took place before than 1.5 msec. Possible reasons for these discrepancies may stem from the distribution of pressure fields in the upstream region and the complex dynamics of the plasma column propagation in the nozzle throats under the action of the gas flow, directly depending on the design of the arc-quenching device. As it is shown in the paper [4], the arc-quenching process may be slowed down in case of formation of the gas flow stagnation zone marked by a high temperature, minimum mass flux, and high pressure. The formation of such stagnation area depends on the geometry of the nozzle channel (more distinctive for the double-flow system) and defines the pre-zero arc conductivity.

The arc conductivity, G, before CZ was used as a performance indicator in [5], including the results of short line fault tests in the range 16–70 kA on a 300 kV single break model SF_6 circuit breaker. For current 50 kA and 63 kA, a distinct limiting value of G (–200 nsec) was found of 1.5 mS, implying that in all cases where G (–200 nsec) more than 1.5 mS the test resulted in reignition, and all G (–200 nsec) value below 1.5 mS showed interruption. The pre-zero arc conductivity value depends on an accident and, also, the environment influence on residual arc column. The research [6] presents a fast rise in the dielectric recovery for 100 μsec after CZ. During this time the reignition occurred in the axis of the breaker. The breakdown voltages in the first 100 μsec were showed to scale mainly with the pressure, i.e. temperature decays were similar for different pressures and were independent of current. Therefore, the SGI must provide the necessary extinction pressure into the time interval ±0.1 msec around CZ. To limit the gas flow critical mode through the nozzle throat, the SGI pressure is to be more than the main gas flow pressure by 2–3 times.

In the paper [7], the formation of the upstream region in relation to the place of the SGI supply was studied on the example of a classical mono-flow arc quenching device. The impact of the SGI should be directed to the areas of key importance in the subsequent arc quenching process in the thermal and dielectric phases of the breakdown. These areas include nozzle throat and stagnation points in the upstream region. It was found that the most effective injector is the one closest to the nozzle throat in the upstream region. The intensification of the gas flow by the SGI at simultaneous destruction of the stagnation points [4] can lead to the accelerated displacement of the arc column into the nozzle throat. Well-balanced and stable gas flow across the nozzle throat contributes to the more effective arc-gas interactions, provides the enhanced deionization between the electrical contacts, additional energy removal from the arc column through diffusion and convection. In the research [8], the formation of a stable gas flow between contacts after ~1 msec is shown by the example of the double-flow arc-quenching systems of different designs using numerical simulation for a transonic flow of compressible gas (air) with dynamic mesh. The SGI is to be initiated from ~1 msec before CZ to reach the maximum interaction between the gas flow and the residual plasma column in the thermal mode. The shape of the SGI should be chosen from the condition of minimum mass flow with maximum performance.

Therefore, the following parameters of the SGI are selected:

a. The SGI pressure exceeds the basic pressure by 3 times;

b. The site of injection is selected in view of the most effective point of the SGI impact on the most probable arc quenching area in the initial part of the QC nozzle diffuser as the closest to the nozzle throat in the upstream region;

c. The pulse duration is 2 msec, its shape is shown in Fig.2. The SGI is initiated when the main flow becomes stationary and corresponds to the time of 1 msec before CZ to achieve maximum influence at the vicinity of CZ;

d. The size of the injection site, d, is taken from the ratio $d = 0.1d_c$ to minimize the SGI consumption, where d_c is the nozzle throat diameter.

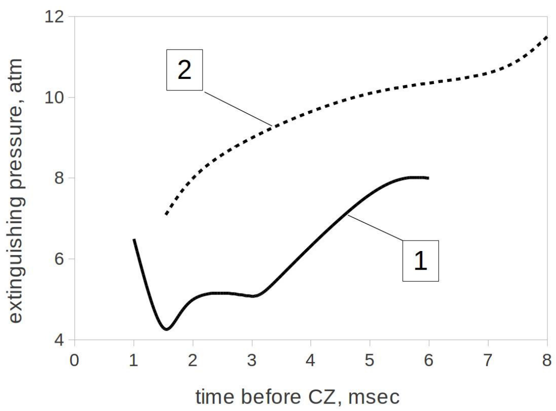

Fig.1. Extinguishing pressure versus time of contacts opening at various current phases for the different type of model devices: 1 – mono-flow, 2 – double-flow systems.

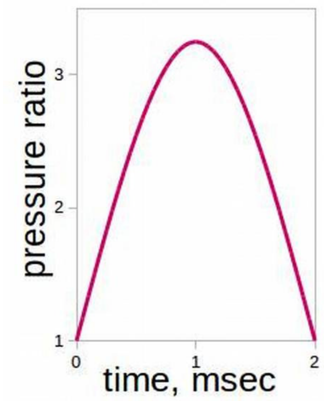

Fig.2. SGI pulse shape.

3. Mathematical model

The model of the mono-flow gas arc quenching device (QC) with controlled switching [2] is shown in Fig.3. The air flow direction is indicated by blue arrows. The QC with the closed contacts was filled with the compressed gas up to the required pressure. The pressure was controlled by an induction pressure sensor (3). Then the pressure was set, and the circuit discharge current passed through the closed contacts. Then an induction-dynamic mechanism (IDM) (6) triggered, which activated movable contact (1) at a certain current phase. When opening an arc appeared between the contacts in the nozzle channel (2), which was quenched in the longitudinal flow of compressed gas.

As the CZ process is investigated in the study the plasma is described as a compressed gas of high energy (with high temperature and velocity). The laws of conservation of mass, momentum and energy, supplemented by the equation of state are the base for the numerical simulation used to describe the transonic flow of compressible gas in the continuous-medium approximation and in disregard of mass forces. The electromagnetic forces in the law of conservation of momentum are negligible, and in the law of conservation of energy, the contribution of the electromagnetic component is absent (the current is zero), therefore, they are neglected. The mathematical model was verified on the experimental stand of the IEE RAS [9–11] and showed a close agreement between the calculated and experimental data.

The mathematical model is realized in a library with support of the mesh motion and topological changes rhoCentralDyMFoam in OpenFOAM. The problem is solved as a two-dimensional symmetric one (Fig.4). Compressed air of basic pressure enters the working volume, when the contacts start their opening. SGI of high pressure is introduced via SGI sites (see Fig.4) at 1 msec before CZ. A refined mesh is used in the area between the opening contacts and in the plasma flow area to avoid the mesh degradation. Opening of the contacts is simulated by the mesh rearrangement between the contacts.

It is well-known the temperature range of the plasma column is 10000–20000 K on the arc axis depending on current. At these temperatures and low gas density, the plasma accelerates due to the axial pressure gradient and can reach ~6000 m/sec in the nozzle throat. The plasma temperature drops down to ~2000 K in the shear boundary layer. The diameter of the plasma residual region in the experimental data [2] is about 2 mm. To simulate the arc in the gap between the contacts, a narrow arc channel of the specified diameter, velocity and temperature is used. Heat exchange with the walls is neglected due to high-speed process (adiabatic character of filling of the working volume). Considering the above, the initial and boundary conditions are determined in the mathematical model.

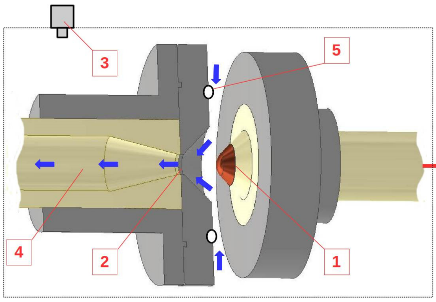

Fig.3. Model mono-flow QC: 1 – movable contact, 2 – nozzle, 3 – induction pressure sensor, 4 – exhaust pipe, 5 – contact spring, 6 – to induction-dynamic mechanism

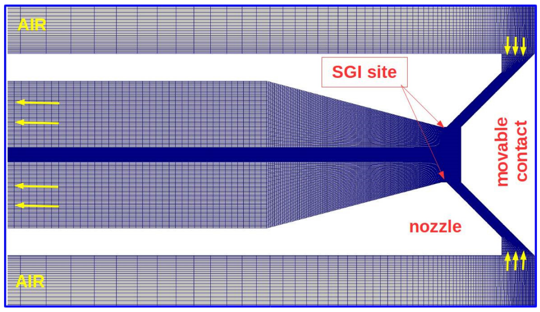

Fig.4. Geometry of computational domain with adaptive mesh.

4. Results and discussion

The empirically derived relations based on the analysis of experimental data on the model QC [2] in conjunction with the numerical simulation are used for the SGI validation. All the dependencies given below are valid for conditions that closely coincide with the conditions of the experiments carried out, both in terms of the geometric similarity of the studied QC, and in the nature of the processes occurring.

Fig.5 shows the fluctuations of the region-averaged values of pressure ratio P_{av}, temperature ratio T_{av}, mass flux ratio Q_{av} (in relation to the corresponding parameters of the basic gas flow without injection) at the outlet of the nozzle throat under the impact of the SGI, depending on the relative distance between the movable contact and the critical cross section of the nozzle s/d_c. Series of tests [2] confirms unique value of ratios $s/d_c \approx 0.6$–0.7 at the contacts opening in different current phases for the model QC with the tuning minimum for extinguishing pressure. An area between the vertical dotted lines limits the area of impact of the SGI with a time base of 2 msec, the yellow vertical line indicates the conditionally accepted CZ in the numerical simulation with maximum amplitude of the SGI.

Analysis of data in Fig.5 shows that at the maximum amplitude value of the SGI the total gas flow provides cooling in the average of ~41%, the averaged value of pressure increases by ~25% with synchronous mass flux advancement of ~18% at the initial part of the nozzle diffuser. Some decrease in the mass flow rate near the maximum SGI could be explained by the fact that the flow process through the nozzle goes into the subcritical mode. At the end of the SGI action, the distributions of gas-dynamic parameters in the area under consideration attain a horizontal plateau: the accumulated effect of the injection impact is observed. The calculation was also carried out for basic pressure from 4 to 10 atm (SGI pressure from 12 to 30 atm accordingly) with similar simulating results for the region-averaged gas dynamic parameters P_{av}, T_{av}, Q_{av} (see Table 1).

One of the most important characteristics affecting the arcing time is the arc resistance, R_{arc}. The change in R_{arc} near CZ characterizes the processes occurring in the arc residual column subject to the environmental impact. In this region, as the cross section of the nozzle is almost occupied by cold gas flow, energy diffusion from arc column into the outer cold gas flow depends upon pressure, kind of gas and the nozzle design. For the moment of time ~1 μsec to CZ, the arc resistance is analytically derived as $R_{arc} \sim K \cdot e^{0.11p}$ [2], where K is the coefficient depending on the arc quenching intensity, K = 9.3 when the contacts are opened 2 msec before CZ with air as arc quenching medium for the QC design. Therefore, it is possible to estimate the nature of the arc resistance change in the vicinity of CZ depending on the pressure value (Fig.6). The value of R_{arc} increases by ~15% when exposed to the SGI amplitude.

A decrease of the arc time constant, τ_{arc}, favours an increase of the arc-quenching efficiency. The physical meaning of the parameter τ_{arc} is the delay time of the decaying plasma at the arc-quenching near CZ. The analysis of the experimental results for the value τ_{arc} for ~1 μsec to CZ in Fig.6 shows that an increase in pressure at the maximum SGI will lead to a decrease in the value τarc (by ~13%, Δp = 4 atm) for this QC design by linear approximation in terms of pressure.

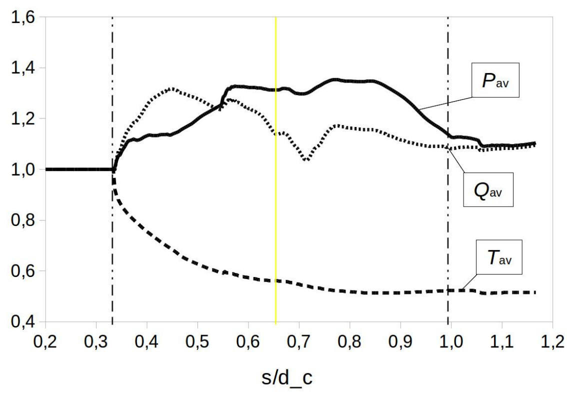

Fig.5. Relative change in the gas dynamic parameters at the outlet of the nozzle throat under the impact of the SGI versus the relative distance between the movable contact and the critical cross-section of the nozzle (Δp = 4 atm).

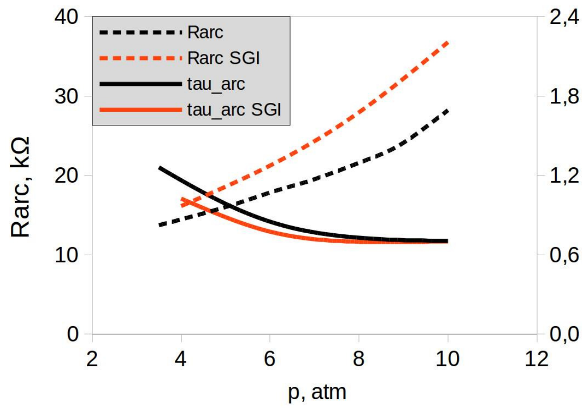

Fig.6. Comparative analysis of changes in R_{arc} (dotted lines) and τ_{arc} (solid lines) in the experiments without the SGI (black) and calculated data with the SGI (red) for different values of basic pressure.

The current and voltage oscillograms [2] allow to determine the rate of change of current at CZ (dI/dt), which is an important indicator of the change in the rate of rise of recovery voltage (*RRRV*). The dependence of the average $(dI/dt)_{av}$ on the cross-average pressure $p_{av}(t)$ in the initial cross-section of the nozzle diffuser when the arc contacts are opened 2 msec before the CZ was analytically determined as $(dI/dt)_{av} = 0.33 + 0.014 p_{av}(t)$. We can estimate the increase of the interruption performance in the thermal phase of the breakdown for the given QC design due to the well-known equation $RRRV \sim p^n(\mathrm{d}I/\mathrm{d}t)^{-m}$, the coefficients were analyzed in papers [7, 8]: $1 < n < 1.6$, $0.7 < m < 3$. Here we assume $n = 1.05$, $m = 1.2$ (dry air medium) [3, 12] with due regard for the minimum value of normalized *RRRV* (by pressure and nozzle throat diameter) versus d*I*/d*t*.

Table 1. Generalized evaluation results of SGI impact efficiency

Parameter, %	Pressure			
	4 atm	6 atm	8 atm	10 atm
P_{av}	+25	+25	+25	+25
T_{av}	-41	-41	-42	-42
Q_{av}	+18	+18	+19	+19
$(R_{arc})_{av}$	+12	+18	+25	+33
$(\tau_{arc})_{av}$	-11	-9	-7	-
$(RRRV)_{av}$	+21	+19	+17	+16

The generalized results of the SGI impact efficiency at different pressure of the main flow, averaged over the cross-sectional area of the initial part of the nozzle diffuser, are given in Table 1 by analyzing both experimental data and numerical simulation.

5. Conclusion

The application of the SGI technique is particularly actual for short-circuit interruption with much loss of extinction pressure at the end of interruption window for HV AC circuit breakers. The parameters of SGI are as following: the SGI pressure exceeds the basic pressure by 2–3 times; the site of injection (with size of 10% of the nozzle throat diameter) is selected as the closest to the nozzle throat in the upstream region; the SGI is to provide the maximum influence on the residual arc column at the vicinity of CZ (±0.1 msec); the pulse duration is 2 msec with introduction into the upstream region at 1 msec before CZ. From the analysis of the obtained values in the study, it can be concluded that the SGI increase the recovery performance in the thermal mode in the range of 16–21% subject to the initial pressure of the compressed air providing the main flow in the model QC under consideration. Increase of the nozzle diameter and optimization of the model QC design to consider the $(RRRV)_{av}$ for pressures 6–10 atm is likely to lead to an improvement in performance.

6. References

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