

# Transformer Oil Dielectric Strength in the Contact Gap of the Explosive Arc-Extinguishing Device

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**Abstract:** The article describes the experimental results on the breakdown of the high-speed flow of transformer oil. In real conditions, the flow moves in the contact gap of a high-voltage explosive switch with speeds from 67 to 152 m / s. The geometry of the contact gap is sharply inhomogeneous and forms turbulence in the flow zone. In the arc chute medium the air inclusions pass from the dissolved state to the gaseous and the emerging bubbles enter to the electric field. Breakdown occurs, mainly through gas inclusions. In the moment, the gradient of the breakdown voltage is reduced by 91.6% compared to the static state of the oil. The experiments were carried out on the model of a high-voltage explosive switch, connected to the power circuit of the surge generator. The probing of the gap was made by a standard pulse of 1.5 / 50  $\mu$ s. As a result, the dependences of the gradient of the breakdown voltage on the flow rate of the transformer oil for the usual geometry of the high-voltage explosive switch contact system are constructed.

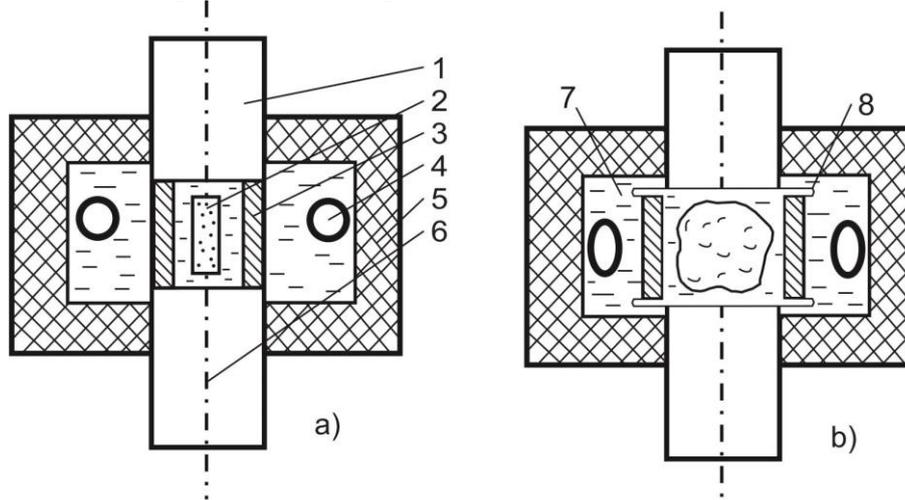
## 1. Introduction

The study of arc extinguishing process in the explosive switch model allowed to explain its high current-limiting effect of the high speed arc extinguishing fluid on the electric arc [1]. The flow quickly pulls the arc immediately after the breaking the circuit, and the formation rates of contact gap as well as its length do not affect the growth of arc voltage. In practice this means that the current-limiting capacity remains constant with the increasing of the device rated current, i.e. with the increase in the section and current conductor mass to be destroyed as well as the decrease in the gap formation rate. Explosive switch in its initial condition (Figure 1), where (a) is initial switching stage; (b) 1, 6 are current conducting electrodes; 2 is explosive charge; 3 is current conducted to be destroyed; 4 is pocket air; 5 is casing; 7 is transformer oil flows; 8 is electric series arcs.

The dynamics of the explosive switch contact gap formation is as follows (Figure 1b). When the explosive switch control system receives the signal to turn off and blow up explosive charge the expanding explosion products dramatically increase the pressure in the cavity of the destroying current conductor and the latter, increasing in diameter, moves towards the arc-extinguishing chamber walls. The transformer oil starts filling the gaps between the destroyable current conductor and fixed electrodes. The oil discharge rate varies in the range 70-150 m/s. The arc



length is increasing with the approximate rate of  $4 \cdot V_n$  for one module of the current conductor being destroyed. This fact explains one of the reasons of current-limitation for the setting level of the device actuation. Another reason is the intense heat removal from the arc column both at the stage of the flow action and due to the high pressure formed when the contact gap reaches its maximum value. The final stage of the high-voltage circuit shutdown process is determined by the recovery speed of contact gap electric strength.



**Figure 1.** Explosive switch in its initial condition.

There is a way to improve the breaking ability and current limiting capacity of the electric device when a fast-acting fuse with a longer period is connected in parallel to the main current conducting terminals. When the explosive switch is used as a power module, the conductor section can be chosen to be so small that it will be destroyed by the electrical explosion. However in this case it will be necessary to coordinate the voltage surge of the conductor electric explosion with the electric strength of power module period. In the case where a current is switched off or commuted to a parallel circuit for than  $70 \div 120$  microseconds, a restrike of the gap may occur in the residual arc channel. But if the time is less than  $50 \div 70$  ms then the weakest point is the shortest distance between the current conductor to be destroyed and fixed electrodes where the oil flows. The latter is just the case when a fault current is switched from the fast-acting power module to the parallel-connected high-voltage fuse.

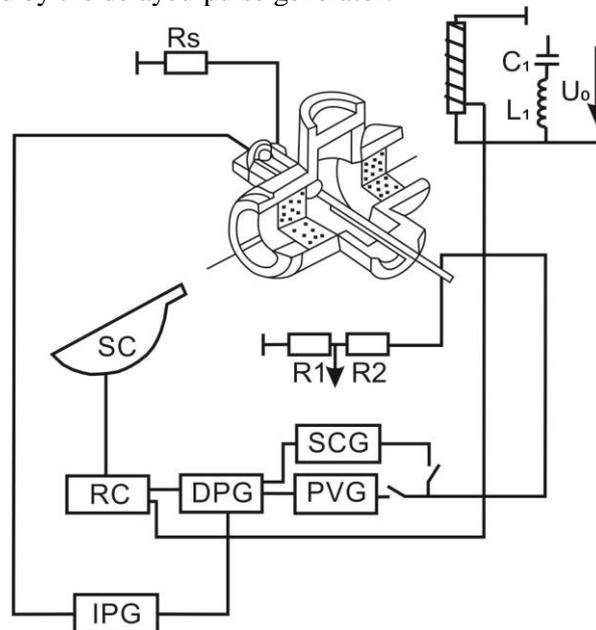
It is known that any fluid perturbation results in a change of its electro-physical properties, e.g. the breakdown voltage [2, 3]. However, quantitative data on the flow dielectric strength of the desired rate range is not found in the literature. This determined the relevance of targeted investigations.

At the same time, occurring vibrations do not have a major impact on the stability of the insulating properties [4].

## 2. Methods of the Experiment

Experiments on the dielectric strength of the transformer oil flow were performed on a model of the explosive switch contact system, simulating the beginning of a current conductor movement (Figure 2). The installation for the process study allows to register electronic and optical phenomena and consists of a pulsed voltage generator, high-speed photographic apparatus, synchronization and high-voltage measurements devices. The flow probing in the gap was performed by standard positive lightning impulse  $1.2/50$  ms with a breakdown in the line part of the front if  $dU/dt = 58 \text{ kV/ms}$ . The breakdown voltage was measured by an active voltage divider and recorded by an oscilloscope. Calibration of the divider and a test of its amplitude and phase distortion are conducted in accordance with the requirements to the measurements of fast processes at high voltage. In the experiments we registered the time span from the beginning of the phenomenon till the breakdown of the studied gap,

the breakdown voltage amplitude as well as the optical picture of the process. The synchronization of the elements was provided by the delayed-pulse generator.



**Figure 2.** Flow chart of the installation, where SCG is surge-current generator; PVG is pulsed-voltage generator; IPG is initiating pulses generator; DPG is delayed-pulse generator; SC is streak camera;  $R_1$ ,  $R_2$  are a voltage divider;  $R_s$  is shunt;  $C_2$ ,  $L_2$  are backlight supply; RC is remote control.

The starting point was the explosive charge detonation initiating. The phenomenon was photographed by a high-speed camera (SC) in a slow-motion mode (time lapse) with a frequency of 62.500 frames per second. Recording was conducted in a transmitting light flux. The light was supplied by the impulse discharge lamp powered by a capacitor bank, which in conjunction with the delayed control signal provided the maximum illumination within the studied time span. The phenomenon was recorded on film. To compare the optical detection of flow dynamics with the electrical characteristics we installed the timer – the discharge gap broken down at the time of detonation initiating.

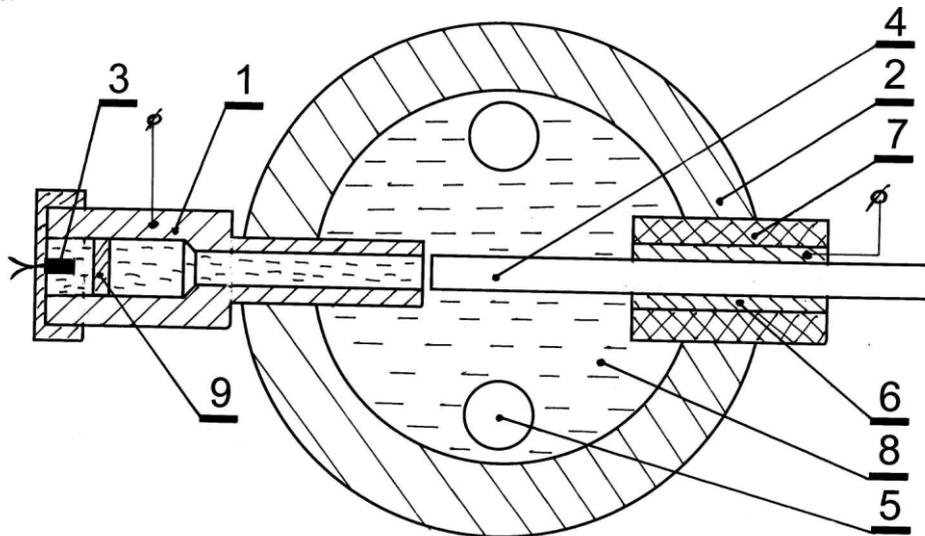
Explosive switch contact gap design is modeled with optically transparent windows that allow to capture images in transmitting light flux. It is presented in Figure 3. The model consists of an explosive 1 and 2 arc-extinguishing chambers filled with transformer oil and simulates the formation of a contact gap in a real device. As in the real apparatus, the model's arc-extinguishing chamber contains air inclusion 5. Explosive charge 3 is located at the end face of the explosion chamber. The model works as follows.

When the charge detonates, expanding explosion products displace oil from the explosion chamber in the arc-extinguishing one. The flow goes to the nozzle opening and wraps around the downstream electrode 4, taking the shape of "umbrella". Hereinafter we call the electrode 4 a lower one. In each experiment, it was fixed and the value of the probed gap remained constant – 1 mm. The measurement of the gap was carried out by the microscope with 2.5% accuracy. The basic experiments used with transformer oil dielectric strength of 20 kV in the standard conditions. Average statistical breakdown voltage excitation pulse was 67 kV to the explosion at an interval of 1 mm.

To control the flow rate in the explosion chamber between the explosive charge and the liquid metal piston 9 (Figure 3) weighing 50-260 g is installed. With the increase in spraying mass the time of flow acceleration increases whereas its maximum speed reduces correspondingly.

Dependence of breakdown voltage gap on the oil flow rate is shown in Figure 4. It shows that with the velocity  $V_n$  increasing in the range of 67 to 152 m / s,  $U_{bd}$  is reduced by (70.5–91.6)% compared with the stationary oil state and lies in the range from 19.8 to 5.6 kV. The graph shows the range of

the mean root square deviation of the experimental data reaching the maximum value 17% at the point  $V_n = 75 \text{ m/s}$ .

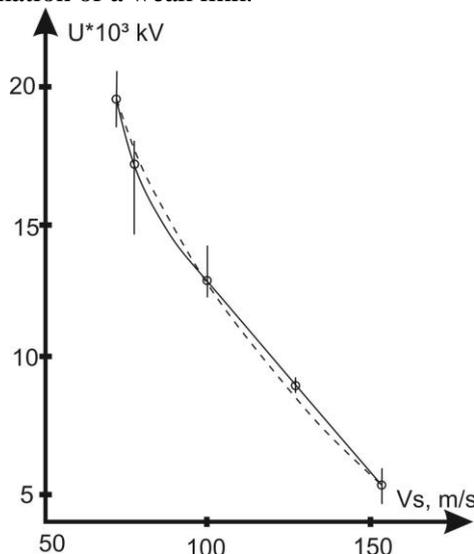


**Figure 3.** Contact system of the high-voltage explosive switch model, where 1 is explosion chamber; 2 is arc-extinguishing chamber; 3 is explosive charge; 4 is movable rod; 5 is pocket air; 6 is guide, 7 is insulator; 8 is transformer oil; 9 is piston.

Function  $U_{np} = f(V_n)$  is close to power dependence and its approximating expression found by the least square method is as follows:

$$U_{bd} = 10^3(223 \cdot V_n^{-0.21} - 72.1) \quad (1)$$

The reduction of the transformer oil dielectric strength in the flow under the influence of power frequency AC voltage is stated in [2, 3]. According to the authors with speed increasing up to 2 m/s  $U_{bd}$  reduction was in 15-35% range depending on the geometry of the electrode system, to a greater or lesser extent increasing the turbulence in the breakdown zone. Reduced strength is explained by the fact that gas or impurities could appear in the gap as well as the influence of dissolved moisture. According to the authors, when oil flows the moisture becomes emulsified and polarized under high voltage contributing to the formation of a weak link.



**Figure 4.** Dependence of breakdown voltage gap on the transformer oil flow rate.

Although conditions [1, 2] differ significantly from the studied in this article, the reduced strength could also be explained by physical processes occurring in the contact gap. Rough explosion chamber walls and friction both in a boundary layer and between layers of fluid give rise to vorticities. Due to the sharp expansion of the flow at the entrance to the arc-extinguishing chamber and flow around the lower electrode the oil in the contact gap becomes intensively turbulent that is clearly visible in the SC-gram. The degree of turbulence is estimated by the dimensionless Reynolds number, which is proportional to the flow rate when the other parameters are constant [5]:

$$\text{Re} = \frac{V_n * \delta}{\lambda}, \quad (2)$$

where  $V_n$  is the flow rate;  $\delta$  is characteristic dimension, in this case, the value of a contact gap;  $\lambda$  is the kinematic viscosity of the medium. In the experiments  $3*10^3 \leq \text{Re} \leq 15*10^3$  and according to [5] the flow relates to the category of high-turbulent ones. It is characterized by chaotic changes of instantaneous speed, pressure and density at various points in the volume. The profile of the explosion chamber outlet and the sharp edges of the lower electrode contribute to the formation and breakdown of vortex on the flow border at the highest Reynolds numbers.

As it is well known [6, 7], transformer oil has complex chemical and fractional composition with a sufficiently high content of dissolved moisture and gases. According to some data the air solubility amounts to 10% of the volume at a temperature of 20 °C and atmospheric pressure. Sudden pressure fluctuations in local flow points with the turbulence in the latter lead to the formation of cavitation bubbles of steam and gas. Thus bubbles in the breakdown region, and in particular, intense cavitation flow along the boundary of the lower electrode, promotes the formation of a weak link in the contact gap. Based on the Reynolds number characteristics bubble inclusions should increase with the degree of turbulence in the flow, and hence the velocity of its movement, which explains the nature of the  $U_{bd}$  decline in in the explosive switch gap.

The experimental evaluation of the moisture effect on the dielectric strength of the flow in the breakdown of the "dry" transformer oil, the strength of which under standard conditions was 50 kV, and the average impulse breakdown voltage in the 1 mm gap was 91.5 kV (static). The dielectric strength of the flow, moving with a speed of 152 m/s turned out to be higher by 34%.

Establishing a quantitative relation between the discharge rate of the transformer oil, the value of the contact gap and dielectric strength will allow to define protective characteristic for the explosive switchboard with currentless circuit opening for two-stage explosive switch design. However in the real switch the contact gap increases with time and the value of the breakdown voltage for the current conductor movement may not follow the linear law of distance increasing. To find out how the dynamics of the contact gap formation affects the gradient of the breakdown voltage at the curve points 67 m/s and 152 m/s in Figure 4 a series of experiments for 2 mm gap was conducted. The results showed that within the ranges of actual oil discharge speed and the size of the explosive switch gap on flow action stage the breakdown voltage gradient remains within the limits of the experimental data. Then using an empirical relationship [1] to calculate the oil flow rate in the actual design of the explosive switch, we can state:

$$E_{np} = \{223[0.29D(\frac{m_z}{m_M}) + 0.00289]^{-0.21} - 72.1\} \quad (3)$$

where  $D$  is detonation velocity;  $m_z$  is explosive charge mass;  $m_M$  is sprayed mass, determined by the dimensions of the current conductor.

The results of the investigation were implemented in education process of Tomsk Polytechnic University also [8, 9].

### 3. Summary

1. The empirical relationship of the impulse breakdown strength for a high-speed flow of transformer oil on the speed of the latter was obtained as a result of investigations.
2. In conjunction with the movement dynamics of the current conductor to be destroyed the relationship allows to calculate the protective characteristics of the explosive switch with currentless circuit opening in the two-stage model of the explosive switch.

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