TRIGGERING REGIME OF OIL-FILLED TRIGATRON DISCHARGERS

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A comparative analysis made in [1, 2] of different types of regulable high-voltage dischargers with liquid insulation showed that trigatrons are currently the most promising for use in high-voltage pulse-operated devices due to their simplicity and reliability. Two basic mechanisms of discharge initiation can be realized in trigatrons — initiation by intensification of the field in the region of the control electrode [2, 3], and triggering by a spark in the ignition gap [4, 5]. The first type of trigatron has been studied sufficiently only for short voltage periods [3, 6, 7], so it is used mainly in switching the pulse-shaping lines of powerful nanosecond pulse generators with "rapid" (0.5-1.5 μsec) charging [8, 9]. Almost no use is now made of the second type of trigatron switch in high-voltage pulse technology due to its unsatisfactory time characteristics. Here we report results of a study of the time characteristics of both types of oil-filled trigatrons operating in a regime whereby they form the leading edge of rectangular voltage pulses with amplitudes up to 800 kV and durations of 1-100 μsec. The goal is to find the optimum conditions for triggering of trigatron dischargers with liquid insulation in the region of microsecond voltage discharges. Experiments were conducted on the unit in [10]. The test discharger was placed in a cylindrical chamber 45 cm in diameter and 27 cm in length. The high-voltage electrode of the discharger was in the form of a cylinder 20 cm in diameter positioned coaxially inside the chamber. The 10-mm-diameter ground electrode was positioned radially in a branch pipe 8 cm long. The control electrode was placed in a 2-cm-diameter hole in the center of the ground electrode. The chamber with the test discharge was filled with transformer oil with a breakdown voltage of about 50 kV. The oil was not replaced or cleaned during the experiment. We did not find that contamination of the oil by discharge products had any effect on the time characteristics of either type of discharger. The results were analyzed by the least squares method, with 50 measurements to a point (it was found that time lag of the discharger triggering conforms approximately to a normal distribution law for both types of discharger).

<u>Trigatron Discharger with Initiation of Discharge by Field Intensification.</u> The application of a steep voltage pulse to the control electrode of the discharger is accompanied by distortion of the initial, nearly uniform electrical field in the main gap of the trigatron. Here, the field becomes sharply nonuniform near the control electrode [11]. The degree of this nonuniformity — which determines the time characteristics of a trigatron discharger with breakdown initiation by field intensification — depends mainly on the combined polarities of the main and ignition voltages, the amplitude of the control voltage, and the geometry of the ignition component. With allowance for the polarity effect characteristic of discharge in a liquid, a trigatron of this type with the best characteristics can be obtained with negative polarity for the main voltage and positive polarity for the ignition voltage. Meanwhile, according to [6], the amplitude of the control voltage U_c should be 0.2-0.3 of the voltage corresponding to uncontrolled breakdown in the discharger U_{uc}.

In choosing the configuration of the ignition component, it is necessary to proceed on the basis of the following requirements: 1) minimal distortion of the field in the main discharge gap until delivery of the control voltage; 2) attainment of significant intensification of the field near the control electrode after the application of U_c. Both of these requirements are satisfied by the component design shown in Fig. 1a (1 is the main electrode and 2 is the ignition electrode). The end face of the control electrode, 0.8 cm in diameter, is placed flush against the surface of the main electrode and is provided with a lengthwise opening 0.5 cm in diameter and 0.6 cm deep. The presence of the opening makes it possible

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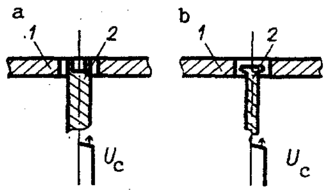

Fig. 1

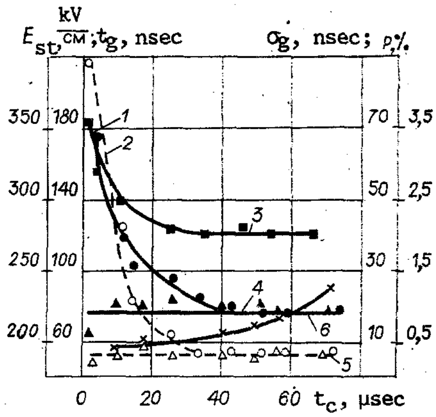

Fig. 2

to nearly double the field amplification factor with delivery of the control voltage compared to a rod control electrode.

A positive control pulse of up to 200 kV, with a front lasting about 10 nsec, is formed by a generator made in accordance with the Arkad'ev–Marks scheme. The design and main characteristics of the generator are given in [12].

Figure 2 shows results of measurement of the lag time t_g in the triggering of the trigatron discharger (line 1) and the scatter of σ_g (line 2) in relation to the time of delivery of the control voltage t_c (t_c is the time interval from the moment of application of the main voltage to the moment of delivery of the ignition voltage) with a constant main-voltage amplitude U_g = 410 kV – which at t_c > 20 μsec corresponds roughly to $0.7U_{uc}$ (U_{uc} is the voltage corresponding to 50% probability of uncontrolled breakdown in the discharger). (In Fig. 2 and subsequent figures, the solid lines show the relation for t_g, while the dashed lines show the relations for σ_g.) The length of the main gap of the discharger d_0 = 3 cm, while the amplitude of the control voltage was 170 kV.

It is evident from Fig. 2 that an increase in the time of delivery of the control voltage is accompanied by a reduction in t_g and σ_g. This reduction is quite large at t_c < 20 μsec and very small in the case of long times. The dependence just mentioned is directly related to the path of the volt-second characteristic for the breakdown of the transformer oil with the application of a rectangular voltage pulse of microsecond duration (line 3 in Fig. 2, obtained by the meaurement of dielectric strength E_{st} in a uniform field with d_0 = 1.2 cm and electrodes with an effective cross-sectional area of 100 cm^2). At t_c < 20 μsec, the value of U_{uc}, increases with a decrease in the time of action of the voltage. Thus, with a constant value of U_g, the ratio U_g/U_{uc} increases. The latter in turn leads to an increase in t_g and σ_g [6]. At t_c > 20 sec, the voltage for uncontrolled breakdown changes only slightly, while the time characteristics of the discharge remain nearly constant.

Lines 4 and 5 show the results of measurement of t_g and σ_g in relation to t_c obtained with a constant ratio U_g/U_{uc} = 0.7. Under these conditions, the time characteristics of the test discharger depend on the time of action of the main voltage only at t_c < 5 μsec, and it is in this range that the dependence of the time characteristics on t_c is fairly weak, i.e., a trigatron discharger in which breakdown is initiated by intensification of the field operates reliably throughout the investigated range of t_c. However, an increase in the time of action of the main voltage is accompanied by an increase in the likelihood of uncontrolled triggering of the discharger [the dependence of the probability of uncontrolled breakdown in the discharger P on t_c at U_g/U_{uc} = 0.7 is shown in Fig. 2 (curve 6)]. Thus, to ensure reliable operation of the discharger at t_c > 20-30 μsec, it is necessary to choose a maximum value of U_g at the level ~$0.7U_{uc}$. This appreciably narrows the range of reliable operation of the discharger (the minimum value of U_g at which the discharge can be reliably operated under the given conditions is about $0.6U_{uc}$).

With consideration of the slight dependence of the time characteristics of a trigatron discharger with field triggering on the time of delivery of the control voltage throughout the investigated range, we can conclude that when the main voltage acts for microsecond time intervals, the regimes recommended in [6] for submicrosecond voltage exposures can be recommended as the optimum triggering conditions. This conclusion was supported by special studies of the characteristics of a trigatron discharger as a function of the parameters of the control voltage and the geometry of the ignition component.

Trigatron Discharger with Triggering by a Spark in the Ignition Gap. Breakdown of the ignition gap is accompanied by the formation of a plasma-filled cavity which expands under the influence of excess pressure. This cavity is the source of high-intensity shock waves which propagate into the depth of the main discharge gap. As the shock wave advances in the liquid, gas-vapor cavitation cavities are formed behind the wave front. Under certain conditions, ionization processes may take place inside these gas-vapor cavities (such processes will occur when the characteristic dimension of the cavities is greater than the mean free path of electrons in the medium occupying the cavity). These ionization processes will lead to the ignition of a discharge and its propagation into the depth of the discharge gap. Volume (or surface) charges may also be created at the boundary between the gas-vapor cavities and the liquid, these charges distorting the field in the main gap of the discharger and thereby further facilitating processes taking place during the stages of ignition and development of the discharge. Since the initiation of a discharge by a spark involves relatively slow hydrodynamic expansion of the channel of the igniting spark (the characteristic rate of this process is on the order of the speed of sound in the liquid), we should expect that this triggering regime will be characterized by greater inertial than the mechanism of discharge initiation by field intensification.

The rate of expansion of the channel of the ignition spark and, thus, the characteristic dimensions of the perturbation region which propagates out from it depend to a considerable extent on the rate of energy supply to the channel. The latter rate is in turn determined by the parameters of the discharge circuit of the pulse generator and the resistance of the spark channel [13]. Proceeding on the basis of these considerations, we chose the generator parameters and ignition-component configuration shown in Fig. 1b. The control electrode is in the form of a rod 0.5 cm in diameter, and the end of the rod is provided with a disk with a sharp edge. Such a design of the ignition electrode makes it possible to significantly shorten the lag time for breakdown of the trigger gap t_{gt} and increase the length of the igniting spark and, its resistance. The latter is achieved by increasing the rate of energy supply in the igniting spark. With a gap length d_c = 0.2-0.35 cm and a control-voltage amplitude >40 kV, the value of t_{gt} is no greater than 0.1 μsec. To reduce distortion of the electrical field in the main gap when the ignition pulse is delivered, the control electrode is recessed 0.15-0.3 cm relative to the working surface of the main electrode.

The charging capacitor of the pulse generator is switched by a gas-filled trigatron, forming voltage pulses of up to 100 kV with a front duration $\leq$0.1 μsec. The inductance of the discharge circuit of the generator is about 1 μH.

We studied the operation of a trigatron discharger with spark triggering using different combinations of polarities of the main and igniting voltages. It was found that when the polarity of the main voltage is positive (with initiation of the discharge from the cathode), the discharger is nearly inoperative even in the regime close to spontaneous breakdown for both cases of control-voltage polarity. This shows that when the discharge develops from the direction of the cathode, the formation of the gas-vapor cavities and the processes which take place in these cavities have no appreciable effect on ignition and development of the discharge in liquids.

When the main voltage has negative polarity, the best time characteristics and the longest period of reliable operation of the discharge are achieved with positive polarity of the ignition pulse. This is illustrated in Fig. 3, which shows results of measurement of t_g and σ_g in relation to the value of U_g/U_{uc} for positive (lines 1 and 2) and negative (lines 3 and 4) polarities of the igniting voltage. The length of the main gap of the discharger is 3 cm, d_c = 0.3 cm, t_c = 10 μsec, U_c = 55 kV, and the capacitance in the discharge of the trigger generator C_c = 0.2 μF.

With negative polarity of the igniting voltage, the operation of the discharger becomes unreliable even at $U_g < 0.7U_{uc}$. Under the same conditions with positive polarity of the control voltage, stable operation of the discharger is seen even at $U_g < 0.5U_{uc}$. The smaller range of reliable operation of the discharger with negative control-voltage polarity and the low time characteristics are evidently due to the difference in the spatial structure of the discharge in the ignition gap with a shift in the polarity of a point electrode [1], which in our case is the control electrode. With positive polarity of the point electrode, the discharge in the liquid develops in the form of a branching "bush" which occupies a relatively large volume. With negative polarity, the discharge is formed as individual unlaced

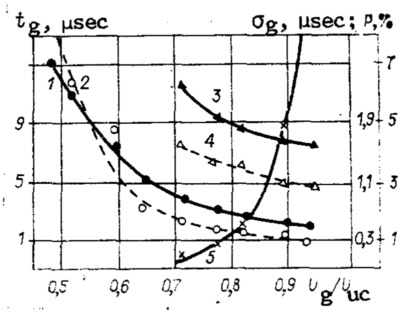

Fig. 3

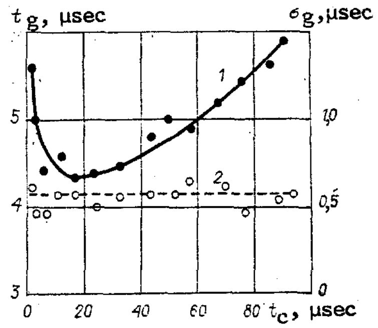

Fig. 4

filaments [1]. The large volume of the perturbed region of the liquid in the case of positive polarity of the point electrode facilitates processes during ignition and formation of the discharge in the main gap. These processes are also promoted by a significant positive potential (due to the large longitudinal gradient of the field in the spark channel with the breakdown of liquids [13]) introduced into the main gap by the spark and leading to a redistribution of the field in the gap.

It follows from analysis of the time characteristics of the discharger with spark triggering and the probability of uncontrolled breakdown of the main gap (line 5 in Fig. 3) that with negative polarity of the main and igniting voltages, reliable operation of the discharger is possible only when $U_g \sim 0.7U_{uc}$. This makes it inexpedient to use this combination of the polarities of U_g and U_c in practice. Thus, we will henceforth focus our investigation on the case of negative polarity of the main voltage and positive polarity of the igniting voltage.

With a constant inductance in the discharge circuit of the pulse generator and a constant length of the trigger gap, the energy expended in the igniting spark and, thus, the time characteristics of the discharger with spark triggering will depend on the capacitance in the generator discharge and the amplitude of the igniting voltage. Measurement of the time characteristics of the discharger in relation to C_c with a change in the latter from 0.05 to 0.6 µF (U_c = 655 kV) showed that the characteristics improve with an increase in C_c up to $C_c \approx$ 0.3 µF. A further increase in C_c is accompanied by an increase in the triggering lag time. There is almost no change in the stability of triggering in this case. Oscillograms of current in the igniting spark $i_c(t)$ and of the control voltage $U_c(t)$ were used to evaluate the energy released in the spark channel up to moment of triggering of the dishcarger W_r(W_r = $\left.\int_0^{t_g} i_c(t)\,U_c(t)\,dt\right)$, which also determines processes in the main gap of the discharger and their rate. It was found that energy release in the spark decreases with an increase in C_c above 0.3 µF, which is evidently connected with a reduction in the resistance of the spark channel with an increase in C_c. This in turn leads to an increase in t_g at $C_c > 0.3$ µF.

We studied the time characteristics of the discharger in relation to U_c with a change in the amplitude of the main voltage in the range 200-800 kV. It was found that a control-voltage amplitude of 40-60 kV is sufficient. At $U_c > 60$ kV, a discharge was initiated by intensification of the field despite the recessing of the control electrode. As a result, there was a substantial increase in the scatter of the discharger triggerings. At $U_c > 40$ kV, there was a marked reduction in the size of the perturbed region resulting from the spark, which led to a significant deterioration in the main characteristics of the discharger.

Figure 4 shows results of measurement of the time characteristics of the discharger in relation to the time of delivery of the control voltage t_c with a constant main-voltage amplitude U_g = 410 kV. The length of the main gap of the discharger was 3 cm, d_c = 0.3 cm, U_c = 50 kV, and C_c = 0.1 µF.

It is evident from Fig. 4 that the function $t_g = f(t_c)$ (line 1) has two sections: on the first section, t_g decreases with an increase in t_c up to 10 µsec; on the second section, the increase in t_c at $t_c > 20$ µsec leads to an increase in the triggering lag time. The stability of the triggering changes very little (line 2) throughout the investigated range of t_c. The first section is related to the path of the volt-second characteristic for breakdown of the transformer oil (line 3 in Fig. 2). The increase in t_g on the second section is evidently connected with a drop in the peak of the main voltage pulse (this drop is about 15% with a pulse duration of 100 μsec). With an increase in the time of action of the main voltage to more than 50 μsec, there is an increase in the minimum value of the ratio U_g/U_{uc} at which the operation of the discharger remains stable. For example, at t_c = 90 μsec, the minimum value of $U_g/U_{uc} \sim 0.55$, while this ratio is equal to 0.4 at t_c = 10 μsec.

Thus, the completed studies showed that it is possible to use trigatron dischargers with discharge initiated by intensification of the field and with spark triggering in high-voltage pulse-operated equipment within a broad range of times of action of the main voltage. Near-optimum conditions were found for triggering of both types of dischargers. It was determined that the first type, characterized by high speed and stable connection, has a narrow range of working voltages. Triggering of this type of switch requires a high control voltage. The spark-triggered discharger, with satisfactory time characteristics, has a broader range of reliable operation and requires 1/4 to 1/5 the control voltage. This significantly enhances the reliability of the insulation of the ignition component and transmission cable.

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