Modeling of high voltage periodically attenuating discharge in liquid with controllable high voltage switch thyratron

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Abstract **The usage of high voltage discharge in liquid finds many technological applications. Control of the moment when the discharge occurs in systems with capacitive energy storage, suggests the usage of a high voltage controllable switch, most often trigatron or thyratron, i.e. gas discharge occurs. The present work is dedicated to modeling of the discharge processes, arising in liquid medium and control by a high-voltage controllable switch-thyratron.**

Keywords – **capacitive energy storage, high voltage discharge in liquid, thyratron**

I. INTRODUCTION

High voltage discharge in liquid is used for water treatment with different purposes, destructions of deposits and incrustations in pipes and other applications [1,2,3]. Some research on power supply for high voltage application is also studied [4].

The experimental prototype for formation of high voltage periodically attenuating discharge in liquid medium with capacitive energy storage is shown in Fig.1. [5].

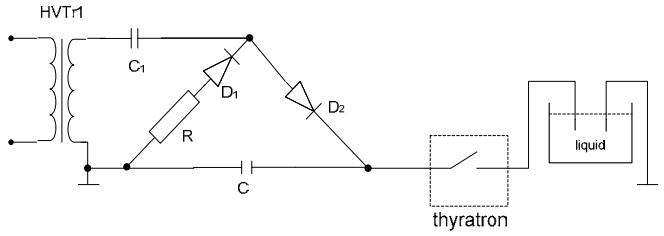

Fig.1 Circuit schematic for formation of high voltage discharge in liquid medium

In Fig.1 C is the capacitance of the capacitor battery, HVTr is a high voltage transformer. As a high voltage controllable switch (HVCS) can be used thyratrons as the can commutate high voltage up to 200kV, current with amplitude up to 100kA, allow pulse width from tens of nanoseconds to hundreds of microseconds and pulse repetitiveness up to 70kHz. In the current experiment is used a hydrogen thyratron ТГИ1-1000/25 – Fig.2. The control circuit of such HVCS is described in the literature [6].

Similar system for realization of high voltage discharge, but with another type HVCS –a trigatron is analyzed in the literature [7], but the described model includes only the discharge current and voltage.

Fig.2. Thyratron ТГИ1-1000/25

The discharge current can be defined by Eq.1:

$$\frac{d^2 i}{dt^2} + 2\delta \frac{di}{dt} + \omega_0^2 i = \qquad (1)$$

where:

- $i(t_0)=0$ – initial condition
- $\delta =$ is damping ratio

The discharge circuit resistance is $R = R_{HVS} + R_W$, where $R_{HVS} = R_{HVS}$ is the resistance of the HVCS (thyratron) and $R_W = R_W$ – resistance of the liquid (water).

- $\omega_0^2 =$ – resonant frequency of the circuit.

The indicated resonant frequency refers to the case of a resonant circuit without losses. Considering that $R = R_{HVS} + R_W$, the resonant frequency is . The adopted relative mistake can be defined by Eq.2:

$$\frac{\omega_0' - \omega_0}{\omega_0} = -\frac{1}{8}., \qquad (2)$$

where $\rho =$ is the characteristic resistance and $R<<\rho$ is considered.

In the cases when $\delta <$, the process is periodically attenuating – Fig..3.

At resonant circuit resistance R=const is valid Eq.3:

$$\frac{A_1}{A_2} = \frac{A_2}{A_3} = \frac{A_3}{A_4} = \cdots \ldots = \frac{A_{n-1}}{A_n} = e^{\delta T} = \text{const} = \qquad (3)$$

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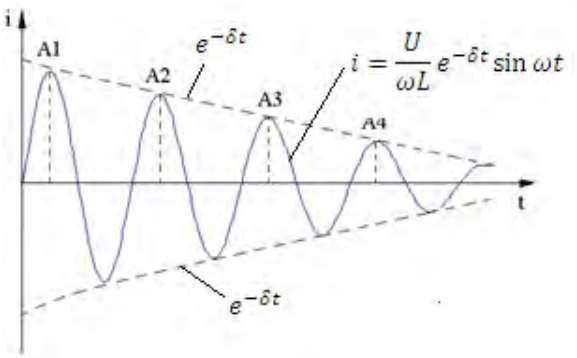

Fig,3 Periodically attenuating oscillation

If we consider that $R_{HVS} = R_{HVS}(t)$ and $R_W = R_W$ and accept that within one period $R_{HVS} = const$ and $R_W = const$, then is valid Eq.4:

$$B_1^* = \ln B_1 = \delta T = \frac{\pi R}{\rho} \frac{1}{\sqrt{1-}} \quad (4)$$

If T is the period of the resonant circuit with losses R, considering that $\omega_0^* = \omega_0 \left(1 - \left(\frac{R}{2\rho}\right)^2\right)$, then Eq.5 is in force:

$$T = \frac{1}{f} = \frac{2\pi}{\omega_0^*} = \frac{2\pi\sqrt{}}{\sqrt{1-}} \quad (5)$$

After transformation of Eq.4 and Eq.5, Eq.6 is obtained:

$$R = \frac{2\sqrt{\frac{L}{C}}}{\sqrt{\pi^2 + B_1^{*2}}} \qquad \frac{2\pi}{T} = \sqrt{\frac{1}{LC} + \cdot} \quad (6)$$

From Eq.6 can be defined R=R( ) and L=L( )– Eq.7.

$$L = \frac{T^2}{4(B_1^{*2}+\pi^2)+B} \qquad R = \frac{2B_1^* T}{4(B_1^{*2}+\pi^2)+R} \quad (7)$$

Note: After modeling of the discharge process, it can be accepted that for the time of one period T ($B_1^* = const$, R and L also don't change.

After experimental obtaining of i=i(t) – Fig.3-oscilogram, referring the current through R – Fig.1, is received for the separate periods, from where R and L can be defined.

The purpose of the present work is experimental study by the usage of a thyratron of:

- Resistance of HVCS – thyratron at discharge $R_{HVS} = R_{HVS}(t)$;
- Resistance of the discharge circuit $R = R_{HVS} + R_W = R(t)$ at two discharge gaps (thyratron and discharge gap in water);

At parameters capacitance of the capacitor battery C – Fig.1 and voltage U_c, to which it is charged. On the basis of the experimental study is created a model, which includes the influence of the parameters C и U_c.

II. EXPERIMENT

Two experiments are conducted:

- Measuring the discharge current I_{D1}, when the capacitor battery discharges only through the thyratron and defining $R_{HVS} = R_{HVS}(t)$ according to the described method;
- Measuring the discharge current I_{D2}- when the capacitor battery discharges through the HVCS-thyratron and a discharge gap in liquid and defining $R = R_{HVS} + R_W = R(t)$;

The experimental data are taken at parameters capacitance of the capacitor battery C=0.5μF, 1μF, 1.5μF, 2μF and voltage U_c=9.5, 10,10.5,11,11.5 kV.

For the case of one discharge gap in the circuit (thyratron) at C=1.5μF and U_c=11kV the results for and calculated R and L are presented in Table 1. The same data for the case with two discharge gaps (thyratron and gap in water) connected in series at the same parameters are shown in Tabl.2.

TABLE 1 EXPERIMENTAL RESULTS FOR A THYRATRON AT PARAMETERS C=1.5μF И U_C=11KV

	A_1/A_2	A_2/A_3	A_3/A_4	A_4/A_5
B_1^*	0.623	0.516	0.462	0.439
R_{HVS}, Ω	0.582	0.402	0.320	0.289
L, μH	33.32	33.41	33.46	33.47

TABLE 2 EXPERIMENTAL RESULTS FOR TWO DISCHARGE GAPS AT PARAMETERS C=1.5μF И U_C=11KV

	A_1/A_2	A_2/A_3	A_3/A_4	A_4/A_5
B_1^*	1.50	1.18	1.04	0.940
R, Ω	3.47	2.20	1.70	1.40
L, μH	36.24	36.99	37.29	37.46

TABLE 3 COEFFICIENTS OF APPROXIMATION a AND b FOR THE CASE WITH ONE DISCHARGE GAP - THYRATRON

U_c, kV	9.5		10		10.5		11		11.5	
C, μF	a	b	a	b	a	b	a	b	a	b
0.5	1.09E-05	0.0278	1.06E-05	0.0600	1.02E-05	0.0910	9.09E-06	0.144	9.4E-06	0.162
1	1.36E-05	0.0999	1.44E-05	0.109	1.41E-05	0.135	1.39E-05	0.161	1.47E-05	0.178
1.5	1.81E-05	0.119	1.72E-05	0.154	1.74E-05	0.172	1.74E-05	0.1943	1.81E-05	0.206
2	1.99E-05	0.154	2.04E-05	0.176	2.15E-05	0.19	2.16E-05	0.2167	2.2E-05	0.224

TABLE 4 COEFFICIENT OF APPROXIMATION a AND b FOR THE CASE WITH TWO DISCHARGE GAPS –THYRATRON AND GAP IN WATER

U_c, kV	9.5		10		10.5		11		11.5	
C, μF	a	b	a	b	a	b	a	b	a	b
0.5	6.52E-05	-0.0155	6.518E-05	0.158	6.82E-05	0.243	6.36E-05	0.506	6.92E-05	0.578
1	8.82E-05	0.264	9.55E-05	0.293	9.9E-05	0.408	9.95E-05	0.577	10.6E-05	0.690
1.5	12.2E-05	0.343	12.01E-05	0.531	12.4E-05	0.663	12.9E-05	0.775	13.6E-05	0.868
2	13.3E-05	0.551	14.2E-05	0.664	15.2E-05	0.755	16.2E-05	0.877	17E-05	0.910

At repeating experiments : includes aggregation of points, which consider the character and the dynamic of the discharge process development.

III. ANALYSIS

The obtained results allow approximation of the curves $R_{HVS} = R_{HVS}(t)$ и $R = R_{HVS} + R_W = R(t)$ with a hyperbola –Eq.8:

$$R = \frac{a}{t} + b \qquad (8)$$

The coefficients a and b are defined by the least square method as the received results are presented in Table 3 (for a thyratron/ and Table 4 /two discharge gaps/.

In Fig.4 and Fig.5 is shown the change of the resistance $R_{HVS}(t)$ and $R(t)$ on the basis of the numeric characteristics in Table 1 and 2 and the curves after approximation for 10 repeated experiments.

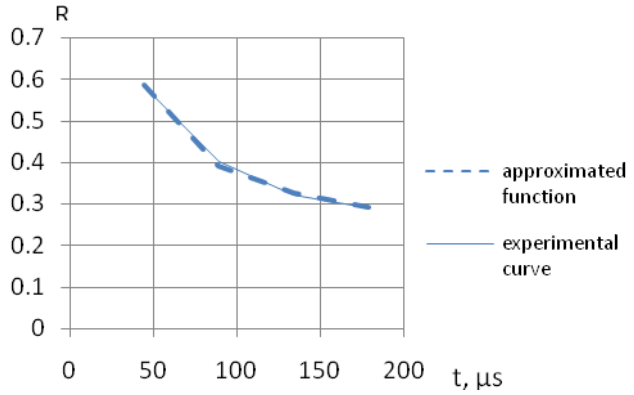

Fig.4 Dependency $R_{HVS}(t)$

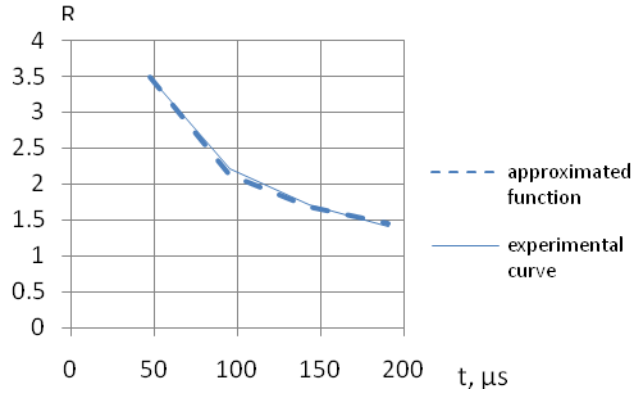

Fig.5 Dependency R(t)

The relative error of the model, defined by Eq.9 is shown in Table 5 and Table 6 for the two cases – with one and two discharge gaps.

$$\Delta = \frac{(R_{exp} - R_{model})}{R_{exp}} . 100 \qquad (9)$$

The match between the experimental and analytical results is good enough so that the suggested method could be used as a model for analysis of the electrical processes in the discharge circuit.

For the accepted way of modeling, the coefficients a and b depend on the capacitance of the capacitor battery C, the voltage, to which it is charged U_c and the number of experiments. After conducting experimental analysis these dependencies could be analytically modeled.

TABLE 5. RELATIVE ERROR OF THE MODEL FOR $R_{HVS}(t)$

Δ, %	U_c, kV	9.5	10	10.5	11	11.5
C=0,5μF	A_1/A_2	2.56	3.28	2.55	2.46	2.14
	A_2/A_3	13.4	15.3	11.6	10.3	8.48
	A_3/A_4	6.87	4.75	2.17	1.16	1.39
	A_4/A_5	12.7	17.3	12.5	10.5	10.9
C=1μF	A_1/A_2	0.358	0.905	0.619	0.569	0.447
	A_2/A_3	3.07	5.59	4.51	3.56	2.51
	A_3/A_4	5.65	6.02	7.14	4.07	1.91
	A_4/A_5	2.33	0	2.22	0.513	0.476
C=1,5 μF	A_1/A_2	0.885	0.817	0.508	0.509	0.395
	A_2/A_3	5.35	4.75	3.003	2.60	2.61
	A_3/A_4	5.48	4.63	2.90	1.40	3.40
	A_4/A_5	0.182	0.160	0	1.02	0.860
C=2 μF	A_1/A_2	1.18	0.882	0.471	0.719	1.20
	A_2/A_3	6.45	5.48	4.48	4.84	6.93
	A_3/A_4	5.66	6.95	10.2	7.29	8.24
	A_4/A_5	1.01	1.19	4.73	2.14	0.915

TABLE 6. RELATIVE ERROR OF THE MODEL FOR R(t)

Δ, %	U_c, kV	9.5	10	10.5	11	11.5
C=0,5μF	A_1/A_2	3.11	3.76	2.88	3.07	2.69
	A_2/A_3	16.8	17.9	14.1	13.6	11.7
	A_3/A_4	9.68	5.77	4.28	2.43	0.0459
	A_4/A_5	20.1	24.7	16.6	15.8	15.5
C=1μF	A_1/A_2	1.30	0.902	0.984	0.811	0.725
	A_2/A_3	7.58	5.61	6.10	4.34	3.12
	A_3/A_4	5.25	4.63	5.70	1.77	1.48
	A_4/A_5	3.94	1.87	1.23	2.90	5.04
C=1,5 μF	A_1/A_2	1.64	1.43	0.765	0.67	0.558
	A_2/A_3	8.73	7.41	3.70	2.99	2.49
	A_3/A_4	3.80	3.18	0.230	0.773	0.529
	A_4/A_5	7.03	5.26	3.73	3.96	3.11
C=2 μF	A_1/A_2	1.93	1.64	0.899	0.647	0.948
	A_2/A_3	8.61	8.07	5.41	3.74	5.24
	A_3/A_4	0.753	2.68	5.22	2.86	3.61
	A_4/A_5	11.6	6.49	0.548	0.957	1.87

IV. CONCLUSION

Mixed approach is used for the analysis – analytical and identification – for modeling of the discharge processes in a discharge circuit with one and two discharge gaps. The obtained results give possibility to describe the character of the generated high voltage discharge pulse in liquid (water) at the usage of a thyratron as a high voltage controllable switch.

At comparative evaluation of the experimentally and analytically received results for the discharge current amplitudes, the matching is sufficiently good. The assumption that the dependency R=R(t) can be presented with a hyperbola brings to increasing of the differences between the experimental results and analytical ones in the next periods of the periodically attenuating oscillation.

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