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LIMITATION OF APERIODIC TRANSIENT DURATION IN CAPACITORS CIRCUITS OF TWO-CHANNEL ELECTRICAL DISCHARGE INSTALLATIONS

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The mathematical modeling of pulse periodic transients in the circuits of capacitors of two-channel semiconductor electrical discharge installations is performed. The conditions for limiting the duration of the aperiodic transient processes of the discharge of capacitors of such installation through the electro-spark load, the resistance of which can vary from one discharge to another one, are determined. It is shown that the duration of the aperiodic discharge of the capacitors in two-channel installations depends on the frequency of spark discharge pulses in the load and this duration cannot exceed the duration of spark discharge pulses period. The limitation of the aperiodic discharges duration depends on the parameters of the discharge circuit and the duration of recovery of locking properties of the semiconductor (thyristor) switches. It is shown that reducing the duration of discharge currents in the load increases the frequency and stability of the pulsed modes in the load. References 12, figures 3.
Key words: aperiodic transients, capacitor, semiconductor switch, discharge, pulse current.

Introduction. At the structural-parametric synthesis of electric discharge installations (EDI) with reservoir capacitors (RC) [1, 2] and during analysis of transients in its circuits [3, 4] the problem of increasing both the rate of discharge currents rise and impulse power in the load [3], whose electrical resistance can be stochastically and nonlinearly altered [4, 5] is the most complicated. In the production of electro-eroded powders [6, 7] with unique properties [8, 9] and during electro-thermal [10] and hydro-pulse treatment of liquid media [11], the load resistance of the EDI can randomly increase several times, causing an inadmissible long discharge of RC [3–5].

The aim of the work is to develop a technical solution that would limit the duration of random aperiodic discharges in a semiconductor (thyristor) electro-discharge installation with capacitive energy storage devices (capacitors) and electro-spark load, the resistance of which can randomly increase. Fig. 1 shows proposed equivalent circuit of a two-channel EDI, in which charges and discharges of capacitors C_1 and C_2 follow by turns. In this installation, the duration of the random aperiodic discharge of capacitor C_1 through the load impedance R_{load} is limited by beginning of the discharge of capacitor C_2 (or vice versa).

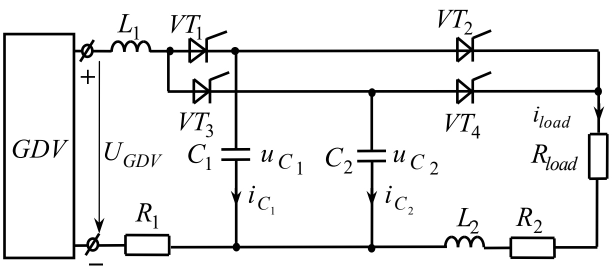

Fig. 1

Analysis of charge-discharge transients in the two-channel EDI. The charge of capacitors C_1 and C_2 in such EDI is carried out from a generator of direct voltage (GDV) U_{GDV} = 500 V after unlocking by turns of corresponding charging thyristors (VT_1 for C_1 and VT_3 for C_2) through a charging choke with inductance L_1 and impedance of the charging circuit R_1. The discharge of the capacitors on the resistance R_{load} is implemented through the inductance L_2 and the impedance of the discharge circuit R_2 when the discharge thyristors VT_2 or VT_4 are switched on respectively.

The analysis of transients in the EDI's circuits was performed using the method of multiparameter functions [12]. According to this method, the charge of capacitor C_1 in the circuit GDV-L_1-VT_1-C_1-R_1-GDV occurs at the first interval of time $\Delta t_1 = t_1 - t_0$. This time interval corresponds to time period from thyristor VT_1 unlocking to its locking. Using the second Kirchhoff law, you can get the following second-order differential equation relative to the instantaneous voltage $u_{1C_1}(t)$ on the capacitor C_1 for this time interval

$$d^2u_{1C_1}(t)\Big/dt^2 = -R_1du_{1C_1}(t)\Big/L_1dt + U_{GDV} - u_{1C_1}(t)\Big/L_1C_1 \,. \qquad (1)$$

By the Runge-Kutta method, the solution of equation (1) for an interval Δt_1 can be obtained in the form of a matrix $\mathbf{U_{1C_1}}$ with step p_1, which is as follows:

$$\mathbf{U_{1C_1}} = \mathrm{rkfixed}\left(u_{1C_1}, t_0, t_1, p_1, D_{1C_1}\right). \qquad (2)$$

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Here D_{1C_1} is a column vector of intermediate solutions relative to the voltage $u_{1C_1}(t)$ on the capacitor C_1.

In the second time interval $\Delta t_2 = t_2 - t_1$, which corresponds to the pause between charge of capacitor C_1 and its discharge to load R_{load}, all thyristors in the circuit are locked. The voltages on the capacitor C_1 for the first and second time intervals at moments t_1 and t_2 correspondingly are the same

$$u_{2C_1}(t_2) = u_{1C_1}(t_1). \qquad (3)$$

In the third interval $\Delta t_3 = t_3 - t_2$ there is a discharge of condenser C_1 over the circuit C_1-VT_2- R_{load}- R_2- L_2-C_1. The following differential equation can be written for the discharge transition process

$$d^2u_{3C_1}(t)\big/dt^2 = -\left(R_2 + R_{load}\right)du_{3C_1}(t)\big/L_2dt - u_{3C_1}(t)\big/L_2C_1. \qquad (4)$$

The solution (3) is defined on the interval Δt_3 in the form of a matrix $\mathbf{U_{3C_1}}$ with step p_3 as

$$\mathbf{U_{3C_1}} = \mathrm{rkfixed}\left(u_{3C_1}, t_2, t_3, p_3, D_{3C_1}\right). \qquad (5)$$

Here D_{3C_1} is a column vector of intermediate solutions relative to the voltage $u_{3C_1}(t)$ on the capacitor C_1.

In the fourth interval $\Delta t_4 = t_4 - t_3$, which corresponds to the pause after the discharge of the capacitor C_1, all thyristor switches are locked and the voltage on the capacitor for the third and fourth time intervals at moments t_3 and t_4 correspondingly are the same

$$u_{4C_1}(t_4) = u_{3C_1}(t_3). \qquad (6)$$

Then the total voltage u_{C_1} is determined by the summation of the voltages found in expressions (2), (3), (5), (6)

$$u_{C_1} = \sum_{i=1}^{4} u_{iC_1}. \qquad (7)$$

Current in the capacitor C_1 is calculated according to the formula

$$i_{C_1} = C_1 \frac{du_{C_1}}{dt}. \qquad (8)$$

The voltage and current during charge and discharge of second capacitor C_2 is determined similarly. It could be written the equations similar to (1) – (8) taking into account that the elements C_2, VT_3 and VT_4 work in the circuit instead of the elements C_1, VT_1 and VT_2.

In the fifth time interval $\Delta t_5 = t_5 - t_4$, the charge of capacitor C_2 occurs over the circuit GDV-L_1-VT_3-C_2-R_1-GDV and the voltage $u_{5C_2}(t)$ of the second capacitor in this time interval is defined as

$$d^2u_{5C_2}(t)\big/dt^2 = -R_1du_{5C_1}(t)\big/L_1dt + \left(U_{GDV} - u_{5C_1}(t)\right)\big/L_1C_1. \qquad (9)$$

The solution (9) is determined by Runge-Kutta method on the interval Δt_5 in the form of a matrix $\mathbf{U_{5C_2}}$ with step p_5

$$\mathbf{U_{5C_2}} = \mathrm{rkfixed}\left(u_{5C_2}, t_4, t_5, p_5, D_{5C_2}\right). \qquad (10)$$

Here D_{5C_2} is a column vector of intermediate solutions relative to the voltage $u_{5C_2}(t)$ on the capacitor C_2.

In the sixth time interval $\Delta t_6 = t_6 - t_5$, which corresponds to the pause after charge of the capacitor C_2 and prior to its discharge through the load, all thyristor switches are locked and the voltage on the capacitor C_2 remains unchanged

$$u_{6C_2}(t_6) = u_{5C_2}(t_5). \qquad (11)$$

In the seventh interval $\Delta t_7 = t_7 - t_6$, when the capacitor C_2 is discharged through the load over the circuit C_2-VT_4-R_{load}-R_2- L_2-C_2, the capacitor voltage is determined by formula

$$d^2u_{7C_2}(t)\big/dt^2 = -\left(R_2 + R_{load}\right)du_{7C2}(t)\big/L_2dt - u_{7C_2}(t)\big/L_2C_1. \qquad (12)$$

The solution (12) is defined on the interval Δt_7 in the form of a matrix $\mathbf{U_{7C_2}}$ with step p_7

$$\mathbf{U_{7C_2}} = \mathrm{rkfixed}\left(u_{7C_2}, t_6, t_7, p_7, D_{7C_2}\right). \qquad (13)$$

Here D_{7C_2} is a column vector of intermediate solutions relative to the voltage $u_{7C_2}(t)$ on the capacitor C_2.

In the eighth interval $\Delta t_8 = t_8 - t$, which corresponds to the pause after the discharge of the capacitor C_2 up to the start of the next charge of the capacitor C_1, all thyristor switches are locked and the voltage on the capacitor C_2 at the moments t_7 and t_8 correspondingly is the same

$$u_{8C_2}(t_8) = u_{7C_2}(t_7). \qquad (14)$$

Then the total voltage u_{C_2} could be found as sum of voltages from expressions (10), (11), (13) i (14)

$$u_{C_2} = \sum_{i=5}^{8} u_{iC_2}. \qquad (15)$$

Current in the capacitor C_2 is calculated as

$$i_{C_2} = C_2 \frac{du_{C_2}}{dt}. \tag{16}$$

The current through resistance R_{load} is defined as the sum of the discharge currents of the capacitors by the formula

$$i_{load} = C_1\, du_{2C_1} \big/ dt + C_2\, du_{7C_2} \big/ dt. \tag{17}$$

Normal operation the EDI is based on the implementation of oscillatory charges and discharges of capacitors. However, in case of a prolonged aperiodic discharge, which may arise due to a random increase in the resistance of the electro-spark load, the proposed circuit (Fig. 1) allows to limit such discharge and return again to normal modes.

To test the efficiency of the scheme, a mathematical modeling of its operation in the program package Mathlab/Simulink was carried out. For modeling the parameters of the circuit elements were chosen as follows: U_{GDV} = 500 V, L_1 = 150 μH, L_2 = 5 μH, C_1 = C_2 = 50 μF, R_1 = R_2 = 0.085 Ohm, switching frequency for all thyristors f_{VT} = 500 Hz. Load resistances at oscillatory modes R_{load} = 0.8 Ohm; and at aperiodic discharges R_{load} = 6 Ohm.

The oscillograms of capacitors voltage $u_{C_1}(t)$, $u_{C_2}(t)$ and load current $i_{load}(t)$ at oscillating discharges of both capacitors are shown in Fig. 2. In should be noted that the pulses of current in the load have a double frequency compared with the frequency of discharges each of capacitors.

Figure 3 shows the oscillograms of the currents $i_{C_1}(t)$, $i_{C_2}(t)$ and $i_{load}(t)$ (Fig. 3, *a*, *b*, *c*) in the capacitors C_1, C_2 and in the R_{load} correspondently when the long aperiodic discharge of the capacitor C_2 (which lasts during the next charge of the capacitor C_1) occurs due to increase of load resistance. Then, after the next unlocking of the discharge thyristor VT_2, the higher reverse voltage will be applied to the unlocked thyristor VT_4, which will cause its locking and interrupting the long-term aperiodic discharge. The limitation of duration of the aperiodic load current can be seen in Fig. 3, *c*.

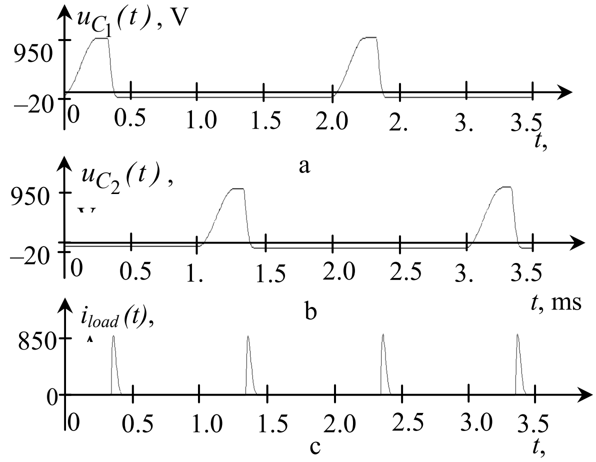

Fig. 2

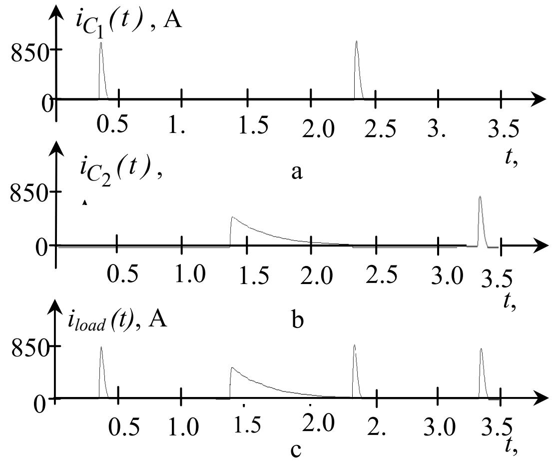

Fig. 3

As can be seen from oscillograms in Fig. 3, the duration of the aperiodic discharge of the capacitors in the two-channel EDI depends on the frequency of oscillatory (spark-discharge) pulses in the load. Due to the presence of two channels, the duration of the possible aperiodic discharge cannot exceed half switching period of the thyristors (and correspondently half period of oscillatory pulses, taking into account the pause between them). It should be noted that the time interval for equalization the discharge voltages of first and second capacitors should be sufficient to restore the locking properties of the thyristor VT_4. Otherwise it can open again and the duration limitation of the aperiodic discharge of the capacitor C_2 will not happen.

Conclusions. An electrical circuit of a semiconductor two-channel electro-discharge installation with two reservoir capacitors and electro-spark load was developed. The circuit allows to limit the duration of possible aperiodic discharge pulse in the load arising as a result of a random increase its resistance. The duration limitation of aperiodic discharges depends on both the parameters of the discharge circuit and the restoring time of locking properties of the semiconductor (thyristor) keys. Reducing the duration of discharge currents in the load increases their frequency and improves stability of the pulse modes of the electro-discharge installations, even when its load resistance increases randomly.

1. Vovchenko A.I., Tertilov R.V. Synthesis of capacitive non-linear-parametrical energy sources for discharge-pulse technologies. *Zbirnyk naukovykh prats Natsionalnoho universytetu korablebuduvannia*. 2010. No 4. Pp. 118–124. (Rus)

2. Kravchenko V.I., Petkov A.A. Parametrical synthesis of high-voltage pulse test device with capacitive energy storage. *Elektrotekhnika i Elektromekhanika*. 2007. No 6. Pp. 70–75. (Rus)

3. Shcherba A.A., Suprunovska N.I., Ivaschenko D.S., Beletsky O.A. Processes of energy exchange between nonlinear and linear links of electric equivalent circuit of supercapacitors. *Tekhnichna Elektrodynamika*. 2015. No 5. Pp. 3 – 11. (Rus)

4. Shcherba A.A., Suprunovska N.I., Ivaschenko D.S. Modeling of Nonlinear Resistance of Electro-Spark Load Taking into Account its Changes During Discharge Current Flowing in the Load and at Zero Current in it. *Tekhnichna Elektrodynamika*. 2014. No 5. Pp. 23 – 25. (Rus)

5. Livshitz A.L., Otto M.Sh. Pulse electrotechnology. Moskva: Energoatomizdat, 1983. 352 p. (Rus)

6. Nguyen, P.K., Sungho J., Berkowitz A.E. MnBi particles with high energy density made by spark erosion. *Journal of Applied Physics*. 2014. Vol. 115. No 17. Pp. 17A756-1.

7. Ivanova O.M., Danylenko M.I., Monastyrskyy G.E., Kolomytsev V.I., Koval Y.M., Shcherba A.A., Zakharchenko S.M., Portier R. Investigation of the formation mechanisms for Ti-Ni-Zr-Cu nanopowders fabricated by electrospark erosion method in cryogenic liquids. *Metallofizika i Noveishie Tekhnologii*. 2009. Vol. 31. No 5. Pp. 603–614.

8. Kokorin V.V., Perekos A.O., Tshcherba A.A., Babiy O.M., Efimova T.V. Intermartensitic phase transitions in Ni-Mn-Ga alloy, magnetic field effect. *Journal of Magnetism and Magnetic Materials*. 2006. Vol. 302. Issue 1. Pp. 34–39.

9. Ochin P., Gilchuk A.V., Monastyrsky G.E., Koval Y., Shcherba A.A., Zakharchenko S.N. Martensitic transformation in spark plasma sintered compacts of Ni-Mn-Ga powders prepared by spark erosion method in cryogenic liquids. *Materials Science Forum*. 2013. Vol. 738–739. Pp.451–455.

10. Shcherba A.A., Podoltsev O.D., Kucheriava I.M., Ushakov V.I. Computer Modeling of Electrothermal Processes and Thermomechanical Stress at Induction Heating of Moving Copper Ingots. *Tekhnichna Elektrodynamika*. 2013. No 2. Pp. 10–18. (Rus)

11. Shcherba A.A., Kosenkov V.M., Bychkov V.M. Mathematical closed model of electric and magnetic fields in the discharge chamber of an electrohydraulic installation. *Surface Engineering and Applied Electrochemistry*. 2015. Vol. 51. Issue 6. Pp 581–588.

12. Makarenko M.P., Senko V.I., Yurchenko M.M. System analysis of electromagnetic processes in semiconductor converters of electric power. Kyiv: Institute of electrodynamics of NAN Ukraine, 2005. 241 p. (Ukr)

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ОБМЕЖЕННЯ ТРИВАЛОСТІ ПЕРЕХІДНИХ АПЕРІОДИЧНИХ ПРОЦЕСІВ У КОЛАХ КОНДЕНСАТОРІВ ДВОКАНАЛЬНИХ ЕЛЕКТРОРОЗРЯДНИХ УСТАНОВОК

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Виконано математичне моделювання імпульсно-періодичних перехідних процесів у колах конденсаторів двоканальних напівпровідникових електророзрядних установок. Визначено умови обмеження тривалості аперіодичних перехідних процесів розряду їхніх конденсаторів на електроіскрове навантаження, опір якого може змінюватися від розряду до розряду. Показано, що в двоканальних установках тривалість аперіодичних розрядів конденсаторів залежить від частоти виникнення іскророзрядних імпульсів у навантаженні і не може перевищувати тривалість їхнього періоду. Обмеження тривалості аперіодичних розрядів залежить від параметрів розрядного контуру та тривалості процесів відновлення запірних властивостей напівпровідникових (тиристорних) комутаторів. Скорочення тривалості розрядних струмів у навантаженні сприяє підвищенню їхньої частоти та стабільності імпульсних режимів у навантаженні. Бібл. 12, рис 3.

***Ключові слова**:* аперіодичні перехідні процеси, конденсатор, напівпровідниковий комутатор, розряд, імпульсний струм.

ОГРАНИЧЕНИЕ ДЛИТЕЛЬНОСТИ ПЕРЕХОДНЫХ АПЕРИОДИЧЕСКИХ ПРОЦЕССОВ В ЦЕПЯХ КОНДЕНСАТОРОВ ДВУХКАНАЛЬНЫХ ЭЛЕКТРОРАЗРЯДНЫХ УСТАНОВОК

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Выполнено математическое моделирование импульсно-периодических переходных процессов в цепях конденсаторов двухканальных полупроводниковых электроразрядных установок. Определены условия ограничения длительности апериодических переходных процессов разряда их конденсаторов на электроискровую нагрузку, сопротивление которой может изменяться от разряда к разряду. Показано, что в двухканальных установках длительность апериодических разрядов конденсаторов зависит от частоты возникновения искроразрядных импульсов в нагрузке и не может превышать длительность их периода. Ограничение длительности апериодических разрядов зависит от параметров разрядного контура и длительности процессов восстановления запирающих свойств полупроводниковых (тиристорных) коммутаторов. Сокращение длительности разрядных токов в нагрузке способствует повышению их частоты и стабильности импульсных режимов в нагрузке. Библ. 12, рис 3.

***Ключевые слова**:* апериодические переходные процессы, конденсатор, полупроводниковый коммутатор, разряд, импульсный ток.

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