мальные динамические свойства электротехнического комплекса при движении.

Практическая значимость. На основе разработанного критерия определена процедура расчетов параметров оптимальной кривой движения, что позволяет проектировать системы автоматического регулирования и управления системами тяговых электроприводов, осуществлять испытание, усовершенствование, ремонт и диагностику систем подвижного электротехнического комплекса.

Ключевые слова: *подвижный комплекс, работа, минимизация затрат, кривая движения, электрическая передача*

Рекомендовано до публікації докт. техн. наук П.Д. Андрієнком. Дата надходження рукопису 03.03.15.

УДК 621.314:621.373

T. M. Lytvynenko

Zaporizhzhia State Engineering Academy, Zaporizhzhia, Ukraine, e-mail: tnlit@meta.ua

SYNTHESIS OF HIGH-VOLTAGE CONVERTER FOR ELECTROTECHNOLOGY

Т. М. Литвиненко

Запорізька державна інженерна академія, м. Запоріжжя, Україна, e-mail: tnlit@meta.ua

СИНТЕЗ ВИСОКОВОЛЬТНОГО ПЕРЕТВОРЮВАЧА ДЛЯ ЕЛЕКТРОТЕХНОЛОГІЇ

Purpose. Development of the theory of design of the generators of high-voltage pulses, creation of a generator with less loss of energy.

Methodology. The high-voltage converter scheme synthesis was done by the synthesis algorithm with variable structure based on the graph of state changes. The synthesis procedure is the ideal arrangement of keys in a circuit with a constant structure so that the nature of electromagnetic processes in the received circuit with variable structure conforms to the originally specified graph of state changes.

Findings. The synthesis of high-voltage circuit converter was performed in accordance with the requirements of energy loss reduce: the assurance of the of IGBT operation modes, which reduce current and voltage loading of the device, and allow switching the transistor with zero current or voltage, or in the case of neutral switching.

Originality. A new circuit of a converter was synthesized. It can halve the working voltage of the primary capacitive storage, and reduce the current and voltage loading of the power switches. Thereby, it becomes possible to increase the allowable frequency of operation of the high-voltage converter in comparison with a single-cycle circuit of the converter.

Practical value. The proposed method of implementation and the high-voltage converter device can be used in electrotechnics of cleaning of sulphur-containing gases from sulphur dioxide, since the high-voltage converter has better mass and size (by reducing the amount of magnetic knots) than similar devices based on single-cycle thyristor schemes and loses less energy (efficiency of 70 % vs. 60 %).

Keywords: *electrotechnology, high-voltage converter, graph of state change*

Definition of the problem: The primary task of modern competitive industrial production is the mastery of high-performance technologies based on sustainable use of natural resources, saving energy and reducing harmful emissions [1, 2]. The development of such technologies is facilitated by the use of high-voltage pulse technique of the nanosecond and submicrosecond bands in particular for the purposes of purification of waste gases of metallurgical production from sulfur dioxide.

Unsolved aspects of the problems. The development of highly efficient method of neutralization of sulfur-containing gases is based on the method of processing gases of electric discharge and promising method of cleaning gases from sulfur dioxide with crucial assistance of activated absorption solution. The key factor is the power specific volume which can be created in the discharge gap. From this point of view, pulsed action of high voltage (tens to hundreds of kilovolts) with low pulse duration (no more than several hundreds of ns) is of great interest; under the action a streamer discharge is formed and the transition discharge to the form of the spark discharge is prevented, since the spark discharge leads to a sharp drop of the specific power by volume in the discharge chamber. To form a streamer discharge it is necessary to develop a high-voltage impulsive energy sources – a high-voltage impulsive converter.

In the middle of the last century, high-voltage pulse power sources began to be created for research programmes with a view to their use in particle accelerators and fusion processes. In this direction the main efforts are concentrated on getting record-high output power.

A large number of scientists have been engaged in the problem of the design and creation of the high-voltage pulse generator: I. S. Garber, L. A. Meerovich, G. A. Mesyats,

V. V. Kremnev, B. M. Koval'chuk, Ju. F. Potalicyn, I. M. Vatin, Je. F. Zajcev, V. M. Kandykin, A. N. Meshkov, N. G. Shubkin, S. P. Sychev, V. A. Vizir.

However, high-voltage devices for research programmes do not meet the requirements for installations with a range of industrial applications: high level of average power, compactness, efficiency and long service life.

Therefore, the creation of high-voltage converters for use in industrial electrotechnology plants for flue gas cleaning, which ensure the reduction of energy consumption, have a simple structure and high reliability, is an topical scientific and technical problem.

Analysis of the recent research. The greatest use and distribution is attributed to the generators which were implemented according to the Arkadiev-Marx scheme. As a rule, gas spark gaps are used as switches in such generators [3]. The main disadvantage of Arkadiev-Marx generators is the low efficiency (less than 50 %) due to losses in the charging circuits. Application of the converters for forming a charging currents in the Arkadiev-Marx scheme generators the converters for forming a charging currents can increase the efficiency; however, it results in a significant complication of the scheme of such generators and increases its cost. Significant disadvantages of the generator are low resource of its work and poor stability of generated pulses.

Generators which are developed on the basis of thyratron switches are more practical and demonstrate a high degree of efficiency compared to the Arkadiev-Marx generators [4]. However, a common drawback of thyratron devices is the relatively short lifetime of the thyratrons, which introduces limitations in the service life of the generator. In addition, the application of pulsed hydrogen thyratrons compels to solve a number of additional tasks – providing a hydrogen environment to thyratrons (the use of hydrogen generators), the need for heating circuit. Apart from that, when thyratrons switch large currents, *x*-ray emission occurs (it is necessary to have an additional protection against radiation).

There known driver circuits on the basis of reversible-switch dinistors (RSD) [5]. However, the technical capabilities of the RSD switch do not allow shaping the pulses of a nanosecond range. To shorten the duration of the output pulse together with the RSD switches it is necessary to use sharpening circuits. Furthermore, when using the RSD diodes-switches, the complexity of their control circuits becomes a significant drawback.

The alternative to RID generators is the generator of high voltage pulses based on SOS-diodes [6]. Devices based on SOS-diodes can generate pulses with a voltage of tens to hundreds of kilovolts with duration of tens and hundreds of nanoseconds at the load of tens to hundreds of Ohms. However, to create the initial excitation pulse in the SOS-generators thyristors are applied, which leads to high losses during the formation of short pulses and increases the number of interlinked magnetic contours (magnetic knots).

Unsolved aspects of the problem. The works [6, 7] described the principles of construction of high-current nanosecond generators with solid-state switching system energy in which a semiconductor opening switch (SOS-diode) carries out the function of the final power amplifier. In such generators thyristors are used as primary switches. The magnetic knots of compression match parameters of the node of the primary switch based on thyristor with the outputting shapers and SOS-diodes. To create pulses of primary excitation in such generators thyristors are used in which the mode of generation of short pulses shows a significant loss, which leads to an increase in the number of interlinked magnetic circuits (magnetic knots) and also makes it difficult to configure, to repair the generator and leads to deterioration of technical and economic characteristics of the generator.

To improve technical and economic characteristics of the high-voltage generator, it is important to use high-speed semiconductor devices, such as IGBT, as the primary switches. With the advent of powerful IGBT devices a possibility appeared to create more reliable generators of a smaller size and higher energy efficiency [8].

Objectives of the work. The use of IGBT in the high-voltage generators can significantly reduce the duration of the primary pulses of excitation and thereby reduce the number of magnetic knots, which leads to downsizing and decreasing losses of energy. In addition, the IGBT devices require low power to manage, have a high overload capacity of collector current and erase a problem related to stability of commutation. Thus, to improve the efficiency of formation of pulses with a high voltage converter, it is necessary to develop a method of implementing a high-voltage converter for electrical technology using IGBT transistors as switches of primary excitation pulses.

The main requirements for the synthesis of high-voltage circuit converter are the achievement of the modes of operation of the IGBT at which reduction of the sink and voltage burden of the device occurs. This is possible when the transistor is switched in zero current or voltage, or in the case of neutral switching.

Presentation of the main research. To implement the principle of the formation of high-voltage pulses, using the current interrupter and the inductive energy storage, it is necessary to match electrical parameters of the energy source and the parameters of the electric pulses which must be filed on interrupter in order to obtain pulses of nanosecond duration under load. The high-voltage converter based on a semiconductor interrupter has the following structure shown in Fig. 1: power supply – input capacitive storage – a matching device – terminal capacitive storage – a semiconductor opening switch and inductive energy storage – load.

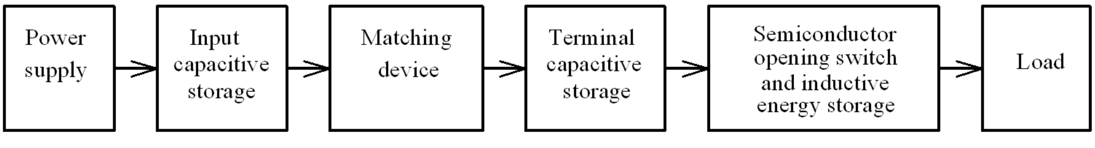

Fig. 1. Schematic structure of the converter

The requirements for the synthesis of high-voltage circuit converter involve the achievement of the modes of the IGBT operation at which the reduction of the sink and voltage burden of the device is achieved. This is possible when the switching mode is in zero current or voltage, or in the case of neutral switching.

The following are selected as stationary intervals for consideration of electromagnetic processes in a matching converter: 1 – the end of the charge process of the input storage capacitor and 2 – the end of the charging of the terminal storage capacitor.

Thus, the exchange of energy between the energy storage should be as follows: the charge of the second storage capacitor occurs on the first and second intervals simultaneously with the overcharge of the first storage capacitor, i.e. both charging circuits are connected to the first and second intervals.

The solutions of the difference equations of States at the intervals using the lookup for the first interval $\varepsilon = \gamma_1$, $\gamma_0 = 0$, to the second interval $\varepsilon = 1$, are as follows

$$u'_{C1}(n+\gamma_1) = E - \left[U_{C1}(n) - U_{C2}(n)\right] \cdot \frac{C_E}{C_1} \times \\ \times \left[1 - e^{-b_{12}\gamma_1 T}\left(\cos\omega_{12}\gamma_1 T + \frac{b_{12}}{\omega_{12}}\sin\omega_{12}\gamma_1 T\right)\right], \tag{1}$$

where ω_{12} is the resonant frequency of the electric circuit; E is EMF of power supply; C_1 is the capacity of the primary storage; C_2 *is the capacity of the second storage;* C_E is the equivalent capacitance,

$$C_E = \frac{C_1 \cdot C_2}{C_1 + C_2};$$

γ_0, γ_1 are the moments of the start of the first and second intervals in relative units; n is a quantity of periods of the converter operation;

$$b_{12} = \frac{R_1}{2L_{12}};$$

$$u'_{C2}(n+\gamma_1) = E + U_{C1}(n) \cdot \frac{C_E}{C_2} \times \\ \times \left[1 - e^{-b_{12}\gamma_1 T}\left(\cos\omega_{12}\gamma_1 T + \frac{b_{12}}{\omega_{12}}\sin\omega_{12}\gamma_1 T\right)\right]; \tag{2}$$

$$i'_{L1}(n+\gamma_1) = i'_{L2}(n+\gamma_1) = \\ = -\frac{U_{C1}(n) - U_{C2}(n)}{\omega_{12}L_{12}} e^{-b_{12}\gamma_1 T}\sin\omega_{12}\gamma_1 T; \tag{3}$$

$$u'_{C1}(n) = -E + \left[U_{C1}(n+\gamma_1) - U_{C2}(n+\gamma_1)\right] \cdot \frac{C_E}{C_1} \times \\ \times \left[1 - e^{-b_{12}(1-\gamma_1)T}\left(\cos\omega_{12}(1-\gamma_1)T + \frac{b_{12}}{\omega_{12}}\sin\omega_{12}(1-\gamma_1)T\right)\right]; \tag{4}$$

$$u'_{C2}(n) = E + U_{C1}(n+\gamma_1) \cdot \frac{C_E}{C_2} \times \\ \times \left[1 - e^{-b_{12}(1-\gamma_1)T}\left(\cos\omega_{12}(1-\gamma_1)T + \frac{b_{12}}{\omega_{12}}\sin\omega_{12}(1-\gamma_1)T\right)\right]; \tag{5}$$

$$i'_{L1}(n) = i'_{L2}(n) = \frac{U_{C1}(n+\gamma_1) - U_{C2}(n+\gamma_1)}{\omega_{12}L_1} \times \\ \times e^{-b_{12}(1-\gamma_1)T}\sin\omega_{12}(1-\gamma_1)T. \tag{6}$$

On the basis of expressions (1) to (6) a graph of state changes (GSCh) is developed [9, 10]. The GSCh is depicted in Fig. 2 with the continuous lines showing relationships characterising the processes observed in the converter in the first interval, and the dotted lines showing relationships characterising the processes observed in the converter in the second interval.

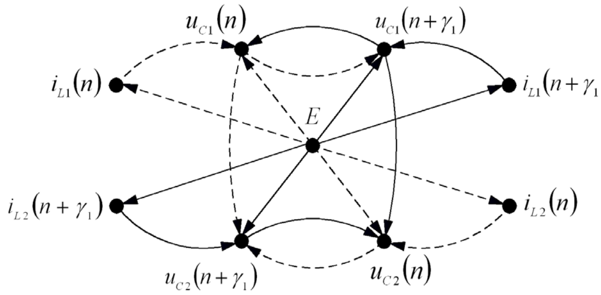

Fig. 2. Graph of state changes

Structural synthesis of the matching converter is performed by the synthesis algorithm with a variable structure-based graph of state changes [10]. The synthesis procedure consists in placement of the perfect keys in the circuit with a permanent structure in such a way that the nature of electromagnetic processes in the received circuit with a variable structure conforms to the one originally specified by the graph of state changes [10]. The equivalent circuit of a constant structure that corresponds to the obtained graph of state changes, is represented in Fig. 3.

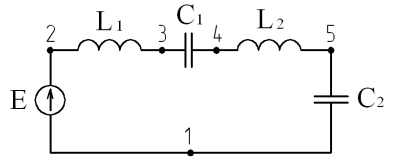

Fig. 3. Equivalent circuit of a constant structure

Based on the graph of state changes (Fig. 2) and an equivalent circuit (Fig. 3) matrices of equivalence relations are composed:

for the 1st interval

$$W^1 = \left\| \begin{array}{ccccc|l} 1 & 1 & 1 & 1 & 1 & E \\ 1 & 1 & 1 & 1 & 1 & L1 \\ 1 & 1 & 1 & 1 & 1 & C1 \\ 1 & 1 & 1 & 1 & 1 & L2 \\ 1 & 1 & 1 & 1 & 1 & C2 \end{array} \right\|; \tag{7}$$

for the 2nd interval

$$W^2 = \left\| \begin{array}{ccccc|l} 1 & 1 & -1 & 1 & 1 & E \\ 1 & 1 & -1 & 1 & 1 & L1 \\ -1 & -1 & -1 & -1 & -1 & C1 \\ 1 & 1 & -1 & 1 & 1 & L2 \\ 1 & 1 & -1 & 1 & 1 & C2 \end{array} \right\| . \quad (8)$$

In this case, the equivalence classes are obtained as follows

$$Y_1^2 = \{E, L1\}; \quad Y_2^2 = \{C1\}; \quad Y_3^2 = \{L2, C2\}. \quad (9)$$

For the equivalence classes obtained, multitude of relationships is determined

$$\Omega_1^2 = \{(2,1),(2,3)\}; \quad \Omega_2^2 = \{(3,4)\}; \quad \Omega_3^2 = \{(4,5),(5,1)\}. \quad (10)$$

Variation of the polarity of the connection element *C1* (Fig. 3) in the second interval to the opposite one is shown in (8) with a "–" sign. The nodes in which the polarity for connection of the part of the electric circuit (element *C1*) to the basic circuit should be changed have numbers 3, 4. These nodes are the nodes of adjacency. In the circuit of a constant structure (Fig. 3) the open-circuited and short-circuited branch are inserted. First, the elements of the subset Y_1^2 are disconnected. The node adjacency 3 is divided into a pair of nodes 3′, 3″, between which an open-circuited branch is inserted. Next, the elements of the subset Y_3^2 are disconnected. To do this, the node adjacency 4 is divided into a pair of nodes 4′, 4″ between which an open-circuited branch is inserted.

In the subset of items Y_2^2 Hamiltonian cycle does not occur, so it is necessary to place short-circuited branches so that they are opposite to open-circuited branches, in this case short-circuited branches should be included between nodes 3′, 4′ and 3″, 4″.

After inserting the short-circuited branches in the indicated nodes, the Hamiltonian cycle will be created for subsets Y_1^2, Y_3^2 as well.

As a result of placing short-circuited and open-loop branches, the following circuit is developed, Fig. 4.

The placing of ideal switches should be performed as follows: switch S_1 is to be placed between nodes 3′ and 3″; switch S_2 – between nodes 3′ and 4′; switch S_3 – between nodes 3″ and 4″; switch S_4 – between nodes 4′ and 4″.

The synthesized electric circuit with the ideal switches placed is presented in Fig. 5.

Group of switches, S_1, S_4 and S_2, S_3 operate in antiphase. As a result of synthesis there obtained two electric circuit, however, only one meets the requirements that were put forward by the problem statement on the synthesis circuit converter (Fig. 5). Combining synthesized circuit and a circuit that allows to create flowing of direct and inverse currents through the semiconductor opening switch [11], which in turn is necessary for the operation of the interrupter in the mode of the fast current interruption and the formation of a high-voltage pulse, the result is a general electric circuit of the high voltage converter to generate pulses on the basis of the IGBT shown in Fig. 6.

The circuit in Fig. 6 is a push-pull electrical circuit, that is why each time while recharging a primary storage capacitor C_1 the energy from a power supply will be transferred to the capacitor storage C_2.

The load factor of the power switch on the voltage κ_u, can be represented by the following relationship

$$\kappa_u = \frac{U_{VS\,m}}{E} = \frac{E}{E} = 1, \quad (11)$$

where $U_{VS\,m}$ is the amplitude of the voltage on the power switch; E is EMF of power supply.

The load factor of the power switch on the current κ_I, can be expressed as follows

$$\kappa_I = \frac{I_{VS\,d}}{I_{0\,d}} = 0{,}5, \quad (12)$$

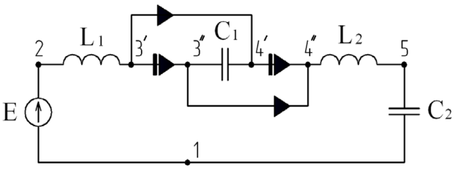

Fig. 4. Partitioning of the electric circuit with a constant structure

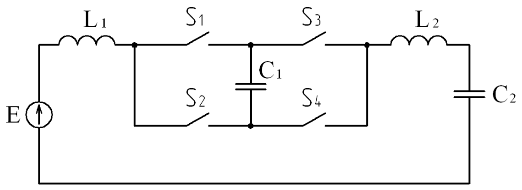

Fig. 5. The synthesized electric circuit with ideal switches

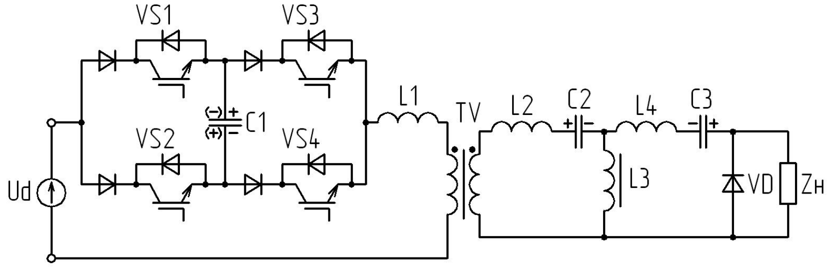

Fig. 6. Electric circuit of a high-voltage converter

where $I_{VS\,d}$ is the mean value of the current through the power switch; $I_{0\,d}$ is the mean value of the input current.

As it can be seen from (11), the voltage on the power switch does not exceed the voltage level of the power supply, while in the single-cycle circuits, the voltage at the switch is twice as high. From (12) it follows that the load of the power switch for current is twice as small as that of the single-cycle circuits. With the load of power keys decreasing for current and voltage, the frequency of the converter operation can increase. In addition, since the voltage on the capacitive storage coincides with the voltage level on the power switch, installed power (power-to-size ratio) of the storage capacitor will be twice as small as that for the single-cycle circuit converter.

In the converter circuit shown in Fig. 6 reactive elements create three oscillating circuits: the first circuit includes the primary capacitive storage *C1,* intermediate capacitive storage *C2* and inductive reactor *L1*; the second circuit consists of the intermediate capacitive storage *C2,* inductive reactor *L2* and capacitive storage *C3*; the third circuit includes the capacitive storage *C3* and inductive reactor *L4.* Oscillations in the contours occur sequentially, i. e. first, oscillations are observed in the first circuit, then, when the circuit structure changes due to the switching of the key switch, oscillations occur in the second circuit and then in the third one. Thus, the scheme is built on the resonance energy transfer from the source to the load.

Fig. 7 shows the time dependence of currents and voltages in the circuit of the high voltage converter.

The time intervals presented in Fig. 7 have a different scale for all the diagrams. This is done for better visualization of the diagrams. The interval $t_0 - t_1$ corresponding to the process of charge the capacitive storage *C2,* amounts to units of microseconds by duration; the interval $t_1 - t_2$ corresponding to the process of discharge capacitive storage *C2* and the charge capacitive storage *C3* is about half a microsecond; the interval $t_2 - t_3$ during which the reverse current of the semiconductor opening switch (diode VD) reaches the maximum value, makes a range from tens to several hundreds of nanoseconds. In the last interval, an output pulse is generated $t_3 - t_5$ the duration of which depends on the load characteristics and ranges from tens to hundreds of nanoseconds.

The dependence of the voltage on the capacitive storages *C1, C2, C3* (Fig. 6) is described by the following expressions

$$u_{C1} \approx U_d\left(1-\frac{C_2}{C_1+C_2}\right)-U_{C1(0)}\frac{C_2}{C_1+C_2}+ \\ +\left(U_d+U_{C1(0)}\right)\frac{C_2}{C_1+C_2}e^{-\frac{1}{2Q_2}\vartheta_2}\cos\vartheta_2; \quad (13)$$

$$u_{C2}(\vartheta) \approx \left(U_d+U_{C1(0)}\right)\frac{C_1}{C_1+C_2}\left(1-e^{-\frac{1}{2Q_2}\vartheta_2}\cos\vartheta_2\right); \quad (14)$$

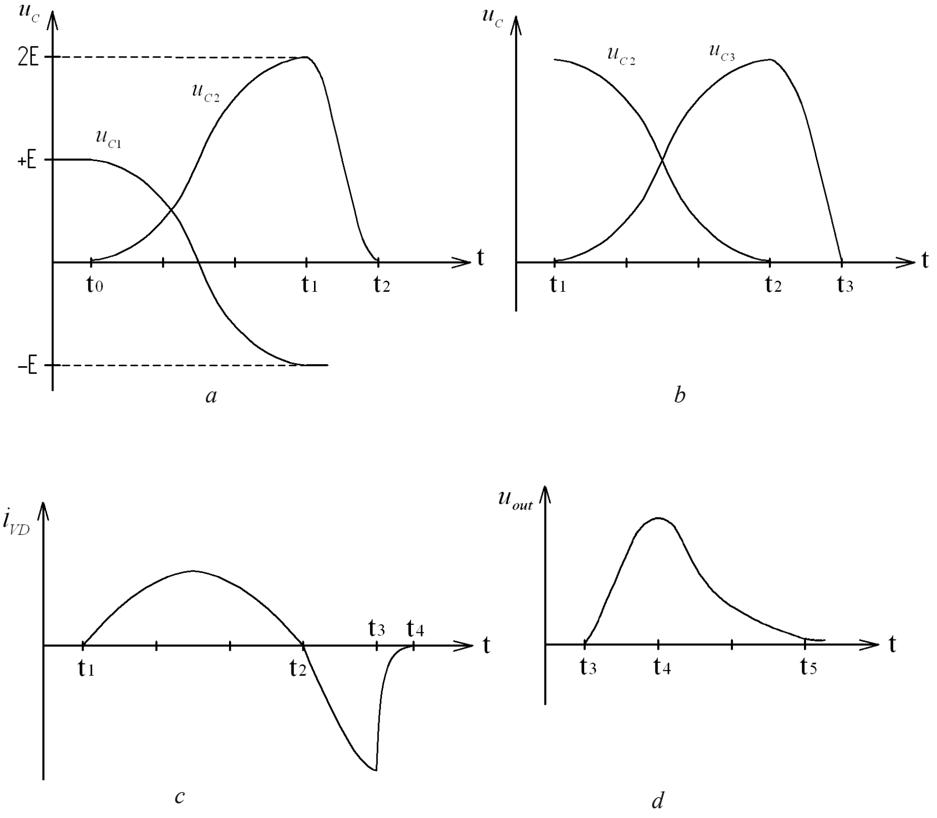

Fig. 7. Time dependencies of processes in the circuit of the high-voltage converter: a — the charge of capacity storage C2; b — the charge of capacity storage C3; c — the dependence of forward and reverse current through a semiconductor opening switch VD; d — the process of voltage pulse generation; u_{C1} *is the voltage of the storage C1;* u_{C2} *is the voltage of the storage C2;* u_{C3} *is the voltage of the storage C3;* i_{VD} *is the current through a semiconductor opening switch VD;* u_{out} *is the output voltage*

$$u_{C3}(\vartheta) \approx U_{C2(0)} \frac{C_2}{C_2 + C_3}\left(1 - e^{-\frac{1}{2Q_3}\vartheta_3} \cos \vartheta_3\right), \qquad (15)$$

where Q_2, Q_3 are the Q-factors of contours charge of the capacitive storages C_2 and C_3 accordingly; ϑ_2, ϑ_3 stand for relative time, $\vartheta_2 = \omega_2 t$, $\vartheta_3 = \omega_3 t$; U_d is the voltage of the power supply; $U_{C1(0)}$ is the initial value of the voltage of the capacitive storage C_1; $U_{C2(0)}$ is the initial value of the voltage of the capacitive storage C_2.

Research conclusions and recommendations for further research in the area. The synthesized electric circuit of the high-voltage converter allows decreasing the load on the IGBT power switches on the current and voltage and provides zero current switching of the power switches; due to the high speed of the IGBT devices, this circuit achieves a reduction in the number of magnetic knots, which reduces the weight and dimensions as well as energy losses compared with a single cycle thyristor circuits.

The proposed method of implementing a high-voltage converter can be used in electrotechnology of cleaning sulphur-containing gases from sulphur dioxide; in the course of the experimental verification on the basis of the proposed converter, increase in the degree of neutralization of sulphur dioxide up to 96 % with the specific power consumption of 40 kW/m^3 was observed.

References / Список літератури

1. Pivnyak, G., Busygin, B. and Nikulin, S., 2010. Geoinformation system RAPID as the means of solving the problems of environment and nature management. In: *12th International Symposium on Environmental issues and Waste Management in Energy and Mineral Production SWEMP-2010*. Czech University of Life Sciences Prague, Czech Republic, May 24–26. pp. 431–436.

2. Rudakov, D.V. and Lyakhovko, A.D. 2014. Prediction of environmental impact of modernization of gas treatment equipment at industrial enterprises. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, no. 3, pp. 111–117. ISSN 2071-2227.

Рудаков Д.В. Прогнозирование экологического эффекта модернизации газоочистного оборудования промышленных предприятий / Д.В. Рудаков, А.Д. Ляховко // Науковий вісник НГУ. – 2014. – № 3. – С. 111–117. ISSN 2071-2227.

3. Mesyats, G.A. 2004. *Impulsnaya energetika i elektronika* [Pulse power and electronics]. Moscow: Nauka. ISBN 5-02-033049-3.

Месяц Г.А. Импульсная энергетика и электроника / Месяц Г.А. – М.: Наука, 2004 – 704 с. ISBN 5-02-033049-3.

4. Vereshchagin, N.M. and Kruglov, S.A. 2002. High-voltage pulse generator with inductive energy storage and a thyratron. *Pribory i Tekhnika Ehksperimenta*, no. 2, pp. 82–85. ISSN 0032-8162.

Верещагин Н.М. Генератор высоковольтных импульсов с индуктивным накопителем энергии и тиратроном / Н.М. Верещагин, С.А. Круглов // Приборы и техника эксперимента. – 2002. – №2. – С. 82–85. ISSN 0032-8162.

5. Grekhov, I.V., Korotkov, S.V. and Hristyuk, D.V. 2002. RID-switch diode obstacles switched current pulses. *Pribory i Tekhnika Ehksperimenta*, no. 5, pp. 94–96. ISSN 0032-8162.

Грехов И.В. РВД – переключатель с диодным обострителем коммутируемых импульсов тока / И.В. Грехов, С.В. Коротков, Д.В. Христюк // Приборы и техника эксперимента. – 2002. – №5. – С. 94–96. ISSN 0032-8162.

6. Lyubutin, S.K., Rukin, S.N. and Slovikovskiy, B.G. 2000. Compact generator with solid-state current interruption with a voltage of 300 kV and pulse repetition rate up to 2 kHz. *Pribory i Tekhnika Ehksperimenta*, no.1. pp. 82–86. ISSN 0032-8162.

Любутин С.К., Компактный генератор с полупроводниковым прерывателем тока с напряжением 300 кВ и частотой следования импульсов до 2 кГц / С.К. Любутин, С.Н. Рукин, Б.Г. Словиковский // Приборы и техника эксперимента. – 2000. – № 1. – С. 82–86. ISSN 0032-8162.

7. Bushlyakov, A.I., Ponamorev, A.V., Rukin, S.N. Slovikovskiy, B.G. and Timoshenkov, S.P. 2002. Megavoltage nanosecond generator with semiconductor current interruption. *Pribory i Tekhnika Ehksperimenta*, no. 2, pp. 74–81. ISSN 0032-8162.

Мегавольтный наносекундный генератор с полупроводниковым прерывателм тока / А.И. Бушляков, А.В. Понаморев, С.Н. Рукин [и др.] // Приборы и техника эксперимента. – 2002. – №2. – С. 74–81. ISSN 0032-8162.

8. Litvinenko T.N. and Semenov, V.V., 2004. The generator of high-voltage sub-microsecond pulses. *Tekhnichna Elektrodynamika. Tem. vypusk: Problemy Suchasnoi Elektrotekhniky.* Ch. 4, pp. 49–54. ISSN 0204-3599.

Литвиненко Т.Н. Генератор высоковольтных субмикросекундных импульсов / Т.Н. Литвиненко, В.В. Семенов // Технічна електродинаміка. Тем. випуск: Проблеми сучасної електротехніки. – 2004. – Ч. 4. – С. 49–54. ISSN 0204-3599.

9. Artemenko, M.Yu., Zhuykov, V.Ya., and Yakymenko, Yu.I., 2001. *Matrychno-typolohichnyi syntez ventylnykh peretvoriuvachiv* [Matrix-topological synthesis of switched converters]. Series *Elektronni komponenty ta systemy dlia enerhetyky*. Kyiv: Politekhnika. ISBN 966-622-062-8.

Артеменко М.Ю. Матрично-топологічний синтез вентильних перетворювачів. Серія „Електронні компоненти та системи для енергетики“ / Артеменко М.Ю., Жуйков В.Я., Якименко Ю.І. – К.: „Політехніка“, 2001. – 230 с. ISBN 966-622-062-8.

10. Rudenko, V.S., Zhuykov, V.Ya., Suchyk, V.E. 2010. *Analiz protsessiv v napivprovodnykovykh peretvoriuvachakh na osnovi grafiv* [Analysis of processes in semiconductor converters based on graphs]. Kyiv: NTUU Kyivskyi Politekhnichnyi Instytut.

Руденко В.С. Аналіз процесів в напівпровідникових перетворювачах на основі графів / Руденко В.С., Жуйков В.Я., Сучик В.Е. // НТУУ „Київський політехнічний інститут“. – 2010. – 68 с.

11. Darznek, S.A., Mesyats, G.A. and Rukin, S.N., 1997. Dynamics of electron-hole plasma in semiconductor interruption of superdense currents. *Zhurnal Tekhnicheskoy Fiziki*. vol. 67, issue 10, pp. 64–70.

Дарзнек С.А. Динамика электронно-дырочной плазмы в полупроводниковых прерывателях сверхплотных токов / С.А. Дарзне, Г.А. Месяц, С.Н. Рукин // Журнал технической физики. – 1997. – Т. 67. – Вып. 10. – С. 64–70. ISSN 0044-4642.

Мета. Подальший розвиток теорії проектування формувачів високовольтних імпульсів, створення формувача з меншими втратами енергії.

Методика. Виконано синтез схеми високовольтного перетворювача за алгоритмом синтезу із змінною структурою на основі графа зміни станів. Процедура синтезу полягає в розстановці ідеальних ключів у схемі з постійною структурою таким чином, що характер електромагнітних процесів в отриманій схемі зі змінною структурою відповідає заздалегідь заданій графом зміні станів.

Результати. Виконано синтез схеми високовольтного перетворювача у відповідності до вимог зниження втрат енергії: забезпечення режимів роботи IGBT, за яких досягається зниження завантаження приладу як за струмом, так і за напругою, здійснення комутації транзистора в нулі струму або напруги, або у випадку нейтральної комутації.

Наукова новизна. Синтезована нова схема перетворювача, що дозволяє зменшити робочу напругу первинного ємнісного накопичувача у два рази, знизити завантаження силових ключів по струму й напрузі, унаслідок чого можливе збільшення допустимої частоти роботи високовольтного перетворювача в порівнянні з однотактною схемою перетворювача.

Практична значимість. Запропонований спосіб реалізації та пристрій високовольтного перетворювача може знайти застосування в електротехнології очищення сірковмісних газів від діоксиду сірки, оскільки високовольтний перетворювач має переваги перед аналогічними пристроями на базі однотактний тиристорних схем у масогабаритних показниках (за рахунок зменшення об'єму магнітних вузлів) і відрізняється меншими втратами енергії (ККД 70 % проти 60 % у аналогів).

Ключові слова: *електротехнологія, високовольтний перетворювач, граф зміни станів*

Цель. Дальнейшее развитие теории проектирования формирователей высоковольтных импульсов, создание формирователя с меньшими потерями энергии.

Методика. Выполнен синтез схемы высоковольтного преобразователя по алгоритму синтеза с переменной структурой на основе графа изменения состояний. Процедура синтеза заключается в расстановке идеальных ключей в схеме с постоянной структурой таким образом, что характер электромагнитных процессов в полученной схеме с переменной структурой соответствует первоначально заданному графом изменению состояний.

Результаты. Выполнен синтез схемы высоковольтного преобразователя в соответствии с требованиями снижения потерь энергии: обеспечение режимов работы IGBT, при которых достигается снижение загрузки прибора как по току, так и по напряжению, осуществление коммутации транзистора в ноле тока или напряжения, либо в случае нейтральной коммутации.

Научная новизна. Синтезирована новая схема преобразователя, позволяющая уменьшить рабочее напряжение первичного емкостного накопителя в два раза, снизить загрузку силовых ключей по току и напряжению, вследствие чего возможно увеличение допустимой частоты работы высоковольтного преобразователя в сравнении с однотактной схемой преобразователя.

Практическая значимость. Предложенный способ реализации и устройство высоковольтного преобразователя может найти применение в электротехнологии очистки серосодержащих газов от диоксида серы, так как высоковольтный преобразователь имеет преимущества перед аналогичными устройствами на базе однотактных тиристорных схем в массогабаритных показателях (за счет уменьшения объема магнитных узлов) и отличается меньшими потерями энергии (КПД 70 % против 60 % у аналогов).

Ключевые слова*: электротехнология, высоковольтный преобразователь, граф изменения состояний*

Рекомендовано до публікації докт. техн. наук Т. В. Критською. Дата надходження рукопису 14.03.15.