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MATHEMATICAL MODEL OF A SEMICONDUCTOR CONVERTER WITH EIGHT-ZONE REGULATION OF OUTPUT VOLTAGE

Vladyslav Mykhaylenko, Serhii Karelin, Julia Kunyk, Julia Chunyak

"Kyiv Polytechnic Institute" National Technical University of Ukraine, Kyiv, Ukraine

VladislavMihailenko@i.ua

Abstract: In this article the analysis of electromagnetic processes in electrical circuits with semiconductor switches has been performed. A mathematical model for analysis of electromagnetic processes in semiconductor converter with pulse-width regulation of output voltage has been developed. Time diagrams reflecting electromagnetic processes in electrical circuits are presented.

Today one of the most powerful tools for calculations, analysis and optimization of semiconductor converters (SCC) of electrical energy and devices of power and information electronics are modern software packages of personal computers (PC). The practical use of this software is especially relevant and justified now, when the capacity and software of modern PCs in the age of enchanced informativity have been developed to such an extent that users only need to focus their efforts on solving scientific and technical problems in a certain fields of their specialization. In this work the package MATHCAD has been applied.

Key words: electromagnetic processes, output voltage and current, the load current, method of modulating many parametric functions.

1. Introduction

Recent trends in the qualitative transformation of electricity and the successful development of semiconductor technology allow using the high-frequency units with the valve switching frequency considerably larger than the frequency of alternating voltage of industrial networks. The appropriateness of using frequency converters (FC) with a single modulation in the construction of secondary power supplies for diagnostic complexes of electromechanical devices with various types of input energy was shown in [1-18]. In this work, the analysis of using the same FC structure as the high frequency unit is carried out. It concerns the construction and analysis of converters for electromechanical complexes with time-proportional control (TPC) of direct voltage by eight-zone control.

The goal of this work is the use of the method of multiparameter functions using MATHCAD packages for the analysis of electromagnetic processes in electrical circuits with the semiconductor switchboard.

2. Development of the mathematical model of the converter

A generalised block diagram of the converter is shown in Fig. 1 [3-5]. In the block diagram there are such units marked: PM*A*, PM*B*, PM*C* are power modulators (PM) of phase voltage *A*, *B*, *C* respectively, HFR is a high-frequency rectifier, L denotes a load. The universe of PMs, connected to the power network in parallel and connected in the output in series, is the unit of the high frequency converter. The structure of the PM is shown in Fig. 2, where IRV is the inverter of rectified voltage, AT denotes an accommodating transformer, n is the number of the IRVs.

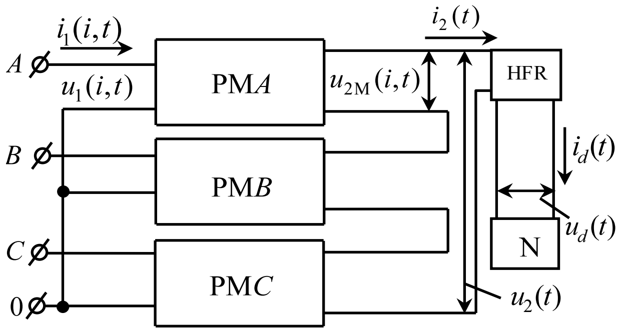

Fig. 1. Block diagram of the converter.

Thus, each of PMs contains *N* IRVs, where *N* is the number of inverters. The creation of a mathematical model of the converter implies the design of mathematical support able to conduct the analysis of its electromagnetic processes concerning generated energy. It should take into account the character of load, energy consumed and energy that is transforming in separate units and in separate circuit elements of the converter. Developing the mathematical model of the converter intended for computer application we use the method of modulating multiparameter functions that provides initiation of algorithmic equation of the converter. At the same time we assume that input power network is symmetric and its internal resistance is equal to zero; transistors and diodes of the IRV are presented as ideal keys, matching transformers do not have any losses and load of the converter is of equivalent active-inductive nature.

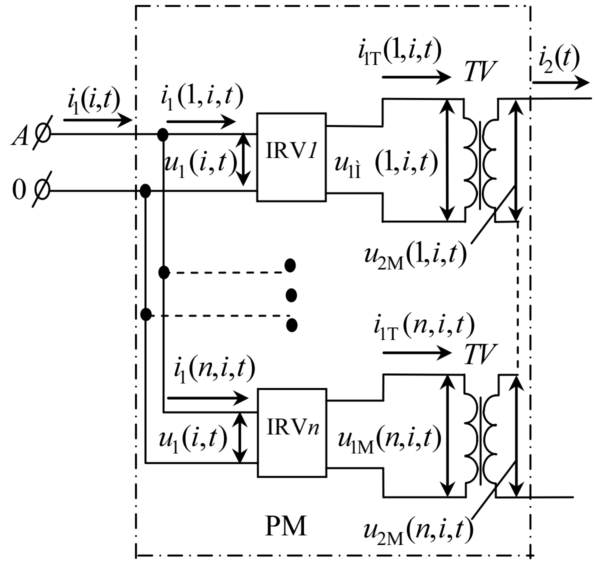

Fig. 2. Block diagram of the power modulator.

This structure allows realizing multichannel transformation of the parameters of network electromagnetic energy at which the branched modulation of instantaneous values of previously rectified phase vlotages $u_1(i,t)$, frequency ω1 of the three-phase power network is performed in the PM by the apropriate equivalent modulating effects $\psi(\alpha_P,t)$, frequency ω2. As a result of this operation on the ouput of each IRV modulating voltage is formed

$$u_{2M}(p,i,t)=\frac{1}{k_T}u_1(i,t)\phi(i,t)\psi(\alpha_P,t) \quad , \qquad (1)$$

where: i = 1, 2, 3 are numbers of power network phases; k_T is a transformation ratio of matching transformer; P = 1, 2, 3, …, n are the numbers of regulation zones of ouput voltage; $\phi(i,t)$ are rectangular-sine functions that coinside in time with the position of appropriate phase of network voltage; $u_1(i,t)$ is the instantaneous value of network input voltage.

Rectangular-sine functions are given as

$$\phi(i,t)=\text{sign}\left\{\sin\left(\omega_1 t-\frac{(i-1)2\pi}{3}\right)\right\}, \qquad (2)$$

An instantaneous value of network input voltage is presented as

$$u_1(i,t)=U_{1m}\sin\left(\omega_1 t-\frac{(i-1)2\pi}{3}\right), \qquad (3)$$

where U_{1m} is a peak value of phase voltage.

Equivalent moduling effects are presented in such an expression

$$\psi(\alpha_P,t)=\frac{1}{2}\sum_{2}\text{sign}\left[\sin\left(\omega_2 t\pm\alpha_P(t)-\varphi\right)\right],$$

where $\alpha_P(t)$ denote angles of control, whose changes provide the PWC of output voltage of the converter; φ is the initial phase of equivalent modulating effects.

The alternate cnange of the control angles in the range from 0^0 to 90^0 is provided in the converter. There are three inverters involved in voltage forming in each control zone which are connected to appropriate phases of network supply. The conditions of changing control angles in separate zones are given in the next form: $\alpha_P(t)=0$ if $t<\frac{(p-1)T}{N=8}$; $\alpha_P(t)=\pi$ if $t>pT/8$, else $\alpha_P(t)=f_X(p,N,t)$, where $f_X(p,N=8,t)$ is a function that sets a change law $\alpha_P(t)$ depending on a zone number p and quantity of zones N=8.

3. Application of the mathematical model

Time diagrams in the output of power modulators graphed by expression (1) are given in Fig. 3–5.

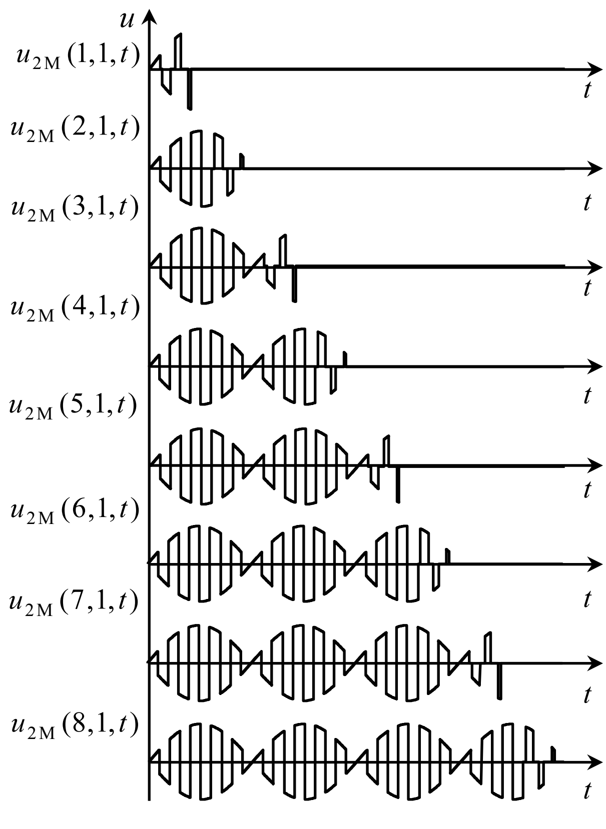

Fig. 3. Diagrams of output voltages of power modulators of phase A.

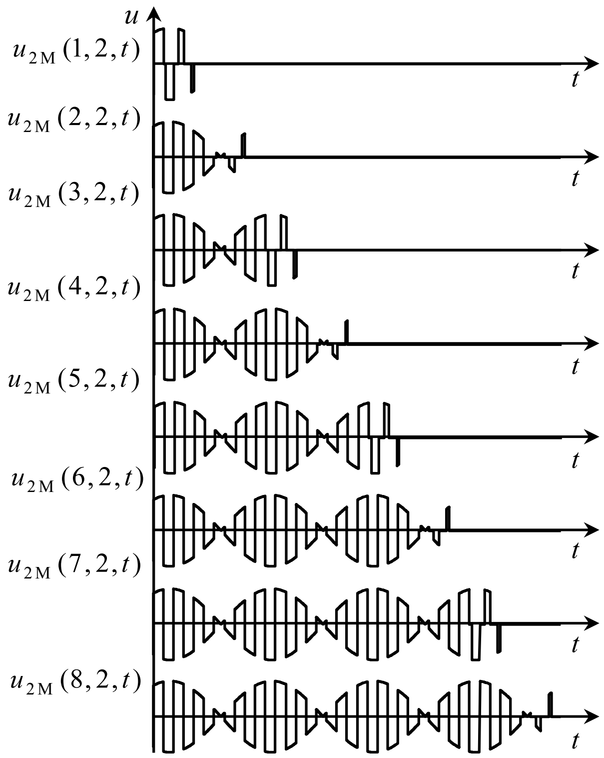

Fig. 4. Diagrams of output voltages of power modulators of phase B.

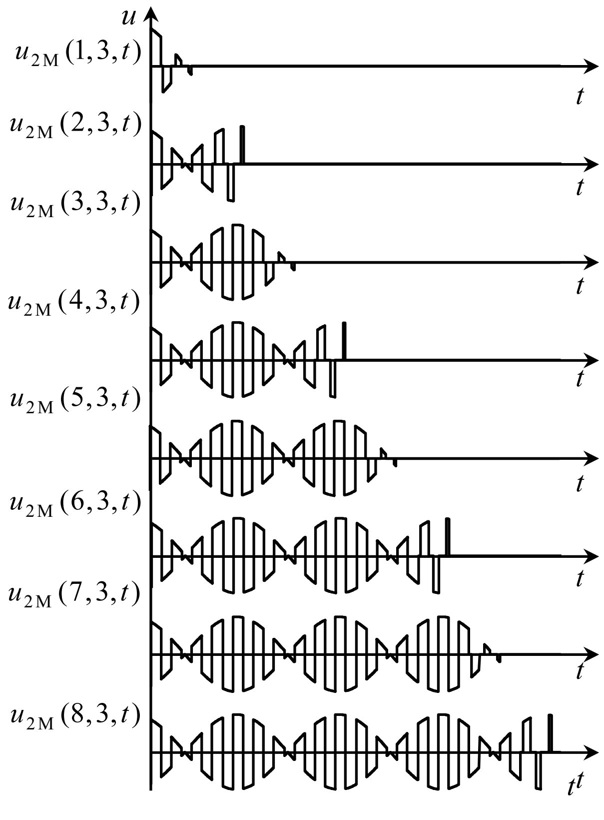

Fig. 5. Diagrams of output voltages of power modulators of phase C.

Output voltage $u_2(t)$ of the high frequency unit of the converter according to its structure and using expression (1) is presented by sum

$$u_2(t)=\sum_{P=1}^{8}\sum_{i=1}^{3}\frac{1}{k_{\text{T}}}u_1(i,t)\phi(i,t)\psi(\alpha_P,t)\,, \qquad (5)$$

and output voltage of converter $u_d(t)$, as rectified voltage (5), is given by a further expression

$$u_d(t)=\sum_{P=1}^{8}\sum_{i=1}^{3}\frac{1}{k_{\text{T}}}u_1(i,t)\phi(i,t)\psi(\alpha_P,t)\,v(t)\,, \qquad (6)$$

where $v(t)$ is the rectangular sine function coinciding by time with output voltage $u_2(t)$ of the high frequency unit of the converter

$$v(t)=\text{sign}(u_2(t))\,. \qquad (7)$$

Fore more detail analysis of output voltage of the converter in (5) we designate $u_1(i,t)\phi(\alpha_P,t)=|u_1(i,t)|$, and taking into account (3) and (4), and also $\psi(\alpha_P,t)v(t)=|\psi(\alpha_P,t)|$ in (6), we rewrite the algorithmic equation in the form

$$u_d(t)=\frac{1}{2k_{\text{T}}}\sum_{P=1}^{8}\left(\sum_{i=1}^{3}\left(\left|U_{1m}\sin\left(\omega_1 t-\frac{(i-1)2\pi}{3}\right)\right|\times\right.\right.$$

$$\left.\left.\times\left|\sum_{2}\text{sign}\left[\sin(\omega_2 t\pm(\alpha_P/2)-\varphi)\right]\right|\right)\right). \qquad (8)$$

Time diagrams of the high frequency unit $u_2(t)$ and the converter $u_d(t)$ built by the expressions (5) and (8) by changing the angle of control α_P linearly in coordinates of time *t*, are given in Fig. 6.

From the expression (8) it can be seen that output converter voltage will get its maximum in the case of $\alpha_P(t)=0$. In this case pulsation frequency of output voltage is $\omega_{\text{п}}=6\omega_1$, and (8) becomes

$$u_d(t)=\frac{1}{k_{\text{T}}}\sum_{P=1}^{8}\sum_{i=1}^{3}\left|U_{1m}\sin\left(\omega_1 t-\frac{(i-1)2\pi}{3}\right)\right|\,. \qquad (9)$$

From the last expression it is easy to find the mean value of output voltage that is given as

$$U_{d_0}=\frac{2{,}7}{k_{\text{T}}}\left(U_{11}+U_{12}+U_{13}+U_{14}+U_{15}+\right.$$
$$\left.+U_{16}+U_{17}+U_{18}\right)=2{,}7\left(U_{21}+U_{22}+U_{23}+\right. \qquad (10)$$
$$\left.+U_{24}+U_{25}+U_{26}+U_{27}+U_{28}\right)$$

where: U_{11}, U_{12}, U_{13}, U_{14}, U_{15}, U_{16}, U_{17}, U_{18} i U_{21}, U_{22}, U_{23}, U_{24}, U_{25}, U_{26}, U_{27}, U_{28} are respectively current values of voltages of primary and secondary windings of matching transformer for the first, second, third, fourth, fifth, sixth, seventh and eighth zone of regulation.

Instantaneous and mean values of output voltage $u_d(t)$ will get zero value if $\alpha_P(t)=\pi/2$. In the full range of $\alpha_P(t)$ changes the regulating characteristic of the converter has the form

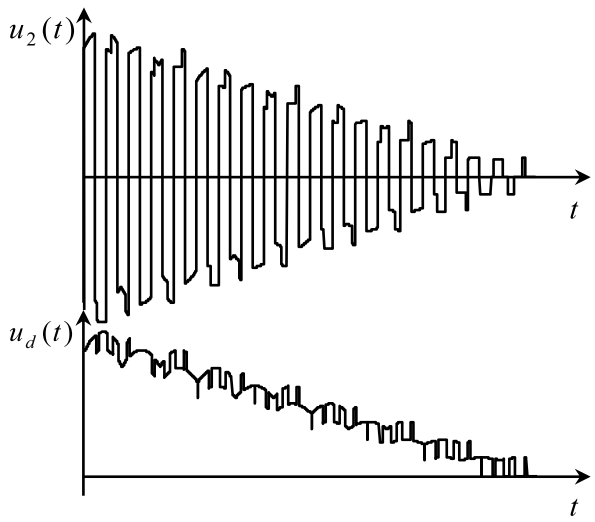

Fig. 6. Diagrams of output voltages of high frequency unit $u_2(t)$ and converter $u_d(t)$.

$$U_{d\alpha} = 2{,}7\sum_{P=1}^{N} U_{2P}\gamma \ , \qquad (11)$$

where $\gamma = t_i/T_2$ is a fill factor; t_i is a pulse width of the output voltage at TPC; T_2 is a period of the modulating influence; $t_i = 0 \div T_2$; $T_2 = 2\pi/\omega_2$.

The load current we will find as the reaction of single-circuit *RL*–unit to the effect of voltage (7). For doing this the differential equation composed for output circuit of the converter will be presented in the form

$$D(t,y) = \frac{u_d(t)}{L} - \frac{R}{L}y_0 \ , \qquad (12)$$

where: y_0 is determined from initial conditions; *R* i *L* are resistance and inductance of the load respectively.

The solution of expression (12) concerning load current we find by the numerical method in the matrix form.

$$i_d(t) = \text{rkfixed}\left(y,0,k,s,D\right), \qquad (13)$$

where: y is a vector of initial conditions; 0, *k* is a time interval of decisions; *s* is the number of points at the time interval of decisions; *D* is a vector function of the differential equation.

Equivalent modulating functions (4) and (7) that are dimensionless and have the unit amplitude can be seen as the transformation functions that determine the dependence of input current on output current which is shown in the form of the solution of (12) by correlation (13). To determine input current $i_2(t)$ of a high frequency rectifier we need to divide (13) by (7). If the transformation function has the zero level, the division can not be performed during the full existence period (8). It causes the need of finding current before the high frequency rectifier at the intervals of non-zero values with subsequent storage of the results of single calculations. However presentation (7) by the function of the unit amplitude allows determining current $i_2(t)$ by multiplicating (13) by (7) and thus simplifying the calculation process presenting the results from the full range of existence (7) and (13). Thus input current of the high frequency rectifier has a form

$$i_2(t) = i_d(t)v(t) \ . \qquad (14)$$

To determine input currents of inventers of the *i*th phases for each Pth zone of regulation we will consider that $i_2(t)$ flows in general circuit of all PM formed by sequentially connected secondary windings of transformers and take into consideration algorithmic equation (6) and the fact that (2), (4) and (7) are functions of the unit amplitude.

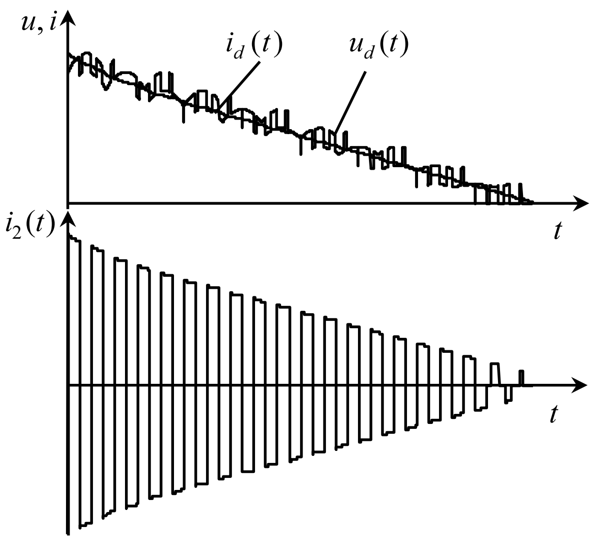

Fig. 7. Diagrams of load current and load voltage and output current of high frequency unit.

Time diagrams of load current in coordinates of output voltage of converter and current at input of HFR built by the expressions (13) and (14) for eight-zone regulation are presented in Fig. 7.

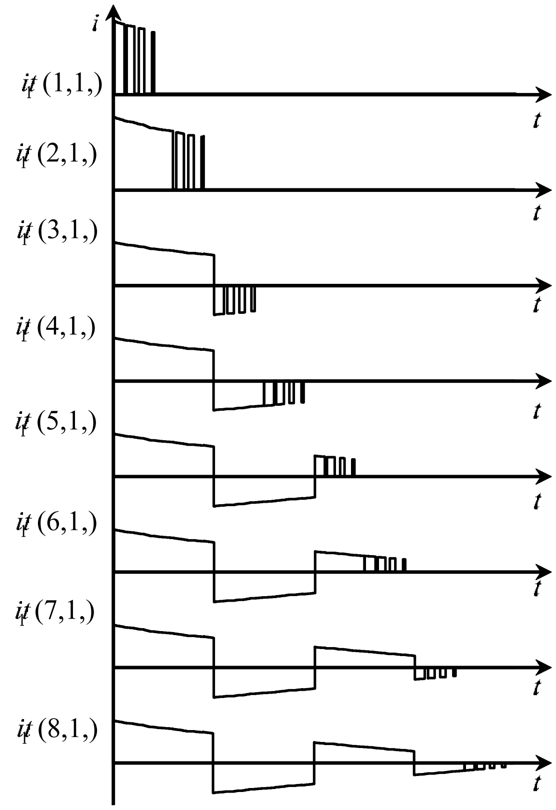

Fig. 8. Time diagrams of input currents of inverters of phase A.

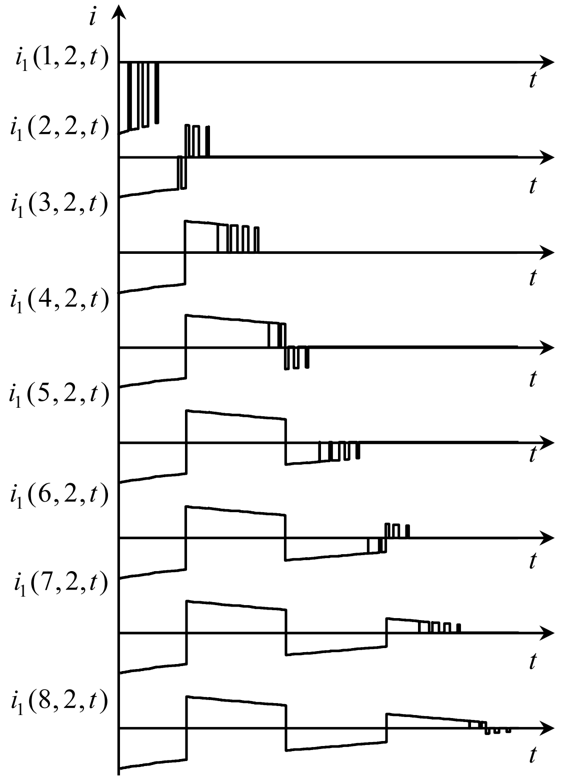

Fig. 9. Time diagrams of input currents of inverters of phase B.

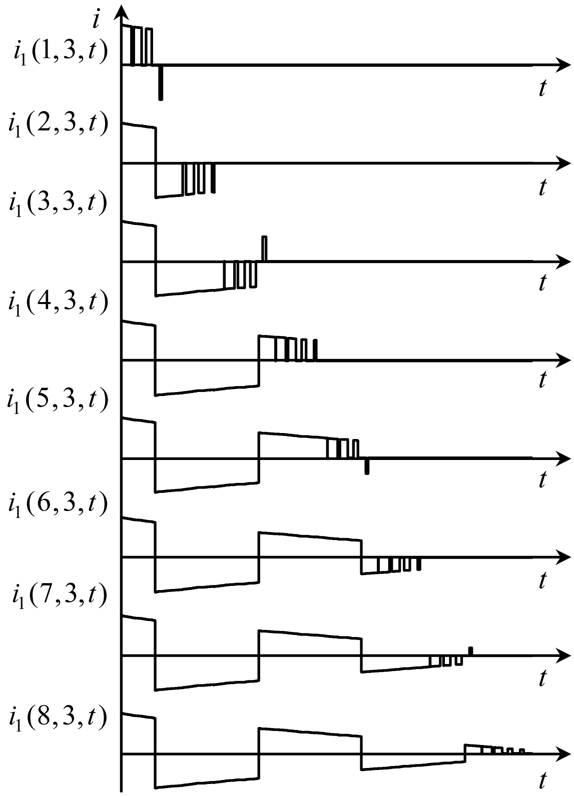

Fig. 10. Time diagrams of input currents of inverterof phase C.

In the general form

$$i_1(n,i,t) = \frac{i_2(t)\psi(\alpha_P,t)\phi(i,t)}{k_T}. \qquad (15)$$

Time diagrams of input currents of inverters built by expression (15) for eight-zone regulation are presented in Fig. 8–10.

Input currents of inverters $i_1(n,i,t)$ can be determined with a known load current without the preliminary calculation of output current $i_2(t)$ of high frequency unit (14).

For this we need to take into consideration algorithmic equation (6) and than considering (13), we obtain

$$i_1(n,i,t) = \frac{i_d(t)\phi(i,t)\left|\psi(\alpha_P,t)\right|}{k_T}. \qquad (16)$$

To determine currents of the *i*-th phase of power network at the whole range of output voltage regulation we will perform summation of the input currents of the inverters of all regulation zones in each *i*-th phase. Taking into account the equation (16), general expression for *i*-th phase currents of the power network we will present as

$$\begin{aligned} i_1(i,t) &= i_1(1,i,t) + i_1(2,i,t) + i_1(3,i,t) + i_1(4,i,t) + \\ &+ i_1(5,i,t) + i_1(6,i,t) + i_1(7,i,t) + i_1(8,i,t) \end{aligned}, \qquad (17)$$

where: $i_1(1,i,t)$, $i_1(2,i,t)$, $i_1(3,i,t)$, $i_1(4,i,t)$, $i_1(5,i,t)$, $i_1(6,i,t)$, $i_1(7,i,t)$, $i_1(8,i,t)$ are input currents of *i*-th phase inventers for the first, second, third, fourth, fifth, sixth, seventh and eighth zones of regulation.

Diagrams of *i-th* phase input currents of the power network in phase voltage coordinates are built by equation (17) and presented in Fig. 11.

To find peak values of currents through power transistors IRV it is enough to analyse currents $i_{1\text{T}}(n,i,t)$ of primary windings of matching transformers situated in the circuits of currents flowing through power transistors. Considering (14) and a number of changing energy transforming channels we will get: $i_{1\text{T}}(n,i,t) = \frac{i_2(t)}{k_\text{T}}$.

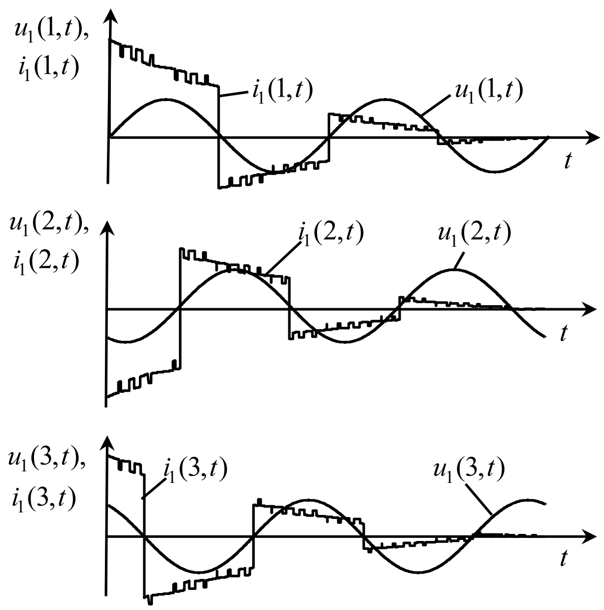

Fig. 11. Diagrams of i-th phase input currents of the power network in phase voltage coordinates.

These currents coincide in time with the output current of the high frequency unit of the converter.

3. Conclusion

In this work the analysis of electromagnetic processes in electrical circuits with semiconductor commutators has been conducted. Using the method of multiparameter modulating functions, the load current and load voltage as well as the input currents of the converter have been obtained. Generalising multiparameter functions are effective for other modulating converters either.

The appropriateness of using MATHCAD software package for the analysis of electromagnetic processes and optimization of semiconductor converters has been confirmed. Such approach can reduce the instability modes in technological loads and modes of electricity consumption from the power network.

On the basis of analysis of the diagrams of input currents in *i*-th phases of power network shown in Fig.6 we can conclude that these currents are sinusoidal with superimposition of high frequency pulsations.

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МАТЕМАТИЧНА МОДЕЛЬ НАПІВПРОВІДНИКОВОГО ПЕРЕТВОРЮВАЧА З ВОСЬМИЗОННИМ РЕГУЛЮВАННЯМ ВИХІДНОЇ НАПРУГИ

Владислав Михайленко, Сергій Карелін,
Юлія Куник, Юлія Чуняк

Проведено аналіз електромагнітних процесів в електричних колах з напівпровідниковими комутаторами. Створено математичну модель для аналізу електромагнітних процесів у напівпровідникових перетворювачах з широтно-імпульсним регулюванням вихідної напруги. Наведено графіки, що відображають електромагнітні процеси у електричних колах. Сьогодні одним з найпотужніших інструментів для розрахунків, аналізу та оптимізації напівпровідникових перетворювачів (НПП) електроенергії та пристроїв силової та інформаційної електроніки є сучасні пакети програмного забезпечення персональних комп'ютерів (ПК). Практичне використання такого програмного забезпечення особливо актуальне і виправдане зараз, коли в умовах розширеної інформаційності потужність та пакети програм сучасних ПК стали такими, що їхнім користувачам тільки потрібно зосередити свої зусилля на вирішенні науково-технічних задач, притаманних лише певним профілям їхньої спеціалізації. У цій роботі використано пакет MATHCAD.

Vladyslav Mykhaylenko – graduated from "Kyiv Polytechnic Institute" in 2000. He was awarded Ph. D in Technical Sciences. Senior lecturer of theoretical electrical engeenering of "Kyiv Polytechnic Institute" National Technical University of Ukraine. Areas of research: electrical engineering and electronics.

Serhii Karelin – student of sophomore year at Department of Electrical Power Plants of "Kyiv Polytechnic Institute" National Technical University of Ukraine. Area of scientific interest: electrical engineering and electronics.

Julia Kunyk – student of sophomore year at Department of Electrical Power Plants of “Kyiv Polytechnic Institute” National Technical University of Ukraine. Area of scientific interest: electrical engineering and electronics.

Julia Chunyak – graduated from “Kyiv Polytechnic Institute” in 1998. Assistant Professor of Department of Theoretical Electrical Engeenering of of “Kyiv Polytechnic Institute” National Technical University of Ukraine. Area of scientific interest: electrical engineering.