Запропоновано метод удосконалення аналізу енергетичних характеристик електричних кіл з напівпровідниковими перетворювачами в аналітичному вигляді. Метод базується на застосуванні одиничної комутаційної функції шляхом та реалізован у частотній області з використанням алгоритму дискретної згортки. Перевірка методу здійснювалась на прикладі схеми з керованим ключовим регулятором напруги. Представлений метод дозволяє спростити реалізацію аналітичних розрахунків шляхом їх програмної автоматизації

Ключові слова: енергетичний процес, напівпровідниковий перетворювач, комутаційна функція, аналітичний аналіз, частотна область, перетворення Фур'є

Предложен метод усовершенствования анализа энергетических характеристик электрических цепей с полупроводниковыми преобразователями в аналитическом виде. Метод базируется на использовании единичной коммутационной функции и реализован в частотной области с использованием алгоритма дискретной свертки. Проверка метода проводилась на примере схемы с управляемым ключевым регулятором напряжения. Представленный метод позволяет упростить реализацию аналитических расчетов путем их программной автоматизации

Ключевые слова: энергетический процесс, полупроводниковый преобразователь, коммутационная функция, аналитический анализ, частотная область, преобразование Фурье

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IMPROVEMENT OF THE ENERGY PROCESSES ANALYSIS METHOD OF ELECTROMECHANICAL SYSTEMS WITH SEMICONDUCTOR CONVERTERS

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1. Introduction

The problem of research of the processes taking place in circuits with semiconductor converters, being elements with explicit nonlinearity, is still topical nowadays [1–5]. The basic issues that researchers face during the analysis of such systems include the following ones: identification of the regularities and improvement of the efficiency of energy conversion [1–3], determination of the nature of reactive power occurrence [5], development of efficient methods for the current calculation [6, 7].

The use of numerical methods essentially simplifies the researchers' task, as, along with relative easiness of realization, it allows one to obtain information concerning practically any processes in nonlinear electric circuits [8–12]. Due to rapid development of computer hardware and availability of a great number of specialized software products such as SAPWIN [8, 9], SPICE [10], SEQUEL [11], MATLAB [12], making it possible to perform calculation and numerical simulation, numerical methods are used most often. However, it should be noted that these methods have the following drawbacks:

– a numerical solution is partial, one of many solutions, which prevents a generalized analysis of the process or the system [13, 14];

– a numerical solution to equations with explicit nonlinearity requires a great number of iterations, which causes significant time consumption [15];

– the calculation accuracy essentially depends on correctly chosen initial approximations and the circuit configuration as well as on the method and the step of integration [16].

Analytical methods have significant advantages in comparison with numerical methods. They enable one to single out a generalized algorithm of the analysis of nonlinear electric circuits, to perform a high-quality analysis and provide an adequate assessment of the processes in nonlinear electric circuits, to estimate the influence of all factors in the system operation, their contribution and significance [5, 7, 15, 17]. So, today it is topical to work out an efficient and practically simple analytical method that will provide sufficient accuracy of calculation, will be well adapted to automation of numerical and analytical calculations, and also will make it possible to perform the analysis of the mechanisms of generation of current and voltage components.

2. Literature review and problem statement

The analysis of Ukrainian and foreign authors' papers dealing with the research of processes taking place in circuits with semiconductor converters made it possible to come to a significant conclusion. The analysis of the signals of current, voltage and power only in the time domain, i. e. only with the use of instantaneous values of electric units, does not provide obtaining maximum information as to operation of the "power supply network – nonlinear load" system [1, 2, 5].

Nowadays, a method of studying energy conversion processes in hydraulic complexes that is based on the interpretation of instantaneous power components in the frequency domain is commonly used [17, 18]. Besides, a method of spectral analysis of instantaneous active and reactive powers, i. e. the analysis of energy processes in the frequency domain is one of the methods for diagnostics of breakages of induction motor with controlled frequency converter. This method is proposed by the authors in [19, 20]. It should be noted that when a problem of creation of fault-tolerant control is solved [21], feedbacks by components of instantaneous active, reactive powers and electromagnetic moments are introduced into the circuits of variable-frequency electric drives [22, 23]. In this case, an analysis of energy processes in the time domain is used [24, 25]. However, even in the latter case, an analysis of energy processes in the frequency domain in an analytical form proved to be efficient for the research of the processes of forming control impacts [26]. Moreover, the research of active and reactive power components in the frequency domain was a required task for improvement of the processes of compensation for the nonlinear equipment operation negative impact on the electricity network [27–30]. Thus, taking the above said into consideration, a conclusion can be made that it is expedient to complexly use numerical and analytical methods of the research of energy conversion processes using the time and the frequency domains. It will enable improving the efficiency of the analysis of energy conversion processes in nonlinear systems with semiconductor converters.

The paper [3] contains a method for the analysis of electric circuits with semiconductor converters, according to which the calculation of currents and voltages in the electric circuit is performed with the assignment of the converter input voltage, a commutation function [4] and a load type. The use of the commutation function properties allows the essential simplification of the procedure of the researched systems with semiconductor converters in an analytical form [3]. The use of such an approach to a case with linear load makes it possible to reduce the analysis of a factually nonlinear circuit with semiconductor elements to the solution of a linear problem of the analysis of linear circuits at the polyharmonic supply voltage. According to this method, the analysis is performed by means of the expansion of the known functions into the Fourier series with their following multiplication. The multiplication of the functions of the cosine and sine of different frequencies, being the components of current and voltage signals requires cumbersome and complex trigonometric transformations and is time-consuming. If there are a lot of harmonic components, the mentioned trigonometric transformations may cause an unpredictable or even an incorrect result. Such calculations are also badly adapted to automation.

Taking the above said into consideration, to overcome a number of difficulties, it is proposed to use this method in the frequency domain. In this case, it is offered to use the method of automated generation of electric values components in the frequency domain [31], which is based on the algorithm of discrete convolution [32]. It allows adaptation of analytical calculations performed with the use of the discrete convolution operation to automate the calculation. In its turn, it will enable obtaining the predicted result.

3. The purpose and tasks of the research

The purpose of the paper consists in the development of the method for the analysis of energy characteristics of the electromechanical systems with semiconductor converters in an analytical form with the use of a single commutation function via realization in the frequency domain. It will provide the possibility for improvement of the efficiency of the analysis of the processes in the mentioned nonlinear systems.

To achieve the posed purpose, the following problems were formulated and solved:

– performance of the method for the analysis of the consumption and conversion of energy in electric circuits with semiconductor converters in an analytical form, based on the use of a single commutation function in the frequency domain;

– adaptation of the analytical method for the analysis of the mechanisms of generation of the components of voltage, current and power of electric circuits with semiconductor converters to automation.

4. The materials and the results of the research of the method for the analysis of electric circuits with semiconductor converters, based on the use of a single commutation function

To verify the proposed method for the analytical research, let us consider an electric circuit with a controlled key voltage regulator and active-inductive load (Fig. 1) [3].

It should be noted that the power key in the considered circuit (Fig. 1, *a*) is based on a power transistor with a reverse diode (Fig. 1, *b*).

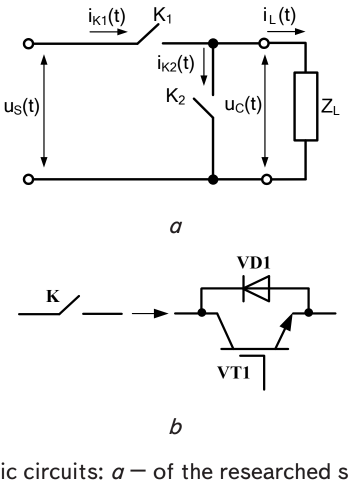

Fig. 1. Electric circuits: *a* — of the researched system with a controlled key voltage regulator; *b* — of the power key

Supply voltage $u_s(t)$ of the researched circuit is assigned by a sine component of the first harmonic:

$$u_S(t)=U_m\sin(\omega t), \tag{1}$$

where U_m – amplitude of the supply voltage, ω – angular frequency.

Operation of the proposed circuit (Fig. 1) is described by single commutation function F(t), presented in the form of the Fourier series with corresponding coefficients [3]:

$$\begin{cases} a_0=\dfrac{\alpha}{\pi}; \\ a_n=\dfrac{1+(-1)^n}{\pi n}\sin(n\alpha); \\ b_n=\dfrac{1+(-1)^n}{\pi n}\left(1-\cos(n\alpha)\right), \end{cases} \tag{2}$$

where α – control angle; n – harmonic number.

According to (2), we obtain:

$$\Phi(t)=a_{k0}+ \\ +\sum_n a_{kn}\cos(n\omega t)+b_{kn}\sin(n\omega t). \tag{3}$$

According to expression (3), the sets of the cosine and sine components of the commutation function in the frequency domain will be of the form:

$$\Phi_{an}=\begin{pmatrix} \dfrac{2\alpha}{\pi} \\ 0 \\ \dfrac{\sin(2\alpha)}{\pi} \\ 0 \\ \dfrac{\sin(4\alpha)}{2\pi} \\ 0 \\ \vdots \\ 0 \\ \dfrac{\sin(16\alpha)}{8\pi} \\ 0 \end{pmatrix};$$

$$\Phi_{bn}=\begin{pmatrix} 0 \\ 0 \\ \dfrac{\left(1-\cos(2\alpha)\right)}{\pi} \\ 0 \\ \dfrac{\left(1-\cos(4\alpha)\right)}{2\pi} \\ 0 \\ \vdots \\ \dfrac{\left(1-\cos(14\alpha)\right)}{7\pi} \\ 0 \\ \dfrac{\left(1-\cos(16\alpha)\right)}{8\pi} \end{pmatrix}. \tag{4}$$

To plot the commutation function (Fig. 2), control angle α was taken 110 el. degrees, the quantity of the researched harmonics n=17.

The following stage consists in identification of the load voltage $u_C(t)$, calculated as the product of the commutation function F(t), expanded into the Fourier series (3), and supply voltage $u_S(t)$:

$$u_C(t)=\Phi(t)u_S(t). \tag{5}$$

To realize (5) in the frequency domain, the algorithm of generation of electrical values components [31] on the basis of discrete convolution [32] is used. It enables simplification of the process of analytical determination of cosine and sine voltage and load components due to substitution of trigonometric transformations by the discrete convolution operation.

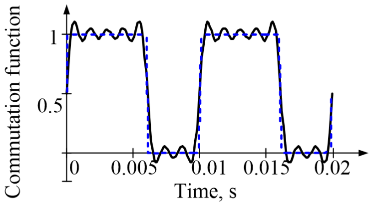

Fig. 2. The commutation function curves, (- - -) – the output commutation function; (——) – the commutation function obtained by the inverse Fourier transform of the results of the operations with it in the frequency domain

Expression (5) in the frequency domain is written down in the following way:

$$U_C=\Phi * U_S, \tag{6}$$

where $*$ – discrete convolution operation.

$$U_{Can}=\begin{pmatrix} 0 \\ \dfrac{1+\cos\left(\dfrac{2}{9}\pi\right)}{2\pi} \\ 0 \\ \dfrac{-\left(1+2\cos\left(\dfrac{2}{9}\pi\right)+2\cos\left(\dfrac{4}{9}\pi\right)\right)}{4\pi} \\ 0 \\ \dfrac{-2+3\cos\left(\dfrac{4}{9}\pi\right)}{12\pi} \\ 0 \\ \vdots \\ 0 \\ \dfrac{-1+\cos\left(\dfrac{2}{9}\pi\right)}{16\pi} \end{pmatrix};$$

$$U_{Cbn}=\begin{pmatrix} 0 \\ \dfrac{11\pi+9\sin\left(\dfrac{2}{9}\pi\right)}{18\pi} \\ 0 \\ \dfrac{-\left(2\sin\left(\dfrac{2}{9}\pi\right)-\sin\left(\dfrac{4}{9}\pi\right)\right)}{4\pi} \\ 0 \\ \dfrac{\sqrt{3}+3\sin\left(\dfrac{4}{9}\pi\right)}{12\pi} \\ 0 \\ \vdots \\ 0 \\ \dfrac{-1\sin\left(\dfrac{2}{9}\pi\right)}{16\pi} \end{pmatrix}, \qquad (7)$$

where U_{Can}, U_{Cbn} – respectively the cosine and sine components of load voltage.

To confirm the correctness of the obtained analytical expressions of the cosine and sine components of load voltage, the corresponding curves were compared. The following was compared – a curve obtained by the multiplication of the Fourier series of commutation function F(t) and supply load $u_S(t)$, with a curve based on expression (7) with the transfer from the frequency domain to the time domain by means of inverse Fourier transform (Fig. 3).

If in the analyzed electric circuit total load Z_L is of an active-inductive character, it can be written down in the following way

$$Z_{Ln}=Z_1\sqrt{\cos^2(\varphi)+n^2\sin^2(\varphi)}, \qquad (8)$$

where

$$Z_1=\sqrt{R^2+(\omega L)^2}. \qquad (9)$$

In expressions (8), (9), Z_1 – impedance of the fundamental harmonic; φ – angle of load resistance shift; R – resistive impedance; L – inductance.

Taking (8) into account, load current in the frequency domain is determined in the following way:

$$i(t)=\frac{a_1}{Z_1}\cos(\omega t+\varphi_1)+\frac{b_1}{Z_1}\cos(\omega t+\varphi_1)+$$
$$+\sum_n\left[\frac{a_n}{Z_{Hn}}\cos(n\omega t+\varphi_n)+\frac{b_n}{Z_{Hn}}\sin(n\omega t+\varphi_n)\right]. \qquad (10)$$

According to (10), it is possible to write down expressions for determination of the cosine I_{an} and sine I_{bn} components of load current in the frequency domain:

$$I_{an}=\frac{U_{Can}\sqrt{R^2+(n\omega L)^2}}{R^2+(n\omega L)^2}\cos(\varphi_n)+$$
$$+\frac{U_{Can}\sqrt{R^2+(n\omega L)^2}}{R^2+(n\omega L)^2}\sin(\varphi_n),$$

$$I_{bn}=\frac{U_{Cbn}\sqrt{R^2+(n\omega L)^2}}{R^2+(n\omega L)^2}\cos(\varphi_n)-$$
$$-\frac{U_{Cbn}\sqrt{R^2+(n\omega L)^2}}{R^2+(n\omega L)^2}\sin(\varphi_n). \qquad (11)$$

According to (11), the analytical expressions for cosine and sine components of load current (12) of the researched electric circuit were obtained. Correctness of the obtained analytical expressions (12) was confirmed by comparison of the current curves shown in Fig. 4.

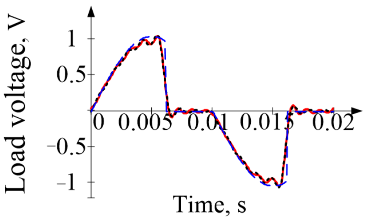

Fig. 3. Load voltage curves,
(– – –) — obtained by multiplication of the output commutation function F(t) and supply voltage;
(——) — obtained by multiplication of Fourier series of the commutation function and supply voltage;
(- - -) — based on expressions (7)

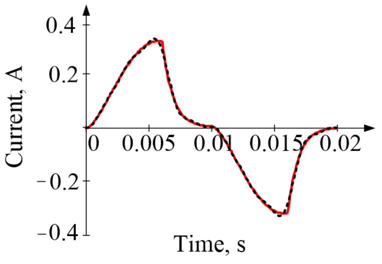

Fig. 4. Load current of the researched electric circuit,
(——) — curve obtained by inverse Fourier transform of the results of operations in the frequency domain;
(- - -) — curve based on expressions (12)

$$I_{an}=\begin{pmatrix} 0 \\ \dfrac{9R\left(1+\cos\left(\frac{2}{9}\pi\right)\right)-9\omega L\sin\left(\frac{2}{9}\pi\right)-11\omega L\pi}{18\pi R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}} \\ 0 \\ -\dfrac{R\left(1+2\cos\left(\frac{2}{9}\pi\right)+\cos\left(\frac{4}{9}\pi\right)\right)-3\omega L\left(2\omega L\sin\left(\frac{2}{9}\pi\right)+\sin\left(\frac{4}{9}\pi\right)\right)}{4\pi R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}} \\ 0 \\ \dfrac{R\left(-2+3\cos\left(\frac{4}{9}\pi\right)\right)-5\omega L\left(3\sin\left(\frac{4}{9}\pi\right)+\sqrt{3}\right)}{12\pi R\sqrt{R^2+9\omega^2L^2}\sqrt{\dfrac{R^2+9\omega^2L^2}{R^2}}} \\ 0 \\ \vdots \\ -\dfrac{R\left(1+8\cos\left(\frac{4}{9}\pi\right)+7\cos\left(\frac{2}{9}\pi\right)\right)+\omega L\left(120\sin\left(\frac{4}{9}\pi\right)+105\sin\left(\frac{2}{9}\pi\right)\right)}{112\pi R\sqrt{R^2+225\omega^2L^2}\sqrt{\dfrac{R^2+225\omega^2L^2}{R^2}}} \\ 0 \\ \dfrac{R\left(-1+\cos\left(\frac{2}{9}\pi\right)\right)+17\omega L\sin\left(\frac{2}{9}\pi\right)}{16\pi R\sqrt{R^2+289\omega^2L^2}\sqrt{\dfrac{R^2+289\omega^2L^2}{R^2}}} \end{pmatrix};$$

$$I_{bn}=\begin{pmatrix} 0 \\ \dfrac{\pi R\left(11+9\sin\left(\frac{2}{9}\pi\right)\right)+9\omega L\left(\cos\left(\frac{2}{9}\pi\right)+\omega L\right)}{18\pi R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}} \\ 0 \\ -\dfrac{R\left(2\sin\left(\frac{2}{9}\pi\right)+\sin\left(\frac{4}{9}\pi\right)\right)+3\omega L\left(1+2\omega L\cos\left(\frac{2}{9}\pi\right)+\cos\left(\frac{4}{9}\pi\right)\right)}{4\pi R\sqrt{R^2+9\omega^2L^2}\sqrt{\dfrac{R^2+9\omega^2L^2}{R^2}}} \\ 0 \\ \dfrac{R\left(\sqrt{3}+3\sin\left(\frac{4}{9}\pi\right)\right)-5\omega L\left(-3\cos\left(\frac{4}{9}\pi\right)+2\right)}{12\pi R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}} \\ 0 \\ \vdots \\ \dfrac{R\left(8\sin\left(\frac{4}{9}\pi\right)+7\sin\left(\frac{2}{9}\pi\right)\right)-15\omega L\left(1+8\cos\left(\frac{4}{9}\pi\right)+7\cos\left(\frac{2}{9}\pi\right)\right)}{112\pi R\sqrt{R^2+225\omega^2L^2}\sqrt{\dfrac{R^2+225\omega^2L^2}{R^2}}} \\ 0 \\ -\dfrac{R\sin\left(\frac{2}{9}\pi\right)+17\omega L\left(1-\cos\left(\frac{2}{9}\pi\right)\right)}{16\pi R\sqrt{R^2+289\omega^2L^2}\sqrt{\dfrac{R^2+289\omega^2L^2}{R^2}}} \end{pmatrix}. \quad (12)$$

Using analytical expressions (7) and (12), it is possible to determine cosine and sine components of the load power for the following research of the analyzed circuit energy characteristics.

Power in the time domain is determined by the known expression:

$$p(t)=u_C(t)i(t). \quad (13)$$

Using the discrete convolution operation, expression (13) can be written down in the frequency domain in the following way:

$$P=U_C*I. \quad (14)$$

It should be mentioned that analytical expressions for the power cosine and sine components for 17 analyzed current and load harmonics are too cumbersome to be presented in the text of this paper, but this is not a problem for automatic calculation. To make the analytical calculations more demonstrable and to provide the possibility for their introduction in the text, they were performed with the use of three harmonic components. The obtained analytical expressions of the power cosine and sine components are given in (15).

For the presented expressions (15), Fig. 5 contains a comparison of the power curves, whose high coincidence, even at a small number of the researched harmonics, proves the correctness of the obtained expressions for the analyzed circuit power.

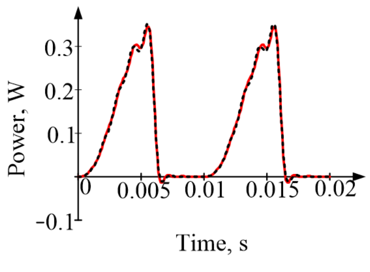

Fig. 5. Load power of the analyzed electric circuit, (——) – curve obtained by inverse Fourier transform of the results of operations in the frequency domain; (- - -) – curve based on expressions (15)

On the basis of the obtained analytical dependences of the instantaneous power (15) of the analyzed electric circuit (1), it is possible to determine the system energy indices according to the frequency components of the instantaneous power.

$$P_{an}=\begin{pmatrix} U_m^2\left[\begin{array}{l}\dfrac{\left[R+R\left(2\sin^2(\alpha)-1\right)-2\alpha\omega L+\omega L\sin(2\alpha)\right]}{4\pi^2R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}}+\\ +\dfrac{\sin(2\alpha)-2\alpha\left[R+R\left(2\sin^2(\alpha)-1\right)+5\alpha\omega L\sin(4\alpha)\right]}{16\pi^2R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}}\end{array}\right] \\ 0 \\ U_m^2\left[\begin{array}{l}\dfrac{\sin^2(\alpha)\left[R+R\left(2\sin^2(\alpha)-1\right)-2\alpha\omega L+\omega L\sin(2\alpha)\right]}{4\pi^2R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}}-\\ -\dfrac{\sin(2\alpha)-2\alpha\left[R+R\left(2\sin^2(\alpha)-1\right)+5\alpha\omega L\sin(4\alpha)\right]}{16\pi^2R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}}\end{array}\right] \\ 0 \\ U_m^2\left[\begin{array}{l}\dfrac{2\sin^2(2\alpha)-4\sin^2(\alpha)\left[R+R\left(2\sin^2(\alpha)-1\right)-2\alpha\omega L+\omega L\sin(2\alpha)\right]}{16\pi^2R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}}-\\ -\dfrac{\sin(4\alpha)-2\sin(2\alpha)\left[R+R\left(2\sin^2(\alpha)-1\right)+5\alpha\omega L\sin(4\alpha)\right]}{32\pi^2R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}}\end{array}\right]\end{pmatrix};$$

$$P_{bn}=\begin{pmatrix} 0 \\ 0 \\ U_m^2\left[\begin{array}{l}\dfrac{\cos(2\alpha)-1\left[R-R\cos(4\alpha)+5\omega L\sin(4\alpha)\right]}{16\pi^2R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}}-\\ -\dfrac{\sin(2\alpha)-2\alpha\left[R-R\cos(2\alpha)-2\alpha\omega L+\omega L\sin(2\alpha)\right]}{8\pi^2R\sqrt{R^2+\omega^2L^2}\sqrt{\dfrac{R^2+\omega^2L^2}{R^2}}}\end{array}\right] \\ 0 \\ U_m^2\left[\begin{array}{l}-\dfrac{2\sin^2(2\alpha)-4\sin^2(\alpha)\left[R+R\left(2\sin^2(\alpha)-1\right)+5\omega L\sin(4\alpha)\right]}{32\pi^2R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}}-\\ -\dfrac{\sin(4\alpha)-2\sin(2\alpha)\left[R+R\left(2\sin^2(\alpha)-1\right)-2\alpha\omega L+\omega L\sin(2\alpha)\right]}{32\pi^2R\sqrt{R^2+25\omega^2L^2}\sqrt{\dfrac{R^2+25\omega^2L^2}{R^2}}}\end{array}\right]\end{pmatrix}. \quad (15)$$

5. Discussion of the results of improving the method for the analysis of electric circuits with semiconductor converters that is based on the use of a single commutation function

The proposed method makes it possible to significantly decrease the time spent on the analysis and to simplify the analytical calculations due to the substitution of trigonometric transformations in the time domain by a discrete convolution operation in the time domain and obtain the predicted result.

It should be noted that the presented method makes it possible not only to obtain the currents and voltages instantaneous value, which is insufficient for a high-quality analysis of energy processes, but also to determine the power at the elements and energy characteristics. That is why it can be used to solve the problems of designing electricity power converters, e. g. voltage and current regulators and stabilizers, power supplies, rectifiers, etc., in which power determination is most important.

The most important advantage of the proposed method consists in the possibility for the analysis of the mechanisms of generating the components of voltage, current and power in an analytical form. Undoubtedly, it increases the effectiveness of solving the problem of formulation of the regularities and improvement of the efficiency of energy conversion. In its turn, the latter will enable the creation of the ways for the development and improvement of the methods for the diagnostics of breakages of alternating current IM and correct choice of the methods of active and passive filtration for the compensation for their operation impact on the energy supply network.

6. Conclusions

1. The method of the analysis of energy consumption and conversion in electric circuits with semiconductor converters with the use of the commutation function has been improved. It has been achieved by means of its realization in the frequency domain with the use of the method of automated generation of electrical values components. It has been proved that the presented method is efficient and simple for practical use.

2. The improved method makes it possible to determine the mechanisms of generating the components of voltage, current and power of the electric circuits with semiconductor converters in an analytical form. In this case, the analytical calculation is well adapted to automation in the mathematical environment due to the use of the automated method for generating electrical values components.

3. The use of the proposed method allows one to simplify the realization of analytical calculation during the analysis of the energy processes in the electric circuits with semiconductor converters due to the substitution of trigonometric transformations in the time domain by the discrete convolution operation in the frequency domain and obtain the predicted result.

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