UDC 62-83-523.003.12

EVALUATION OF ELECTROMECHANICAL COMPLEX PARAMETERS BY ENERGY METHOD

D. Mosiundz, D. Rodkin
Kremenchuk Mykhailo Ostrohradskyi National University
vul. Pershotravneva, 20, Kremenchuk, 39600, Ukraine. E-mail: darya_mosyundz@mail.ru

Energy conversion processes are complicated by the presence of nonlinear processes elements and therefore worsens the quality of the transformed energy, electromechanical equipment wears out faster, losses increase have been shown. Therefore, for the effective use and management of energy processes relevant is the determination of estimates of energy processes in electrical circuits by means of parameter identification of nonlinearities significantly affect the energy conversion processes in the system. The proposed identification method is based on the instantaneous power concept. It is known that even with sinusoidal supply voltage and the presence of nonlinear elements the current in circuit is non-sinusoidal. Using instantaneous power apparatus allows us to get quantitative assessment of energy processes components at each harmonic and form a system with a sufficient number of equations for determining the unknown parameters of both linear and nonlinear energy systems.

Key words: electromechanical systems, nonlinearity, instantaneous power, spectra analysis.

ОЦІНКА ПАРАМЕТРІВ ЕЛЕКТРОМЕХАНІЧНИХ КОМПЛЕКСІВ ЕНЕРГЕТИЧНИМ МЕТОДОМ

Д. А. Мосюндз, Д. Й. Родькін
Кременчуцький національний університет імені Михайла Остроградського
вул. Першотравнева, 20, м. Кременчук, 39600, Україна. E-mail: darya_mosyundz@mail.ru

Показано, що процеси перетворення енергії ускладнюються при наявності нелінійних елементів або процесів, у зв'язку з чим погіршуються показники якості перетвореної енергії, швидше відбувається знос електромеханічного обладнання, збільшуються втрати й т.ін. Тому для ефективного використання та управління енергопроцесами актуальним є визначення оцінок енергопроцесів в електричних ланцюгах шляхом ідентифікації параметрів нелінійностей, що істотним чином впливають на процеси енергоперетворення в системі. Запропоновано метод ідентифікації, заснований на понятті миттєвої потужності. Відомо, що навіть при синусоїдальній живлячій напрузі й наявності нелінійних елементів струм у ланцюзі несинусоїдальної форми. Використання апарату миттєвої потужності дає можливість отримати кількісну оцінку складових енергопроцесів на кожній гармоніці, що дозволяє скласти систему з достатньою кількістю рівнянь для визначення невідомих параметрів як лінійних, так і нелінійних енергетичних систем.

Ключові слова: електромеханічна система, нелінійність, миттєва потужність, спектральний аналіз.

PROBLEM STATEMENT. Electromechanical system is the system with electric power supply devices, devices which convert one type of energy into another (mechanical to electrical and back), switching devices, control and protective modules [1]. Electromechanical complex is a collection of the electric drive system, the transmission mechanism and the movable operating element of the technology mechanism. The role of the complex in this case is technically and technologically justified providing the technology mechanism with appropriately transformed energy.

Pertinent to note that such a formulation deliberately narrows the role of electromechanical devices as an object with a large amount of functionality. The unique capabilities of electric energy conversion by electric machines allows us to use electromechanical systems as elements which capable (with appropriate control) to change the function of load devices and systems. Thus there are possibilities of realization of test signal of loading modes directly as electric machine and converting devices, power devices, devices of technical interaction of engine and technology mechanism (kinematic connections, fasteners, etc.). Analysis of electromechanical systems from the broader perspective of functionality allows us to solve some problems, including those that until recently did not even staged due to inability to obtain acceptable results. For example:

− determination of electrical power parameters of electromechanical systems, in particular, power supply devices, their susceptibility to distortion flow from the converter devices, the effects on the power supply device, communication, etc.;

− the study of energy processes in power supply with nonlinear distortion in real-time, integrated assessment of the influence of factors on the consumer, including electromechanical system powered from unit load;

− the study and evaluation of the nonlinearity parameter included in the power circuit of energy conversion, including the inverter, motor, mounting elements, gear and technological object;

− determination of electronic and electromechanical parameters of electric machines that due to a number of factors may differ significantly from the design, and some change in service and repair operations.

Getting this quite specific information can be achieved only if there is a real requirement for the full analysis of the processes of energy transformation in the basic elements as direct drive system and nonlinearities of the transfer and production mechanisms [2].

All of the variable speed drive, both DC and AC has the ability to create test modes with the realization of the above requirements. Electrical systems with DC motors in cognitive terms, is more convenient because of the simplicity induction system and field circuit, although, as will be shown, and other electric drive system available for the creation modes arising from the previously formulated requirements [3].

Especially it is a question of formation control actions in the power circuits and control circuits, first of all, because it is the standard signals: constant, harmonic, periodic polyharmonic etc.

EXPERIMENTAL PART AND RESULTS OBTAINED. All elements of the electric drive are closely interconnected and interdependent. Physical processes occurring in any unit of energy conversion, not only contribute to the implementation of a given technological problem, but also affect the characteristics of the mechanism as a whole. Therefore, understanding and taking into account the nature and characteristics of these connections is obligatory and necessary condition for establishment of systems for the effective management and development of new features of electromechanical systems (EMS).

Two fundamental principles of electromechanical energy conversion can be formulated in a simplified physical model of the electromagnetic energy conversion. The first one is the principle of reversibility. This principle is due to the universality of the magnetic field as a source of energy. Electromechanical converter (EMC) can implement both a direct and inverse energy, i.e. operate as an electric generator and mechanically engine. The second one is the principle of self-regulation. Electromagnetic and mechanical processes in EMC so adjust their exposure that energy outflow, supplied to EMC on conversion, corresponded to transform the energy outflow from it. The mechanical power is always determine the value of energy conversion in EMC. In the generator is supplied to the shaft mechanical power, at the engine is a mechanical power, is removed from the shaft, and delivered directly to the shaft of the technology mechanism. The mechanism of self-regulation is due to the physical properties of the electromagnetic power that arises in the course of electromechanical energy conversion [4].

In the real EMC energy obtained after the conversion is always less than the energy supplied for conversion, due to inevitable losses caused by physical essence interacting physical processes and heat release in constructive elements. It should be noted that the principle of self-regulation is a common manifestation of the law of conservation of energy [5].

Consider the scheme of energy conversion the electromechanical complex (Fig. 1), which includes five units: the power supply, converter (for example, alternating voltage into direct) transmission and technological mechanisms. Transmission circuit of energy (figure of power units) and the corresponding loss ΔP for each part have been shown on the Fig. 1.

This diagram is quite clearly reflects the conversion process, which can represented by the expression

$$P_s = \Delta P_s + \Delta P_c + \Delta P_e + \Delta P_g + \Delta P_{tm} + \Delta P_{con}, \qquad (1)$$

where ΔP_s, ΔP_c, ΔP_e, ΔP_g, ΔP_{tm}, ΔP_{con} are power loss in the power supply, on the converter, at the engine, on gear and technology mechanisms and power loss of consumer.

The reduced dependence characterizes that side of the issue, without detailing which you can get a general idea about the components.

Formalization of components in general nature can be estimated by parameters of power and its losses, obtained with the voltage, current, torque, speed, etc. in each the elements according to the physical haracteristics of the energy conversion. The general idea of the mentioned features give individual waveforms corresponding elements, the power is then equal to the product of the signals that determine the process, for example: $P(t) = U(t)I(t)$; $P_e(t) = M(t)\omega(t)$ etc.

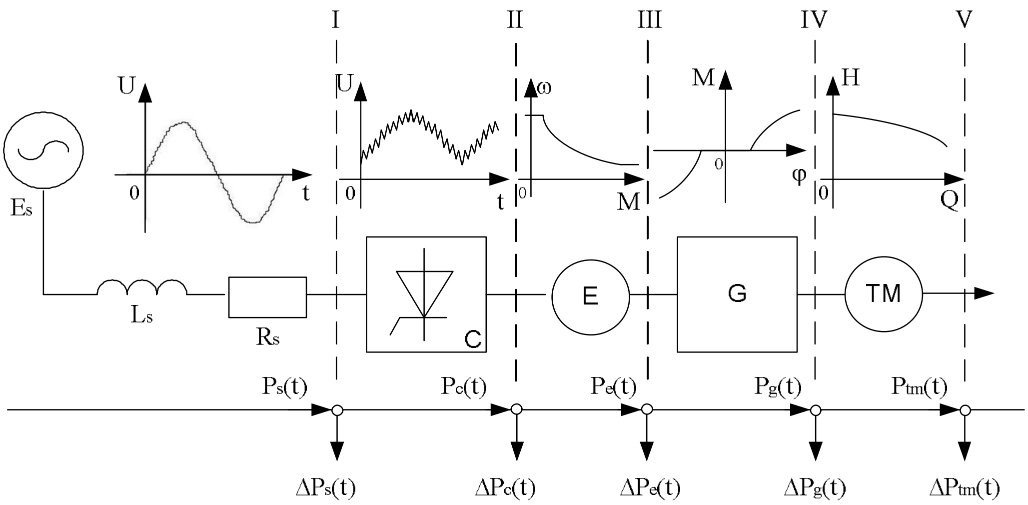


Figure 1 – The scheme of the energy conversion in electromechanical complex:
PS is power system; C is energy converter; E is engine; G is gear; TM is technology mechanism;
ΔP is power loss in the corresponding unit of the complex

The apparent simplicity of these relationships is quite obvious, however, given the fact that each of the elements of the conversion circuit has a number of specific, inherent properties, including those that are largely complicate the overall picture of energy transformations i.e. nonlinear properties [6].

In addition to the above, we note the fact resulting from the analysis of the literature [7, 8]: there are two trends in view of energy signals, and primarily the power signals on the elements; for the first is typical representation integral power characteristics at a certain time interval $\Delta t = t_2 - t_1$, for the second is typical representation the instantaneous power at any given point in time (Fig. 2).

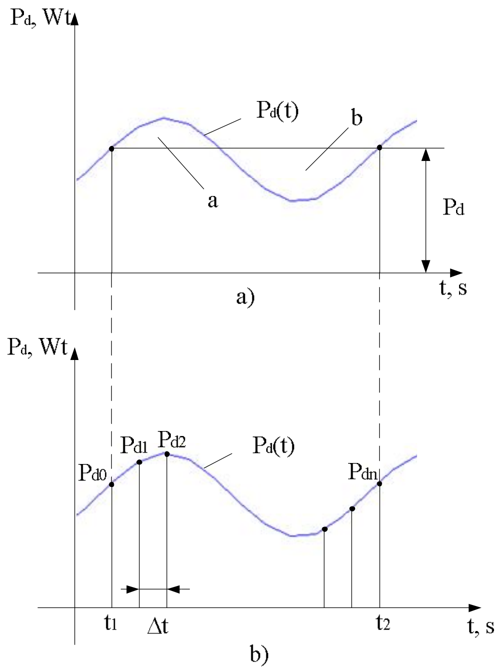


Figure 2 – Types of signal analysis: a) integrated power values; b) discrete values of power

The figure shows the signals of engine power, defined as the integral:

$$P_e(t) = \frac{1}{t_2 - t_1} \int_0^{t_2 - t_1} P_e(t) dt. \qquad (2)$$

Fig. 2,b shows the discrete values of P_e, obtained by discretization of formula $P_e(t)$. It should be noted that $P_e(t)$ and P_e are on the one hand, the physical parameter of the engine power, and on the other hand is her approach on the given interval. It is obvious discrepancy value P_e near the points "a" and "b". The discrete values of P_e, as known, may be the starting material for evaluation $P_e(t)$. It should be noted that the rms estimate of $P_e(t)$ is

$$P_e(t) = \sqrt{\frac{1}{t_2 - t_1} \int_0^{t_2 - t_1} \left(P_e(t)\right)^2 dt}, \qquad (3)$$

which determines the ratio of $P_{ey} > P_l$ due to the harmonic components of the power P_k on the range of function decomposition. Amplitudes of the power harmonics are determined from the next expression:

$$P_{kea}(t) = \frac{1}{t_2 - t_1} \int_0^{t_2 - t_1} P_e(t) cos(k\Omega t) dt;$$
$$P_{keb}(t) = \frac{1}{t_2 - t_1} \int_0^{t_2 - t_1} P_e(t) sin(k\Omega t) dt, \qquad (4)$$

where k=1, 2…K, $\Omega = 2\pi(t_2 - t_1)^{-1}$.

If we assume that the voltage U(t) and current I(t) are components of energy process, you should be aware that they can be quite complex functions depending on a number of factors and, to a certain extent, on whether there is a non-linear elements in circuits that form the parameters of the energy mode. Typically, each of the units in the power conversion circuit has one or more nonlinear elements in the conversion circuit. Importance of nonlinear elements estimating is obvious. Since they are, to a certain extent, determine the picture of the energy conversion, efficiency of this process and, to a large extent, the reliability of power [9]. It is known that multiplication of *U(t)* and *I(t)* get us $P(t) = U(t)I(t)$. This arithmetic operation is to determine the nonlinear function, even in cases when the components are simple trigonometric functions sin and cos; significantly more complex results will be in cases where *U(t)* and *I(t)* expressed some complex trigonometric dependencies, such as trigonometric series.

It is worth noting that the problem of the product of two components in the form of trigonometric series as a nonlinear problem though and put in electrical engineering and formalized to some extent but until now has no complete list of assessments of energy transformations, as well as identifying ways to use them to solve practical problems. Firstly it is the determination of the parameters of nonlinearities in the power circuit of energy systems.

The above indicates that the starting material for determining parameters and nonlinearities determination of estimates of energy processes of mentioned nonlinear problem are formed in a single energy basis, which is based on the energy balance equation. This conclusion adopted by authors of the study, is the basis of the energy method, applicable for a wide range of nonlinear tasks, in particular for the identification of nonlinear parameters. It is based on the Telledzhen's theorem applied to the instantaneous power values [10].

Since the method, despite a good perspective of its application, is not fully described in the literature, it should to give this issue some attention. First, despite the complexity, any electromechanical system can be divided into several units as shown in Fig. 1.

Processes in the units have their own nature, mathematical interpretation according to the particular design scheme, or equivalent circuit. As the full circuit design, and in separate elements complied the law of energy conservation. At the boundaries of relevant units are no discontinuities (different values of output power at the previous element and input is subsequent), which is one of the conditions for the law of conservation. The last remains in effect for the integral, and for the instantaneous power:

$$P_s(t) = \Delta P_s(t) + \Delta P_p(t) + \Delta P_d(t) + \\ + \Delta P_{pm}(t) + \Delta P_{tm}(t) + \Delta P_{pot}(t), \quad (5)$$

where each of the terms on the right side, and $P_s(t)$ in accordance with well-known mathematical postulates can be represented as an infinite or truncated trigonometric series that contains a constant component and the alternating orthogonal components of the corresponding frequency. This position allows us to formulate a conclusion that follows from Telledzhen's theorem for harmonic components for left and right sides of the above equation of energy balance. Since the process of energy transformation on all elements of the electromechanical complex analyzes on the same range for all of its elements (supply, inverter, motor, etc.), the dependence of the instantaneous power of the power supply will take the next form:

$$P_s(t) = \sum_{k=0}^{k=M} P_{kc} = \sum_{k=0}^{k=M} P_{kc0} + \sum_{k=0}^{k=M} P_{kca} + \sum_{k=0}^{k=M} P_{kcb}. \quad (6)$$

In a corresponding manner may be presented power of each element. For example, input power of conversion device will be:

$$P_p(t) = P_s(t) - \sum_{k=0}^{k=M} \Delta P_{kc} = \sum_{k=0}^{k=M} P_{kc0} + \sum_{k=0}^{k=M} P_{kca} + \\ + \sum_{k=0}^{k=M} P_{kcb} - \sum_{k=0}^{k=M} \Delta P_{kc0} - \sum_{k=0}^{k=M} \Delta P_{kca} - \sum_{k=0}^{k=M} \Delta P_{kcb}, \quad (7)$$

where P_{kc0}, ΔP_{kc0} are values of the constant component of the power supply and the losses in it; P_{kca}, ΔP_{kca} are amplitude values of the cosine component of the power harmonic of the corresponding order at the power supply input and the alternating component of the loss; P_{kcb}, ΔP_{kcb} are amplitude values of the sine harmonic components power and the power loss.

In accordance with the above expression of the instantaneous power of the load, i.e. at the output of electromechanical complex in the general form will have the next form

$$P_n(t) = P_s(t) - \Delta P_s(t) - \Delta P_p(t) - \\ - \Delta P_d(t) - \Delta P_{pm}(t) - \Delta P_{tm}(t). \quad (8)$$

Also, the balance equation in the form of harmonic components:

$$\sum_{k=0}^{k=M} P_{ks} = \sum_{k=0}^{k=M} P_{ck} - \sum_{k=0}^{k=M} \Delta P_{sk} - \sum_{k=0}^{k=M} \Delta P_{pk} - \\ - \sum_{k=0}^{k=M} \Delta P_{dk} - \sum_{k=0}^{k=M} \Delta P_{pmk} - \sum_{k=0}^{k=M} \Delta P_{tmm}, \quad (9)$$

which holds for any harmonics of the instantaneous power (order zero (*k=0*); cosine component $(k \neq 0)$, as well as the sine component of the corresponding order).

Attention should be paid to components under the amounts symbols. The expressions for the ΔP_k of each of the units are determined based on its equivalent circuit. Thus, the equivalent circuit of the DC motor includes two electric parameters (armature resistance losses $\Delta P_{R(t)} = I^2_{arm}(t)R$ and Inductance with instantaneous power $\Delta P_{L(t)} = L_{arm}\frac{dI_{arm}(t)}{dt}$), as well as a mechanical parameter determining the mechanical power losses $\Delta P_{M(t)} = M_e(t)\omega_e(t)$. Here $M_e(t)$ is losses of idle moment, $\omega_e(t)$ is the speed of rotation of the engine shaft. Last value is important in the sense that the loss of ΔP as structural and other parameters are specific electrical or mechanical components (including nonlinearity), the determination of which is the main purpose of solving identification problems [11]. Hence it is evident that the completeness of the solution of the problem of identity is directly related to completeness of submissions of processes in the electrical equivalent circuit. Therefore the determination of estimates of energy processes in electric circuits by identifying the parameters of nonlinearities which significantly affect the energy conversion processes in the system, is relevant.

Consider the above provisions of DC machines example. As a part of electromechanical systems this type of engine is the easiest and most convenient for the analysis of the formation of any control actions. Considering the function of the electric machine from a position of not only the technology mechanism, but also to the control unit, there are possibilities of analysis of the principles of formation of the control actions, the study of energy-exchange processes, as for power supply as for consumer, requirements definition to the energy source, measurement and diagnostic equipment, etc.

The first aspect of the problem involves a qualitative analysis of the processes in order to determine the type of control actions and can be viewed from a general point of energy balance, suggesting the presence of a functioning electric machine with stocked kinetic energy and electromagnetic components.

In dynamic loading systems [12] as a storage appear the rotating parts (motor armature, clutches, flywheels) reserving the kinetic energy, as well as the winding inductance, stocking up on electromagnetic energy. Entering the appropriate notation for the components of energy, the energy balance equation takes the next form:

$$W_I = W_C + W_K + W_M, \quad (10)$$

where W_I is energy, consumed from the power source; W_C is energy, dissipated by the load device; W_K is the energy of the rotating parts; W_M is the energy of the magnetic field in the gap of the machine.

Considering the engine without load on the shaft, let's excluding energy loss from the left and right sides of the above equation. As a result energy balance equation takes the form:

$$W_I = W_K + W_M \,. \quad (11)$$

Power circulating between the electric machine and the power supply, including the drive circuit can be represented by the next expression:

$$P_I(t) = \frac{d}{dt} W_I \,. \quad (12)$$

Perform analysis (12) for a DC motor, taking into account that

$$W_K = J \frac{\omega^2}{2}, \quad (13)$$

where J is the moment of inertia of the armature; ω is speed of rotation.

Assuming that the velocity of rotation is proportional to the voltage U and inversely proportional to the coefficient of flux $k\Phi$, we obtain:

$$W_K = J \frac{U^2}{2(k\Phi)^2} = \mathrm{J} \frac{U^2}{8C^2(0{,}5 L_V I_V)^2} = \mathrm{A} \frac{U^2}{\mathrm{W_M}}, \quad (14)$$

where L_V is the excitation winding inductor; I_V is excitation current; C is proportionality coefficient, $A = \frac{J}{8C}$.

Taking into account the above, expression for W_I can be written:

$$W_I = A \frac{U^2}{W_M} + W_M \,. \quad (15)$$

The case under consideration corresponds to the motor with separate excitation.

When exposed to the voltage applied to the motor with separate excitation:

$$P(t) = A \frac{1}{W_M} \frac{d}{dt} U^2(t) \,. \quad (16)$$

Instantaneous power of engine when exposed to the magnetic flux of the engine ($U{=}const$) is:

$$P(t) = -A \frac{\mathrm{U}^2 \frac{\mathrm{d}}{\mathrm{dt}} W_M(t)}{W_M^2(t)} + \frac{\mathrm{d}}{\mathrm{dt}} \mathrm{W}_M(\mathrm{t}). \quad (17)$$

The first component defines the power circuit, and the second of the drive circuit. It is clear that under certain conditions, the power consumption from the power supply may be negative with the positive power of armature circuit. This is due to the fact that for large values of L_v decreasing of W_M must be accompanied by a translation of the power supply the excitation winding mode regenerative power to power supply.

In this context it is obvious that as transducer devices of anchor chain and circuit of excitation can be used machines converters, DC generators, reverse, thyristor or transistor inverters with a phase or PWM control.

Considering the above, energy processes we may in relation to the general scheme of electromechanical complex when energy balance equations involving all the elements and units (power supply, engine, etc.), and also in relation to the separately taken unit, for example to a DC motor. In this case, as follows from the above considerations, necessary condition is the information about energy mode at input of the engine, and load parameters.

Fig. 3 shows the circuit of an electromechanical system by means of which can be analyzed as previously load modes for evaluating the energy state of any elements (the power supply, inverter, motor, transmission and technological mechanisms).

The scheme includes the power supply transformer T, converter C, motor M, gear G, technology mechanism TM, sensors for measuring the values S1−S9, excitation L_e. Control unit controls the inverter and the motor exciter. The signal parameters U_{c1} and U_{c2} can be different, in particular, to estimate the motor voltage U(t) possible to maintain unchanged or changed using effects U_{c2} on the current of the motor, so that the speed of the engine, its time, the armature current will change. So, if the excitation current will have constant and alternating components, the appropriate (to have a permanent and alternating components) will change the above parameters.

Modes of operation of the equipment controlled through a system of sensors, whose outputs are applied to inputs of measurement unit MU; its outputs, processed appropriately, is signals U_{out}, containing, for example, the components of the analyzed signal (constant component, a sine and cosine components of the harmonics). Outputs of MU fed to a calculation module by which carried out further processing the signals, calculating harmonic signal components, in particular the coefficients of the identification equations.

Using computing module we are forming control action on the transformative power of the motor armature device and its excitation circuit. Technological mechanism is not specified. It can be a turbo machine (pump, fan) for the signals output from the pressure productivity; possible and a test mode when the process mechanism is absent and test modes are generated in an idling mode.

Thus, from the aforesaid follows, that the formation of specific, beforehand justified by requirements, control signals is the possibility of obtaining an instantaneous power at any of the available power conversion circuit elements [13]: power source $P_s(t)$, converter $P_c(t)$, engine $P_e(t)$, gear $P_g(t)$, technology mechanism $P_{tm}(t)$.

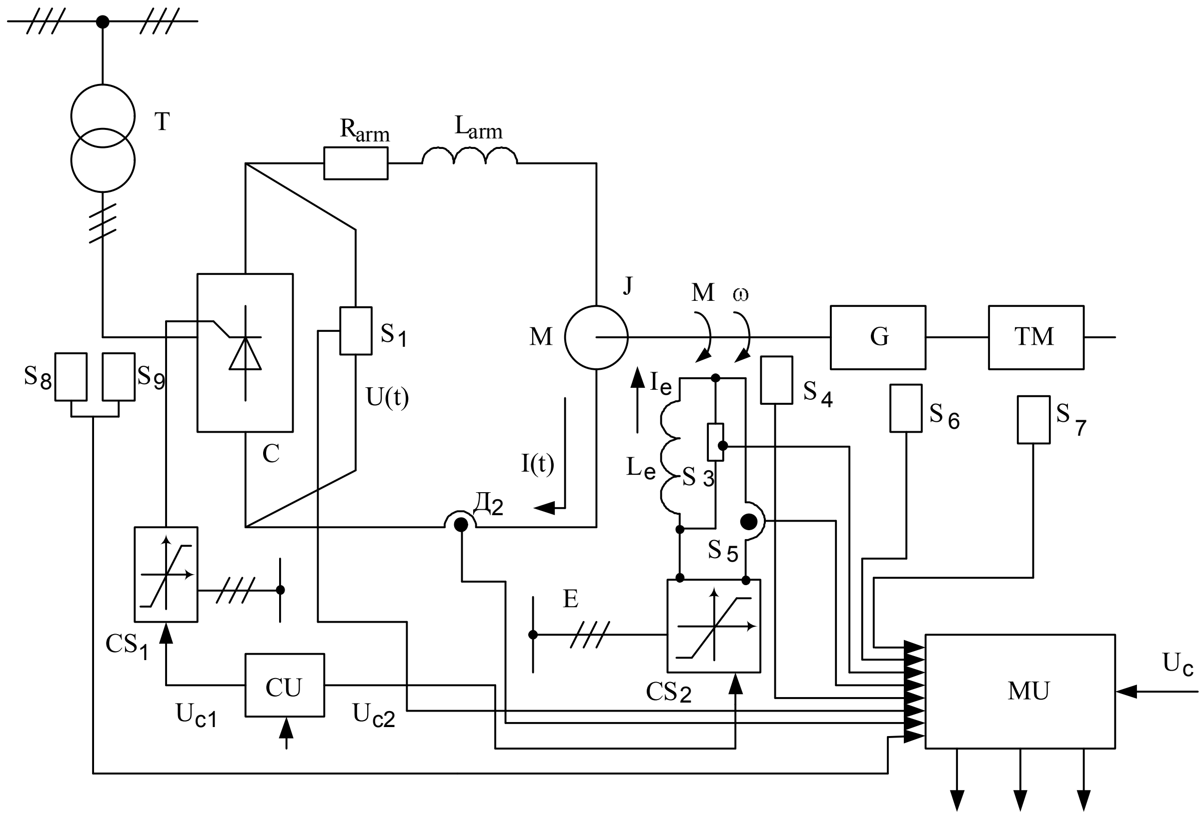


Figure 3 – Block diagram of electromechanical complex: M is motor; C is converter; E is excitation; CS1, CS2 are control signals; CU is control unit; MU is measurement unit; TM is technology mechanism; S1−S9 are sensors for measuring the values; R_{arm}, L_{arm}, J, M, ω are electrical and mechanical parameters of the engine

The analysis of energy processes is the main to assess the efficiency of electrical machines in the test. In practice one has to solve a number of issues affecting both the mode of loading of electric machines, and identify some of its parameters. In this case, a convenient mathematical apparatus, which allows to consider the characteristics of the energy distribution on the elements of the circuit and to determine the necessary parameters, is the energy method, based on the instantaneous power balance equations.

The development of the energy method using the apparatus of the instantaneous power [14] significantly expanded the boundaries of the effective use of the results of the analysis to estimate the parameters of the equivalent circuits of the objects, definitions of quality power conversion, assess the impact of energy conversion processes on the behavior of electromechanical systems and complexes.

Analysis of instantaneous values of energy parameters at any point of time interval eliminates error, peculiar to integral evaluation methods because the result, obtained by integrating, characterized by that it does not contain elements with periodic nature due to the fact that the integral of the harmonic function on its period of recurrence is equal to zero, and this leads to loss of information.

This method is entirely based on the concept of instantaneous power that allows us to consider separate the power of harmonics, defining features of the energy transformation and quantify the energy conversion process. The main advantages of the energy method are that it is based on the law of conservation of energy and the approach is used to determine the parameters of any electrical circuit.

Using the energy method for the analysis of processes of energy exchange allows us to get a more informative assessment, as takes into account the actual physical processes occurring in the electrical circuit. Experience shows a sufficient efficiency of energy method for the identification and analysis of energy modes for both linear and nonlinear circuits.

The energy method is a convenient apparatus for the analysis of energy processes of electrical circuits with nonlinearity, because allows to examine separately the power harmonics, which define features of the transformation of energy in polyharmonic signals, and quantify the process of energy conversion.

An analysis of existing methods [15−17], based on the linearization of nonlinear processes showed that the lacks of such approaches are the consideration only the first harmonic in the description of the output parameters of the system with nonlinear characteristics and the neglect of the higher frequency harmonics, which directly characterize the effects of nonlinear element in the system. However, using the power balance in the separate harmonics allows us to avoid a loss of information. Thus, the energy method can not only determine the necessary circuit parameters, but also to analyze the internal energy transfer processes due to the presence of nonlinear elements, and also to formulate indicators to measure the quality of energy conversion, to show the power conversion in a nonlinear element: its consumption, generation and dissipation.

The general formulation of the issue in evaluating parameters of the equivalent circuit is in the provisions that follow from Telledzhen's theorem, the essence of which is described as in "broad", and in "general" case. In a broad sense, the theorem is fundamental in exposition of the law of conservation of energy as applied to electrical circuits with any number of branches, and the restrictions imposed by the Kirchhoff's laws for voltage and current. In the case, if the circuit has several independent sources, on the basis of the Telledzhen's theorem we can conclude that sum of the power, consumed by independent sources on the elements of electromechanical circuit, equal to the sum of the power, consumed by the elements in all branches of the circuit. Formally, the circuit can be divided into the appropriate number of parts, between which there is an exchange of energy. In this case, consider the energy transfer between the source and the consumer. Then, according to the law of conservation of energy, the power, transmitted by source, is equal to the power of the consumer. As the power is a characteristic of instantaneous energy state $P(t)=\frac{dW(t)}{dt}$, then mentioned balance characterizes power balance at a particular time. Thus, the instantaneous input power of the circuit is equal to sum of instantaneous powers of all circuit elements.

So, the instantaneous input power of the circuit equal to sum of instantaneous powers of all circuit elements. It should be noted that the instantaneous power at each harmonic is determined by multiplying the corresponding current and voltage values of the same harmonic.

The solution of the parameter estimates of nonlinearities consider on the example of the DC motor (Fig. 3). The energy method consists in the fact that all electrical parameters are represented in the form of trigonometric series, made the equation of instantaneous power for each element in equivalent circuit of the electromechanical system (Fig. 4). With the use of these expressions are compiled balance equations of instantaneous power for each harmonic. Unknowns are determining by solving the system of equations.

The definition of nonlinear parameters of the engine is a complex task because the number of unknowns can be significantly increased. Therefore, the solution of this problem can be done in several stages. In the first stage perform replacement determined parameters by the equivalent function (EMF):

$$E(\mathrm{t})=E_0+E_{1a}\cos(\Omega t)+E_{1b}\sin(\Omega t)+ \\ +E_{2a}\cos(2\Omega t)+E_{2b}\sin 2(\Omega t), \quad (18)$$

where E_0 is a constant component; E_{1a}, E_{1b}, E_{2a}, E_{2b} are alternating components of the equivalent functions of EMF.

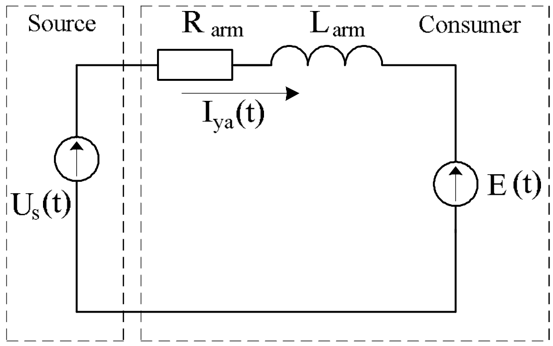


Figure 4 – Equivalent circuit for the scheme with DC motor

It is obvious that equivalent EMF represent a set of electromagnetic parameters of the electrical machine. Thus, the first task is to determine the electromagnetic parameters of the anchor circuit, where the unknowns are E_0, E_{1a}, E_{1b}, E_{2a}, E_{2b}.

To define the EMF components write the system of equations

$$\begin{cases} U_s(t)=E(t)+I_{arm}(t)R+L_{arm}\frac{dI_{arm}(t)}{dt}; \\ M_e(t)-M_r(t)=J\frac{d\omega(t)}{dt}; \\ M_e(t)=I_{arm}(t)k\Phi(t), \end{cases} \quad (19)$$

where M_r, J are resisting moment and the moment of inertia of the motor.

Expressions, characterizing the energy mode represent as:

$$I_{anc}(t)=I_0+I_{1a}\cos(\Omega t)+I_{1b}\sin(\Omega t)+ \\ +I_{2a}\cos(2\Omega t)+I_{2b}\sin(2\Omega t);$$

$$E(t)=k\Phi(t)\omega(t)=E_0+E_{1a}\cos(\Omega t)+ \\ +E_{1b}\sin(\Omega t)+E_{2a}\cos(2\Omega t)+E_{2b}\sin(2\Omega t); \quad (20)$$

$$k\Phi(t)=k\Phi_0+k\Phi_{1a}\cos(\Omega t)+k\Phi_{1b}\sin(\Omega t);$$

$$\omega(t)=\omega_0+\omega_{1a}\cos(\Omega t)+\omega_{1b}\sin(\Omega t).$$

In the case when the unknowns are only parameters of equivalent EMF identification system of equations we can make on the balance of voltage (like in this case), however, when it is necessary to determine such parameters as $R_{arm}(t)$ and/or $L_{arm}(t)$, system is made on the balance of power. In this paper, we consider the simpler case, so the identification system of equations in the general form we obtain from the next expression:

$$U_{arm}=R_{arm}I_{arm}(t)+L_{arm}\frac{dI_{arm}(t)}{dt}+E(t). \quad (21)$$

Then, according to the superposition principle, the identification system of equations can be made on the balance of voltage at each harmonic. Given the above parameters, we obtain a system of five equations, which in general takes the form:

$$\begin{cases} U_{arm} = E_0 + R_{arm} I_0; \\ 0 = E_{1a} + R_{arm} I_{1a} - \Omega L_{arm} I_{1b}; \\ 0 = E_{1b} - R_{arm} I_{1b} - \Omega L_{arm} I_{1a}; \\ 0 = E_{2a} - R_{arm} I_{2a} + 2\Omega L_{arm} I_{2b}; \\ 0 = E_{2b} + R_{arm} I_{2b} - 2\Omega L_{arm} I_{2a}. \end{cases} \quad (22)$$

A result of solving of this system we obtain an expression

$$E(t) = E_0 + E_{1a}\cos(\Omega t) + E_{1b}\sin(\Omega t) + \\ + E_{2a}\cos(2\Omega t) + E_{2b}\sin(2\Omega t). \quad (23)$$

Further, we proceed to definition of nonlinear parameters. In this case, go back to the previously made replacement i.e. to the electromagnetic parameters of the engine, described by the expression

$$E(t) I_{arm}(t) = k\Phi(t)\omega(t) I_{arm}(t). \quad (26)$$

Considering the fact that

$$M_e(t) - M_r(t) = J\frac{d\omega(t)}{dt}, \quad (27)$$

$$M_e(t) = I_{arm}(t) k\Phi(t), \quad (28)$$

if $M_r(t) = 0$, then:

$$E(t) I_{arm}(t) = J\frac{d\omega(t)}{dt}\omega(t). \quad (29)$$

From the obtained expression as described above we can to define $\omega(t)$.

The method of calculation of nonlinear parameters of the DC motor consider on an example of engine with next parameters: nominal power $P_n = 560\,kW$, nominal voltage $U_n = 440\,V$, nominal armature current $I_n = 1370\,A$, nominal speed $\omega_n = 1000\,rot/min$, number of poles $2p = 6$, engine torque $J = 74{,}65\,kg \cdot m^2$.

Presented earlier principles the formation of loading conditions indicate to the need for studies processes of formation of the load with the impact on the flux of the engine. This allows us to assess qualitative and quantitative indicators for fixed effects from the excitation, because analytical expressions for components determining of the armature current does not exist. From the model of DC motor with separate excitation (DCM SE) show that by the impact on the motor winding by a periodic signal with a frequency Ω get the speed, armature current and engine torque, which contain constant and variable components. Voltage of engine and armature current are $U_e = 54{,}7 - 2{,}2\cos(\Omega t) + 1{,}3\sin(\Omega t)$, $U_{arm} = const$,

$$I_{arm} = 92 - 3774\cos(\Omega t) + 1805\sin(\Omega t) - \\ - 5{,}1\cos(2\Omega t) - 153\sin(2\Omega t). \quad (29)$$

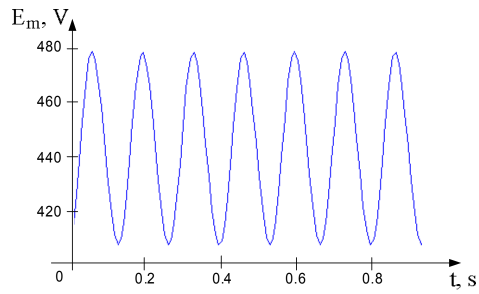
The number of harmonics is limited due to the insignificance of the amplitude values of harmonics in relation to the first.

With the above parameters, the system of equations for determining the parameters of the EMF takes the next form:

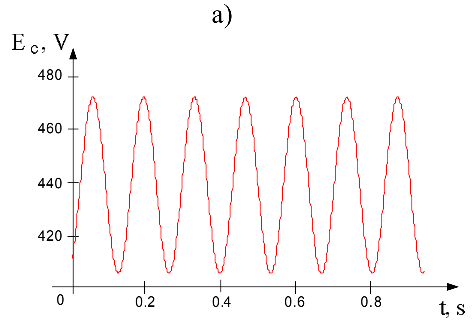
$$\begin{cases} 440 = E_0 + 8{,}1; \\ 0 = E_{1a} + 33{,}5 - 3{,}2; \\ 0 = E_{1b} - 16{,}3 - 6{,}5; \\ 0 = E_{2a} - 3 + 1{,}5; \\ 0 = E_{2b} + 1{,}2 - 1{,}6. \end{cases} \quad (30)$$

By solving the resulting system we obtain an expression:

$$E(t) = 432 - 30\cos(\Omega t) + 22\sin(\Omega t) + \\ + 1{,}5\cos(2\Omega t) - 2{,}8\sin(2\Omega t). \quad (31)$$



a)



b)

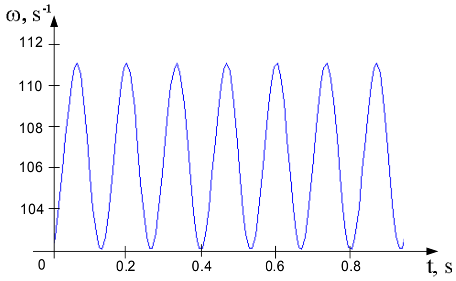
Figure 5 – Curves for E(t): a) obtained by simulation; b) obtained by calculating

When the parameters of equivalent EMF are known from (29) compose a system to determine $\omega(t)$:

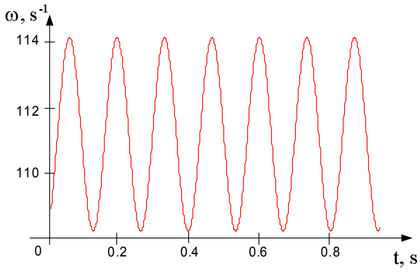
$$\begin{cases} -765889 = -3732{,}5\omega_0\omega_{1a}; \\ -184666 = 3732{,}5\omega_{1a}\omega_{1b}; \\ 140489 = -1866\omega_{1a}^2 + 1866\omega_{1b}^2. \end{cases} \quad (32)$$

The solution of the resulting system of equations can be done by Levenberg–Marquardt's method [18]. The accuracy of the data depends on the number of harmonics. In this case, for simplicity, consider an example including the first harmonic. The expression for the $\omega(t)$ will have the next form:

$$\omega(t) = 111{,}2 - 2{,}2\cos(\Omega t) + 1{,}9\sin(\Omega t). \quad (33)$$



a)



b)

Figure 6 – Curves for ω(t): a) obtained by simulation; b) obtained by calculating

To determine $k\Phi(t)$ we use the next expression

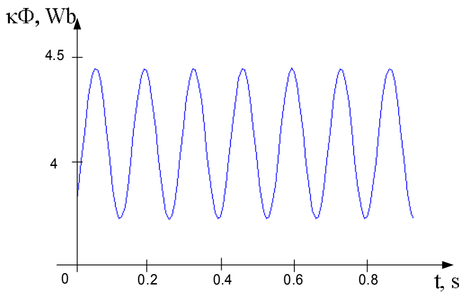
$$E(t)I(t) = k\Phi(t)\omega(t)I(t). \qquad (34)$$

Then the system takes the form:

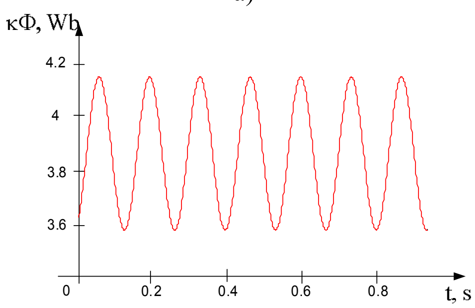
$$\begin{cases} 313981 = 206559k\Phi_{1a} - 99877{,}5k\Phi_{1b} + 94657k\Phi_0; \\ 1595906 = 74152{,}8k\Phi_{1a} + 12620{,}5k\Phi_{1b} + 413118k\Phi_0; \\ -766052 = 12620{,}5k\Phi_{1a} + 115161k\Phi_{1b} - 199755k\Phi_0. \end{cases} \qquad (35)$$

A result of solving we obtain the expression:

$$k\Phi(t) = 3{,}9 - 0{,}2\cos(\Omega t) + 0{,}13\sin(\Omega t). \qquad (36)$$



a)



b)

Figure 7 – Curves for kΦ(t): a) obtained by simulation; b) obtained by calculating

Thus, analysis of the figures shows that the error in the calculation of electromagnetic parameters of the engine by the energy method in this case is less than 2 % and if it necessary can be reduced (by taking into account higher harmonics).

CONCLUSIONS. The increased interest in issues of consumption of electric energy, its efficient use and management of energy flows requires a detail analysis of the conversion issues at all units, which form a complete electromechanical complex: in the electricity supply network, energy converter of one type to another in electrical machines, transfer devices and technology mechanisms. The unity of the energy circuit requires a unified mathematical apparatus i.e. describe energy transformations as a process and set of its parameters.

Nonlinear properties, inherent almost in every element of the electromechanical system, have a significant effect on the energy conversion processes. Therefore, relevant and important task is to determine their characteristics as units, which determine the energy processes. The success of its solution is possible by identifying the parameters of nonlinearities.

Together with the solution of this problem requires a thorough mathematical interpretation of nonlinear transformations that underlie the formation of energy flow and energy transformations. The most important in this regard is the issue of evaluation of energy transformations in the complex dependencies of the components included in the fundamental expression for the power. The complexity of nonlinear transformations in many ways related to the presence or absence of nonlinear elements of power circuit. The important energy component which characterize the nonlinearity and in the analysis of the energy processes is the law of energy conservation.

Completeness of energy processes research, in this part, depends entirely on how well the process corresponds to the mathematical interpretation of fundamental law. In electrical circuits, characterizing electromechanical systems, erroneously limited by balance of constant power components, the balance so-called reactive power and especially full power. Instantaneous power is the only parameter describing the energy process in accordance with all aspects of the law of conservation. Balance of instantaneous power on power supply and consumer is a mathematical and energy base for solving problems related to identity issues, the search for evaluations of processes as nonlinear transformations.

Energy method is reliable and effective apparatus for solving the problems of nonlinearities parameter identification. The method is based on the system of identification equations, consisting of a set of balance equations of instantaneous power at each harmonic, obtained from the product of harmonic series of described components, included in this product for the most complete description of the energy process in a particular unit of the electromechanical system.

Using the harmonic series as the basis of the energy method distinguishes it from other mathematical approaches because such a product provides a sufficient number of equations to solve complex problems of assessing the parameters of nonlinearities.

Energy method of analysis of energy processes in electromechanical systems applies to both periodic processes with constant fundamental frequency and processes with varying frequency and amplitude. Method can be used to research of systems with non-periodic signals because of universality of the Fourier's approach (including cases of transient processes). The energy method is applicable for the analysis of energy processes of the electromechanical units with nonelectric energy conversion parameters.

The use of the energy method for solving problems of identification is simplified by partial analysis of energy processes, wherein the identification system of equations is composed for one of the elements of the electromechanical system with the known input signals.

REFERENCES

1. Firago, B.I. (2004), *Teoriya electroprivoda* [Theory of electric drive], Tehnoperspectiva, Mynsk, Belarus. (in Russian)

2. Skubov, D.Y. and Khodzhaev, K.S. (2003), *Nelyneinaya elektromehanika* [Nonlinear electromechanics], Fizmatlit, Moscow, Russia. (in Russian)

3. Voldek, A.I. (1966), *Electricheskie mashyny* [Electrical Machines], Energiya, Moscow, Russia. (in Russian)

4. Meisel, J. (1996), Principles of Electromechanical Energy Conversion, McGraw-Hill, New-York, USA.

5. Tonkal, V.E. (1992), *Balans energiy v sylovykh tsepyakh* [The energy balance in power circuits], Naukova dumka, Kyiv, Ukraine. (in Russian)

6. Wcislik, M. (2010), "Powers Balances in AC Electric Circuit with Nonlinear Load", *IEEE Transactions on Industry Applications, Harmonics and Quality of Power*, pp. 1−6.

7. Depenbrock, M. (1993) "Some remarks to active and fictitious power in poly phase and single-phase systems", *European Transactions on Electrical Power*, Vol. 3 (1), no. 4, pp.15−19.

8. Akagi, H. and Watanabe, M. (2007), Instantaneous Power Theory and Applications to Power Conditioning, Wiley, New York, USA.

9. Engberg, J. and Larsen, T. (1995), Theory of Linear and Nonlinear Circuits, The University of Aalborg, Denmark.

10. Rodkin, D.Y. (2010), "On the inconsistency of some theory of the energy processes with Telledzhen's theorem", *Problems of automated electric drive. Theory and practice, Kharkov: NTU "KhPI"*, Vol. 28, pp. 127–135. (in Russian)

11. Suguru, A. (1996), Control Theory of Nonlinear Mechanical Systems, Clarendon Press, Oxford, Great Britain.

12. Davydkovych, V.M. and Rodkin, D.Y. (1994), "Dynamic loading device of asynchronous motors for amplitude modulation voltage", *Electrotekhnika,* Vol. 4, pp. 28–33. (in Russian)

13. Nabai Akira, Tanaka Toshihko (1996), "A New Definition of Instantaneous Active-Reactive Current and Power Based on Instantaneous Space Vectors on Polar Coordinates in Three-Phase Circuits", *IEEE Transactions on Power Delivery*, Vol. 11, pp. 1238−1244.

14. Depenbrock, M., Staudt, V. and Wrede, H. (2003), "A theoretical investigation of original and modified instantaneous power theory applied to four-wire systems", *IEEE Transactions on Industry Applications,* Vol. 39, pp. 1089−1095.

15. Jordan, A. and Nowacki, J.P. (2004), "Global Linearization of Non-Linear State Equations", *International Journal Applied Electromagnetics and Mechanics*, Vol. 19, pp. 637−642.

16. Forenc, J. and Bycul, R. (2005), "A computer program for nonlinear state equations linearization", Silesian University of Technology, XXVIII International Conference on Fundaments of Electrotechnics and Circuit Theory: IC–SPETO'2005, proceedings, Gliwice, Poland.

17. Jordan, A. and Kaczorek, T. (2005), "Global linearization of a non-linear electrical circuits", *Proceedings SPIE 5775*, Wilga, Poland.

18. Seaty, T.I. (1981), Modern nonlinear equation, Dover Publisher, New York, USA.

ОЦЕНКА ПАРАМЕТРОВ ЭЛЕКТРОМЕХАНИЧЕСКИХ КОМПЛЕКСОВ ЭНЕРГЕТИЧЕСКИМ МЕТОДОМ

Д. И. Родькин, Д. А. Мосюндз

Кременчугский национальный университет имени Михаила Остроградского

ул. Первомайская, 20, г. Кременчуг, 39600, Украина. E-mail: darya_mosyundz@mail.ru

Показано, что процессы преобразования энергии усложняются при наличии нелинейных элементов или процессов, в связи с чем ухудшаются показатели качества преобразованной энергии, быстрее происходит износ электромеханического оборудования, увеличиваются потери и т.д. Поэтому для эффективного использования и управления энергопроцессами актуальным является определение оценок энергопроцессов в электрических цепях путем идентификации параметров нелинейностей, существенным образом влияющих на процессы энергопреобразования в системе. Предложенный метод идентификации основан на понятии мгновенной мощности. Известно, что даже при синусоидальном питающем напряжении и наличии нелинейных элементов ток в цепи несинусоидальной формы. Использование аппарата мгновенной мощности дает возможность получить количественную оценку составляющих энергопроцессов на каждой гармонике, что позволяет составить систему с достаточным количеством уравнений для определения неизвестных параметров как линейных, так и нелинейных энергетических систем.

Ключевые слова: электромеханическая система, нелинейность, мгновенная мощность, спектральный анализ.

Стаття надійшла 28.08.2013.