UDC 62.83.523:621.3.011.001.3

CONCERNING THE PROBLEM OF NONLINEARITY PARAMETERS IDENTIFICATION IN ELECTROMECHANICAL SYSTEMS

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Existing methods of estimation and parameter identification of electromechanical systems have been considered. It has been shown that the main disadvantage of the known methods is the inability to obtain a sufficient number of equations to determine the identity of the electromagnetic parameters of the systems, taking into account nonlinearities. A mathematical apparatus for determining the parameters of nonlinear electromechanical systems on the basis of the energy balance of instantaneous power for each harmonic has been proposed. The possibilities of the power method application have been shown taking the identification of nonlinear inductance parameters as an example. It has been shown that this approach based on the source and consumer power elements balance for each harmonic allows one to get the required number of equations to determine all parameters of electromechanical systems.

Key words: energy method, nonlinearity, method of instantaneous power, the parameter identification.

ЩОДО ІДЕНТИФІКАЦІЇ НЕЛІНІЙНИХ ПАРАМЕТРІВ ЕЛЕКТРОМЕХАНІЧНИХ СИСТЕМ

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Розглянуто існуючі методи оцінювання та ідентифікації параметрів електромеханічних систем. Показано, що основним недоліком відомих методів є неможливість отримання достатньої кількості ідентифікаційних рівнянь для визначення електромагнітних параметрів систем з урахуванням нелінійностей. Запропоновано математичний апарат для визначення параметрів нелінійних електромеханічних систем на основі енергетичного балансу миттєвої потужності кожної гармоніки. Розглянуто можливості застосування енергетичного методу на прикладі ідентифікації параметрів нелінійної індуктивності. Показано, що такий підхід на основі балансу потужностей елементів джерела і споживача на кожній гармоніці окремо дозволяє отримати необхідну кількість рівнянь для визначення будь-яких параметрів електромеханічних систем.

Ключові слова: енергетичний метод, нелінійності, апарат миттєвої потужності, ідентифікація параметрів.

PROBLEM STATEMENT. In modern engineering the use of electro-mechanical systems is broad and varied. The elements of such systems include motors, generators, converting devices, etc. [1], and one of the most important trends in electrical engineering is to look for ways to describe with precision processes caused by the presence of nonlinear elements.

The tasks for the study of nonlinear electrical systems are caused by the need to consider the physical phenomena that affect the energy conversion process in the circuit. To describe the dynamic and energetic processes in such systems it is necessary to take into account the various properties and characteristics of every circuit element. It is most difficult to estimate the energy processes in electromechanical systems (EMS) and complexes including nonlinear elements. In the absence of a simple and efficient method for the analysis of such systems, it is important to create a theoretical framework for describing the energy processes of electromechanical systems, which will provide the necessary accuracy of the assessment of the features of physical processes in nonlinear circuits without significant loss of information relating to electro-mechanical and energetic properties of non-linear objects.

The need to obtain reliable data on the non-linear elements in the electromechanical system is caused by the nonlinearities typical not only of the most important structural parts of electrical machines, i.e. of electrical steel, but also of other parts of the energy conversion devices such as power converter power motors (voltage converters, frequency, etc.), kinematic chains connecting the motor with the technological mechanism, the working body of the said mechanism. Energy conversion processes in circuits with nonlinearities have their own characteristics which significantly influence the work of the technological mechanism and require their formalization and accounting. The physical aspects of these features lie in the fact that the nonlinearities in the energy conversion are the source of its lower quality, which leads to the so-called harmonic distortion of voltage and current in the network, torque of the motor, i.e. the parameters that determine the longevity and efficiency of electromechanical and mechanical equipment [2]. Reduced quality of energy conversion in consequence of the presence of nonlinearities in the system leads to a decrease in the energy efficiency of the equipment due to the increase of power losses in the nonlinear and other links.

On the other hand, the identification of parameters is caused by the need to determine the characteristics of electrical equipment after its running repair or overhaul. Analysis of the energy process is essential in assessing the efficiency of electrical machines in their testing [3]. In practice one has to solve a number of problems affecting the identification of a number of parameters of the machine. For example, the determination of the electromagnetic parameters of the electric machine (resistors, inductors, etc.), the determination of operational characteristics (current overload capacity, torque, stability and quality of the switching, levels of vibration and noise), etc. Part of these phenomena is caused by the presence of non-linear processes, so the development of this area is important in electromechanical problem in general.

The problem of parameter nonlinearities estimation in the structure of control systems, including electromechanical, was not considered in detail for the reason that the theoretical developments are usually based on common and often unjustified assumptions. The practical application of the results in terms of the desired effect is achieved in the process of so-called adjustment.

The necessity to find reliable data on the nonlinear elements of automatic control systems is conditioned to a great extent by practical needs, as taking into account the influence of characteristics of nonlinear elements is caused not only by the fact of their existence, but also by the fact that their parameters vary during operation, depending on several factors. Thus, the identification of nonlinearities is also conditioned by their varying parameters, and it is directly linked to the overall task of EMS diagnostics.

In the EMS basic elements of the structure elements in which physical processes providing electromechanical energy conversion directly take place are the basic EMS elements. These elements are the most important component in the description of energy processes, as they carry out the main energy transfer in electric machines, which often contain one or more non-linear elements. A control device also often has a non-linear characteristic. For example, all electric machines are characterized by a magnetic flux non-linear and ambiguous dependence on the excitation current. Machine windings inductance also depends on the currents. Some non-linear elements are introduced into the system intentionally to improve the quality of control. These nonlinearities include, for example, relay control devices, providing control process high performance. Nonlinear corrective devices are also used.

Insufficient attention to the problem of determining the parameters of nonlinearities is explained to a significant extent by the difficulties which are inevitable in a theoretical analysis and experimental research of real objects with non-linear characteristics.

The most significant feature of the analysis of nonlinear circuits with alternating currents (AC) consists in the need to consider, in general, the dynamic properties of nonlinear elements. Another important feature of nonlinear elements in the AC circuit is occurrence of higher harmonics caused by these elements, even if the circuit contains only sinusoidal voltage sources [4].

The main difficulty in the analysis of nonlinear circuits, as researchers believe, is the inability to use the principle of superposition. It explains a minor use of energy methods in the evaluation of energy conversion and determination of the nonlinearities parameters.

The known methods are based on the linearization of non-linear objects or their approximation by mathematically simple dependences, which affects the accuracy of the results. In this case, the energy side of the problem is not practically analyzed, although one of the forms of nonlinearities in the process of energy conversion consists in a significant complication of the energy processes, and in consequence, the deterioration of energy data. This is confirmed by the occurrence of distortion of voltage and current in the power networks with sinusoidal and non-linear load.

With regard to the existing methods, based in particular on integrated methods of analysis, they are unable to explain a number of phenomena that take place during the processes of energy conversion. The use of integrated methods [5], as it was pointed out in several studies, leads to loss of information in the analysis of circuits with nonlinearities.

Analysis of the literature showed that the existing methods of calculation of electric circuits can be divided into three groups: graphic, analytical and numerical [6]. For graphic groups main operations include graphical representations, often accompanied by supporting computational steps. Analytical ones suggest either analytical expression of the nonlinear element characteristics or their polygonal approximation, and numerical ones are based on replacing differential equations by algebraic ones.

The main disadvantages of the above methods include a limited number of equations, and therefore the unknowns, the complexity in the mathematical representation of the physical features and consideration of non-linear circuits, lack of accuracy, etc.

It follows from the above said that the need to identify the parameters of nonlinearity is a separate and independent task. This problem is often seen as a minor one because of its complexity, namely, the lack of appropriate mathematical tools, which would allow investigation and description of the energy processes in nonlinear circuits.

Thus, in the absence of a simple and efficient method for the analysis of systems and devices with non-linear characteristics, the actual creation of a mathematical apparatus that will provide the necessary accuracy of evaluation and analysis of the characteristics of the physical processes in nonlinear electromechanical systems is topical.

EXPERIMENTAL PART AND OBTAINED RESULTS. The theory of energy processes began to actively develop as a result of creating converter devices [7]. Interest in the topic has increased for several reasons, one of which is improved technical feasibility and demand for them. This increased the requirements for accuracy, information content and quality of computing and measuring equipment. Works in this direction are numerous and almost all of them are interconnected, because they are based on previous results. Common and most difficult issue was the consideration of energy exchange processes in an electrical system with nonlinear elements. The main difficulty of analyzing such systems is the need to address the dynamic properties of the element and its effect on the system, and changing the definition of the characteristics that depend on the parameters of circuits, load, time, etc. [8].

For example, we know that when a non-linear element operates in an AC circuit, current consisting of an infinite number of harmonic, multiples of the line frequency, flows in it [9]. Thus, the non-linear element is not only the harmonic oscillator, but also affects the quality of the supply voltage.

There are a number of other features, caused by the presence of non-linear elements. Therefore the mathematical apparatus to describe the energetic processes in such systems must take into account the dynamic properties and the nature of the nonlinearity.

The concept of active, reactive and apparent power is widely used for the analysis of energy processes in electrical engineering. However, several studies have shown that this approach does not comply with the law of conservation of energy [10, 11]. The use of the instantaneous power method, whose mathematical apparatus allows assessment of energy processes and the efficiency of energy use by the consumer, is justified. Development of the theory of instantaneous power led to the conclusion that a higher number of components than two (active and reactive), and the corresponding representation of data on energy processes of the objects can reveal the energy modes features and the nature of the exchange and storage processes between the power source and the individual consumer elements. This approach allowed us to create an energy method used to identify items on the basis of the analysis of real signals in complex electrical circuits and systems [12].

The development of the energy method using the apparatus of the instantaneous power greatly expanded the boundaries of the effective use of analysis to estimate the parameters of equivalent circuit of the objects, the definition of quality power conversion, assessment of energy conversion impact on the behavior of electromechanical systems and complexes.

Analysis of instantaneous energy performance at any point of the time interval eliminates the error inherent in the integral evaluation methods. The result obtained in the integration is characterized by the fact that it contains elements of the periodic nature because the integral of a harmonic function on a period of repetition is zero, which leads to loss of information.

The energy method is entirely based on the concept of instantaneous power, which allows one to consider separately the harmonic powers defining energy transformation features in polyharmonic signals and to 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 this approach can be used to determine any parameters of the electrical circuit.

The use of the energy method to analyze the processes of energy makes it possible to obtain a more informative assessment because it takes into account the real physical processes in the electrical circuit. The analysis shows sufficient efficiency of the energy method for the identification and analysis of energy modes of both linear and nonlinear circuits.

The method was developed in the early 2000s after a series of papers on the subject, published in Ukraine [13, 14].

The energy method is a convenient tool for the analysis of energy process circuits with non-linearity, as allows one to consider separately the power of harmonics defining characteristics of energy conversion in polyharmonic signals and quantify the energy conversion process.

Using the power balance on the individual harmonics is conditioned by the fact that such a consideration of the balance equations will be sufficient, with any number of unknowns.

In [15, 16] it is shown that the energy method allows not only to determine the options circuit but also to analyze the internal processes of energy caused by the presence of non-linear elements, formulate indicators to measure the quality of the energy conversion, show power conversion in a nonlinear element: its consumption, dissipation and generation.

The general formulation for the estimation of parameters of the equivalent circuit is the outcomes of Telledzhen's theorem [17], the essence of which is set out in the "broad" and in the "general" case. In a broad sense, the theorem is fundamental in the presentation of the law of conservation of energy applied to the electrical circuits with any number of branches and restrictions on the voltage and current, imposed by the Kirchhoff's laws. If the circuit has a number of independent sources, then by Telledzhen's theorem it can be concluded that the amount of power consumed by independent sources on the elements of an electromechanical circuit is 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 from the source is equal to the consumer power. Since power is a characteristic of instantaneous state of energy $P(t)=\frac{dW(t)}{dt}$, then mentioned balance characterizes the balance of power at any given time. The instantaneous power at the circuit input is the sum of the instantaneous powers of the circuit elements.

Thus, the value of the instantaneous power at the input of the circuit is the sum of the instantaneous powers of all elements of the circuit. It should be noted that the value of the instantaneous power at each harmonic is determined by the product of the corresponding voltage and current of the same harmonic. In Fig. 1 there is a diagram of the electrical circuit including sources of energy $E(t)$, the resistance *R*, and inductance *L*.

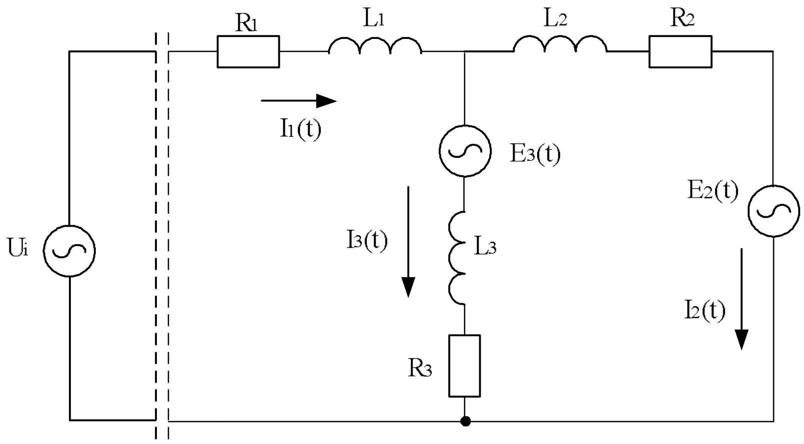

Figure 1 – Scheme of the electrical circuit

The interpretation of the Telledzhen's theorem with respect to the analyzed circuit is as follows: instantaneous power source $P_i(t)$ is the sum of the instantaneous power of the circuit elements. The balance equation for the circuit in Fig.1 has the following form:

$$U_i(t)I(t) = E_2(t)I(t) + E_3(t)I(t) + I_1^2(t)R_1 + \\ + I_2^2(t)R_2 + I_3^2(t)R_3 + L_1\frac{dI_1(t)}{dt}I_1(t) + \\ + L_2\frac{dI_2(t)}{dt}I_2(t) + L_3\frac{dI_3(t)}{dt}I_3(t). \quad (1)$$

The above equation of energy balance is general in nature and is practically not suitable for the analysis of the electrical circuit, and especially to determine the parameters. In case if in one way or another the parameters of current $I(t)$, voltage $U(t)$, and the e.m.f. $E(t)$ provide a set of components with specific values of frequency and amplitude, the energy balance equation can be divided into a larger number of independent equations, each of which is characterized by the fact that the frequency parameter (power) on all elements is the same. Separation of the components is then carried out on the basis of frequency.

Fourier unit is an effective means to carry out the separation parameters of instantaneous power on the basis of the components in the frequency [18]. For purposes of this task, restrictions should be made, aiming at the fact that the Fourier series representation of a function is to be performed in the general range for all elements of the electrical circuit. The expressions for the voltage and current in the common way of writing are of the following form:

$$U(t) = \sum_{n=1}^{n=k} U_n \cos(n\Omega t - \psi_n) = \\ = \sum_{n=1}^{n=k} (U_{na}\cos(n\Omega t) + U_{nb}\sin(n\Omega t)); \quad (2)$$

$$I(t) = \sum_{m=1}^{m=k} I_m \cos(m\Omega t - \varphi_m) = \\ = \sum_{m=1}^{m=k} (I_{ma}\cos(m\Omega t) + I_{mb}\sin(m\Omega t)), \quad (3)$$

where U_n, I_m are the amplitude values of current and voltage on the relevant harmonics; Ω is the angular frequency of each harmonic; ψ_n, φ_m are phase angle between current and voltage; m is the number of harmonics.

Thus, the features of the method consist in the fact that the energy balance equations, which are based on method of using the instantaneous power, most fully reflect the energy side of the analyzed process. Expressions for the instantaneous power of specific physical elements are complex and include derivatives, integrals of orthogonal components of the harmonic signal. However, the basis for determining the instantaneous power at each element is the following components:

$$P(t) = P_{k0} + P_{kac}(t) + P_{kbc}(t) + P_{kas}(t) + P_{kbs}(t), \quad (4)$$

where $P_{k0} = \frac{1}{T}\int_0^T \left(\sum_{n=m=k}^{K} U(t)I(t) \right) dt$ is constant component of the instantaneous power; $P_{kac} = \frac{2}{T}\int_0^T \left(\sum_{\substack{n=m=k \\ m=n}}^{K} U(t)I(t) \right) \cos(k\Omega t)dt$ is the cosine component of the instantaneous power of the canonical order; $P_{kac} = \frac{2}{T}\int_0^T \left(\sum_{\substack{n=m=k \\ m=n}}^{K} U(t)I(t) \right) \cos(k\Omega t)dt$ is the sine component of instantaneous power of the canonical order; $P_{kas} = \frac{2}{T}\int_0^T \left(\sum_{\substack{n=m=k \\ m\neq n}}^{K} U(t)I(t) \right) \cos(k\Omega t)dt$ is the cosine component of the instantaneous power of non-canonical order; $P_{kas} = \frac{2}{T}\int_0^T \left(\sum_{\substack{n=m=k \\ m\neq n}}^{K} U(t)I(t) \right) \cos(k\Omega t)dt$

is the sine component of instantaneous power of non-canonical order.

The concept of balance equations in the analysis is broader than, for example, the balance equations of active power or reactive components. Thus, each of the harmonics of the instantaneous power has three levels of balance. Each of them can be the basis for the identification equation. Their totality is known to give the system from which it is possible to determine the necessary parameters of the equivalent circuit.

So, if you write down all the values of instantaneous power at each element for the circuit in Fig. 1, with the number of voltage harmonics $v_{nU}\{1;3;5;7\}$ and current $v_{nI}\{1;3;5;7\}$, then, according to the superposition principle [19], the system of identification equations takes the following form:

$$\begin{cases} P_{0i} = P_{0R1} + P_{0R2} + P_{0R3}; \\ P_{2ai} = P_{2aR1} + P_{2aR2} + P_{2aR3} + P_{2aL1} + P_{2aL2} + \\ + P_{2aL3} + P_{2aE3} + P_{2aE2}; \\ P_{2bi} = P_{2bR1} + P_{2bR2} + P_{2bR3} + P_{2bL1} + P_{2bL2} + \\ + P_{2bL3} + P_{2bE3} + P_{2bE2}; \\ P_{4ai} = P_{4aR1} + P_{4aR2} + P_{4aR3} + P_{4aL1} + P_{4aL2} + \\ + P_{4aL3} + P_{4aE3} + P_{4aE2}; \\ P_{4bi} = P_{4bR1} + P_{4bR2} + P_{4bR3} + P_{4bL1} + P_{4bL2} + \\ + P_{4bL3} + P_{4bE3} + P_{4bE2}; \\ P_{6ai} = P_{6aR1} + P_{6aR2} + P_{6aR3} + P_{6aL1} + P_{6aL2} + \\ + P_{6aL3} + P_{6aE3} + P_{6aE2}; \\ P_{6bi} = P_{6bR1} + P_{6bR2} + P_{6bR3} + P_{6bL1} + P_{6bL2} + \\ P_{6bL3} + P_{6bE3} + P_{6bE2}; \\ P_{8ai} = P_{8aR1} + P_{8aR2} + P_{8aR3} + P_{8aL1} + P_{8aL2} + \\ + P_{8aL3} + P_{8aE3} + P_{8aE2}; \\ P_{8bi} = P_{8bR1} + P_{8bR2} + P_{8bR3} + P_{8bL1} + P_{8bL2} + \\ + P_{8bL3} + P_{8bE3} + P_{8bE2}; \\ P_{10ai} = P_{10aR1} + P_{10aR2} + P_{10aR3} + P_{10aL1} + \\ + P_{10aL2} + P_{10aL3} + P_{10aE3} + P_{10aE2}; \\ P_{10bi} = P_{10bR1} + P_{10bR2} + P_{10bR3} + P_{10bL1} + \\ + P_{10bL2} + P_{10bL3} + P_{10bE3} + P_{10bE2}; \\ P_{12ai} = P_{12aR1} + P_{12aR2} + P_{12aR3} + P_{12aL1} + \\ + P_{12aL2} + P_{12aL3} + P_{12aE3} + P_{12aE2}; \\ P_{12bi} = P_{12bR1} + P_{12bR2} + P_{12bR3} + P_{12bL1} + \\ + P_{12bL2} + P_{12bL3} + P_{12bE3} + P_{12bE2}; \\ P_{14ai} = P_{14aR1} + P_{14aR2} + P_{14aR3} + P_{14aL1} + \\ + P_{14aL2} + P_{14aL3} + P_{14aE3} + P_{14aE2}; \\ P_{14bi} = P_{14bR1} + P_{14bR2} + P_{14bR3} + P_{14bL1} + \\ + P_{14bL2} + P_{14bL3} + P_{14bE3} + P_{14bE2}. \end{cases} \quad (5)$$

Thus, making the system of equation by Kirchhoff's law for this scheme, we obtain only seven equations while it is possible to get fifteen ones if energy method is used. If we consider that parameters $E_2(t)$, $E_3(t)$ include only the first harmonic, the number of unknowns is equal to ten that makes the system of equations unsolvable by the Kirchhoff's law. Solution of the above shown system is carried out either by direct methods, such as using the determinant of Gauss, or by iterative methods [20].

In the case when the system of equations is nonlinear (with several nonlinear elements), it is a convenient way to solve it by Newton method. If the initial approximation is non-zero, and there is no limit, the Newton method and Gauss-Newton method are equally most efficient [21–23].

Consider the above provisions on example of the electrical circuit, including the power supply, the resistance and the nonlinear inductance.

Curve showing variation of the inductance depending on the current is presented by the dependence:

$$L(I) = a_0 + a_2 I^2 + a_4 I^4, \quad (6)$$

where a_0, a_2, a_4 are approximation coefficients.

Obtaining analytical dependence $L(t)$ has not been discussed in the literature, although the question is of direct interest. To obtain dependence $L(t)$ it is necessary to substitute values $I(t)$ in (6). The coefficients a_0, a_2, a_4 are unknown. Thus, expression for $L(t)$ will take the form:

$$L(t) = a_0 + a_2 I^2(t) + a_4 I^4(t), \quad (7)$$

where coefficients a_0, a_2, a_4 represent complex dependences obtained as a result of the frequency conversion of the trigonometric function describing the current.

To determine the parameters we use the energy method. Essence of the method is that the currents and voltages are presented in the form of harmonic functions:

$$I(t) = I_{1a}\cos(\Omega t) + I_{1b}\sin(\Omega t) + I_{3a}\cos(3\Omega t) + \\ + I_{3b}\sin(3\Omega t) + I_{5a}\cos(5\Omega t) + I_{5b}\sin(5\Omega t); \quad (8)$$

$$U(t) = U_{1a}\cos(\Omega t) + U_{1b}\sin(\Omega t). \quad (9)$$

Then power on each element:

power supply output

$$P_i(t) = U_i(t) I(t) = (U_{1a}\cos(\Omega t) + U_{1b}\sin(\Omega t)) \times \\ (I_{1a}\cos(\Omega t) + I_{1b}\sin(\Omega t) + I_{3a}\cos(3\Omega t) + \\ I_{3b}\sin(3\Omega t) + I_{5a}\cos(5\Omega t) + I_{5b}\sin(5\Omega t)); \quad (10)$$

the active resistance

$$P_R(t) = U_R(t) I(t) = R I^2(t) = R(I_{1a}\cos(\Omega t) + \\ I_{1b}\sin(\Omega t) + I_{3a}\cos(3\Omega t) + I_{3b}\sin(3\Omega t) + \\ + I_{5a}\cos(5\Omega t) + I_{5b}\sin(5\Omega t))^2; \quad (11)$$

the inductance

$$P_L(t) = U_L(t) I(t), \quad (12)$$

where $U_L(t) = L(t)\frac{dI(t)}{dt} + I(t)\frac{dL(t)}{dt}$.

The dependence of $I(t)$ is a set of trigonometric functions which, when raised to an even power, give a constant and an alternating components. The nonlinear inductance has the form of:

$$L(t)=L_0+a_2\left(\sum_{m=1}^{m=k}\left(I_{ma}\cos\left(m\Omega_m t\right)+I_{mb}\sin\left(m\Omega_m t\right)\right)\right)^2+$$
$$+a_4\left(\sum_{m=1}^{m=k}\left(I_{ma}\cos\left(m\Omega_m t\right)+I_{mb}\sin\left(m\Omega_m t\right)\right)\right)^4, \qquad (13)$$

where $L_0=a_0+a_2\left(\sum_{m=1}^{M}I_{0_{(2)}}\right)+a_4\left(\sum_{m=1}^{M}I_{0_{(4)}}\right)$; $I_{0_{(2)}},I_{0_{(4)}}$ is a constant current component obtained by raising a trigonometric series of the current in the second and fourth power.

According to the superposition principle, the identification system of equations is:

$$\begin{cases}
U_{1a}I_{1a}+U_{1b}I_{1b}=RI_{1a}^2+RI_{1b}^2+RI_{3a}^2+RI_{3b}^2+\\
+RI_{5a}^2+RI_{5b}^2+a_2\left(\sum_{m=1}^{M}I_{0_{(2)}}\right)+a_4\left(\sum_{m=1}^{M}I_{0_{(4)}}\right);\\
U_{1a}I_{1a}+U_{1b}I_{3b}-U_{1b}I_{1b}+U_{1a}I_{3a}=RI_{1a}^2-\\
-RI_{1b}^2+2RI_{3a}I_{1a}+2RI_{5b}I_{3b}+2RI_{1b}I_{3b}+\\
+2RI_{3a}I_{5a}+a_0+a_2\left(\sum I_{2a_{(2)}}\right)+a_4\left(\sum I_{2a_{(4)}}\right);\\
U_{1b}I_{1b}+U_{1a}I_{1b}+U_{1a}I_{3b}+U_{1b}I_{3a}=\\
=2RI_{1a}I_{1b}+2RI_{1b}I_{3a}+2RI_{5a}I_{3b}+\\
+2RI_{1a}I_{3b}+2RI_{3a}I_{5b}+a_0+\\
+a_2\left(\sum I_{2b_{(2)}}\right)+a_4\left(\sum I_{2b_{(4)}}\right);\\
-U_{1b}I_{3b}+U_{1a}I_{3a}+U_{1a}I_{5a}+U_{1b}I_{5b}=\\
=2RI_{3a}I_{1a}+2RI_{5a}I_{1a}-2RI_{1b}I_{3b}+2RI_{1b}I_{5b}+\\
+a_0+a_2\left(\sum I_{4a_{(2)}}\right)+a_4\left(\sum I_{4a_{(4)}}\right);\\
U_{1a}I_{3b}+U_{1a}I_{5b}-U_{1b}I_{3a}=2RI_{3a}I_{1b}+\\
+2RI_{3b}I_{1a}+2RI_{1a}I_{5b}-2RI_{1b}I_{5a}+a_0+\\
+a_2\left(\sum I_{4b_{(2)}}\right)+a_4\left(\sum I_{4b_{(4)}}\right);\\
U_{1a}I_{5a}-U_{1b}I_{5b}=RI_{3b}^2+2RI_{1a}I_{5a}-\\
-2RI_{1b}I_{5b}+a_0+a_2\left(\sum I_{6a_{(2)}}\right)+a_4\left(\sum I_{6a_{(4)}}\right);\\
U_{1b}I_{5a}+U_{1a}I_{5b}=2RI_{3a}I_{3b}+2RI_{1b}I_{5a}+\\
+2RI_{1a}I_{5b}+a_0+a_2\left(\sum I_{6b_{(2)}}\right)+a_4\left(\sum I_{6b_{(4)}}\right),
\end{cases} \qquad (14)$$

where $I_{2a_{(2)}},I_{2a_{(4)}}$ are the cosine component of the current at the second harmonic after raising to the second and fourth power; $I_{2b_{(2)}},I_{2b_{(4)}}$ are the sine component of the current at the second harmonic after raising to the second and fourth power; $I_{4a_{(2)}},I_{4a_{(4)}}$ are the cosine component of the current in the fourth harmonic after raising to the second and fourth power; $I_{4b_{(2)}},I_{4b_{(4)}}$ are the sine component of the current in the fourth harmonic after raising to the second and fourth power; $I_{6a_{(2)}},I_{6a_{(4)}}$ are the cosine component of the current in the sixth harmonic after raising to the second and fourth power; $I_{6b_{(2)}},I_{6b_{(4)}}$ are the sine component of the current in the sixth harmonic after raising to the second and fourth power.

The analysis of the obtained equations showed that the number of identification equations is larger than the number of the equivalent circuit parameters, due to the formation of the components of instantaneous power by means of harmonic analysis of the product of the initial voltage and current signals.

For example, consider a circuit where the power supply voltage $U(t)=220\cos(\Omega t)$, angular frequency $\Omega=100\,c^{-1}$ and current $I(t)$:

$$I(t)=1{,}37\cos(\Omega t)-1{,}01\sin(\Omega t)+0{,}08\cos(3\Omega t)-$$
$$-0{,}3\sin(3\Omega t)+0{,}017\cos(5\Omega t)-0{,}085\sin(5\Omega t). \qquad (15)$$

Active resistance and coefficients a_0, a_2, a_4. are the unknowns in this case.

Given the above parameters, the identification system of equations will take the form:

$$\begin{cases}
150=3{,}1a_2-4{,}8a_4+1{,}5R;\\
160=-3385a_4-171{,}5a_0-875a_2+0{,}9R;\\
-144=-2273a_4-87a_0-555a_2-1{,}7R;\\
10{,}6=1078a_2-5111a_4-117a_0-0{,}09R.
\end{cases} \qquad (16)$$

After solving system (16) the following parameters are obtained: $R=99$ Ом; $a_0=1{,}44$; $a_2=-0{,}4$; $a_4=0{,}05$.

Nonlinearity parameter identification is performed by substituting the obtained parameters in the expression (13): $L_0=0{,}91$; $L_{2a}=0{,}18$; $L_{2b}=0{,}39$; $L_{4a}=-0{,}024$; $L_{4b}=0{,}065$.

Then the dependence will take the form:

$$L(t)=0{,}93+0{,}18\cos(2\Omega t)+0{,}39\sin(2\Omega t)-$$
$$-0{,}024\cos(4\Omega t)+0{,}065\sin(4\Omega t). \qquad (17)$$

Based on these results, we can conclude that the solution of identification equations system allows us to obtain dependences for determination of all the circuit components parameters.

In the problems of nonlinearities identification the use of the energy method allows to divide EMS into separate units and simplify the analysis of energy processes by performing parameter identification in several stages. It makes the energy method applicable to complex challenges of branched circuits with multiple nonlinearities, etc. In this case, the coordinate components of the power harmonics of different elements are added arithmetically regardless of the configuration of the equivalent circuit.

Consider a more complicated case i.e. branched chain (Fig. 2) with nonlinear inductance L_3.

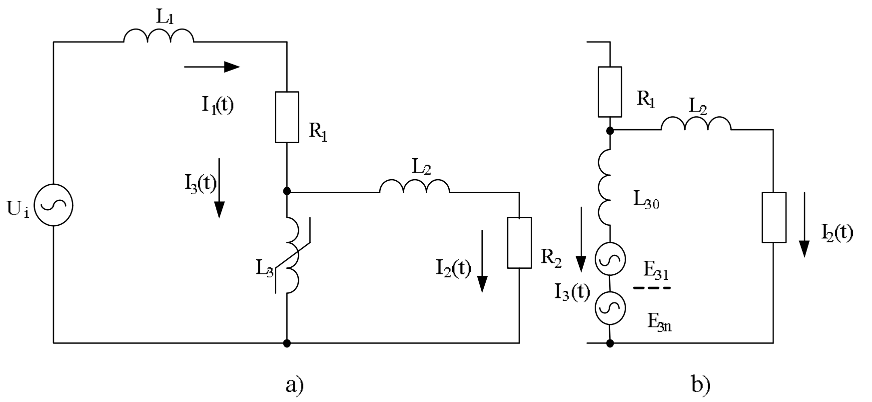

Figure 2 – Circuit diagram a) the complex structure of the consumer, and b) the equivalent circuit of nonlinearity L_3

Nonlinearity identification by the energy method is a specific task, based on identification equations system i.e. set of power components balance equations for each harmonic between the power source and the elements of the equivalent circuit of the consumer. Nonlinearity parameter identification is carried out in two stages:

at the first stage an identification equations system to determine the corresponding equivalent circuit e.m.f is created;

at the second stage another equivalent circuit is created according to the equations of energy transformations in the nonlinear inductance to determine the coefficients in the dependence describing the nonlinearity.

Thus, with solving the problem of identifying the parameters of the nonlinear inductance in several stages let us first make the substitution of $L_3(t)$ by a set of the equivalent e.m.f. $E_{31},...E_{3n}$, and then directly define inductance parameters. As in the previous case, the power supply is a sine AC voltage. In accordance with the foregoing, it can be assumed that the currents I_1, I_2, I_3 have a non-sinusoidal pattern:

$$I_1(t)=\sum_1^M I_1 cos(\Omega t-\varphi_1)=\sum_1^M(\dot{I}_{1a}-\dot{I}_{1b}); \quad (18)$$

$$I_2(t)=\sum_1^M I_2 cos(2\Omega t-\varphi_2)=\sum_1^M(\dot{I}_{2a}-\dot{I}_{2b}); \quad (19)$$

$$I_3(t)=\sum_1^M I_3 cos(3\Omega t-\varphi_3)=\sum_1^M(\dot{I}_{3a}-\dot{I}_{3b}). \quad (20)$$

Analysis of energy transformation mode is based on the following features:

the number of unknowns is determined basing on the quantity of e.m.f. in the equivalent circuit, the number of elements in it ($L_1, R_1, L_2, R_2, L_0,\ E_{1a}, E_{1b},...E_{na}, E_{nb}$), current of one of the circuits ($I_{2a}, I_{2b},...I_{ma}, I_{mb}$);

the number of identification equations includes 2M+1 balance equations of cosine, sine and constant component of power, where m is the number of harmonics.

Harmonic spectrum is determined by the capacity of the first voltage harmonic and the M current harmonics whose frequencies are multiples of network frequency.

The above approach can be applied to the identification of nonlinearities in the process of electromechanical systems of different physical nature. For example, in practice, it is necessary to solve a number of problems affecting both the loading conditions of electrical machines, and identification of some of its parameters (Fig. 3). The principle of operation of the scheme is to establish recurring energy exchange processes between the network and the motor, the motor and other energy converters [24]. These processes involve elements of electric machine structure defining its technical part as electromechanical converter, i.e. rotating mass of the rotor winding inductance, their resistances. The use of accumulation and compensation devices in the power supply of the electric machine under test, in this case, most closely matches the compensation rule of alternating power components in the place where they are produced.

Analysis of the energy process is a key in assessing the performance of electric vehicles in the test. In this case, the energy method based on the instantaneous power balance equations is a convenient tool that allows one to consider the characteristics of the energy distribution on the elements of the circuit. In this paper the analysis is performed for one motor. M1.

Because of the complexity of the mathematical apparatus for solving problems on the characterization of electromechanical systems it is performed in several stages. The first stage involves the replacement of nonlinear electro-motor parameters ($k\Phi(t)$ and $\omega(t)$) by equivalent e.m.f. $E(t)$. In the second stage we proceed to define the parameters of the nonlinear system.

The problem of determining the parameters of the motor. Known are the electrical parameters of the load mode i.e. current and armature voltage.

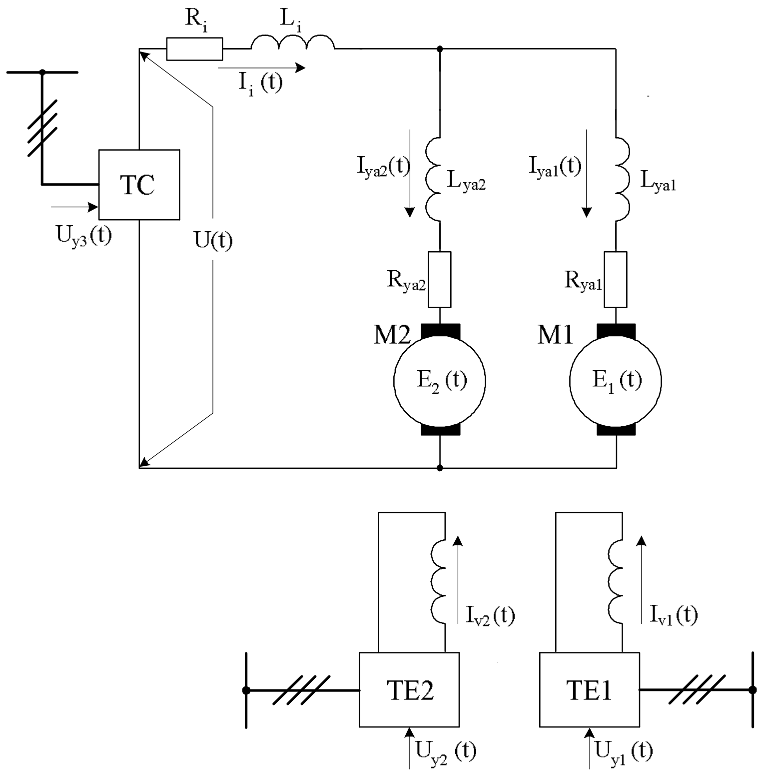

Figure 3 – The test circuit of DC machines with electric machine compensator

For system (Fig. 3) balance equation can be written as:

$$U_i(t) = E_1(t) + I_{ya}(t)R + L_{ya}\frac{dI_{ya}(t)}{dt}; \quad (21)$$

$$M_d(t) - M_c(t) = J\frac{d\omega(t)}{dt}; \quad (22)$$

$$M_d(t) = I_{ya}(t)k\Phi(t), \quad (23)$$

where M_c, J are moment of resistance and moment of motor inertia.

Dependences characterizing loading mode can be represented as:

$$I_{ya}(t) = I_0 + \sum_{n=1}^{N} I_n(t); \quad (24)$$

$$E_1(t) = k\Phi(t)\omega(t) = E_0 + \sum_{m=1}^{M} E_m(t); \quad (25)$$

$$k\Phi(t) = k\Phi_0 + \sum_{k=1}^{K} k\Phi_k(t); \quad (26)$$

$$\omega(t) = \omega_0 + \sum_{j=1}^{J} \omega_j(t). \quad (27)$$

Using these expressions we make up the balance equations for the components of the instantaneous power of each harmonic. $E(t)$, R_{ya} and L_{ya} are unknown parameters in this case. In general, the system of equations has the form:

$$\begin{cases}
U_i I_0 = R_{ya}I_{1a}^2 + R_{ya}I_{1b}^2 + R_{ya}I_{3a}^2 + R_{ya}I_{3b}^2 + R_{ya}I_{5a}^2 + \\
+ R_{ya}I_{5b}^2 + E_0 I_0 + E_{1a}I_{1a} + E_{1b}I_{1b} + E_{3a}I_{3a} + E_{3b}I_{3b} + \\
E_{5a}I_{3a} + E_{5b}I_{3b}; \\
0 = R_{ya}I_{1a}^2 - R_{ya}I_{1b}^2 + 2R_{ya}I_{3a}I_{1a} + 2R_{ya}I_{5b}I_{3b} + \\
+ 2R_{ya}I_{1b}I_{3b} + 2R_{ya}I_{3a}I_{5a} - L\Omega I_{1a}I_{3b} + L\Omega I_{1a}I_{1b} + \\
+ L\Omega I_{1a}I_{1b} + L\Omega I_{1b}I_{3a} - 3L\Omega I_{3a}I_{1b} - 3L\Omega I_{3a}I_{5b} + \\
+ 3L\Omega I_{1a}I_{3b} + 3L\Omega I_{5a}I_{3b} - 5L\Omega I_{5a}I_{3b} + 5L\Omega I_{3a}I_{5b} + \\
+ E_{1a}I_{1a} + E_{1a}I_{3a} - E_{1b}I_{1b} + E_{1b}I_{3b} + E_{3a}I_{1a} + E_{3a}I_{5a} + \\
+ E_{3b}I_{1b} + E_{3b}I_{5b} + E_{5a}I_{3a} + E_{5b}I_{3b}; \\
0 = 2R_{ya}I_{1a}I_{1b} + 2R_{ya}I_{1b}I_{3a} + 2R_{ya}I_{5a}I_{3b} + 2R_{ya}I_{1a}I_{3b} + \\
+ 2R_{ya}I_{3a}I_{5b} - L\Omega I_{1a}^2 - L\Omega I_{1a}I_{3a} + L\Omega I_{1b}^2 + L\Omega I_{3b}I_{1b} - \\
- 3L\Omega I_{3a}I_{1a} - 3L\Omega I_{3a}I_{5a} + 3L\Omega I_{3b}I_{1b} + 3L\Omega I_{3b}I_{5b} - \\
- 5L\Omega I_{5a}I_{3a} + 5L\Omega I_{5b}I_{3b} + E_{1a}I_{1b} + E_{1a}I_{3b} + E_{1b}I_{1a} + \\
+ E_{3a}I_{1b} + E_{3b}I_{5b} + E_{3b}I_{1a} + E_{3b}I_{5a} + E_{5a}I_{3b} + E_{5b}I_{3a}; \\
0 = 2R_{ya}I_{3a}I_{1a} + 2R_{ya}I_{5a}I_{1a} - 2R_{ya}I_{1b}I_{3b} + 2R_{ya}I_{1b}I_{5b} + \\
+ L\Omega I_{1b}I_{3a} - L\Omega I_{5b}I_{1a} + L\Omega I_{3b}I_{1a} + L\Omega I_{1b}I_{5a} + \\
+ 3L\Omega I_{3a}I_{1b} + 3L\Omega I_{1a}I_{3b} - 5L\Omega I_{5a}I_{1b} + 5L\Omega I_{1a}I_{5b} + \\
+ E_{1a}I_{3a} - E_{1b}I_{3b} + E_{3a}I_{1a} - E_{3b}I_{1b} + E_{1b}I_{5b} + E_{1a}I_{5a} + \\
+ E_{5a}I_{1a}; \\
0 = 2R_{ya}I_{3a}I_{1b} + 2R_{ya}I_{1a}I_{3b} - 2R_{ya}I_{1a}I_{5b} + 2R_{ya}I_{1b}I_{5a} - \\
- L\Omega I_{1a}I_{3a} + L\Omega I_{1b}I_{3b} - L\Omega I_{1a}I_{5a} + L\Omega I_{1b}I_{5b} - \\
- 3L\Omega I_{3a}I_{1a} + 3L\Omega I_{3b}I_{1b} - 3L\Omega I_{5a}I_{1a} + 3L\Omega I_{5b}I_{1b} + \\
+ E_{1a}I_{3b} + E_{1a}I_{5b} + E_{1b}I_{3a} + E_{1b}I_{5a} + E_{3a}I_{1b} + E_{5a}I_{1b} + \\
+ E_{3a}I_{1b} + E_{5b}I_{1a};
\end{cases}$$

$$\begin{cases} 0=-R_{ya}I_{3b}^2+2R_{ya}I_{5a}I_{1a}-2R_{ya}I_{1b}I_{5b}+L\Omega I_{5b}I_{1a}+ \\ +L\Omega I_{1b}I_{5a}+3L\Omega I_{3a}I_{3b}+3L\Omega I_{1a}I_{3b}+5L\Omega I_{5a}I_{1b}+ \\ +5L\Omega I_{1a}I_{5b}+E_{1a}I_{5a}-E_{1b}I_{5b}+E_{3a}I_{3a}-E_{3b}I_{3b}+ \\ +E_{1a}I_{5a}-E_{5b}I_{1b}; \\ 0=2R_{ya}I_{1a}I_{5b}+2R_{ya}I_{1b}I_{5a}+2R_{ya}I_{3b}I_{3a}-3L\Omega I_{3a}^2+ \\ +3L\Omega I_{3b}^2+L\Omega I_{1b}I_{5b}-L\Omega I_{1a}I_{5a}+5L\Omega I_{5a}I_{1a}+ \\ +5L\Omega I_{5b}I_{1b}+E_{1b}I_{5a}+E_{3a}I_{3b}+E_{3b}I_{3a}+E_{5a}I_{1b}+E_{5b}I_{1a}; \\ 0=2R_{ya}I_{5a}I_{3a}-2R_{ya}I_{5b}I_{3b}+3L\Omega I_{3a}I_{5b}+3L\Omega I_{5a}I_{3b}+ \\ +5L\Omega I_{5a}I_{3a}+5L\Omega I_{3a}I_{5b}+E_{3a}I_{5a}-E_{3b}I_{5b}+E_{5a}I_{3a}- \\ -E_{5b}I_{3b}; \\ 0=2R_{ya}I_{3a}I_{5b}+2R_{ya}I_{3b}I_{5a}-3L\Omega I_{3a}I_{5a}+3L\Omega I_{3b}^2- \\ -5L\Omega I_{5a}I_{3a}+5L\Omega I_{5b}I_{3b}+E_{3b}I_{5a}+E_{3a}I_{5b}+E_{5a}I_{3b}+ \\ +E_{5b}I_{3a}; \\ 0=R_{ya}I_{5a}^2-R_{ya}I_{5b}^2+5L\Omega I_{5a}I_{5b}+5L\Omega I_{3a}I_{3b}+E_{5a}I_{5a}- \\ -E_{5b}I_{5b}; \\ 0=2R_{ya}I_{5a}I_{5b}-5L\Omega I_{5a}^2+5L\Omega I_{5b}^2+E_{5a}I_{5b}+E_{5b}I_{5a}. \end{cases}$$

A result of solving the above system, we obtain the expression $E(t)$, R_{ya} and L_{ya}.

To determine the electromechanical parameters of EMS we create the instantaneous power balance equation from expression

$$E(t)I_{ya}(t)=k\Phi(t)\omega(t)I_{ya}(t)+J\omega(t)\frac{d\omega(t)}{dt}. \quad (28)$$

The coefficients, which form dependences $k\Phi(t)$ and $\omega(t)$ in the form of trigonometric series, are unknown.

The peculiar feature consists in the fact that, in contrast to the previously considered problem, this is the product of three dependences $I_{ya}(t)$, $k\Phi(t)$ and $\omega(t)$, which is due to rather complex and specific frequency transformations. Thus, by multiplying the three trigonometric functions we obtain four components with different frequencies.

This example shows the potential of the energy method to calculate the electromagnetic parameters of DC machines. It is shown that the use of the instantaneous power balance equations for each harmonic provides enough equations with any number of unknowns.

CONCLUSIONS. The analysis showed that the energy method is effective at treating the energy processes of electromechanical systems. The proposed method allows us to analyze the processes of energy transformation on each element of the system, taking into account the law of conservation of energy. The main feature of the energy method is the possibility of allowing for nonlinear properties of the elements of electrical circuits. When identification of nonlinearities is carried out, energy method, in contrast to existing methods, allows one to make a system with required number of equations to determine the parameters and to obtain not only a quantitative but also a qualitative assessment of the processes occurring in the circuit.

Energy method of parameters identification is applicable for both simple and complex electromechanical systems. Evidence-based approach allows us to perform analysis of energy processes between the source and the consumer in the space of instantaneous voltage, current and power. Also, solution of the problem in two stages considerably simplifies mathematical calculation, which makes the method universal, i.e. for treating the system, where the character of the nonlinearity is of a complex nonlinear dependence.

The above approach can be applied to the identification of nonlinearities in the process of electromechanical systems of different physical nature. It can be hydrosystem, the energy canal of which is characterized by complex processes of energy transformation, due to the nonlinear properties of the elements within its structure: pumps, pipeline network, valves and fittings, as well as occurring hydrodynamic processes (turbulence, cavitation, surge, etc.), and various non-linearities in the mechanical systems, such as non-linearity with negative friction, nonlinear characteristics of the connection between the shafts, backlash, various nonlinearities of the converter devices and electric control systems, etc.

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ОБ ИДЕНТИФИКАЦИИ НЕЛИНЕЙНЫХ ПАРАМЕТРОВ ЭЛЕКТРОМЕХАНИЧЕСКИХ СИСТЕМ

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Рассмотрены существующие методы оценки и идентификации параметров электромеханических систем. Показано, что основным недостатком известных методов является невозможность получить достаточное количество идентификационных уравнений для определения электромагнитных параметров систем с учетом нелинейностей. Предложен математический аппарат для определения параметров нелинейных электромеханических систем на основе энергетического баланса мгновенной мощности по каждой гармонике. Рассмотрены возможности применения энергетического метода на примере идентификации параметров нелинейной индуктивности. Показано, что такой подход на основе баланса мощностей элементов источника и потребителя на каждой гармонике позволяет получить необходимое количество уравнений для определения любых параметров электромеханических систем.

Ключевые слова: энергетический метод, нелинейности, аппарат мгновенной мощности, идентификация параметров.

Стаття надійшла 28.01.2013.