1.Nadir ALİYEV[1], **2. Elbrus AHMEDOV**[2], **3. Samira KHANAHMEDOVA**[3], **4. Sona RZAYEVA** [4].

Azerbaijan State Oil and Industry University (1, 2, 3, 4)
ORCID: 1. 0009-0001-3165-1493; 2. 0000-0003-3348-7946; 3. 0000-0001-8862-1570; 4. 0000-0001-7086-9519.

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Synthesis of the Exact Parameters of the Electromagnetic Brake of a Wind Electric Installation

***Abstract**. The article considers the problem of optimal modeling of an electromagnetic brake, as applied to a wind power plant to reduce dangerous fluctuations at high wind speeds and obtain electricity of the required quality. The effectiveness of using the frequency method with the subsequent compilation of equivalent circuits is shown to develop a simplified method for calculating the electromagnetic torque of a brake with a massive magnetic circuit. Taking into account the peculiarities of the study of machines with a massive magnetic circuit, in order to develop an engineering calculation method, the electromagnetic slip clutch (ESC) is considered as an object with lumped parameters. Based on the results of the excitation current damping experiment, an algorithm and a program for solving the problem of synthesizing the parameters of an improved equivalent circuit for an electromagnetic brake with multiloop structures have been developed.*

***Streszczenie.** W artykule podjęto problem optymalnego modelowania hamulca elektromagnetycznego zastosowanego w elektrowni wiatrowej w celu zmniejszenia niebezpiecznych wahań przy dużych prędkościach wiatru i uzyskania energii elektrycznej o wymaganej jakości. Wykazano skuteczność zastosowania metody częstotliwości z późniejszym zestawieniem obwodów zastępczych w celu opracowania uproszczonej metody obliczania momentu elektromagnetycznego hamulca z masywnym obwodem magnetycznym. Biorąc pod uwagę specyfikę badania maszyn z masywnym obwodem magnetycznym, w celu opracowania inżynierskiej metody obliczeniowej elektromagnetyczne sprzęgło poślizgowe (ESP) jest uważane za obiekt o parametrach skupionych. Na podstawie wyników eksperymentu tłumienia prądu wzbudzenia opracowano algorytm i program do rozwiązania problemu syntezy parametrów udoskonalonego obwodu zastępczego hamulca elektromagnetycznego o strukturach wielopętlowych.. (**Synteza dokładnych parametrów hamulca elektromagnetycznego elektrowni wiatrowej**)*

Keywords: wind power plant, massive magnetic circuit, electromagnetic brake, equivalent circuit, frequency response.
Słowa kluczowe: elektrownia wiatrowa, masywny obwód magnetyczny, hamulec elektromagnetyczny, obwód zastępczy. .

Introduction

One of the main tasks of modern energy is to increase the trend of using renewable energy sources. One of the main problems of electricity supply is remote rural areas, which are located far from the central power supply systems.

One of the most affordable sources of renewable energy is wind power. Wind power is a dynamically developing branch of the energy industry of the leading countries of the world. By the beginning of the XXI century, it has become a separate branch of alternative energy [1-6].

Wind power plants (wind turbines), despite a number of undeniable advantages, are not without drawbacks. The wind, passing through the wind wheel, does work, converting the wind force into mechanical power, then the mechanical power is converted into electrical power.

$$P_m = \frac{1}{2} R^2 v^2 C_p$$

where C_p is the coefficient of wind energy use, ρ - is the air density, πR^2 is the habitable area of the wind wheel, v -is the air speed.

As you can see, the most important energy characteristic of the wind is its speed. The speed and direction of the wind changes according to a random law, and the kinetic energy is proportional to the cube of its speed. To obtain electricity of the required quality, it is necessary to combine the theoretical knowledge of aerodynamics and electromechanics.

Most of the currently known designs of wind turbines are characterized by a low efficiency and are not sufficiently reliable in operation. Vibration oscillations generated by wind turbine components during operation under the influence of disturbing aerodynamic and inertial moments are also a serious problem. Resonances of disturbing influences and eigenoscillations of wind turbines are especially dangerous [7-9]. This can lead to the destruction of the installation.

The development of methods for reducing the harmful and dangerous effects of the general vibration generated by wind turbines is an urgent task and requires the improvement of theoretical and experimental existing data and the development of new schemes and technologies for the use of wind energy.

The solution of the task

As you know, the dynamic moment on the wind generator shaft changes periodically. They must maintain the established parameters of the generated energy under any energy impact. Solving the problem of stabilization, as well as issues of starting and braking, increasing reliability is an urgent task.

The use of an electromagnetic slip clutch (ESC) for damping undesirable dynamic processes is an effective way. The use of ESC or electromagnetic brake (EMB) in a wind turbine is considered in some works [8-10] and is a relatively new approach in this area with competitive advantages. In accordance with this, mathematical modeling, research and analysis of transient processes in the system gearbox ESC synchronous generator is of current importance. From the point of view of technological requirements, electrodynamic braking in case of an accidental and dangerous gust of wind has the best characteristics and can ensure the safe operation of wind farms.

Main part

ESC serves to transmit torque from the drive shaft to the driven shaft by an electromagnetic field. When used in a wind turbine, the torque of the wind wheel is transmitted to the generator. Thus, the required range of wind performance at high speeds, efficiency, reliability and the possibility of remote control are provided. Regulation of the excitation current makes it easier to use, makes it possible to smoothly brake in case of gusts of wind and protects the device from breakage and damage.

Structurally, ESC (or EMB) consists of a massive cylindrical armature and a salient-pole inductor with a massive core. ESC with a claw-shaped and massive anchor provide a more rational use of the magnetic system and allow you to form the mechanical characteristics of a given shape.

Numerous works of a theoretical and experimental nature, carried out in the field of machines with a massive magnetic circuit, as well as ESC and EMB, were aimed at improving the design, as well as optimizing their parameters and characteristics [13,14]. At the same time, the authors usually set themselves the goal: to improve the mechanical characteristics, that is, to create such machines that they provide the technical and technological needs of productive mechanisms.

Providing an electric generator with the necessary electromagnetic moment when the wind speed changes is a major and difficult task. The results of research in the field of ESC and EMB with a massive magnetic circuit showed that the electromagnetic torque is complexly dependent on the rotational speed (slip). To ensure the appropriate form of the mechanical characteristic *M=f(s)* and the required torque, based on relevant considerations, requires further research. Some aspects of this issue have been considered [6].

In this paper, we consider the issue of synthesizing the parameters of EMB equivalent circuits, which allow us to find the optimal form of the mechanical characteristic when the slip changes over a wide range.

Mathematical model

It is known that electromagnetic processes in electrical machines with a massive magnetic circuit can be studied by two methods:

- based on Maxwell's equations in differential form, considering them as an object with distributed parameters.
- equivalenting of a massive magnetic circuit by lumped contours and application of the Park-Gorev equation.

When solving the problem, using the second method, it is assumed that the massive magnetic core is equivalent along the longitudinal and transverse axes, respectively, with three and one circuit. The definition of a more accurate equivalent circuit and the synthesis of its parameters is of great interest. The initial information for the synthesis of the equivalent circuit can be the damping curve of the excitation current when the rotor is stationary, or the curve of the electromagnetic torque at a given excitation current.

The technique and algorithm for synthesizing equivalent circuits and determining parameters based on the damping of the excitation current, developed for synchronous and asynchronous machines, is fully applicable to ESC and EMB [15-17]. The synthesized multi-loop equivalent circuits quite correctly reflect the processes occurring in the machine in a wide range of slip changes, taking into account the massive elements of the armature. For the preliminary construction of equivalent circuits, we carried out an experiment on the attenuation of the excitation current of an electromagnetic brake at ω=0.

The electromagnetic brake has the following data:

- nominal braking torque *M*=400 *Nm*;
- nominal rotational speed n_1=1500*, rpm*.
- nominal excitation voltage U_{ex}=24 *V*;
- nominal excitation current i_{ex}=12 *A*;
- number of pairs of poles *p*=8.

To assess the influence of the magnetic state on the EMT parameters, the oscillograms were taken at three initial values of the damped excitation current (i_y=2.34 A, i_y=11.9 A, i_y=17.8 A).

One of the oscillograms at i_y=11.9A is shown in figure 1.

The results of processing the oscillogram by known methods [9, 12] are shown in Table 1.

The calculation of the electromagnetic moment was made according to the well-known method of using the system of relative units [18-20] using the MATLAB/Simulink software package. Based on the results obtained, the calculated mechanical characteristic of the electromagnetic brake was built (Fig. 3).

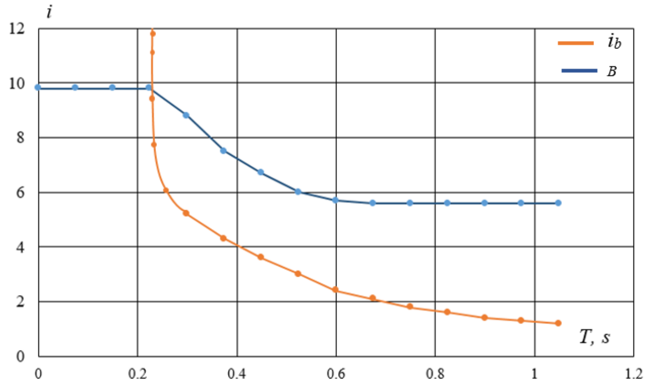


Fig. 1 Oscillogram of the damping of the excitation and induction current

Table 1. Results of processing the oscillogram by known methods

n	i_y*, A*	*i′, A*	*i″, A*	*i‴, A*	*T′, s*	*T″, s*	*T‴, s*
0	2.34	1.88	0.22	0.11	0.75	0.116	0.008
0	11.9	5.65	4.87	1.38	0.74	0.075	0.012
0	17.8	6.38	6.14	5.28	0.76	0.1	0.018

As can be seen from Table 1, the waveform contains 3 simple exponential components with their initial values *i′, i″, i‴* and constant times *T′, T″, T‴*.

According to the components of the current, we build the equivalent circuit shown in figure 2.

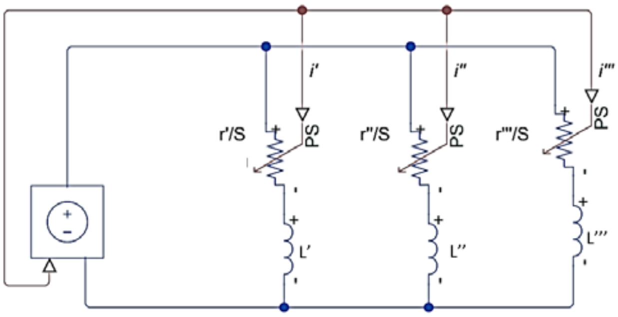


Fig.2 EMB design equivalent circuit

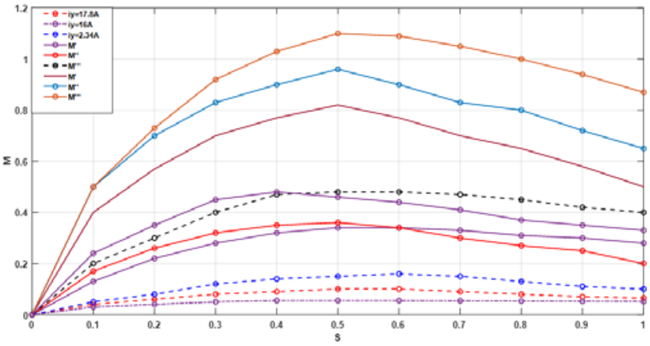


Fig.3 Calculated mechanical characteristic of electromagnetic brake EMB

Despite the simplicity, this approach and the algorithm for determining the electromagnetic torque is not rigorous. This is explained as follows: the calculated equivalent circuit 3 formally includes active resistance. This resistance, not reflected in the equivalent circuit, actually changes the magnitude of the currents *i′, i″, i‴*, individual circuits that are involved in creating the electromagnetic torque of the brake. Based on this, the value obtained will differ from the actual value. Thus, the equivalent circuit does not fully disclose the content of the electromagnetic processes occurring in the machine. Therefore, it is necessary to switch to another equivalent circuit corresponding to the known structure of the object's contours (Fig. 4.).

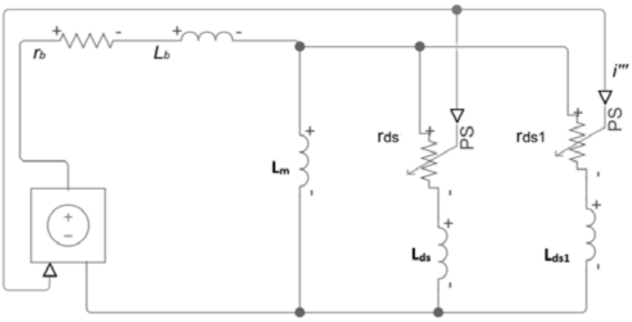


Fig.4 Refined EMB equivalent circuit

In the indicated circuit in Fig. 4, r_b and L_b are, respectively, the ohmic resistance and inductance of the excitation winding; L_m - mutual inductance between the excitation winding and the massive armature; r_{ds}, L_{ds}, r_{ds1}, L_{ds1} – respectively active resistances and leakage inductances, lumped circuits, equivalent to a massive armature of the machine.

The advantage of the equivalent circuit in Fig. 4 is that here the active resistance r_b and the inductance L_b of the excitation winding are separated and, together with the parameters of the equivalent armature circuits corresponding to the real ones, participate in the creation of an electromagnetic torque. Parameters r_{ds}, L_{ds}, r_{ds1}, L_{ds1} - take into account the damping effect of the massive pole.

The transition from figure 2 to figure 4 is made according to the following algorithm. Assume that all the parameters of figure 4 are unknown. In this case, you must first build the frequency response of the equivalent circuit, shown in figure 2. For this purpose, the input conductivity of the circuits is determined in the form:

$$Y_{in} = \frac{1}{r' + PL'} + \frac{1}{r'' + PL''} + \frac{1}{r''' + PL'''} = \frac{b_0 p^2 + b_1 p + b_2}{a_0 p^3 + a_1 p^2 + a_2 p + a_3} \tag{1}$$

where the coefficient of a rational fraction has the following expressions:

$$\mathrm{a}_0 = \mathrm{L'L''L'''} \tag{2}$$

$$\mathrm{a}_1 = \mathrm{L'L''r''' + L''L'''r' + L'L'''r''} \tag{3}$$

$$\mathrm{a}_2 = \mathrm{r'r'''L'' + r''r'''L' + r'r''L'''} \tag{4}$$

$$\mathrm{a}_3 = \mathrm{r'r''r'''} \tag{5}$$

$$\mathrm{b}_0 = \mathrm{L'L'' + L''L'''} + L'L'' \tag{6}$$

$$\mathrm{b}_1 = \mathrm{r''L''' + r'''L'' + r'L'' + r''L' + r'L'''} \tag{7}$$

$$\mathrm{b}_2 = \mathrm{r''r''' + r'r''' + r'r''} \tag{8}$$

Next, we calculate all the coefficients of equation (1), using the results of the experiment on the attenuation of currents in the excitation winding of the EMB.

The calculated coefficients of equation (1) give the following values: a_0=0.3477; a_1=34.166; a_2=433; a_3=523.6; b_0=2.411; b_1=102; b_2=230.

Substituting $p=j\omega$ into equation (1), we get:

$$Y_{in} = \frac{b_0 (j\omega)^2 + b_1 (j\omega) + b_2}{a_0 (j\omega)^3 + a_1 (j\omega)^2 + a_2 (j\omega) + a_3} = \frac{(b_2 - b_0\omega)^2 + j\omega b_1}{(a_3 - a_1\omega^2) - j(a_0\omega^3 - a_2\omega)} \tag{9}$$

After some transformations and groupings, we get the real and imaginary part of the conductivity of the equivalent circuit, presented in Figure 2 as:

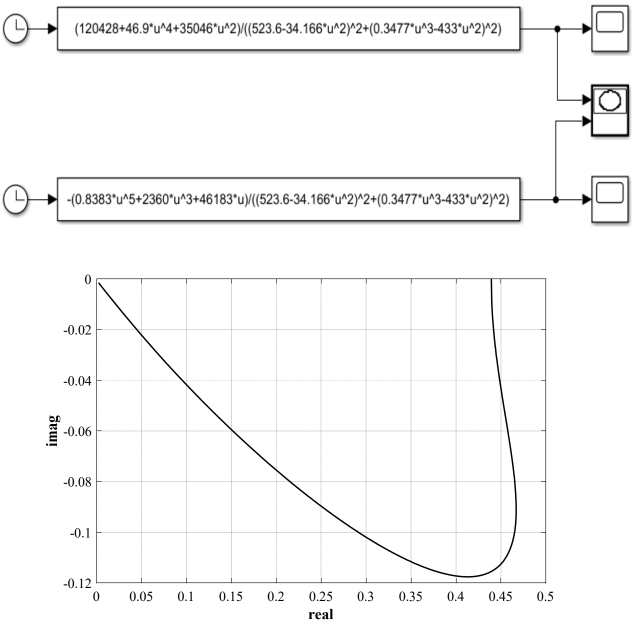
$$Y_{in} = g(\omega) + jb(\omega) \tag{10}$$

Where,

$$g(\omega) = \frac{b_2 a_3 + \omega^2 (a_2 b_1 - a_3 b_0 - a_1 b_2) + \omega^4 (a_1 b_0 - a_0 b_1)}{(a_3 - a_1\omega^2)^2 + (a_2\omega - a_0\omega^3)^2} \tag{11}$$

$$b(\omega) = \frac{-a_0 b_0 \omega^5 - \omega^3 (a_1 b_1 - a_2 b_0 - a_0 b_2) - \omega (a_2 b_2 - a_3 b_1)}{(a_3 - a_1\omega^2)^2 + (a_2\omega - a_0\omega^3)^2} \tag{12}$$

Substituting the calculated coefficients into (11) and (12) and varying within 0÷∞, we compose a model and obtain a graph of the amplitude-phase frequency response shown in Fig.5.



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(120428+46.9*u^4+35046*u^2)/((523.6-34.166*u^2)^2+(0.3477*u^3-433*u^2)^2)
-(0.8383*u^5+2360*u^3+46183*u)/((523.6-34.166*u^2)^2+(0.3477*u^3-433*u^2)^2)
```

Fig.5 Amplitude-phase frequency response of EMT

Next, the input conductivity of the equivalent circuit is determined, shown in Figure 2 as:

$$Y'_{in} = \frac{B_0 p^2 + B_1 p + B_2}{A_0 p^3 + A_1 p^2 + A_2 p + A_3} \tag{13}$$

$$A_0 = L_{ds} L_{ds1} L_{bs} + L_{ds1} L_m L_{bs} + L_{ds} L_m L_{bs} + L_{ds} L_{ds1} L_m \tag{14}$$

$$A_1 = L_{ds} L_{ds1} r_b + L_{ds1} L_m r_b + L_{ds} L_m r_b + L_{ds1} L_{bs} r_{ds} + L_{ds} L_{bs} r_{ds1} + \\ + L_m L_{bs} r_{ds1} + L_m L_{bs} r_{ds} + L_{ds1} L_m r_{ds1} \tag{15}$$

$$A_2 = r_b r_{ds} L_{ds1} + r_b r_{ds1} L_{ds} + r_b r_{ds1} L_m + r_b r_{ds} L_m + r_{ds} r_{ds1} L_{bs} + r_{ds1} r_{ds} L_m \tag{16}$$

$$A_3 = r_{ds1} r_b r_{ds} \tag{17}$$

$$B_0 = L_{ds} L_{ds1} + L_{ds1} L_m + L_{ds} L_m \tag{18}$$

$$B_1 = r_{ds} L_{ds1} + r_{ds1} L_{ds} + r_{ds1} L_m + r_{ds} L_m \tag{19}$$

$$B_2 = r_{ds} r_{ds1} \tag{20}$$

In equation (13) we substitute $p=j\omega$ and for each value of ω we determine the real and imaginary parts of the conductivity of the equivalent circuit shown in Figure 4.

$$Y_{in} = g'(\omega) + jb'(\omega) \tag{21}$$

Where

(22) $$g'(\omega)=\frac{B_2A_3+\omega^2\left(A_2B_1-A_3B_0-A_1B_2\right)+\omega^4\left(A_1B_0-A_0B_1\right)}{\left(A_3-A_1\omega^2\right)^2+\left(A_2\omega-A_0\omega^3\right)^2}$$

(23) $$b'(\omega)=\frac{-A_0B_0\omega^5-\omega^3\left(A_1B_1-A_2B_0-A_0B_2\right)-\omega\left(A_2B_2-A_3B_1\right)}{\left(A_3-A_1\omega^2\right)^2+\left(A_2\omega-A_0\omega^3\right)^2}$$

By varying ω in (22) and (23) within 0÷∞, the frequency response corresponding to the equivalent circuit shown in figure4 is determined.

The equivalent circuit parameters are determined from the condition of coincidence of frequency characteristics for both cases for characteristic discrete values ω. After determining $Y_{in}=g(\omega)+jb(\omega)$ and $Y_{in}=g'(\omega)+jb'(\omega)$, using the conditions $g(\omega)=g'(\omega)$ and $b(\omega)=b'(\omega)$, we obtain a system of nonlinear algebraic equations. By jointly solving the obtained systems of equations, we find the unknown parameters (r_d, r_{ds}, r_{ds1}, L_d, L_{ds}, L_{ds1}) of the equivalent circuit in Figure 4. To solve the systems of equations, an algorithm was compiled on the MATLAB/Workspace command window, and the obtained characteristics are shown in Figure 5.

```
w=0:0.001:10;
A0=0.7381;
A1=18.5645;
A2=24.3654;
A3=0.27;
B0=3.37;
B1=23.18;
B2=9;
i=(B2*A3+w.^2*(A2*B1-A3*B0-A1*B2)+w.^4*(A1*B0-
A0*B1))./((A3-A1*w.^2).^2+(A2*w-A0*w.^3).^2);
im=-(B0*A0*w.^5+w.^3*(A1*B1-A2*B0-A0*B2)+w.*(A2*B2-
A3*B1))./((A3-A1*w.^2).^2+(A2*w-A0*w.^3).^2);
plot(i,im)
>> hold on
w=0:0.001:10;
A0=1.4424;
A1=37.00143;
A2=41.651;
B0=4.965;
A3=0.63;
B1=23.18;
>> B2=14;
>> i1=(B2*A3+w.^2*(A2*B1-A3*B0-A1*B2)+w.^4*(A1*B0-
A0*B1))./((A3-A1*w.^2).^2+(A2*w-A0*w.^3).^2);
>> im1=-(B0*A0*w.^5+w.^3*(A1*B1-A2*B0-
A0*B2)+w.*(A2*B2-A3*B1))./((A3-A1*w.^2).^2+(A2*w-
A0*w.^3).^2);
>> plot(i1,im1)
>> hold on
>> w=0:0.001:10;
>> A0=2.352;
A1=54.2376;
>> A2=64.0248;
>> A3=1.152;
>> B0=6.36;
>> B1=46.08;
>> B2=19.2;
>> i2=(B2*A3+w.^2*(A2*B1-A3*B0-A1*B2)+w.^4*(A1*B0-
A0*B1))./((A3-A1*w.^2).^2+(A2*w-A0*w.^3).^2);
>> im2=-(B0*A0*w.^5+w.^3*(A1*B1-A2*B0-
A0*B2)+w.*(A2*B2-A3*B1))./((A3-A1*w.^2).^2+(A2*w-
A0*w.^3).^2);
>> plot(i2,im2)
>> hold on
>> grid
```

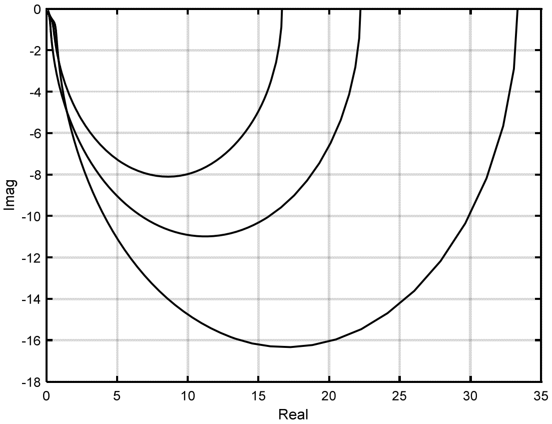

Fig.5 Characteristics Based on the Algorithm

Conclusion

The possibility of using an electromagnetic slip clutch (ESC) in a wind power installation is proposed to dampen undesirable dynamic processes and thereby improve the operation of the installation. The problem is considered for the purpose of optimal modeling of ESC with a massive magnet wire. Techniques and an algorithm for calculating the parameters and electromagnetic torque of ESC using the frequency method with subsequent compilation of equivalent circuits have been developed. Analytical equations of connection between the parameters of the transient process of attenuation of the excitation current and the parameters of equivalent circuits for their determination are obtained. The developed algorithm and program for solving the problem makes it possible to synthesize the parameters of an improved equivalent circuit for a machine with multiloop structures in order to obtain the required mechanical characteristic. The proposed technique can be used for other types of machines with massive elements.

Authors

Aliyev Nadyr Abdurakhman. Candidate of Technical Sciences, Associate Professor of the Electromechanics Department of the Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20, E-mail: nadir.aliyev@asoiu.edu.az

Ahmadov Elbrus Nasi. Associate Professor, Candidate of Physical and Mathematical Sciences. Head of the Department of Electromechanics Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20,E-mail: elbrus.ahmedov@asoiu.edu.az.

Khanakhmedova Samira Alkhadi. Doctor of Philosophy in Engineering, Associate Professor of the Electromechanics Department of the Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20, E-mail: samira.khanahmedova@asoiu.edu.az

Rzayeva Sona Vagif. Head of the Laboratory of the Department of Electromechanics of the Azerbaijan State University of Oil and Industry. Baku city, Azadlyg avenue 20, E-mail: sona.rzayeva@asoiu.edu.az

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