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Asynchronous Generators with Phase-Wound Rotor for Power Stations Operating Parallel to a Network

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ABSTRACT: The article discusses the results of the analysis of wind energy and hydropower surveys, consumed per 1 kW of electricity, carried out in the Republic of Uzbekistan. The amount of natural gas and coal, the construction of small and micro hydropower plants, their reliability, and economic efficiency are scientifically justified.The substitution scheme of the motor mode and the difference in the inductive resistance of the scattering of the rotor winding are given, which are not constant with a wide change in the parameters of the primary energy source.

KEYWORDS: hydraulic power plants, renewable energy sources, generator, engine, synchronous, asynchronous, power station, mechanical characteristic, power, voltage, current.

I.INTRODUCTION

It is known that in Uzbekistan, the production of electricity is mainly carried out at thermal power plants by burning fossil fuels.Few people know that to produce 1 kWh of electric energy, 0.3 cubic meters of natural gas is consumed, or an average of 2.5 kg of coal [1], the explored underground reserves of which are not infinite.Power plants with renewable energy sources (RES) - hydraulic power plants (HPPs) - produce no more than 10% of the total electricity production in the country.

In recent years, in the field of science and production, there has been a noticeable intensification of the search for ways to use renewable energy sources in electricity production. For example, a German consortium of Inter Gopa and Geonet companies in Uzbekistan carried out measurements of wind parameters, which showed that the wind energy potential of Uzbekistan is more than 512 GW [2]. This makes it possible to build thousands of wind power plants (wind farms), allowing them to produce electricity in the number of tens of times higher than today's release. According to research by the German company Fichtner [3], the hydropower potential of small mountain rivers in Uzbekistan is more than 4 GW. With such a large potential for renewable energy, the population of distant regions of the country feels a shortage of electricity. It should be noted that one of the main directions of the development strategy of Uzbekistan for the coming years is to improve the social situation of the population in remote areas, the main obstacle of which is the lack of electricity. In this regard, today the issues of introducing renewable energy - the conversion of solar, wind and small river energy are relevant for our country. The demand for electricity is growing day by day in connection with the planning for the coming years of the construction of energy-intensive enterprises in engineering, metallurgy, mining, processing, textile, light industry, and transport.

By the Decree of the President of the Republic of Uzbekistan No. PP-3012 dated 05/26/2017, by 2021, a wind farm with a capacity of 100 MW will be built near Nukus. Also, a similar power plant with a capacity of 200 MW is being built near the city of Zarafshan [3]. Following this Decree, by 2021, old and new small hydropower plants with a total capacity of 600 MW will be modernized.

The enterprises of countries with advanced economies have mastered the serial production of small hydroelectric power stations (mini hydroelectric power stations - up to 2 MW and micro-hydroelectric power stations - up to 0.2 MW) and RES with a synchronous generator [4,5].The use of synchronous generators for low-cost mini- and micro-hydroelectric power plants, which are recommended for implementation in small mountain rivers of Uzbekistan and RES with often changing technical parameters of water and wind flows, is not advisable from the point of view of the need for frequency controllers that maintain a constant output voltage frequency.Therefore, they are used mainly for the autonomous operation of HPPs and RES. The inclusion of mini-, micro-HPPs and RES in parallel operation with

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the grid is associated with difficulties in synchronizing the generator with the grid and significant equipment cost due to complex, expensive systems for controlling the rotor speed when the energy parameters (wind speed and water flow) fluctuate.

The use of a squirrel-cage rotor asynchronous motor (AM) as a generator [6] for the above mentioned power plants with variable energy parameters and operating in parallel with the existing network is also not advisable due to the fact that the working range of the rotor speed of such an engine is limited with a narrow strip, characterized by the interval between idle and maximum electromagnetic moment (Fig. 1 segment $\Delta\omega = \omega_0\omega_{k2}$ -working zone). Consequently, outside the range of rotor speeds of an asynchronous squirrel-cage generator, it is not possible to change the parameters of the primary energy carrier in the generator mode.

The use of an asynchronous generator with a phase rotor in such power plants will not only expand the operating range of the rotor speed by tens of times (a segment in Fig. 1 $\Delta\omega_3 = \omega_0\omega_{k3}$),causing their reliable operation but also simplifying the process of their manufacture and operation, allows maintaining the output power of the generator, when the parameters of the energy carrier fluctuate and simplify the process of inclusion in parallel operation with the network [9].The development of industrial production of mini-, micro-hydro and wind power plants based on an asynchronous generator with a phase rotor and their mass operation in our country will allow not only to use the hydropower potential of small mountain rivers and winds, but also provide electricity to remote settlements, reliably (predictably) transmit excessive electricity into the power grid and open up thousands of new jobs.

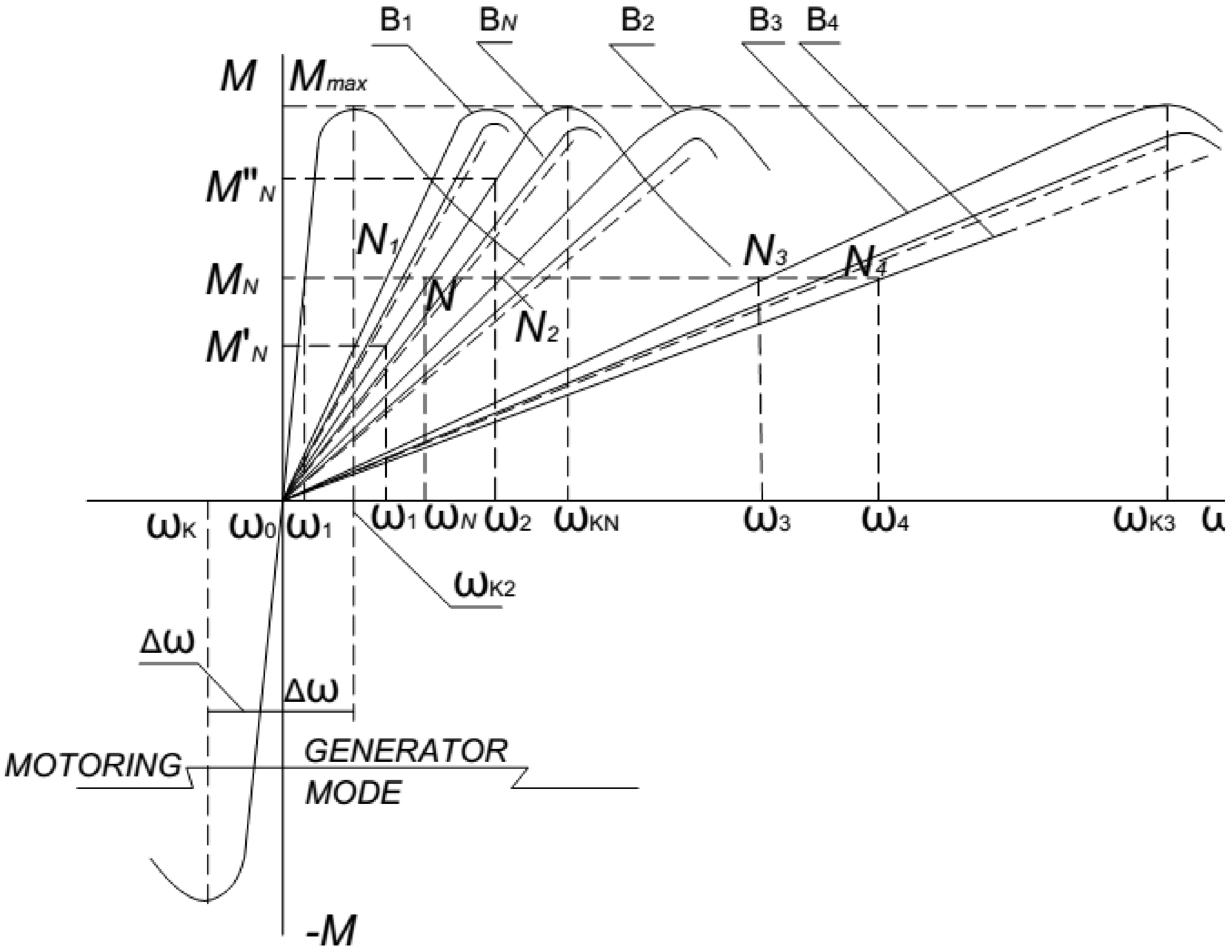

Fig. 1. Mechanical characteristics of an asynchronous machine

It is known that asynchronous machines are mainly used in the motor mode [7], therefore, in the scientific literature the theory of asynchronous machines is described mainly for the motor mode.

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Little attention is paid to the study of the generator mode, while it is believed that the assumptions made for the motor mode are acceptable for the generator mode as well, and its operation in the motor mode is taken as the starting point for the presentation of individual theoretical positions of the asynchronous generator [8].So, for example, when determining the constant parameters of an induction motor, it is assumed that the range of variation of the slip of the rotor rotation is not large and equal to the segment of the mechanical characteristic from the idle point to the critical slip point $\omega_0\omega_{k2}$ with a maximum moment.

In the generator mode, due to the wide range of changes in the parameters of the primary energy carrier, to ensure reliable operation of the power plant, the rotor speed must also be changed over a wide enough range (Fig. 1 segment $\Delta\omega_3 = \omega_0\omega_{k3}$). Therefore, the mechanical characteristics of an asynchronous generator that is constructed using analytical methods are significantly different from those constructed using experimental data.Based on these considerations, the generally accepted assumption that the parameters of the electrical equivalent circuit of the asynchronous machine are constant for the generator mode are unacceptable.For example, due to a change in the frequency of the current in the rotor winding over a wide range, the inductive scattering resistance of the rotor $x_2 = 2\pi f_2 \cdot L_2 = x_2(s)$ will not be a constant value.

This work aims to determine the analytical dependence of the mechanical characteristics of an asynchronous generator $M = f(\omega)$ by analyzing the distinctive features of equivalent circuits under various operating conditions associated with changes in the parameters of the primary energy carrier and the asynchronous machine itself. Moreover, when studying physical processes occurring in an asynchronous generator, simplifying the derivation of the analytical dependence of the electromagnetic moment using the developed AG equivalent circuit, we will accept the generally accepted assumptions that instead of a real asynchronous machine, we consider an idealized machine. Besides, we will take into account the fact that the energy flow in the asynchronous generator is directed from the rotor to the stator. Therefore, the parameters and variables of the rotor will be considered primary and denoted by the index "1", and the stator - secondary and denoted by the index "2".

It is known that the theory of asynchronous machines is based on the similarity of electromagnetic processes of asynchronous machines and transformers. Based on this, a system of equations of the voltages and currents of the stator and rotor is compiled, an equivalent circuit is built, an analytical expression of the electromagnetic moment and mechanical characteristics are determined. At the same time, as in transformers, it is necessary to bring the parameters of the rotor winding to the parameters of the stator winding by introducing the corresponding reduction factors.

In the process of deriving the equivalent circuit of an asynchronous generator, it is necessary to take into account the fact that the active power flow, unlike the motor mode, is directed from the rotor to the stator, and the reactive power, per revolution, is directed from the network (or from the compensating capacitor at the stator terminals) to the stator winding. We believe that the unchanged MDS of the reduced rotor winding is kept constant and real, we obtain the reduced current of the rotor winding

$$\dot{I}_1' = \dot{I}_1 \frac{m_1 w_1 k_{01}}{m_2 w_2 k_{02}} = \dot{I}_1 k_I , \tag{1}$$

wherem_1,m_2 – the number of phases of the rotor and stator windings; w_1, w_2 – the number of phases of the rotor and stator windings;k_{01}, k_{02} – winding coefficients of the rotor and stator windings.

We also believe that the magnetic flux in a machine with a given number of turns of the winding and with the actual number of turns will not change [7.8]

$$\Phi_m = \frac{\dot{E}_1}{4,44 w_1 k_{01} f_2} = \frac{\dot{E}_1'}{4,44 w_2 k_{02} f_2}, \tag{2}$$

we obtain

$$\dot{E}_1' = \dot{E}_1 \frac{w_2 k_{02}}{w_1 k_{01}}. \tag{3}$$

From the conditions for maintaining losses in the rotor

$$m_1 I_1^2 r_1 = m_2 (I_1')^2 r_2' \tag{4}$$

we find the reduced resistance of the rotor winding

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$$r_1' = \frac{I_1^2 m_1}{(I_1')^2 m_2} r_1 = \left(\frac{m_2 w_2 k_{02}}{m_1 w_1 k_{01}}\right)^2 \frac{m_1}{m_2} r_1. \quad (5)$$

From the condition of constant reactive power, we obtain the reduced inductive resistance of the rotor winding

$$x_1' = \frac{r_1'}{r_2} x_1 = x_1 \frac{m_1}{m_2}\left(\frac{w_2 k_{02}}{w_1 k_{01}}\right)^2. \quad (6)$$

Thus, it is possible to show the reduction factors for the rotor current from (1)

$$k_I = \frac{m_1 w_1 k_{01}}{m_2 w_2 k_{02}}, \quad (7)$$

coefficient of reduction for voltage and EMF from (3)

$$k_U = \frac{w_2 k_{02}}{w_1 k_{01}}, \quad (8)$$

and reduction coefficient for the active and inductive resistances of the rotor from (5) and (6)

$$k_Z = \frac{k_U}{k_I} = \frac{m_2 (w_2 k_{02})^2}{m_1 (w_1 k_{01})^2}. \quad (9)$$

From the theory of transformers and induction motors it is known that, according to the law of the total current, the magnetic flux Φ created by the joint action of the MDS of both windings. If we assume that the currents change according to a sinusoidal law, then we can write

$$\dot{I}_2 m_2 w_2 k_{02} + \dot{I}_1 m_1 w_1 k_{01} = \dot{I}_0 m_2 w_2 k_{02} \quad (10)$$

then, using the coefficient of current reduction can be replaced $I_1' = I_1 (m_1 w_1 k_{01} / m_2 w_2 k_{02})$ and get the equation of currents

$$\dot{I}_2 + \dot{I}_1' = \dot{I}_0 \quad (11)$$

where I_0 - magnetization current.

Such an equation is valid for a transformer and an asynchronous machine with a fixed rotor, in which the current frequency is equal. In an asynchronous generator, when the rotor rotates, the frequency of the secondary current is different by an order of magnitude. Although a method is presented in the literature for converting the amplitude values of the current and the EMF of the rotor winding to the current and the EMF of the stator winding, information on bringing the arguments of these functions is not presented. For this reason, the T-shaped equivalent circuit of an asynchronous machine presented in Fig. 2, a, based on the similarity of transformers, has not found practical application.

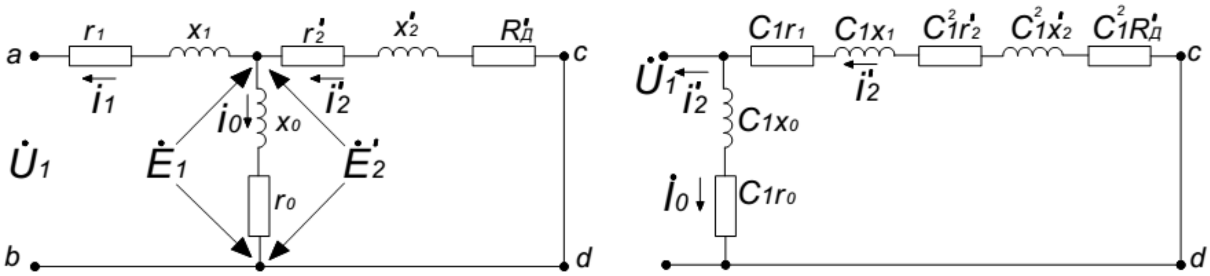

Fig. 2. T-shaped (a) and L-shaped (b) equivalent circuits of an asynchronous generator

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In an asynchronous generator, when the rotor speed changes, the analytical relationship between the frequency of the current and the EMF of the stator and rotor will be $f_1 = f_2 s$. Therefore, considering the magnetic flux unchanged, we can record the relationship between the EMF of the stator and rotor windings

$$E_2 = E_1' = 444 f_1 w_1 k_{01} \Phi_m . \tag{12}$$

Substituting the frequency value $f_1 = f_2 s$ to (12), we get the reduced current in the rotor of the generator, taking into account the reduction of the current argument

$$\dot{I}_1' = \frac{\dot{E}_{1s}'}{z_{1s}'} = \frac{s \cdot \dot{E}_1'}{r_1' + R_Д + js \cdot x_1'}, \tag{13}$$

where $z_{2s}' = r_2' + R_Д + js \cdot x_2'$

is the total reduced resistance of the rotor circuit to the stator circuit taking into account the reduction, both in amplitude and in the current argument.

Then in the calculations it will be possible to use the L-shaped equivalent circuit of the asynchronous generator (Fig. 2, b). In the equivalent circuit, the value

$$\dot{C}_1 = \frac{(r_2 + jx_2) + (r_0 + jx_0)}{r_0 + jx_0} \tag{14}$$

is a complex coefficient.

The electromagnetic moment of an asynchronous generator is created as a result of the interaction of the rotor winding current with a rotating magnetic flux. In steady state, when the rotor speed is constant $n = const.$, turbine power applied to the shaft P_1 balanced by electromagnetic moment M , which is a moment of resistance and is developed by an asynchronous generator. Derivation of the analytical expression of the electromagnetic moment in the slip function $M(s)$ can be implemented in several ways, one of which can be determined if the mechanical power is known P_1 turbines or rotor electrical losses $p_{эл.1} = s \cdot P_1$

$$M = \frac{P_1}{\omega_c} = \frac{p_{эл.1}}{s\omega_c} = \frac{m_1 r_1' (I_1')^2}{s\omega_c}, \tag{15}$$

where ω_c - synchronous angular velocity of the rotating magnetic flux of the machine. From the L-shaped equivalent circuit, we determine the rotor current reduced to the stator

$$I_1' = \frac{U_2}{\sqrt{\left[c_1 \frac{r_1'}{s} + c_1 R_Д + r_2\right]^2 + \left[x_2 + c_1 x_1'(s)\right]^2}}. \tag{16}$$

Substituting (16) into equation (15), we define

$$M = \frac{m_1 U_2^2 r_1'}{s\omega_c \left[\left[c_1 \frac{r_1'}{s} + c_1 R_Д + r_2\right]^2 + \left[x_2 + c_1 x_1'(s)\right]^2\right]} \tag{17}$$

Thus, in an asynchronous generator, in contrast to the motor mode, the analytical dependence of the electromagnetic moment has an inductive scattering resistance of the rotor winding, which varies significantly with sliding changes due to changes in the frequency of the rotor current. In addition, the additional resistance in the rotor

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circuit $R_Д$, included in the denominator of equation (17) leads to a decrease in the magnitude of the electromagnetic moment.

To determine the maximum moment and critical slip corresponding to this maximum, we carry out a mathematical analysis of function (17). For this, it has been assumed that all quantities in (17) are constant, except M and s , although we know that the inductive scattering resistance of the rotor winding depends on the slip frequency. Then equating to zero the derivative of the moment with respect to the slip, we find the critical slip s_k , and maximum torque, which differ from similar functions of the motor mode only by the presence of a variable $x_1'(s)$.

Thus, the mechanical characteristics of the asynchronous generator constructed from the derived analytical dependence (17) (thin lines in Fig. 1) are close to coinciding with the curves constructed from the experimental data (broken lines).However, the characteristics calculated by the approximate method - without taking into account the dependence $x_2'(s)$, significantly diverge from the experimental characteristics (thick lines in Fig. 1).

To determine reliable calculations of the desired curves, studies were carried out to analyze the function (17) using a mathematical model and using the Matlab computer program. Comparisons of the solution of dependence (17) with allowance for variable inductive scattering resistance on a PC at various constant values of additional resistance with experimentally measured mechanical characteristics of an asynchronous generator showed their similarity. The error was not more than 5%. As an object of study, an induction motor with a power of 2.2 kW and a synchronous speed of 1000 rpm was adopted. MTF012-6 series.

II.CONCLUSION

The constructed L-shaped scheme of an asynchronous generator, although similar in structure to a resembling equivalent circuit of the motor mode, however, it differs significantly in that the inductive scattering resistance of the rotor winding is not constant with a wide change in the parameters of the primary energy source.

Since the inductive scattering resistance of the rotor winding is a function of the rotor current frequency, which must vary over a wide range, the experimental mechanical characteristics of an asynchronous generator are significantly different from the mechanical characteristics constructed by the known method.

The mechanical characteristics based on the proposed analytical dependence of the electromagnetic moment slightly differ from the experimentally measured characteristics.

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