Power Losses Of Asynchronous Generators Based On Renewable Energy Sources

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Abstract. This article discusses the possibility of using asynchronous generators in wind turbines, in particular asynchronous generators with phase rotors, in parallel with the network. Currently, due to the decrease in non-renewable energy sources around the world, the use of renewable energy sources, especially wind energy, is being considered. Also in this article, the power losses and energy balance of asynchronous generators with a phase rotor, all losses in an asynchronous generator, its efficiency, and torque are considered. In addition, a functional diagram of an asynchronous generator in a wind turbine has been developed, as have methods for simplifying calculations due to the generator substitution scheme. Due to this, methods for calculating the impedance of an asynchronous generator are given. With the help of an experimental research stand, the state of a number of parameters was analyzed during the parallel operation of an asynchronous generator with a phase rotor and a network. Taking into account that the indicators of the wind potential of land plots identified for the construction of wind turbines in Uzbekistan are higher than the average indicators of existing wind turbines in the world, it is assumed that the use of asynchronous generators in wind farms in the near future is considered promising.

1. Introduction

Renewable energy sources can technically be used by any type of generator, such as DC or AC, where AC generators can be either synchronous or asynchronous type. Today, DC machines can only justify themselves for small power plants since their relatively large power requires maintenance, and a relatively low efficiency factor is also calculated [1-3]. There are modern designs based on permanent magnets, but they are also used in low power ranges. In power plants based on small renewable energy sources, this is mainly applied to asynchronous machines, as they are easy to maintain and yet considered cost-effective compared to other types of machines. They are also easy to use with high-power power systems since the power grid itself regulates voltage and frequency [4-5]. On the other hand, static and reactive compression capacitors can be used for power factor correction and harmonic reduction. Since asynchronous generators are important for use in small hydropower and wind farm systems, we summarize a detailed discussion that will allow you to understand how to use this electric machine. Induction machines work well as both motors and generators; they have a very robust construction that provides natural protection against short circuits, making them the cheapest generators available. Lack of synchronism in synchronous generators can cause frequency fluctuations and instability in the power systems to which they are connected. In the future, it will be possible to carry out a large-scale popularization of asynchronous generators by combining the control system and engineering work [6-7]. Currently, due to the reduction in the use of non-renewable energy sources, the use of renewable energy sources, especially wind energy, is developing worldwide. In recent years, Uzbekistan has been paying serious attention to the construction of wind farms and other renewable energy sources. This direction remains the most dynamically developing in the energy sector. Considering that the number of water sources in the Central Asian region is decreasing, it is important to further accelerate the use of this type of alternative energy [8-9].

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The "Concept of Electricity Supply of the Republic of Uzbekistan" was developed for 2020-2030. It set as one of the main goals the construction of 3,000 MW of power plants in the Republic by 2030.

It can use generators of direct current and alternating current (asynchronous and synchronous). The use of asynchronous generators in the near future in hydroelectric power plants as alternators is considered very promising.

Wind potential indicators on land plots identified for the construction of their HPPs in Uzbekistan are considered to be higher than the average for existing HPPs in the world. That is, when comparing the energy consumption coefficients, it turns out that the Republican indicators are 1.5 times higher than the world average [10-13].

2. Materials and Methods

The asynchronous generator has the same design as induction motors, whose efficiency can be improved by changing their design. An important difference in performance is that the rotation speed of the rotor is greater than the rotation of the stator magnetic field. Quantitatively, if the asynchronous mechanical speed n_s is equal to f_s at the synchronous frequency, the resulting electrical power is determined by the induced voltage, which is proportional to the relative speed difference between the synchronous rotation and the mechanical rotation range. The slip coefficient is determined using the expression for it [14-16]:

$$s = \frac{n_s - n_r}{n_s} \tag{1}$$

Here s - is the slip coefficient and n_r - is the rotor speed (rpm). The current stator frequency at the output is equal to f_s, the rotor frequency will be related to the current frequency through f_r [14, 15]:

$$f_s = \frac{p}{120}(n_s - n_r)\frac{n_s}{n_s} = sf_s \tag{2}$$

When there is no relative difference between the rotor and stator speeds, the rotor speed is constant. At a different angular velocity, quantitatively, the voltage created in the rotor is exactly proportional to the slip coefficient s, through which it is transmitted to the stator windings. Based on this definition, E_{r0} is set in the rotor with respect to the voltage for any speed of rotation of the rotor excited by the induced E_r; those

$$E_2 = E_r = sE_{r0}$$

Using the conversion factor, the voltage across the stator is equal to the voltage across it.

$$E_1 = a_{rms}\frac{E_r}{s} \tag{3}$$

In the same way, the rotor current is equal to the current.

$$I_2 = \frac{I_r}{a_{rms}}$$

and

$$Z_r = \frac{E_r}{I_r} = \frac{sE_{r0}}{I_r} = R_r + jsX_{r0} \tag{4}$$

Based on this expression, it will be possible to express the impedance of the rotor circuit for any rotor speed.

$$Z_{r0} = \frac{E_{r0}}{I_r} = \frac{R_r}{s} + jX_{r0} = \frac{Z_r}{s} \tag{5}$$

here X_{r0} - is the inductive resistance of the rotor coil and R_r - is the active resistance of the rotor coil

$$Z_2 = a_{rms}^2\left(\frac{R_r}{s} + jX_{r0}\right) \tag{6}$$

Depending on the parameters of the stator, the rotor resistance will be equal to the resistance.

$$Z_2 = \frac{E_1}{I_2} = \frac{R_2}{s} + jX_2 \tag{7}$$

Equivalent to rotor current:

$$I_2 = \frac{E_1 s}{R_2 + jX_2 s} \tag{8}$$

In asynchronous machines, the voltage induction is similar to that of a transformer, except that it is the part that rotates like the secondary windings of the transformer. Since there is an air gap in electrical machines, a magnetic connection is formed between the primary and secondary windings [15]. The slope of the magnetic coupling curve is much smaller than that of a transformer. Therefore, the saturation of an induction generator is much less, resulting in a much higher magnetizing current compared to a transformer. Rotor power at variable speeds can also be expressed by equations (5) and (6).

$$S_2 = E_1 I_2 = I_r^2\left(\frac{R_r}{s} + jX_{r0}\right)$$

or

$$S_2 = \frac{E_1^2 s}{R_2 + jX_2 s}$$

As can be seen from these expressions, the power factor of the rotor of an asynchronous generator does not depend on the load, but on the slip coefficient and other parameters. The square value of the fundamental current (relative to voltage) of the output terminals will be almost constant for voltage and for all given frequencies. Thus, the reactive power obtained according to this scheme is supplied from an external source through a synchronous generator, capacitor banks or power compensators, with the help of which the reactive power of the electrical network is condensed.

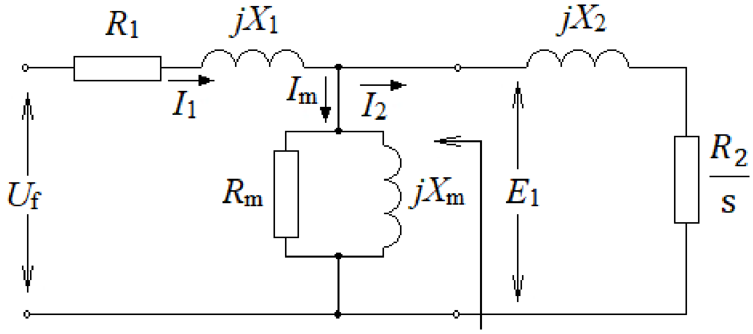

Fig. 1. Equivalent model of the induction generator

$$Z = R_1 + jX_1 + \frac{1}{\frac{1}{jX_m} + \frac{1}{R_m} + \frac{1}{(R_2/s) + jX_2}} \tag{10}$$

It is convenient to use a switching circuit to simplify the analysis and facilitate the calculation formula in the process. Thus, the total resistance of the asynchronous generator can be determined as follows:

$$Z_1 = R_1 + jX_1, \;\; Z_2 = \frac{R_2}{s} + jX_2, \;\; Z_m = \frac{1}{1/R_m + 1/jX_m} \tag{11}$$

The power balance of an asynchronous generator can be expressed as follows.

$$P_{out} = P_{in} - P_{losses} \tag{12}$$

Total waste can be expressed in terms of all energy waste:

$$P_{losses} = P_{copper} + P_{iron} + P_{f\&w} + P_{stray} \tag{13}$$

The waste copper in the stator is straight and P_{stCu} ¼ I2 1R_1 is obtained Magnetic core losses are caused by hysteresis losses, that is, remagnetizing and grinding currents, the current that occurs in the magnetic core. It should be noted that the magnetic losses in the stator and rotor are usually calculated and generalized by experimental methods. It is very difficult to distinguish between their shares. Therefore, the waste resistance P_M in the switching circuit of an induction generator is almost all of this waste combined with mechanical waste. This waste includes frictional waste as good as additional waste caused by the movement of the rotor in relation to the air.

$$P_{stCu} = 3I_1^2 R_1 \tag{14}$$

The amount of loss in the magnetic core is determined by:

$$P_{iron} = \frac{3E_1^2}{R_m} \tag{15}$$

The only possible dissipation of power (active power) in the second part of the circuit shown in Figure 1 is due to the resistance of the rotor; hence,

$$P_g = 3I_2^2 \frac{R_2}{s} \tag{16}$$

However, the rotor waste from the switching circuit shown in Figure 1 is in active resistors.

$$P_{rCu} = 3I_r^2 R_r \tag{17}$$

In any ideal machines without losses, the power of the rotor remains unchanged with respect to the stator, and therefore, from equations (16) and (17),

$$P_{rCu} = 3I_2^2 R_2 = sP_g \tag{18}$$

The energy converted into electricity is subsequently produced in the form of mechanical parts, copper, core and other waste. All of them can be expressed as follows

$$P_{losses} = P_{stCu} + P_{rCu} + P_{iron} + P_{f\&w} + P_{stray}$$

Using equations (14) and (18), the copper waste in the stator and rotor can be expressed as follows.

$$P_{copper} = 3I_1^2(R_1+R_2) = \frac{3U_\Phi^2(R_1+R_2)}{(R_1+R_2/s)^2+F^2(X_1+X_2)^2} \tag{19}$$

The mechanical power converted into electrical or electrical power under negative slip is the difference between the power generated in the rotor passing through the air space and the power dissipated in the rotor [4-6]. Equations (16) and (18) can be expressed as follows.

$$P_{mech} = 3I_2^2\frac{R_2}{s} - 3I_2^2R_2$$

This expression, after simplification, will look like:

$$P_{mech} = 3I_2^2R_2\frac{1-s}{s} = (1-s)P_g \tag{20}$$

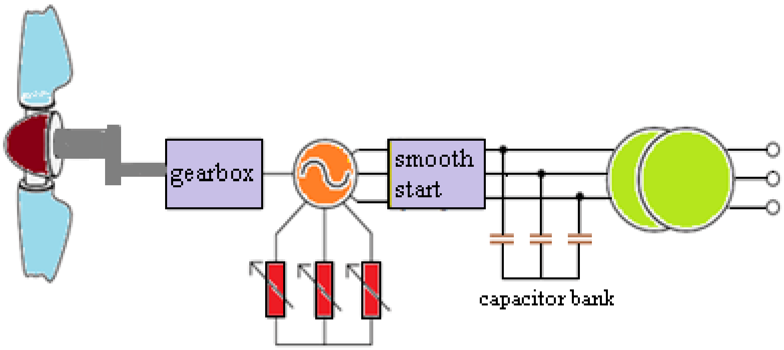

Fig. 2. Functional diagram of an asynchronous generator with a phase rotor

It is necessary to take into account how the frequency affects the parameters of the asynchronous generator. These differences are used to determine the parameter associated with the unit frequency.

$$F = \frac{f}{f_{meas}} = \frac{\omega}{\omega_{meas}} = \frac{p}{120}\frac{n_r}{60} \tag{21}$$

here f; ω – operating frequency (Hz and rad/s, respectively), f_{meas}, ω_{meas} – frequency of the parameter as a result of measurement (Hz and rad/s, respectively), p – number of machine poles, n_r – rotor speed (rpm). The correction of machine values to obtain laboratory test parameters at frequencies other than the operating frequency using F is considered very important when using the induction generator model.

Because the excitation resistance is much greater than the pulling resistance, usually the induction generator model is provided with a separate waste resistance; RL pulses are injected into the generator output terminals to represent normal load. From Figure 2, we see that when an inductive charge is connected to the generator, we will see a decrease in the capacitance value in the process of self-excitation, since part of the reactive power is compensated by the reactive charge. The determination of the effective capacitance value is carried out according to the following equation:

$$C_{eff} = C - \frac{L}{R_L^2+(\omega_s L)^2} \tag{24}$$

From this equation, we can conclude that how small the load inductance L will be, it will practically not affect C_{eff}. However, at large values of the load inductance L, this inductance becomes important for the output voltage. Because the slope of the straight line of capacitive response is almost close to the straight part of the excitation curve (air gap line). Dramatically reduces the voltage drop at the output ends of the generator. The advantage of this system is that if the load resistance is too low, the self-excited capacitor discharges very quickly, providing natural protection against high currents and short circuits. On the other hand, higher capacitance self-excitation values will be limited by magnetic groove saturation. In the case of high saturation, the point of intersection on the straight line of capacitive reactance corresponds to very large currents for the generator. As a result, a large circular current passes through the chimney, and the magnet can severely damage the insulation and magnetic properties of the chimney. Applying the basic principles of power balance, this allows one to obtain equations (25) and (26) of the active and reactive power equalizer from Figure 2:

$$I_2^2R_2\frac{1-s}{s} + I_2^2(R_1+R_2) + \frac{U_\Phi^2}{R_m} + \frac{U_\Phi^2}{R_{Lp}} = \sum P = 0 \tag{25}$$

$$\frac{U_\Phi^2}{X_p} + \frac{U_\Phi^2}{X_m} - \frac{U_\Phi^2}{X_c} + \frac{U_\Phi^2}{X_{Lp}} = \sum Q = 0 \tag{26}$$

here $X_m = wsL_m$ R_{Lp} and X_{Lp} are parallel equivalent terminating resistors and reactance resistors connected to the generator output ends. To evaluate the performance of asynchronous generators, it must be taken into account that the only power entering the circuit is the power from the main machine in the form of active power, which is given by equation (25). The reactive power must also be in balance, as in equation (26). (25) The first part of the equation is the energy supplied to the generator through the mechanical shaft. s_1 or s_0 in the first part are reversed and respectively represent the generator or braking mode of the asynchronous machine. Dividing equation (25) by, after simplification we obtain.

$$(\frac{R_2}{s} + R_1 + \frac{U_\Phi^2}{I_2^2}\left(\frac{1}{R_m} + \frac{1}{R_{Lp}}\right) = 0 \tag{27}$$

From figure 4, the following expression is obtained

$$\frac{U_\Phi^2}{F^2 I_2^2} = \left(\frac{R_2}{Fs} + \frac{R_1}{F}\right)^2 + (X_1 + X_2)^2 \tag{28}$$

Using equation (27), one can obtain the expression.

$$\left(\frac{R_2}{s} + R_1\right)R_{mL} + \left(\frac{R_2}{s} + R_1\right)^2 + F^2(X_1 + X_2)^2 = 0 \tag{29}$$

Using equation (29) of the second level and equation (30), taking into account the unchanged parameters, the slip can be calculated as follows:

$$s = \frac{2R_2}{-2R_1 - R_{mL} \pm \sqrt{R_{mL}^2 - 4F^2(X_1 + X_2)^2}} \tag{30}$$

The root values of the denominator in equation (30) are always negative to satisfy the practical condition, if X_1 and X_2 are too small, loading R_{mL} has almost no effect on s, then the constraint is invalid. Thus, equation (30) can be expressed as:

$$s \cong -\frac{R_2}{R_1 + R_{mL}} = -\frac{R_2(R_m + R_{Lp})}{R_1 R_m + R_1 R_{Lp} + R_m R_{Lp}} \tag{31}$$

The iterative method can be used when using equation (30) instead of equation (31), the efficiency factor can be expressed as.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{losses}}{P_{in}} \tag{32}$$

R_1 and R_2 must be removed due to the mechanical power of the inlet, rust resistance, and loss of R_m magnetic resistance. Using equation (28), with equations (12) and (25) for the three-phase state, the load capacity is as follows, as in the expression corresponding to ($R_{Lp} \to \infty$).

$$P_{inx} = P_{in} - P_{losses} = 3I_2^2 R_2 \frac{1-s}{s} + 3I_2^2(R_1 + R_2) + \frac{3U_\Phi^2}{R_m}$$

where $P_{in} = 3I_2^2 R_2[(1-s)/s]$. Using these values, it becomes possible to express equation (32) in the following form

$$\eta = \frac{I_2^2 R_2[(1-s)/s] + I_2^2(R_1 + R_2) + U_\Phi^2/R_m}{I_2^2 R_2[(1-s)/s]} \tag{33}$$

By dividing the image and the denominator of equation (33) byI_2^2 (28), it becomes possible to express the equation in the following form.

$$\eta = \frac{[(R_2/s) + R_1] + 1/R_m\left[\left((R_2/s) + R_1\right)^2 + F^2(X_1 + X_2)^2\right]}{R_2[(1-s)/s]} \tag{34}$$

In electrical machines, in the transformation of electrical energy into mechanical energy or mechanical energy into electrical energy, part of the energy is wasted by turning it into thermal energy and heating parts of electric machines. It is for this reason that their useful power will be less than that given to it.

3. Results and Discussion

From there – magnetization of the electrical machine magnetic system, the magnetic wastes ($P'_{ed.cur.} \equiv (f \cdot B_{max} \cdot \Delta)^2$ Δ – thickness of steel sheet) are generated in its main parts, which are converted to heat, due to the phenomenon of grinding currents ($P'_{his} \sim f \cdot B_{max}^2$), in which the thickness of the coil-steel list) and the hysteresis (P'_m). Alternating current machines change in proportion to the square (U^2) of the voltage given by the main wastes in the steel core.

Accounting for wastes in steel as a value proportional to the square of magnetic induction leads to large errors, since such a connection is valid only for an unsaturated chain.

When analyzing the dynamic modes of an asynchronous machine, it is the most effective to apply the full differential equations of an asynchronous motor, obtained on the basis of the theory of General Electric machines. In this case, it becomes easier to calculate the nonlinearity.

To research the dynamics of the asynchronous machine, it is necessary to highlight the tasks that take into account the saturation of the machine magnetic chain, since the saturation of the machine steel plays an important role in the formation of torque curves and wastes in the start-up and brake modes. The dynamic modes and duration of the start-up and braking processes actually determine the dimensions, cost, reliability and efficiency of the power transmission used for many manufacturing enterprises and technologies.

A significant increase in the magnetic flux of the machine leads to an increase in the degree of saturation of its magnetic chain. Therefore, ignoring waste in steel leads to significant errors in determining braking moments.

The purpose of the study is to calculate the waste in steel using the exact model of the asynchronous machine, taking saturation into account, and compare it with experimental data.

The asynchronous machine was modeled, and wastes in steel were calculated in relative units, taking into account saturation. Wastes in steel are determined according to the following expression:

$$\Delta P_{st} = \Delta P_{s50} f^2$$

Here, in the case of experimental curves at a frequency of ΔP_{s50} – 50 Hz, Figure 1, es shown in a waste associated with EDF. The experimental dependence of E_{s50} on the magnetization current is calculated by approximating it using polynomials of Least Squares.

The experimental and computational values of the magnetization curve are given in relative units (r.u.) in Table 1 and the graph in Figure 3.

Table 1. The value of the experimental and computational values of the magnetization curve in relative units

$I_{\mu(r.u.)}$	0,1	0,2	0,3	0,45	0,6	1	1,5
$E_{exp(r.u.)}$	0	0,3	0,8	1,05	1,2	1,35	1,4
$E_{comp(r.u.)}$	0,2	0,45	0,7	0,95	1,15	1,38	1,35

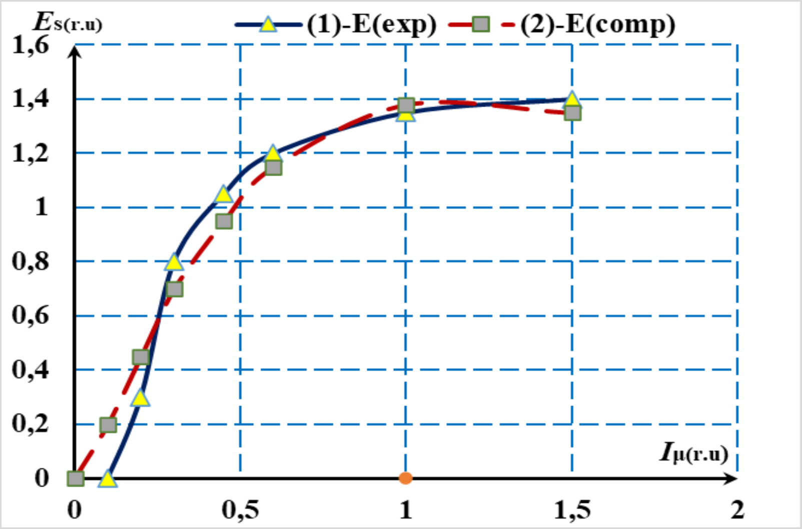

Fig. 3. Magnetization curves: 1-experimental, 2-computational

Likewise, the experimental and computational values of wastes in steel are given in relative units in Table 2 and the line graph of wastes in steel in Figure 4.

Table 2. The experimental and computational values of wastes in steel are the value in relative units

$E_{s(r.u.)}$	1	1,1	1,2	1,3	1,4	1,5	1,6	1,7
1 - $P_{exp(r.u.)}$	0,1	0,11	0,12	0,15	0,22	0,4	0,8	1,05

2-$P_{\text{comp(r.u.)}}$	0,12	0,11	0,11	0,13	0,17	0,32	0,88	1,1

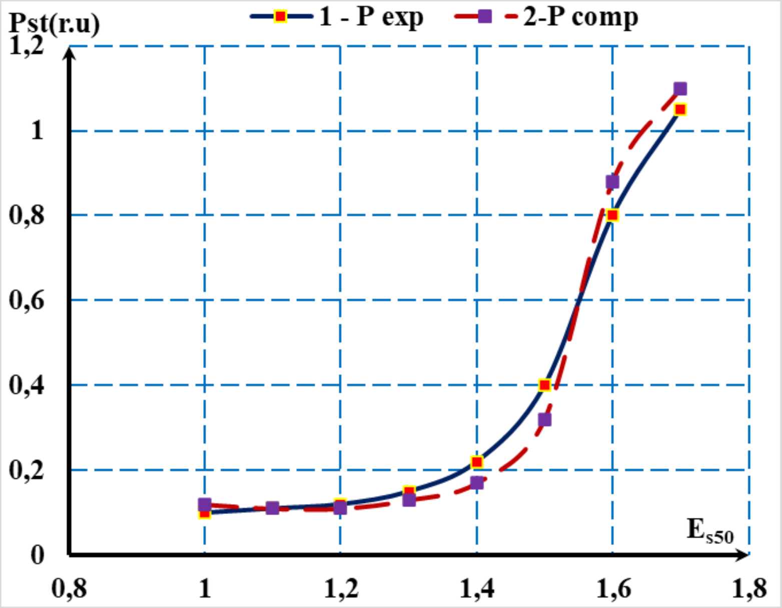

Fig. 4. Steel losses: 1-experimental, 2-computational

The most convenient model when considering saturation is variable rotor flow coupling and stator current. The equation of the asynchronous machine non-linear model, taking into account the variable saturation in the direction of the main magnetic flux, is written as:

$$\begin{gathered}
i_{s\alpha}p=\frac{1}{x_{\sigma s}}\left[u_{s\alpha}-(r_s-r_r)i_s+r_r\frac{1}{x_m}\psi_{m\alpha}+\omega_r\psi_{m\beta}\right]\\
i_{s\beta}p=\frac{1}{x_{\sigma s}}\left[u_{s\beta}-(r_s-r_r)i_{s\beta}+r_r\frac{1}{x_m}\psi_{m\beta}+\omega_r\psi_{m\alpha}\right]\\
-\psi_{m\alpha}p=r_r\frac{1}{x_m}\psi_{m\alpha}-r_ri_{s\alpha}-\omega_r\psi_{m\beta}\\
-\psi_{m\beta}p=r_r\frac{1}{x_m}\psi_{m\beta}-r_ri_{s\beta}-\omega_r\psi_{m\alpha}\\
\frac{1}{x_m}=f\left(\psi_m^2\right);\qquad \psi_m^2=\psi_{m\alpha}^2+\psi_{m\beta}^2;
\end{gathered}\tag{35}$$

4. Conclusions

The power factor of the asynchronous generator rotor is calculated not depending on the load but on the slip coefficient and other parameters. The square organizers of the main current (relative to the voltage) and the output clamps will be almost constant for the voltage and for all specified frequencies. Thus, the reactive power obtained through this circuit is supplied from an external source via a synchronous generator, capacitor batteries, or power compensators, through which the electrical network's reactive power condensation is carried out.

Power 2,2 kW for a 4MTH 012-6 U1 type asynchronous machine, waste in steel at nominal magnetic flux is 47 W. If saturation is not taken into account with a 1,5-fold increase in flow, the wastes increase by 2,25 times and are 109 W. Accounting for waste in steel proportional to the square of magnetic induction leads to a large error. The use of approximations using polynomials of least squares makes it possible to accurately calculate the wasted curves in steel, both in the experiment and in the modeling.

It can be concluded that no matter how small the load inductance L is, it does not greatly affect Sef. However, at large values of the load inductance L, this inductance becomes important for the output voltage. Because the slope of the straight line of capacitive response is almost close to the straight part of the excitation curve (the air gap line). Dramatically reduces the voltage drop at the output ends of the generator. The advantage of this system is that if the load resistance is too low, the self-excited capacitor discharges very quickly, providing natural protection against high currents and short circuits. On the other hand, higher values of self-excitation of the capacitance will be limited by the saturation of the magnetic circuit.

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