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doi:10.15199/48.2024.08.50

Optimization of the Design of an Electromagnetic Slip Clutch for a Wind Power Plant

***Abstract**: The present article addresses issues and resolutions pertinent to the utilization of electromagnetic slip clutches (ESC) in the context of wind energy applications. Wind generators, recognized for their environmental sustainability and renewable energy contributions, are widely employed for electricity generation. Nonetheless, the inherent variability in wind speed poses a persistent challenge, resulting in dynamic torque fluctuations on the wind generator shaft. To mitigate the impact of fluctuating wind speeds and regulate excess power on the rotor, electromagnetic slip clutches featuring a substantial armature are frequently employed. Conventional designs of electromagnetic slip clutches, as well as established research methodologies, encounter challenges, particularly when striving to optimize these clutches with respect to technical and economic criteria. In this article, a novel approach to optimal design is proposed, grounded in a mathematical technique known as fractional factorial experimental design. Furthermore, the utilization of a regression equation is recommended to enhance the precision of describing dependencies between various ESC parameters. An algorithm and program in Workspace/MATLAB have been developed to solve systems of regressive equations.This approach holds the potential to significantly enhance the optimization process of electromagnetic clutch design by accommodating diverse technical and economic constraints.*

***Streszczenie**: W artykule omówiono zagadnienia i rozwiązania związane z wykorzystaniem elektromagnetycznych sprzęgieł ślizgowych (ESC) w kontekście zastosowań energetyki wiatrowej. Generatory wiatrowe, znane ze swojego zrównoważonego rozwoju dla środowiska i wkładu w energię odnawialną, są szeroko stosowane do wytwarzania energii elektrycznej. Niemniej jednak nieodłączna zmienność prędkości wiatru stanowi ciągłe wyzwanie, powodując dynamiczne wahania momentu obrotowego na wale generatora wiatrowego. Aby złagodzić wpływ zmiennych prędkości wiatru i wyregulować nadmiar mocy na wirniku, często stosuje się elektromagnetyczne sprzęgła poślizgowe o solidnym tworniku. Konwencjonalne konstrukcje elektromagnetycznych sprzęgieł poślizgowych, a także ustalone metodologie badawcze napotykają wyzwania, szczególnie przy dążeniu do optymalizacji tych sprzęgieł pod względem technicznym i ekonomicznym. W artykule zaproponowano nowatorskie podejście do projektowania optymalnego, oparte na technice matematycznej znanej jako frakcyjny plan eksperymentalny. Ponadto zaleca się stosowanie równania regresji w celu zwiększenia precyzji opisu zależności pomiędzy różnymi parametrami ESC. Opracowano algorytm i program w programie Workspace/MATLAB do rozwiązywania układów równań regresywnych. Podejście to może znacznie usprawnić proces optymalizacji projektowania sprzęgła elektromagnetycznego poprzez uwzględnienie różnorodnych ograniczeń technicznych i ekonomicznych. (**Optymalizacja konstrukcji sprzęgła poślizgowego elektromagnetycznego dla elektrowni wiatrowej**)*

Keywords: *wind-electric installation, electromagnetic slip clutch, electromagnetic torque, factorial experimental planning, optimization..*
Słowa kluczowe: instalacja wiatrowo-elektryczna, elektromagnetyczne sprzęgło poślizgowe, moment elektromagnetyczny, czynnikowe planowanie eksperymentów,optymalizacja.

Introduction

By the year 2050, the proportion of renewable energy sources within the overall volume of primary energy supplies is projected to rise from the 14% recorded in 2015 to 63% [1-3]. A substantial portion of this energy is derived from wind power plants (WPP). The advantages and drawbacks associated with harnessing wind energy are widely acknowledged. Based on the generated power, wind installations are categorized into distinct groups: low-power wind turbines, medium-power wind turbines, and high-power wind turbines. Each of these groups exhibits unique operational characteristics. Typically, most wind turbine manufacturers design their products to attain rated power at a wind speed of (10-12) m/s. However, wind speeds exhibit significant fluctuations and adhere to a stochastic pattern. Consequently, the dynamic torque acting on the wind generator shaft undergoes periodic changes.

When the wind speed exceeds a certain threshold, it becomes imperative to curtail the power transmitted to the wind turbine rotor. Presently, various methods exist for limiting power on a wind turbine rotor. One effective approach to attenuating undesired dynamic processes involves the utilization of an electromagnetic slip clutch (ESC) with massive armature in wind power plants (WPP). The application of ESC has been explored in several studies [4-7]. These clutches facilitate efficient energy transfer from the rotating shaft to the generator, exhibiting compatibility with high rotation speeds typical of wind generator components. ESC possesses the capability to mitigate speed variations and vibrations, thereby contributing to a more stable power generation process. This functionality offers overload protection, averting potential equipment damage arising from abrupt load changes.

Statement of a question

As evident from the foregoing discussion, supplying an electric generator with the requisite electromagnetic torque during a sudden alteration in wind speed poses a challenging endeavor. The operational history of electromagnetic slip clutches (ESC) reveals that, contingent upon the technical and technological specifications of the production mechanism, a myriad of issues arises in achieving the desired performance characteristics. Overcoming these challenges is crucial for enhancing the technical and economic efficiency of the facility without necessitating the incorporation of supplementary technical devices. In many instances, it is imperative for the ESC to exhibit a rigid mechanical characteristic and a sufficiently high torque value at low slip values, particularly in applications such as wind power.

It is well-established that designing and studying ESC operating modes, considering variations in magnetic permeability, electrical resistivity of steel, edge effects, and hysteresis losses, using traditional methods based on Maxwell's equations [6] or the method of equivalenting a massive magnetic circuit with lumped circuits [7], poses significant challenges, even with the aid of computers. These challenges are particularly exacerbated when optimizing such machines based on technical and economic criteria.

The quest for an optimal solution has traditionally relied on a comparative analysis of various design options, leading to difficulties in unequivocally determining the global optimum during ESC design. Optimal design represents a qualitatively new approach to machine calculations, wherein a combination of geometric dimensions and electromagnetic loads is sought to satisfy the fundamental requirements for the ESC.

Considering that electromagnetic processes in machines with a massive magnetic core are complex for mathematical analysis and require precise consideration of factors such as the configuration of the magnetic system, the reaction of a massive steel armature, the edge effect, etc., optimal design should be based on the mathematical foundations of theory and synthesis methods. Without this search for the best option would be impossible [8, 9]. Considering that existing research in the field of electromagnetic system design has been carried out using various methods, the generalization of the optimal design method, which is the subject of this work, becomes important. The optimization problem is formulated in accordance with specific technical requirements.

The design specification includes the maximum electromagnetic torque that the coupling must generate at a given speed of rotation of the wind wheel (drive part).

Problem setting

Torque and the same operating conditions, several versions of the machine can be developed. In other words, its main optimized characteristics are determined by combinations of various variable factors x_i, belonging to hyperspace *A*.

$$x_1, x_2 x_3, ...x_n, \in A$$

For ESC, such factors are the diameter of the massive armature *D*, the number of pairs of poles of the inductor *p*, the active length of the armature *l*, the induction in the air gap in idle mode B_0, the design and material of the active part of the armature. In this case, the problem under consideration can be analytically described by a series of linear or nonlinear equations that establish the relationship between the optimized parameters and characteristics with variable quantities.

(1) $$F_j = f(x_1, x_2, x_3, ..., x_i)$$

where, $i = 1,2,3,....n;\ j = 1,2,3,....m$.

Combinations of variables x_i that satisfy condition (1) belong to the set M located inside the hyperspace A. When composing equations in the form (1), the number of variables x_i that describe the characteristics of ESC may be greater than the number of equations. Therefore, within the set, a large number of machine states are obtained that satisfy the given technical conditions.

The optimal option is determined by a quantitative assessment of the selected optimality criterion, which is usually written in many cases in the form of a functional dependence on the accepted variables and determines the technical and economic characteristics.

(2) $$k = f(x_1, x_2, x_3, ..., x_n)$$

When designing, the choice of one or another optimality criterion is explained by the specific features of the task at hand. Unlike conventional electric machines, ESC cannot be characterized by unambiguous parameters such as rated power and rotation speed. Since the ESC is installed between the wind wheel and the generator, the transmission of a certain torque can be carried out at different rotation frequencies. It follows that an individual ESC is characterized by its mechanical characteristic $M = f(s)$. Considering that these machines are simple in design, relatively cheap and reliable in operation, these factors can be taken as limitations when choosing an optimality criterion.

Thus, when designing these special machines, as an optimality criterion, it is advisable to take the necessary form of mechanical characteristics that satisfies the technological requirements of the production mechanism (in this case, an electric generator). As a constraint of the first kind, we take the minimum reduced production costs in the form:

(3) $$\sum C = k_n C_m + C_O = \min$$

where, k_n is the coefficient of return on capital investments in sum with the coefficient of depreciation and the coefficient of maintenance and repair costs: C_m - price of the car; C_O - operating costs.

Mathematical model

After specifying the optimality criteria, a calculation method and program are needed to conduct the search. It is known that the electromagnetic torque ESC significantly depends on the geometric dimensions and other electromagnetic parameters. These dependencies are complexly nonlinear and are determined as a result of the full scope of machine design. Some issues of compiling design algorithms are equipped with. Currently, there are several mathematical programming methods that are successfully used to optimize electrical machines [10-12].

From the above it follows that it is of great relevance to determine a convenient form of expression for the electromagnetic moment depending on all the main factors and solve optimization problems on its basis. Such an expression $M = f(s)$ can be a regression equation [15, 16]:

(4) $$M = b_0 + b_1 x_1 + b_2 x_2 + ... + b_n x_n + b_{12} x_1 x_2 + ... + b_{1n} x_{1n} + ...$$

where $x_1, x_2, ...x_n$ are independent variable factors.

The main advantage of (FDE) is that with a minimum number of experiments (calculations) at pre-planned points, it provides a fairly complete picture for assessing the object under study. The geometric and electromagnetic parameters of the machine are taken as a factor, which significantly influence the magnitude and formula of the electromagnetic moment.

We have accepted the following factors: length of the armature and pole core l_z; electrical resistivity of steel ρ; air gap induction B_{1mo}; at idle, the degree of induction reduction k_1, the factor taking into account the armature gearing α. All these factors vary based on their base values within a certain range. Note that slip is not included among the factors in any other form. It is carried out in discrete values, for example, s=0.05; 0.1; 0.2; 0.5; 1 and regression equation (4) are determined for each slip value. We used a fractional factorial experiment (FFE) [15, 17], which allows us to reduce the number of experiments to $N=2^{n-1}=16$. The above analysis shows that triple or higher order interactions of factors can be neglected due to their smallness. Based on the above, a matrix for conducting experiments was compiled (Table 1).

All 16 experiments were carried out and calculations of the electromagnetic moment were made for all sixteen elements of the planning matrix using the full design algorithm. Based on these calculations, all coefficients of the regression equation were determined:

(5) $$b_{ij} = \sum_{i,j=1}^{N} M_{ij} x_{ij} / N$$

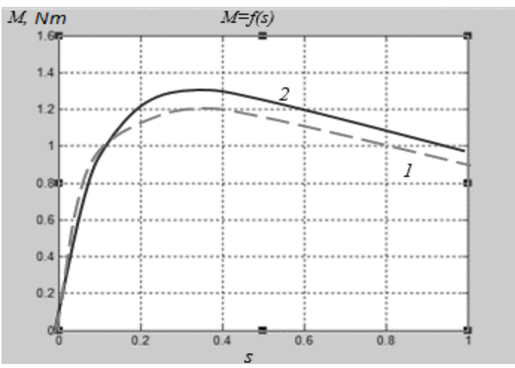
Next, the values of the coefficients and the adequacy of the obtained regression equations for the electromagnetic torque of the machine are checked using the well-known method [18-20].

The resulting system of equations m for five slip values makes it possible to optimize the ESC object according to the shape of the torque characteristic. As an example, let us consider the optimization of a designed, manufactured, tested ESC of the induction electromagnetic clutch with a torque of 800 Nm with the following basic values of factors and areas of their variation: armature and inductor pole length $l_z = (26 \pm 2{,}6)$ cm; electrical resistivity of steel $\rho = (245 \cdot 10^{-9} \pm 24{,}5 \cdot 10^{-9})$ Ohm.cm; no-load induction $B_{1mo} = (1{,}02 \pm 0{,}102)$ T; degree of induction reduction $k_1 = 0{,}835 \pm 0{,}418)$; armature gearing factor $\alpha = 1{,}5 \pm 0{,}5)$. It should be noted that the values for the induction electromagnetic clutch with a torque of 800 Nm with a smooth massive armature and claw-shaped mass poles were also taken as the basic values of the factors. The resulting system of regression equations for five slip values, after checking significance and adequacy, has the following form:

(6) $$\begin{cases} M_{s=0.05} = 6090 + 2056\alpha + 757l_z - 601\rho + 1710B_{1mo} + 598\alpha B_{1mo} \\ M_{s=0.1} = 1059 + 3507\alpha + 1276l_z - 1013\rho + 2979B_{1mo} - 1279k_1 + 1006\alpha B_{1mo} \\ M_{s=0.2} = 16286 + 3507\alpha + 1995l_z - 1590\rho + 4622B_{1mo} - 3891k_1 + 1579\alpha B_{1mo} - 1345\alpha k_1 \\ M_{s=0.5} = 21734 + 7254\alpha + 2736l_z - 2215\rho + 6169B_{1mo} - 117921k_1 + 2201\alpha B_{1mo} - 3968\alpha k_1 - 1376l_z\rho - \\ -1627l_z k_1 + 1382\rho k_1 \\ M_{s=1.0} = 19204 + 6448\alpha + 2453l_z - 2006\rho + 5492B_{1mo} - 16087k_1 + 1202\alpha l_z - 1156\alpha\rho + 1994\alpha B_{1mo} - \\ -5418\alpha k_1 - 1735l_z\rho + 1162l_z B_{1mo} - 2105l_z k_1 - 1160\rho B_{1mo} + 1745\rho k_1 - 4620B_{1mo}k_1 \end{cases}$$

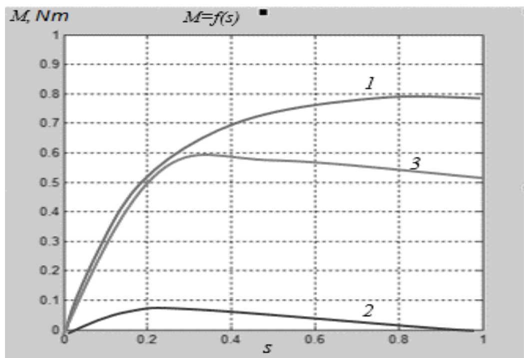
Table 1.- Matrix of fractional factorial experiment

l / u	x_0	x_1	x_2	x_3	x_4	x_5	$x_1 x_2$	$x_1 x_3$	$x_1 x_4$	$x_1 x_5$	$x_2 x_3$	$x_2 x_4$	$x_2 x_5$	$x_3 x_4$	$x_3 x_5$	$x_4 x_5$
1.	+	–	–	–	–	+	+	+	+	–	+	+	–	+	–	–
2.	+	+	–	–	–	–	–	–	–	–	+	+	+	+	+	+
3.	+	–	+	–	–	–	–	+	+	+	–	–	–	+	+	+
4.	+	+	+	–	–	+	+	–	–	+	–	–	+	+	–	–
5.	+	–	–	+	–	–	+	–	+	+	–	+	+	–	–	+
6.	+	+	–	+	–	+	–	+	–	+	–	+	–	–	+	–
7.	+	–	+	+	–	+	–	–	+	–	+	–	+	–	+	–
8.	+	+	+	+	–	–	+	+	–	–	+	–	–	–	–	+
9.	+	–	–	–	+	–	+	+	–	+	+	–	+	–	+	–
10.	+	+	–	–	+	+	–	–	+	+	+	–	–	–	–	+
11.	+	–	+	–	+	+	–	+	–	–	–	+	+	–	–	+
12.	+	+	+	–	+	–	+	–	+	–	–	+	–	–	+	–
13.	+	–	–	+	+	+	+	–	–	–	–	–	–	+	+	+
14.	+	+	–	+	+	–	–	+	+	–	–	–	+	+	–	–
15.	+	–	+	+	+	–	–	–	–	+	+	+	–	+	–	–
16.	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+



Fiq.1 Mechanical characteristics of the electromagnetic slip clutch with a torque of 800Nm: 1– experimental; 2-calculated.

Here all factors are taken in relative units (±1), and the value of the moments is in Nm. A comparison of the results of the experiment (curve 1) and calculations (curve 2) in Fig.1 shows that these mechanical characteristics, plotted for the basic values of the factors, practically coincide. This check is an additional confirmation of the adequacy of the obtained regression equations.



Fiq.2 Calculated mechanical characteristics of electromagnetic slip clutch with a torque of 800 Nm 1, 2 – boundary; 3-optimal.

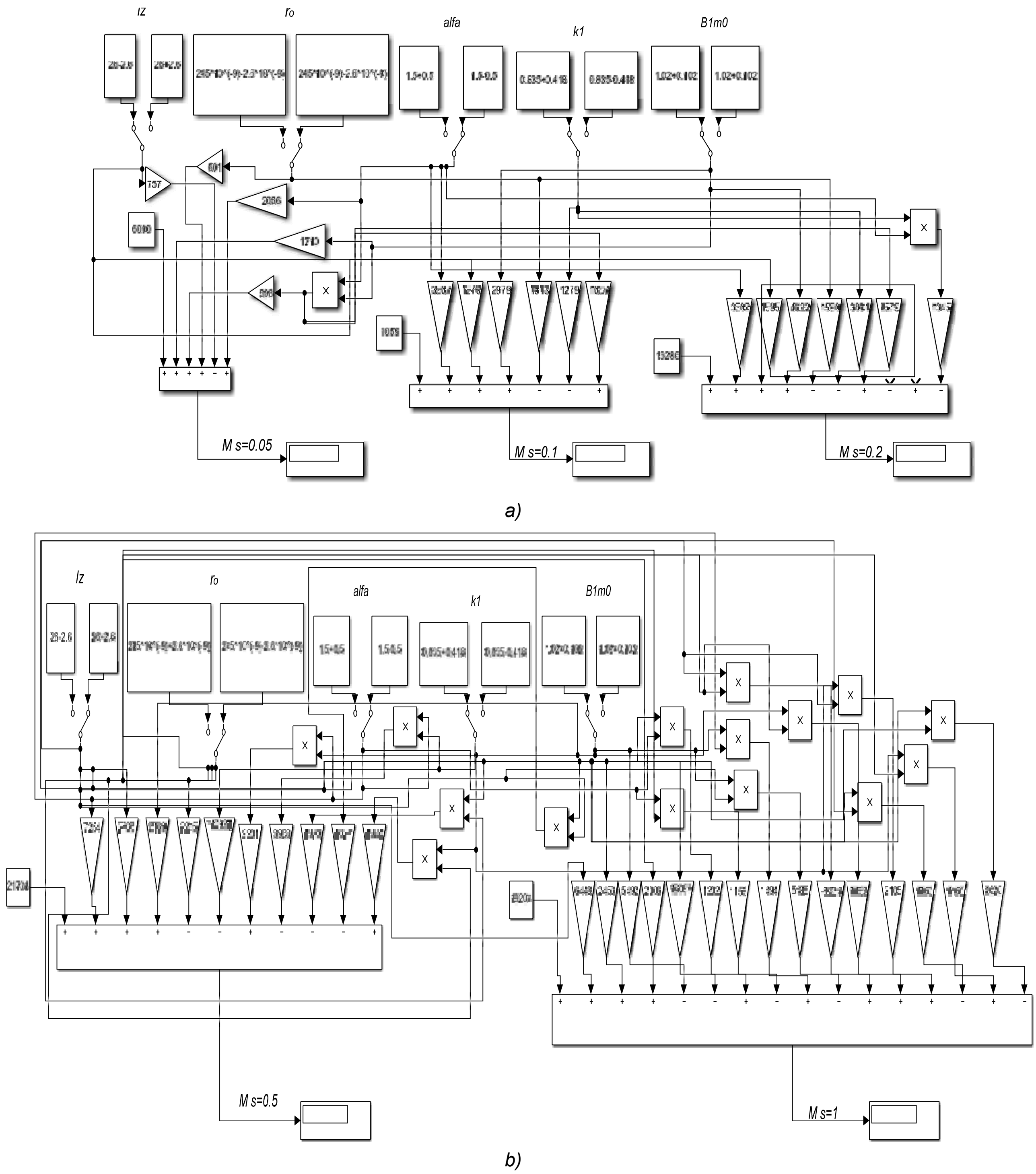


Fig.3 Simulink model of systems of regressive equations for five slip values. a) for M_s=0.05, 0.1, 0.2; b) M_s=0.5, 1.

Fig.2 shows the area of possible changes in the mechanical characteristics of the EMC, constructed according to formulas (6), setting in them the corresponding boundary values of the factors (curves 1 and 2). Optimization of the shape of the mechanical characteristics of an object consists in setting the shape $M = f(s)$ required for technical and technological reasons in the area (1-2) of Fig.2, for example, in the form of curve 3, to determine the corresponding extreme values of the factors.

Thus, having specified the optimal shape $M = f(s)$, we determine the values of the corresponding moments for sliding s=0.05; s=0.1; 0.2; s=0.5; s=1 and, solving together all the equations of system (6), we obtain the value of the factors. These algebraic equations are nonlinear and can be easily solved in MATLAB using the gradient method as follows:

1) Set the left sides of all equations;
2) We assign all variables (factors) their basic values;
3) We calculate the right sides using the formula;
4) Determine the difference between the left and right sides of the equations;
5) We calculate the error of all equations using the formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{5}\left(y_{ei} - y_{\rho i}\right)^2}{5}} \quad (7)$$

where, y_{ei} are the numerical values of the left sides of the equations; y_{pi} - numerical values of the right sides of the equations (7).

The found experimental values of the factors are then converted from relative units to absolute ones; based on this algorithm, a program for solving the system of equations (6) was compiled in Workspace/MATLAB. Simulink model of systems of regression equations for five slip values is shown in Fig3.

By solving the system of equations (6) the following values of the factors were obtained:

a) in relative units:α=0; l_z=0,41; ρ=-0,401; B_{1mo}=0,2; k_1=-0,602;

b) in absolute units:α=1,5; l_z=27, cm; $\rho=236\cdot10^{-9}$ Ом см; B_{1mo}=1,04 T; k_1=0,725.

The error in solving equations does not exceed 10%.

Conclusions

Based on the analysis of optimal design methods, an optimality criterion has been established that takes into account the specific features of the electromagnetic slip clutch in wind power plants. For this criterion, the form of the mechanical characteristic was chosen and presented as a function of the slip coefficient M=f(s). The work demonstrates the effectiveness of using the mathematical method of modeling-factorial design of an experiment to approximate the shape of a mechanical characteristic. An analysis of the influence of the main variables on the optimized object was carried out. Regression equations for electromagnetic torque were obtained, establishing relationships between the main geometric dimensions and electromagnetic parameters in the context of synthesizing the required form of mechanical characteristics for an electromagnetic slip clutch. To solve the problems, the MATLAB/Simulink environment was implemented.

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