General Approach to Calculation of Magnetic System of Slow-Moving Linear Magneto-Electric Drive as Part of Electrical Complex

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Abstract. Article discusses approach to development of linear magneto-electric drive using slow-moving electromechanical converter with permanent magnets Design of electrical complex uses solution of problem of optimization of linear magneto-electric motor design according to criterion of maximum developed traction force. The law of force change is implemented sinusoidal with constant component, frequency of oscillations up to 10 Hz. The weight and size of the electromagnetic parameters of the linear magneto-electric drive are refined using the finite element method. The article presents the results of calculation of the main geometric parameters of the magnetic system.

1. Introduction
Progress in the field of creation of new materials and alloys, introduction of new products and devices based on them determine a clear tendency to create high-tech electrical complexes (HTEC) based on electromechanical energy converters with improved starting and operating characteristics. Modern HTECs are characterized by a number of indicators that determine their quality, reliability and economy (Fig. 1).

![Figure 1. Characteristics and components of HTEC](image-url)
2. Task setting and its mathematical formulation

The study of design issues of electrical complexes with slow-moving synchronous magneto-electric machines with permanent magnets is not sufficiently studied, as at low speeds of movement of the working mechanism in the absence of energy-efficient HTEC in the composition of transmission and conversion mechanisms it is possible only in the way of improvement of energy characteristics of magnetic systems, and this in turn represents a complex multi-factor task. The factors determining the energy efficiency of electrical complexes (ETC) with slow-moving synchronous magneto-electric machines are the peculiarities of magnetic systems structures, which allow to reduce the anchor reaction, start-up moment, increase the permissible winding current.

Along with other types of electromechanical converter in the HTEC, slow-moving synchronous magneto-electric machines with permanent magnets find application in many industries of production and daily human activity. For example, slow-moving wind power plants (WPP), electric power generation devices in transport systems (including railway systems), piston compressor and pump drives of various uses, test stands for studying the properties of materials requiring mechanical action have become widespread.

At the same time, the combination of the actuator and the working machine makes it necessary to take into account the load requirements when solving the general task of developing the electrical complex. The latter fact makes it necessary to determine the energy efficiency of the individual components included in the complex and to take into account the relationship between the processes taking place in its individual subsystems.

Considering that the current elementary base of semiconductor and microprocessor units used in control systems and electric converter devices generating voltage and currents with specified parameters in HTEC has high energy efficiency (low electric losses), output characteristics of HTEC are largely determined by output characteristics of slow-moving synchronous magneto-electric machines with permanent magnets. In turn, the output characteristics of slow-moving synchronous magneto-electric machines with permanent magnets can be represented by two groups: starting and operating.

Thus, the general direction of increasing the energy efficiency of HTEC is to find new optimal designs of magnetic systems slow-moving synchronous magneto-electric machines with permanent magnets, improving their output characteristics.

As a rule, as criteria of optimality in the development of HTEC for a specific purpose, including slow-moving synchronous magneto-electric machines with permanent magnets, criteria are selected that are rigidly connected with the provision of requirements of the technical assignment, which in turn causes a large variety of structures of magnetic systems effective in one case and, on the contrary, requiring clarification in another.

Thus, the search for a common criterion of optimality, the solution of the problem of optimization on its basis, the development of a design methodology and the practical implementation of HTEC for various purposes in order to test its energy efficiency is an important scientific task requiring its consideration.

The mathematical formulation of the LME optimization problem is as follows. It is necessary to find values of variables determining ratios of design parameters of the drive, which maximize the criterion of optimality (function of the purpose)

$$P_{\text{max}}(x_1, x_2, \ldots, x_n) = \max$$

At limitations in the form of equations of connection between parameters of magnetic system

$$q_k(x_1, x_2, \ldots, x_n) = 0, \quad k = 1, 2, \ldots, s, \quad s < n,$$

and inequalities that determine the physical feasibility of the drive design based on the actual characteristics of the active materials used and the design parameters varied during design

$$p_j(x_1, x_2, \ldots, x_n) < 0, \quad j = 1, 2, \ldots, m, \quad m < n.$$

General approach to optimal design of linear magneto-electric motor requires consideration of complex factors determining values of drive parameters that would satisfy different criteria of optimality, depending on requirements [1-4].
In the case of a design calculation of a drive to solve the problem of optimizing its magnetic system, the output parameters of the drive, such as the value of the traction force developed by it, may be considered as input data. The magnetic system configuration, geometrical dimensions, magnetic core and permanent magnet material, winding data and other parameters at which the traction force value can be realized in the best way are to be determined. Obviously, the best of the many embodiments of the magnetic drive system is one that implements the specified specifications and meets a certain criterion of optimality [5].

For the magnetic system of the linear magneto-electric drive shown in Fig. 2

![Figure 2. Magnetic System](image)

The developed specific electromagnetic force:

$$F_{em} = \frac{\mu_0 H_k k_z J k_m}{\gamma_w} \frac{n}{(1+k_m)} \left(1+\frac{\mu_0 H_c}{B_r} \frac{n^2 k_m}{\gamma_w}\right)$$

(4)

In order to find the extremum of the objective function, we equate its partial derivatives to zero and solve the system of equations to determine the unknown $n_{opt}$ and $k_{m, opt}$:

$$\frac{\partial F_{em}}{\partial n} = 0 \quad \text{and} \quad \frac{\partial F_{em}}{\partial k_m} = 0.$$  

(5)

The solution to the problem of optimal design will be:

$$n_{opt} = \sqrt{\frac{B_r}{\mu_0 H_c}} \frac{\gamma_w}{\gamma_m},$$

(6)

$$k_{m, opt} = 1.$$

$$F_{em, max} = \frac{k_z J}{4} \sqrt{\frac{\mu_0 H_c B_r}{\gamma_w \gamma_m}}$$

(7)

$$\left(\frac{Q_x}{Q_m}\right)_{opt} = \sqrt{\frac{B_r}{\mu_0 H_c} \frac{\gamma_m}{\gamma_w}}.$$  

(8)

With the following independent variables:
\[ n = \frac{d}{\delta}, \quad k_m = \frac{m_w}{m_m}, \quad (9) \]

\[ m_w = 2Q_m \delta \gamma, \quad m_m = Q_m \gamma d, \quad (10) \]

In the optimal design of the magnetic drive system, the relative induction in the neutral section of the magnet satisfies the condition

\[ b_{m,\text{opt}} = 0.5. \quad (11) \]

3. Modeling
The optimization task can be refined based on the calculation of the magnetic field in the application software.

Field of permanent magnets and field of windings with current are given in Fig. 3 a, b.

![Figure 3](image1.png)

**Figure 3.** Calculation of magnetic field of LMED: a – magnetic field of permanent magnet, b – magnetic field of windings

Calculated traction force obtained in ANSYS software acting on the mobile anchor 146 N.

4. Results of researches
Values of mass and size electromagnetic parameters of LMED are obtained on the basis of solution of optimization problem.
Table 1. Calculated values of LMED design

| Parameter name                                                                 | Parameter value |
|-------------------------------------------------------------------------------|-----------------|
| Weight of LMED active part                                                    |                 |
| Weight of LMED magnet, kg                                                     | 1.05            |
| Weight of the active part of the winding per pair of poles, kg                 | 1.05            |
| Induction                                                                     |                 |
| Induction in the neutral section of a magnet, T                               | 0.5             |
| Induction in a gap, T                                                          | 0.53            |
| Main geometrical dimensions of LMED magnetic system                           |                 |
| Magnet height $\lambda$, m                                                    | 0.053           |
| Winding thickness, $\delta$, m                                                | 0.007           |
| Wall thickness of outer core of magnetic core, $\Delta$, m                    | 0.0014          |
| Average magnet radius                                                         | 0.053           |
| Radii of LMED magnetic system                                                 |                 |
| Radius of inner core of magnetic core, $r_1$, m                               | 0.042           |
| Winding radius, $r_2$, m                                                       | 0.05            |
| Magnet radius, $r_3$, m                                                        | 0.06            |
| Radius of outer core of magnetic core, $r_4$, m                               | 0.07            |
| LMED parameters                                                               |                 |
| Specific electromagnetic force, N                                             | 23.77           |
| Magnetizing force of the active part of the winding on a pair of poles, A     | 329.4           |
| Magnet conductivity to a pair of poles, H                                     | $3 \times 10^{-4}$ |
| Relative conductivity of air gap                                               | 1               |

The solution of the problem of optimization at the preliminary stage of calculation of the magnetic system geometry determines the maximum electromagnetic force acting on the anchor LMED equal to 170.64 N, as a result of the verification calculation based on the magnetic field study determines the traction force equal to 141.7 N. In order to obtain the specified output force 150 N, it is necessary to correct the main dimensions of the magnetic system.

5. Conclusions
1. The mathematical formulation of the LMED optimization problem is presented and its solution is obtained taking into account the use of the finite element method.
2. Calculation of electromagnetic parameters of linear magneto-electric drive based on expressions obtained during solution of optimization problem [1]

6. References
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