Optimum weight and dimensional characteristics within mining machinery

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Abstract. The issues of the electric motor of mining machinery coordination with the power supply is considered in this article. In consideration of this question, there is a need to solve some issues: control of the regulation accuracy and achieving minimization of weight and dimensional parameters of this system. The article contains the optimization criterion and the mathematical solution of the electric motor coordination with the power supply by weight and dimensional parameters within mining machinery. The solutions of the power elements materials choice are presented. The criterion of the power elements mass minimization of the autonomous electric drive is presented and analyzed. The shape of the triangle, formed by the magnetizing force vectors, is optimized considering the specific costs for each component in the generalized electric machine within mining machinery. The results of optimization of specific electric drives with different power supplies and their analysis are also presented in this article.

1. Introduction
A task of coordination of the electric motor with power supply within mining machinery has two sides: providing the set point of accuracy for control and achieving of minimum weight and dimensional proportions.

Power supply parameters are selected to minimize the control error with the spectral distribution of the control and disturbing signals. The choice is reduced to the required structure and parameters of the compensating links (optimization of the minimum control error “in the small”) based on the methods of linear theory of automatic regulation [1, 9, 11]. Secondly, this choice is required for determination of the limiting level of power supply rated voltage of the armature (or stator) circuits and excitation circuits. Quite acceptable results are given, e.g., in [10]. The issue of coupling the limiting level is solved at the output of one of the control elements in the frequency domain (the maximum voltage at the output of the power supply e.g.). In addition, the issue of the limiting input signal is solved through frequency characteristics of the control object and regulators. Values are pointed for different electric drives and their operations accepted for the maximum voltage at the power supply output (quantity of their rated values).

The issue of coordination of the electric motor with power supply is solved otherwise with minimizing the dimensions. Today it is possible to mark several valuable researches about condition’s optimization of the minimum weight of power electromagnetic elements, e.g., electrical machines [2, 9], power supplies [14] within mining machinery.
Solution of a problem of the optimum proportions for electrical machine active electromagnetic materials is given below from a position of the system approach to “power supply – generalized electrical machine” with a mining machinery complex. The solution provides a minimum of total weight of the rated power electric equipment.

2. Mathematical modeling

The dimension of the electric machine is determined by its electromagnetic torque, what is known from the practice of design of electrical machines [4, 13]. An electromagnetic torque value in the generalized electrical machine may be presented as the modulus of vector product [3, 4]:

\[ M = \frac{m}{2} L |I_A \cdot I_B| = \frac{m}{2R} |F_A \cdot F_B| = \frac{m}{R} \]  

where, \( m \) – the number of phase; \( L \) – inductance of excitation current; \( R \) – magnetoresistance to electromagnetic flux in the electrical machine; \( I_A, I_B, F_A, F_B \) – amplitude currents values of the first harmonic of armature and exiting windings and the magnetizing forces corresponding to them; \( S \) – area of a triangle which is formed by vectors-composed \( F_A \) and \( F_B \), and a summing vector \( F=F_A+F_B \) (a triangle of flux linkage in the electrical machine).

Graphic interpretation of expression (1) was turned out useful during creation of modern high-quality systems of the torque regulation, especially an AC power drive system. The triangle of the flux linkage area corresponds to the value of the electromagnetic torque. This triangle form defines regulation processes and degree of active electromagnetic material usage in the electrical machine.

In this case, the control system of the electromagnetic torque is multidimensional. Moreover, different ways of its realization are possible. These ways are associated with corresponding geometrical interpretation of creation ways of the triangle of flux linkage. That gave the following main options:

— Triangle of flux linkage creation by the three of its sides. In this case, creation and operation of three parallel systems of regulation are assumed due to measurement and control of the rotor current, currents in the stator windings and the flux in the gap of the electric drive system. That is possible for electric drive systems, which are realized in this way of the electromagnetic torque forming. Electric drive systems with this way of electromagnetic torque forming exist, e.g., in well-known system Transvektor [5].

— Triangle of flux linkage creation by two sides and an angle between them (with values \( F_A \) and \( F_B \) and on the angle between \( F_A \) and \( F_B \), rather, sine of this angle). Synchronous frequency, controlled electric drive of a cement mill, developed by BBC, e.g., is high-quality realization of this option [15]. Which successful practice was repeatedly used when developing high-quality AC power drive systems [4, 9].

It is not necessary to build all three subsystems by the closed loop principle. It is possible to control an angle between \( F_A \) and \( F_B \) vectors as open loop (i.e. without feedback) for electric drive simplification. Angle between these vectors is established at maintenance of the electric drive. Then it is not changed and not regulated during the operation. Wide group of frequency-current system of electromagnetic torque formatting are corresponded to this case [1, 3]. It is effective and gained almost monopoly extension by electric drives for machine-tools and special AC servo drive systems.

— The triangle of flux linkage creation by the value of rotor current and projections of a stator current vector to longitudinal and cross axes of the electrical machine (an axis \( d \) and \( q \)). This method is provided the basis for synchronous frequency controlled high power electric drives with high requirements to dynamics quality and to energy efficiency of regulation processes [4, 6]. In addition, this method is very difficult.

The triangle of a flux linkage idea in the electrical machine was convenient due to the synthesis of the modern high-precision electromagnetic torque forming systems in a.c. drive systems and optimization of the regulation process in these electric drives.
The idea of a triangle of flux linkage generalized with a design procedure of an electrical machine. That especially refers to autonomous drives and other electric drives which are allowed for individual choice design of parameters for the power elements.

It is important to provide the best weight-dimensions parameters of the electric drive when there are coordinated parameters of the electric motor power circuit and controlled power supply. It is achieved because of the minimum cost of active materials in power elements of electric drive. It may be allowed by introduction of an optimization criterion:

\[ q = \frac{Q}{M_n}, \]  

(2)

where, \( Q \) – mass of the active materials in electric drive elements; \( M_n \) – rated electromagnetic torque.

Costs of the active materials in the electric motor may be presented as a sum:

\[ Q = a \cdot F_B + b \cdot F_A + c \cdot F. \]  

(3)

where, \( F_A, F_B, F \) – electrical machine first harmonic amplitude values of armature (stator) windings magnetizing forces, excitation windings and magnetizing of electric machine; \( a, b, c \) – distribution weight coefficients, which are known by electrical machines design of definite series. The cost per unit of copper for excitation and armature (stator) windings is evaluated by coefficients “a” and “b”. The cost per unit of magnetic system steel is evaluated by coefficient “c”.

Considering expressions (1) and (3), the expression for quality functional may be written due to the electric motor, coordinating with the power supply in the form [8, 10, 12]:

\[ q = \frac{R}{m} \cdot \frac{2F_B + bF_A + cF}{S}. \]  

(4)

It is useful to pay attention on clear physical sense of the presented functional: efficiency of used active materials in the electric motor is estimated by the triangle area \( S \). Effect of regulated power supplies is considered in the distribution weight coefficients. Connection of the exciting increases coefficient “a”, and connection of the power supply in an armature (stator) circuit increases coefficient “b”. Efficiency of active materials usage in the electric drive and the power supply will be the best, when value of “q” in terms of (4) is minimal with defined initial torque of the electric drive.

The issue of optimal weight-and-dimensional proportions of adapting the electric drive with a power supply can be formulated mathematically:

– it is necessary to find a minimum of function:

\[ Q = a \cdot x + b \cdot y + c \cdot z; \]

– under conditions:

\[ p \cdot (p - x)(p - y)(p - z) = S^2; \]
\[ x + y > z > 0. \]

Here \( p = (x + y + z)/2 \) – half-perimeter of triangle of flux linkage with lengths of sides, \( x = F_B, \)
\( y = F_A, \) \( z=F; \) \( S \) – triangle area, which was calculated on Gerona formula [3]; “a”, “b”, “c” – constant positive values.

Lagrange multiplier method [7] will be used and presented in terms of expression:

\[ \Phi(x, y, z, h) = Q + h \cdot f. \]
where \( h \) – Lagrange multiplier;

\[
f = p \cdot (p - x)(p - y)(p - z) - S^2 .
\]

A necessary extremum condition is set by the system of equations. This system of equations is turned out after a differentiation of Lagrange function by \( x \), \( y \), \( z \), and \( h \):

\[
\begin{align*}
\Phi_x' &= a + h \cdot f_x' = 0, \\
\Phi_y' &= b + h \cdot f_y' = 0, \\
\Phi_z' &= c + h \cdot f_z' = 0, \\
\Phi_h &= f = 0 .
\end{align*}
\]

Let us find after differentiation:

\[
\begin{align*}
f_x' &= x(-x^2 + y^2 + z^2)/4, \\
f_y' &= y(x^2 - y^2 + z^2)/4, \\
f_z' &= z(x^2 + y^2 - z^2)/4.
\end{align*}
\]

As a result, the main system of the equations (5) leads to a form:

\[
\begin{align*}
4a &+ hx(-x^2 + y^2 + z^2) = 0, \\
4b &+ hy(x^2 - y^2 + z^2) = 0, \\
4c &+ hz(x^2 + y^2 - z^2) = 0, \\
[(x + y)^2 - z^2][(x - y)^2 + z^2] + 16S &= 0.
\end{align*}
\]

Let us receive from the first three equations:

\[
\frac{x(-x^2+y^2+z^2)}{a} = \frac{y(x^2-y^2+z^2)}{b} = \frac{z(x^2+y^2-z^2)}{c}.
\]

\( \alpha \), \( \beta \), \( \gamma \) will mark angles, which are opposite to sides \( x \), \( y \), and \( z \) in a triangle of flux linkage. In addition, let us apply the cosine law:

\[
\begin{align*}
-x^2 + y^2 + z^2 &= 2yz \cdot \cos \alpha, \\
x^2 - y^2 + z^2 &= 2xz \cdot \cos \beta, \\
x^2 + y^2 - z^2 &= 2xy \cdot \cos \gamma.
\end{align*}
\]

Then, finally:

\[
\frac{\cos \alpha}{a} = \frac{\cos \beta}{b} = \frac{\cos \gamma}{c} .
\]

The system of equations, added by formula:

\[
\alpha + \beta + \gamma = 180^\circ
\]

is the theoretical solution of the application task.

Let us find \( \alpha \), \( \beta \), \( \gamma \) from the formula (7) of the expression for the triangle area:

\[
2S = xy \cdot \sin \gamma = yz \cdot \sin \alpha = xz \cdot \sin \beta .
\]

It is possible to find the sides \( x \), \( y \), \( z \) and \( Q \) minimum.

Necessary formulas have an appearance:
\[ x = (2S \cdot \sin \alpha / \sin \beta \cdot \sin \gamma)^{0.5}, \\
 y = (2S \cdot \sin \beta / \sin \alpha \cdot \sin \gamma)^{0.5}, \\
 z = (2S \cdot \sin \gamma / \sin \alpha \cdot \sin \beta)^{0.5}. \]

In case of numerical methods of the equations (7) solution, it is possible to write system (8) in the following form:

\[
\begin{align*}
    b \cdot \cos \alpha &= a \cdot \cos \beta, \\
    c \cdot \cos \alpha &= a \cdot \cos \gamma.
\end{align*}
\]

Let us consider that:

\[
a \cdot \cos \gamma = -a \cdot a \cdot \cos(\alpha + \beta) = a \cdot \sin \alpha \cdot \sin \beta - a \cdot \cos \alpha \cdot \cos \beta.
\]

Then,

\[
\begin{align*}
    b \cdot \cos \alpha &= a \cdot \cos \beta, \\
    c \cdot \cos \alpha &= a \cdot \sin \alpha \cdot \sin \beta - b \cdot \cos \alpha \cdot \cos \beta.
\end{align*}
\]

Let us use the first equation into the second:

\[
c \cdot \cos \alpha = a \cdot \sin \alpha \cdot \sin \beta - b \cdot \cos \alpha \cdot \cos^2 \alpha.
\]

The received equation is turned out to the following cubic equation relative to \( \cos \alpha \):

\[
2b \cdot c \cdot \cos^3 \alpha + (a^2 + b^2 + c^2) \cdot \cos^2 \alpha = 0. \tag{9}
\]

Which has the single decision on the interval \( 0 < \alpha < 90^\circ \). In addition, it is solved simply by numerical methods.

In some cases, it is necessary to introduce additional boundary \( \cos \gamma = 0 \) for the synchronous electric drive with current-frequency controlled with the mutually orthogonal spatial orientation of the magnetizing forces of rotor and stator in a condition of the main issue (4). In addition, it is important for the DC motor, where it is necessary to set brushes on a geometrical neutral.

In this case, issue is solved similarly – \( Q \) minimum is being found, where:

\[
Q = ax + by + cz,
\]

under condition of:

\[
xy = 2S; z = (x^2 + y^2)^{0.5}.
\]

It is possible to present the system of equations (7) for the considered case:

\[
\begin{align*}
    a + cx/z + hy &= 0, \\
    b + cy/z + hx &= 0.
\end{align*}
\]

Variable “a” is entered, based on formulas:

\[
x = z \cdot \cos \alpha, y = z \cdot \sin \alpha;
\]
then:

\[ a + c \cdot \cos \alpha = -h \cdot z \cdot \sin \alpha, \]
\[ b + c \cdot \sin \alpha = -h \cdot z \cdot \cos \alpha. \]

This system of equations is reduced to the trigonometric equation:

\[ a \cdot \sin \alpha + c \cdot \sin^2 \alpha = b \cdot \cos \alpha + c \cdot \cos^2 \alpha, \quad (10) \]

which is solved simple by numerical methods.

3. Results

Weight-and-dimensional proportions are compared for several DC motors, where electric motor armature windings connect to different power supplies. The DC motor was selected for a basic option of the autonomous drive. That drive was optimized by a minimum of its weight, according to the standard method of electrical machines calculation [10, 13]. Its rated power is \( P = 3,0 \) kW, voltage on an armature winding - \( U_a = 27 \) V, armature current is \( I_a = 139 \) A, the angular rate of motor axis rotation - \( n = 314 \) rad/s, the armature windings magnetizing forces has a value equal to \( P_a = 416 \) A, the excitations windings magnetizing forces are \( F_v = 1580 \) A, total magnetizing forces (in a gap) - \( F = 1630 \) A, distribution coefficients of active materials in the electric motor are \( a = 1,18 \) kg/kA, \( b = 6,6 \) kg/kA, \( c = 9,4 \) kg/kA, attribute \( q = 1,94 \) kg/nm.

An implementation of several schemes of the electric motor armature windings in power supplies was considered: ideal power supply, the reverse transistor converter with pulse-width modulation and the booster generator were switched in the differential electric drive armature circuits (Table 1).

| Electric drive system | Value, unit | Option       |
|----------------------|-------------|--------------|
|                      | Base        | Optimized    |
| Ideal power supply – electric motor | q, kg/Nm | 1,94 | 1,35 |
|                       | \( F_B, A \) | 1580 | 1116 |
|                       | \( F_a, A \) | 416 | 939 |
|                       | \( F, A \) | 1630 | 703 |
| Reverse transistor converter with pulse-width modulation – electric motor | q, kg/Nm | 6,5 | 6 |
|                       | \( F_B, A \) | 1580 | 3630 |
|                       | \( F_a, A \) | 416 | 181 |
|                       | \( F, A \) | 1630 | 3620 |
| Differential electric drive with booster generator | q, kg/Nm | 4,11 | 3,6 |
|                       | \( F_B, A \) | 1580 | 2440 |
|                       | \( F_a, A \) | 416 | 271 |
|                       | \( F, A \) | 1630 | 2430 |

4. Conclusion

1. The issue of optimization of the “power supply- electric motor” within the mining machinery complex is set and solved from the position of the active materials mass minimization of its power elements. The criterion of minimum mass of the power elements is considering and analyzed for an autonomous electric drive. At the same time, the form of the triangle is raised by the magnetizing forces vectors, which are optimized in the generalized electrical machine, with considering specific costs of each item.
2. Results of the optimization show that the form of the triangle of flux linkage, formed by the magnetizing forces vectors in the electric motor, depends on the active materials specific costs. It depends on the specific costs in the electric motor and in power supplies of an armature (stator) and excitation circuits. Efficiency of the electric motor power circuits’ coordination depends on the value of the power supply specific costs with optimum on weight-dimensional parameters and the power supply substantially; that has specific costs for electric drives with small values of power supply.

3. Optimum weight-dimensional parameters in a power range (0.5...5.0) kW are given by the diagram of the differential electric drive for autonomous electric drives with voltage power line \( U_c = 27 \text{ V} \). The effect is achieved by a small power range and a triangle of flux linkage form optimization (i.e. the electric motor and electromagnetic system components costs redistributions) with considering power supply parameters within mining machinery.

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