Magnetic flux control laws in differential electric drive

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Abstract. This paper considers scheme options of the multimotor differential electric drive system. These schemes have competitive energy and weight-size parameters. The number of independent control commands exceed the number of controlled coordinates. Magnetic flux magnitude of the electric machine may be accepted as a control command. Methods of nonlinear programming synthesized the flux control laws in a multimotor differential electric drive system. The minimum weight-size characteristic of the electric power equipment was taken as an optimization criterion. Possibility of founded control laws approximation was shown by the simple piecewise linear equation. Speed control of the electric drive was changed only by one electric machine flux for each of the segments. Fluxes of other machines remained unchanged, equal to the nominal values. Additional losses did not exceed few percent in case of refusal from the exact control law in the area of small loads. Also, it was not observed in the rated area at all.

1. Introduction

An engineer should be more focused on searching for the best multimotor electric drive control law because of a large quantity of controlling actions [1]. On the other hand, the number of independent coordinates exceeds the number of coupling equations, so it is actual to define statement of the problem of finding the optimal magnetic flux control method.

The accent is made on getting a static optimization. It is necessary to estimate the maximum expected effect of using different control laws [2].

Magnetic fluxes of the electrical machine were taken as parameters for solving an optimization problem. Boundary conditions were imposed on the magnitude of the magnetic fluxes in the form of inequalities.

\[ |\Phi_1| < \Phi_{1R}, \] where \( \Phi_1 \) is a value of the standed magnetic flux of the first machine; \( \Phi_{1R} \) is a value of the rated magnetic flux of the first machine.

The merit functional is represented:

- in the case of minimizing the over-all dimensions of power equipment:

\[ J_1 = \sum_{i=1}^{m} \max |I_i| \cdot \max |\Phi_i|. \] (1)

This expression is represented as the sum of maximum electromagnetic torques of electrical machines.
The functional relationships between the variables were considered by the system of equations. They describe the static mode of electric drives considered in this paper:

- for the scheme (figure 1):

\[
\begin{align*}
n_1 + n_2 &= n_3 = n; \quad (2) \\
I_3 &= I_1 + I_2; \quad (3) \\
T_1 &= T_2 = T_4; \quad (4) \\
T_5 &= T_4 + T_3; \quad (5) \\
U &= n_2 \Phi_2 + n_3 \Phi_3 + I_2 R_2 + I_3 R_3; \quad (6) \\
U &= n_1 \Phi_1 + n_3 \Phi_3 + I_1 R_1 + I_3 R_3; \quad (7) \\
T_i &= I_i \Phi_i \quad (i=1, 2, 3). \quad (8)
\end{align*}
\]

![Diagram](image)

**Figure 1.** Design circuits of force loop: three-machine differential electric drive system.

2. **Algorithm of magnetic fluxes control optimization**

Solving the problem should start with specifying any allowed set of fluxes control (even not optimal) because the coordinate-wise improving method is local. After that, an accepted variant may be improved.

Further, values of the currents \( I_1 \) and fluxes \( \Phi_1 \) of electric machines are included in the expression for the functional (1) explicitly. Therefore, we should express explicit values of currents in the form of fluxes for the definite scheme of the differential electric drive system in accordance with the equations, solving the system of functional links equations (3–8). Systems are solvable by the method of successive elimination of intermediate variables [3].

It is necessary to find maximum deviation of variables from zero and calculate the functional for accepted original law of magnetic fluxes control \( \Phi_1 \). After that, it is possible to start the process of minimizing functional [4].

An approved scheme of the algorithm for solving the problem of minimizing the functional (1) consisted of the following stages:

1. The source data input. State equations of the definite electric drive are specified by the settings for components and work conditions (load torque, a variation range of speed, etc.) relevant from the point of view of the problem being solved.

2. There is a choice of any obtainable fluxes law changes \( \Phi_1 \) in the regulation of output differential electric drive system speed in a given range. Therefore, the law presented in figure 2 was chosen as an initial law the for a differential electric drive system (figure 1).

3. Calculation of the functional components. Each measurement point for output speed is based on the equations of the differential electric drive system, an allowable value of flux and the corresponding values of currents and other characteristics. As a result, there is some discrete set of flows and the corresponding set of current functions.
4. Calculation of «peak» functional is necessary to organize the process of selecting the point of greatest deviation from zero for each function constructed in [1]. We selected the point of greatest deviation from zero and calculated the function (1).

5. Minimization of the functional by the method of coordinate descent. First, it is necessary to do an elementary step of minimization [5]. We pick up values of control to an approach to zero at the point of maximum deviation of the function from zero. That reduced the deviation of the function from zero.

The problem of reducing deviations from zero at the point of maximum deviation ("cut" peak) was solved by the method of coordinate descent for each component of functional (1). We should point that changing one of the differential electric drive system characteristics changes the others. Therefore, deviation from other functions may be increased by reducing the deviation from zero of one function. If deviation from zero of the function is decreased, then an elementary step of minimization is successful [6]. In addition, the values of other functional components (1) were changed, thus an elementary step of the minimization value, at least, did not increase. In this case, one must go to step 6.

It is necessary to restore the settings of the system and repeat the elementary step of minimization if the elementary step of minimization does not satisfy these changes.

6. Checking conditions for the end of the optimization method. If none of the components of the functional could be improved, then it is considered that the work is completed, and it is necessary to go to step 7.

7. Output of results, where there is a specified value of the functional and a set of fluxes that control the differential electric drive system.

**Figure 2.** The dependences of the electric drive variables on the reference signal: a – magnetic flux, b – motor speed, c – EMF.

If the value of the functional was not decreased, but at least one of the component functionality changed, the peak is shifted to the other point. Therefore, it is needed to find this point and repeat optimization procedure in it. It is required to find the point where the function has a maximum deviation from zero once again from the received modes. Therefore, the procedure of sort is organized in an ascending order for the deviation from zero of these functions [7]. The procedure demonstrates that peaks were shifted if the result demonstrated that the functional improvement was impossible (1). Otherwise, one must go to the elementary optimization step once again.

Some control law of the differential electric drive system is built up, during which the weight-size characteristic will be less than that in the initial version [8].

It is necessary to repeat a set of calculations because the method of coordinate descent has not given global minimum of the functional (1) in each variant of calculations. It is required to obtain consistent results, starting each time with a new valid set of fluxes. However, limitation of the method is not matched with the real electric drive system due to the possibility to check its functioning in some familiar operating modes for an engineer [9]. Equations and the physical phenomenon status of the system are simplified and turned out possible for the usual methods of analysis, if theoretic idle stroke or torque brake (short-circuit conditions) are used as the modes of the electric drive.
3. The results of the optimization with minimum dimensions of the electric drive

The search for optimal fluxes change laws in the electric machine was produced when the speed of an actuating unit was regulated from zero to a maximum value at fixed time of stationary load torque. As initial fluxes, the changed law for the first scheme (figure 1) was accepted as the law, illustrated in figure 2. The calculations showed a full coincidence of the optimum control law with initial speed in regulation of an actuating unit on the idle stroke. All the curves are parallel shifted to the left with stationary load torque. The curves are shifted more, the greater the value of the stationary load torque. It is caused by the necessity of compensating pickoff on the resistance of the electric motor armature. The received control law is stable enough and it is impossible to find a better variant.

The optimal law, illustrated in figure 3, was accepted as the law of fluxes changes on the scheme (figure 1). The calculations showed that finding a different law from an original one with a lower value of the quality functional (1) is impossible [10].

![Figure 3. Magnetic fluxes control laws in differential electric drive: 1 – motor M1, 2 – motor M2.](image)

This is because of the point that, defining the maximum value of the functional (1), turned out to be a point with the maximum output speed of the actuating unit [11]. The maximum value of all variables is included in the functional, achieved at this point. Calculations are confirmed for the case of actuating the unit speed regulation into a smaller range. The value of the functional (1) is reduced, but the critical point is the point with a maximum output speed.

The better law of fluxes changes as such law where the maximum numbers of threads are supported, is equal to their rated (i.e. maximum) values from the view point of weight-size indicators minimization. The optimal law fluxes change consisted of several partial systems [12]. Two of the fluxes remained the same, equal to its nominal value. Speed is regulated by changing the flux of a third machine. Change of the partial system occurs when reaching the nominal (maximum) value of the third machine flux. In the next partial system, it is regulated by speed control varying three fluxes.

4. Conclusion

Methods of nonlinear programming synthesized the flux control laws in a multimotor differential electric drive system. The minimum weight-size characteristic of the electric power equipment was taken as an optimization criterion [13].

Possibility of founded control laws approximation was shown by the simple piecewise linear equation. Speed control of the electric drive was changed only by one electric machine flux for each of the segments. Fluxes of other machines remained unchanged and equal to the nominal values.
Additional losses did not exceed few percent in case of refusal from the exact control law in the area of small loads. Also, it was not observed in the rated area at all.

Well-known algorithms of nonlinear programming are quite suitable to search for the optimal fluxes control laws in the differential electric drive system [14]. In particular, the algorithm of coordinate descent was accepted in the differential electric drive system with minimization of dimensions.

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