Design of fast response electric drive of agricultural objects

V V Fediakov¹, L A Zhuravleva² and M N Kornienko¹

¹ Gmbh Anvilex, 94 Enderstrasse, Dresden, Deutschland
² JSK Proektneftegaz, Saint Petersburg, Russia

E-mail: Energochel2017@gmail.com

Abstract. The main stages of synthesis of high-speed agricultural AC electric drives are considered in the article. As the main criterion, the mass ratio of the rotating parts of the motor to the nominal torque can be applied. It is rational to solve the following problems in the article: synthesis and justification of the stages in the methodology for the development of high-speed electric drives; assessment of the possibilities of each of the design stages; comparison of the developed electric drives' characteristics according to the original method with existing objects. Proposed the concept of synthesis drives that implement a limit on the operation speed and handling ability, which from the position of a systematic approach contains a number of stages: synthesis of generalized mathematical models of the object, taking into account a detailed description of the system implementing the limit operating modes; assessment of possibilities of the control object; parametric optimization of electrotechnical complex with the position of the marginal characteristics; selection of simplified mathematical models of the electric drive; synthesis of structures and control systems that realize the limit operating modes; search phase trajectories of motion of the system “Electric drive - working body” implementing extreme modes of operation. The proposed algorithm is a series of interrelated stages, where in each stage can be done the clarification on the results of second stage, for example, detailing the requirements of the technological process at the last stage of the search for phase trajectories provides for a return to the parametric optimization of the agricultural objects electric drive.

1. Introduction
The emergence of new technologies and improvement of existing technologies not only increases requirements to the agricultural electric drive, but also requires the implementation of the new nature movement. The usual requirements for electric drive which are control range of speed and torque, the bandwidth of frequencies of the agricultural objects electric drive, the energy efficiency are dramatically increased.

In [1] there are systematic requirements for the regulated electric drive on the part of some technological objects, in which most strongly manifested these requirements. As technological objects the objects of metallurgical production and traction mechanisms were taken. The development of these facilities is the most relevant for the Ural region due to historical reasons and taking into account priority directions of development of the South Ural region.

Analysis [2] showed that at remaining requirements for the range of speed regulation, the most relevant are indicators of extension of the control range torque (up to 1:10 traction mechanisms), maximum speed (up to 10:1) and limit overload time (to 4Tn) [3].
Therefore, for further analysis two groups of mechanisms were selected. First group is those mechanisms in which the most important are the indicators in question: the drives agricultural objects, traction mechanisms for electric transport and tractors that are characterized by extreme modes, the speed and handling abilities. The second group consists of objects of technological production, which meet reasonable demands for the regulation of coordinates of electric drive, but who work in aggressive, and therefore, severe process conditions.

Special cases of electric drives that were considered in [4] and which are implemented with the use of new approaches, showed that due to the redistribution of active materials improved performance can achieve in the simple design of the electric machine. In this regard, the actual problem is the systematization of the design stages of the electric drives that implement the limit operating modes for technological mechanisms, wherein the heavy and very heavy operating conditions [5].

2. Setting of the problem
Taking into account the large number of variables in the electric drive, when designing high-speed electric drives, the task is to synthesize the method and stages of developing regulated drives in accordance with specified quality criteria.

As the main criterion, the mass ratio of the rotating parts of the motor to the nominal torque can be applied.

In this case, it is rational to solve the following problems in the article:

- synthesis and justification of the stages in the methodology for the development of high-speed agricultural electric drives;
- assessment of the possibilities of each of the design stages;
- comparison of the developed electric drives’ characteristics according to the original method with existing objects.

3. Development stages of high-speed electric drives
The concept of the synthesis (design) of electrical systems which provide the ultimate in features function was formulated (see figure 1).

![Figure 1. The concept of synthesis of electrical systems that implement limit operating modes.](image)

The first stage of the synthesis is required, because the existing mathematical models usually describe the system with lumped parameters and do not take into account the particular configuration of the
electric machines. Moreover, the value of this stage is that using the generalized mathematical model could justify simplified design scheme [6].

The second step is the evaluation of thresholds system. At this stage it is the choice of the electric drive system, which is able to solve a specific technological problem in providing electric specific trajectory.

A rational choice of the ratio of the active material in electric drive can be solved at the stage of parametric optimization of electric drive [7]. At this stage we receive the answer if the traditional approaches can be applied to the selection of the dimensions of electric machines or require clarification, if the efficiency criterion is an index of a low mass (or high handling) [8].

The choice of structures and parameters of corrective relations requires a preliminary assessment of the adopted simplified model of the electric drive (steps 4 and 5) [9].

The optimal trajectory of the working element can be formulated after a detailed study of the technological process. The result obtained at stage 6 gives the answer how successful the solution is [10]. If necessary, the machine returns to the previous stage. As a rule, it is necessary to specify performance indicators and again to solve the problem of parametric optimization (stage 3) [11].

We will give a preliminary assessment of the possibilities 3 and 6 stages, which are the most labor-intensive. Perform the calculation on the example of electric drive with field regulated reluctance machine (FRRM) [12].

4. Features of parametric optimization of electric machines by analytical method
At the level of the effectiveness principle of the rotor design and shape of the phase current can be explained as follows [13]. Even in the original version (figure 2, a) the rotor has a perfect not equal pole design and does not contain windings. On the stator evenly around the circumference are placed infinitely large number of conductors that create a uniform line load is an ideal two-pole winding with full pitch. Let the currents in the conductors along the arc of the semicircle abc, flowing “from us” and in conduits located along an arc of a semicircle cda is “towards us”. Divide the entire circumference of the bore of the stator into four equal arcs ab, bc, cd and da. Then the conductors belonging to the arcs ad and bc will create MDF excitement, that direction is convenient to display by vector $F_1$, and conduits, located along ab and cd, by vector $F_2$. Conductors that are lying along arcs ad and bc, and interacting with the flux generated by MDF $F_1$, create a rotor torque $T_1$, directed counterclockwise. Similarly, conductors located along the arcs ad and bc, interacting with the flow of excitement generated by MDF $F_2$ cause the rotor to generate a torque $T_2$ acting in a clockwise direction [14]. Due to the symmetry of the machine, and both components $T_1$ and $T_2$ are equal in magnitude and opposite in sign, so the motor torque does not develop [15].

Now let’s cut on the rotor slots of a width corresponding to the arcs ad and bc (figure 2, b). Thus the motor becomes salient pole structure without winding on the rotor. In this case, the component of the flow created by the MDF $F_1$ can be taken constant, but the component of the flow that is created by $F_2$ will decrease [16]. For this reason, the torque $T_1$ we can accept the former, but due to the reduction of the flow of excitation $T_2$ decreases. In the end, the resulting motor torque is different from zero [17].

In function $x=\alpha R$ along the bore of the stator will build graphs of the distribution of linear load $A$, MDF $F$, induction $B$, specific tangential force $\sigma = BA$ (see left part of figure 3 and 4) and give analytical expressions for these dependencies (see right part of figure 3 and 4). The radius of the bore of the stator will take equal R=1, then the linear and angular displacement along the bore of the stator coincide numerically: $x = \alpha$
Figure 2. Options of the cross-section electric machine with not salient pole (a) and salient pole (b) rotor.

In function $x = \alpha R$ along the bore of the stator will build graphs of the distribution of linear load $A$, MDF $F$, induction $B$, specific tangential force $\sigma = BA$ (see left part of figure 3 and 4) and give analytical expressions for these dependencies (see right part of figure 3 and 4). The radius of the bore of the stator will take equal $R = 1$, then the linear and angular displacement along the bore of the stator coincide numerically: $x = \alpha$.

Shows dependence obtained with the following idealization electrical machines: magnetic circuit is linear, there are no stray fields, the magnetic resistance of the interpolar gap is infinitely large [18].

If the spatial wave linear load $A$ make a perfect rectangular shape (figure 3, a), the dependence of MDF describe the polyline (figure 3, b), induction in the air gap describe the discrete curve (figure 3, b) and specific tangential force describe the curve (figure 3, g). These dependences are shown when the rotor is in the position corresponding to the maximum electromagnetic torque (figure 3, d) [19].

Take the magnitude of the linear load $A = A_m = 1$, then the average and the average square value of the current consumed by the motor from the power source are $I_m = I_{m.s.} = \pi$. Take the maximum value of MDF observed at $\alpha = \pi$, $F_m = 1$ (figure 3, b) [20]. Then in the analytical expressions for MDF $F$ and constructive induction $B$ ratio for the motor is $k = 2/\pi$. In relative units induction curve $B$ (figure 3, c) repeats the curve $F$ in areas located opposite poles, and $B = 0$ on sites belonging to the interpolar gap [21].

Electromagnetic torque is

$$T = RQ = RL \int_{0}^{2\pi} BA \cdot d\alpha = 2RL \int_{\pi/2}^{\pi} B(-1 + 2\alpha/\pi) \cdot 1 \cdot d\alpha = \pi/2$$

Here, $Q$ is a circumferential electromagnetic force; $L$ – the longitudinal length of the rotor [22].

When the spatial wave of linear load $A$ has a sinusoidal form (figure 4, a), the dependence of MDF is described by cosinusoidal (figure 4, b), induction in the air gap – by the discrete curve (figure 4, c) and specific tangential force by curve (figure 4, d) [23].

In this case, if the value of the average square current makes the same as in the first case, i.e. $I_{m.s.} = \pi$, the amplitude of linear load $A_m = \sqrt{2}$ (figure 4, a), the amplitude of the MDF $F_m = 2\sqrt{2}/\pi$ (figure 4, b), the amplitude of induction $B_m = 2\sqrt{2}/\pi$ (figure 4, b). Specific tangential electromagnetic forces, which are developing a motor according to the edges of the poles are too small, because one end has the small induction in the gap, and another has small linear load (figure 4, d) [24]. In addition, the root mean square value of the linear load is greater than its average value in $\pi/2$. As a result, at equal to the mean square currents the motor with a sine wave linear load develops smaller electromagnetic torque [25]:

$$T = RQ = 2RL \int_{0}^{\pi/2} (-2\sqrt{2}/\pi \cdot \cos\alpha) \cdot \sqrt{2} \sin\alpha \cdot d\alpha = 4/\pi.$$  

Comparing the magnitude of the electromagnetic torque at a rectangular spatial wave linear load and sinusoidal load, we see that in the first case [26], the electric motor develops specific electromagnetic torque more than in $\pi/8 \approx 1.23$.

At the last stage (figure 1, stage 6) assessment of possibilities of optimization of the trajectory of the electric drive was carried out on the example of the positional servodrive cold rolling mill pipes [27]. In this case, the electric drive was shown in figure 3 in the form of a two-mass system [28], where the first
circuit is loop speed control [29]; the second circuit is the circuit that takes into account the presence of the elastic element with torsional stiffness $C_1$ [30]. Circuit 3 takes into account the electromechanical influence of elastic vibrations on the operation of the circuit speed control [31]. The idea of selecting gear ratios is reduced to criterion of accuracy, which was proposed in [32].

![Diagram](image)

**Figure 3.** Graphs of the distribution along the circumference of the bore of the stator linear load (a) MDS (b), the magnetic induction in the gap (c) and specific tangential force (d) at a given rotor position, (e) and graph rectangular linear load.

5. **Practical results**
The practical application results of the proposed technique for high-precision mechanisms of rolling mills of tube-rolling production are presented below [33].

In figure 4 show the dependences taken from [34]. Figure 4, a shows how the amplitude of the resonance maximum depends on the gear ratios [35], and figure 4 is set to increase the load of the electric drive when changing the mechanical parameters of the converter [36]. If as a criterion to select the gear ratio $j$ according to the criterion [37] of ensuring the minimum amplitude [38] of the high frequency characteristics, it is possible to increase the speed of the drive approximately two times [39].

6. **Practical results**
1. The rapid growth of power electronics and computing in recent decades has led to a revision of traditional solutions in regulated agricultural electric drives, for example, steel optional traditional solutions such as 3 phases, sinusoidal currents in multiphase drives, and that, on the one hand opened new opportunities, and on the other hand, demanded a revision of many conventional views on the design of the adjustable electric drive. An example of this solution is the drive with FRRM that to be considered as a separate class of agricultural electric drives, designed primarily for the production
mechanisms of heavy and very heavy operating conditions, has elevated ranges of torques of the loads and velocities. The extension of these capabilities is achieved without increasing the nominal power of the electric drive and provides a significant improvement in the quality of technological regimes.

\[
A = A_n \cdot \sin(a) = \sqrt{A}
\]

\[
F = F_t + k \int \sin(a) = \frac{2\sqrt{A}}{\pi} \cos(a)
\]

where \( F_t = 0; k = \frac{2}{\pi} \)

\[
B = \begin{cases} 
0 & \text{at } 0 \leq a \leq \frac{2}{\pi} \\
\frac{2\sqrt{A}}{\pi} \cos(a) & \text{at } \frac{2}{\pi} \leq a \leq \pi \\
0 & \text{at } \pi \leq a \leq \frac{3\pi}{2}
\end{cases}
\]

\[
BA = \begin{cases} 
0 & \text{at } 0 \leq a \leq \frac{2}{\pi} \\
\frac{2}{\pi} \sin(2a) & \text{at } \frac{2}{\pi} \leq a \leq \pi \\
0 & \text{at } \pi \leq a \leq \frac{3\pi}{2}
\end{cases}
\]

\[
T = BQ = 2\pi \int_{\pi/2}^{\pi} \left( \frac{2\sqrt{A}}{\pi} \cos(a) \right) \sqrt{A} \cdot \sin(a) \cdot \frac{4}{\pi}
\]

**Figure 4.** Graphs of the distribution along the circumference of the bore of the stator linear load (a) MDS (b), the magnetic induction in the gap (c), and specific shear force (d) at a given rotor position, (e) sinusoidal graph linear load.

2. Proposed the concept of synthesis drives that implement a limit on the operation speed and handling ability, which from the position of a systematic approach contains a number of stages:

- synthesis of generalized mathematical models of the object, taking into account a detailed description of the system implementing the limit operating modes;
- assessment of possibilities of the control object;
- parametric optimization of electrotechnical complex with the position of the marginal characteristics;
- selection of simplified mathematical models of the electric drive;
- synthesis of structures and control systems that realize the limit operating modes;
- search phase trajectories of motion of the system “Electric drive - working body” implementing extreme modes of operation. The proposed algorithm is a series of interrelated stages, where in each stage can be done the clarification on the results of second stage, for example, detailing the requirements of the technological process at the last stage of the search for phase trajectories provides for a return to the parametric optimization of the electric drive.

**References**

[1] Sivkov A A and Gerasimov D Y. 2018 *Russian Electrical Eng.* 89(5) 340-2
[2] Gorozhankin A N, Gryzlov A A and Khayatov E S 2017 *Russian Electrical Eng.* 88(4) 201-4
[3] Mustafayev R I, Hasanova L H, Musaev M M 2018 *Russian Electrical Eng.* 89(5)322-7
[4] Zhuravlev A M and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 222-7
[5] Marikin A N, Miroshchenko V A, Nikitin V V and Tret’yakov A V 2017 Russian Electrical Eng. 88(10) 639-42
[6] Konyaev A Y, Bagin D N 2018 Russian Electrical Eng. 89(3) 168-73
[7] Belykh I A, Grigor’ev M A and Belousov E V 2017 Russian Electrical Eng. 88(4) 205-8
[8] Il’in M V, Bespalov N N, Kapitonov S S and Gulyaev I V 2017 Russian Electrical Eng. 88(6) 336-41
[9] Tereshkin V M, Grishin D A and Makulov I A 2018 Russian Electrical Eng. 89(5) 343-9
[10] Smirnov A Y, Dar’enkov A B, Zimin A Y and Usnunts-Kriger TN 2018 Russian Electrical Eng. 89(3) 147-51
[11] Chupin S A and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 240-4
[12] Bardin V M and Zemskov A V 2017 Russian Electrical Eng. 88(4) 229-232
[13] Myatezh S V, Shchurov N I and Ivanov V V 2018 Russian Electrical Eng. 89(5) 350-4
[14] Sandomirskii S G 2018 Russian Electrical Eng. 89(3) 199-203
[15] Belousov E V, Grigor’ev M A and Gryzlov A A 2017 Russian Electrical Eng. 88(4) 185-8
[16] Gulyaev I V, Tutaev G M and Volkov A V 2017 Russian Electrical Eng. 87(12) 693-7
[17] Denisov V A, Madyshev R R 2018 Russian Electrical Eng. 89(3) 210-4
[18] Gizatullin Z M, Nuriev M G and Gizatullin R M 2018 Russian Electrical Eng. 89(5) 328-31
[19] Khayatov E S and Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 197-200
[20] Andreev A M, Andreev I A and Lyakhovskii Y Z 2018 Russian Electrical Eng. 89(5) 318-21
[21] Tsytovich L I and Brylina O G 2016 Russian Electrical Eng. 87(12) 672-6
[22] Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 189-92
[23] Yakimov N D and Dmitrieva O S 2018 Russian Electrical Eng. 89(6), pp. 367-70
[24] Troitskii O A, Skvortsov O B and Stashenko V I 2018 Russian Electrical Eng. 89(3)143-6
[25] Dergachev P A, Kulaev Y V, Kurbatov P A and Kurbatova E P 2016 Russian Electrical Eng. 87(6) 356-62
[26] Rubtzov V P and Khomyakov I V 2018 Russian Electrical Eng. 89(6) 371-5
[27] Men’shenin A S and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 228-33
[28] Maznev A S, Plaks A V and Urashev S V 2016 Russian Electrical Eng. 87(5) 270-4
[29] Larin V S, Matveev D A and Zhuikov A V 2018 Russian Electrical Eng. 89(5) 313-7
[30] Baikov A I, Dar’enkov A B, Sosnina E N 2018 Russian Electrical Eng. 89(3) 161-7
[31] Gryzlov A A and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 245-8
[32] Nikitin V V, Marikin A N and Tret’yakov A V 2016 Russian Electrical Eng. 87(5) 260-5
[33] Zhukov V V, Shmelev A V and Mikhayev D V 2018 Russian Electrical Eng. 89(5) 332-9
[34] Butorin V A, Tkachev A N 2018 Russian Electrical Eng. 89(3) 182-5
[35] Belykh I A and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 234-9
[36] Alekseev V V, Emel’yanov A P and Kozyaryuk A E 2016 Russian Electrical Eng. 87(4) 181-8
[37] Gryzlov A A, Grigor’ev M A and Imanova A A 2017 Russian Electrical Eng. 88(4) 193-6
[38] Maiorov A V, Chelaznov A A and Shuntov A V 2018 Russian Electrical Eng. 89(6)398-401
[39] Denisov V A, Tret’yakova M N, Borodin O A 2018 Russian Electrical Eng. 89(3) 137-42