Design of electric drives with the improved mass-dimensional indicators for agricultural facilities

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Abstract. The article systematizes information on the structure of regulation of non-contact agricultural electric drives with improved mass-size parameters. Regulatory structures with independent control two-zone speed control and sequential excitation are proposed. It is shown that the best indicators are achieved in the scheme of sequential excitation and they reach values of 20-25%. Attention is drawn to the fact that structures with independent excitation are most relevant for dynamic mechanisms that realize the trajectory of motion with the maximum speed. Schemes of sequential excitation are most relevant for mechanisms with a large range of load variations on the motor shaft, for example, agricultural facilities. Schemes with two-zone speed control are most relevant for mechanisms that, with a large increase in speed, significantly reduce the load on the motor shaft.

1. Introduction
Agricultural electric drives with non-contact electrical machines can have improved mass and dimensional parameters due to the additional possibility of independent control of the armature excitation fluxes and the reaction field [1]. Therefore, the choice of the control laws of phase currents is an actual scientific and technical task. Taking into account the requirements of the technological process when selecting control structures, significantly better results than with traditional asynchronous electric drives can be achieved [2].

A variety of control systems of the agricultural electric drive with field regulated reluctance machine (FRRM) demands their classification [3]. The most important classification signs are way of excitation, scheme of power chains and functional sign (figure 1).

So, depending from a way of excitation of FRRM the control system of the agricultural electric drive can have several options: independent, sequential and two-zonal regulation.

The simplest at adjustment is the scheme of independent excitation since the flow of excitation remains to constants and consequently, there are constants coefficients: $C_T$ – proportionality of the torque to armature current; $C_E$ – proportionality of the electromotive force of speed EMF. For electric drives with a big range of change of the torque of loading inclusion of FRRM according to the scheme of sequential excitation is reasonable [4]. For those electric drives at which work at high speeds happens to the reduced values of the torque of a static load regulation of speed can be conducted below the main speed as in the electric drive with constant excitation, and at speeds above the main weakening of the field of excitation. Here the benefit from weakening of the motor field is higher the main and it turns out due to decrease in rated capacity of the converter [5].
Phase windings of FRRM can be connected to the individual current sources (CS). A power supply of the motor from two three-phase inverters is possible (in case of hexaphase FRRM) [6]. Generally, the m-phase motor the scheme of the m-phase inverter is applicable.

The scheme with individual power supplies gives the fullest use of the machine on dimensions, but in this case the number of valves of the converter will be maximum and equal 4m (m – number of phases). The scheme with m/3 three-phase bridge inverters gives the best use of the converter (provided that the number of phases of the machine is multiple to three). In this case the number of keys is equal 2m, at the same time specific indicators of the machine decrease by 15% [7]. If the number of phases of the machine isn't multiple to three, it is possible to use the m-phase inverter. Total number of keys is defined similarly 2m. Unfortunately, m-phase converters in the form of uniform modules are not produced by the electrotechnical industry in lots.

At last functional feature considers design features of the machine’s winding. In the simplest case each phase of the machine performs jointly functions of excitation and the armature [8]. Generally, if we set the task of the fullest use of the converter of dimensions, FRRM design with the stator windings performing separately functions of excitation and the armature can appear more optimum [9].

Further we will stop on structures with individual power supplies as simpler by the principle of work and allowing to investigate possibilities of the electrical machine.

2. Setting of the problem
On the basis of foregoing, the task of designing an electric drive system cannot be solved without a preliminary analysis of the control structures capabilities and the comparison of the specific indicators of electric drives with various types of electric machines, namely:

- synthesis of control structures of non-contact electric machines with independent control;
- analysis of specific indicators of asynchronous and non-contact electric drives;
- synthesis of control structures of systems with sequential excitation;
- analysis of specific indicators of electric drives’ control systems in sequential drive circuits and asynchronous electric drives;
- synthesis of control structures of electric drive systems with two-zone control;
- comparison of specific indicators with two-zone speed regulation.

3. The scheme of control with constant excitation of the electrical machine
One of possible versions [10] of the electric drive’s function scheme is shown in figure 2. Here stator windings are powered from six current sources. The task for current of armature windings (tension +

![Figure 1. Classification of control systems of the electric drive with FRRM.](image-url)
$U_{AR}$, and $-U_{AR}$) moves from exits of the speed control AR and A2 inverter through the node of forming of phase currents of NFPC. The non-regulated task for field current ($tension + U_i, -U_i$) moves from exits of a potentiometer of RP1 and the I2 (A3) inverter.

NFPC manages currents of current sources in chains of phase windings as the provision of a rotor $\alpha_r$ so that to be able to regulate the field of excitation and the field of reaction of the armature independently in the machine. Most visually the idea of work of this node is illustrated by option of contact (collector) NFPC (figure 3). Here on a shaft of a rotor of the motor four contact rings are established, K1 …, to K4 to which through brushes tension $+U_{AR}$ and $-U_{AR}$ moves and also $+U_f$ and $-U_f$. These rings are connected electrically with four commutator bars of P1, …, P4. Length of an arch of a commutator bar corresponds a polar arch of a rotor (plates of P2 and P4, on them move tension $+U_{AR}$ and $-U_{AR}$), or width of an interpolar interval (plates of P1 and P3, on them move $+U_f$ and $-U_f$). On the brush holder along a collector circle through each 30 electric degrees (in the hexaphase motor) six brushes from which signals of a task for all six current sources are removed are installed. At rotation of the motor’s shaft the entrance managing plug of a current source of each phase stator winding is connected in turn to the corresponding tension of a task: $+U_{AR}$, $+U_f$, $-U_{AR}$ and $-U_f$.

![Figure 2. The function chart of the electric drive with the electrical machine of independent excitation.](image)

Of course, in real schemes of the electric drive [11] contactless sensors of the rotor supply are used today. But the described collector sensor most visually illustrates the idea of work of NFPC: it is necessary to switch four managing signals as a turning angle of a rotor of $\alpha_r$ ($+U_f$ and $-U_f$, $+U_{AR}$ and $-U_{AR}$), giving them in the set sequence on managing entrances of current sources in chains of stator windings.

The external circuit – a contour of regulation of speed (figure 2) – is executed according to the standard scheme of the subordinated regulation, and it is adjusted by the AR speed controller, on one of entrances of which the signal from an exit of the adjuster of intensity AJ (on the scheme it isn't shown) is applied, and to another – tension of the UV speed sensor (on the scheme isn't shown) connected through RP potentiometer to the tacho generator BR is given. The speed controller contains the block of restriction of A1 which sets extreme values of currents of the armature and consequently, extreme values of the torque of FRRM [12].

At giving tension at AJ exit increases by an entrance of AJ of tension of Uen, then – tension at AR exit, and it causes emergence of tasks $+U_{AR}$ and $-U_{AR}$ on armature current. Tension $+U_{AR}$ and $-U_{AR}$ will cause course of the corresponding currents in current sources and armature windings, in turn these currents interact with the field of excitation so the motor M develops the torque, its rotor will come to rotation.

When tension at the exit of AJ is made even to Uen, its growth will stop. Transitional process of increase of speed of the electric drive will continue, until themselves tension from an exit of AJ and UV
won’t be made even yet. Then tension at the exit of AR will reduce or to zero (it will occur if the electric drive works in the mode of ideal idle running), or to the \( U_{AR} \) value corresponding to the torque of a static load on an motor shaft.

![Diagram](image)

**Figure 3.** Example of implementation of the simplest brush and contact (collector) sensor of provision of a rotor and node of forming of phase currents.  

When braking the electric drive work proceeds similarly, only the sign of tension at the exit of AR will change on opposite and, therefore, the sequence of tasks changes: + \( U_{AR} \), + \( U_t \), – \( U_{AR} \) and – \( U_t \) on – \( U_{AR} \), + \( U_t \), + \( U_{AR} \) and – \( U_t \) that will lead to change of the sequence of currents of the stator and consequently, to change of the sign of the electromagnetic torque.

Comparison of specific indicators of electric drives was carried out on the basis of physical and mathematical modeling data presented in [13, 14] and according to data presented in a number of sources on asynchronous electric drives [15, 16].

Thus, the results of the comparison showed that in electric drives with independent control, the specific indicators are better than asynchronous electric drives by 10-15% [17, 18]. The proposed regulatory schemes are most relevant for dynamic mechanisms that implement a trajectory with maximum speed.

4. **The scheme of control with sequential excitation of the electrical machine** 

In case of the scheme of the electric drive with sequential excitation [19] the excitation current changes in proportion to an absolute value of tension of \( U_{AR} \) for that the functional converter (figure 4, a) which tension at the exit is proportional to the \( U_{AR} \) module is used to.

In a zone of the small torques of loading tension AR at exit is little, therefore, also tension of a task for excitation currents \( U_t \) and – \( U_t \) are small, so, the value of an excitation current and the related losses in the electric drive decreases [20].

In a zone of the small torques of loading tension AR at exit is little, therefore, also tension of a task for excitation currents \( U_t \) and – \( U_t \) are small, so, the value of an excitation current and the related losses in the electric drive decreases [21].

In a zone of overloads increase in a signal of \( U_{AR} \) leads to increase a task for an excitation current. Growth of an excitation current allows to weaken or even to suppress the armatures degaussing influence of cross reaction at the expense of what the motor is capable to maintain short-term overloads on the torque (to 4 and more) significantly big, than in electric drives asynchronous or direct current.

Unlike the direct current drive in this scheme there are no difficulties in implementation of the brake modes and a reverse of the drive. So, at smooth decrease in a signal of a task at the exit of \( AJ U_{AR} \) signal changes the sign, as a result, – the sign of a task of current of the armature changes. Since the task for
an exitation current passes through the functional converter, there is no change of the sign of a task for an exitation current therefore the electromagnetic torque changes the direction, i.e. becomes brake.

Comparison of specific indicators of electric drives in structures with sequential excitation was performed on the basis of physical and mathematical modeling data presented in [17] and according to data presented in a number of sources on asynchronous electric drives.

Thus, the results of the comparison showed that in electric drives with sequential excitation, the specific parameters are better than asynchronous electric drives by (20-30)%.

5. The scheme of management with two-zonal regulation of motor speed

There is a number of industrial mechanisms at which operation of the electric drive at high speeds stems with the reduced values of a static load. For example, there are parallel planing machines at which during backward motion of a cutter shaving from the processed detail isn’t peeled therefore it is reasonable and possible to make backward motion with the increased speed belong to such mechanisms. Further, on reverse camps of hot rolling the last admissions of the rolled ingot proceed with small sizes of static torque, and length in these admissions is the biggest. It also promotes increase in speed of the drive.

In these cases it is reasonable to conduct regulation of rotational speed of the motor both change of a flow of excitation, and voltage variation on an equivalent armature winding. To improve power indicators of the drive, regulation of rotational speed of the motor ranging from zero to the main is carried out using voltage variation on equivalent armature windings at non-regulated tasks for current $+U_f$, $-U_f$, and in the range of speed higher the main – using change only an excitation flow at an invariable tension on the armature winding.

The scheme of the electric drive with two-zonal regulation of speed consists of two systems of regulation (figure 4, b): the systems of regulation with impact on tension of an equivalent armature winding and the system of regulation with impact on an motor flow. The first includes contours of current regulation of the armature and speed, differs in nothing from the described scheme with constant excitation. The second system is a voltage regulation contour on the armature (it is possible for motor EMF). The maximum of voltage output is limited by means of the block of restriction of BR and corresponds to rated current of excitation of the motor.

At a rotational speed below the main while tension at the exit of voltage sensor VS is lower than $U_i$ task tension, the voltage controller VC is in a saturated state therefore the exitation current of the motor is supported constant, equal to rated. Regulation of rotational speed of the motor is carried out only by the voltage variation on the armature winding.

When tension on the armature of the motor increases to the value corresponding to $U_i$, the VC regulator reduces the output signal, reducing thereby and settings $+U_i$ and $-U_i$. The flow in the motor begins to be weakened. If we use the VC voltage controller of integral type, then in the set electric drive modes of behavior at a speed above the main equality will always be observed.
In case of two-zonal regulation of speed the options with independent management of the field of excitation in which the signal on weakening of a flow of the motor is given as tension size at the exit of the setter of intensity of $ZI$ are possible.

Comparison of specific indicators of electric drives in structures with two-zone control was performed on the basis of physical and mathematical modeling data presented in [12] and according to data presented in a number of sources on asynchronous electric drives.

Thus, the results of the comparison showed that in electric drives with two-zone regulation the specific parameters turned out to be comparable with asynchronous electric drives. The proposed control schemes are most relevant for mechanisms that, with a significant increase in speed, significantly reduce the load on the motor shaft.

6. Synthesis of an external circuit of regulation of speed
We will consider that a current contour and consequently, the contour of indirect regulation of electromagnetic torque (at independent excitation) is ready for optimum high-speed performance. In this case it is necessary to perform tuning of a contour of speed which can be carried out on the same algorithm, as for electric drives of direct current.

The type of the speed regulator is defined by requirements of technology process. If the contour of speed regulation with the proportional regulator gives the required accuracy of maintenance that it should be applied as simpler. When required accuracy will be higher it is necessary to use more difficult proportional and integral regulator. Anyway setup of the speed regulator begins with proportional channel which coefficient is chosen by the rule of a technical optimum. Its extreme values will be limited not to stability conditions, but availability of reverse pulsations from a speed sensor exit. As shows the analysis of sizes of possible admissions at assembly of the details providing mechanical interface of the speed sensor and an output shaft of the operating mechanism, expected total sizes of misalignments of shaft of a reducer and rotor of the sensor according to the existing opportunities of technology of metalworking can be not less than $\varepsilon = 0.2$ mm at processing of the interfaced details by grinding, not less than 0.4 mm – at processing by boring, they can reach 0.5 mm and more – at turning. If we assume connection of shaft of sensors through the one-manual coupling, accept the radius of rotation of a lead of $R = 10$ mm, then there is a reverse error having rotating speed (a reverse error) and amplitude of $\varepsilon/R \approx 4 \ldots 5\%$. The regulations given on an entrance of high-precision system (or systems with high high-speed performance) and consequently, with high coefficient of strengthening of system of regulation, these signals lead to big forced fluctuations of current of the armature at constants of the torque of a static load and rotational speed of the drive. To increase high-speed performance of system and consequently, control band of speed it is possible to use the high-precision speed sensors and special couplings having high pliability in the axial and radial directions and which are very rigid at torque transfer. Setup of the integral channel of the $AR$ regulator is carried out according to the rule of symmetrical optimum.

7. Conclusions
As a result of comparison of specific indicators, it is established that due to the choice of the appropriate control structure in contactless agricultural electric drives, it is possible to significantly improve the mass-dimensional parameters of the systems. In this case, the sequential excitation schemes are most relevant for mechanisms with a large range of load variations on the motor shaft, for example traction mechanisms. Schemes of two-zone regulation are most relevant for mechanisms in which, with a significant increase in speed, the load on the motor shaft is significantly reduced.

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