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Synthesis of energy-efficient agriculture electric drives control system

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Synthesis of energy-efficient agriculture electric drives control system

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Abstract. In this paper the capabilities of the agriculture electric drive with rectangular shape of the phase current were analyzed, the level of pulsations of the electromagnetic torque in synchronous reluctance electric drives was found, the synthesis of the electric drive control system was considered, the characteristics of the electric drive under different control laws were compared. It is found that the use of high-speed current circuits (cutoff frequency => 200 rad/s) can significantly suppress the level of pulsations of the electromagnetic torque. It is shown that the use of flexible positive current feedback in switching phase currents can be considered as an additional opportunity to improve the performance of the current control circuit, as well as in conjunction with the previous method for suppressing torque pulsations in both static and dynamic modes.

1. Introduction
Several technological mechanisms of agriculture technological objects as an aggregated multi-motor electric drive, in which the speeds of several devices (grain cleaning systems) are consistent, impose increased requirements for electric drives on accuracy and reliability indicators [1, 2]. In this case, the electric drives must be contactless. Electric drives with synchronous reluctance machine are the most promising [3, 4]. Today can be called a few papers in which such problems as the problem of the design of contactless electrical machines, control systems synthesis, the problem of optimizing the weight and size indicators are solved [5]. At the same time, the problems of choosing the optimal form of phase current in a multiphase electric machine and a semiconductor frequency converter have not been solved. The urgency of solving this problem is dictated by the need to reduce the electrical losses on the switching while maintaining the mass of the machine.

2. Research problem statement
In order to improve the weight and size of the electric drive the problem of synthesis of the control structure, which allows to form the best conditions for the use of the machine on the electromagnetic torque, should be solved in the work. These problems are:

- analysis of the electric drive capabilities with the rectangular shape of the phase current;
- analysis of the torque pulsations in synchronous reluctance electric drives;
- synthesis of electric drive control system;
- the results of the comparison of the electric drive characteristics for different control laws.

In addition to the study of the specific characteristics of the electric drive using torque characteristics of some interest is the comparison of the electric drive acceleration time, depending on the form of current in the winding. Interest in this is caused by the publications of several authors who note the low dynamics of electric drives with high weight and size indicators [6, 7]. To study the influence of the phase current form on the speed of the electric drive, we use the assumption that the mechanical connections in the laboratory electric drive are absolutely rigid.

To study the effect of the phase current form on the acceleration speed of the electric drive, several experiments were carried out on the laboratory model. At the initial time in each of the experiments a current was supplied to the electric drive by a jump (from 3 to 8 A). Speed transients were recorded according to the speed sensor readings on the shaft of the unit using the Fluke 192 oscilloscope. The experiments were duplicated for each of the variants of the phase current form. The results are presented as a function of the acceleration time of the electric drive from the current value of the phase current in figure 1: curve 1 – sinusoidal current form, 2 – rectangular current form, 3 – three-stage current form. The shortest acceleration time in the entire range of amplitudes is achieved by using a rectangular current form. If we compare the data obtained in the experiments with the data given in the publications on modern electric drives of different types of close power [8, 9], it is possible to be convinced that the electric drive with FRRM does not concede in dynamism to modern adjustable electric drives of an alternating current and often surpasses samples of traditional options of electric drives.
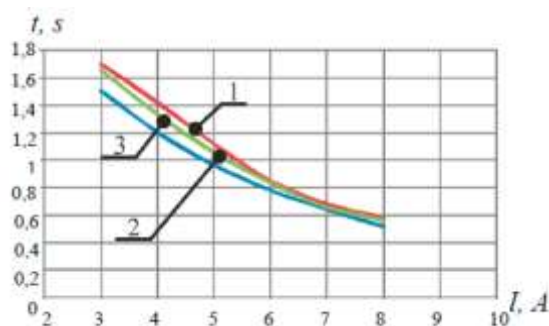

Figure 1. The dependence of the electric drive acceleration time on the current value of the phase current.

Summarizing the consideration of the phase current form options, the most promising option for obtaining high dynamic parameters and high weight and size parameters is a rectangular current form, which is confirmed by experimental research. However, sinusoidal and three-stage current forms can be recommended for use in the case of power from autonomous inverters, rather than individual current sources.

3. Analysis of torque pulsations in synchronous reluctance electric drives

The question of reducing the pulsations of the electromagnetic torque was first raised in asynchronous electric drives with frequency converters [10]. The use of vector torque control has solved most of these problems in this class [11]. However, this problem is still acute in multi-motor electric drives of this type, where vector control is not used [12, 13]. Other types of electric drives, in which the question of pulsations of the electromagnetic torque is quite acute is the class of switched electric drives, where the source of pulsations is the switching of phase currents in the rotor position function [14, 15]. This class includes the FRRM [16]. The most acute problem is in the switched-reluctance motors [17, 18]. In these publications [19, 20], the authors offer constructive solutions, with little consideration of the problem from the perspective of the control system.

Consider the pulsation of the electromagnetic torque of the FRRM due to the switching currents of the stator as a function of the rotation angle β [21]. Their physical appearance can be explained by experimental angular characteristics. As mentioned above, the electromagnetic torque depends on $\sin 2\beta$, therefore, the angular characteristic has two periods per rotation (curve 2, figure 2).
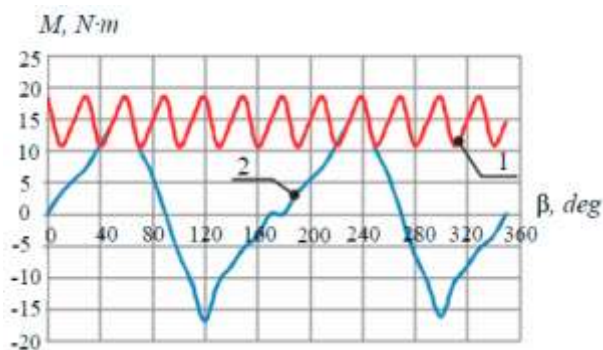
Figure 2. The design model of the grounding device of the open distributing device of the South Ural city district power station.

The rotor windings are sequentially switched, and they move from the excitation zone to the armature zone. Therefore, the curve of the electromagnetic torque in the function of the angle of the rotor rotation goes along the envelope of the group of angular characteristics shifted relative to each other by the value of the phase zone equal to 30 degrees for the 6-phase machine (curve 1, figure 2). From figure 2 it is seen that the maximum value of the pulsation in open-loop scheme for six-phase motor can be up to 40% of developed electromagnetic torque, which may lead to significant drawdown of the static torque. In addition, when powering FRRM from the switched converter, due to the finite speed of both the switched converter and control system components, the original pattern of pulsations (see figure 2) will be distorted, which may lead to a further increase in the amplitude of the pulsations. Therefore, when developing a control system, it is necessary to develop measures to combat pulsations. In the modern literature, the issues of electromagnetic torque pulsations in switched electric drives are considered without specifying specific methods for accounting for this phenomenon in the construction of control systems. The recommended methods for controlling pulsations are increasing the number of motor phases, as well as the use of additional windings, similar to the winding of additional poles of a DC machine. In the literature on FRRM one of the main assumptions in most studies [12] is that the current in the phase is switched instantly. Taking into account the accepted model of the reversed DC machine, as a starting point, we assume that at the optimal setting of the electric drive and the final number of phases m (in our case m=6), the amplitude of the pulsations depends on the switching time of the phase current in each of the windings and on its magnitude.

4. Synthesis of electric drive control system

This question is most acute when feeding the stator windings with a rectangular current form, since in this case the front of the current waveform changes when switching is the steepest. In the future, we assume that the switching time is the time of the current rise from zero to a given amplitude value with a single-phase switching.
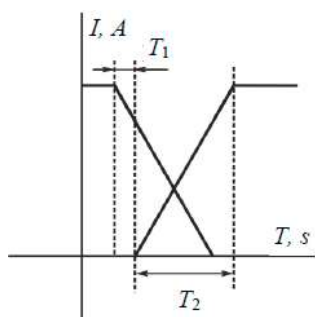

Figure 3. Diagram for the determination of the current switching time of FRRM.

Figure 3 shows the waveform view of the two-phase currents at the time of switching. Here, the delay time T_1 shows the software delay between switches due to the speed and correctness of the phase current formation node (PCFN); rise time T_2 shows the rise time of the current in the phase, determined by the speed of the current control circuit. To achieve the minimum pulsation of the electromagnetic torque it is necessary to achieve the minimum value of the designated time constants. This circumstance requires

an increase in the speed of the current control circuit. On the other hand, it is possible to compensate for the "failure" of the torque, if before switching artificially overestimate the value of the phase current. To do this, you can enter a flexible positive current feedback, triggered depending on the readings of the rotor position sensor. In order to experimentally check the validity of the above assumptions and assess the magnitude of the delay time and of rise T_1 and T_2 in the real electric drive, we consider the experimental waveforms of the phase current of the FRRM prototype electric drive. Figure 4 depicts the curves of a current: 1 – phase A, 2 – phase B (six-phase motor). The rise time of the current in the T_2 phase was 1 ms. The delay time T_1 is not shown in the figure, since it is necessary to significantly increase the scale of the oscillograms, which would lead to a loss of clarity of the figure. Indeed, the delay time T_1 depends on the speed of the PCFN, and since the controller operates at a clock frequency of 16 MHz, this time constant is small, and it can be neglected.
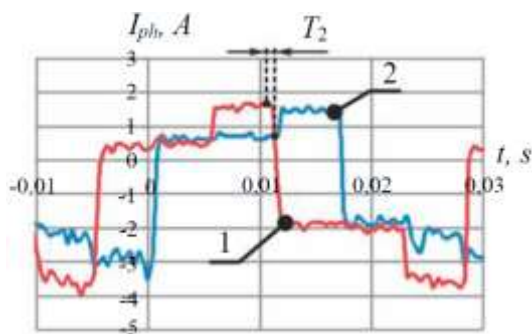

Figure 4. Experimental waveforms of the FRRM's current.

To reduce the effect of electromagnetic torque pulsations, we introduce a flexible positive corrective feedback on the phase current. Corrective link is implemented in software inside the microcontroller. Functionally, it works according to the following algorithm: when the rotor reaches a position close to the switching position, an additional U_C correction signal is fed to the CCR input (see figure 5).
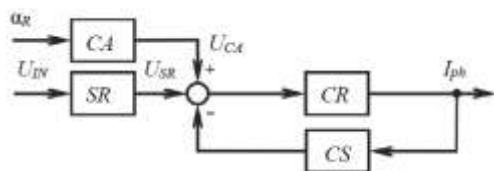

Figure 5. Structural scheme of the correction connection.

5. The results of the comparison of the electric drive characteristics for different control laws
When the rotor reaches the switching position, the corrective link is switched off. In the study of the corrective coupling, the following parameters were selected: the ratio of the correction signal amplitude U_C to the amplitude of the signal for setting the phase current U_{RS}, as well as the position of the rotor at which the correction signal is turned on. In the course of the experimental study, an absolute encoder with a resolution of 256 pulses was used as a position sensor, therefore, the correcting coupling also varied in terms of the torque of switching on the correction signal (P_C), which was counted by the number of pulses until the torque at which the P_F phase currents were switched. Figure 6 shows the dependence of the amplitude of the first harmonic of pulsations A (as a percentage of the effective value of the torque T) on the amplitude of the correction signal U_C (as a percentage of the signal setting U_{RS}). Curve 1 corresponds to $P_C = 1$ pulse to P_F, curve 2 – $P_C = 2$ pulses to P_F, curve 3 – $P_C = 3$ pulses to P_F. The figure shows that the most favorable from the point of the minimum torque pulsation are three points: $P_C = 1$, $U_C = 10\%$; $P_C = 1$, $U_C = 15\%$ and $P_C = 2$, $U_C = 10\%$. Of the three options, let us stop at the first, since in this case the time of action U_C and its amplitude are the smallest, therefore, the current value of the stator will be less.
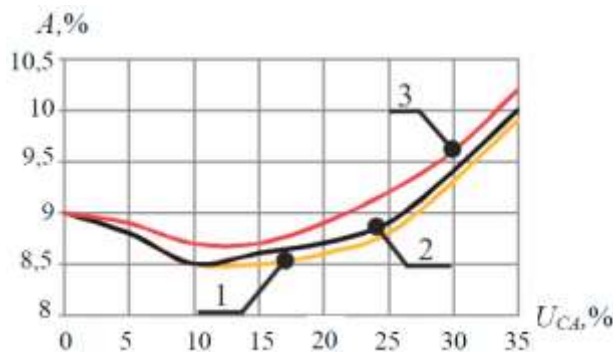
Figure 6. Diagram for the determination of corrective flexible feedback.

To track the effect of the current rise time in the phase T_1 on the pulsation of the electromagnetic torque, we will experimentally change the speed of the CCR, thereby changing the rise time of the current. In this case, fixed the average value of the torque on a shaft FRRM with the load machine. Since one of the initial conditions of the experiments took the optimal setting of the CCR, the delay time T_1 from 1 ms (see figure 4) up to 50 ms.

The dependence of the first harmonic amplitude of pulsations A on the delay time T_1 is considered. Three variants of the electric drive operation were compared: in the first variant, the corrective coupling was absent (figure 7 – curve 1), in the second case, the corrective coupling affected only the switched-off current period (falling front) (curve 2), in the third case, the corrective coupling affected both the falling front and the rising front (curve 3). With a switching time of up to 5 ms, the amplitude of the torque pulsations appears slightly, but by the switching time equal to 50 ms, the pulsation value reaches a tangible value and can lead to poor-quality operation of the electric drive. This fully confirms the hypothesis of an increase in torque pulsations in the non-ideal operation of the CCR.

Given that the current switching time depends on the speed of the current control circuit and, taking the maximum value of the delay time $T_1 = 5$ ms, at which the amplitude of the pulsation is small, we take the cutoff frequency of the CCR, necessary to eliminate the negative influence of the electromagnetic torque pulsation, approximately equal to 200 rad/s. This argument speaks in favor of a functional circuit with individual current sources, which has the maximum speed of the CCR among other variants of power circuits.

Regarding the correction relationships, it can be concluded that the correction on two fronts (falling and rising) allows to obtain an average torque of 10% more than in the system without correction in the case of high values of T_1. Therefore, the use of corrective feedback is most effective for control systems in which it is not possible to implement a high-speed speed control loop. In this case, we can achieve both the greatest efficiency of the corrective feedback, and significantly reduce the amplitude of the pulsations of the electromagnetic torque.

6. Conclusion

Summing up the experimental study of electromagnetic torque pulsations, let's formulate the main results of the study. First, we can recommend the creation and use of high-speed current circuits (cutoff frequency => 200 rad/s) as means of suppressing the pulsations of the electromagnetic torque. Secondly, the use of flexible positive current feedback in switching phase currents can be considered as an alternative to the previous method if it is impossible to create a high-speed CCR, as well as in conjunction with the previous method for suppressing torque pulsations in both static and dynamic modes.
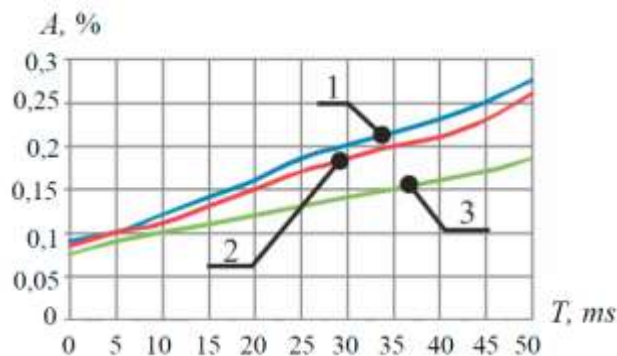
Figure 7. The dependence of the torque pulsations amplitude on the shaft of the current delay time.

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