The stages of development of high-performance adjustable AC drives for the objects of metallurgical production

M A Grigorev, A A Gryzlov and V S Katrichek
South Ural State University, 76, Lenin prospekt, Chelyabinsk, 454080, Russia

E-mail: grigorevma@susu.ru

Abstract. In the scientific article the requirements for regulated energy-efficient AC electric drives of metallurgical production facilities are formulated. The main stages of development of synchronous reluctance electric drives, including the development of power units, the synthesis of the control system, the choice of mathematical apparatus, as well as the experimental study of the developed system are shown. For the mechanism of a flying shear at PJSC “Chelyabinskii metalurgicheskiy kombinat” the use of contactless synchronous electric drive with brushless salient pole rotor is most effective, as this allows you to implement over the time of 4-6 times of the rated value and the ability to work in chemically aggressive conditions. It is shown that the task of providing the trajectory of motion can be implemented only in systems with independent control over the excitation channel and the armature. It is shown that as a mathematical description of the system, the structure of the electric drive can be used, similar to the DC drive, but the control signals are supplied from the phase current formation node. The method of experimental research shows that the synthesis of current control circuits can be performed by frequency response methods. Analysis of the experimental current waveforms showed that the separate control of the armature and excitation current is realized independently, while the specific indicators of the system were better than synchronous frequency-controlled electric drives by about 25.

1. Introduction
Modern regulated AC electric drives for metallurgical production facilities implement complex trajectories and at the same time provide the specified quality indicators with a high degree of accuracy [1]. With the improvement of technological processes, the requirements for modern regulated electric drives are increasing and they cannot always be implemented based on existing solutions [2]. So, on the one hand, the DC electric drive allows to realize movement with high quality but has a limited range of overloads on the torque and thus cannot be operated in aggressive conditions due to the presence of brush-collector contact. Contactless asynchronous electric drives have limitations on the limit value of the moment, as well as a limited range of speed control [3, 4]. Moreover, the adjustment indicators deteriorate significantly at low speed tasks. Synchronous electric drives with electromagnetic excitation have a maximum speed limit and cannot work in aggressive operating conditions [5].

On the other hand, there is a class of synchronous reluctance electric drives, which have high potential, namely, have a wide range of speed and torque control, and in the absence of contact nodes can operate in aggressive operating conditions [6].
Meanwhile, today there are no reliable and reasonable methods of engineering design of electric drives with such types of electric machines. In this context, the scientific objective of the development of controlled AC drives with highly effective electric machines based on FRRM is relevant.

2. Formulation of the research problem
Statement of the research problem. The scientific and technical problem of development of regulated AC drives requires solving the following tasks:

- analysis of the requirements of the process and the construction of load diagrams of the working member;
- the problem of designing an electromechanical converter is solved based on the analysis of the load diagram;
- the synthesis of the electric drive control system is performed according to the requirements of the electric drive control parameters;
- experimental studies of the electric drive, confirming the possibility of implementing the limit values of the system.

3. Development of the electric drive’s power part
The sample SGNW was made in the case of the asynchronous motor 4А100L4. This sample has the following parameters: \( P_H = 1.9 \) kW, \( U_H = 50 \) V, \( n_H = 1500 \) rpm; \( J = 0.011 \) kg/m\(^2\). The technical characteristics of the STCW and its prototype are presented in [7, 8]. To create an active mechanical load on the shaft of the investigated SRDNV, a DC machine of independent excitation P-41U4 (\( P_H = 3.2 \) kW, \( U_H = 220 \) V, \( n_H = 1500 \) rpm; \( J = 0.037 \) kg/m\(^2\)) was used, connected to the shaft of the investigated motor by a lobe clutch. The data of the loading machine are given in [9, 10]. The functional scheme of the stand is shown in figure 1.

![Figure 1. Functional diagram of the laboratory layout of the electric drive.](image)

As the power source for coils FRRM was selected converters brand Maxi-Maestro 200-25/50. These devices are two-link converters containing an uncontrolled rectifier and a transistor bridge with PWM. Converters Maxi-Maestro have an internal negative feedback current, therefore, represent the current...
sources. Due to the use of switches at the output with full controllability, these converters have high dynamic characteristics, do not have current fluctuations characteristic of thyristor rectifiers. Technical data of Maxi-Maestro converters are given in [11, 12].

As a power source for the windings of the loading machine, a thyristor converter of the MentorII M45R brand was chosen. This converter has adjustable armature current and armature voltage circuits, which allows the use of the loading machine as a source of speed and as a source of torque. Technical data of the converter of the loading machine are given in [13, 14].

4. Synthesis of electric drive control system

The use of individual current sources to power the phases of the motor involves the design of a frequency-current electric drive. The main element of the control system of such an electric drive is the phase current forming unit (PCFU), since the quality of the operation of this unit directly affects the operation of the current control circuits and significantly affects the operation of the electric drive. PCFU controls the currents of the current sources in the circuits of the phase windings as a function of the position of the rotor \( \alpha_p \) so that the excitation field and the field reaction of the armature windings when powering FRRM with rectangular current waveform can be regulated independently.

ATmega8535 microcontrollers were used as the main element of the PCFU, an absolute encoder of the OMRON E6C3-AG5C brand was used as the rotor position sensor. The encoder case was connected by a housing to the FRRM bearing shield, the motor and encoder shafts were connected by a lobe coupling. The absolute encoder is good because it gives a signal at a specific position of the rotor, which allows to simplify the operation of the control system. The disadvantage of this encoder (a small number of pulses per revolution – 256) is offset by the fact that the switching must be made only once in 30 degrees (for a six-phase motor), therefore, high accuracy is not required.

5. Mathematical model of the developed electric drive

The digital signals of the rotor position in the form of the gray code received on three of the microcontrollers: two of them intended for generating reference signals for the individual current sources of the FRRM’s phases, and the third for generating a feedback signal for speed. Setting signals were generated with a positive phase shift from 0 to 150 electric degrees for each phase. It may seem that the number of microcontrollers is excessive, however, the choice of such a number was dictated by two reasons: each microcontroller has only three independent analog outputs, the second reason was the separation of programs that perform different functions to avoid a negative decrease in performance when performing different purposes by one microcontroller at the same time.

The setting for microcontrollers came in the form of three analog signals. The first signal formed the setting for the armature current when the motor was powered by a rectangular current form and was the only reference signal when the motor was powered by a sinusoidal and three-stage current. The second signal formed a setting for the excitation current when the motor is powered by a rectangular current. The third signal made it possible to shift the encoder readings along the rotor position in the range of one turn, thereby achieving a shift between the stator field axis and the rotor axis. In the literature, this angle is usually denoted by \( \beta \) [15, 16]. The presence of such a signal requires additional adjustment of the electric drive but gives another tool to influence the torque triangle and allows you to optimally orient the rotor relative to the stator field (also the position sensor readings relative to the real position of the rotor).

When the motor is powered by various forms of current, different algorithms of programs were used, optimization of algorithms led to a mismatch of phase alternation when using different forms of current [17, 18]. Therefore, when setting up the electric drive, special attention was paid to the correct alternation of phases. It is worth paying attention to the following aspects: marking of the winding pins (the correct direction of the magnetic flux), setting the optimal angle between the encoder and the motor rotor.

In the case of the study of three-phase operation (as a traditional reluctance motor), the windings were connected according to the scheme (see figure 2) and the power was supplied from three current
sources. Power was produced as in the traditional three-phase symmetric system [19]. However, both the control laws of the FRRM and the variable current form were maintained [20]. This configuration is an intermediate between FRRM and classic reluctance machine, especially clearly in the power windings of a sinusoidal current waveform [21]. Experimental study of three-phase mode of operation allowed to estimate the reserves of this type of electric drive (the ability to work at the phases ICS failure or failure of one of the PCFU) [22, 23]. In addition, this mode made it possible to experimentally obtain a mode of operation corresponding to the operation of a traditional reluctance machine. Given the fact that both electric drives are made according to the same type of scheme, the reliability of the comparison can be considered high enough.

![Figure 2. Connection diagram of windings for three-phase mode.](image)

Analog controllers that set the signals for the first two analog inputs of the PCFU are standard elements of the system of pulse-phase control (SPPC) [24]. They are also implemented on OP-07C operational amplifiers. The controls are proportional, and the default gain is 1. The values of the input resistances and the feedback resistances defaults to 20 kΩ. The resistance of the feedback will also be exposed to 40, 100 and 400 ohms for the formation of different coefficients.

One of the common problems encountered when working with operational amplifiers is zero drift [25]. To avoid this phenomenon, the 1 and 5 legs of the operational amplifier were supplied with balancing voltage, reverse to the zero drift. This measure made it possible to adjust each operational amplifier individually and to achieve the absence of asymmetry of the task signals.

The control system is powered by DC +5, +15 and -15V. Power controls include microcontroller protection elements. The protection is organized for the following reasons: the input analog voltages of the microcontroller are the output voltages of the regulator. When exceeding the voltage of +6V or at a negative voltage in excess of 1V, the microcontroller can burn. For negative or high voltage protection, the analog inputs are protected by Schottky 1N5819 diodes.

The second problem with the setup was the elimination of interference with the system [26]. Initially, the output of the control system was interfered with a signal, which had a level of about +15V, which caused sharp current surges. To eliminate this phenomenon, the outputs were equipped with 1N5819 Schottky diodes to protect against voltages above +5V. The second effective measure was the potential separation of setting signals into current, excitation and displacement.

The microcontroller can output voltages from 0 to +5V. To control the phase currents, control voltages in the range -5V...+5V are required. The range expansion is achieved in 2 times by amplifying the signal with the output active filter on the operational amplifier. It is logical to assume that it is necessary to shift the input voltage of the filter to -2.5 V. Obtaining a stable voltage of -2.5 V was achieved by using the element LM431 (TL431). This element is a diode assembly for voltage stabilization.

Obtaining the necessary voltage was provided by connecting 1 and 3 pins of the element to a common point, and 2 pin through a resistor of 4.7 kΩ is connected to-15V. At the point of connection of the resistor and 2 pin, a stable voltage source of -2.5 V is formed. The schematic diagram of the control system is shown in [27].
The designed laboratory layout is a combination of analog and digital elements and has the following advantages:

- Simplicity and low-cost items of PCFU.
- Interchangeability of elements in the event of an accident.
- Flexibility-possibility of modernization.
- Small size and ease of assembly.

During the synthesis of the control system, the electronic elements were assembled on the printed circuit board. The board is supplied with supply voltage, setting signals and signals from the encoder. The general view of the printed circuit board is shown in [28, 29].

The prototype of FRRM adapted to replace the massive rotor on the rotor of a special form [30, 31]. The use of a specially shaped rotor was recommended in publications on the study of traditional reluctance motors, but this problem was not covered in the study of the FRRM. This interchangeability makes it possible to test experimentally the benefits of using a rotor with non-magnetic gaskets. Both types of rotors are shown in [32, 33].

6. Experimental studies of the developed system

The specifics of the work involved a large number of experiments. Some of them are typical, some of the experiments are unique and require description.

During the study of the physical properties of the converter-motor complex, the evaluation of the current values was carried out not only with the help of digital and switch devices, but also with the help of sensors on the Fluke oscilloscope [34]. This allowed to combine different methods of measurement and registration of physical quantities, which allows to obtain the most complete and accurate experimental data. In addition, this oscilloscope allows you to transfer experimental data to a personal computer for processing and processing with the help of software. Oscillograms of currents of different shapes are shown in figures 3. On the waveform of the rectangular current shape is deliberately shown the case where the armature current is not equal to that of the excitation current and clearly shows which of the time intervals what are the functions of the investigated phase. In addition to the specific parameters of the converter-motor complex, the dynamic parameters of this complex were estimated. In figure 4. the type of experimental curves of current and speed at acceleration of the electric drive is shown.

**Figure 3.** Waveform of sinusoidal current and rectangular current.
Figure 4. The experimental curves of velocity and phase current during acceleration: 1 – the speed of the electric drive, 2 – phase current of the electric drive.

For taking experimental frequency characteristics the device “Vector 2M” was used. The principle of construction of means of the Vector type frequency response analysis is based on direct digital measurement of real and imaginary frequency characteristics with use of the high-frequency generator of a test signal and vectors of switching, and also the integrator for averaging of signals from an output of synchronous detectors. Measurement errors of frequency characteristics can be divided into two groups: errors associated with the quality of the test signal; errors caused by noise in the measured signal. According to the error analysis of the first group of the direct method of measuring the frequency characteristics of the links with differentiating properties, the error in determining the frequency response will not exceed 2% if the harmonic coefficient of the test signal does not exceed 2%, which is achieved by the method of step approximation of the sine wave, which is implemented on the ROM (capacity is 256 binary 8-bit words). The second group of measurement errors due to noise in the measured signal decreases with increasing averaging periods of the detected signals. Given that the electric drive systems have a characteristic interference spectrum of frequencies that are multiples of 50 Hz mains supply, as shown in [35], the error of measurement of frequency characteristics will be in the range 3...4%, if: the interval of averaging of the detected signals will be approximately 6...12 seconds; the test signal frequency and signal interference are not less than 20%; and as the switching vector a “perfect” sine wave is used. This technique has been tested with the help of modern digital oscilloscope Fluke on a simple closed system. During the experiments, the readings obtained by the oscilloscope and the device “Vector 2M” diverged by no more than 3%.

7. Conclusion
For the mechanism of a flying shear at PJSC “Chelyabinskiy metalurgicheskiy kombinat” the use of contactless synchronous electric drive with brushless salient pole rotor is most effective, as this allows you to implement over the time of 4-6 times of the rated value and the ability to work in chemically aggressive conditions.

It is shown that the task of providing the trajectory of motion can be implemented only in systems with independent control over the excitation channel and the armature.

It is shown that as a mathematical description of the system, the structure of the electric drive can be used, similar to the DC drive, but the control signals are supplied from the phase current formation node.

The method of experimental research shows that the synthesis of current control circuits can be performed by frequency response methods. Analysis of the experimental current waveforms showed that the separate control of the armature and excitation current is realized independently, while the specific indicators of the system were better than synchronous frequency-controlled electric drives by about 25%.

Acknowledgement
South Ural State University is grateful for financial support of the Ministry of Education and Science of the Russian Federation (grant No 13.9662.2017/BP).

References
[1] Mikhailov V M and Sen’kov A P 2017 Russian Electrical Engineering 88(12) 814-7
[2] Faizrakhmanov R A, Polevshchikov I S, Khabibulin A F and Shklyaev F I 2017 Russian Electrical
Tarasov V A, Petrochenkov A B and Kavalerov B V 2017 Russian Electrical Engineering 88(11) 725-7

Zaitsev A A, Evstat’ev A M, Pegov D V and Krylov A V 2017 Russian Electrical Engineering 88(10) 676-80

Maznev A S, Nikitin A B, Kokurin I M, Kostrominov A M and Makarova E I 2017 Russian Electrical Engineering 88(10) 661-5

Marikin A N, Miroshchenko V A, Nikitin V V and Tret’yakov A V 2017 Russian Electrical Engineering 88(10) 639-42

Ivanov I A, Kiselev I G and Urushev S V 2017 Russian Electrical Engineering 88(10) 653-6

Pudovikov O E, Bespal’ko S V, Kiselev M D and Serdobintsev E V 2017 Russian Electrical Engineering 88(9) 563-7

Bestem’yanov P F 2017 Russian Electrical Engineering 88(9) 557-62

Baranov L A 2017 Russian Electrical Engineering 88(9) 579-82

Kotel’nikov A V, Shevlyugin M V and Zhumatova A A 2017 Russian Electrical Engineering 88(9) 586-91

Khorol’skii V Y, Ershov A B and Efano V A 2017 Russian Electrical Engineering 88(8) 490-3

Atanov I V, Khorol’skii V Y, Ershov A B and Efano A V 2017 Russian Electrical Engineering 88(8) 475-9

Baranov M I 2017 Russian Electrical Engineering 88(1) 19-22

Abramov B I, Datskovskii L K, Kuz’min I K and Shevyrev Y V 2017 Russian Electrical Engineering 88(3) 159-65

Voronin P A and Voronin I P 2017 Russian Electrical Engineering 88(8) 544-50

Anikuev S V, Atanov I V, Vorotnikov I N and Sharipov I K 2017 Russian Electrical Engineering 88(8) 494-7

Mironov Y M and Mironova A N 2017 Russian Electrical Engineering 88(7) 395-9

Kuvshinov G E, Komlev A V and Korshunov V N 2017 Russian Electrical Engineering 88(1) 34-9

Afanas’ev V V, Zaitsev Y M, Nikitina O A, Russova N V and Svidtsov G P 2017 Russian Electrical Engineering 88(7) 416-19

Mikheev G M, Ivanova T G, Konstantinov D I and Turdiev A K 2017 Russian Electrical Engineering 88(7) 423-9

Lapshina V A, Popov A A and Gulyaev I V 2017 Russian Electrical Engineering 88(6) 347-50

Sandovskii V A 2017 Russian Electrical Engineering 88(6) 372-7

Tereshkin V M and Grishin D A 2017 Russian Electrical Engineering 88(2) 71-6

Aliferov A I, Bikeev R A, Vlasov D S, Blank A V and Oshchepkova T B 2017 Russian Electrical Engineering 88(1) 30-3

Simakov G M and Filyushov Y P 2017 Russian Electrical Engineering 88(5) 296-302

Nemtsov M V and Trifanov G D 2017 Russian Electrical Engineering 88(5) 285-8

Vanyayev V V, Kopelovitch E A and Troitskiy M M 2017 Russian Electrical Engineering 88(5) 303-9

Abakumov A M, Gulyaev I V and Randin D G 2017 Russian Electrical Engineering 88(6) 326-30

Mitrofanov A N, Tret’yakov G M and Kopeikin S V 2017 Russian Electrical Engineering 88(3) 109-14

Rubtsov V P, Shcherbakov A V, Rubtsov M V and Zubarev M S 2017 Russian Electrical Engineering 88(2) 87-90

Golov V P, Martirosyan A A, Moskvin I A and Kormilitsyn D N 2017 Russian Electrical Engineering 88(2) 81-6

Bondar’ S N, Mastepanenko M A, Gabrielyan S Z and Vorotnikov I N 2017 Russian Electrical Engineering 88(8) 498-502
[34] Tutaev G M, Bobrov M A and Gulyaev I V 2017 *Russian Electrical Engineering* **88**(6) 321-5

[35] Bakhvalov Y A, Gorbatenko N I, Grechikhin V V and Yufanova A L 2017 *Russian Electrical Engineering* **88**(1) 15-8