Automation of adjustment stages by high-performance semiconductor converters

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Abstract. In this paper, methods of frequency synthesis of semiconductor converter control are proposed, allowing automation of the commissioning stages of high-performance semiconductor frequency converters. Attention is paid to increasing the reliability of the synthesis of the regulation system using the method of synchronous detection of measured signals. It is shown that the proposed frequency synthesis methods allow us to construct a mathematical model of the object being identified. The proposed generalized methods for the synthesis of current control loops, electromagnetic moment, based on the method of experimental frequency characteristics can be useful for technological objects, which allow the study of frequency characteristics without disturbing the conditions of the process. The proposed method has been quite successfully tested on the example of objects of drilling rigs: electric drive for lifting winch and electric drives for drilling pumps. By increasing the reliability of the synthesis of the current control loops and the electromagnetic torque of semiconductor converters, it was possible to significantly expand the uniform transmission band of the current control loop by about 20%. It is established that an experimental technique for determining the frequency characteristics of CCL has been proposed and tested, which makes it possible to evaluate the capabilities of CCLs of various electric drives and indicates the possibilities for expanding the band of uniform transmission of the frequencies of the CCLs under investigation. On the other hand, the extension of the band of uniform transmission of CCL allows increasing the limiting values of the rotational speed of the motor. This allows you to raise the speed of powerful compressor units without the use of multipliers to 6000 - 9000 rpm.

1. Introduction
Modern mechatronic systems are powered by semiconductor frequency converters. Mechatronic modules drive the actuating mechanisms that realize the specified trajectories of motion. In this case, the systems may be required to implement this motion on a high-precision trajectory, or to provide requirements for high overload capacity. The specified quality indicators can be provided only at high speed of the control circuits of electromagnetic torque and speed regulation. In systems of subordinate regulation, the task can be solved only if the maximum speed of the current control loop realized in a semiconductor frequency converter.

2. Setting the research problem
Synthesis of the control system of the regulated object involves the selection of the structure and parameters of the corrective relationships. These corrective relationships are based on the properties of the control object and the requirements of the working mechanism (technical specification). From the
point of view of the current development level of technology, there are typical tasks, the solution of which provides the majority of classes of typical electric drives. Among these tasks are:

1. Maintaining and limiting currents in dynamic modes of operation;
2. Maintaining a given speed over the entire control range;
3. Providing positional and tracking modes of operation;
4. Wide ranges of regulation of the coordinates of the electric drive.

The subordinate control system is the most common among the closed systems. The internal control circuit of the moment is covered by the external control circuit speed. Such a structure has several advantages [1], first of all, it has simplicity of setting up and universality of the scheme. Such schemes are typical both for DC drives [2] and for AC drives [3]. The similar system is also relevant for electric drives with field regulated reluctance machine FRRM. The use of a control system with a subordinate regulation for an electric drive with FRRM combines the convenience of customization according to traditional methods and the possibility of controlling armature currents and excitation according to the required law.

However, the number of tasks under consideration is not exhausted. For the class of electric drives with FRRM, there is an area of specific tasks that are typical only for this class of electric drives and are due to the additional attractive features of these electric drives. One of these tasks can be called the task of implementing high-speed electric drives for turbo mechanisms. The increased relevance of such a task for the class of electric drives with FRRM is dictated by the fact that FRRM has no limitations on the speed of an electromechanical nature. In this case, the electric drive has limitations only of mechanical (mechanical strength of structural elements) and electromagnetic (electromagnetic inertia of phase windings) of nature. In addition, the rotor has not a winding and the stator has multiphase design of the winding. It implies a lower inductance of the stator circuits, which in turn implies a lower electromagnetic inertia of the FRRM compared to traditional engine designs.

A similar problem was repeatedly solved in publications on low-power electric drives due to low electromagnetic time constants of systems [4]. The creation of high-speed electric drives is difficult in the electric drives of medium and high power, due to the higher electromagnetic inertia of the circuits. The most common design options in this class are systems in which an adjustable synchronous electric drive transmits motion to the turbo mechanism shaft through a multiplier [5].

Accounting for electromagnetic inertia in this case is very important, since a closed AC electric drive is a system with forced oscillations. Frequency is proportional to the speed of rotation. In the case when the object of regulation is little studied, there is a sharp increase in interest in the frequency methods of studying the developed electric drive systems. There is an apparatus for determining the experimental frequency characteristics of real objects. All this increases the value of experimental research. In the study of the experimental frequency characteristics of different systems, a practical mathematical model of the system acquires special value, which allows to analyze and substantiate the obtained characteristics.

The linear and linearized control systems have frequency analysis and synthesis methods, which allow a simple relationship of the frequency response with the structure and parameters of the circuit and its links. The possibility of experimental determination of frequency characteristics eliminates the need to determine the exact mathematical description of links. In addition, the principle of superposition is valid for linear systems: the response of the system to several simultaneous effects is equal to the sum of the reaction to each impact separately [6].

The direct experimental determination of the frequency response of any link or system of links implies the stability of this link (system). The equipment has capability for forming a harmonic signal of sufficient power at the system input and fixing the response of the system to it, i.e. the output signal of the system. Secondly, it has capability to analyze these signals and build the desired frequency characteristics [7].

As the experience of the development and experimental research of control systems of industrial electric drives shown that it is better to perform the experimental determination of the frequency response of the electric drive in closed systems. In this case, the real influence of the elements on each
other is preserved, which may be very far from the calculated one, primarily due to various interferences. Also, the presence of the main (external) feedback, even if during the experiment and far from the optimal setting, guarantees the existence of a drive mode near the working (or calculated) point. This not only preserves the real nature of the influence of the links on each other but is also important from the point of view of a safe experiment (for example, the appearance of high voltages and currents on the stator winding) [8].

Summarizing the above circumstances, we can conclude that the main task for this chapter is to approximate the method for determining the parameters and the synthesis of corrective links on the electric drive with the FRRM, taking into account the structural and functional features of this class of electric drives.

3. Methods of frequency synthesis of the control system for semiconductor converters

Consideration of the dynamic characteristics of the current circuit is fundamental importance. They are affecting not only the transient, but also the steady-state operating modes of the drive, because the AC drive has the physical properties of a system with forced oscillations. Due to this, the limited bandwidth of the current control loop will actually limit the maximum speed of the drive. For a long time, domestic authors paid little attention to this circumstance, but attempts were made in foreign literature to analyze [9] or propose solutions for this problem [10]. This gap should be explained by the fact that most high-speed electric drives are low-powered, due to this they have low electromagnetic inertia [11]. High speeds were achieved using multipliers between the electric drive and the turbo mechanism in electric drives of higher power [12].

The electric drive with FFRM has higher speed capabilities of current control circuit due to the absence of windings on the rotor and the low inertia of the stator circuits. We see the idea of solving the above problem by expanding the uniform frequency bandwidth. Since the well-known literature does not give an explicit answer to this question [13], it is necessary to experimentally compare and refine the dynamic properties of the control loop of the FRRM current using experimental frequency characteristics. The method of obtaining characteristics is maintained, as for electric DC drives [14].

In the previous paragraph, it was determined that the most interesting and convenient for research is the variant of structure with subordinate regulation. Proceeding from the analogy with the electric drive of direct current, we first draw a block diagram of one phase of the studied electric drive in the form presented in Figure 1. The direct channel has links: current regulator, autonomous inverter, phase winding, motor, feedback channel contains a current sensor link.

![Figure 1. Block diagram of current control loop.](image)

The properties of the motor under study play a decisive role in the description of the dynamics of the current drive control loop. Unlike DC electric drives, the current control loop of AC drive is located in each phase of a multiphase motor. Therefore, the properties of each individual current control loop will be superimposed properties due to the mutual influence of the phases on each other. Even in the absence of current in the remaining windings, dissipation fluxes are induced in the current control loop, this especially affects high frequencies. The effect of leakage fluxes can lead to a...
distortion of the shape of the frequency response, which can affect the assessment of the frequency properties of the phase current loop and, in the future, the dynamics of the drive with an FRRM.

Of particular interest are the features of the influence of this factor in close but having different design features of the performance of engines, such as FRRM and synchronous electric drive. Synchronous electric drive is widespread in industry. The development of modern conversion technology is increasingly expanding its use due to high specific indicators. Several scientific works of well-known domestic authors [15] are devoted to the examination and study of the properties of both a directly synchronous motor and a synchronous electric drive.

At the same time, the electric drive with FRRM has similar physical and design features, which in turn suggests the idea of an experimental study and comparison of the dynamic properties of these electric drives. The need for an experimental study is also dictated by the fact that in well-known publications on FRRM there is no detailed description of its dynamic properties [16]. At the same time, one of the most urgent tasks of the FRRM research is to compare various properties (in this case, dynamic) of this type of engines with engines of similar design with similar dimensions. Therefore, studies were conducted on electric motors of similar power (3 kW) and dimensions, which allows to increase the purity of the experiment and the entire comparative analysis.

The task of analyzing the properties of current control loop of an AC electric drive is complicated by the fact that in addition to the dynamic properties of each of the individual phase circuits directly. There is also a mutual influence between the phase circuits due to scattering flows. To consider the effect of the scattering fluxes, when comparing the current control loop of the synchronous machine and the FRRM, two experiments were conducted for each of the contours. On one of the windings, the current control loop was formed; in the first experiment, the rest of the motor windings were short-circuited, in the second case, the windings remained open. Further, both experiments were duplicated for the second electric motor. To more accurately account for this effect, the experiments were carried out without external feedbacks and an external current regulator. An input specifying action was taken as an input coordinate, and a signal from a current sensor was used as an output coordinate (see figure 1). For the greatest clarity, the results of all four experiments are presented in a single figure 2.

By the appearance of the characteristics, several conclusions can be drawn. Firstly, it is noticeable that current control loop of synchronous motor loses in speed of current control loop of FRRM. Secondly, the influence of the leakage fluxes in the current control loop of synchronous motor is much greater than in the current control loop of FRRM. This is explained by the presence of a large inductance of the excitation winding, which has a significant effect on the characteristics. Also, these two circumstances should be explained by the fact that with an increase in the number of phases m of the stator winding (the experiment was carried out at m = 6 for FRRM and m = 3 for synchronous motor) and the constant diameter of the stator bore decreases the phase zone width, the number of turns of the winding and its inductance scattering. For greater completeness, the picture also shows the current control loop phase response.

The type of phase characteristics is consistent in appearance with the shape of the amplitude-frequency characteristics. The system has a phase margin of about 90 degrees. Such a small value of the stock is because the system is open. In the case of current control loop of synchronous motor, the phase response is noticeably distorted due to the influence of leakage fluxes, thereby losing the stability margin even at very low frequencies. Based on the type of curves, it can be determined that the system in terms of dynamic properties on the structural diagram can be approximated in the frequency range from 0 to 10,000 rad / s either by an inertial link of the second order, or by two sequentially connected inertial links of the first order:

\[ W_{cl} = \frac{1}{((1+T_{1p})(1+T_{2p}))}. \]  

(1)
4. Suggestions and results of implementation
The proposed generalized methods for the synthesis of current control loops, electromagnetic torques based on the method of experimental frequency characteristics [17] can be used on technological objects where the study of frequency characteristics is allowed without violating the conditions of the technological process [18]. So, the proposed technique was successfully applied at the objects of drilling rigs [19] when adjusting the electric drive of a drilling rig. The proposed technique has made it possible to refine and improve the speed of the EMC regulation loop by about 20% [20].

5. Conclusions
Summing up the experiment, several valuable observations can be made out. Firstly, in electric drives with traditional synchronous motors, it is necessary to consider the influence of leakage fluxes on dynamic properties. Hypothetically, it can be argued that in larger machines the effect will increase. Secondly, the influence of scattering fluxes can be neglected due to the insignificance of their influence in electric drive with FRRM. In view of this influence, the dynamic properties of the FRRM current loop are higher than the corresponding dynamic properties of the current loop of a traditional synchronous motor. This allows us to conclude that the hypotheses expressed at the beginning of the chapter turned out to be true.

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