Methods of synthesis of energy-efficient structures for regulating semiconductor frequency converters

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Abstract. A mathematical model of the power part of the semiconductor converter was developed in this article. The analysis of processes in systems with synchronous electric drives. Experimental and analytical studies have shown that in electric drives with traditional synchronous motors with electromagnetic excitation it is necessary to take into account the influence of winding stray fluxes when setting up a control system. In electric drives with powers exceeding 1000 kW, the effect of leakage fluxes will increase significantly. Experimental methods have established that in multiphase electric drives, when the number of phases is greater than three, the influence of inductive scattering resistance can be neglected, and the mathematical model of the power section of a semiconductor converter is simplified. At the stages of adjustment, it is allowed to approximate the mathematical model of the system by sequential connection of aperiodic links of the first order, the time constants of which are specified during the study of frequency characteristics. The parameters of corrective relationships should also be refined by frequency response methods. Considered recommendations were successfully used in adjusting frequency converters for high-speed objects for LLC “RiK-Energo”.

1. Introduction

AC and DC drives are implemented as subordinate control structures. Multi-circuit control schemes are based on the principle that the internal subordinate circuit is a current loop or an indirect torque control loop [1]. This circuit is subordinated to an external speed control loop. In turn, the speed contour can be performed as a subordinate to the external contour of the regulation of the working body’s position. The main advantage of such structures is the simplicity of adjustment and configuration of the regulation structures, which includes replacing adjustment and configuration of a complex multi-loop scheme with a multi-stage adjustment, during which only one control loop is configured at each of the stages [2, 3]. The same regulatory structures are used when building a control system for frequency converters and other semiconductor devices [4]. When using structures of subordinate regulation for semiconductor devices, it is possible to apply already existing synthesis techniques used in electric drive systems, and this allows the implementation of structures with independent control channels for excitation and armature [5].

There are several technological mechanisms that impose increased demands on electric drives and semiconductor converters on speed limits and increasing the upper limit of the maximum output frequency of a semiconductor device [6, 7]. Thus, at sites with a turbomechanical characteristic, the expansion of the speed control range will make it possible to abandon the mechanical converter (gearbox) and attach the motor directly to the working member [8]. The main problem in building
systems of electric drives and semiconductor converters is the problem of reducing the electromagnetic inertia of power circuits, as well as expanding the range of speed control of an electric machine by increasing the mechanical strength of the rotor [9]. For example, the problems in question can be solved by using multiphase power circuits, which can significantly reduce the inductive resistance of the stator circuits [10, 11]. With this approach, the electromagnetic inertia of the armature and excitation control channels is significantly reduced.

The considered problem was previously solved for a class of low-power mechanisms, which are characterized by small time constants and, as a result, have high speed in the control circuit of the electromagnetic torque [12, 13]. If we consider the drives of medium and high power, the solution of the task is difficult. This is due to both the large electromagnetic inertia of the current control loop and the complexity of identifying the parameters of the unchanged part of the system. With this in mind, the task of developing an electric drive control structure, which allows to expand the range of speed control is relevant and needs to be addressed.

2. Formulation of the research problem

Adjustment and configuration of the system of regulation of the electric drive consists of a number of stages, namely, the solution of the problem of choosing the control structure, as well as the parameters of the corrective devices of the system. These tasks are solved based on the analysis of the requirements of the process and technical specifications. With that said, to achieve the goal, the following tasks must be accomplished:

- The choice of the mathematical apparatus and the synthesis of the mathematical model’s system;
- Development of a mathematical apparatus for describing processes in the power circuits of a semiconductor converter;
- Analysis of operating modes and processes in the frequency converter;
- Development of recommendations for the synthesis of the control system of a semiconductor frequency converter.

3. Review and selection of a mathematical model of the frequency converter

Expansion of the speed control range is possible only with a wide band of uniform transmission of the torque control loop [14]. In AC drives, with an increase in the speed demand, oscillatory processes may occur when the frequency referenced to speed is comparable to the cutoff frequency of the speed control loop [15]. Very often one has to deal with a situation when, when setting up an electric drive system, the system parameters are undefined or their values, which are given in the project documentation, are very approximate. In this situation, the methods of experimental analysis become relevant [16]. Special equipment may be available for analysis purposes. So, using devices that provide frequency identification of an object, one can obtain a reliable mathematical description of the system in the absence of information about the control object [17].

It is known that for systems whose parameters practically do not change, there is a rigid connection between the amplitude-frequency characteristics and the behavior of the system in the time domain [18, 19]. Moreover, knowing the experimental frequency characteristics of an object, one can get to recover the parameters of such a system and obtain a reliable mathematical description of the control object [20]. In the systems under consideration, the control action can be represented as the sum of the components of these actions.

To determine the bode plot of the control object, a harmonic test signal is sent to the system's input, as well as a synchronous signal detection device that allows the first harmonic of the output signal to be distinguished, since most of the objects studied are non-linear and therefore a wide spectral composition is formed at the output [21]. Since the adjustment and configuration of the system is performed for linear objects, it is necessary to single out the first harmonic of the output signal.

Under production conditions, the determination of system parameters and the study of amplitude-frequency characteristics are mostly reliably performed in systems closed in the main coordinate [22].
This approach allows us to consider the real interaction of the links on each other, namely: electromagnetic interaction of the motor windings [23], electromagnetic interference to the control channels [24]. In addition, setting up and configuring of the system in the presence of feedback allows you to simplify the conditions of the experiment, as well as reduce the likelihood of emergency situations, as well as set the nominal mode of operation and conduct research near operating points [25]. Moreover, the presence of armature current feedback allows us to limit the overload currents and thereby secure the operation of the semiconductor converter and the electric machine [26].

Thus, the development of structures of adjustable electric drives and semiconductor converters is recommended by using experimental frequency regulation methods. This approach allows, on the one hand, to reliably determine the parameters of the control object, and on the other hand, to select the parameters of control devices [27].

4. Mathematical description of the control object - semiconductor frequency converter

In general, a semiconductor converter can be described by a sufficiently complex function, since the processes of forming output variables contain a few complex algorithms: PWM modulation, direct coordinate transformation, spatial vector modulation, inverse coordinate transformation [28]. The elements of a semiconductor converter generally contain non-ideal links, on which direct and reverse voltages fall, they have limited speed and in the simplest case can be described by links of pure retardation [29]. The semiconductor converter control system is organized based on digital signal processors; therefore, when solving mathematical operations, it is required to consider the finite time of one program scan [30]. When an electrical machine is connected to the output of a semiconductor frequency converter, the mathematical description of the system is significantly complicated, so the number of cross-links increases significantly [31].

In multiphase AC drives the inductive scattering resistance of stator winding is very small [32], while in synchronous reluctance drives there is no winding on the rotor, which opens additional possibilities for increasing the speed of the current control loop [33]. In the existing scientific and technical literature there are no methods for the synthesis of current control loops for objects with a current frequency greater than 100 Hz.

The most common are structures with subordinate regulation of variables in which the internal control loop is subordinate to an external contour [34]. As a rule, such structures are made in the form of two-circuit, sometimes the number of which can be increased. If in traditional electric drives the internal control circuit is the torque circuit and the external is current circuit, then in semiconductor converters the internal high-speed circuit is a voltage regulation circuit, which allows linearizing the characteristics of the semiconductor converter near small voltages [35]. The external control loop is the current loop. Let us take as a model of a semiconductor converter the following sequential connection of elements of an autonomous inverter $AI$, phase winding of the $PW$ electrical machine, a regulating device $CR$, which compares the reference signal at the input with the output of the current sensor $CS$.

![Figure 1. Mathematical model of semiconductor converter and electric drive.](image)

When developing a mathematical model of the system, it is necessary to consider the properties of the load. Usually, the phase winding of an electrical machine is connected to the output of a semiconductor converter. Multiphase AC drives can be considered as multichannel systems with the mutual influence of each channel on each other, due to the magnetic coupling between the phase windings of electric machines [36]. When operating drives at higher speeds, this effect is enhanced [37]. Leakage flux can significantly distort the parameters of the system and, consequently, affect the setup and configuring conditions of the control loops. System setup conditions can be greatly facilitated if the
current control circuit received the largest possible speed and thereby compensate for the effect of external disturbances (including the effect of mutual inductance) on the frequency converter.

In the proposed model, the characteristics of semiconductor converters will be compared, to the output of which a synchronous reluctance motor and a synchronous motor with electromagnetic excitation are connected. This is due to the new features that allows modern semiconductor converters, as well as improved weight-size and control parameters of synchronous frequency-controlled drives [38]. A number of scientific publications present methods of setup and configuring, but there is no information on the possibility of identifying equipment parameters [39, 40].

5. Experimental studies and comparison of different control circuits for electric drives and semiconductor converters

The problem of analyzing the dynamic properties of a semiconductor converter is complicated by the need to consider the discrete mode of operation of modern frequency converters. In the discrete mode, the control system, which is made based on microprocessor control devices, and the power part, of the switch converter, which is regulated in the spatial vector modulation mode, also works. Studies were conducted for different modes of operation. First, all phase windings were short-circuited, and the test signal was applied only to one phase. In the next stage, the phase windings opened, and the same test signal was applied to one phase of the power plant. The same studies were carried out for other types of load: a synchronous reluctance motor with a reluctance rotor, a synchronous motor with electromagnetic excitation. These measurements were carried out in idle mode and at full load. The measurement results are shown in figure 2.

6. Analysis of the results

Analysis of the curves obtained (see figure 2) showed that: the speed of the current control loop of a synchronous motor is inferior to the current drive control loop with a synchronous reluctance machine; the mutual influence of leakage fluxes in an electric drive with a synchronous reluctance machine is attenuated significantly to a greater extent than in an electric drive with an excited rotor, which is caused by large values of the inductance of the excitation winding in a synchronous motor with an excited rotor. Since phase inductive scattering resistances in multiphase machines are significantly lower, they are much faster in electric drives with a synchronous reluctance machine in the current control loop (experimental studies were carried out for a laboratory sample with six phases). For a more accurate assessment of the stability of the system, figure 2 also shows the phase-frequency characteristics of current circuits for all cases of drive structures.

Analysis of the phase characteristics of the electric drive systems showed that they belong to the minimum phase links, and the phase margin exceeds 100 electrical degrees. This phase margin is because the control system was open at a variable speed. For a synchronous electric drive, the phase characteristic of the current loop of a synchronous motor differs significantly from the ideal one and is explained by the increased values of inductive scattering resistances. The obtained experimental curves of bode plot allow us to identify the object, as well as to approximate the system with analytical dependencies. Therefore, in the frequency range from 0 to 15 000 rad/s, the system can be approximated by a series connection of several links. In the simplest case, it can be two aperiodic links of the first order:

$$W_{CCL} = \frac{1}{(1+T_1p)(1+T_2p)}.$$  

7. Conclusion

Experimental and analytical studies have shown that in electric drives with conventional synchronous motors with electromagnetic excitation, when setting up a control system, it is necessary to consider the influence of winding stray fluxes. In electric drives with powers exceeding 1000 kW, the effect of leakage fluxes will increase significantly. Experimental methods have established that in multiphase electric drives, when the number of phases is greater than three, the influence of inductive scattering
resistance can be neglected, and the mathematical model of the power section of a semiconductor converter is simplified. Considered recommendations were successfully used in setting up frequency converters for high-speed objects for LLC “RiK-Energo”.

Figure 2. Frequency response for studying the effect of leakage fluxes:
1 – SM with open windings,
2 – SM with closed windings,
3 – SRM with open windings, 4 – SRM with closed windings.

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