Method of modeling electric drives with digital control systems

A. Mashkin^{1,*}, S. Fedotovskiy¹, M.G. Gunina², Ya.Ya. Solov'ev², and R.R. Dyganova³

¹ Vologda State University, Vologda, Russia

² Kyrgyz State Technical University named after I. Razzakov, Bishkek, Kyrgyzstan

³ Kazan State Power Engineering University, Kazan, Russia

Abstract. The use of computer equipment in the form of industrial controllers in the control systems of automated electric drives leads to the fact that standard methods and techniques for numerical simulation of such systems do not provide sufficiently reliable results. The feature of such systems is different mathematical description of the digital control system and the analog power section of the electric drive. The article proposes a modeling technique which takes into account the specifics of construction of modern electric drives.

1 Introduction

The emergence of fully controlled power semiconductor switches capable of switching sufficiently large currents at sufficiently large voltages, as well as development of sufficiently fast microcontrollers and industrial controllers, made it possible to switch to commercial production of automated electric drives (ED) with digital control systems in the 90s of the 20th century. The performance of modern controllers allows implementation of very complex control algorithms (with appropriate power supply from the power section of ED). The complexity of such systems implies that their investigation usually begins with construction of a mathematical model and analysis of its behavior. In this case, the electromechanical energy converter is a continuous (analog) part of the system, described by a system of differential equations. The control system is a discrete part of the system with its own discretization interval and, consequently, it should be described by a system of difference equations with its own cycle (interval) of quantization. Of course, modern semiconductor controlled energy converters are also discrete devices, however, the modulation frequencies of such keys are much higher than the quantization interval of the digital control system, especially if the latter is implemented by software. Thus, in order to ensure the accuracy of numerical modeling of such discrete-continuous systems, it is necessary to take into account this feature of its operating principles. The study of such ED systems began from the moment of their appearance [1–10] and continues at present [11–17]; however, during study of these systems by the method of mathematical modeling, they do not take into account this feature.

2 Method of modeling

The general methodology for modeling ED digital control systems can be divided into two steps. At the beginning calculation of control action with the selected quantization cycle is performed by solving the difference equation. Then transmission of this calculated control signal to the analog part occurs as well as calculation of transients in the analog subsystem with the selected integration step. At this, the signal at the input of control object during the current quantization cycle is considered unchanged. In fact, after output the control signal in the current quantization cycle and until the next cycle, the system will be in the open state (or in a state without control), but this is actually what happens in computer numerical control (CNC) systems.

The generalized algorithm used for modeling digital systems of electric drive is shown in Figure 1.

The first step is entering the initial data, including parameters of engine, semiconductor power converter, digital-to-analog converter, feedback sensors; integration step Δt ; quantization cycle; final time for calculating T_k , and some others. In the next step of the algorithm, the number of integration steps in the quantization interval of the digital control system K_{sh} is set equal to zero. After input of initial data, the DREG subroutine is called, which calculates the difference equation, with the help of which the digital control system is described. Next, the transition process is calculated in an electromechanical energy converter, which is a continuous (analog) part of the ED, by solving a system of differential equations describing it (the DIFUR subroutine). After checking the condition of reaching the final simulation time ($t \geq T_k$), the program is either stopped or the number of integration steps K_{sh} is increased by one. Further a check for reaching the maximum value K_{shmax} is performed, and if the condition is not met, the control actions remain

* Corresponding author: alexu79@mail.ru

unchanged or a new value of the digital control system output is calculated. The proposed method is suitable for modeling any ED with digital control systems (if there are appropriate mathematical models).

Fig. 1. The generalized algorithm for modeling.

As an example, we use the proposed methodology to simulate processes during the start-up of a direct current motor (DCM) with independent excitation 2PN90L, the parameters of which are given in Table 1.

Table 1.

P_n , kW	U_n , V	I_n , A	J , kg·m ²	N_n , rpm	L_a , H	r_y , Ohm	$r_{d.p.}$, Ohm
0.9	220	5.06	0.02	2120	0.064	2.85	1.731

In accordance with initial data presented in Table 1, the transfer function of the DCM is defined as:

$$W(p) = \frac{1.129}{(0.1009p + 1)(0.0163p + 1)}$$

We will compensate the highest time constant using the proportional-integral (PI) controller, assuming that the input driving voltage level of 10 V corresponds to the nominal motor speed. To simplify the analysis, we assume that semiconductor converter and the speed sensor are inertia-free and are described by proportional links with gain coefficients $k_{con} = 22$ (converter) and $k_{ss} = 0.045$ (speed sensor). Then the transfer function of the PI speed controller will be described as follows:

$$W_{sc}(p) = \frac{2.686(0.1009p + 1)}{0.1009p}$$

At the same time, for application of the described method, it is desirable to present a mathematical description of the DCM as a system of differential equations [18]:

$$\begin{cases} u_a(t) = i_a(t) \cdot R_a + L_a \cdot \frac{di_a(t)}{dt} + E_a \\ M - M_c = J \cdot \frac{d\omega(t)}{dt} \end{cases}$$

Figure 2 presents charts of speed and voltage at the engine armature when it is started and the rated load is charged.

The next step in the study is simulation of a discrete-continuous system, where the control object is described by the differential equations presented above, and the digital PI controller (in the case of its software implementation) is described by the following difference expression:

Fig. 2. The transient process charts when starting the DCM and charging the rated load: a) speed; b) armature voltage.

Fig. 3. Initial segment of the transient process chart when starting the DCM using the digital PI-controller: a) speed; b) armature voltage.

$$y[k] = y[k-1] + 2.699(x[k] - 0.99x[k-1]),$$

where $y[k]$ is the PI controller output in the current cycle; $y[k-1]$ is the PI controller output in the previous cycle; $x[k]$, $x[k-1]$ are the input signals of the PI controller (speed error signal) in the current and previous cycles, respectively.

Figure 3 shows the transient section when using a digital PI controller.

3 Conclusions

The obtained results allow us to make the following conclusions:

1. Transients with respect to the output coordinate in a continuous and discrete-continuous system are identical, consequently, the quality of control with a correctly synthesized digital controller is completely analogous to continuous control.

2. The behavior of the internal coordinates of the system (the input signal on the converter and, possibly, the output signal of the converter) differ significantly. The neglect of this feature does not provide an adequate picture of the behavior of all coordinates of the investigated (constructed) system. The described method allows one to simulate the dynamics of discrete-continuous systems as accurately as possible.

3. By changing the quantization cycle (with a corresponding recalculation of coefficients of the digital correction device), it is possible at the design stage to select the most appropriate quantization cycle (not necessarily the minimum) from the point of view of the control of the technological installation (process). In this case, the model of the control object remains unchanged; only the coefficients of the difference equation that describe the digital control system change.

The proposed method was successfully tested by the authors of this article in the systems described in Chapters 5–16, 5–17 and 6–9 of [3], although the methodology itself is practically not described in this book. Moreover, there are no recommendations given regarding the ratio of the quantization interval and the integration step, as well as that the digital control system

and the analog object are modeled differently in one program.

However, the application of this technique, in the opinion of the authors, will make it possible to simulate the behavior of electric drives controlled by a digital computer as accurately as possible, to obtain detailed information about the behavior of the internal coordinates of the system and, possibly, will ensure the acceleration of design and commissioning works.

References

- [1] M. Tomizuka, T.C. Tsao, K.K. Chew, *Amer. Contr. Conf. Rec. Discrete-time domain analysis and synthesis of repetitive controller* 860-66 (1988)
- [2] H.I. Cha, S.S. Kim, M.G. Kang, Y.H. Chung, *Real-time digital control of PWM inverter with PI compensator for uninterruptible power supply// IEEE IECON Conf. Rec.*, 1124-1128 (1990)
- [3] A.V. Basharin, Yu.V. Postnikov, *Examples of calculating an automated electric drive using a computer: A textbook for universities. - 3rd ed. - Leningrad: Energoatomizdat. Leningrad Department*, 512 (1990)
- [4] A.V. Basharin, L.P. Kozlova, S.B. Fedotovskij, *Principles of developing digital systems to control electric drivers, based in microprocessors. - Basharin A.V., Kozlova L.P., Fedotovskij S.B., Elektrotehnika*, **2**, 54-58 (1994)
- [5] A.M. Wu, J. Xiao, D. Marković, S.R. Sanders *Digital PWM Control: Application in Voltage Regulator Models//IEEE PESC*, 77-83 (1999)
- [6] A.V. Peterchev, S.R. Sanders, *Quantization resolution and limit cycle in digitally controlled PWM converters//IEEE PESC*, 465-471 (2001)
- [7] Z.Lu, Z. Qian, Y. Zeng, *Reduction of digital PWM limit ring with novel control algorithm//IEEE Applied Power Electronics Conference*, **1**, 521-534 (2001)
- [8] A. Prodic, D. Maksimovic, *Design of a digital PID regulator based on look-up tables for control of high-frequency DC-DC converters// Proc. IEEE Workshop on Computers in Power Electronics*, **18-22**, 3-4 (2002)

- [9] H. Peng, D. Maksimovic, A. Prodic, E. Alarcon, Modeling of quantization effects in digitally controlled DC-DC converters//35th Annual IEEE Power Electronics Specialists Conference 2004 (PESC'04) **6**, 4312-4318, June 2004.
- [10] D.M. Van de Sype, K. De Gusseme, F. De Belie, A.P. Van, den Bossche, J.A. Melkebeek, Small-signal z-domain analysis of digitally controlled converters//IEEE Trans. On Power Electronics, **21(2)**, March 2006.
- [11] A.V. Epifantsev, V.P. Krivosheev Parametric synthesis of a digital PI controller for objects of the first and second kind // Territory of New Opportunities. Bulletin of the Vladivostok State University of Economics and Service **2**, 95-100 (2011)
- [12] A. Anuchin, Methods of calculating the parameters of the digital PI controller in the electric drive // Electrical Engineering. **5**, 32-39 (2014)
- [13] A. Anuchin, Structures of a digital PI controller for an electric drive // Electrical Engineering. - **7**, 2-6 (2014)
- [14] B. Nasir, A. Raychowdhury, On limit cycle oscillations in discrete-time digital linear regulators//Proc. IEEE Appl. Power Electron. Conf. Expo., 371-376 (2015)
- [15] S.B. Fedotovskiy, *Synthesis of optimal digital control system for nonlinear electromechanical objects* / S.B. Fedotovskiy, O.A. Shakhov // Automation and energy saving of machine-building and metallurgical production, technology and reliability of machines, devices and equipment: materials of the International Scientific and Technical Conference. - Vologda: VOGU, 236-240 (2017)
- [16] Z. Zhang, Y. Wu, D. Gu, , et al: Current ripple mechanism with quantization in digital LLC converters for battery charging applications//IEEE Trans. Power Electron., **33(2)**, 1303–1312 (2018)
- [17] S.B. Fedotovskiy, *Method of calculating the quantization cycle for control systems of electromechanical objects* // Actual problems of science and practice in various sectors of the national economy: a collection of reports of the National Scientific and Practical Conference. Part 4 - Technical Sciences. Penza: PGUAS.164-169 (2018)
- [18] A.V. Mashkin, *Assessment current's pulsations in the PWM converter- DC motor system* // Modern informatization problems in the technological and telecommunication systems analysis and synthesis: Proc. of the XXIV-th International Open Science Conference – Yelm, WA, USA: Science Book Publishing House. 341-346 (2019)