Synthesis of an algorithm for controlling
an electric servo drive with a hybrid stepper motor

O V Goryachev and A O Stepochkin
Tula State University, 92, Lenin prospekt, Tula, 300012, Russia
E-mail: olegvorsau@mail.ru, s.a.o.1984@yandex.ru

Abstract. One of the promising directions in the development of an electric servo drive systems is the use of a hybrid stepper motor without a rotor position sensor in precise positioning systems. A procedure for synthesizing an algorithm for controlling an electric servo drive based on a hybrid stepper motor is considered. A method is proposed for switching the windings of an operating motor, which makes it possible to exclude resonance phenomena in the drive power system. An algorithm for vector control of the torque of a stepper motor is developed using the algorithm for observing the speed and angle of rotation. A simulation model of the electric servo drive with vector control and adaptive speed observer has been developed in the package Simulink. The effectiveness of the proposed methods for controlling the operating motor is confirmed by the results of dynamic modeling.

1. Introduction
Electric servo drive systems of devices are implemented, as a rule, on the basis of brushless DC motors (BLDC) using speed and angular position sensors. However, of considerable interest is the possibility of using a hybrid stepper motor instead of a BLDC, which will increase the reliability and reduce the total cost of the system by reducing the elemental composition of the drive by rejecting the corresponding sensors. When developing a control system for a motor of this type, it is necessary to take into account such features as the discreteness of the change in the angle of rotation and resonance phenomena that arise when the frequency of the supply voltage of the stator windings of a hybrid stepper motor coincides with the natural oscillation frequency of its electromechanical system, which causes a drop in the value of the torque developed by the motor and skipping steps [1]. To eliminate them, when implementing the drive control, as a rule, the step crushing mode (microstepping mode of operation of the hybrid stepper motor) is used, which is characterized by such disadvantages as a decrease in the maximum power and speed of the operating motor, as well as increased heat generation in the stator windings. At the same time, the most preferable from the point of view of dynamic and energy characteristics, the mode of operation of the hybrid stepper motor is the full-step mode, in which the tracking accuracy is limited by the step size.

2. Formation of a control algorithm for a hybrid stepper motor in an electric servo drive
Consider a variant of the implementation of a control system for an electric servo drive with programmed control of a hybrid stepper motor in two modes that differ in the set values of the drive mismatch $\Delta \theta$:
The operation of the motor in the mode $\Delta \theta \geq h$ is carried out in full-step mode in accordance with the well-known and widely used motion algorithms for stepper motors with constant speed or constant acceleration. At the same time, the control algorithm provides a real-time analysis of the specified angular displacement of the rotor of the hybrid stepper motor, and when it enters the range of values, $\Delta \theta < h$ it switches to the mode $\Delta \theta < h$ with vector control of the torque of the operating motor and feedback on speed and position, implemented using the algorithm for observing the speed and angle of rotation. A generalized functional diagram of the drive with a given control switching condition is shown in figure 1.

**Figure 1.** Generalized functional diagram of the electric servo drive on the basis of the hybrid stepper motor with control switching.

Figure 1 indicates: $h$—value of the step of the hybrid stepper motor; $\theta_{SP}$—specified value of the angle of rotation of the control object; $\theta_M$—angle of rotation of the motor; $\theta_M^*$—estimation of the angle of rotation of the motor; $\theta_L$—angle of rotation of the load; $\omega_M$—motor speed; $\omega_M^*$—estimation of motor speed; $\omega_L$—load speed; $U_{AC}$—pulse width modulation (PWM) phase A control input voltage signal; $U_{BC}$—pulse width modulation (PWM) phase B control input voltage signal; $i_A$—current in the winding of phase A of the motor; $i_B$—current in the winding of phase B of the motor; $i_A^*$—signal from the phase A current sensor; $i_B^*$—signal from the phase B current sensor; $\xi_{\theta \geq h}$—control signal for the mode $\Delta \theta \geq h$; $\xi_{\theta < h}$—control signal for the mode $\Delta \theta < h$.

Let’s consider separately each of the presented modes.

**3. Electric servo drive $\Delta \theta \geq h$ mode**

In order to fulfill the requirements for the electric servo drive in terms of accuracy, it is necessary to ensure the stable functioning of the operating motor in the entire operating frequency range, for which it is required to minimize or completely eliminate the drop in the value of the developed torque and the skipping of the steps of the hybrid stepper motor caused by resonance phenomena in the motor. In the context of this work, in order to eliminate resonance, it is proposed to use the method of commutation of the hybrid stepper motor windings in full-step mode, developed by the authors [2]. In order to calculate the value of the resonant frequencies, a system of mathematical models of the hybrid stepper motor was formed, presented in [3], including a numerical field
model with distributed parameters and an analytical model with lumped parameters based on the equivalent circuits of the electric and magnetic circuits of the machine. The view of these models is shown in the figures 2 and 3.

Figure 2. Numerical field model of the hybrid stepper motor.

Using the numerical field model, a system of assumptions was formed on the basis of which the analytical model of the electric motor was developed. These assumptions relate to the spatial structure and parameters of the magnetic field in a hybrid stepper motor in various operating modes.

Figure 3. Analytical model with lumped parameters based on the equivalent circuits of the electric and magnetic circuits.

Figure 3 indicates: \(A, B\) — phase windings; \(G_A, G_B\) — conductivity of air gaps between the rotor and stator in accordance with the location of the stator winding; \(i_A, i_B\) — currents in the phase windings; \(w\) — number of turns of the winding; \(H_{CF}\) — fictitious coercive force of the permanent magnet of the rotor; \(l_M\) — length of the section of the permanent magnet of the rotor along the center line.
With the help of the analytical model, the mechanical characteristics of the electric drive were calculated in various operating modes. This made it possible to analytically determine the ranges of resonant frequencies of the system. To ensure the required characteristics of the electric servo drive system in terms of speed and accuracy, an option for the implementation of an open-loop control of the hybrid stepper motor with a control algorithm that allows minimizing resonance phenomena at frequencies calculated using the resulting model is proposed.

The principle of the formation of phase voltages in the windings for the proposed method for switching the stator windings of the hybrid stepper motor in the mode is shown in figure 4.

**Figure 4.** Proposed method for switching the phase voltages of the hybrid stepper motor.

Figure 4 indicates: $U_A$, $U_B$—voltage in the phase windings; $T_1$, $T_2$, $T_3$, $T_4$—periods of energizing the phase windings; $t$—time.

The essence of this method is as follows. At the moment when the frequency of supplying the supply voltage of the motor phase reaches the calculated value equal to the value of the resonance frequency, the phase voltages are shifted relative to each other by a predetermined value. In this case, the number of equilibrium states of the rotor of the hybrid stepping motor does not change and has the same value as in the full step mode, but the duration of the periods of voltage supply alternates sequentially. It should be noted that the number of steps of the motor during the total period of power supply $T_1$, $T_2$, $T_3$, $T_4$ does not change. Experimental transient process that illustrates the operation of the proposed algorithm is shown in figure 5.

**Figure 5.** Experimental transient when the drive is operating at a resonant frequency.
To calculate the characteristics of an electric drive in the mode $\Delta \theta \geq h$, its simulation Simulink-model was developed [4]. Calculated transient processes that illustrate the operation of the electric servo drive system in the mode $\Delta \theta \geq h$ are shown in figure 6.

4. Electric servo drive $\Delta \theta < h$ mode

Examples of implementation of a vector control system for an electric drive are considered in a number of publications [5, 6]. In this study, for the operating mode of the drive $\Delta \theta < h$, the vector control system of the torque of the hybrid stepper motor is applied using the algorithm for observing the speed and angle of rotation. The type and structure of the state observer are proposed in accordance with the classification considered in [7]. Based on the given structure of the system and the number of measured parameters, for the implemented electric servo drive system, an adaptive speed observer can be used based on the mathematical model of the hybrid stepper motor considered in [4].

At the same time, the value of the angle of rotation is estimated by the integral of the speed estimate.

To ensure the fulfillment of the specified requirements for accuracy and speed, a proportional-integral-derivative (PID) controller is used in the control loop of the electric drive. The issues of selecting the parameters of the PID controller are discussed in detail in [8]. Based on [8], a comparative analysis of the presented methods was carried out, which showed that it is advisable to use a genetic algorithm to calculate the parameters of the PID controller, since the model of the power system of an electric drive is nonlinear. The method for calculating the parameters of the controller using a genetic algorithm is considered in publications [9] and [10]. Formed on the basis of the given structure, the Simulink-model of the electric servo drive based on hybrid stepper motor with vector control, adaptive speed observer and PID controller is shown in figure 7.
Figure 7. Simulink-model of the electric servo drive based on hybrid stepper motor with vector control, adaptive speed observer and PID controller.

This model can be used to calculate the static, dynamic and frequency characteristics of the electric servo drive system. In particular, results of calculating the transient process by the angle of rotation of the electric servo drive in the vector control mode are presented in figure 8.

Figure 8. Results of calculating the transient process by the angle of rotation of the electric servo drive based on hybrid stepper motor in the vector control mode.

The analysis of the presented transient process shows that the electric servo drive in the mismatch development mode $\Delta \theta < h$ meets the general requirements for static accuracy and quality indicators of the transient process for the servo-systems of an electric drive of various functional purposes.
5. Conclusions
An algorithm for controlling an electric servo drive based on hybrid stepper motor is presented, which makes it possible to effectively use the advantages and compensate for the disadvantages of the hybrid stepper motor when using it as an operating one in an electric drive system. Two modes of control of the motor in the electric servo drive are considered: 1) programmed control mode without feedback using a constant speed motion algorithm; 2) vector torque control mode using feedback implemented by an algorithm for observing the speed of the angle and motor rotation. The effectiveness of the proposed methods for controlling the operating motor is confirmed by the results of experimental research and dynamic modeling of the electric servo drive characteristics in the Simulink software package.

References
[1] Emelyanov A V and Shilin A N 2005 Stepper motors. Tutorial (Volgograd: VSTU)
[2] Goryachev O V, Efremeev A G, Morozov O O and Stepochkin A O 2019 Patent RU 2708380 Method for controlling a 2-phase electric stepper motor (Moscow: Rospatent)
[3] Volkov S V, Goryachev O V, Efremeev A G and Stepochkin A O 2019 Calculation of the parameters of a mathematical model of a hybrid electric stepper motor based on an analysis of the magnetostatic field pattern Mechatronics, automation and control 20(8) 482–9
[4] Stepochkin A O 2018 Modeling the operation of a hybrid electric stepper motor in the Simulink package Tidings of TalSU. Technical science 8 308–15
[5] Borisevich A V and Glebko D V 2014 Sensorless vector control of a stepper motor based on an extended Kalman filter Modern mechanical engineering. Science and education 4 473–84
[6] Kalachev Yu N 2013 Vector control (practice notes) (Moscow: EFO)
[7] Kalachev Yu N 2015 State observers in an electric vector drive (Moscow: EFO)
[8] O’Dwyer A 2009 Handbook of PI and PID controller tuning rules. 3rd ed. (London: Imperial College Press)
[9] Burakov M V 2008 Genetic Algorithm: Theory and Practice: A Study Guide (St. Petersburg: GUAP)
[10] Kucyj N N and Lukyanov N D 2012 Application of a genetic algorithm to optimize automatic systems with a PID controller Bulletin ISTU 6(65) 6–10