Simulink-aided Design and Implementation of Sensorless BLDC Motor Digital Control System

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Abstract. The paper describes the process of creating of brushless direct current motor’s digital control system. The target motor has no speed sensor, so back-EMF method is used for commutation control. Authors show how to model the control system in MatLab/Simulink and to test it onboard STM32F4 microcontroller. This technology allows to create the most flexible system, which will control possible with a personal computer by communication lines. It is possible to examine the signals in the circuit of the actuator without any external measuring instruments – testers, oscilloscopes, etc. – and output waveforms and measured values of signals directly on the host PC.

1. Introduction
Brushless direct current motor (BLDC) is becoming more widely used in various technical systems. From warships to tiny drones. In addition to the known advantages of these motors they have one major drawback – the need to control the rotor position. In most cases, their design does not include position sensors, which increases their reliability, and simplifies design, but it complicates the management process.

The study of the principles of management of such motors is necessary when training. Therefore, we have developed a number of laboratory applications including BLDC motor and control system. The installation can be programmed and controlled from MATLAB/Simulink. They also enable research and testing of adaptive control systems.

2. The structural design of the laboratory bench
The laboratory bench includes a control system, a control object, the set of feedback to monitor the state of the control object, the communication line with a PC for programming and debug the program loaded in the control system [1], as well as a line of communication with the personal computer to enable communication of the control system with control software and displays, installed on a personal computer.

This structure allows to create the most flexible system, which will control possible with a personal computer by communication lines. It is possible to examine the signals in the circuit of the actuator without any external measuring instruments – testers, oscilloscopes, etc. – and output waveforms and measured values of signals directly on the PC screen.

The structural diagram shown in figure 1.

Programming and debugging are loaded in the DSPS programs is made through a separate line ST-Link v2. Data exchange with a personal computer through the USB port of DSP.
The currents of the windings U, V and W are commutated by CMOS (or MOSFET) transistors [2] of the inverter, the channels of which are controlled by the signals Ch1-3 and Ch1n-3n of TIM8 timer counters.

![Diagram](image)

**Figure 1.** The functional diagram design of the laboratory bench.

The position control of the BLDC’s rotor is implemented using monitor value of the back EMF in (at the moment) the coil, one end of which is currently "in the air", i.e. not connected to ground nor to "+" supply. At this time, the winding rotating field of the rotor induced EMF the signal of which it is possible to determine the time of switching of the winding. Back EMF signals arrive at the inputs of the ADC unit.

Monitoring the current in each winding during the opening of the relevant transistor takes place via measurement of the voltage drop on the source resistor Rcs.
3. ARM Cortex-M microcontroller based control system
Modeling and writing a program control system is made in MATLAB/Simulink [3]. The program consists of two main blocks – start BLDC and the maximum speed with the office of the induced EMF in the windings.

Thus, the identification of the position of the rotor, due to the lack of built-in plug-in position sensors of the rotor is performed by controlling the induced EMF in the free phase. In each moment of time one of the phases of the motor is connected “+” power supply, and the other is “-”, and the remaining third phase is not connected to the power source, as if hanging in the air. Rotating the rotor moves through installed on the powerful permanent magnets of EDS in this free winding. As a result, change of magnetic poles extending in the rotation by the loose winding, the voltage on it is changed by changing the induced EMF. Measuring voltage on the free phase, we can determine the time of switching to the next position of the rotor. Usually determine the time of the voltage transition to the free phase through the zero point (half of the supply voltage). That is, system needs to track the moment when the passive phase’s voltage will be equal to the average point. Of course, for this method to work, the motor must rotate. This method works well at relatively high motor speeds. At low speed induced EMF may be insufficient to clearly determine the rotor position. However, this method is applied.

However, in most cases the midpoint is not available. I.e. there is no way to physically connect to it without disassembling the motor. In this case, often use the scheme with the creation of a virtual central point. This scheme is very simple and is used very often [4], but it has its drawbacks. For speed control BLDC motors use PWM to regulate power accordingly. Due to the PWM voltage mid-point is not permanent. It varies in a wide range of voltages. In order for the microcontroller was able to measure the voltage apply circuit coordination of the signals, voltage dividers and RC filters to smooth out fluctuations (Fig. 1). Thus, the midpoint voltage can be in the range from 0 to the supply voltage. In this case, for matching the signal levels of the digital control system (DCS) the necessary additional circuit solutions. In addition, to prevent accidents it is necessary to apply protection schemes the DCS. The presence of the voltage divider leads to a decrease in sensitivity at low motor speeds, and the presence of filter introduces latency. The delay is causing errors in determining the position of the rotor and may be critical for motor control at high speeds. Since the circuit with the virtual mid-point quite "noisy", it is possible to resort to another scheme where stable voltage mid-point is set separately and is dependent on the supply voltage.

Consider implementing the control of BLDC motors with digital control system. For formation of desired forms of voltages in phases and plug-phase displacements between the voltages necessary to implement a particular algorithm of switching of power switches of the inverter plug. For BLDC motors with trapezoidal distribution of magnetic field shape of the voltages in the windings shall be as given in figure 2 [4-5].

Figure 2. The switching sequence for all phases.
As can be seen from the diagrams, the phase is formed of a three-phase sequence voltages are shifted relative to each other at angle $120^\circ$. The data voltage can be generated switching sequence described by the truth table. This switching sequence has been implemented in the “Table of Truth” block. The internal structure of this block is presented in figure 3.

![Diagram](image)

**Figure 3.** The “Table of Truth” block implementation in Simulink.

The input “in1” of the block is fed a digital code represented by the number varying from 1 to 6, which, as a multiband switches (Multport Switch) depending on the values of the received code commute from one of six inputs of each switch on its output. Six outputs of the six switches correspond to the control channels of the respective power switches of the inverter plug.

The code input unit is formed by a counter (Fig. 4). Before applying for the entrance block of the truth table to the output code of the counter adds a unit to code the input to satisfy the input combinations of the truth table.
The pulse input of the counter are supplied either from the internal setpoint at the input “Clock”, or from the circuit of detection of the moments of switching of the induced EMF. The source select signal is produced via the control input of the “Switch” block (Fig. 5).

4. Detection of the moments of switching of the induced EMF

The detection scheme presented in the corresponding drawing graphic part. The scheme detects the achievement of the induced EMF thresholds “REFp” or “REFn”, corresponding to transitions of the EMF from the negative value to the positive and vice versa [5,13,14].

As noted, this method of detection does not work until the rotor is stationary. Therefore, the motorstart is carried out with supply on the winding of the sequence of voltages of low frequency. Created by the rotary field at the end of the poles “interlock” with the magnetic field of the rotor and drags it along, bringing the rotor from the stationary state. As a rule, before the rotor comes in random movement, the twitching of the rotor, often oscillatory in nature, which can be seen in the diagrams of signals of the drive.

When the rotor comes in uniform rotation, its speed can increase accelerating the change of condition of power switches according to the truth table. And then it can go to the control mode according to the detection. In this mode, the time of change of the output status table will be determined not by hard account the above-described counter, namely identifying moments.

As shown by case studies on a laboratory bench (Fig. 6, 7), form, character transitions and thresholds changes with the rotational speed of the rotor and load. From figure 7 it is seen that the uncorrected thresholds that gave an accurate detection at a low speed of rotation of the BLDC (Fig. 6), starts to give error detection with increasing speed of rotation.
In this regard, the control program introduced the ability to set thresholds in real-time through the communication control program on a PC with a digital control system. As can be seen, with the change of parameters of rotation of the motor, its load, the shape of the induced EMF, in many cases radically different from the theoretical shape. All this significantly complicates the process of automatic control of the BLDC motors without rotor position sensor, which requires a search for appropriate technical solutions.

The laboratory equipment is shown in Figure 8.

5. Conclusion
We have created the laboratory bench which allows us to study the BLDC motor and control systems of modern polyphasemotors. The system allows to simulate and control all the main signals in the power circuits and the control system by means of MATLAB/Simulink environment.

The system can be used for educational and research purposes.
6. Reference

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