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ELECTRONIC SPEED CONTROLLER DESIGN FOR A QUADCOPTER

BY

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Abstract. Mobility was, and it is one of the most important topics in our life. The main device that it is used for mobility is the motor, and nowadays more and more importance is granted to electric motors. For controlling such an electric motor, we need an Electronic Speed Controller (ESC). Increasing the performance of an electronic speed controller also increase the precision of an electric motor and in this way the mobility is improved in this area.

Key words: Electronic speed controller, PWM signals, BLDC motor control, gate driver, microcontroller.

1. Introduction

Electric motors are of several kinds: DC motors, BLDC motors and others. For each types of motors, different ESC are needed. In this article the ESC is designed for a BLDC motor (Cheng, 2011) without Hall sensors (Gamazo, 2010). Currently there are lots of ESC (Dejan, 2024) designs with lots of features.

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Some of them are very compressed, others are very powerful, others have safety features and so on. This article presents a solution that combines two main features – middle power and small size.

The main purpose of this ESC is to be used in controlling the motors of a quadcopter. This is mentioned because the requirements of a quadcopter or a drone emphasise: device weight, low noise, high efficiency and reliability, compact PCB and other. Due to these reasons the following components (motor and LiPo battery) were chosen with the following characteristics:

- EMAX C2216 BLDC motors

Table 1
Motor parameter

<table>
<tr><th>MODEL</th><th>KV (rpm/V)</th><th>Voltage (V)</th><th>Prop</th><th>Load Current (A)</th><th>Pull (g)</th><th>Power (W)</th><th>Effic. (g/W)</th><th>LiPo Cell</th><th>Weight</th></tr>
<tr><td rowspan="2">C2216</td><td rowspan="2">810</td><td>11.1</td><td>1147</td><td>12.9</td><td>832</td><td>143</td><td>5.8</td><td>3S</td><td rowspan="2">66</td></tr>
<tr><td>14.1</td><td>1038</td><td>15.6</td><td>1065</td><td>231</td><td>4.6</td><td>4S</td></tr>
</table>

- 4S LI-PO battery cells

Table 2
4S LiPo Cell parameters

Battery	Nr. Cells	Voltage	Capacity	Discharge rate
URUAV	4	14.8V	2200mA	70C

2. Electronic speed control design

Mainly an ESC consists of 3 main blocks: power, command and control. These main parts are shown in Fig. 1. Each main block will be explained in more detail at schematic level.

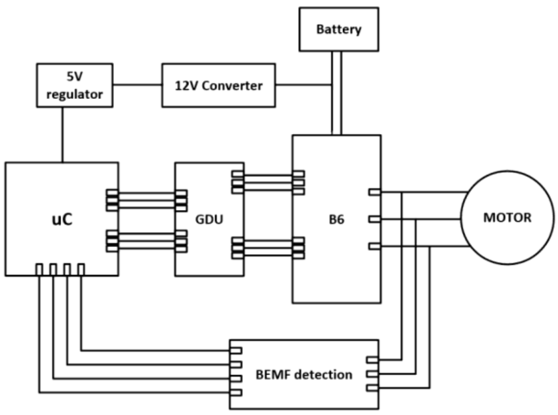

Fig. 1 – ESC – Block diagram.

The **Power block** consist of:
– A switching voltage source 12 V;
– A linear voltage stabilizer 5 V.
Figure 2 present a switching voltage source in order to obtain 12 V.

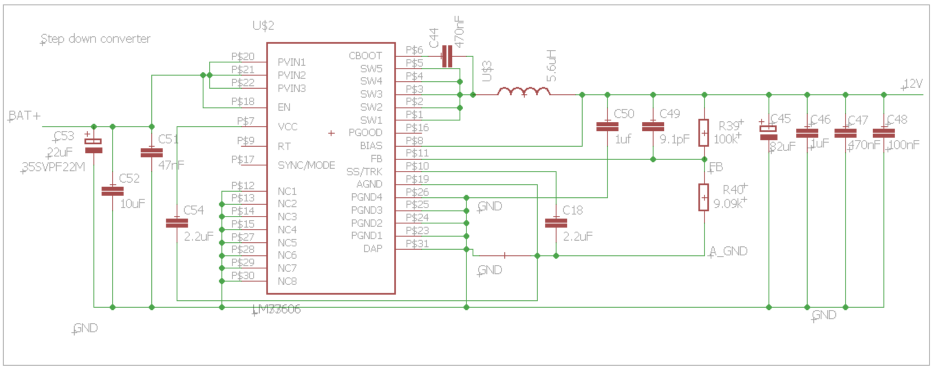

Fig. 2 – Power supply.

The buck converter made up with LM73606 (Neacsu, 2014) has the advantages that both power transistors (one for high-side and one for low-side) are integrated, and this increases its efficiency and eases its layout design to be populated on the smallest area possible. This converter is designed to have an output voltage of 12 V with 1.5 A for powering the gate driver and to ensure the voltage input of linear regulator. The output voltage is maintained at 12 V with the help of the voltage divider (R_{FBT} and R_{FBB}) that gives the respective feedback (Drury, 2003). The recommended value for R_{FBT} is 100 kΩ and R_{FBB} is calculated with this formula:

$$R_{FBB} = (VFB / (VOUT - VFB)) * R_{FBT} \qquad V_{OUT} = 12\text{ V} \tag{1}$$

$$V_{FB}\text{ (feedback voltage)} = 1\text{ V},\ R_{FBB} = (1\text{ V} / 11\text{ V}) *100\text{ k}\Omega = 9.09\text{ k}\Omega \tag{2}$$

In parallel with R_{FBT} we have connected a capacitor. This place an additional zero before crossover frequency of the control loop to boost phase margin.

$$C_{FF} = \frac{1}{2 \times \pi \times f_x} \times \frac{1}{\sqrt{R_{FBT} \times (R_{FBT} // R_{FBB})}} \tag{3}$$

Applying this formula will obtain C_{FF} = 9.1 pF

Figure 3 presents the feedback obtained from C_{FF} capacitor.

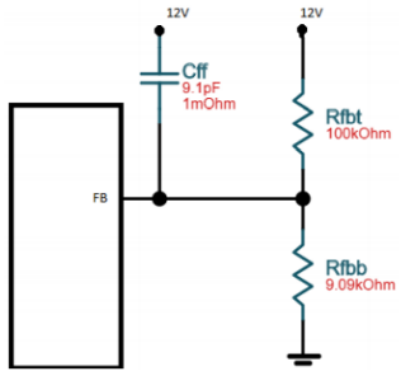

Fig. 3 – Capacitor feedback.

Coil selection – The maximum output current of this converter is 6 A so in order to have the best inductance of the coil, the current ripple must have a value between 10% and 30% from the maximum output current.

$$L = (V_{IN}-V_{OUT})*D / (f_{SW}*I_{Lriplu}) \qquad I_{LMAX}=6\ A \tag{4}$$

$$I_{Lriplu} = (0.1 \text{ -> } 0.3)*I_{LMAX} \qquad D=V_{OUT} / V_{IN} \tag{5}$$

The value of the coil is chosen by applying the formula:

$$L >= V_{OUT} / (N * F_{SW}) \qquad N= 3.6 \tag{6}$$

$$F_{SW} = 500\ kHz \qquad V_{OUT} = 12\ V \tag{7}$$

In this case, for a current of 1.5 A, a 5.6 μH inductor is chosen and the current ripple is 1.63 which means 19%.

Input capacitors – For protecting the IC against voltage spike or voltage drop, is recommended to be placed some capacitors on the input of IC. We chose one bulk capacitor of 22 μF and other two ceramic capacitor for decupling (one of 47 nF and the other one of 10 μF). Also, for ensuring a stable signal we used a 2.2 μF capacitor on VCC pin.

Bootstrap and Bias capacitors – This IC LM73606 has an integrated bootstrap diode and in the datasheet, it is recommended to use a bootstrap capacitor of 470 nF. An output voltage for lower power loss is being connected to the Bias pin and a capacitor of 1uF must be connected to GND near the Bias pin.

Output capacitors - These capacitors are used for filtering the current that flow out from the coil. Here, an polarized capacitor of 82 μF is placed, and for obtaining a lower ESR - Equivalent Series Resistance (Chidley, 2017) some ceramic capacitors are being used: 1 μF, 470 nF and 100 nF.

In Fig. 4 is presented a 5 V Linear voltage regulator.

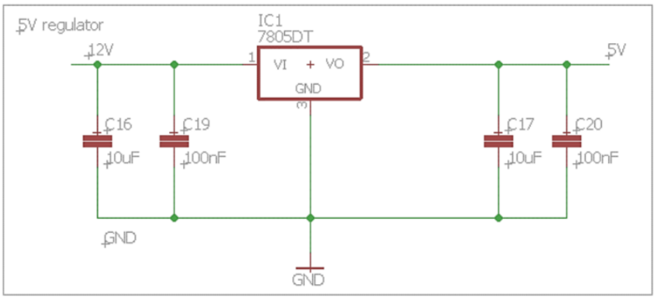

Fig. 4 – Voltage regulator made up with LM7805.

We use a simple LM7805 voltage stabilizer in order to power up the microcontroller. The maximum current provided by this IC is 1.5 Amps which covers the current need. Also, two capacitors are being placed. Both on the input and on the output for noise filtering: one of 10 μF and one of 100 nF.

In the following figures there are presented the command-and-control block made up by a microcontroller, gate driver and transistors. Figure 5 presents the microcontroller.

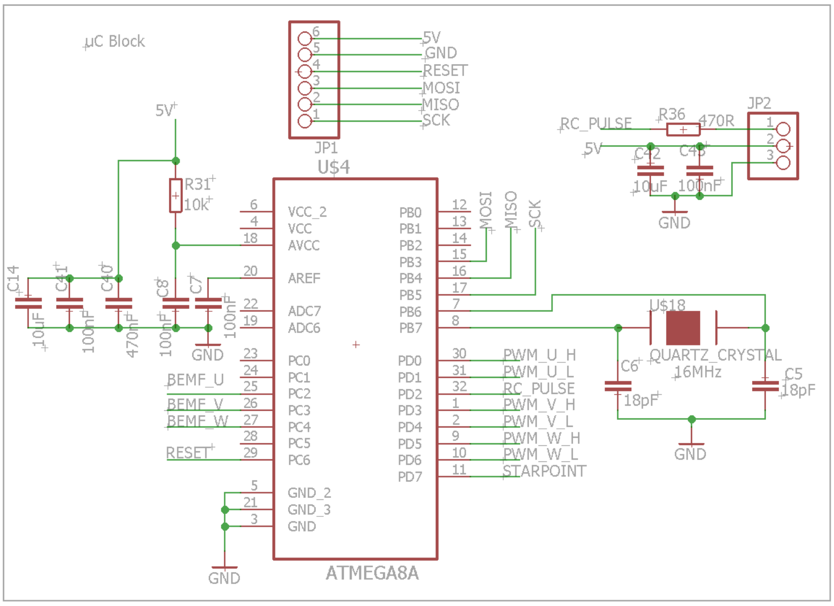

Fig. 5 – Microcontroller connections.

The ATMEGA8A microcontroller (Microchip, 2020) was chosen because it is very used in similar applications, is reliable and has low cost. The code used is open source, is working in a closed loop, has bidirectional operations and has a very quick response. It is written in assembly and has three files:

– M8def.inc - the timers, serial interfaces, ports and so on are being defined here;

– BLHeli.asm (Skaug, 2018) - this is the main file;

– other file in which all the pins and ports are being specified.

An external resonator was chosen because this configuration is more stable (Adafruit, 2024). The resonator is a SMD crystal oscillator ABM3-16.000MHZ-B2-T and in datasheet it is given the formula for calculating the value of capacitors:

$$CL = (C1*C2)/(C1+C2) + Cstray \tag{8}$$

$$CL=18pF,\ Cstray = 2\text{-}5pF \tag{9}$$

For filtering the power on the input of the microcontroller, three ceramic capacitors are being used:10 μF, 470 nF and 100 nF.

In Fig. 6 is presented the gate driver used to amplifies the signals coming from microcontroller, for controlling the output transistors.

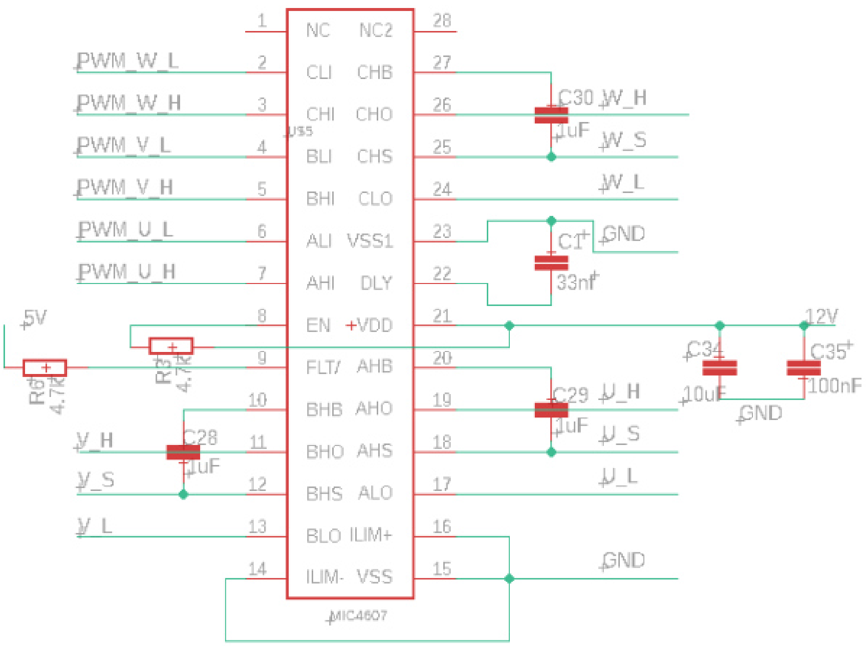

Fig. 6 – Gate driver connexions.

We chose the MIC4607 gate driver because of its advantages:

– It is a three-phase gate driver (all in one Integrated Circuit)

– Supports voltages up to 85 V

– Has protection for overcurrent and short-circuit

– Both transistors and bootstrap diodes are being integrated in case

– It is highly compact

– Has a low power consumption

– Has protection for the simultaneous opening of high side and low side transistors in any mode of operation

– The propagation time is very low – 35 ns.

In this application the first variant of IC is being used, because it has six independent PWM inputs. The other version has only three. The MIC4607 IC has an Enable pin that must be connected to the power supply (12 V) through a resistor.

A delay made up by a capacitor of 33 nF is connected to GND. This determines the time in which the IC outputs are blocked in case of a reset or restart. This capacitor was calculated with the following formula:

$$T_{DLY} = (C_{DLY} * V_{DLY+})/I_{DLY}; \quad C_{DLY} = 33 \text{ nF}; \quad V_{DLY} = 1.5 \text{ V} \tag{10}$$

$$IDLY = 0.44uA \; TDLY = (33*10^{-9}F * 1.5V) / 0.44*10^{-6} = 90 \text{ ms} \tag{11}$$

Overcurrent protection is activated when FLT/ pin is connected to 5 V through a resistor of the order of a few kΩ. In this case a 4.7 kΩ resistor was used. Driver gates used three bootstrap circuits integrated within and it is necessary to connect only the capacitors near xHB and xHS pins. xHS pins are being connected with transistor gates through 3 Ω resistors.

Decoupling capacitors from VDD pin must have at least a capacity of 2.2 μF, so for this purpose 10 μF and 100 nF capacitors were populated for better filtering and lower voltage ripple (Chidley, 2017).

Transistors blocks

SQJB42EP transistors (Vishay Siliconix, 2016) were chosen because they have integrated in one case two N-channel mosfet. Each of them supports 30 Amps at 40 Volts and have an internal resistance of 9.5 mΩ.

R10 – R15 resistors with 10 kΩ resistance are connected between gates and sources for transistor protection so that the signals do not get disturbed. Other resistors from the gates of the transistors are used for protecting the gate.

D1 – D9 also protect the transistors and the gate driver. During the transistors switching, some negative voltages can appear, and these are eliminated through these diodes.

Three bulk capacitors are connected on transistor gates for storing local energy and to eliminate the voltage drops that can be present. Their value is

330 μF. In parallel with each of them there are three ceramic capacitors of 2.2 μF connected for obtaining a lower ESR (Chidley, 2017).

Figure 7 present the transistors block connections in order to obtain a three phase inverter.

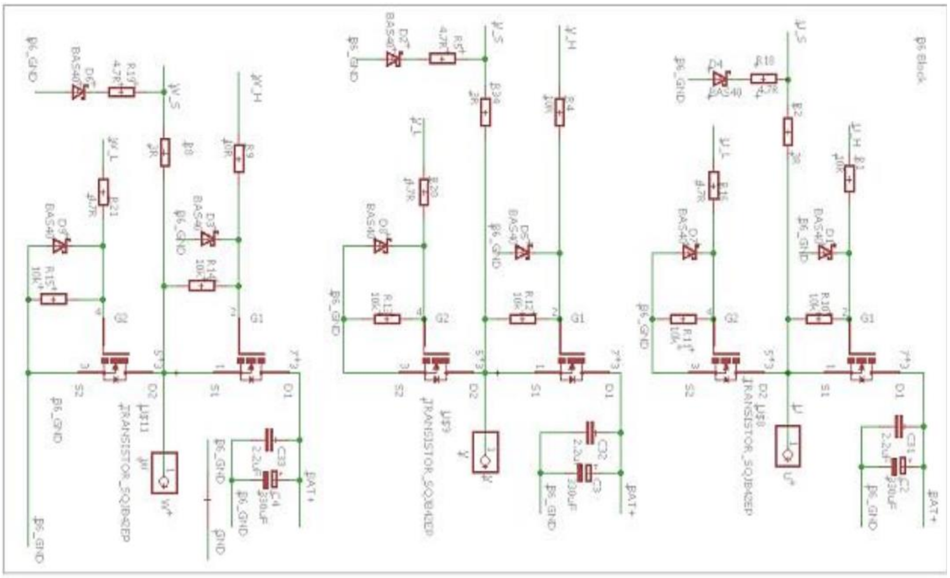

Fig. 7 – Transistor blocks.

In Fig. 8 is presented a star connection circuit in order to obtain a virtual neutral point.

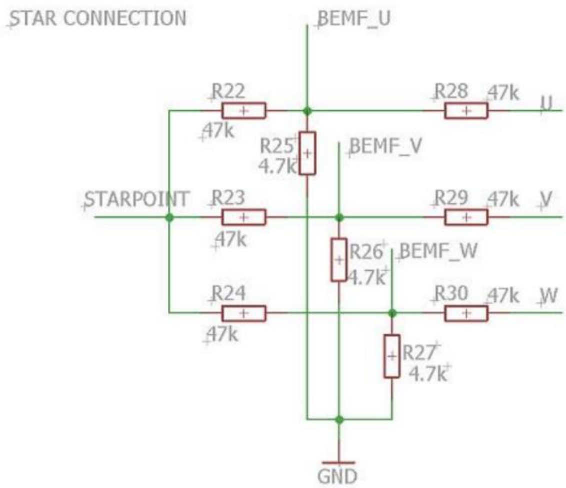

Fig. 8 – Star connection circuit.

Back EMF is a voltage that comes from the motor, and it is helpful for finding out the speed of the motor. With this circuit, all three phases are connected through resistors for sending the right feedback signal to the microcontroller. The value of 47 kΩ and 4.7 kΩ was chosen because the amount of current limited by them is sufficient for the microcontroller.

3. Circuit Testing

In order to prove the right functionality of the hole system, each part of the circuits was tested.

Buck converter testing - The working parameters are presented bellow:

V_{IN} = 14 V – 25 V V_{OUT} = 12 V with a tolerance of 3.79%
F = 500 kHz P_{OUT} = 18 W
I_{OUT} = 1.5 A Efficiency = 96%

In Fig. 9 is presented the output voltage from Buck converter.

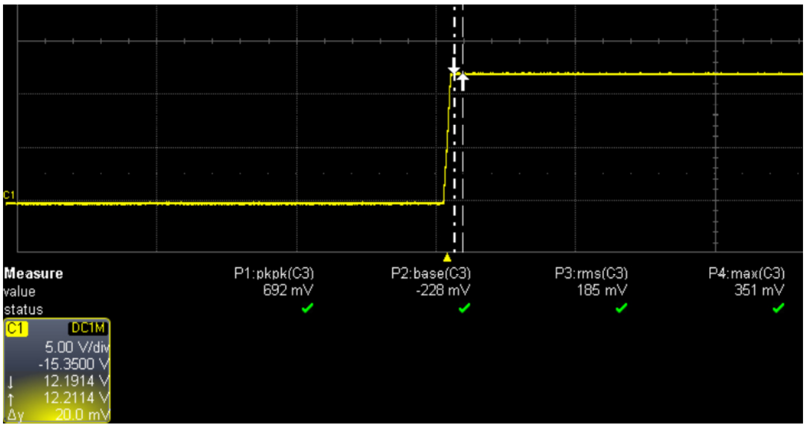

Fig. 9 – Output voltage from Buck converter.

In Fig. 10 is presented the gate driver circuit under testing conditions.

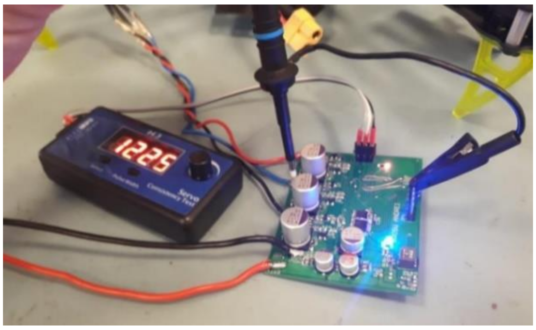

Fig. 10 – Gate driver circuit.

In Fig. 11 is presented one representative voltage at the output of the three phase inverter, when low duty cycle was used in order to get low speed for motor.

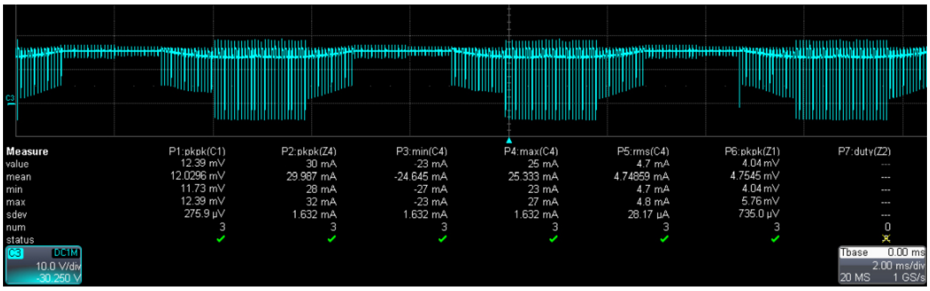

Fig. 11 – Output voltage phase – low speed.

In Fig. 12 is presented the same voltage as in Fig. 11, when medium duty cycle was used in order to get medium speed for motor.

In Fig. 13 is presented the same voltage as in Fig. 11, when high duty cycle was used in order to get high speed for motor.

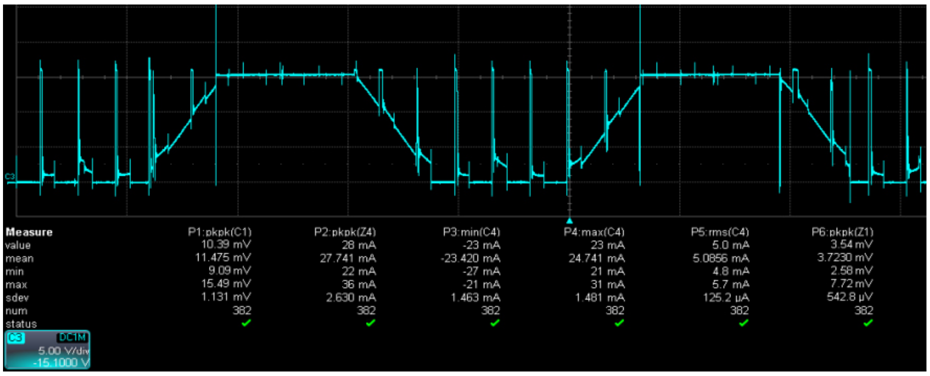

Fig. 12 – Output voltage phase – medium speed.

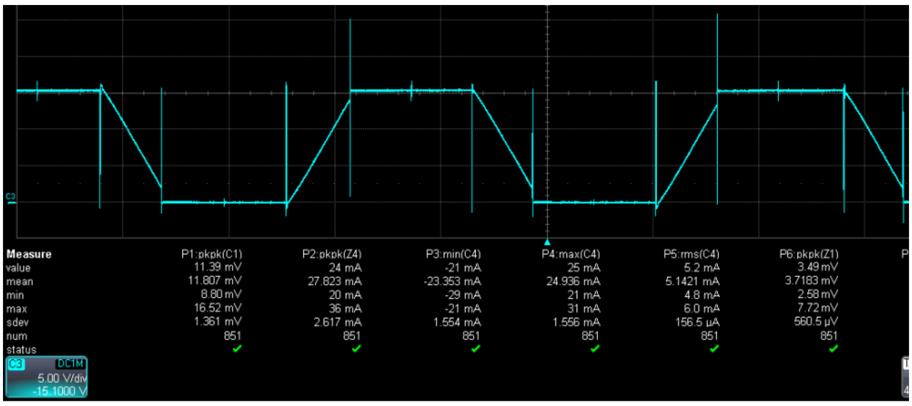

Fig. 13 – Output voltage phase – high speed.

4. Conclusions

As specified in the introduction, currently there are lots of control circuits for BLDC motors with different features. In this paper was presented a circuit which was designed for middle power with small dimensions, also the cost is in the middle range. The testing of this control circuit took place on the workbench where every power, control and other signals were checked and on a quadcopter with excellent results in its handling.

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PROIECTAREA UNUI REGULATOR ELECTRONIC DE VITEZĂ
PENTRU UN QUADCOPTER

(Rezumat)

Motoarele utilizate pentru quadcoptere sau alte drone sunt cele de tip BDLC datorită calităților și performanțelor sale superioare față de alte motoare electrice. Aceste motoare necesită un circuit de control mai complex. În acest articol a fost prezentată proiectarea unui astfel de circuit de control cu specificația că ESC-ul realizat de noi funcționează în gama de putere medie, având performanțe de control dinamic bune și un preț de realizare mic. Buna funcționare a întregului sistem a fost verificată în urma măsurătorilor circuitelor practice.