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A CONTROLLER FOR BRUSHLESS DIRECT CURRENT ELECTRIC MOTORS PART 1: ELECTRICAL AND ELECTRONIC DESIGN

Zenon Syroka

ORCID: 0000-0003-3318-8495
Technical Science Department
University of Warmia & Mazury

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Abstract

A universal controller for brushless direct current (BLDC) motors was designed in the presented article. The system is controlled from the user console where operating parameters are set by the user. Signals are transmitted by cables to microcontrollers which drive and monitor electric motors. Microprocessors communicate via a data bus. The controller contains the user console module and the motor control module. The user console module generates commands, and motors are controlled and monitored by the control module. Motor control modules operate independently, and each brushless motor has a dedicated control module. Brushless motors can be controlled in bipolar or unipolar mode. The control method is selected by the operator. The user console and motor controllers communicate via the I^2C bus.

Introduction

The article consists of two parts. The first part describes the electronic and electrical design of the motor controller, and the second part presents the applied software. The described controller for brushless motors has been designed and patented by Z. SYROKA and K. KRAJEWSKI (patent No. P431380, filing date: 4 October 2019).

Correspondence: Zenon Syroka, Katedra Elektrotechniki, Energetyki, Elektroniki i Automatyki, Wydział Nauk Technicznych, Uniwersytet Warmińsko-Mazurski, ul. Oczapowskiego 11, 10-719 Olsztyn, e-mail: zenon.syroka@uwm.edu.pl, syrokaz@onet.eu.

Industrial machines, vehicles, power tools and household appliances have motor drive elements that power mechanical components. The popularity of electric cars has been increasing in the 21st century. Batteries and motors are the key components of electric vehicles. Batteries are positioned at the bottom of the chassis to lower the vehicle's center of gravity. The motor is located in the front or at the back of the vehicle (Tesla Model S). The motors in electric cars are powered by direct (DC) or alternating current (AC). Brushless motors are one type of DC motors. Rapid advances in electrical and power engineering have introduced novel components to brushless motors, including thyristors, diodes and MOSFET transistors. Electronic subassemblies can turn power supply on and off hundreds or even thousands of times within one second. In electric bicycles, a brushless motor is placed inside the wheel hub. Power is transferred to the wheel, which reduces the physical effort associated with pedaling by 50%.

This article discusses a controller for brushless DC motors that are mounted inside the wheels of land vehicles. The motor is controlled by the user via the user console. The user can change motor speed, driving direction and deploy the electric braking system. The controller controls the steering system, the drivetrain and the braking system. Brushless DC motors can be controlled in unipolar and bipolar mode.

Structure and the basic working principle of a brushless DC motor

A brushless DC (BLDC) motor has the following characteristics:

– two BLCD motors are mounted inside wheel hubs;

– motors operate independently; therefore, the speed and direction of rotation can be controlled independently in each motor;

– the motor controller is controlled from the user console;

– different wheel combinations can be used to turn a vehicle;

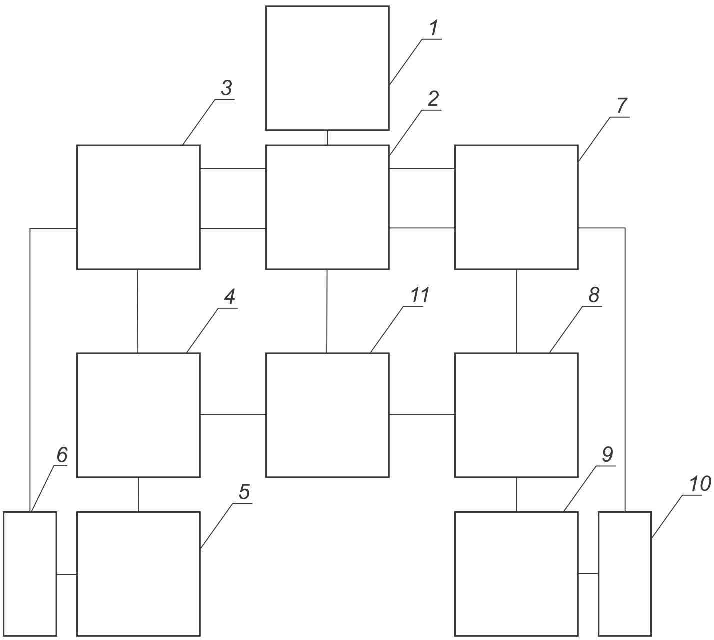
– the motors are powered by a battery installed in the vehicle;

– motor operation is controlled;

– BLDC motors can be controlled in bipolar and unipolar mode.

The system is controlled from the user console where operating parameters are set by the user. Signals are transmitted by cables to microcontrollers which drive and monitor BLDC motors. Microprocessors communicate via a data bus. The controller contains the user console module and the motor control module. The user console module generates commands, and motors are controlled and monitored by the control module. Motor control modules operate independently, and each brushless motor has a dedicated control module. Brushless motors can be controlled in bipolar and unipolar mode. The control mode is selected by the user. The user console and the motor controller communicate via the I²C bus. A simplified diagram of the designed motor control system is presented in Figure 1.

The master microcontroller (*2*) reads the command input from the user console (*1*), processes and converts the data into a signal that is transmitted to the left motor microcontroller (*3*) and the right motor microcontroller (*7*). The left motor microcontroller (*3*) and the right motor microcontroller (*7*) process the data transmitted by the master microcontroller (*2*) and the data from the left sensor (*6*) and the right sensor (*10*) which describe the position of the rotor. The left sensor (*6*) and the right sensor (*10*) monitor the rotor's position during operation. The information about the rotor's position is transmitted to the left motor (5) microcontroller (3) and the right motor (*9*) microcontroller (*7*). The left motor (*5*) microcontroller (*3*) and the right motor (*9*) microcontroller (*7*) transmit signals to the three-phase bridge of the left motor (*4*) and the three-phase bridge of the right motor (*8*), where electric current is passed through the winding of the left (*5*) and right (*9*) BLCD motor according to a given commutation sequence.



1 – control circuit, *2* – master microcontroller, *3* – left motor microcontroller, *4* – left motor three-phase bridge, *5* – left BLDC motor, *6* – left sensor, *7* – right motor microcontroller, *8* – right motor three-phase bridge, *9* – right BLDC motor, *10* – right sensor, *11* – power supply
Fig. 1. Block diagram of the designed controller for BLDC motors

Electrical and electronic design of the motor controller

A controller for driving two BLDC motors has numerous electrical and electronic components, including microcontroller integrated circuits, brushless motors, MOSFET transistors and drivers, a voltage converter, and a battery.

Characteristics of a BLDC motor

Brushless motors rely on electronic commutation to turn stator windings on and off. Stator windings are supplied with current and voltage pulses. In motors with electronic commutation:

– pulses are supplied to stator coils by inverters;
– stator poles are energized sequentially depending on the rotor's position;
– the stator does not have winding, and it is composed of permanent magnets.

Brushless DC motors are also known as permanent magnet synchronous motors with trapezoidal electromotive force (EMF). The distribution of magnetic induction produces trapezoidal EMF. The transistor inverter supplies stator coils with rectangular pulses. Each phase current flows through 1/3 of the phase (120°) in the positive direction and 1/3 of the phase in the negative direction, and current pulses are separated by 60°.

The rotor has a ferromagnetic core composed of metal supports mounted outside the housing. Three-phase star-connected windings are positioned inside grooves on the face of the rotor. The rotor is composed of permanent magnets, metal supports and solid steel components. The types of rotors are applied:

– magnets with diagonal or radial magnetization are mounted on the surface of the rotor;
– magnetic steel plates arranged in a perpendicular direction to the rotor's axis.

The first variant is characterized by a larger air gap, perpendicular distribution of magnetic induction and lower induced voltage in winding. The second variant improves sinusoidal flux distribution in the air gap. When permanent magnets are used, excess power is lost mainly in the rotor, and it is easy to evacuate. The elimination of brushes and mechanical armature increases the motor's reliability and reduces mechanical losses. Brushless DC motors are characterized by high material use and high efficiency.

Brushless motors can be divided into two categories in terms of magnetic field generation:

– motors with permanent magnets with trapezoidal or sinusoidal EMF waveforms;
– switched reluctance motors without permanent magnets.

In motors with trapezoidal EMF, current is supplied to two stator poles and the position of the magnetomotive force vector changes rapidly due to repeatable phase switching. The motor's performance is enhanced when magnetic induction has trapezoidal distribution. The moment when the inverter valve should be turned on is indicated by the location sensor. Hall effect sensors are often used for this purpose. Sinusoidal waveforms are controlled in velocity control zones. Instantaneous current in windings is controlled by a pulse width modulation (PWM) signal to obtain a sinusoidal output wave.

Current pulses can be supplied to motor windings in:
– bipolar mode,
– unipolar mode.

Brushless DC motors have the following advantages:
– high start-up torque,
– long life,
– low weight relative to other DC motors,
– precise speed control,
– rigid mechanical configuration.

Brushless DC motors have the following limitations:
– an expensive microprocessor circuit is required to control commutation and rotor position;
– smooth motion is difficult to produce at low speeds.

Connection diagram for two BLDC motors

The controller relies on two BLDC motors – the left motor and the right motor. The motors have three stator windings, and each motor is connected individually to the control system. The motors have three-phase inverter outputs and a sensor system. The three-phase bridge inverter supplies sequence current to the winding and creates a magnetic field around the conductor, which sets the rotor with permanent magnets into motion. The rotor's position is controlled by a sensor system to accomplish the appropriate commutation. The connection diagram of two BLDC motors is presented in Figure 2.

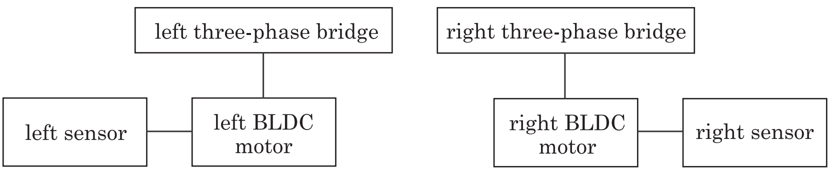


Fig. 2. Motor connection diagram

Power inverter

A BLDC motor is not equipped with a mechanical commutator, and commutation is accomplished electronically with the use of a microcontroller and an inverter. The inverter controls the supply of power between a receiver and the source. The system controls power supply by rapidly turning inverter nodes on and off. Nodes are switched due to changes in the commutation states of inverter branches. The inverter of a BLDC motor relies on voltage-controlled metal-oxide-silicon field-effect transistors (MOSFET). When gate-source voltage alters resistance in the *p*-channel or the *n*-channel, the flow of current changes between the drain and the source.

Methods of controlling a BLDC motor

Brushless DC motors commutate by turning on transistor switches in a given sequence to supply direct current to successive windings. Information about the position of the rotor shaft is provided by the sensor to guarantee that transistors are switched in the appropriate sequence. The inverter control system selects the appropriate transistor pairs by monitoring the rotor's position.

In unipolar mode, pulse amplitude is controlled by groups of positive or negative transistors. Positive transistors control pulse modulation, and negative transistors control commutation. Pulse width is modulated by one transistor group, which simplifies the structure of the electronic circuit. Loads are not evenly distributed across transistors, and switching frequency is irregular. In bipolar mode, upper and lower transistors control PWM and commutation, respectively. This method generates greater losses, but loads are more evenly distributed across transistors, and switching frequency is identical. A universal BLDC motor controller enables the user to select between unipolar and bipolar modes.

Circuit diagram of the three-phase inverter

The controller that powers left and right motor windings at a given commutation sequence features two individual three-phase direct current inverters. Each inverter bridge contains:

– three IR2101 gate drivers,
– three IRLN120N drivers,
– three 1N4148DO rectifier diodes,
– six 100 Ω resistors,
– three 10 uF and 2.2 uF capacitors.

The circuit diagrams of the transistor driver are presented in Figures 3. Coil A_L is connected between the field effect transistor of the top IRLN120N

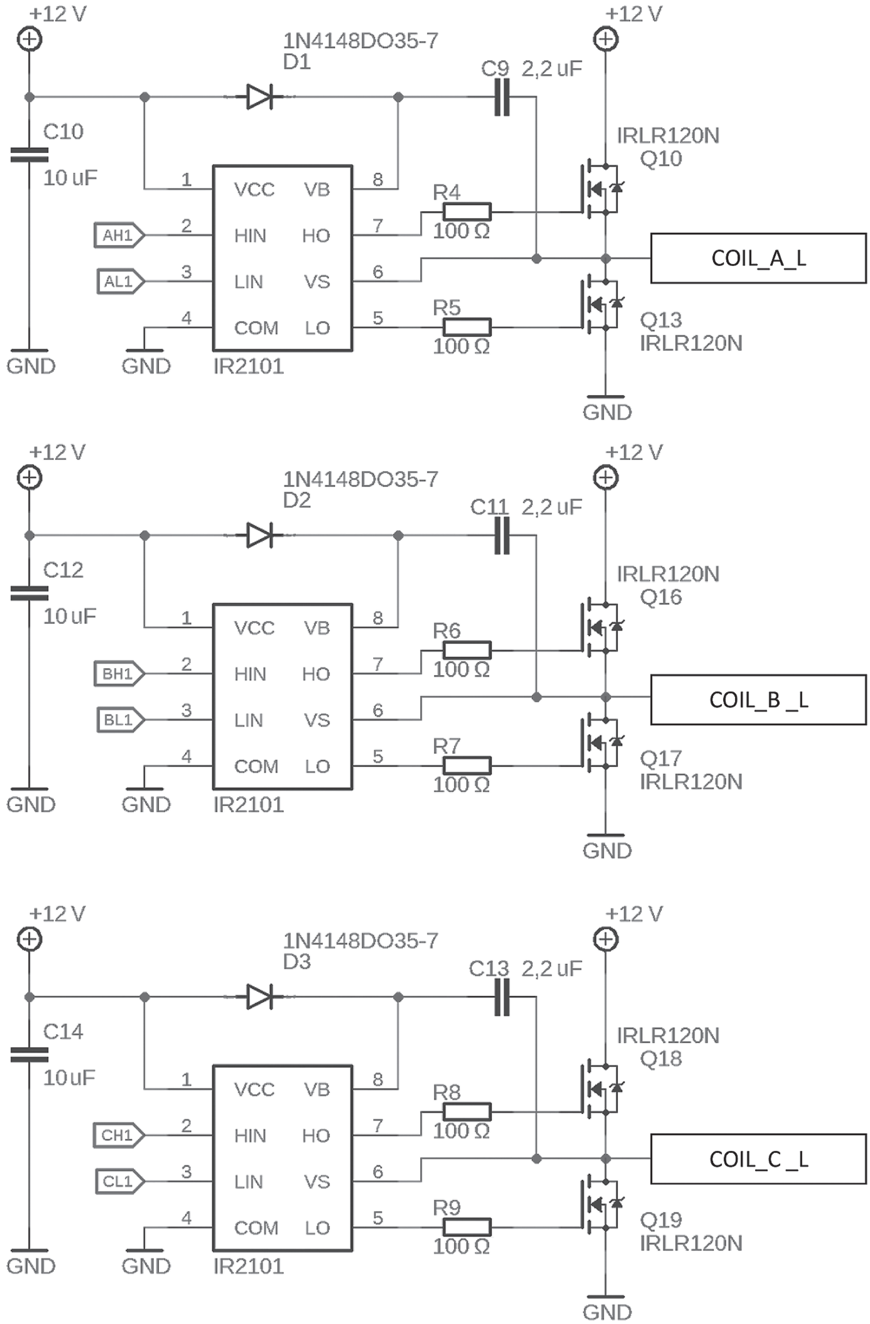


Fig. 3. Circuit diagram of a three-phase inverter connected with coils A_L, B_L and C_L in the left motor and microcontroller output AH1, AL1, BH1, BL1, CH1 and CL1 that control the left motor

driver and the source of the lower driver. Coils AH, AL, BH, BL, CH and CL are connected with transistor drivers, and they are the microcontroller outputs that carry the PWM signal. The outputs of IR2101 drivers are connected in series with MOSFET transistors.

Determination of rotor position

The brushless motor controller relies on Hall effect sensors to detect rotor position. Sensor data are transmitted to the microcontroller which determines the position of the rotor with the use of an algorithm.

Methods for detecting rotor position

The position of the rotor in a brushless motor has to be determined to commutate the current. Various methods for detecting rotor position are used. A block diagram of a brushless motor control system is presented in Figure 4.

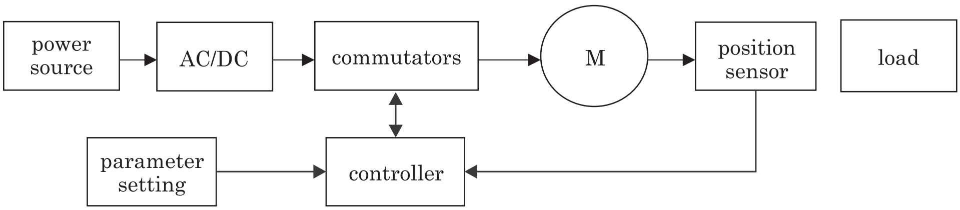


Fig. 4. Block diagram of the motor control system

Four methods are most commonly used to determine rotor position:
– Hall effect sensors,
– optical encoders and pulse sensors,
– rotor and speed calculations,
– counter-EMF measurements.

The first two methods require additional sensors. The following two approaches are sensorless methods that require effective microprocessors to determine the correct moment for energizing stator coils. Hall effect sensors were used in the designed controller. Each stator coil is provided with a Hall effect sensor. The Hall effect is induced when a magnetic field is applied in a direction perpendicular to current flow. The Lorentz force deflects the propagating carriers to one side of the semiconductor. Charges with the opposite sign accumulate on both sides of the semiconductor. Three Hall signals generate six states of commutation in a brushless motor. The resulting information is used to determine the position of the rotor.

Circuit diagram of a Hall effect sensor

Two Hall effect sensor circuits were designed for controlling rotors in the left (Fig. 5) and the right motor.

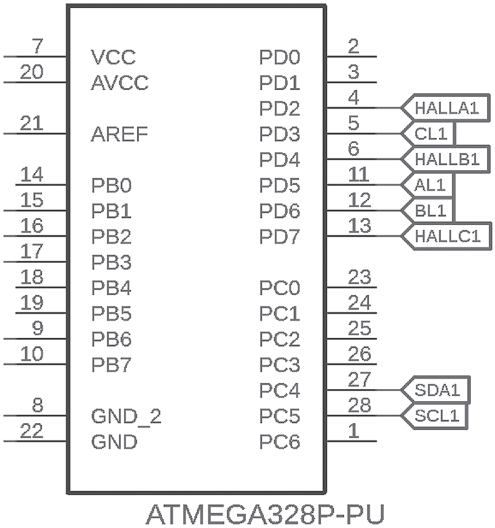


Fig. 5. Circuit diagram for interfacing Hall effect sensors
with the microcontroller in the left motor

The circuits presented in Figures 5 contain three Hall effect sensors interfaced with microcontroller outputs. Hall effect sensors in the left motor are labeled as HALLA1, HALLB1, HALLC1. Hall effect sensors in the right motor are labeled as HALLA2, HALLB2, HALLC2. Rotor position sensors are mounted on motor windings.

User console

Brushless motors are controlled from the user console equipped with five pushbuttons and a potentiometer. Button S1 is the forward drive switch, button S2 is the reverse drive switch, button S3 is the right turn switch, button S4 is the left turn switch, and button S5 is the brake switch. Driving speed is controlled with the R19 10 kΩ potentiometer. A circuit diagram of the user console is presented in Figure 6.

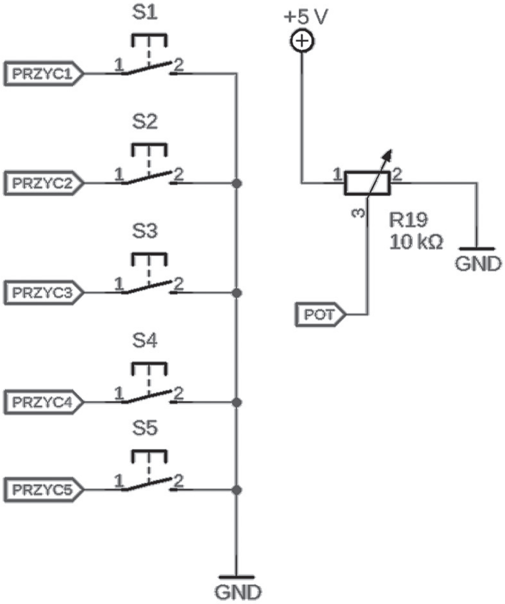


Fig. 6. Circuit diagram of the user console

Buttons 1 to 5 are connected to the inputs of the master microcontroller and the ground terminal GND. Buttons are pressed to initiate current flow between the microcontroller pin and the ground and to execute the corresponding functions in the microcontroller program. A 10 kΩ potentiometer is connected to the analog input of the POT microcontroller and the ground. The potentiometer dial is an adjustable voltage divider that controls resistance between terminals 1-3 and 1-2. Changes in resistance lead to changes in voltage between terminals POT and GND in a range of 0.5 V. The microcontroller checks the voltage applied in the POT analog input and outputs the motor speed.

Communication between microcontrollers

Microcontrollers communicate through a serial bus. The master microcontroller transmits signals to slave microcontrollers that drive the motors. The serial bus supports rapid communication, which ensures the correct operation of motors that power the vehicle's wheels. Data are transmitted with the use of the I^2C bus interface.

Communication interfaces

The microcontrollers are equipped with various communication interfaces that transmit data between sensors, displays and other microcontrollers. Interfaces can operate in serial or parallel mode. Parallel communication is characterized by high-speed data transmission. A higher number of printed circuit boards are required in systems with many communication outputs. The communication interface is controlled by a simple program. The interface circuitry for coupling microprocessors involves various devices such as address decoders, latches and tristate buffers. Serial connections have lower data transmission speeds, they require fewer outputs and simpler printed circuit boards. Serial communication software is complex and characterized by longer processing time. When the number of connections is limited, fewer signal lines are needed, and the system is less sensitive to interference. Both communication modes have their advantages and disadvantages, and they should be selected based on system requirements. The most popular communication interfaces include:

– I^2C – Inter-Integrated Circuits,
– SMBus – System Management Bus,
– SPI – Serial Peripheral Interface,
– Microwire,
– 1-Wire.

The designed controller is equipped with a dual bidirectional I^2C bus. The bus contains two lines: SDA and SCL. The SDA line transfers data, and SCL is the clock line that synchronizes all data transfers over the I^2C bus. The devices on the I^2C bus can operate as masters or slaves:

– the master device controls the bus and data transmission, transmits start and stop sequences, and generates clock pulses;
– the slave device responds to the commands of the master device.

Many systems that rely on I^2C bus communication have one master microcontroller and numerous slave devices, such as input-output ports, non-volatile memory storage, and display drivers. Every slave device is assigned a unique address for communicating with the master microcontroller. A block diagram of an I^2C circuit is presented in Figure 7.

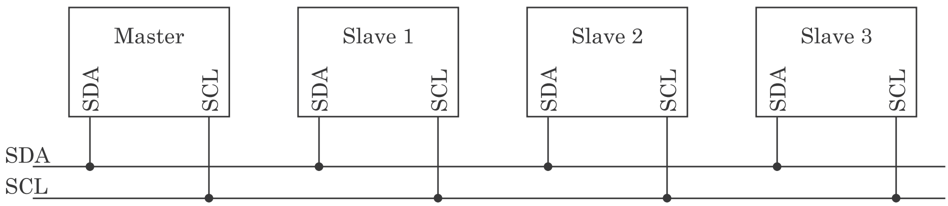


Fig. 7. Block diagram of an I^2C circuit

The I²C interface transmits packets of data with a size of 8-bit frames. The number of transmitted bits changes with the system. The receipt of every data frame is acknowledged (ACK). When larger data packets are transmitted, the frames with the most significant bit (MSB) status are sent first. If data cannot be received at a given moment, the SCL clock line can be set to a low state. The transmitter remains in a wait state until the end of the low state interval.

Circuit diagram of the I²C interface

The master microcontroller communicates with motor microcontrollers via the I²C bus interface. The circuit diagram of the bus interface is presented in Figure 8.

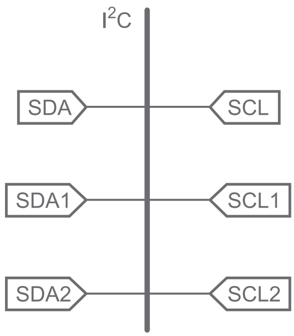


Fig. 8. Circuit diagram of the bus interface

The microcontrollers transmit and receive data via the data bus. In Figure 6, microcontroller pins are labeled as SDA and SCL. SDA1 and SCL1 are the microcontroller pins that control the left motor, and SD2 and SCL2 are the microcontroller pins that control the right motor.

Power supply for the motor controller

The microcontrollers require 5 V DC supply, and motor coils – 12 V DC supply. The described system is powered by a 12 W gel battery. Input voltage for the microcontroller is reduced to 5 V by the Pololu D24V10F5 step-down converter. This 5 V 1 A converter has a high efficiency of 80–93%.

A circuit diagram of the the step-down converter is presented in Figure 7. The gel battery supplies 12 V to the VIN supply voltage input. The VOUT voltage output supplies 5 V to the microcontroller. The GND output is connected to the grounding wire.

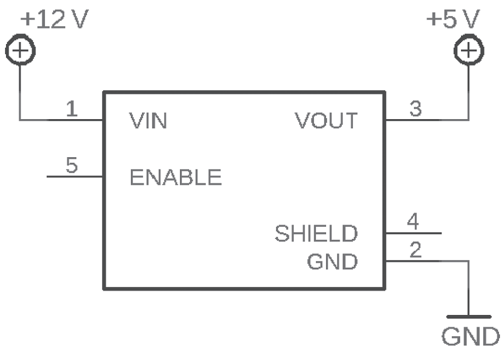


Fig. 9. Circuit diagram of the step-down converter

Summary

The designed controller for brushless DC motors has been patented (SYROKA, KRAJEWSKI 2019) for use in commercial applications. The device can be applied in electric vehicles for controlling BLDC motors mounted in wheels. It was developed as part of a research project at the University of Warmia and Mazury in Olsztyn (Books – Digital Control, SYROKA 2019) dedicated to the construction of electric vehicles and electric drives that rely on renewable sources of energy.

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