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General purpose process control unit

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Abstract

The main purpose of the thesis is to make a control unit where different models can be tested with a number of motors, sensors, indicators, control devices which are used by Fischertechnik in training models. This work observes different types of speed motor control and investigates most useful method that could be implemented at the PLC Lab. It would be very useful to simulate separated parts of the unit by using different software and compare actual results with theoretically expected results. All the results must be realistic and simply implemented in a real lab.

Obtained circuit should be implemented in board layout after succeed simulations and checked for safety using in future. Measured signal, voltage level on each node and behavior of motors should be similar to the theoretical results.

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Nomenclature list

ω_m	Motor speed
I_a	Armature current
R_a	Armature resistance
Φ	Magnetic flux.
PWM	Pulse - Width Modulation
V_{aN}	Output voltage of H-bridge when high side (left) and low side (right) are open
V_{bN}	Output voltage of H-bridge when high side (right) and low side (left) are open
MOSFET	Metal–oxide–semiconductor field-effect transistor
FET	Field-effect transistor
IGBT	Insulated-gate bipolar transistor
IC	Integarted circuit
V_+	Non-inverting input of op amp
V_-	Inverting input of op amp
V_{S+}, V_{S-}	Positive and negative power supply

1 Introduction

Faculty of engineering science and technology of UiT uses products of Fischertechnik for studying and demonstration purposes. Fischertechnik is a company [1] that produces prefabricated models for schools and universities. It uses many types of electrical DC machines with various voltage supplying.

The PLC technical lab needs a general purpose control unit where different models can be tested with a number of motors, sensors, indicators, control devices etc. Currently the laboratory lacks a universal device for controlling various models that are created by university students. Each model has its own control with unchanged quantities of motors or their types. The device that must be created on the basis of this work should help students and university staff make models more flexible and changeable in the process of modifying or demonstrating the capabilities of the PLC or the motors themselves.

The most important questions of this work are the determination of the best way to control motor and its physical implementation in the laboratory. The best way means that the device should consist of the fewest components and be easy to operate and configure, while having a safety margin that will prevent the failure of various parts of the device or its power supply.

Each decision and step should be dictated by the criteria of simplicity, reliability and safety implementation.

This work will consist of the two main parts: 1) theoretical description, 2) choosing and implementing the best optimal solution. The theoretical part should consist of the theory of control of electric motors and a brief description of the functioning of individual parts of the device, also it should be shown electrical circuits and their simulations. The practical part will show the result obtained using the developed circuits.

2 Motor control

Different types of motors have different methods of speed control according to differences in their design or purpose, thus aim of the investigation is to identify:

1. Types of motor;
2. Purpose;
3. Limitation;
4. Most simple and reliable way to implement it in board layout.

Based on this, it should be determined what types of motors are used by this company in their products. After that it should be considered

2.1 Type of used motors

Fischertechnik uses brushed DC machines [1], with a voltage of 3-24 volts, such a big difference in the power supply of different motors is one of the problems that must be solved in this paper. Brushed DC motors or BDC are the most common on the market with so low voltage and there is many equipment that could work together with them.

The BDC with permanent magnets is the most common among the BDC [2]. The inductor of this engine includes permanent magnets that create a stator magnetic field. BDC motors with permanent magnets are commonly used in tasks that do not require large powers. A BDC motor with permanent magnets responds very quickly to a voltage change. Due to the constant stator field, it is easy to control the motor speed. The disadvantage of the constant-current motor with permanent magnets is that over time, the magnets lose their magnetic properties, as a result of which the stator field decreases and the characteristics of the motor decrease.

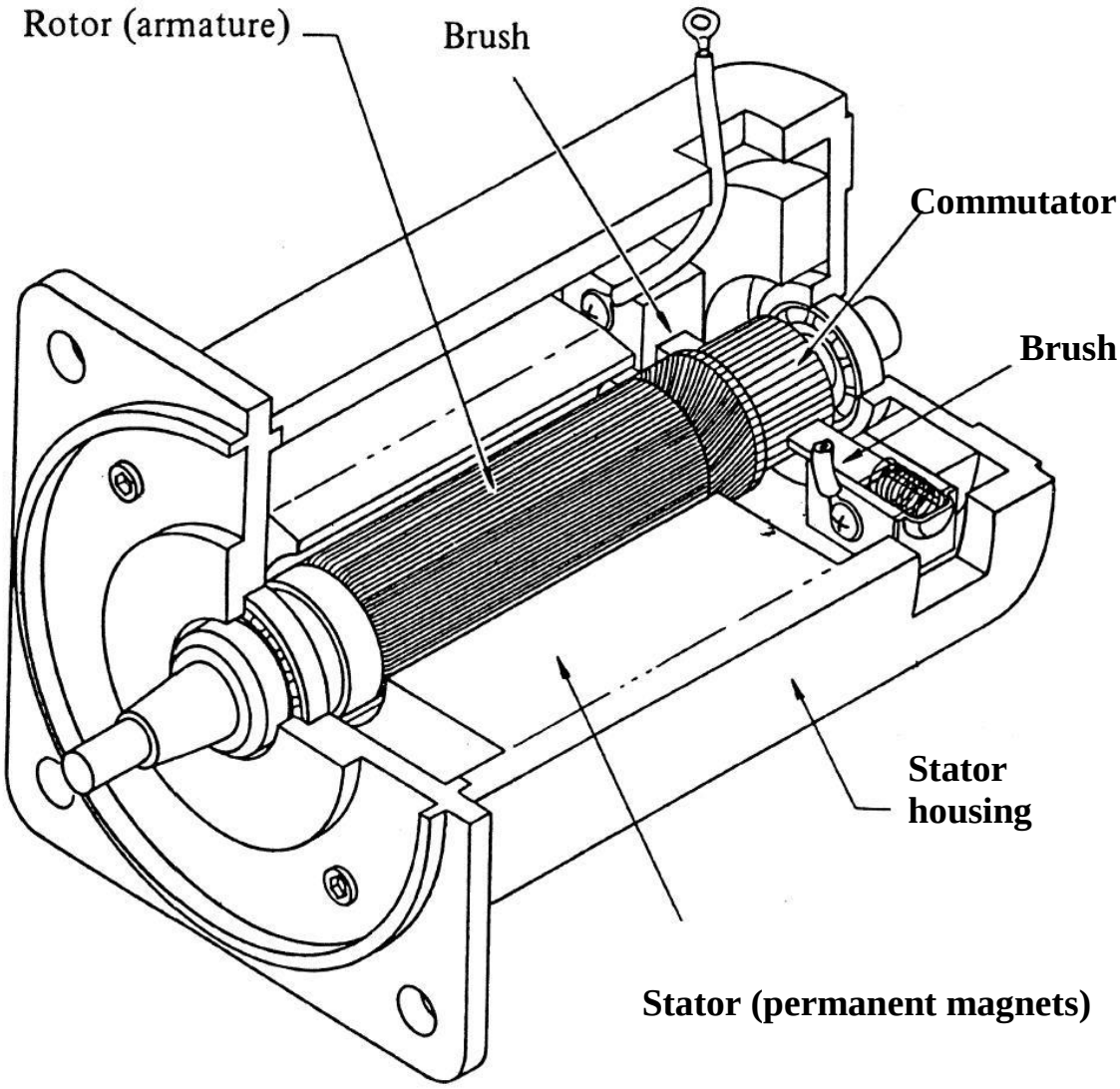

Figure 1: Brushed DC machine [2]

2.2 Method of control

From the equation of the electromechanical characteristic of a DC motor [4]:

$$\omega_m = \frac{U - I_a * R_a}{k * \Phi} \quad (1.1)$$

Where: U – supply voltage, I_a – armature current, R_a – armature resistance, k - the coefficient characterizing the magnetic system, Φ – magnetic flux.

It follows that three ways of regulating its angular velocity are possible:

1. Regulation by changing the resistance value of the resistance in the armature circuit
2. Regulation by changing the excitation flux of the motor Φ,
3. Regulation by changing the voltage U applied to the winding of the motor armature.

The first and second methods are not available in the project, since there is a motor with a permanent magnet.

The third way to regulate speed is to change the voltage applied to the winding of the motor armature. The speed of the DC motor irrespective of the load varies in direct proportion to the voltage applied to the armature. Since all control characteristics are rigid and the degree of their rigidity remains unchanged for all characteristics, the operation of the motor is stable at all speeds and, therefore, a wide range of speed control is provided, regardless of the load. If the power source provides the possibility of a continuous change in the voltage applied to the motor, the speed control of the motor will be smooth.

This method will be used in the project.

2.3. Control loop

There are two control system principles that could be used in the project: open or closed loop system.

Closed systems have feedback, which is an undoubted advantage. After the system requests parameters, it becomes immune to changes and keep the required level of the output signal, comparing it with the parameter. Control by human in such systems is not required [5].

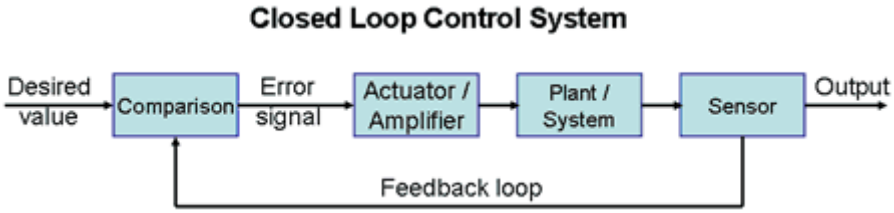

Figure 2:Block diagram of a system with feedback (closed loop) [5]

Open loop systems are controlled manually by the operator.

However, in this case, an open loop system is the most suitable, since the manual speed control mode is suitable for the purposes of the project (training and demonstration). Also, in an open loop system, the position of the shaft position or speed is not required. These sensors are quite expensive and do not guarantee that they are sufficiently standardized for all types of motors that can be used in the laboratory.

2.4 Motor driver

2.4.1 H-bridge control

The term H-bridge, shown in the figure 2.3, resembling the letter H. The H-bridge is assembled from 4 switches, electronic or mechanical (relays). When the switches High side (left) and Low side (right) are closed and High side (right) and Low side (left) are open, the motor rotates in one direction, when High side (right) and Low side (left) are closed, and High side (left) and Low side (right) are open, the motor rotates in the other direction [6].

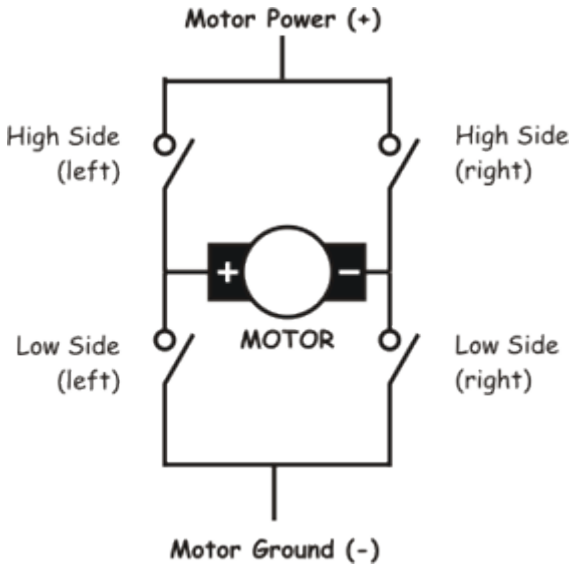

Figure 3:H-bridge [7]

From Figure 2.3. follows that H-bridge is a full-bridge switch-mode dc-dc converter [8]. This converter produces a four-quadrant controllable dc output and works as shown in Table 1.

Table 1: States of bridge

High side (left)	High side (right)	Lower side (left)	Lower side (right)	Quadrant Description
On	Off	Off	On	Motor goes Clockwise
Off	On	On	Off	Motor goes Counter-clockwise
On	On	Off	Off	Motor "brakes" and decelerates
Off	Off	On	On	Motor "brakes" and decelerates

This dc-dc converter controlled by PWM signal, as shown in Figure 4:

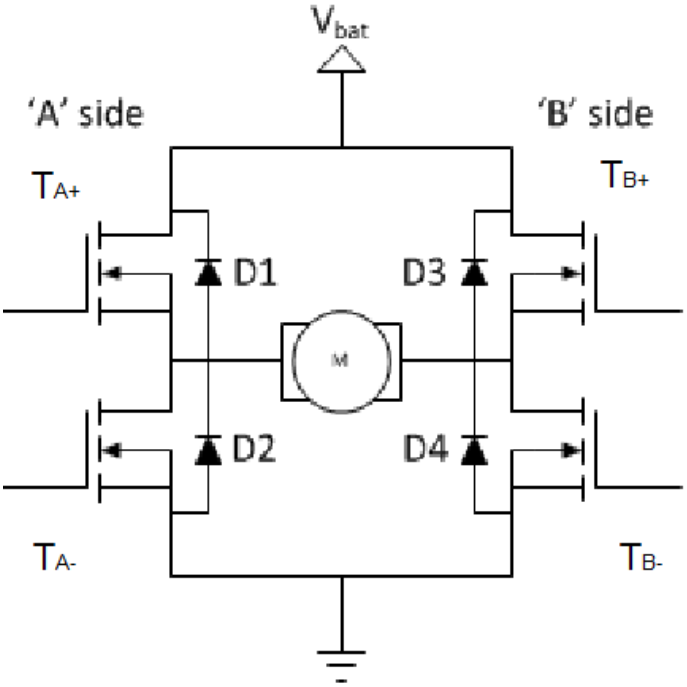

Figure 4: H-bridge with MOSFETs [9]

Figure 4 shows the motor control circuit with H-bridge. The simplest method for regulating the rotational speed of a DC motor is based on the use of pulse width modulation (PWM). The essence of this method is that the supply voltage is supplied to the motor in the form of pulses. In this case, the repetition rate of the pulses remains constant, and their duration can vary. PWM signal is characterized by such parameter as duty cycle (Figure 5):

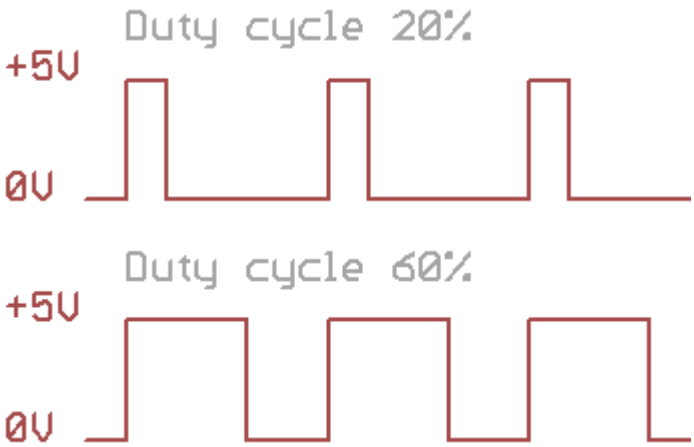

Figure 5: Duty cycle [10]

This method is widespread and effective. The principle of the method performance is the difference between voltage of the opposite parts of the bridge: V_{aN} – T_{A+} and T_{B-} are open and V_{bN} – T_{A-} and T_{B+} are open (Figure 4). PWM signal controls MOSFET T_{A+} and T_{B-} and inverted PWM signal controls T_{A-} and T_{B+}. When voltage is applied to the inputs T_{A+} and T_{B-},

they are opened and the motor starts to rotate in the forward direction and opposite: T_{A-} and T_{B+}. are opened if voltage of inverted PWM applied to them, in that case motor rotates in backward direction. Figure 6 shows the relationship between the duty cycle and the output voltage of the bridge.

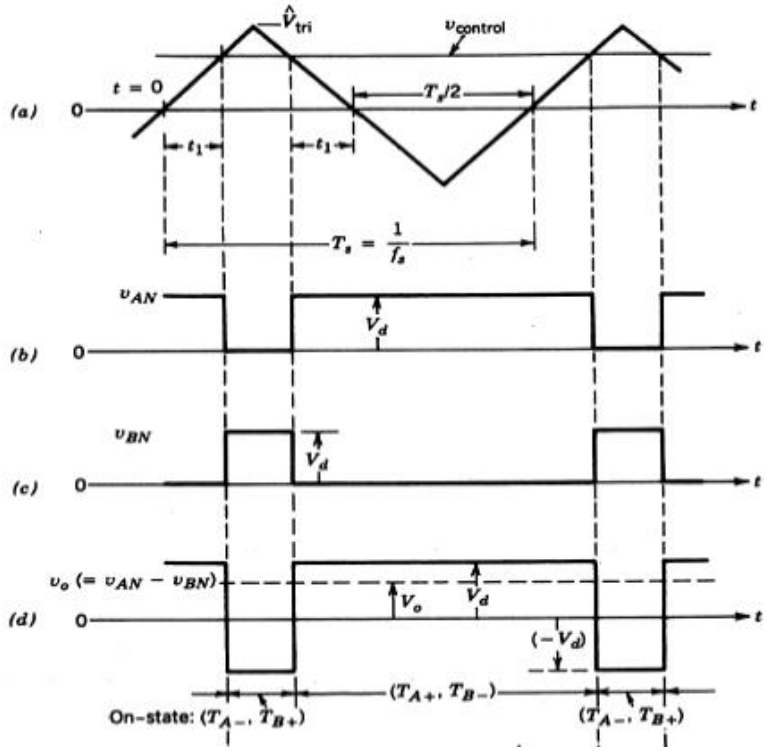

Figure 6: PWM with bipolar switching [8]

Where V_d is input voltage, V_O – output voltage. It is shown that Vo depends on ratio between open time opposite pairs of transistors in the bridge.

From figure 6 follows, that output voltage is maximum when duty cycle is 100%, output voltage is minimum when duty cycle of PWM is 0% (or 100% of inverted PWM). Output voltage equals 0 when duty cycle is 50%.

2.4.2 Transistors

Each H-bridge contains 4 transistors that provide switching at the required speed, which in turn leads to motor control.

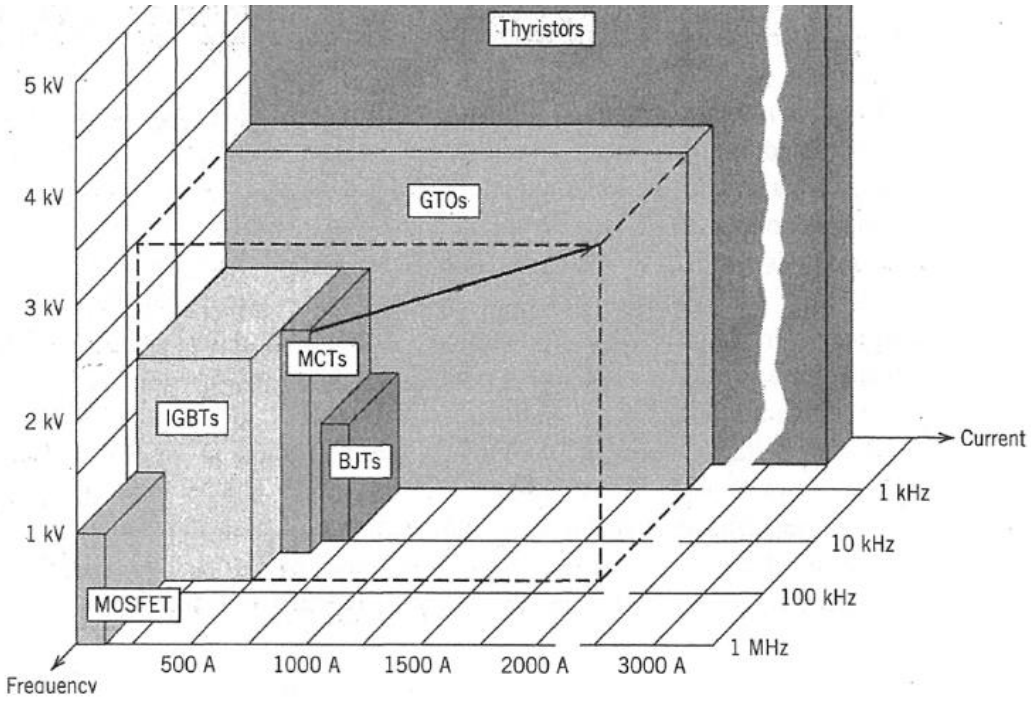

Figure 7: Types of transistors

In this work there will be considered two types of transistors: MOSFET and IGBTs because they satisfied the required frequency of 10-20 kHz, and this frequency will provide smooth work of the motor.

There are few advantages of MOSFETs in compare with IGBT [37]:

1. Due to the very high input impedance, MOSFET circuit consumes very little energy, since it practically does not consume the input current.
2. The current amplification of MOSFETs is much higher than that of IGBTs
3. Significantly higher noise immunity and reliability of operation, due to the lack of current through the gate of the transistor, the control circuit on the gate side is isolated from the output circuit from the side of the drain and source
4. MOSFETs are an order of magnitude higher than the rate of transition between conduction states and current non-conductivity. Therefore, they can operate at higher frequencies than bipolar ones.

Also, many IGBT circuits also need a reverse-blocking (anti-parallel) diode which cannot be fabricated with the IGBT. All these factors led to the selection of MOSFETs in this project.

There exist two types of MOSFETs: p-channel and n-channel.

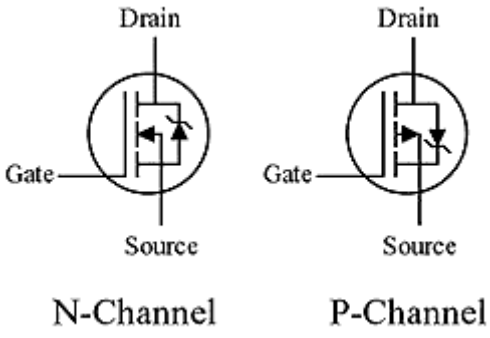

Figure 8: Types of MOSFETs

Like bipolar transistors, field structures can be direct conduction or inverse. That is, with a P-channel or an N-channel.

Drain and source in p-channel MOSFET are doped p+ region and substrate between them – n-type, current flows due to the flow of positively charged holes, it means that when gate is given negative voltage holes conduct drain and source and MOSFET goes in ON condition. N-channel MOSFET has p+ substrate and n- drain and source, in this case electrons conduct drain and source, when positive voltage is applied to gate (shown in Figure 9).

As follows from the above, for the H-bridges the n-channel MOSFETs are used.

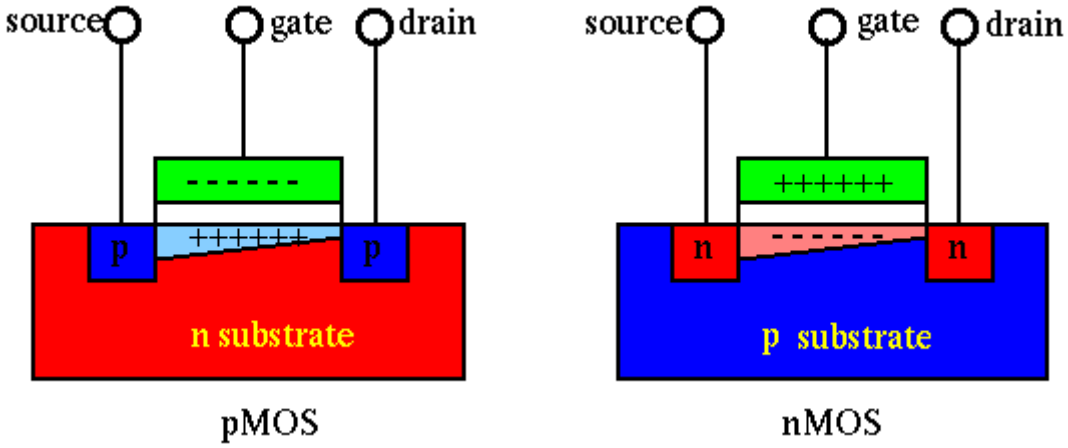

Figure 9: Types of MOSFET [11]

2.4.3 Gate driver

Gates of field-effect transistors have a large electrical capacity (thousands of picofarads), for charging which at high frequency requires a large current (amperes), since the switching time of the MOSFETs is inversely proportional to the current passing through the gate. Since a large current can heat up and damage the controller chip, a gate driver is used in the circuits. The driver provides a large current to quickly charge the gate of the transistor to open it. And also quickly discharges the gate when the transistor needs to be closed. The driver is an

amplifier that receives a signal with a weak current from the controller and outputs a high current signal.

2.5 Motor control simulation

2.5.1 H-bridge

It was decided to create simulation of H-bridge with PWM control. MATLAB was chosen as useful software for this purpose. MATLAB is universal and effective software for simulation of logic or electronic function.

Firstly, H-bridge was built up as a subsystem of motor control system with PWM.

As discussed above, the use of MOSFETs is the most convenient and effective.

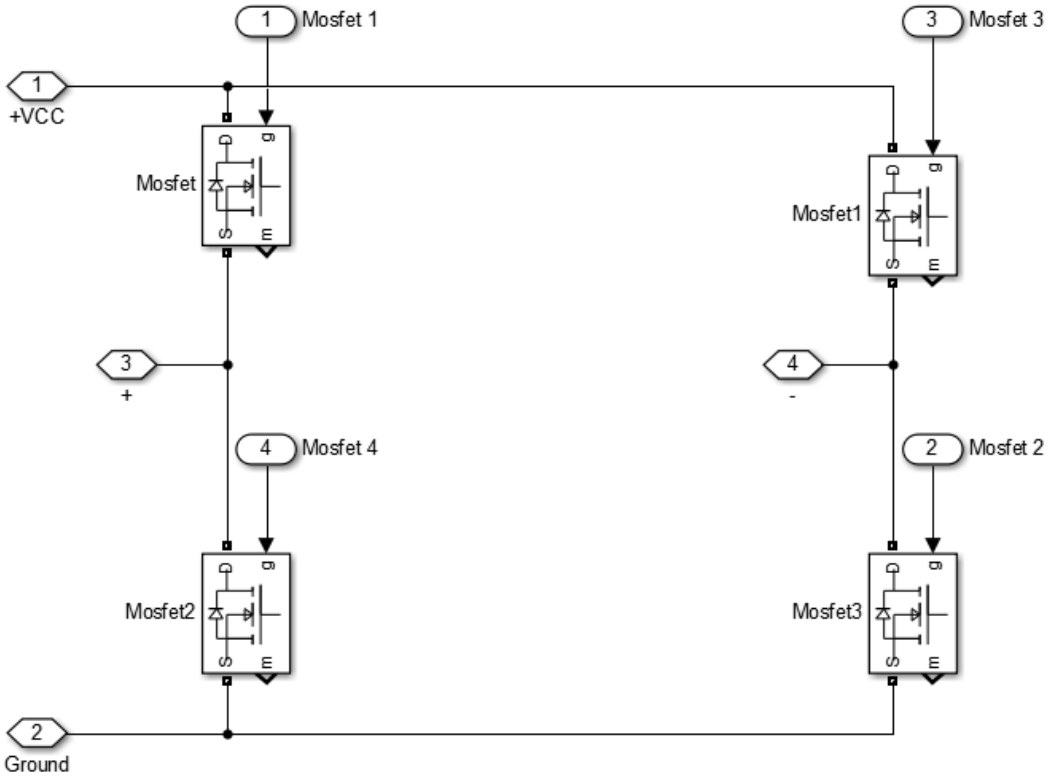

Figure 10:Subsystem H-bridge

The whole model is available in the Appendix A.

According to theory, it is known that PWM with duty cycle 50% gives bridge equilibrium and 0 voltage to the motor.

Therefore, it was made 3 simulations: 20%, 50% and 80% duty cycle. PWM frequency is 10 KHz, torque load – 1Nm. DC machine is standard for MATLAB.

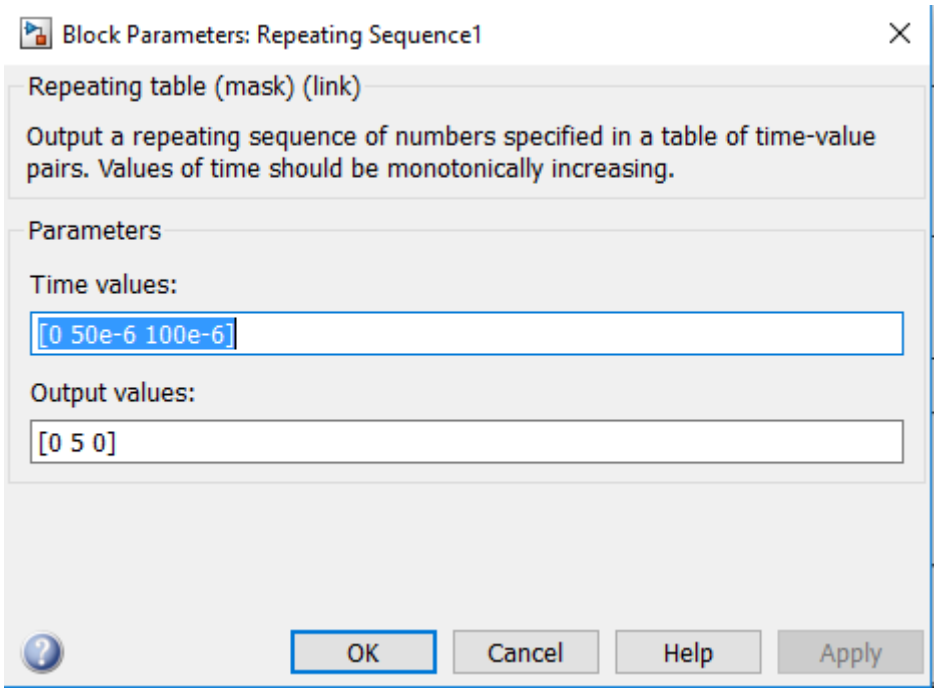

Figure 11: Parameter block for triangle signal

Peak value for triangle signal is 5, hence 20% duty cycle is 1, 50% - 2.5, 80% - 4.

Torque load is 0 in order to show the behavior of the DC machine without load at different voltages.

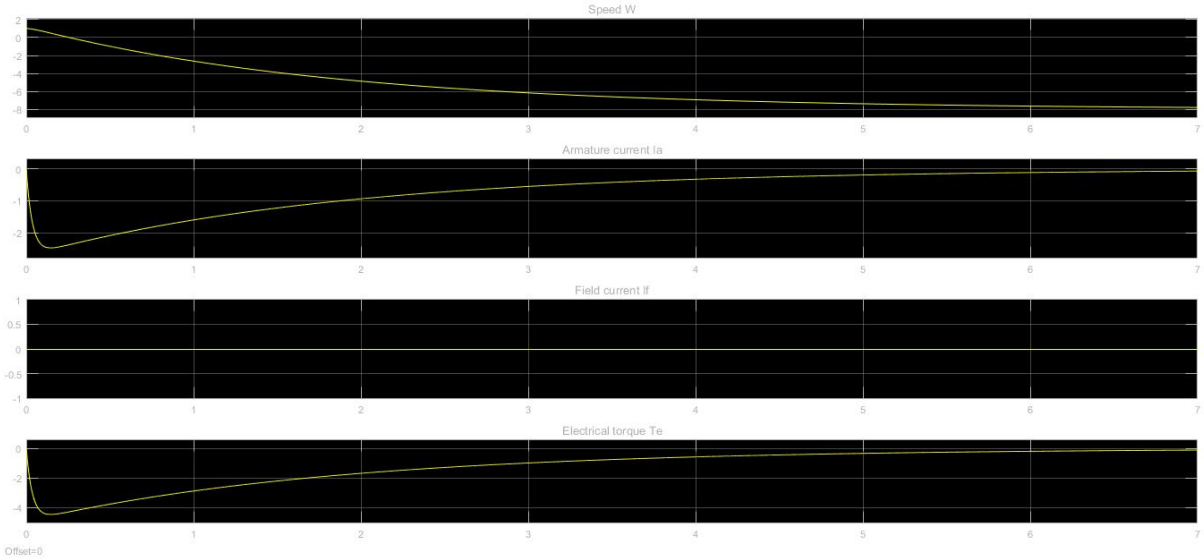

Figure 12: Outputs (20% duty cycle)

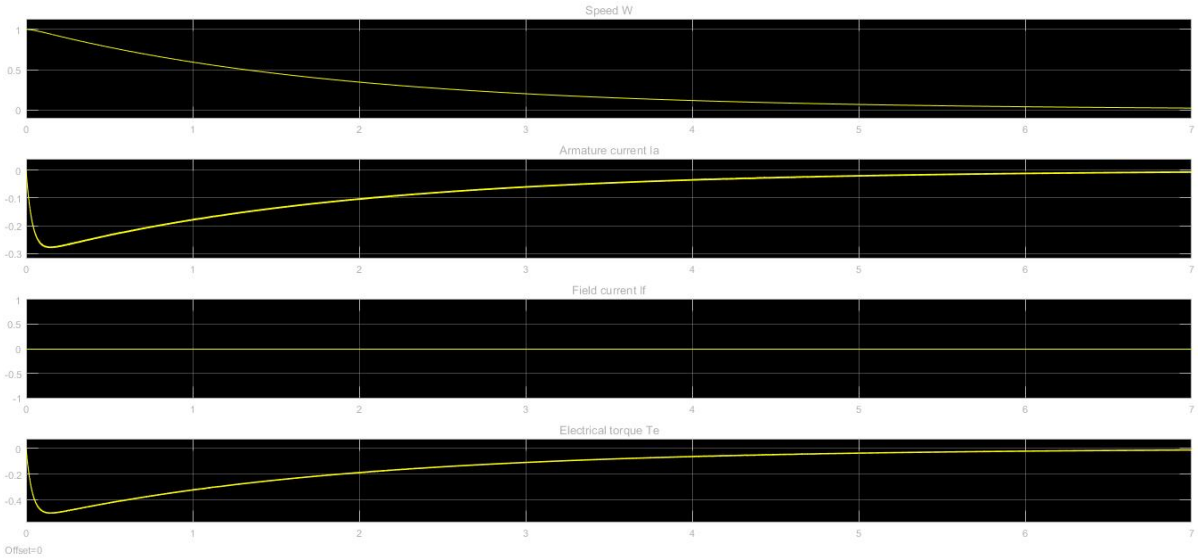

Figure 13: Outputs (50% duty cycle)

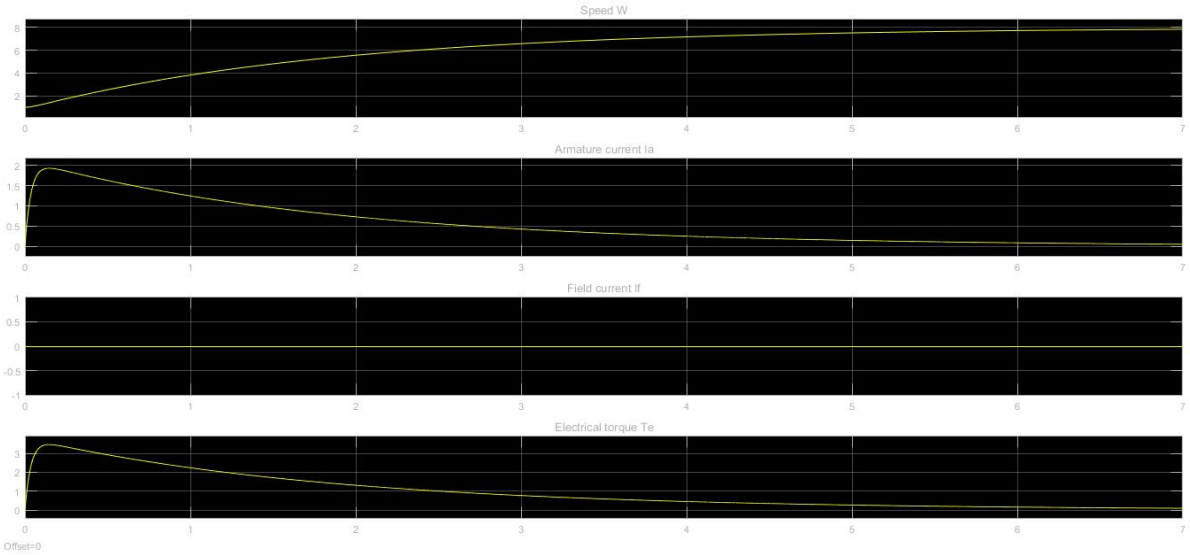

Figure 14: Outputs (80% duty cycle)

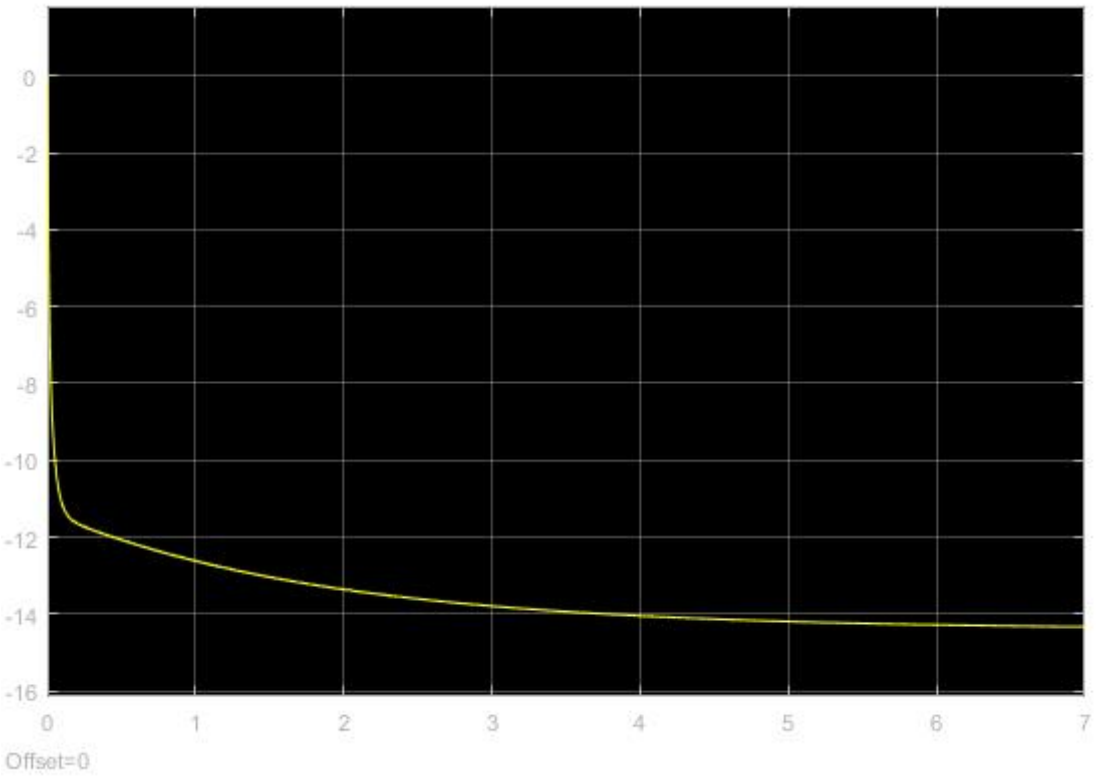

Figure 15: Output voltage at duty cycle 20%

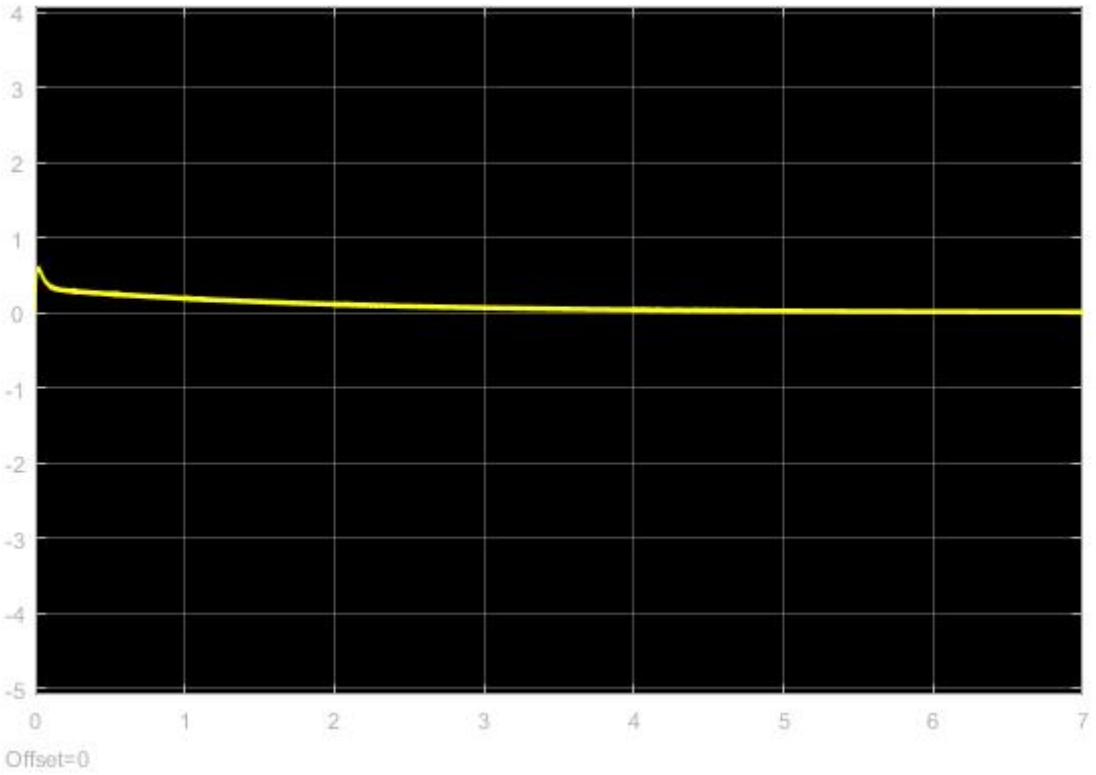

Figure 16: Output voltage at duty cycle 50%

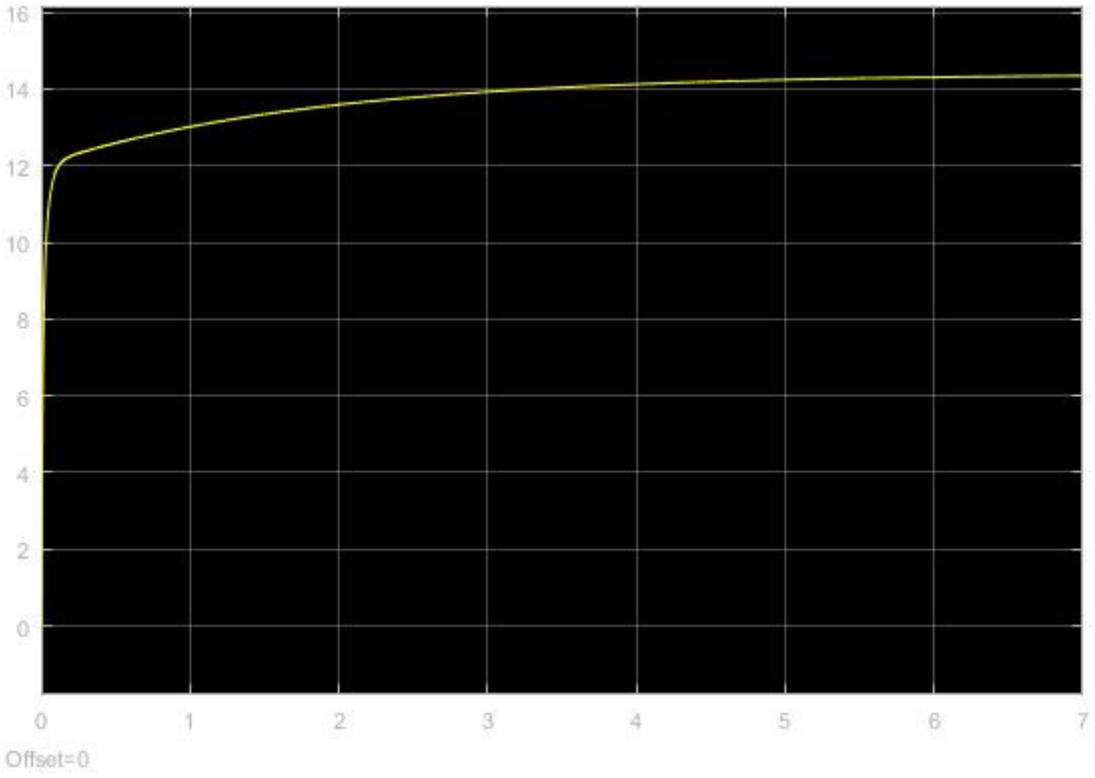

Figure 17: Output voltage at duty cycle 80%

Field current I_f is equal 0 because DC machine with permanent magnet stator is used in the simulations above.

From the graphs above it follows that with the PWM signal it is possible to control the operation of the DC machine, changing its speed and direction. At the same time, 50% is the equilibrium point of the H-bridge, at which the voltage on the motor equals 0, motor stops. More 50% duty cycle – motor goes forward, less than 50% - backward.

The motor control is reduced to a change in the voltage that will be applied to the comparator.

3. PWM signal

MATLAB does not allow creating an electronic circuit using real-world equipment and simulating it. Therefore, it was decided to find another software that would allow to create circuits and make simulations. After considering different options among the programs licensed by UIT, the OrCAD software was chosen, which allows not only to create a circuit using components from the built-in library, but also in the future, based on this circuit, to develop a board layout that can be created on special equipment located on Campus. The main challenge when working with OrCAD is the limitations of the library that does not allow the use of components that are not included in it. Consequently, it was necessary to select components on the manufacturers' websites again and again, since most of the new microchips are missing in the OrCAD library.

One of the tasks of this work is the manual speed control of the motor. That is, as follows from the data described in the previous chapters, the change of PWM duty cycle. The simplest way to form PWM signal with manual control of duty cycle – using comparator.

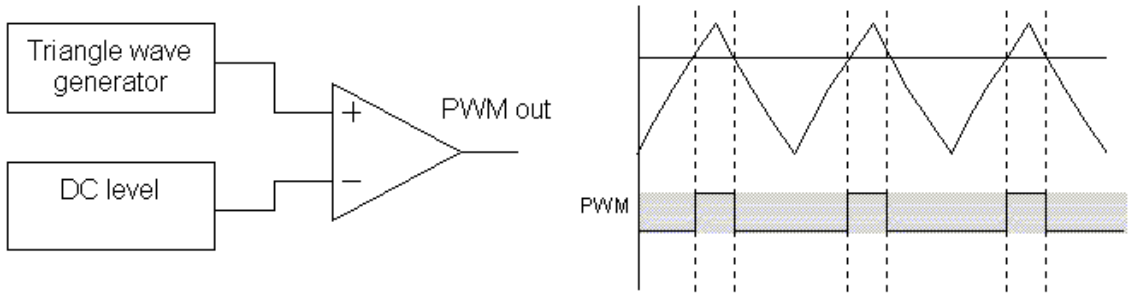

Figure 18: Form PWM signal with comparator [12]

As shown above, user can change DC level to control PWM duty cycle.

Thus, the main challenge of the project was the generation of a triangle wave.

3.1 Triangle wave

3.1.1. 555 timer

555 - integrated circuit, universal timer - a device for generating single and repetitive pulses with stable time characteristics.

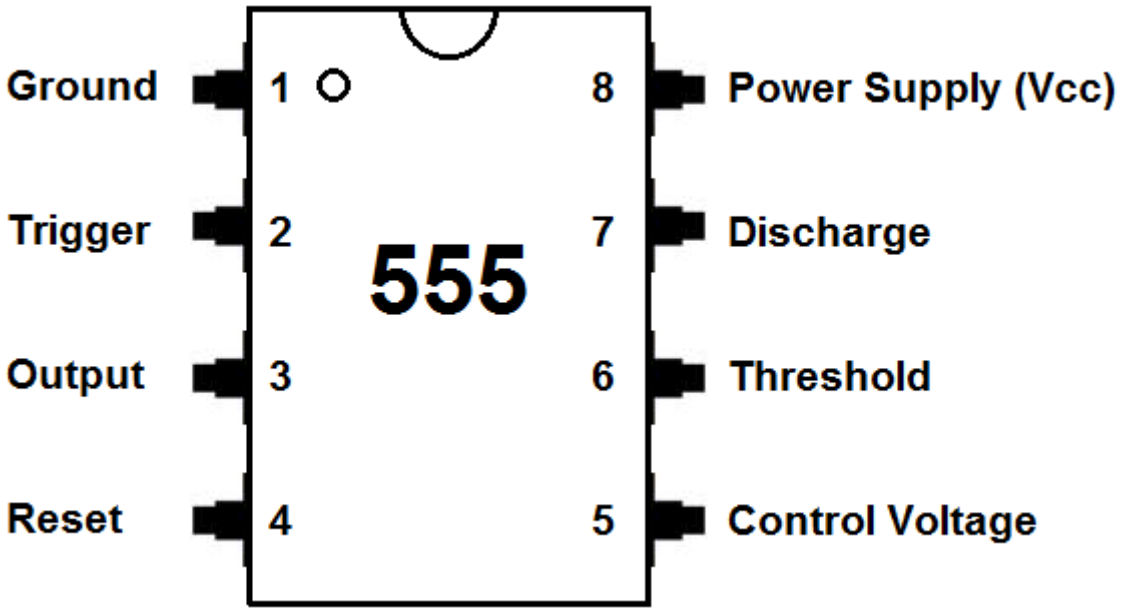

Figure 19: 555 timer [14]

It is an asynchronous RS-trigger with specific input thresholds, precisely defined by analog comparators and an integrated voltage divider. It is used for constructing various generators, modulators, time relays, threshold devices and other nodes of electronic equipment. As examples of the application of the timer chip, you can specify the functions of restoring a digital signal distorted in communication lines, bounce filters, two-position regulators in automatic control systems, pulse voltage converters, pulse width control devices, timers.

The chip consists of a voltage divider with two reference voltages for comparison, two precision comparators (low and high levels), an RS-flip-flop with an additional reset input, an open collector transistor wrench and an output power amplifier for increasing the load capacity.

555 has a three operating modes:

1. Bistable: 555 works in Schmitt's inverting high-precision trigger mode with an RS-trigger.
2. Monostable: output pulse is generated while voltage on capacitor equals 2/3 of the supply voltage. Time to charge capacitor equals multiplication of R and C. Minus of this mode – time between any two triggering pulses must be greater than that multiplication.

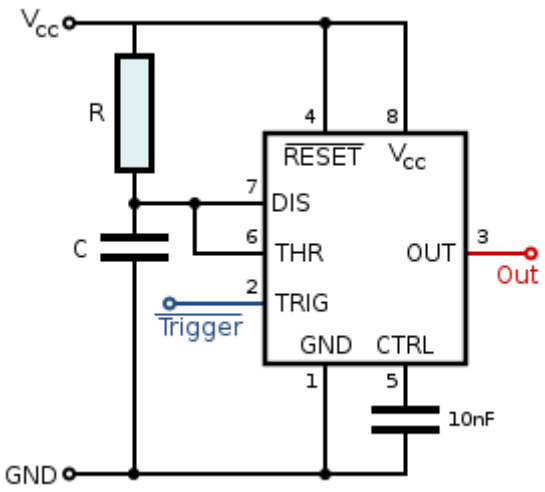

Figure 20: Monostable mode of 555 timer [15]

3. Astable: in this mode 555 timer generates continuous rectangular pulses on the output and triangle wave in the point between C and R_2

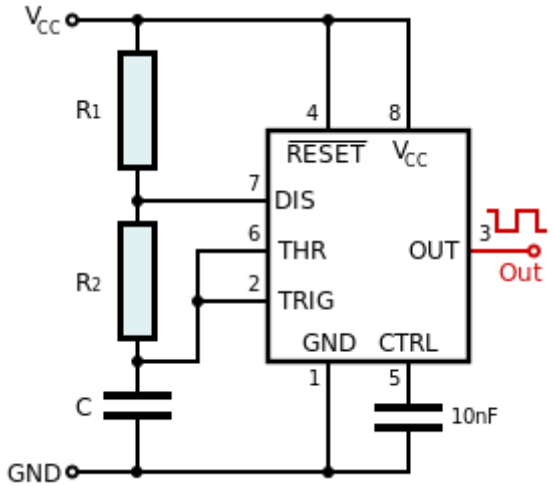

Figure 21: Astable mode of 555 timer

Frequency of pulses can be tuned according to this formula:

$$f = \frac{1}{ln2*(R_1+2*R_2)*C} \quad (3.1)$$

Frequency depends on three components in the circuit: two resistors and one capacitor. Low level in this case equals 1/3 supply voltage and high level – 2/3 supply voltage. This mode satisfies requirements of the project – triangle pulses generate in node between R_2 and C [13]. The model IC555 that was simulated is shown in Appendix B.

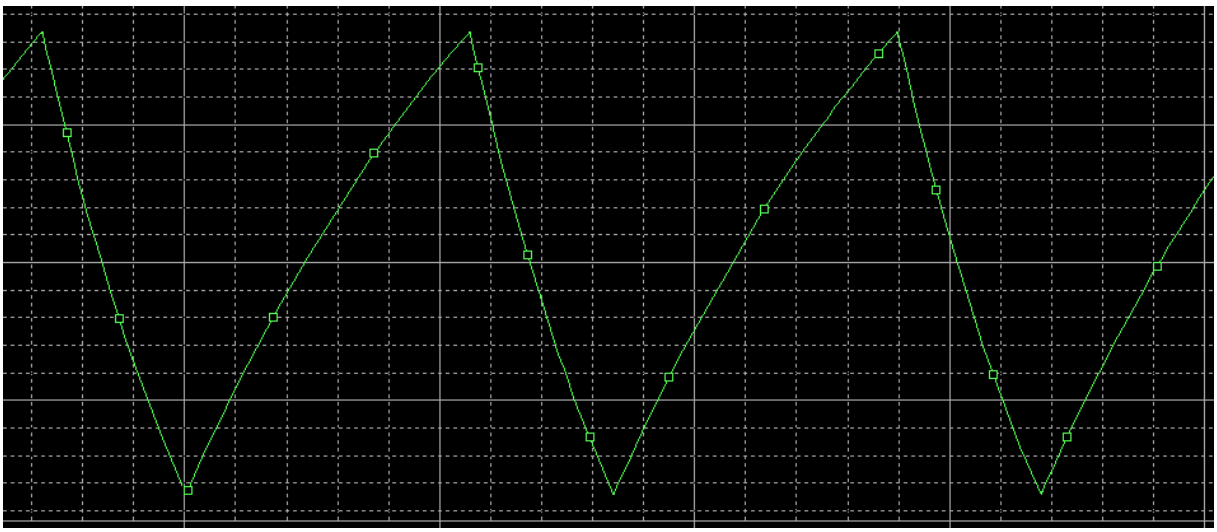

Figure 22: Type of wave of 555 timer

As can be seen from figure 22, 555 timer generates a non-ideal triangle signal, that is, the triangle is not isosceles, but more “sawtooth” wave. Accordingly, this circuit cannot be used in the project because it is impossible to control motor correctly with non-isosceles triangle wave that will not give adequate PWM signal.

3.1.2 Using op amps

An operational amplifier (op amp) is a direct current amplifier with a differential input and, as a rule, the only output having a high gain. The op-amp is a universal block with characteristics close to ideal, on the basis of which it is possible to build many different electronic circuits [16].

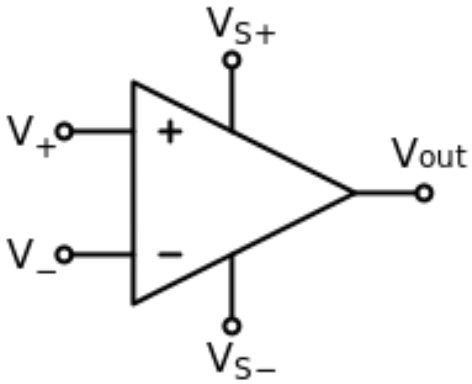

Figure 23: Operational amplifier on the circuits

The figure 23 shows a schematic representation of the operational amplifier. The conclusions have the following meaning:

- V_+ - noninverting input;
- V_- - inverting input;

- V_{out} – output;
- V_{S+} - positive power supply (also can be referred as V_{DD}, V_{CC} or V_{CC+})
- V_{S-} - negative power supply (also can be referred as V_{SS}, V_{EE} or V_{CC-})

These five outputs are present in any op amp and are necessary for its operation.

There are many ways of constructing multivibrators and generators of pulse sequences that are different from the rectangular form. Wide-spreading generators of linearly varying voltage and various types of triangular pulses are used, which are used in oscilloscope sweeps, shapers of a given time shift and other applications. Pulses of the required shape are obtained by appropriate choice of positive and negative feedback circuits. A triangle waveform generator can be obtained using a Schmitt trigger and an integrator [17].

3.1.2.1 Schmitt trigger

The Schmitt trigger is an electronic two-position relay element whose static characteristic has hysteresis loop. Schematically, the Schmitt trigger is a two-threshold comparator with an RS-flip-flop.

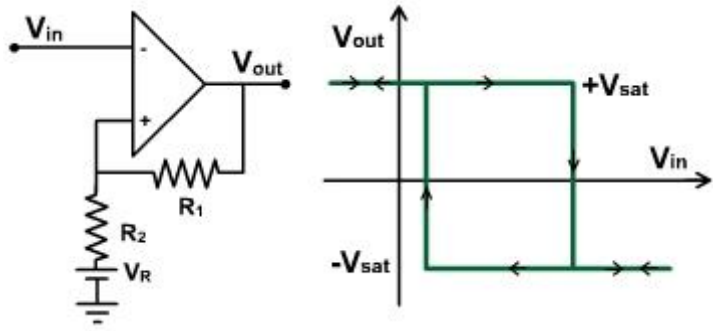

Figure 24: Schmitt trigger

The voltage levels at which the Schmitt trigger are triggered are called the upper level (threshold) of the triggering of the trigger and the lower level (threshold) of the triggering. To implement the Schmitt trigger, op amp covered by positive feedback are used, which is implemented by feeding a part of the output voltage to the non-inverting input. Schmitt trigger uses to compare two noisy or slowly changing signals, which allows excluding the multiple operation of the comparator at close values of input voltage.

3.1.2.2 Integrator

Integration circuits are designed to integrate in time electrical input signals. Different varieties of integrators are used in many schemes, for example, in active filters or in automatic control systems to integrate an error signal.

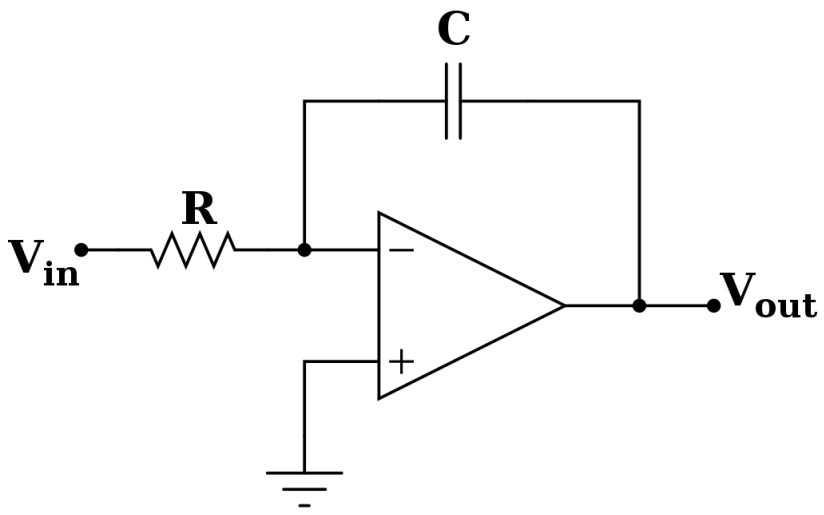

Figure 25: Integrator (op amp)

The integrator's work is based on the fact that the inverting input is grounded, according to the principle of virtual closure. The input current flows through the resistor R, at the same time to counterbalance the zero potential point, the capacitor will be charged with the current of the same value, but with the opposite sign. As a result, the voltage at which the capacitor is charged by this current will form on the integrator output. The input resistance of the integrator will be equal to the resistance of the resistor R, and the output resistance will be determined by the parameters of the op-amp [18].

The magnitude of the input signal is generally described by equation:

$$U_{out}(t) = -\frac{1}{RC}\int_0^t U_{in}(\tau)d\tau + U_{initial} \quad (3.2)$$

Where U_{out} and U_{in} are functions of time, $U_{initial}$ – output voltage at time t = 0.

When a rectangular pulse with ideal fronts is fed to the RC integrating circuit, the output voltage grows exponentially:

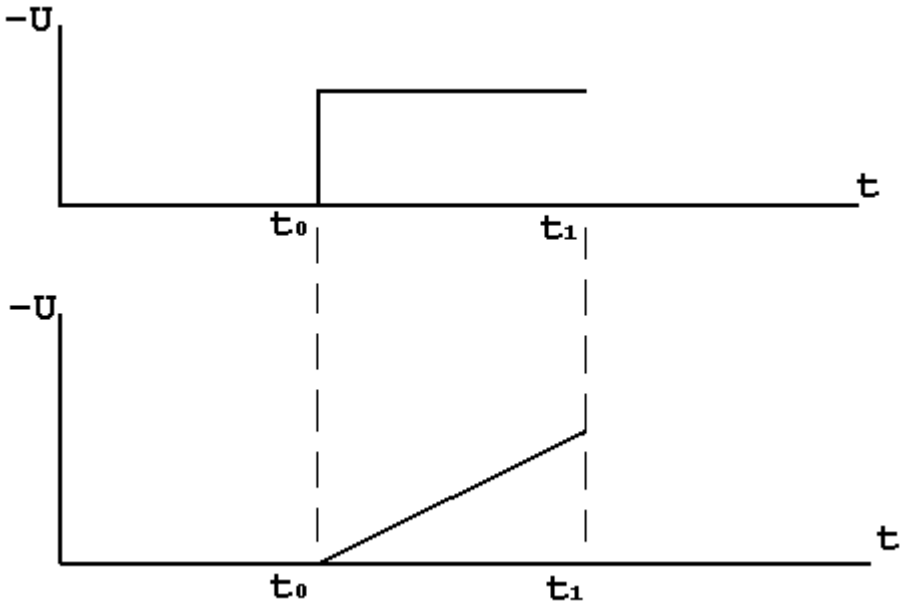

Figure 26: Integrated step signal

$$U_{out} = -\frac{1}{RC}\int U\,dt = -\frac{1}{RC} * U * t \quad (3.3)$$

The change in the output voltage in time is an inclined straight line with the polarity of the input signal.

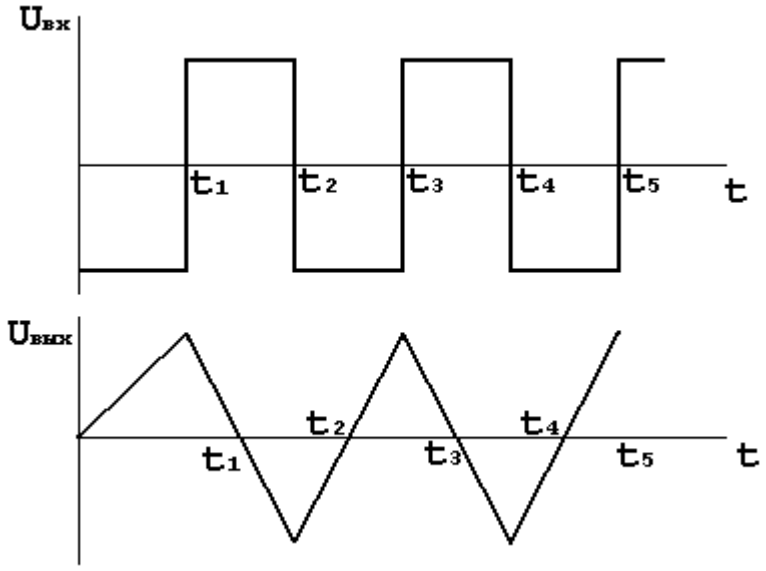

Figure 27: Integrated rectangular signal

Since the signal is periodic, it is sufficient to consider one full period to describe the output voltage. After integration, we obtain an oblique line at each half-period. For any signal at the input, the change in the output signal should start from the value that the output signal had at the time the input signal.

3.1.2.3 Triangle wave generator

The simplest way of obtaining triangular pulses is a circuit containing a Schmitt trigger and an integrator. The trigger's output is connected to the integrator's input, and the output of the integrator is connected with the input of the Schmitt trigger.

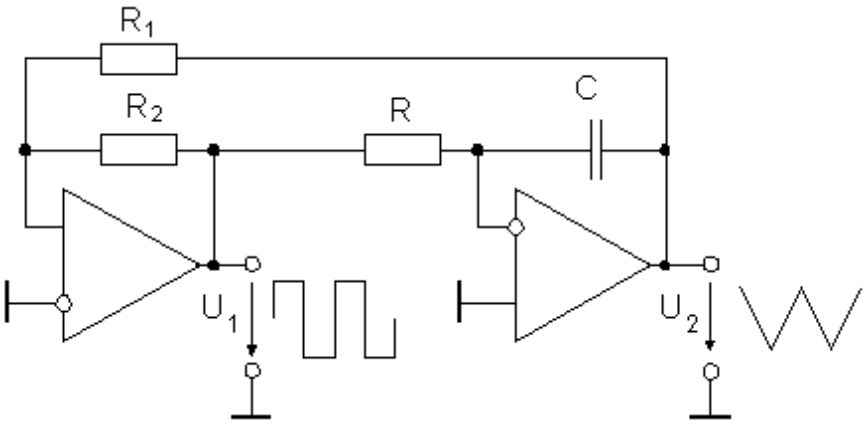

Figure 28: Triangle wave generator

This triangle wave generator consists of a Schmitt trigger on the op amp and resistors R_1 and R_2, as well as an integrator on the op amp and resistor R and the capacitor C. Triangle pulses were got from the output U_2, in addition, from the output U_1 - rectangular pulses.

When the supplying voltage is applied to the circuit at the output of the Schmitt trigger a positive saturation voltage is set. Then the capacitor C begins to be charged, and at the output of the integrator the voltage begins to fall linearly, respectively. Since the output of the integrator and the input of the trigger are connected, then when the linearly falling voltage reaches the level of the lower switching voltage of the trigger, the voltage across its output will go to the negative saturation voltage, and the capacitor C will begin to discharge. As the capacitor discharges, the voltage at the integrator's output will begin to linearly increase to the level of the upper Schmitt trigger voltage, after reaching it the output of the trigger will switch to the level of the positive saturation voltage of the op amp and the charge-discharge cycle of the capacitor C, and hence the triangular voltage, will be repeated [19].

The output voltage has positive stable state $U_2 = +U_s$ and triggered to $U_1 = -U_s$, when U_1 forces non-inverting input negative (where $+U_s$ and $-U_s$ are power supplying of op amp).

According to Millman's theorem:

$$\frac{U_1}{R_1} + \frac{U_2}{R_2} = 0 \quad (3.4)$$

$$U_1 = -\frac{R_1}{R_2} * U_S \quad (3.5)$$

Assume that output voltage at Schmitt trigger has to trigger twice (from positive to negative state) and then goes back. In this case:

$$\Delta U_2 = 2\frac{R_1}{R_2}U_s \quad (3.6)$$

The second stage is integrator, where current flow through resistor R and capacitor C.

$$I_c = \frac{U_S}{R} \quad (3.7)$$

Since this current can change output voltage ΔU :

$$\Delta U = \frac{\Delta Q}{C} = \frac{I_C * \Delta t}{C} \quad (3.8)$$

rearranging

$$\Delta t = \frac{C * \Delta U}{I_C} \quad (3.9)$$

From 3.6 and 3.7 follows:

$$\Delta t = 2\frac{R_1}{R_2}U_s * \frac{R}{U_s} * C = 2\frac{R_1 R}{R_2}C \quad (3.10)$$

Since Δt is half period, hence it follows that:

$$T = 2 * \Delta t = 4\frac{R_1 R}{R_2}C \quad (3.11)$$

Thus, frequency of the triangle wave equals:

$$f = \frac{1}{T} = \frac{R_2}{4R_1 RC} \quad (3.12)$$

4 Simulation model

4.1 Triangle wave simulation

First challenge in design circuit is the choice of components for circuit. Following the circuit that was presented above, it is clear that the main in triangle wave generator is op amps.

I decided to choose op amp that was produced by Texas Instruments, because this company has huge components list and convenient search on website.

First of all, I chose type of op amps. On the website [21] it exists few types:

- Precision op amps
- High-Speed op amps
- General-Purpose op amps
- Ultra-Low-Power op amps
- Audio op amps
- Fully differential amplifiers
- Power op amps

The most appropriate choice is general-purpose op amps.

I decided to choose op amp according to 3 parameters: minimum supply voltage, number of channels and maximum quiescent current per channel:

Part Number Filter by part number	Number of Channels (#)	Total Supply Voltage (Min) (+5V=5, +/-5V=10)	Total Supply Voltage (Max) (+5V=5, +/-5V=10)	GBW (Typ) (MHz)	Slew Rate (Typ) (V/us)	Rail-to-Rail	Vos (Offset Voltage @ 25C) (Max) (mV)	Iq per channel (Typ) (mA)
TL031 - Enhanced JFET Low-Power Precision Operational Amplifier	1	10	30	1.1	2.9	In to V+	1.5	0.217
LM741 - Operational Amplifier	1	10	44	1	0.5		3	1.7
LM301A-N - Operational Amplifier	1	10	36	1	0.5	In to V+	7.5	1.8
LF411-N - Low Offset, Low Drift JFET Input Operational Amplifier	1	10	44	4	15	In to V+	0.4	1.8
LF411QML-SP - Low Offset, Low Drift JFET Input Operational Amplifier - Hi-Rel	1	10					5	1.8
LM101A-N - Operational Amplifier	1	10	44	1	0.5	In to V+	2	1.8
LM201A-N - Operational Amplifier	1	10	44	1	0.5	In to V+	2	1.8

Figure 29: Result of op amps filter [21]

My decision is using 5 and 10 volts in the projects because it is most common used voltages and I can easily get it with help of the voltage regulators. Reason to use one channel op amp is the pursuit of the safety of each motor.

The retrieved search results show that most useful choice is TL031, because it uses less current and I can avoid excessive power consumption and overheating.

Frequency of triangle wave should to be 10-20 KHz. To find out which nominal components to use, I used the formula 3.12. After calculations, I have:

- R_1 = 800 Ohm
- R_2 = 1 kOhm
- R = 5 kOhm
- C = 3 nF

Since the resistors and capacitors are produced only a certain nominal value, I had to choose the nearest values to the calculated:

- R_1 = 825 Ohm

- R_2 = 1 kOhm
- R = 5.1 kOhm
- C = 3.3 nF

The designed circuit, that is shown in Appendix C., consists triangle wave generator with frequency ~14.3 kHz.

Whereas calculated frequency:

$$f = \frac{1}{T} = \frac{R_2}{4R_1RC} = \frac{1000}{4*825*5.1*10^3*3.3*10^{-9}} \sim 18\ kHz \quad (4.1)$$

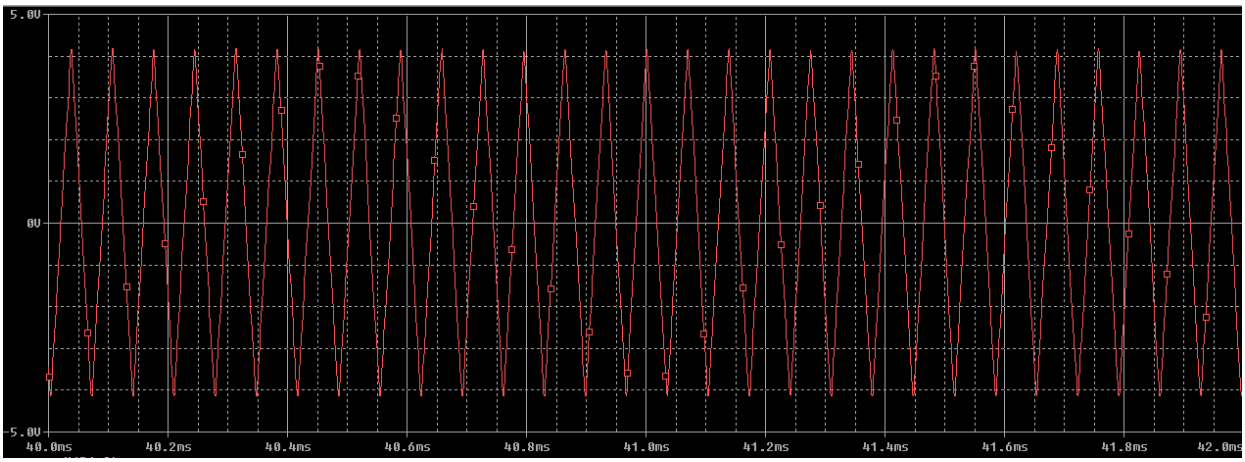

Figure 30: Simulated triangle wave

This difference is due to the fact that maximum peak output voltage (if voltage supply is $\pm 5\ V$) of TL031 are V_{OM+} = 4.3 V and V_{OM-} = 4.2 V.

In this case maximum amplitude achieves with $\frac{R_2}{R_1} \sim 0.825$. Also this are real op amps and Schmitt trigger cannot change states instantaneously.

I can check my calculations later on a real board layout.

4.2 Voltage divider

The second component in obtaining the PWM signal is a constant voltage, which must be compared with a triangular wave in the comparator. In this project, the PWM signal is manually controlled. For this purpose, it was decided to use a voltage divider as the simplest and cheapest method.

A voltage divider is a device in which the input and output voltages are connected by a transmission coefficient. The voltage divider can be represented as two consecutive sections of a chain (Figure 31), the sum of the voltages at which is equal to the input voltage. The

simplest resistive voltage divider consists of two series-connected resistors connected to a voltage source. Since the resistors are connected in series, the current through them will be the same in accordance with the first Kirchhoff`s law. The voltage drops across each resistor according to Ohm's law will be proportional to the resistance [22]:

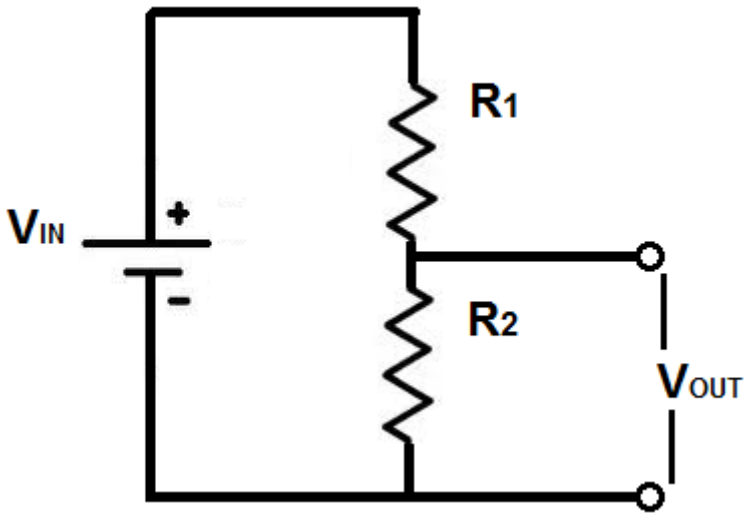

Figure 31: Voltage divider

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2} \quad (4.2)$$

As you can see from the formula, the voltage will never be zero, you can only make it minimum acceptable.

I decided to use $R_1 = 5\ kOhm$ and $R_2 = 200\ Ohm$. This will give me a low minimum voltage level; however, the disadvantage is a very uneven voltage increase when changing R_1.

4.3 PWM signal

PWM signal is the basis of the H-bridge operation, and hence the basis for the operation of the entire circuit. As described above, the PWM signal is obtained by comparing the triangular wave and the DC voltage. For this, there is a special chip, called a comparator.

There are exist a lot types of comparator, but I decided to use comparator that I could find on the university's storage and in OrCAD library at the same time.

The most commonly used and simple comparator is LM393. It is a dual differential comparator that can supply voltage up to 36 V.

Since this comparator has open collector at output, the output must have a 3K resistor. This nominal is designed for 36 volts, the project uses a voltage of 10 volts, so it was decided to use a resistance of 500 ohms

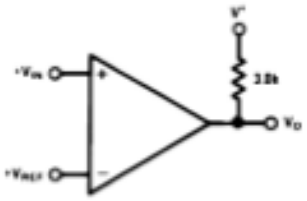

Figure 32: LM393 connection

Simulation of the received circuit, that is shown in Appendix D:

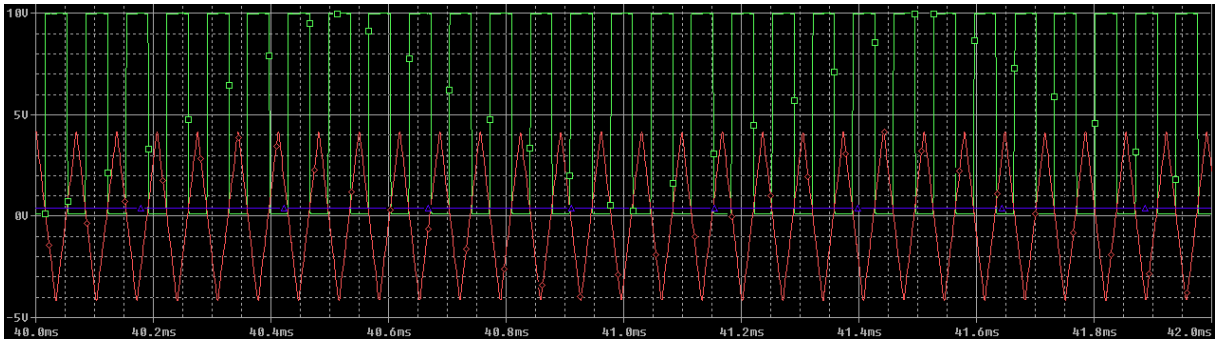

Figure 33: PWM signal with bipolar supplying op amps (DC voltage is minimum)

Figure 33 shows triangular signal (red), DC voltage (blue) and resulting PWM signal (green)

4.4 Corrected PWM signal

As can be seen from the figure 33, with a minimum voltage, the duty cycle of the PWM signal is 50% instead of 0%. This is because I used bipolar supplying amplifiers. This means that the average value of my triangular wave is 0 and duty cycle less than 50% can be obtained by applying a negative voltage to the comparator. It's very easy to do in software, but it's hard to implement on a real board layout, so I decided to use unipolar power and introduce an artificial common point at the level of 5 volts.

I corrected my circuit, implemented an artificial common point. Positive power supply input is supplied by 10 volts and negative power supply is grounded. The corrected circuit is shown in Appendix E:

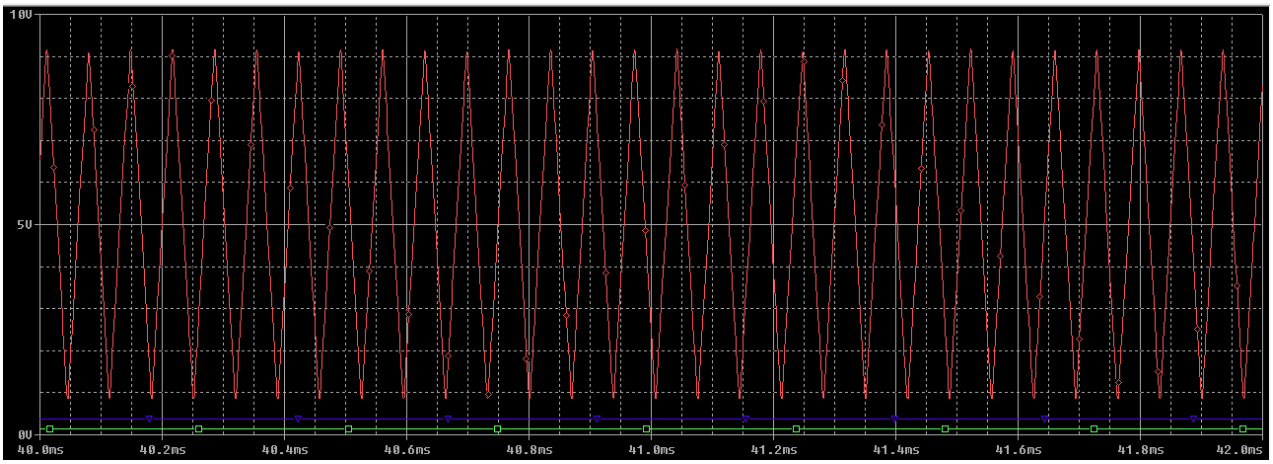

Figure 34: PWM signal with unipolar supplying op amps(DC voltage is minimum)

This circuit allows to control the duty cycle of PWM in the entire range from 0% to 100%.

4.5 Galvanic isolation

Galvanic isolation is a transfer of energy or signal between electrical circuits without electrical contact between them. Galvanic isolation is used for signal transmission, for contactless control and for protecting equipment and people from electric shock.

In my project I needed galvanic isolation, because I had to protect and separate my control loop from power supply loop, that supplies motor and could damage control loop through common chip – motor driver.

There are just a few models of optocouplers in OrCAD library.

I needed an optocoupler with a transistor as an output, minimum collector-emitter voltage is 10 volts and time rise and fall is minimum:

$$t = \frac{T}{2} = \frac{1}{2 * f} = \frac{1}{2 * 14.3 * 10^3} \sim 35\ \mu s$$

Optocoupler with these requirements, which is in the OrCAD library is 3N244 [23]:

Table 2: Optocoupler 3N244

Forward DC Current	40 mA
Reverse Voltage	2 V
Continuous Collector Current	30 mA
Collector- Emitter Voltage	30 V
Output Rise Time	10 μs
Output Fall Time	10 μs

This optocoupler satisfies the stated requirements and is completely suitable for simulations.

4.6 Motor driver

One of the main challenges of this project was the motor driver selection. First of all, I decided to use in the project motor driver instead of gate driver.

Using the motor driver is simpler and more reliable since I decided to not use the additional elements (MOSFETs, diodes) that can be damaged while using. In addition, the market has much more motor drivers with included H-bridge than the gate drivers. This makes it easy to find the item I need.

In the process of searching, I faced the problem of the OrCAD library. There are just few motor driver models [24].

As a result, I found two motor drivers in OrCAD library that are controlled by a PWM signal and have a suitable output voltage (24 volts):

- LM5045
- SA50CE

LM5045 produced by Texas Instruments, this is full-bridge PWM controller with integrated MOSFET drivers.

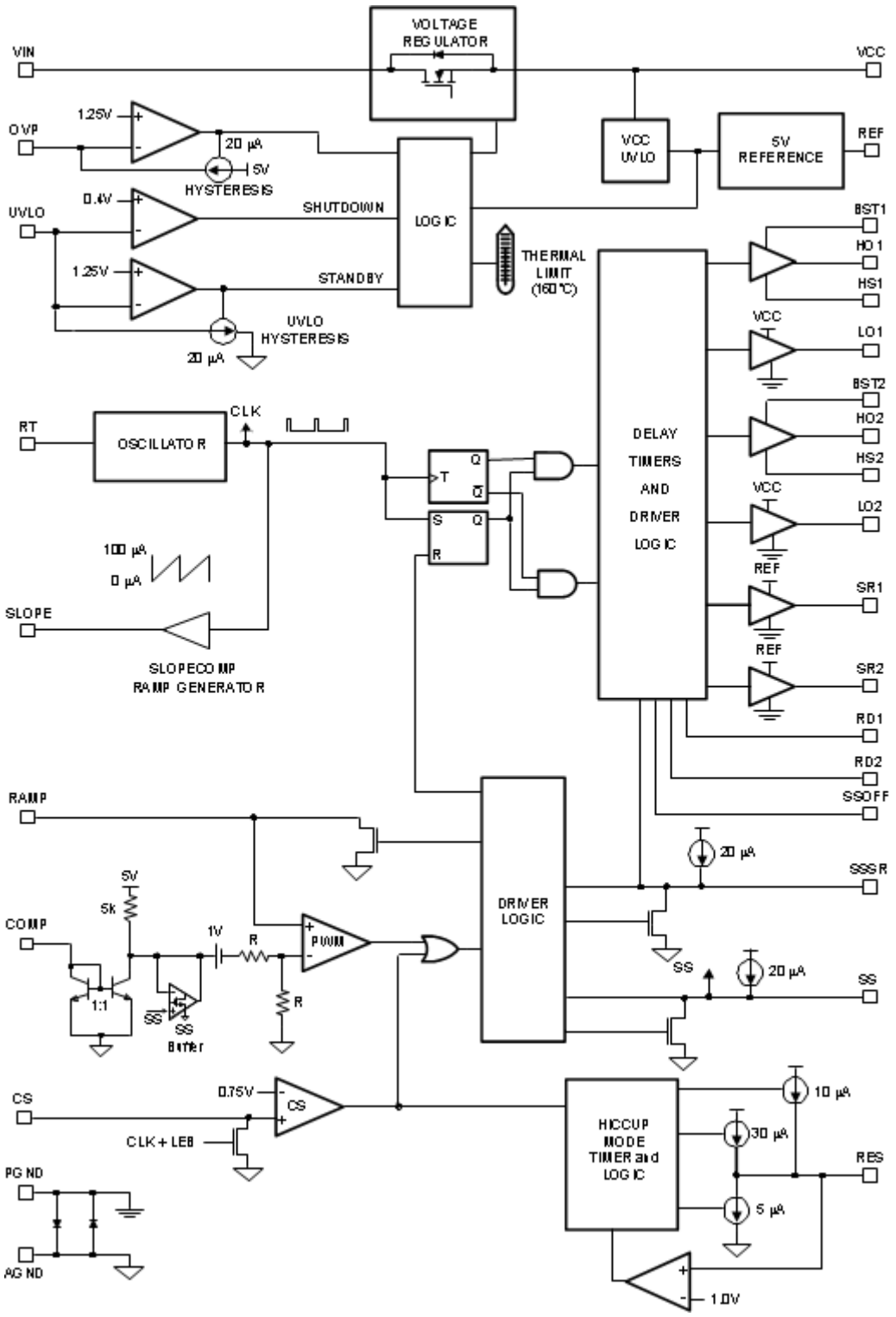

Figure 35:Functional block diagram for LM5045 [25]

Key inputs are COMP and RAMP (Figure 35). Where COMP is PWM input signal and RAMP is Modulation ramp for the PWM comparator. That means that I needed to have an additional input signal with some ramp that would be compared with PWM signal inside motor driver.

This was unacceptable since I needed a motor driver that would drive the motor only based on PWM modulation.

Next I looked at the motor driver that will be produced by the Apex Microtechnology. OrCAD Library consist many motor drivers from Apex and chose SA50CE, because it satisfies the requirements [26]:

Table 3: SA50CE

Type control	PWM
Output Current	5 A
Supply Voltage (max)	80 V
Switching Frequency	45 kHz

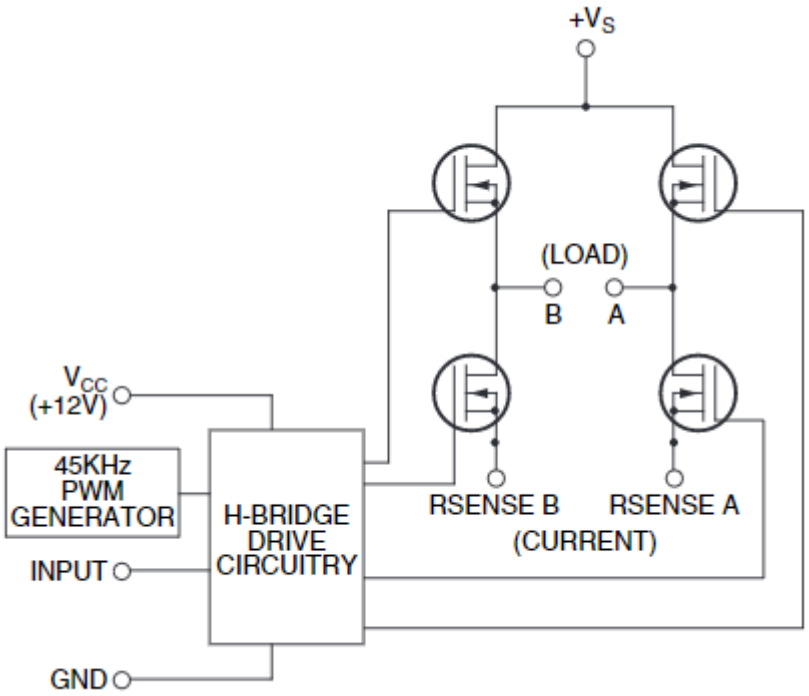

Figure 36: Functional block diagram for SA50CE

This integrated circuit (IC) has 8 pins:

- V_{CC} - low voltage supply for powering internal logic and drivers for the lowside and highside MOSFETS
- V_S - higher voltage H-bridge supply. The MOSFETS obtain the output current from this supply pin
- Input - analog input for controlling the PWM pulse width of the bridge. A voltage higher than VCC /2 will produce greater than 50% duty cycle pulses out of A OUT. A voltage lower than VCC /2 will produce greater than 50% duty cycle pulses out of B OUT
- GND – ground
- RSense A – connection for the bottom of A half bridge
- RSense B – connection for the bottom of B half bridge

- A out - output pin for one half of the bridge. Increasing the input voltage causes increasing duty cycle at this output.
- B out - output pin for one half of the bridge. Decreasing the input voltage causes increasing duty cycle at this output.

Motor control in this motor driver is carried out according to the simplest way: As the duty cycle is increasing, the voltage on A output is increasing, when duty cycle is decreasing – the voltage on B output is increasing. The motor is in equilibrium when the duty cycle is 50%.

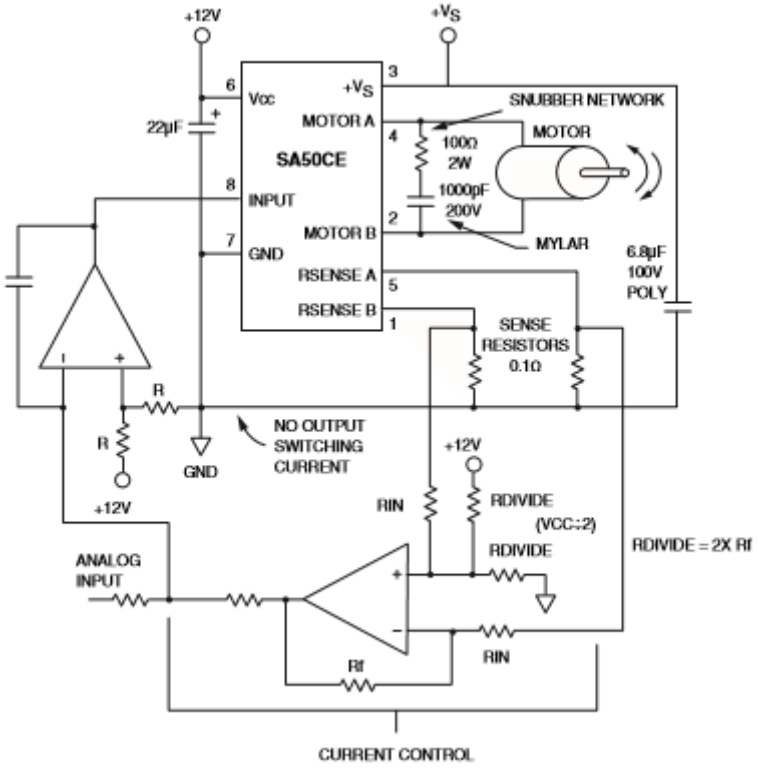

Figure 37: Diagram of a typical application of the SA50CE

I did not use a current control in the project because there is a manual motor control in use, and it was not necessary to have an additional loop to control current.

So, I used this motor driver in my circuit, using a RL circuit as the motor model. I measured the nominal values of the elements in the laboratory on the available motors.

The circuit that simulates motor control unit is shown in Appendix F.

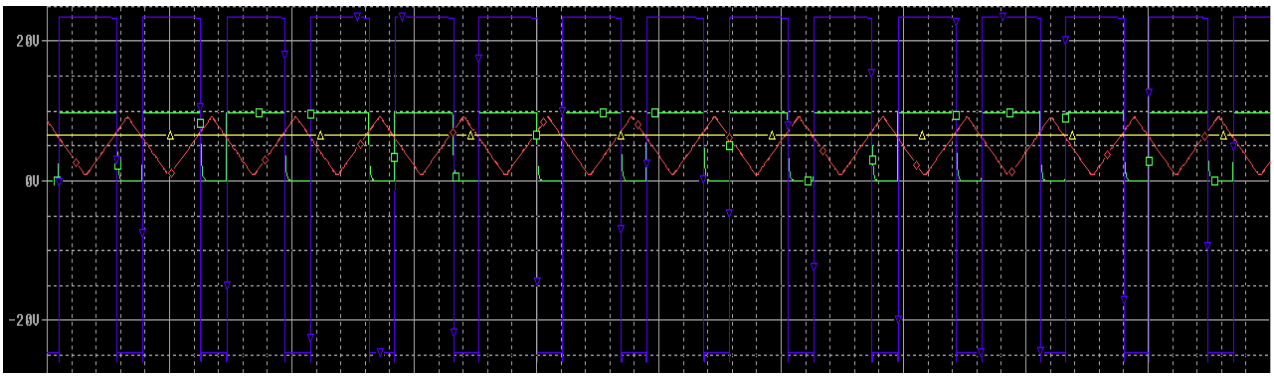

Figure 38: Output voltage (blue) at control voltage level 6.667 volts

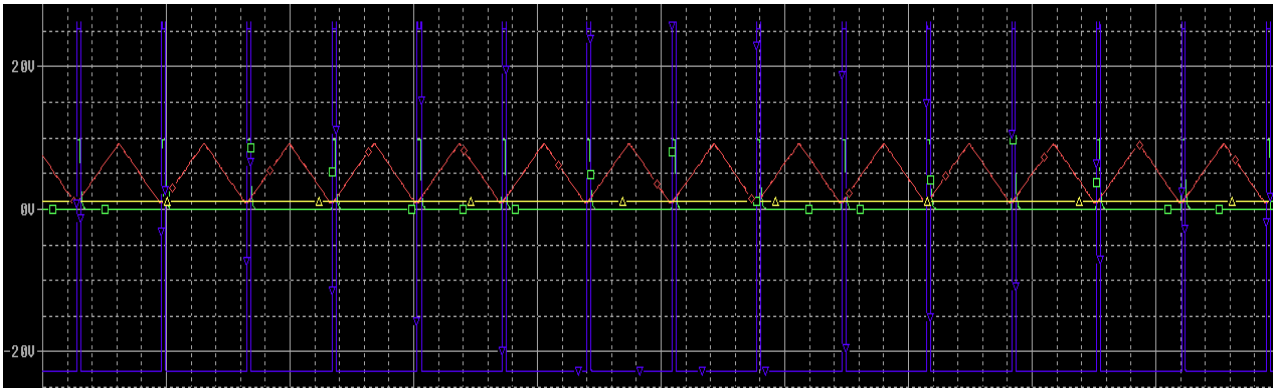

Figure 39: Output voltage (blue) at control voltage level 1.177 volts

Figures 38 and 39 show triangle wave (red) that is compared to a voltage controlled manually (yellow). Obtained PWM signal (green) changes motor driver output voltage (blue) within range -24 V to +24 V. Thus, the motor that will be connected to the circuit, will be controlled in forward and reverse rotation with different speed. This speed depends on the voltage level that is controlled manually through voltage divider.

5 Power supply

This project requires a stable DC voltage for the circuit and motors power supply. As shown above, the circuit uses a voltage is 5 volts, 10 volts and 24 volts.

Thus, the following problem arose: it was necessary to construct DC voltage source of three different values: 5,10 and 24 V. For this purpose, the AC 220 V from the grid must be lowered and rectified to the required values.

5.1 Voltage regulators

The simplest way to get stable voltage in the circuit is using voltage regulators.

The voltage regulator is a device that allows to change the value of the electrical voltage at the output when it acts on the control elements, or when a control signal is received.

Since in the project was used standard voltage, it is easy to use voltage regulator 5, 10 and 24 volts, that could be found on market easily.

I chose voltage regulators that were produced by Texas Instruments:

- LM7805 – 5 volts
- LM7810 – 10 volts
- LM7824 – 24 volts

All these three types of voltage regulators have different parameters [27]:

Table 4: Voltage regulators parameters

	LM7805			LM7810			LM7824			Unit
Input voltage	min		max	min		max	min		max	V
	7		25	12.5		28	27		38	
Output voltage	min	typ	max	min	typ	max	min	typ	max	V
	4.8	5	5.2	9.6	10	10.4	23	24	25	
Output current	1.5			1.5			1.5			A

It was decided to use output voltage of LM7810 as input voltage LM7805, because these two regulators are used in the same control loop and part of circuit. Another thing is LM7824: this is another part of circuit that responsible for motor power supplying. These two loops should to be separated, because of safety.

From the table 4 follows that that at least two input voltages are required, for LM7810 and LM7824. Thus It requires two rectifiers and two transformers.

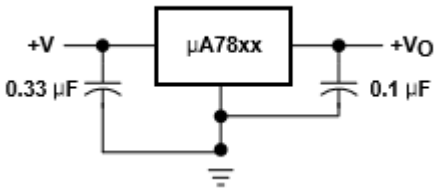

Figure 40: Application LM78xx

Figure 40 shows connection LM7805 (LM7810, LM7824) to circuit.

5.2 Rectifier

Rectifier is a converter of electrical energy, a device designed to convert the input AC current into a DC current. Most rectifiers do not create a constant, but a pulsating current. Voltage regulator uses for convert it to stable DC current.

Rectifiers could be one-phase and multi-phase. In industry multi-phase rectifiers (three-phase usually) are more widespread, but for small machines and mechanisms – one-phase is used usually. The project has one-phase grid and one-phase rectifier accordingly.

Also, there is exist two types of one-phase rectifier that could be used in the project:

- Half-wave rectification
- Full wave rectification

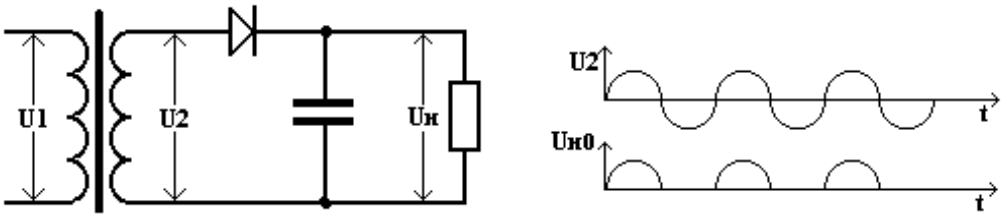

Figure 41: Half-wave rectifier

The simplest circuit of a half-wave rectifier consists of one current-rectifying element (diode) (Figure 41). Disadvantages: high ripple level of rectified voltage, low efficiency, much larger than in other circuits transformer weight.

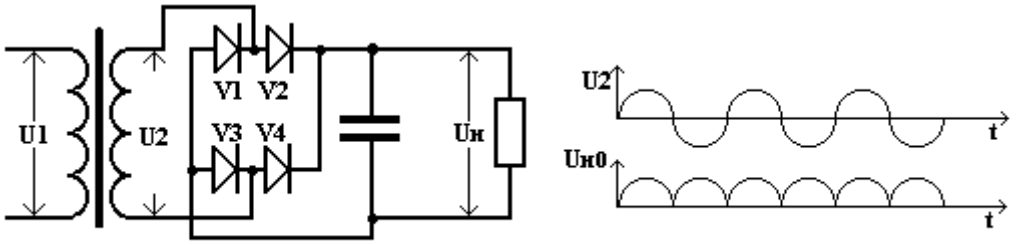

Figure 42: Full-wave rectifier

In comparison with a half-wave circuit, the bridge circuit (Figure 42) has a two times lower level of ripple, higher efficiency, more rational use of the transformer and a reduction in its design capacity. In comparison with the full-wave circuit, the bridge circuit has a simpler transformer design with the same level of ripple. This rectifier circuit is most often used in a variety of devices. This type of rectifier should be used in the circuit [28].

5.3 Transformer

The project requires two transformers for two separate circuits: control and motor supplying.

Could be supposed that voltage drop on one diode is 0.7 volts, consequently voltage drop on the rectifier is 1.4 volts.

Thus, voltage of DC current after diode rectifier [8]:

$$U_d = U_2 * \sqrt{2} - 1.4 \quad (5.1)$$

Formula 5.1 shows DC voltage after rectifier that equals RMS of AC voltage multiplied by $\sqrt{2}$ and minus voltage drop on the diodes.

Given this, the voltage of secondary winding of transformers could be calculated.

Maximum and minimum values of input voltage regulators are limits for transformers that could be chosen.

1. Transformer for LM7810:

- Maximum voltage of secondary winding:

$$U_2 = \frac{U_d}{\sqrt{2}} + 1.4 = \frac{28}{1.41} + 1.4 = 21.25\ V$$

- Minimum voltage of secondary winding:

$$U_2 = \frac{U_d}{\sqrt{2}} + 1.4 = \frac{12.5}{1.41} + 1.4 = 10.26\ V$$

2. Transformer for LM7824:

- Maximum voltage of secondary winding:

$$U_2 = \frac{U_d}{\sqrt{2}} + 1.4 = \frac{38}{1.41} + 1.4 = 28.35\ V$$

- Minimum voltage of secondary winding:

$$U_2 = \frac{U_d}{\sqrt{2}} + 1.4 = \frac{27}{1.41} + 1.4 = 20.55\ V$$

According to Fischertechnik [1], the largest motor they use has 24 volts supplying and 0.3 amperes current. Supposed starting current – 0.5 amperes. Thus, supposed power that will be consumed by one largest motor:

$$P = U * I = 24 * 0.5 = 12\ VA \quad (5.2)$$

At the request of the laboratory engineer, the model will use 4 motors at the same time. Thus, total power consumption, that should to supply transformers, will be 60 VA.

Unfortunately, OrCAD doesn't consist model of LM7824 and LM7810. Therefore, I designed and simulated LM7812 and LM7810. This circuit is shown in Appendix G.

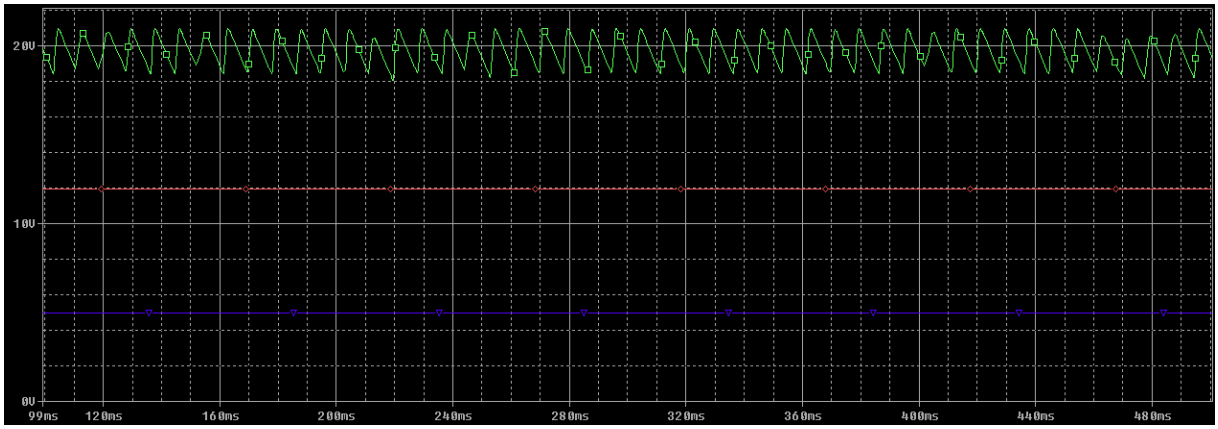

Figure 43: Simulation LM7812 and LM7805

Figure 43 shows DC voltage after rectifier (green), that is input voltage (~20 V) for LM7812, output voltage of LM7812 (red) is 12 volts and output voltage of LM7805 (blue) is 5 volts. This circuit I will use in board layout.

6 Implementation

6.1 Power supply

The first stage of implementation of my circuit is power supplying as the basis of the whole project. As I said in chapter 5, in this project I should to use two transformers 18 V and 25 V. I calculated in previous part that I need transformer for 25 V with power rating 60 VA at least.

Before ordering in the web store, I had to use the components from the storage in the university. There I found two transformers with secondary voltage rating 18 V and 25 V. Power ratings were much more that I needed, but it is not necessary because higher power rating is even better for the project: model could work with numbers of motors more than four. Transformers that was used in the project [29]:

Table 5: Parameters of used transformers

Primary winding	230 V	230 V
Secondary winding	25 V	18 V
Power rating	80 VA	80 VA
Measured voltage	27.5	20.9

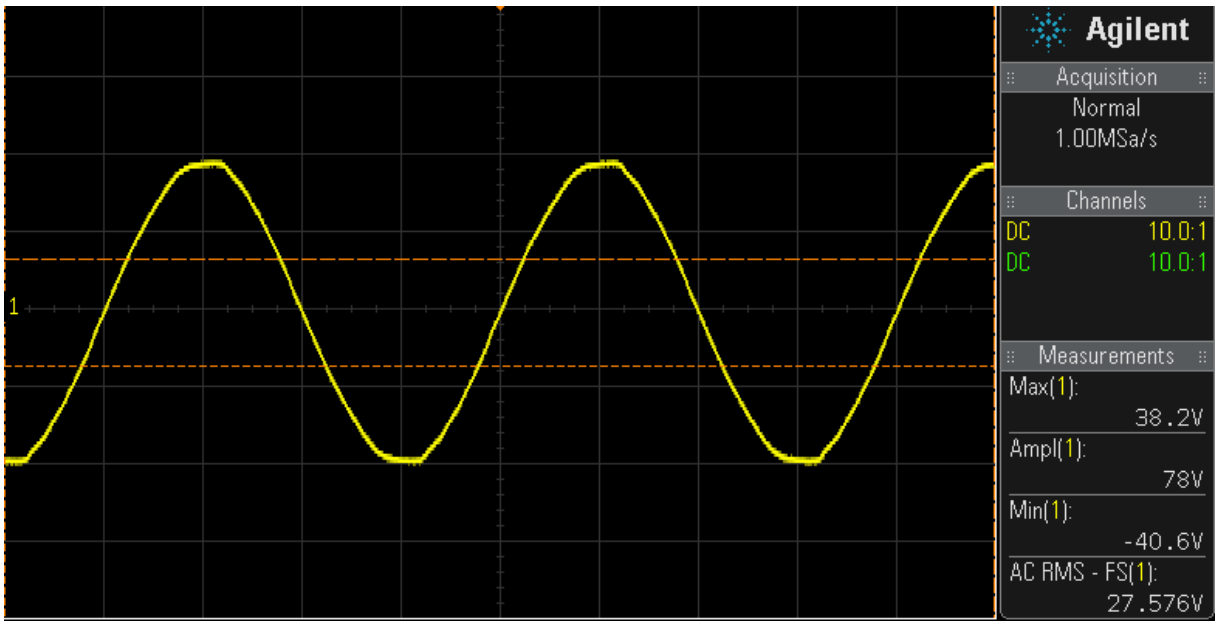

Figure 44:Measured voltage of transformer 230/25

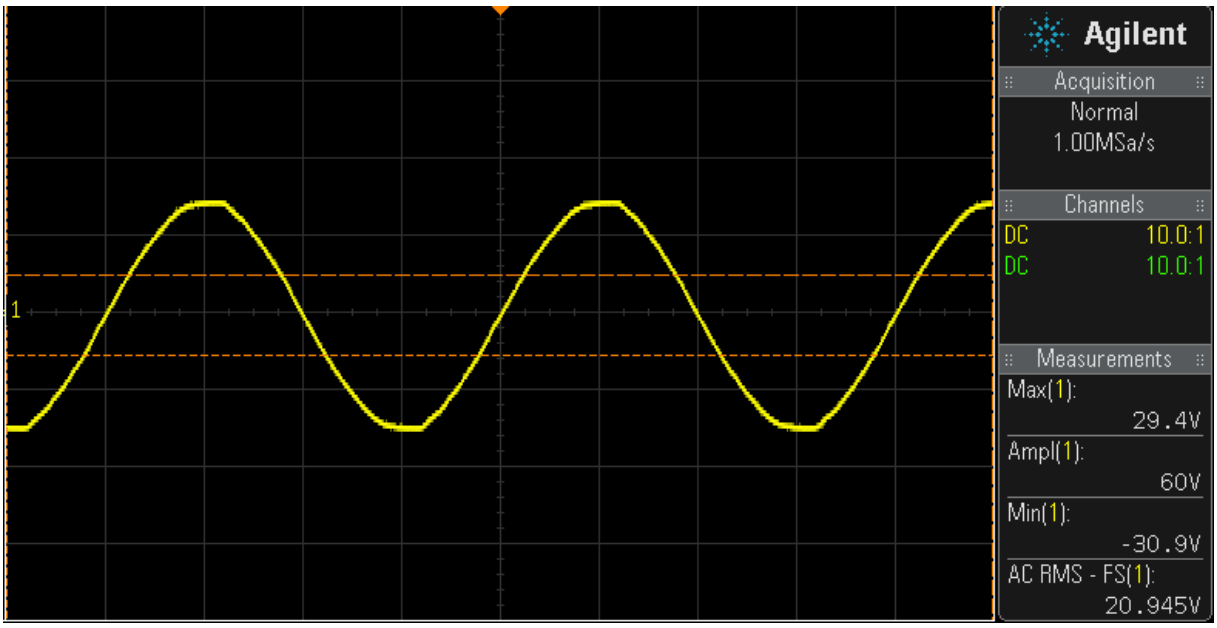

Figure 45: Measured voltage of transformer 230/18

Measured voltage (figure 44 and 45) is higher than it is in datasheet. There are two points to explain it:

1. Measured grid voltage is 237 volts, instead of 230 volts
2. It is indicated in the datasheet that no load secondary voltages are 28.3 volts and 20.4 volts respectively.

The second stage in power supplying is rectifier that consists of diodes. I chose diodes that I found in the storage. I had two requirements for diodes: maximum average forward rectified current is minimum 1 A and maximum reverse recovery time $T = \frac{1}{f} = \frac{1}{60} = 17\ ms$.

The diode that satisfied my requirements – BA197 [30]. This is fast recovery diode with low forward voltage drop and low leakage current. According to Appendix G, I made two rectifiers, with 3 voltage regulators.

Output voltage of the first rectifier (27,5 AC volts) is 37 DC volts. The output voltage of the second rectifier (20.9 AC volts) is 27.1 DC volts. This result correlates with formula 5.1 and satisfied the voltage regulators requirements.

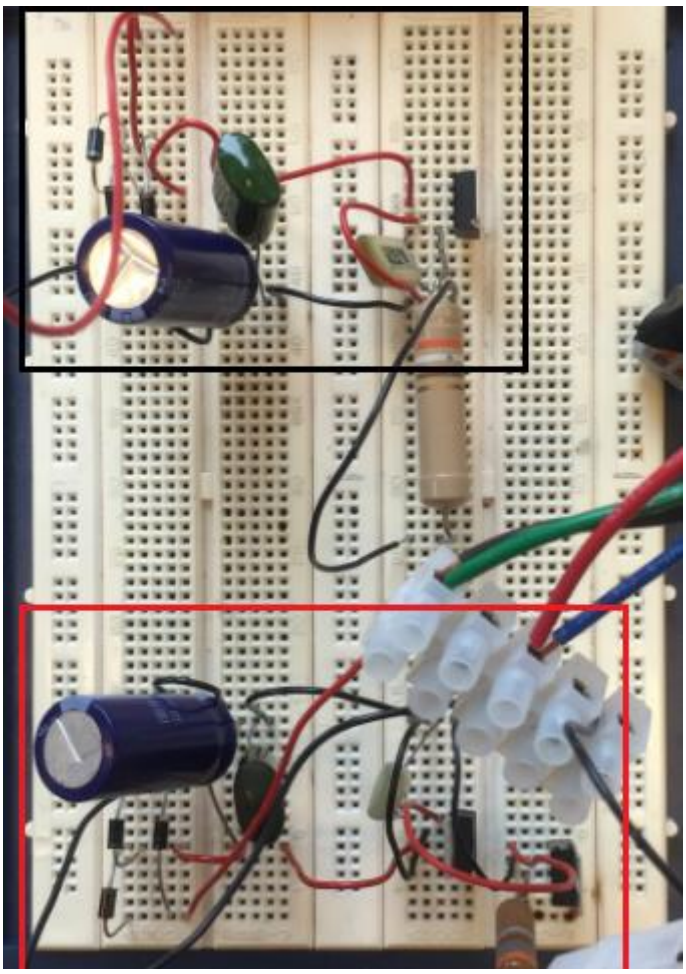

Figure 46:Implemented power supply circuit

Figure 46 shows two rectifiers: black square outlines 27.5 V rectifier and red square – 20.9. As shown, second rectifier has two voltage regulators: LM7810 and LM7805. Outputs from regulators are 24, 10 and 5 volts.

6.2 Triangle wave circuit

It is impossible to construct triangle wave circuit on the trainer, because op amp TL031 is surface mount device. It means that I had to make separated board layout.

I made a circuit with inputs and outputs in OrCAD as shown in figure 47:

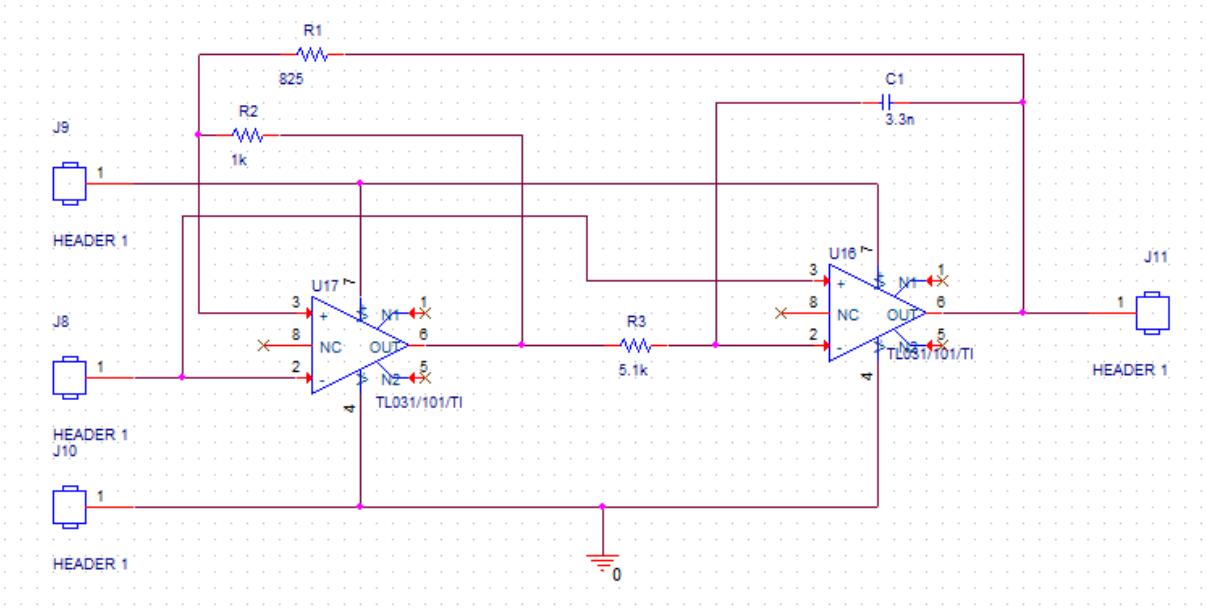

Figure 47: Triangle wave circuit for board layout

After that I converted this file into .brd file and made some manipulations in PCB Editor. I had .brd file which is a model of board layout

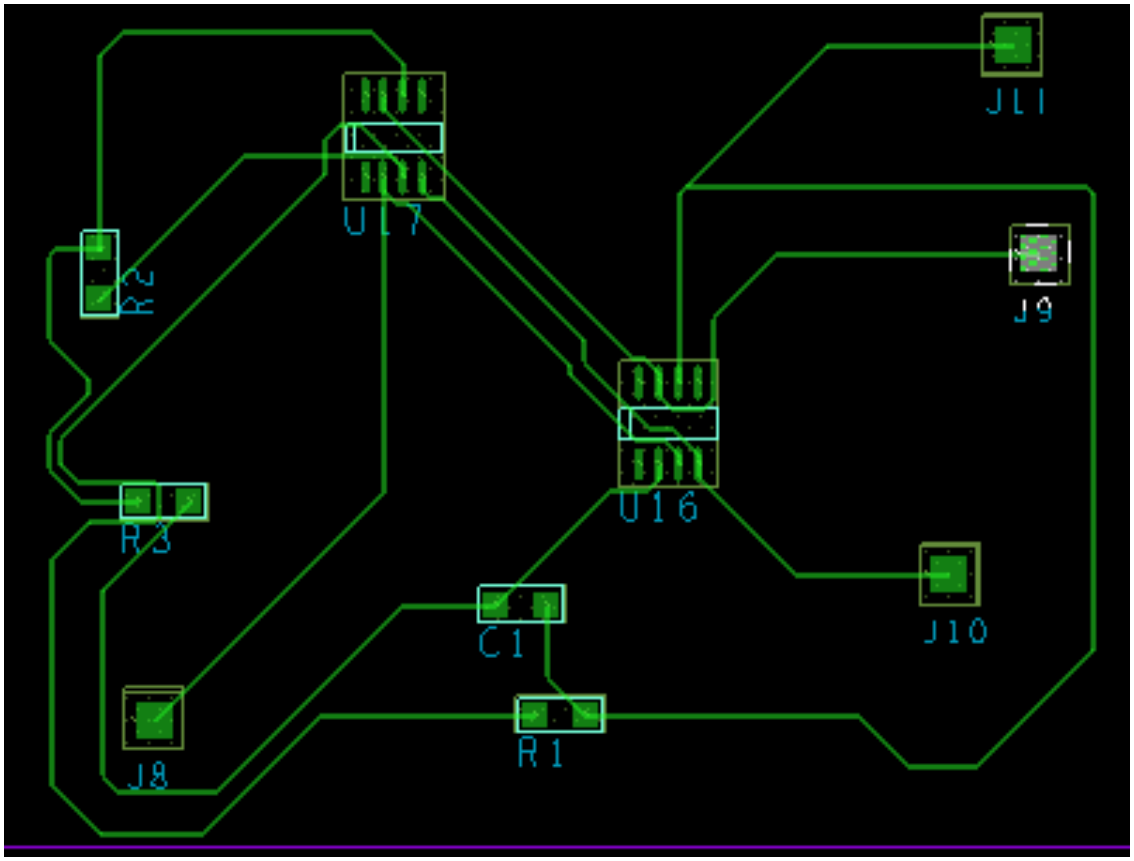

Figure 48: Model of triangle wave generator in PCB Editor

Final point in making board layout is converting file into .LMD file and making blank board with places for op amps, resistors and capacitor and routes between them.

After that I soldered a triangle wave generator with inputs (5 V, 10 V and ground) and an output (triangle signal). This board layout is shown in Figure 49:

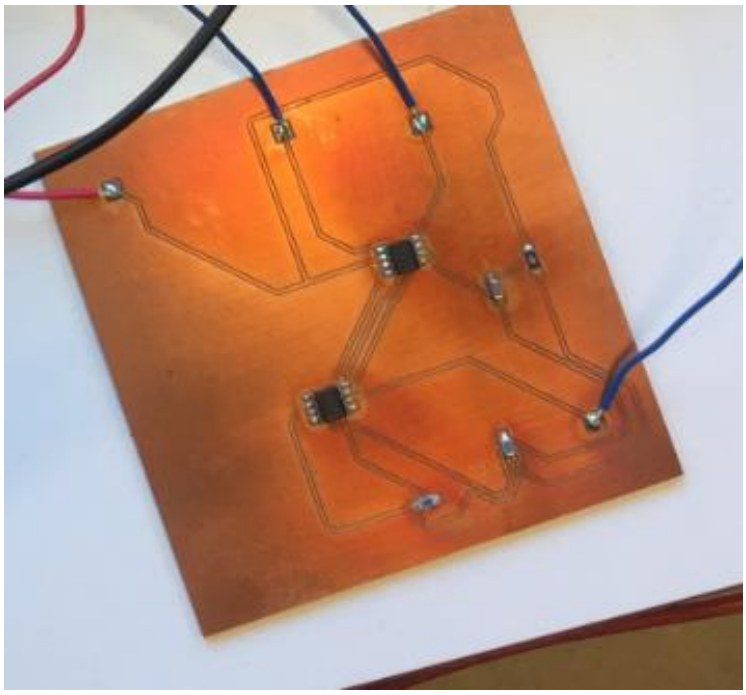

Figure 49: Triangle wave generator (board layout)

Then I connected this board layout to power supply circuit which I had made before. Measured signal from output of this generator is shown in Figure 50:

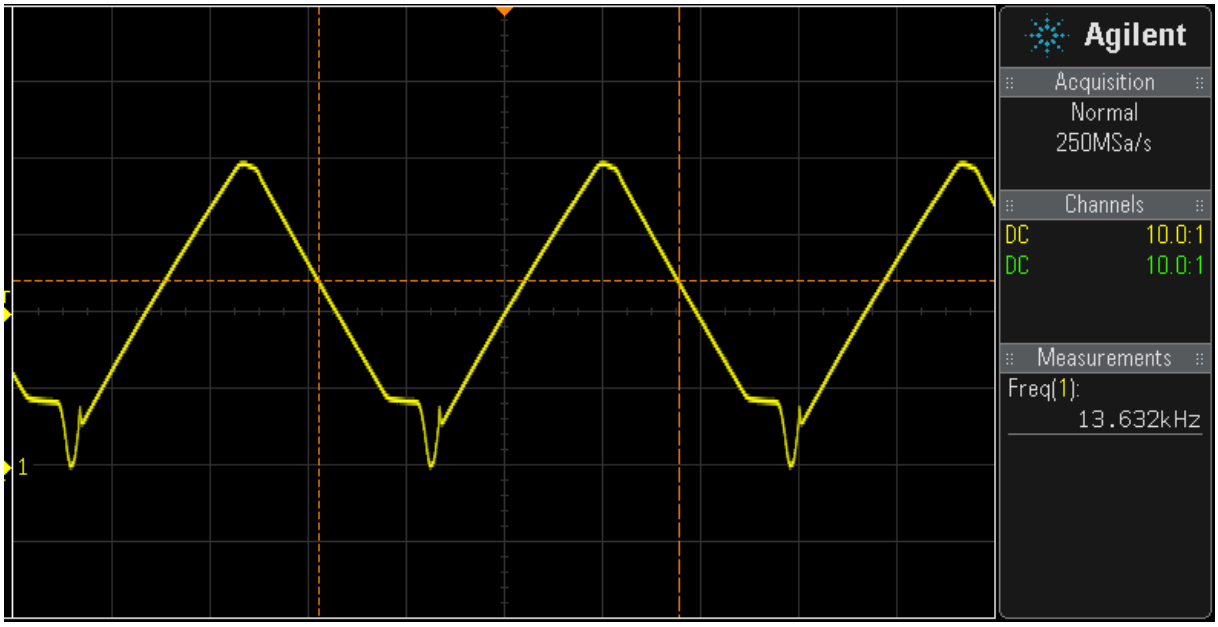

Figure 50: Scope of triangular signal

Obtained wave is not ideal. I supposed that I made some mistakes in soldering process. I had to solder capacitor manually (with soldering iron). It could lead to such results. Frequency $f = 13.6\,kHz$

Frequency has a difference with calculated (chapter 4), which was 14.3 kHz. The relative error is as follows:

$$\delta = \frac{U_1 - U_2}{U_1} * 100\% = \frac{14.3 - 13.6}{14.3} * 100\% = 4.9\%$$

It can be explained by the difference between simulation model op amp in OrCAD and real op amp.

6.3 PWM signal

As was shown in chapter 4, I used voltage divider with two resistors 5 kOhm and 200 Ohm. This voltage is compared to a triangle signal received from the output of the triangle wave generator (6.2).

I connected LM393 with power supply and triangular wave on the trainer as shown in Figure 51:

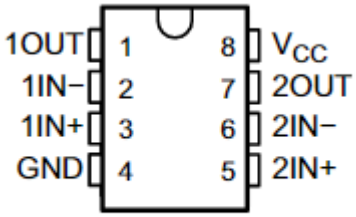

Figure 51: Pin configuration of LM393 [31]

I used one comparator: 1OUT pin is output PWM signal. This pin connects with supply pin V_{CC} through 3K as shown in Figure 32. 1IN- pin – triangular signal input, 1IN+ - DC level input, GND – ground.

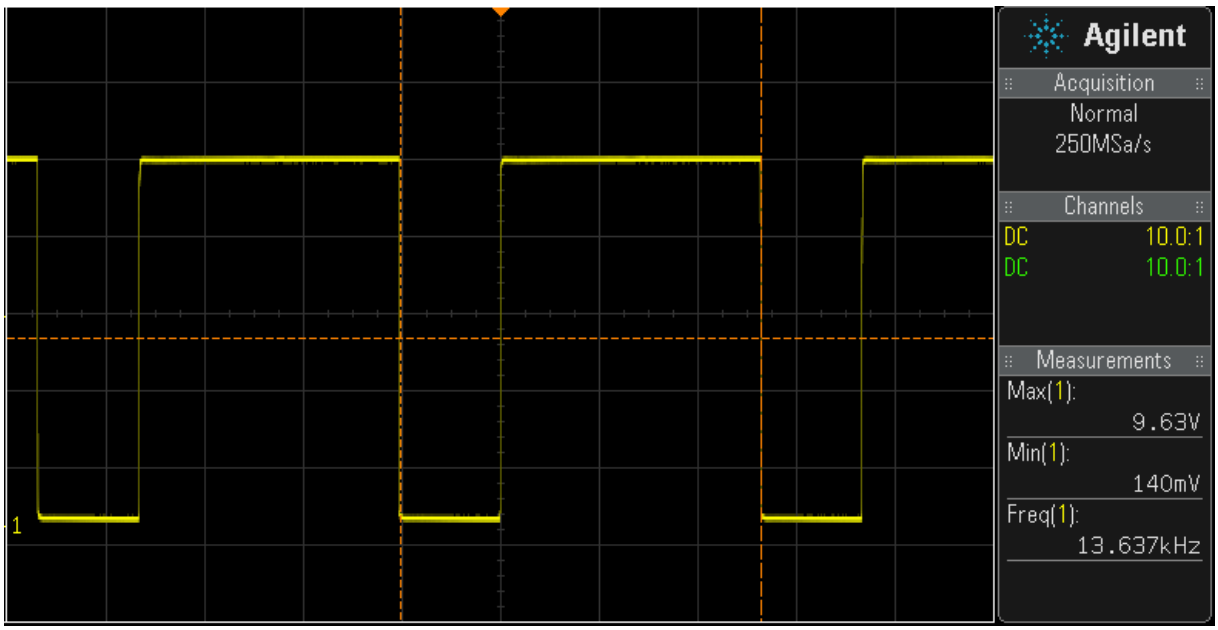

Figure 52: Scope of PWM signal at 6.13 V

Figure 52 shows PWM signal at 6.13 V as DC voltage level (on voltage divider), that was scoped on the circuit.

6.4 Motor driver

It was a great challenge to implement a motor driver in the project. I faced the fact that the motor driver SA50CE, which I chose, is extremely expensive and rare to find. It costs $291.60 on the market [32].

Thus, I had to choose another motor driver that I cannot simulate in OrCAD. I decided to choose a motor driver by Texas Instruments.

I chose between brushed DC drivers with FETs [21]. The selection filter was configured with the following parameters:

- Number of full bridges: 1
- Maximum supply voltage $V_s \geq 24\ V$
- Interface: PWM

Result of applying filter is shown in the figure below:

Part Number Filter by part number	Number of Full Bridges	Vs (Max) (V)	Control I/F	Vs (Min) (V)	RMS Output Current (A)	Peak Output Current (A)	RDS(ON) (HS + LS) (mOhms)	Number of Half Bridges	Additional Features	Rating
DRV8871-Q1 - 3.6A Automotive Brushed DC Motor Driver With Integrated Current Sensing (PWM Ctrl) - New	1	45	PWM	6.5	2	3.6	565	2	Integrated current sensing	Automotive
DRV8872-Q1 - Automotive 3.6A Brushed DC Motor Driver With Fault Reporting - New	1	45	PWM	6.5	2	3.6	565	2	Fault Pin	Automotive
DRV8871 - 3.6A Brushed DC Motor Driver with Integrated Current Sensing (PWM Ctrl)	1	45	PWM	6.5	2	3.6	565	2	Integrated current sensing	Catalog
DRV8870 - 3.6A Brushed DC Motor Driver (PWM Ctrl)	1	45	PWM	6.5	2	3.6	565	2		Catalog
DRV8872 - 3.6A Brushed DC Motor Driver (PWM Ctrl)	1	45	PWM	6.5	2	3.6	565	2		Catalog
DRV8842-EP - 5A Brushed DC or Half-Bipolar Stepper Motor Driver (PWM Ctrl) - Hi-Rel	1	45	PWM	8.2	3.5	6	200	2	complete protection and fault pin, Inrush Current Protection	HiRel Enhanced Product
DRV8842 - 5A Brushed DC or Half-Bipolar Stepper Motor Driver (PWM Ctrl)	1	45	PWM	8.2	3.5	6	200	2	complete protection and fault pin, Inrush Current Protection	Catalog

Figure 53: Suitable motor drivers

The automotive parts go through a qualification process called the AEC-Q100 (automotive electronics council) to check reliability for ICs in the transportation market. Thus, there was no difference for me when choosing between an automotive rating and a catalog rating. So, I decided to choose between motor drivers with a catalog rating. There was also no need to use a motor driver with large output current, so I decided to avoid using the motor driver with 5 A output current.

DRV8870 has analog input voltage (from 0.3 V to 5 V) which limits output current [33]. I chose to avoid using additional voltage input and removed this motor driver from the choosing list.

These two motor driver are almost similar. DRV8871 has input that can set current chopping threshold [34]. This input is grounded through resistor. DRV8872 has input which indicates fault status, this input could be grounded through resistor [35]. Thus, I chose motor that was available – DRV8872.

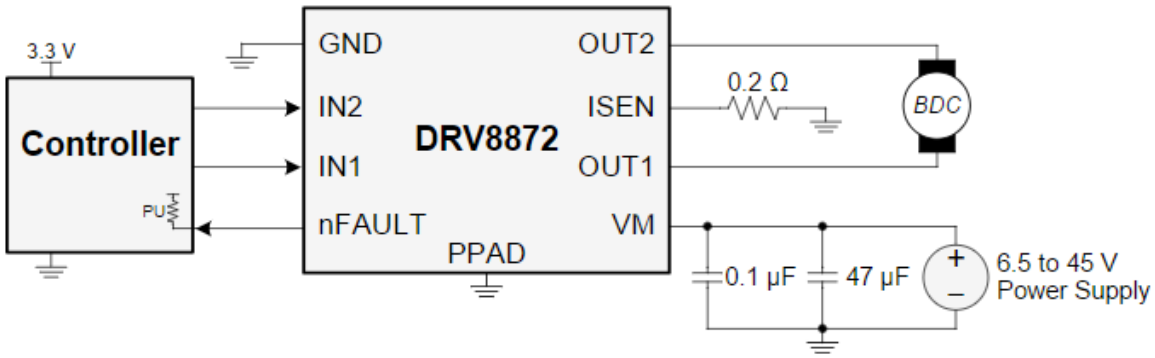

Figure 54: Typical application of DRV8872

As shown in Figure 54, DRV8872 has 8 pins (PPAD – thermal pad, connects to board):

- GND – ground
- IN2 – logic input, PWM signal
- IN1 – logic input, inverted PWM signal
- nFAULT – fault status, could be grounded
- VM – power supply (from 6.5 to 45 volts)
- ISEN – current regulation, if using current regulation, connect ISEN to a resistor to ground. If not using current regulation, connect ISEN directly to ground.
- OUT1 and OUT2 – H-bridge outputs. Connect directly to the motor

Thus, I had to add to the circuit additional components: inverter and optocoupler for obtaining inverted PWM signal.

As mentioned above, the OrCAD library does not include the model of DRV8872. So, I cannot simulate the circuit. I will draw it and implement on the trainer. The circuit with inverted PWM signal and motor driver DRV8872 is shown in Appendix H.

It was created separate circuit for motor driver with inputs and outputs:

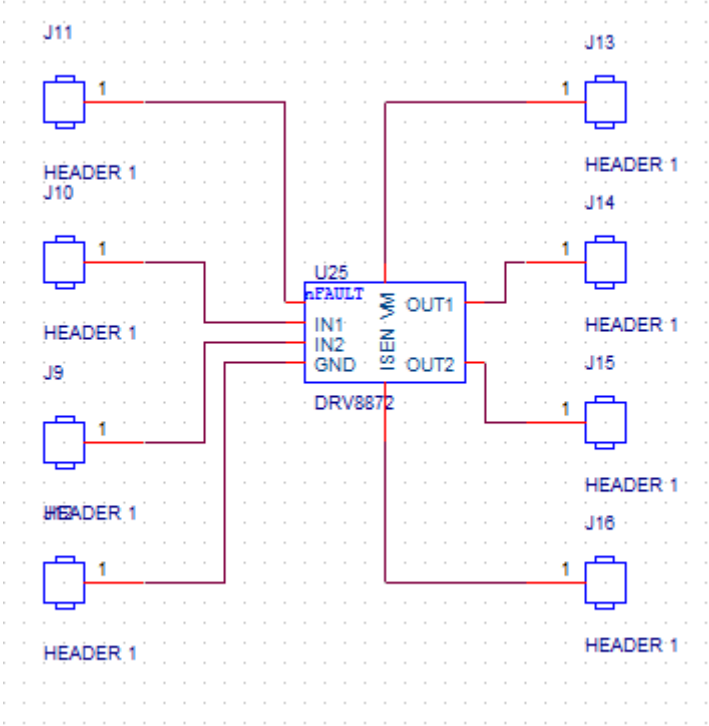

Figure 55: Separate motor driver circuit

After that this file was converted into .brd board layout file:

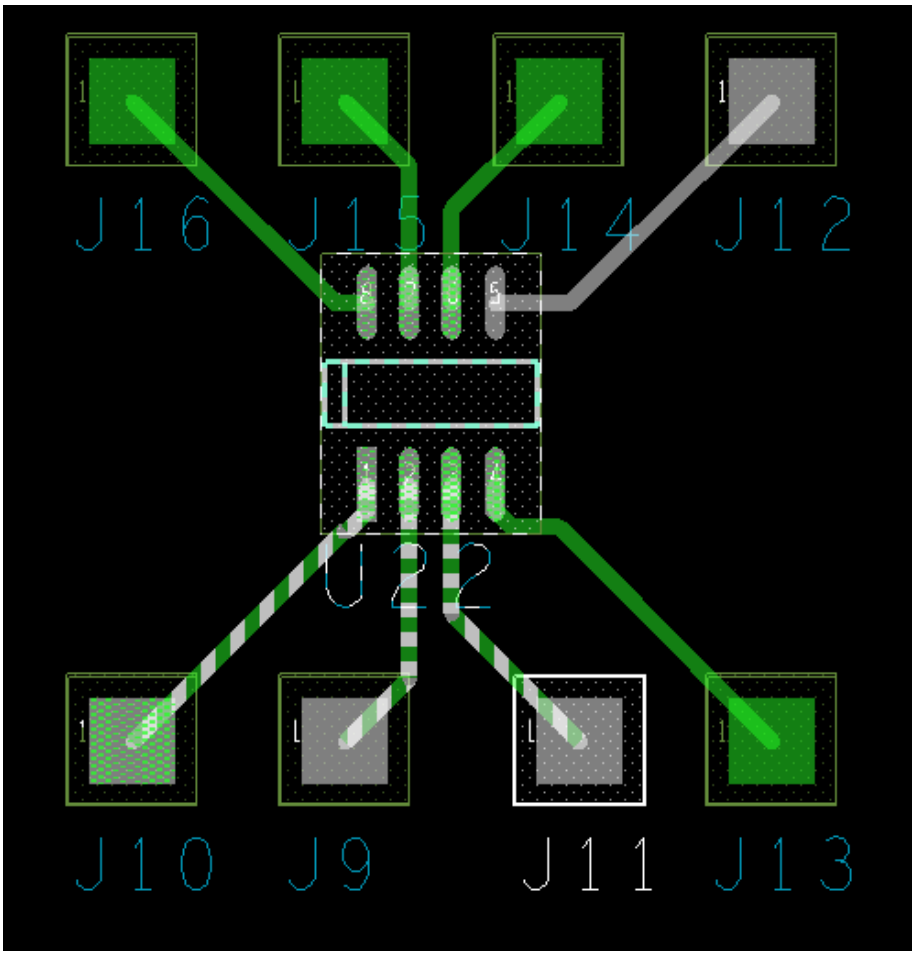

Figure 56: Board model of DRV8872

Board model from Figure 56 was printed in one of the labs. Motor driver and wiring connections was soldered.

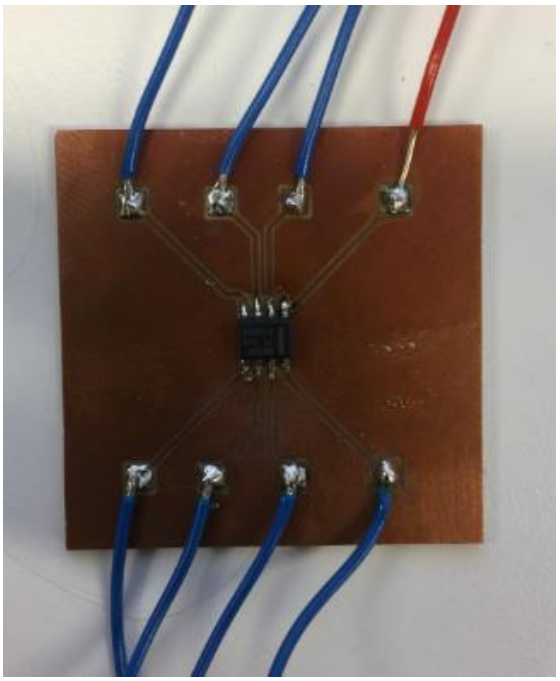

Figure 57: Board layout of motor driver DRV8872

Board layout of DRV8872 that was soldered is shown in Figure 57.

6.5 Optocoupler and inverter

Optocoupler 3N244 is used in the simulation in Appendix F, but it does not exist in the university's storage or on web stores. I chose an optocoupler with similar parameters, which is marked in Table 2. There is one equivalent of 3N244 on the market – OPI110A [35].

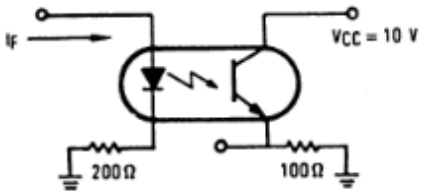

Figure 58: Application of OPI110A

I used the application from Figure 58 for connection OPI110A, as shown in Appendix H.

According to Appendix H, I used inverter SN74S04.

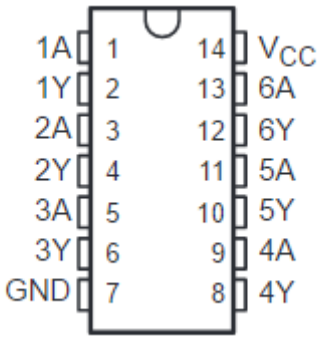

Figure 59: Inverter SN74S04 [36]

On the basis of figure 59 it follows that there are 6 inverters in this package. I needed just one, so I used just 4 pins:

- 1A – input signal
- 1Y – output signal
- V_{CC} – supply voltage
- GND – ground

Maximum supply voltage of SN74S04 is 7 V, so I used 5 V power supply source. After that I connected output from LM393 (Figure 52) with optocoupler OPI110A as shown in Figure 58.

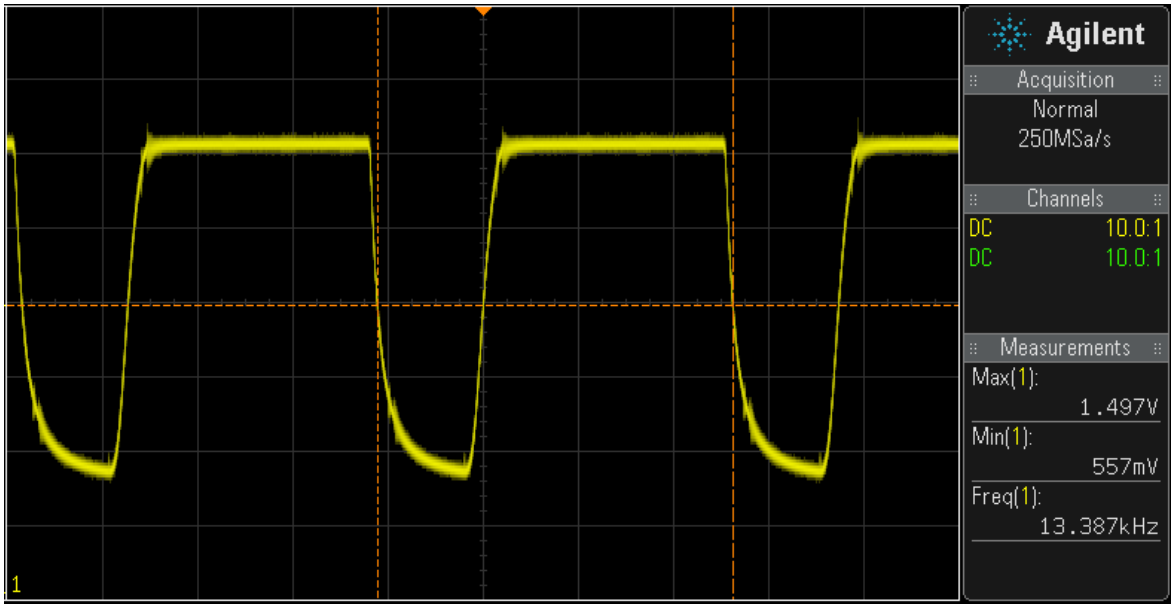

Figure 60: PWM signal after optocoupler

Figure 60 shows PWM signal after optocoupler U21 on the circuit (Appendix H).

This signal is input signal to inverter SN74S04, which is supplied by 5 V. Inverted PWM signal from inverter goes to optocoupler U23 (Appendix H).

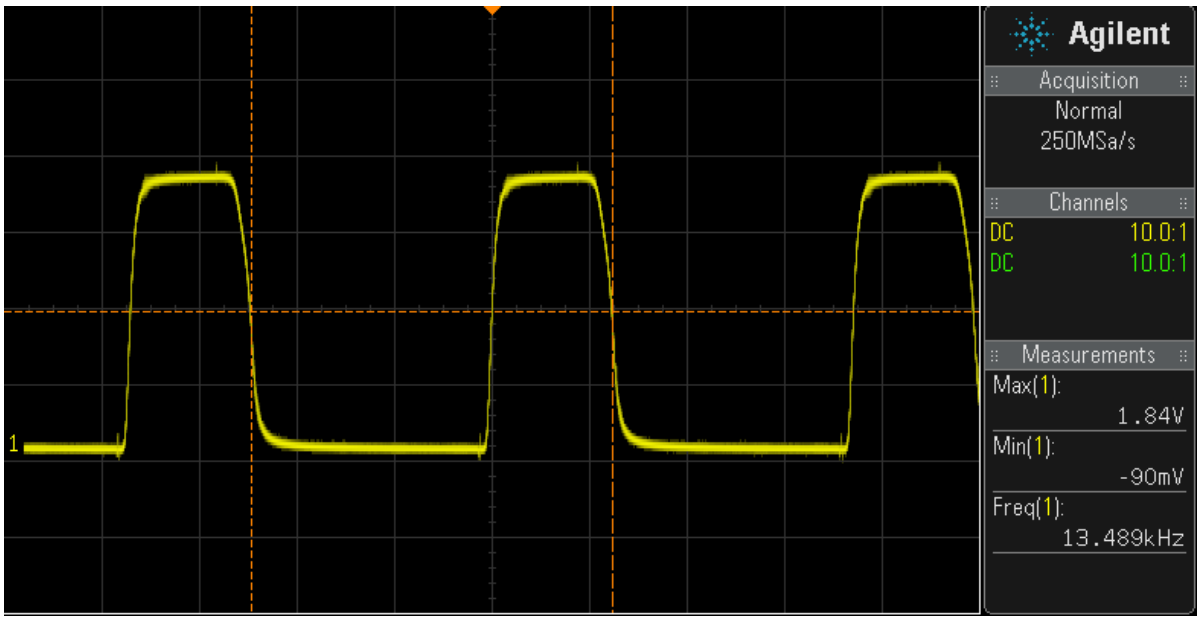

Figure 61: Inverted PWM signal after optocoupler

PWM signal from optocoupler U21 and inverted PWM signal from optocoupler U23 are input signals IN1 and IN2 for motor driver DRV8872. I implemented motor driver connection which is shown in Figure 54.

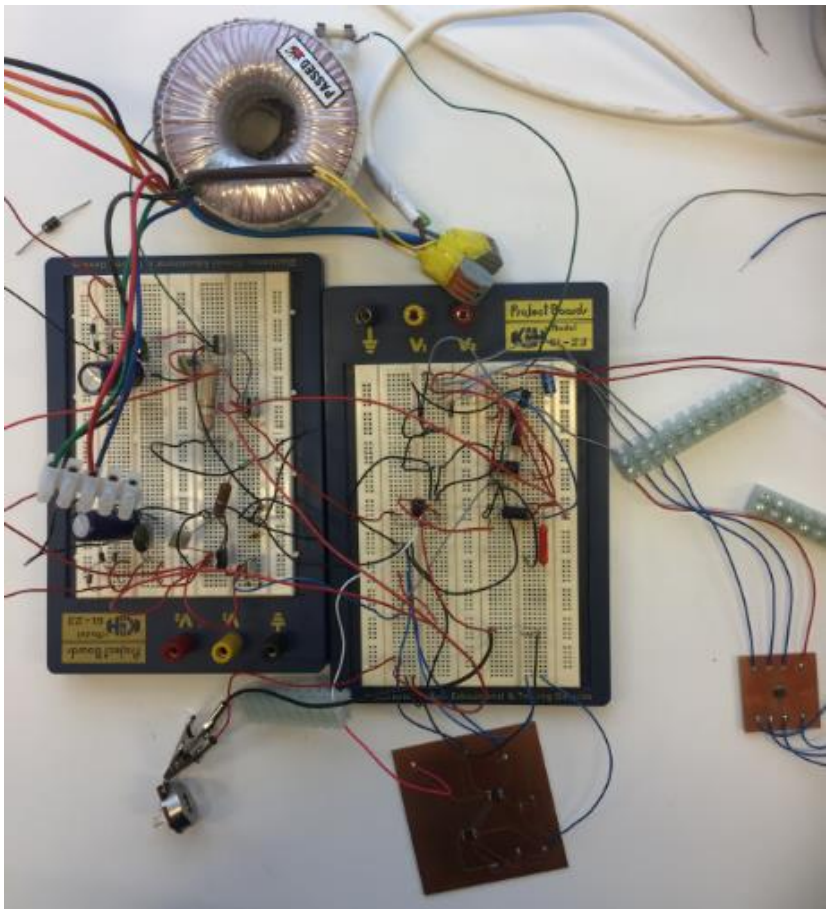

Figure 62: The implemented circuit

The whole implemented circuit is shown in Figure 62. Output voltage of H-bridge is controlled by potentiometer manually in range from -24 V to +24 V.

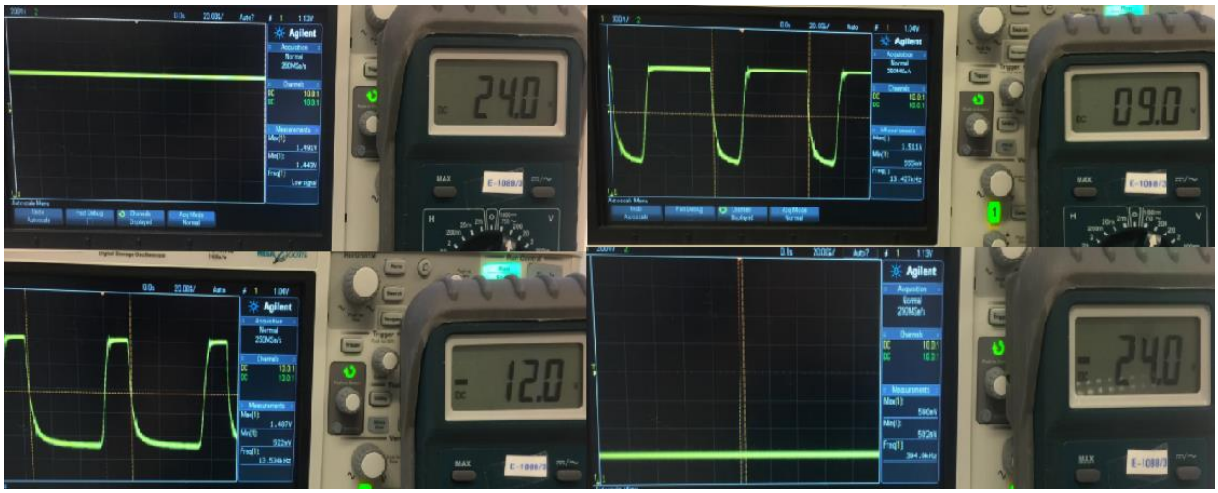

Figure 63: Output voltage of motor driver with different PWM signal

Figure 64 shows two extreme values of the output voltage and two intermediate values. Connected motor rotates in both directions with different speed.

Conclusion

For this work two ways to control the motor were considered, and an open loop control was selected. It was decided to use the H-bridge to control the motor. The H-bridge consists of MOSFETs which are controlled by a PWM signal.

It was decided to use a comparator to obtain the PWM signal by comparing the triangular wave and the DC level voltage. Various methods of obtaining a triangular signal were studied and a method based on the use of the Schmitt trigger and integrator with implementation of an artificial midpoint and unipolar feeding of amplifiers was selected.

Components and IC of the circuit were selected, simulations were made in MATLAB-Simulink and OrCAD-PSpice. The results obtained fully satisfy the requirements.

The implementation of the circuit was carried out on a special training simulator. Some parts of the circuit were drawn in the PCB Editor and created during the soldering process. As the implementation of the circuit was changed, additional elements were implemented and some components and IC were replaced due to their unavailability on the market.

Scopes were obtained using an oscilloscope. The results obtained coincide with the simulations and completely satisfy the requirements. Rotor of the motor connected to the circuit changes the direction and speed of its rotation with manual control of the circuit.

In the process of this project such programs as OrCAD-PSpice and PCB Editor were studied, and the MATLAB-Simulink knowledge was deepened. The knowledge and experience of choosing the components of the circuits is obtained. The experience of micro-soldering has been obtained.

This work is an example of the summation of theoretical knowledge of the electrical sciences obtained during the master's program and practical implementation, which was studied independently on the basis of theory.

Future students can use this project as a basis for development of a multi-purpose model that can control objects using:

1. Programmable logic controller (PLC)
2. Microprocessor
3. LabVIEW input/output interface

By combining measurement and control instruments with the described circuit, it is possible to obtain an autonomous unit for control of any object in laboratory.

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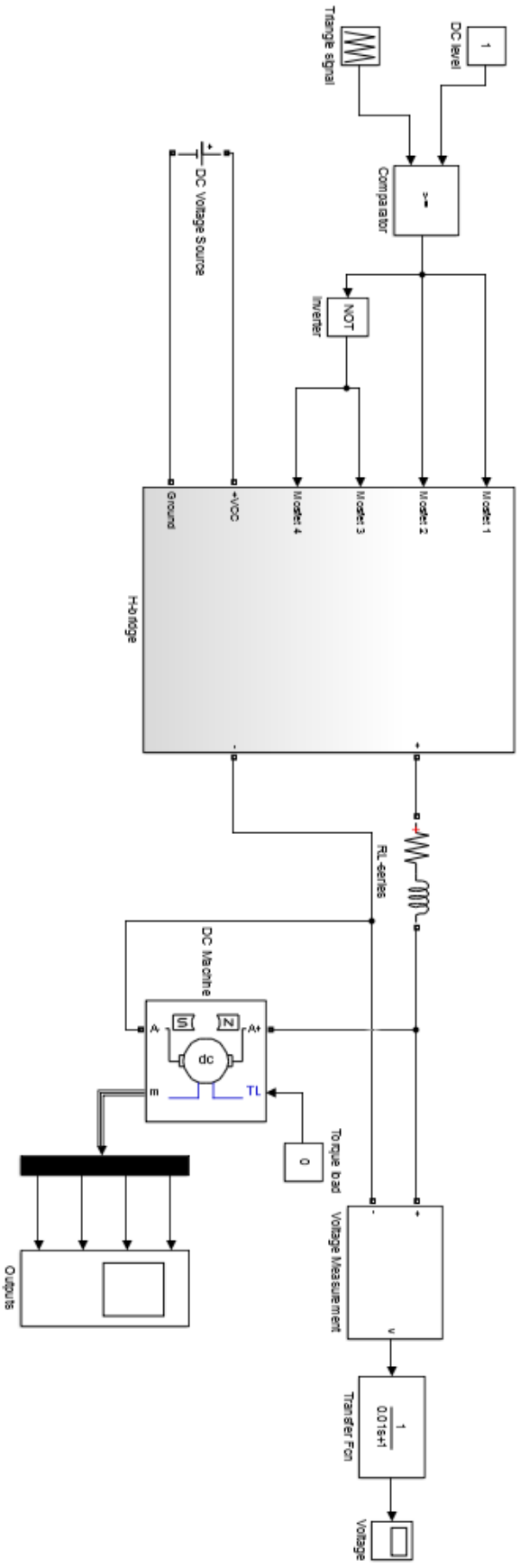
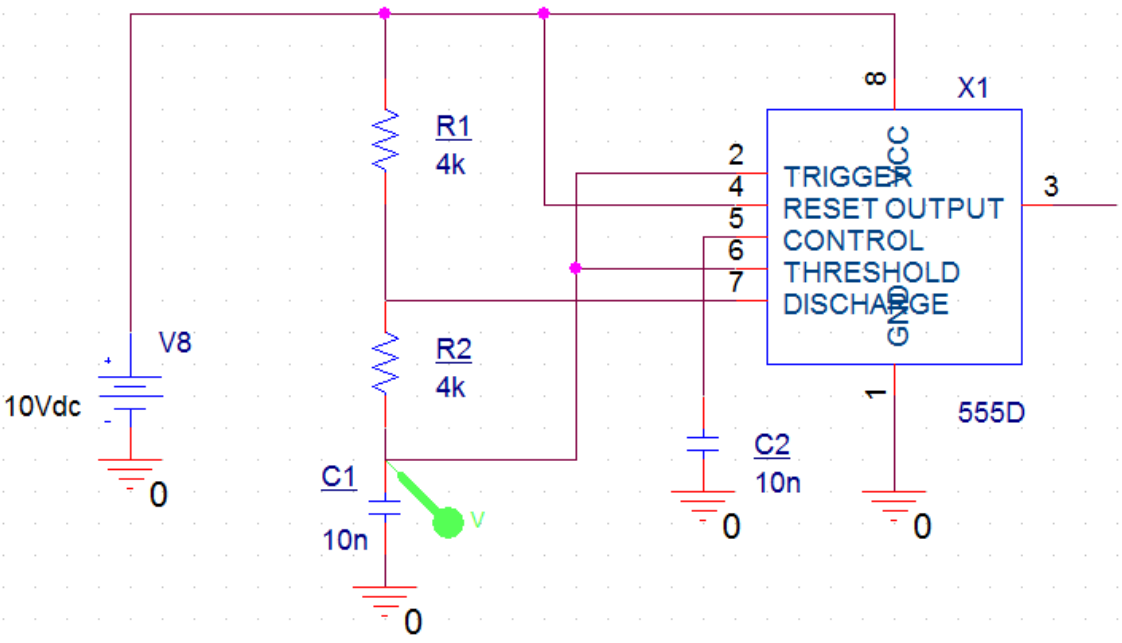
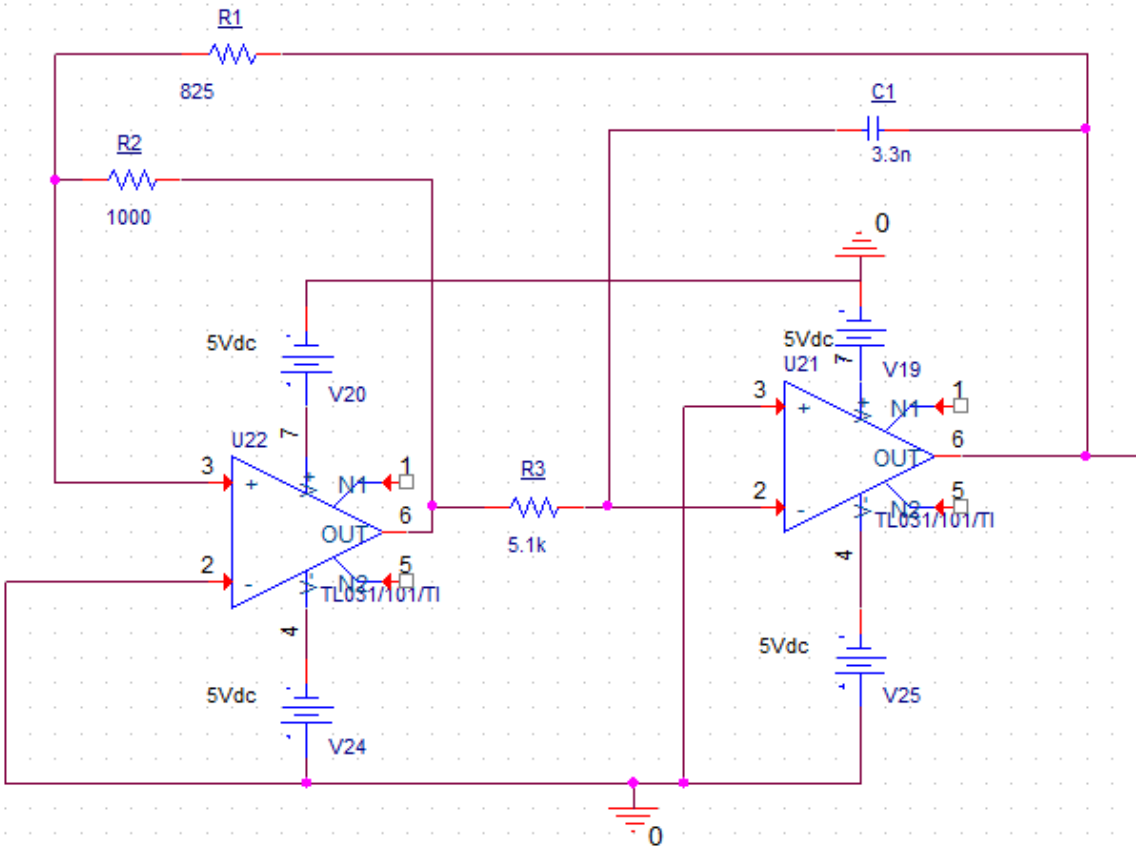
Appendix A. Motor control model in MATLAB



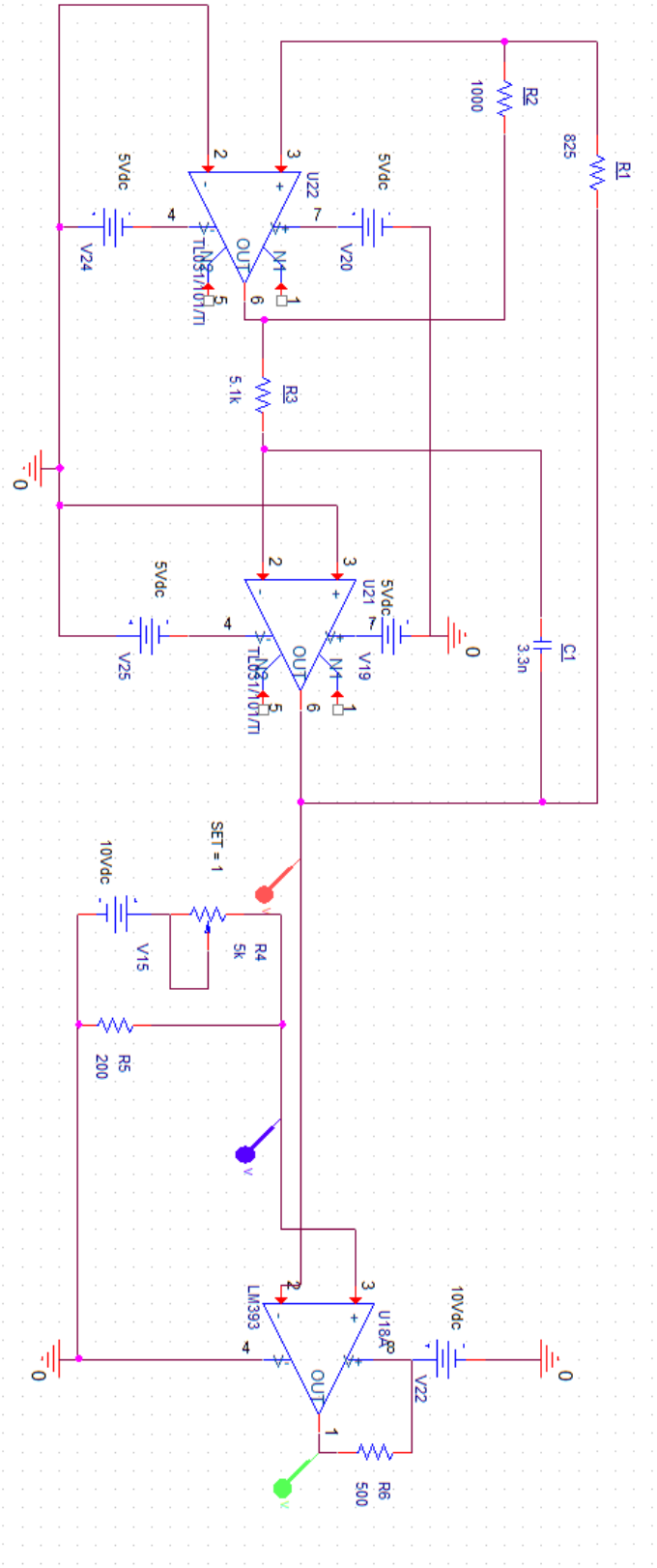
Appendix B. Circuit of 555 timer in OrCAD



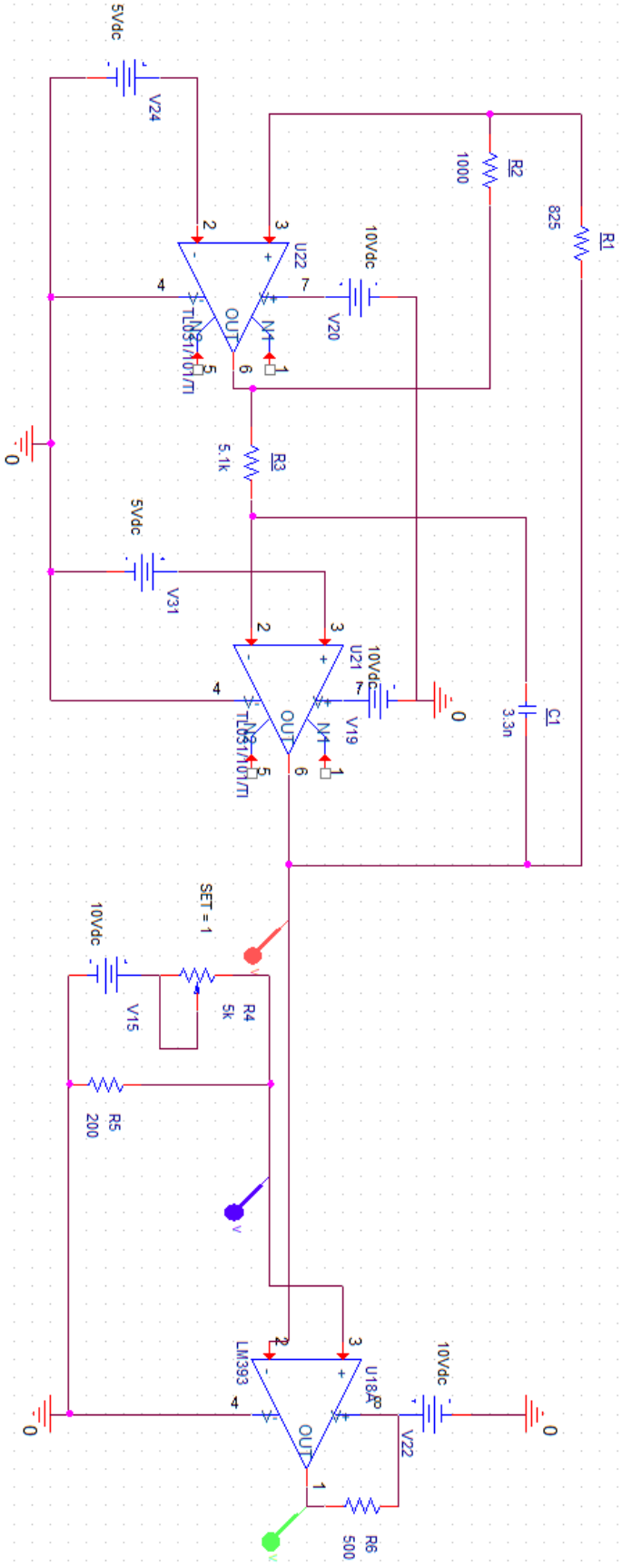
Appendix C. Triangle wave generator in OrCAD



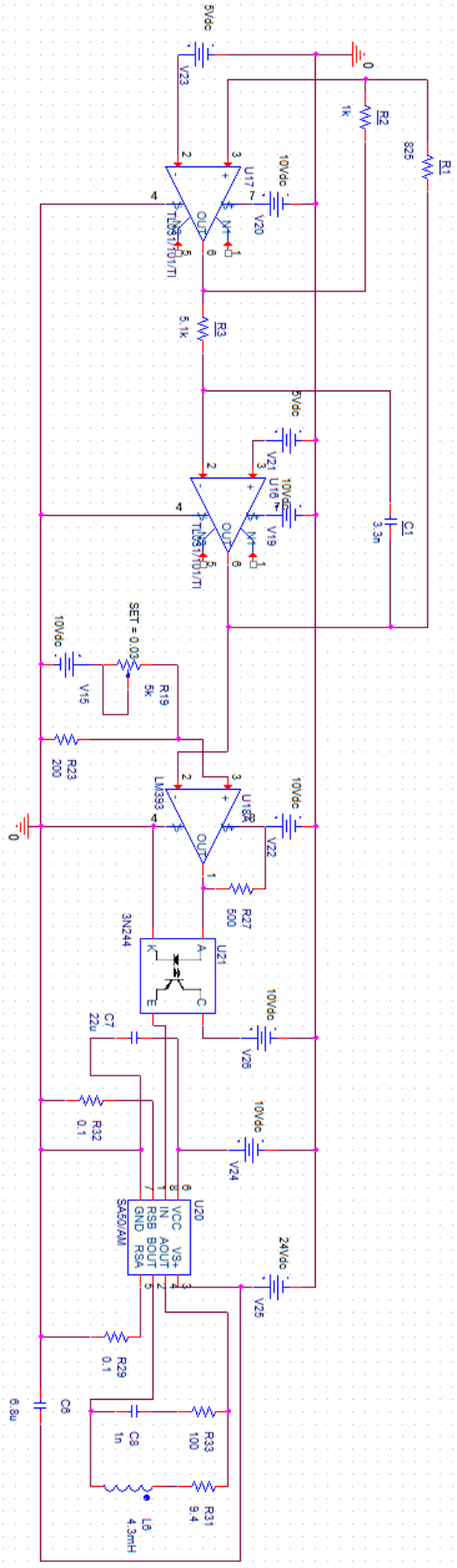
Appendix D. PWM signal circuit with bipolar supplying



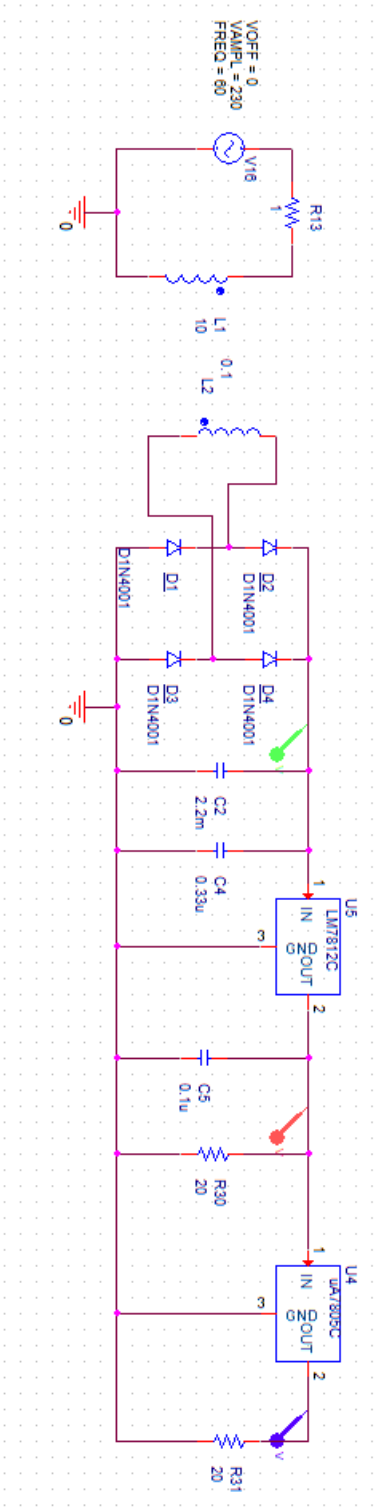
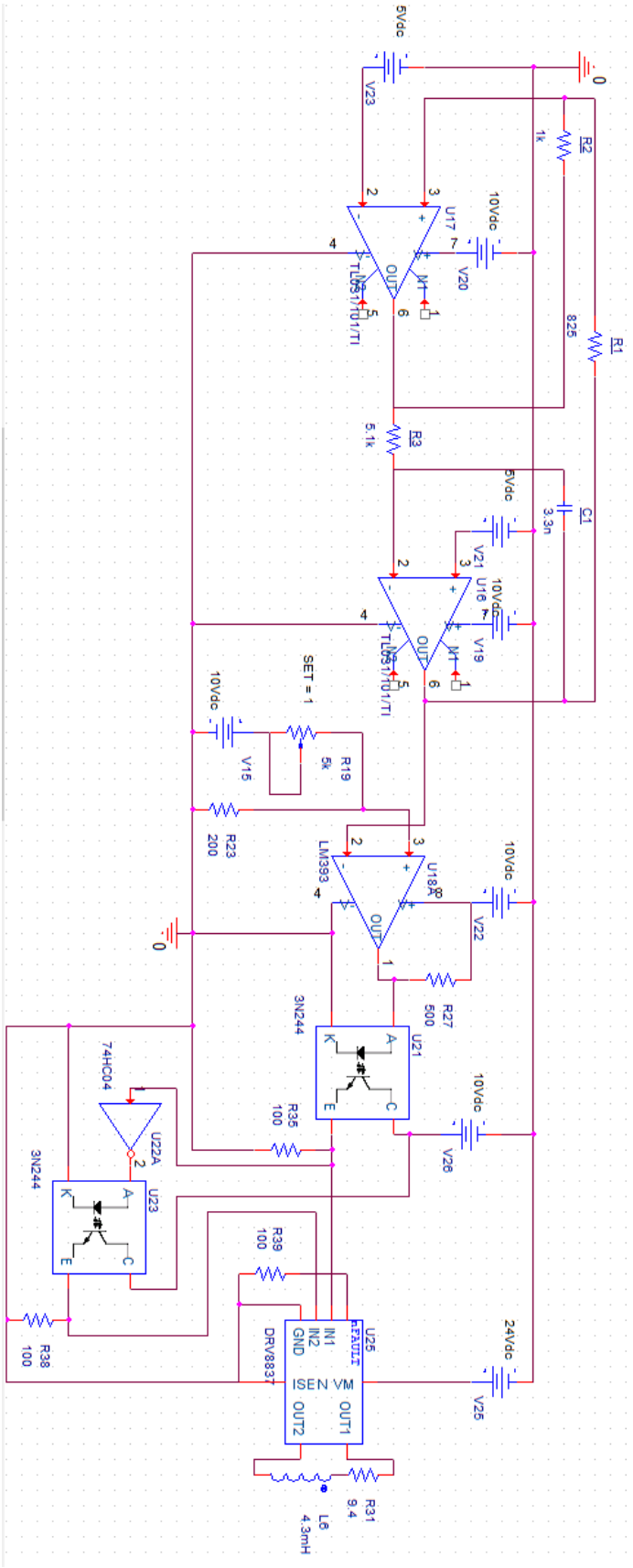
Appendix E. PWM signal circuit with unipolar supplying



Appendix F. Motor control unit



Appendix G. Power supply circuit



Appendix H. Motor control unit with inverted PWM signal and DRV8872