MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

EE 463- Static Power Conversion I - Hardware Project

Enjin Drivers

DC Motor Drive

Simulation Report

Prepared for Assoc. Prof. Ozan KEYSAN

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Introduction & Specification

DC Motors are having great importance for our daily lives. From a simple kettle to a complicated manufacturing machine in a factory. Their proper functioning at this stage, therefore, is critical since we are not able to supply them in DC type as our grids are in AC model. Hence, we as three METU EE senior students, propose an AC to DC Motor Drive circuit. We included simulation findings of overall design and separately for specific parts of the developed model settings in this paper. Topology selection will be explored in the first section of the report. The advantages and disadvantages of the chosen topology will be discussed. We'll also indicate about why we chose it. After applying analytical calculations for our selected topology, with different scenarios, simulation results will be provided. Then, the component selection will be described. Following this section, thermal analysis of critical components can be found. Finally, what we have done so far in the implementation of our design comes with laboratory recordings and a preliminary PCB Design on EasyEDA platform.

Topology Selection

Thyristor Rectifiers

Single Phase Thyristor Rectifiers

Advantages

- It contains less circuit elements compared to other topologies.
- Less cost.

Disadvantages

- High Ripple Voltage.
- Needs a suitable firing angle. Therefore, controlling the thyristor rectifier is harder than the diode rectifier & buck converter topology.
- In order to minimize the ripple voltage, larger capacitors are needed. Therefore, it leads to unnecessary costs.
- Its true power factor is too small compared to the other topologies since it has higher THD value. THD of input current is not suitable for our applications.
- It is not proper for high voltages.

Three Phase Thyristor Rectifiers

Advantages

- It has less ripple voltage compared to single phase thyristor rectifiers.
- Since the ripple voltage is smaller, the average DC voltage is higher than the single-phase thyristor rectifier.
- It needs a smaller capacitor since the ripple voltage is less.
- Can reach 1.35 times of input line-line voltage.

Disadvantages

- More complicated structure.
- The gate control is harder than the single-phase thyristor rectifier.
- It needs more circuit equipment; therefore cost is higher.
- The power factor is still small due to the THD of the input current.

Three Phase Diode Rectifier & Buck Converters

Advantages

- Controlling is easy compared to thyristor rectifiers.
- Using a bridge rectifier, it is more compact.
- Can reach 1.35 times of input line-line voltage.

Disadvantages

- In order to minimize inrush current, an inductor should be added to the circuit.
- Its cost is high since the buck converter is the switching equipment. (IGBT, MOSFET etc.)

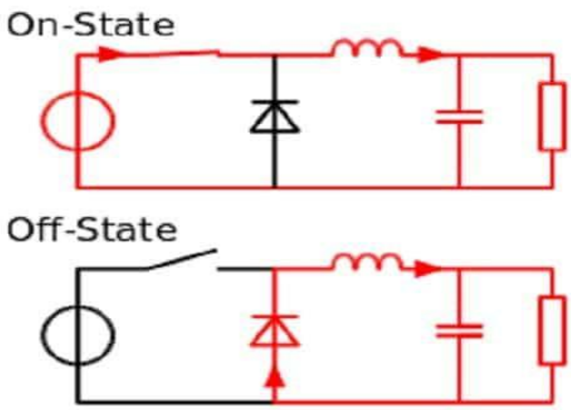
Why Diode Rectifier & Buck Converters

We choose 3-phase diode rectifier and buck converter topology in order to drive the DC machine because of these reasons:

- Constructing a diode rectifier is easier than other topologies.
- Constructing a buck converter is cheaper than other topologies since the DC machine already provides the necessary inductor, capacitor, and resistors.
- By using a 555 timer, we can control the buck converter's switch's gate. This is more complicated in thyristor rectifiers.

Analytical Calculation

Buck Converter Design



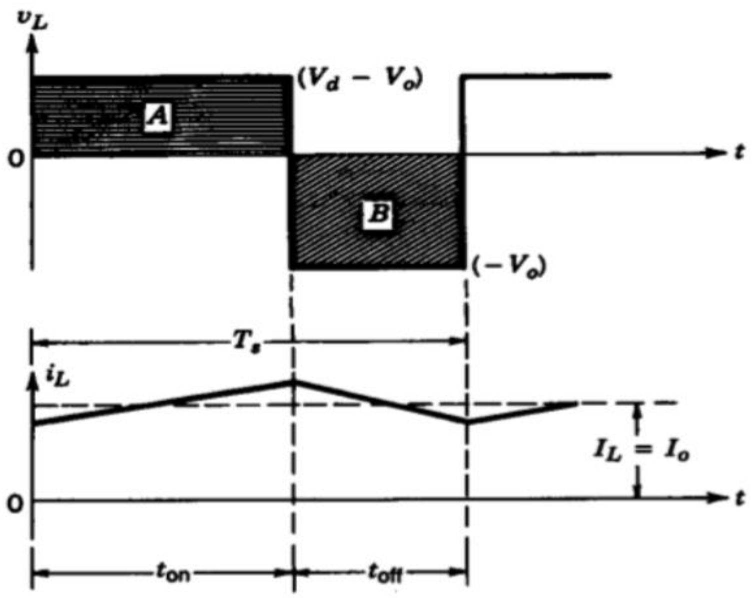
Basic circuit model of a buck converter at on and off states in CCM

On state

$$V_d - V_o = V_L \text{ and } i_c = i_L - \frac{V_o}{R}$$

Off state

$$V_L = -V_o \text{ and } i_c = -\frac{V_o}{R}$$



Voltage and current waveform models of the buck converter

$$A(ON)\ (V_{in} - V_o)DT_S\ = B(OFF)\ V_o(1-D)T_S$$
$$V_{in}D - V_O D = V_o - V_o D$$
$$V_o = V_{in}D$$
$$0 \le V_o \le V_{in}\ and\ I_o = \frac{I_d}{D}$$

Since our motor input (V_o) should be smaller than given 180 V maximum level,

$$180 > V_{in}D$$

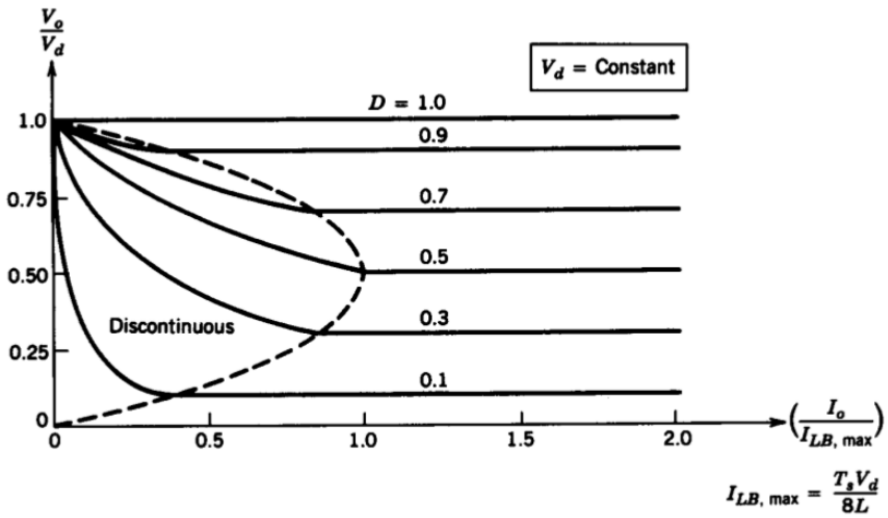
Due to nonideal performance conditions, having 1 or 0 duty cycle is not easy to satisfy. Thus,

$$0.2 \le D \le 0.8\ will\ be\ much\ more\ valid$$

Hence, we can define a condition for the input voltage of the buck converter (V_{in}) as

$$\frac{180}{D} > V_{in} \rightarrow \frac{180}{0.8} > V_{in} \rightarrow V_{in} < 225\ V$$

Throughout the function of the buck converter, we also estimated the minimum inductance value to stay in continuous current mode:



Output voltage and current relations at Continuous and Discontinuous Conduction Modes

As it can be observed, the critical current value occurs when D = 0.5

$$Assuming\ I_{LB} = \frac{i_{L,peak}}{2}\ as\ I_{LB} = \frac{t_{ON}(V_d - V_o)}{2L}\ \ with\ t_{ON} = DT_S$$
$$Then\ \ I_{LB} = \frac{DT_S\ (V_d - V_o)}{2L} \rightarrow\ Inserting\ D = 0.5\ I_{LB,MAX} = \frac{T_S V_d}{8L} = \frac{V_d}{8Lf_S}$$
$$also\ V_o = DV_d$$
$$I_{LB} = \frac{DT_S\ (1-D)V_d}{2L} = \frac{T_S\ (1-D)V_O}{2L} = \frac{(1-D)V_O}{2Lf_S}$$
$$thus, minimum\ inductance\ for\ CCM{:}\ L_{min} = \frac{(1-D)V_O}{2I_{LB}f_S} = \frac{(1-D)Z_{load}}{2f_S}$$

Foer our case D = 0.5, by given armature impedance of the motor and assuming our frequency range 1-5 kHz it is obtained that

$$L_{min} = \frac{Z_{load}}{4f_S} \approx \frac{0.8\Omega}{4 * 1000} = 0.2\ mH$$

$$and\ I_{LB,MAX} = \frac{V_d}{8Lf_S} = \frac{225\ V}{8 * 0.2mH * 1kHz} < given\ motor\ current\ data = 23.4\ A$$

Meaning that throughout our duty cycle choices, even if we do not implement an additional inductor since there is already an inertial inductance of the motor, which is higher than 0.2 mH, we will be in a safe zone for the continuous conduction mode.

Voltage Ripple for the Buck Converter

$$\Delta Q = \frac{\frac{\Delta I_L}{2} * \frac{T_S}{2}}{2} = \frac{T_S(\Delta I_L)}{8}$$

$$also\ \Delta V_o = \frac{\Delta Q}{C} \rightarrow\ \Delta V_o = \frac{T_S(\Delta I_L)}{8C}$$

By using off time ratio (1-D) it is obtained that

$$\Delta I_L = \frac{V_o(1-D)T_S}{L}\ since\ i_L = \frac{1}{L}\int V_L dt$$

$$Then\ we\ get\ \Delta V_o = \frac{T_S V_o (1-D)T_S}{8LC}$$

$$and\ ripple \rightarrow \frac{\Delta V_o}{V_o} = \frac{(1-D)T_S^2}{8LC} = \frac{(1-D)}{8LCf_S^2}$$

For worst case scenario, by taking as $D = 0.2,\ f_S = 1kHz, L = 12.5\ mH\ by\ only\ armature$

$$Ripple\ \approx \frac{0.8}{8 * 12.5mH * 1000^2 * C} = \frac{8\ x\ 10^{-6}}{C}$$

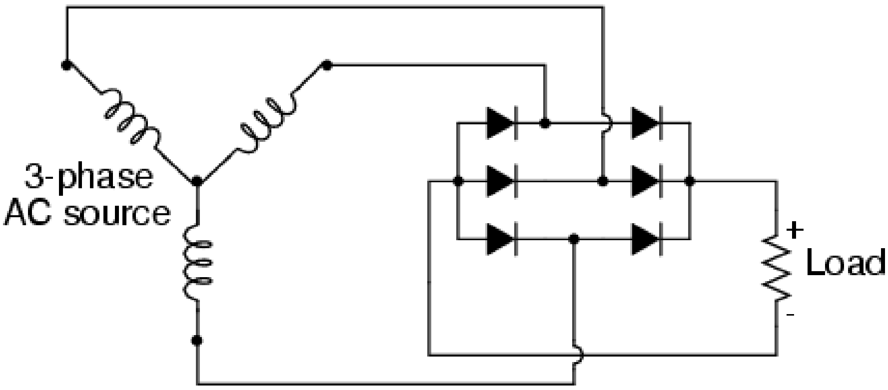
At this point, increasing the frequency or implementing an extremely high capacitor would have been expected as possible solutions to reduce the ripple. However, increasing the frequency means also increasing the switching losses, which can be found in the thermal analysis part, and it can disturb the thermal limit of our components. Moreover, a small capacitance will not be enough to obtain a reasonable ripple range, much higher value can balance that, yet this will cause higher cost and sizes in our design which may not be applicable under experimental conditions. **Thus, it is currently considered that the internal capacitance of the motor will satisfy our conditions.** Besides, if it seems necessary during test periods, by choosing 3.3 µF capacitor will be placed.

Hence the ripple is obtained as

$$\frac{8\ x\ 10^{-6}}{C} \rightarrow \frac{8\ x\ 10^{-6}}{3.3\ x\ 10^{-6}} \cong 2.42\ V$$

which can be accepted as small in the range of our motor input.

Rectifier Design



The circuit connection model of three phase full bridge rectifier design

As it was found previously on the buck converter design part that

$$V_{in} < 225\ V\ for\ the\ motor$$

Since the input voltage of the buck converter is supplied by the output voltage of the rectifier,

$$V_{out} < 225\ V\ for\ the\ rectifier$$

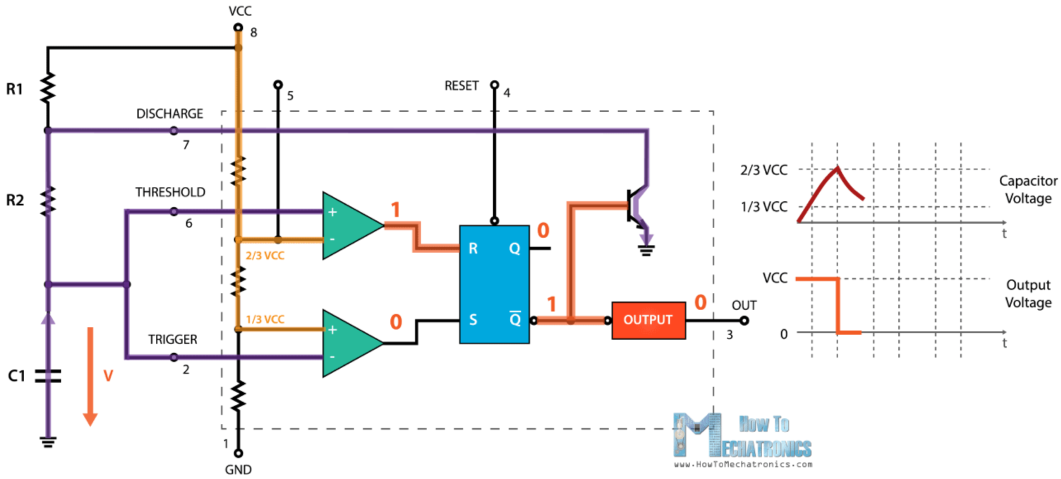
By Yn configuration, the necessary input voltage for the rectifier can be estimated as

$$V_{out} = \frac{3\sqrt{2}}{\pi} V_{l-l} < 225\ V \rightarrow V_{l-l} < \frac{225 * \pi}{3\sqrt{2}} \cong 166.6\ V$$

$$and\ V_{in,phase} = \frac{166.6}{\sqrt{3}}\ V$$

555 Timer Calculations

Basic 555 timer structure can be found in below:



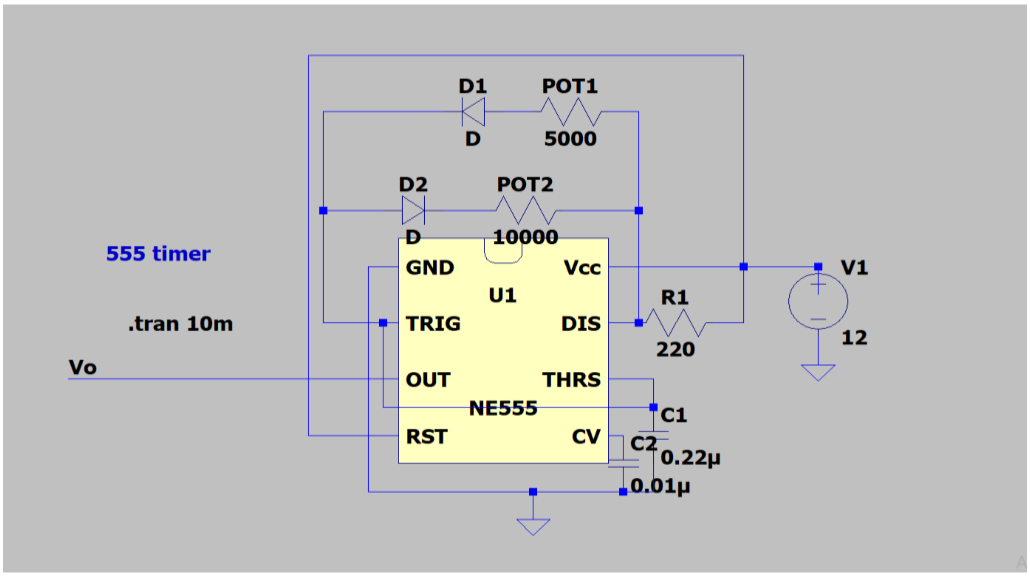
Example schematic of 555 timer

Formulas,

$$T_{on} = 0.693 * (R_1 + R_2) * C_1$$
$$T_{of} = 0.693 * R_2 * C_1$$
$$T_{total} = 0.693 * (R_1 + 2R_2) * C_1$$
$$f = 1/(0.693 * (R_1 + 2R_2) * C_1)$$

$$PWM(\%) = \frac{T_{on}}{T_{total}} = \frac{(R_1 + R_2)}{(R_1 + 2R_2)} * 100$$

In order to create adjustable PWM, we add this configuration to the diodes and POTs via the charging and discharging paths.



555 Timer Circuit unit modelled in LTspice

Calculations,

$$T_{on} = 0.693 * (R_{POT1} + R_1) * C_1$$
$$T_{of} = 0.693 * (R_{POT2} + R_1) * C_1$$
$$T_{total} = 0.693 * (R_{POT1} + R_{POT2} + 2R_1) * C_1$$
$$f = 1/(0.693 * (R_{POT1} + R_{POT2} + 2R_1) * C_1)$$
$$PWM(\%) = \frac{T_{on}}{T_{total}} = \frac{R_{POT1} + R_1}{R_{POT1} + R_{POT2} + 2R_1} * 100$$

We have used 5kΩ and 10kΩ resistance respectively for POT1 and POT2. In real, POT1 is changing between 1.6Ω and 4.8k Ω and POT2 is changing between 2.8Ω and 9.6kΩ. Then,
PWM maximum,

$$T_{on} = 0.693 * (4.8k\Omega + 220\Omega) * 0.22 * 10^{-6} = 0.795ms$$
$$T_{of} = 0.693 * (2.8 + 220\Omega) * 0.22 * 10^{-6} = 0.034ms$$
$$f = 1.19kHz$$
$$PWM(\%) = 98\%$$

PWM minimum,

$$T_{on} = 0.693 * (1.6\Omega + 220\Omega) * 0.22 * 10^{-6} = 0.0337ms$$
$$T_{of} = 0.693 * (4.8k + 220\Omega) * 0.22 * 10^{-6} = 1.558ms$$
$$f = 628Hz$$
$$PWM(\%) = 2.1\%$$

Although we could reach these PWM values, we must stay away from the boundary points of PWM. This is because at the near 0% and 100% PWM values, the switch (IGBT) cannot be operated properly since it has a switching time interval of ON and OFF times, PWM is not enough to compensate for it. Therefore, we changed R1 with 1kΩ and we have adjusted PWM between 17% and 85%. By the same steps,
PWM maximum,

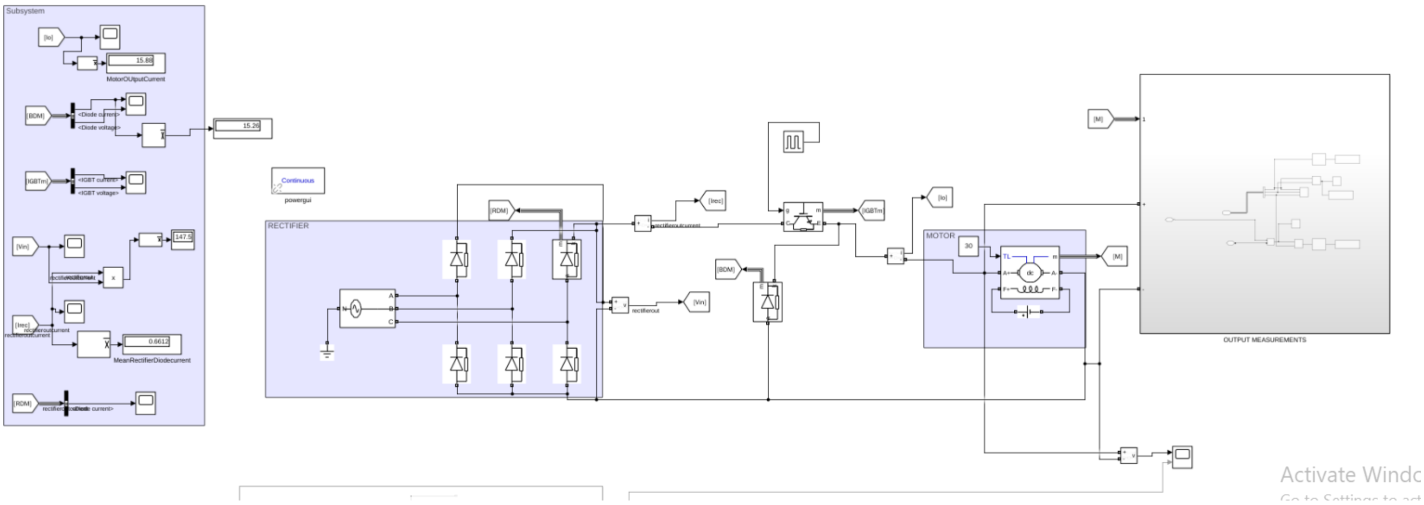
$$T_{on} = 0.884ms$$
$$T_{on} = 0.152ms$$
$$f = 965Hz$$
$$PWM(\%) = 85\%$$

PWM minimum,

$$T_{on} = 0.152ms$$
$$T_{on} = 0.884ms$$
$$f = 965Hz$$
$$PWM(\%) = 17\%$$

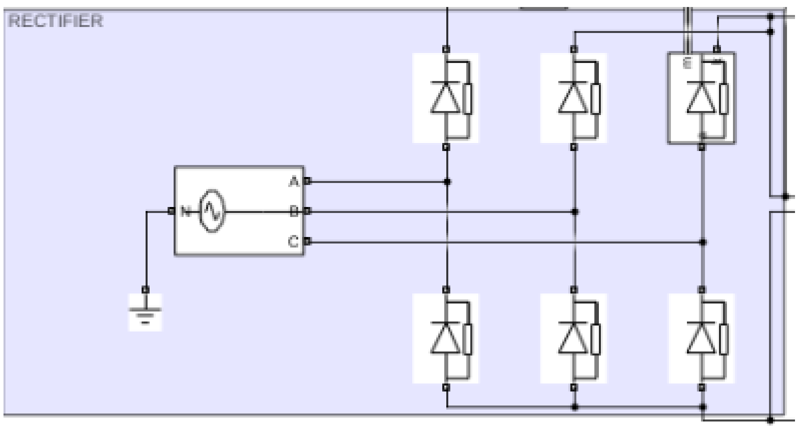
As seen from obtained results, the operating frequency is around 1kHz, so we decide to use IGBT as a switch. The performance of IGBT is greater than MOSFETs and other switches at low frequencies. Also, the current rating of IGBTs can reach up to 1kA.

Simulation

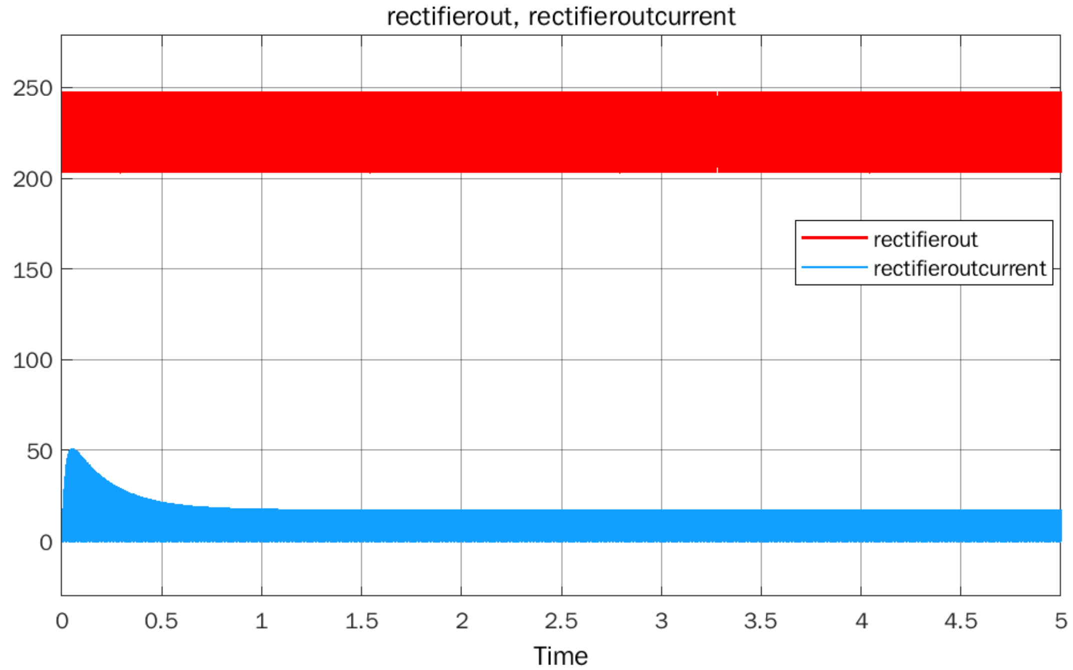


Screenshot of overall circuit design of DC Motor Drive designed in Simulink

3-Phase Diode Rectifier:

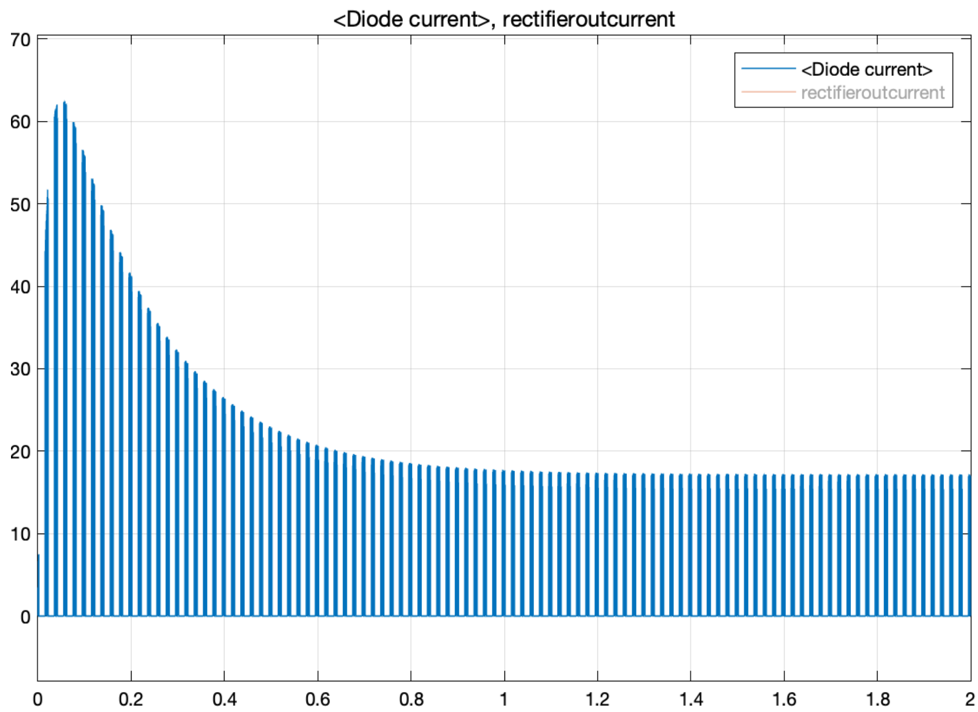


Zoom-in version for rectifier side of overall model



Plots of current and voltage of rectifier output vs. time

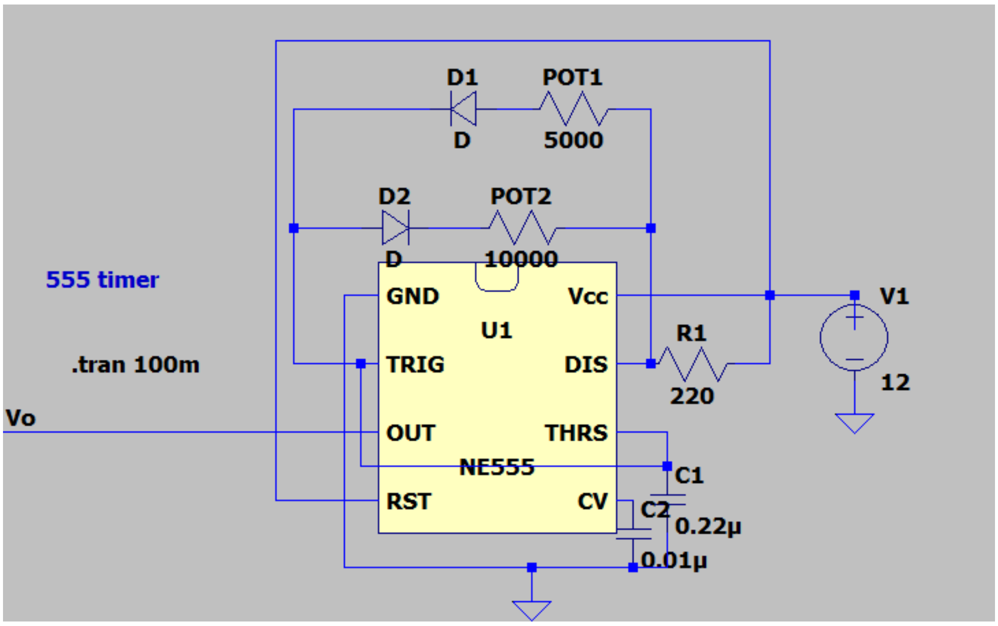
Rectifier diode current and voltage waveforms,



Plot of rectifier diode current vs. time

The graph which can be seen above shows the diode's starting current if we set the initial duty cycle as 0.2. However, since we don't know the line impedance, we didn't add any value to our simulation. Therefore, we expect that less inrush current will be measured in laboratory conditions. Another factor of high starting current is the stationary motor. When the motor is stationary, armature voltage is equal to zero. Then, when we supply voltage to the DC machine, the high current is passing through armatures. This becomes very problematic since it can damage the circuit. Therefore, we still try to stabilize the armature current for soft-starting.

A555 Controller



Schematic of NE555 timer in LTspice

Maximum duty cycle case:

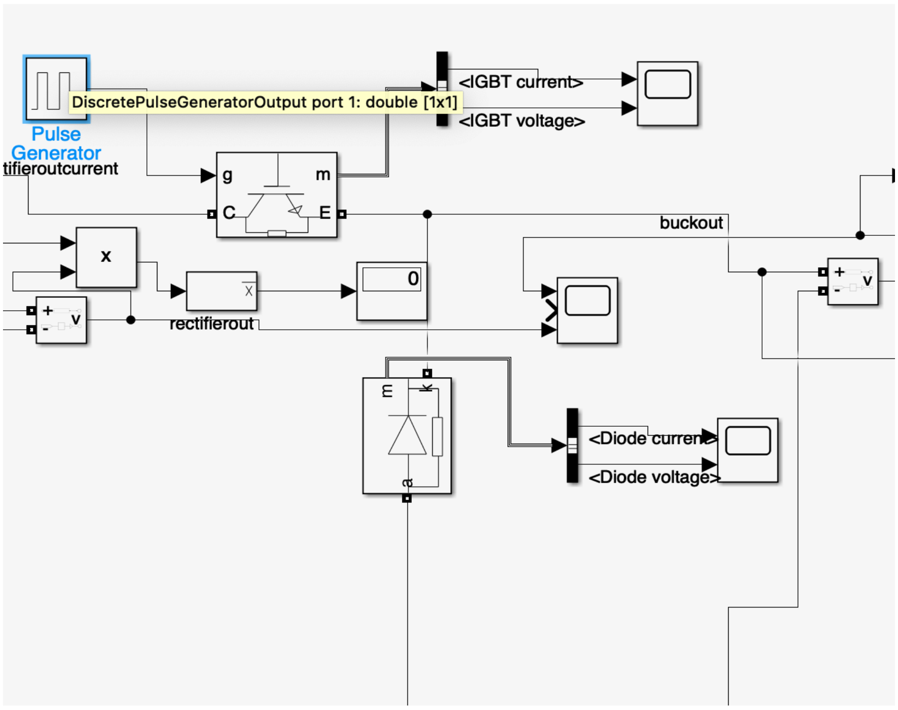
Plot of output voltage of NE555 vs. time for maximum duty cycle

Minimum duty cycle case,

Plot of output voltage of NE555 vs. time for minimum duty cycle

According to our research, we see that the most convenient way to control the buck converter is using the ASTABLE 555 Timer circuit. An Astable timer can be controlled just by using POTs.
The most crucial advantage of this timer is changing duty cycle easily. However, the frequency changes according to the resistor values that we change. Therefore, it may be a disadvantage. On the other hand, we are using an IGBT for buck converter and it is proper for the 1-5kHz interval. Therefore, we calculated the resistance of the timer to work between these frequency intervals. Beside all of these, 555 Timer topology is a familiar concept for us from the last year's EE312 course. We are considering that challenging by a circuit model that we had studied can be more time-saving and root-cause analysis can be done more effectively.
In the timer circuit above, R1 & R2 values determine the frequency and the duty cycle of the circuit. We are planning to change both R1 & R2 during our project. The related formulations and description can be seen in the "Analytical Calculation" part.

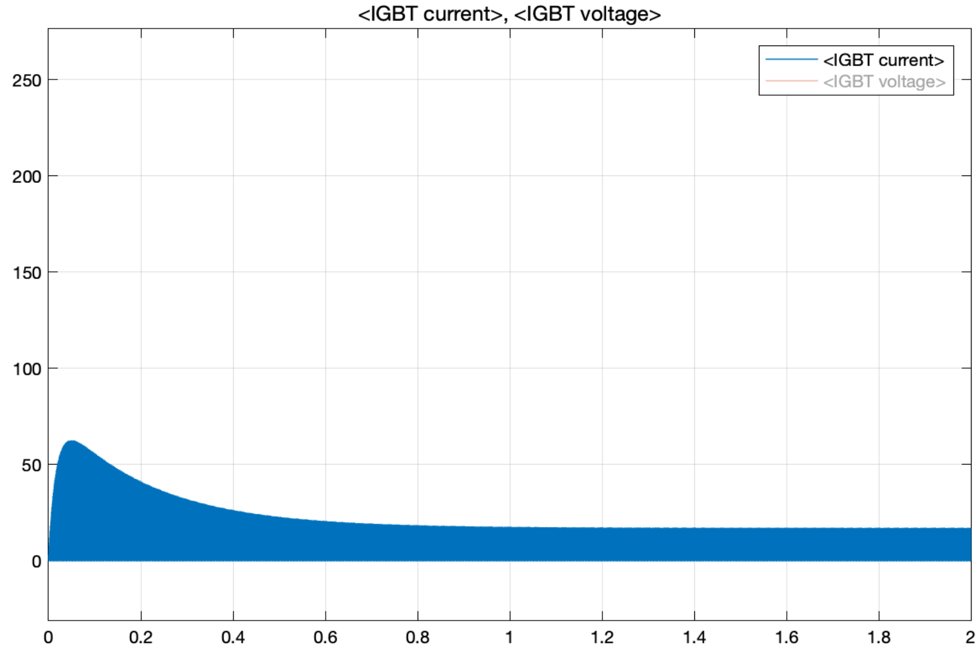
Buck Converter



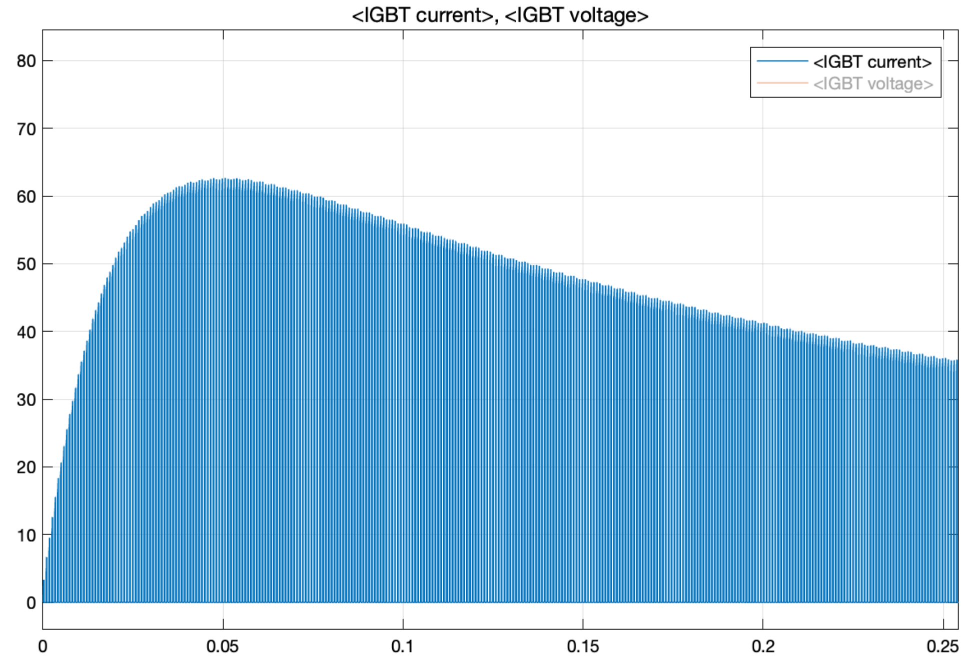
Zoom-in version for buck converter side of overall model

Here we see the buck converter part. As it can be seen, we didn't connect any capacitor, inductor, and resistance because the DC motor already provides these components' characteristics. On the other hand, in case of any necessities, we also bought some capacitors to provide better dc voltage at the input terminal of the DC machine.

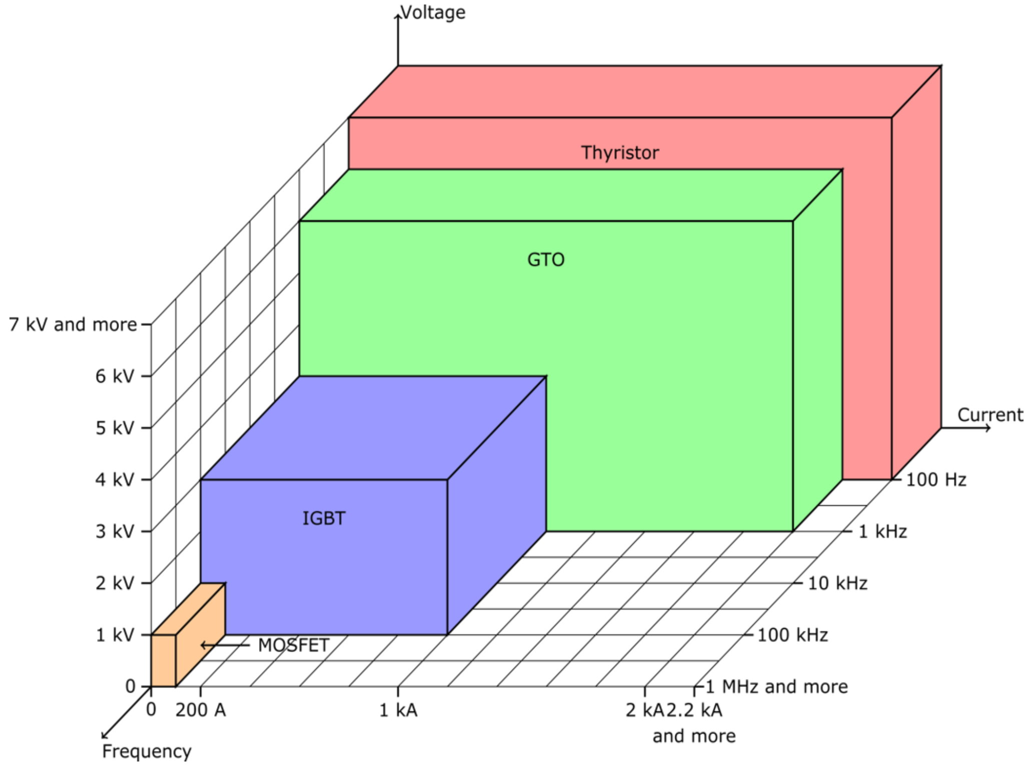
IGBT



Plot of current of IGBT vs. time for D=20%



Waveform of IGBT current in Simulink software with its zoom-in version



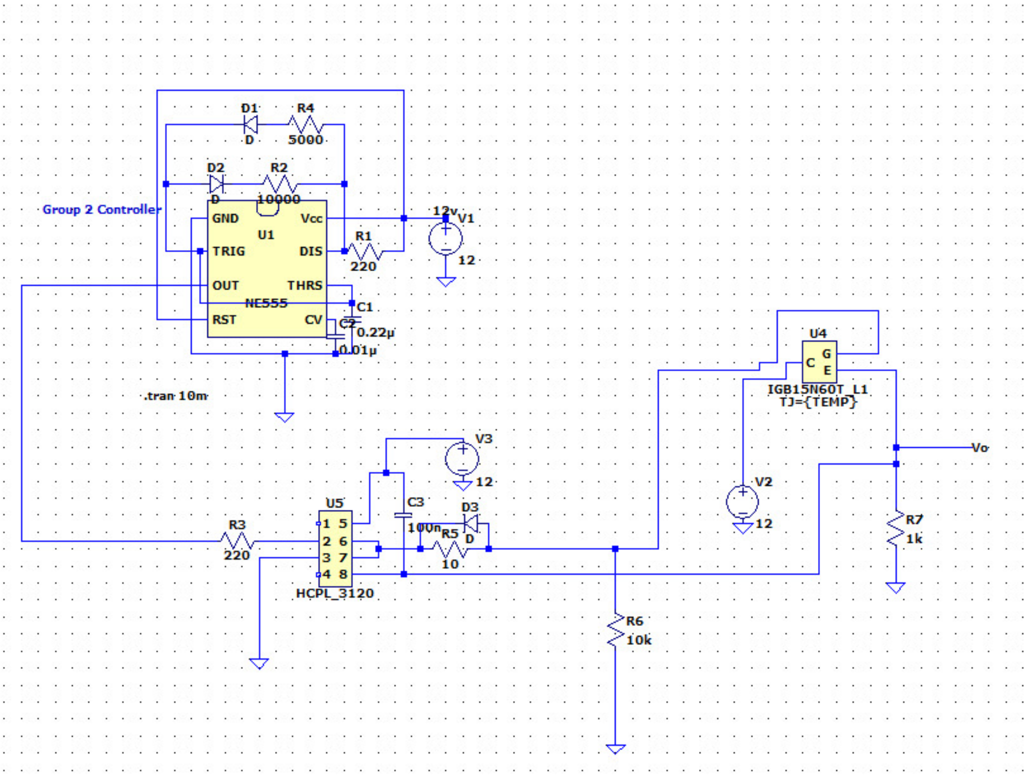
Comparison of different types of transistors (Source:Wikiwand)

In our design, we did a selection between MOSFET and IGBT. Since IGBT can work at low frequency and operates at high current values, we choose the IGBT as a switching device. Above, the steady state and starting currents of IGBT for 0.2 duty cycle can be seen. As can be seen, the starting current is relatively high. However, as mentioned in previous parts, we didn’t add any inductor to the source side. Therefore, the inrush current at start up occurs. Also, in this case, the motor’s initial speed is zero. During the demo, since we set an initial voltage by using variac, we expect that this high current will not occur, and we will not observe any problem.

Gate Driver

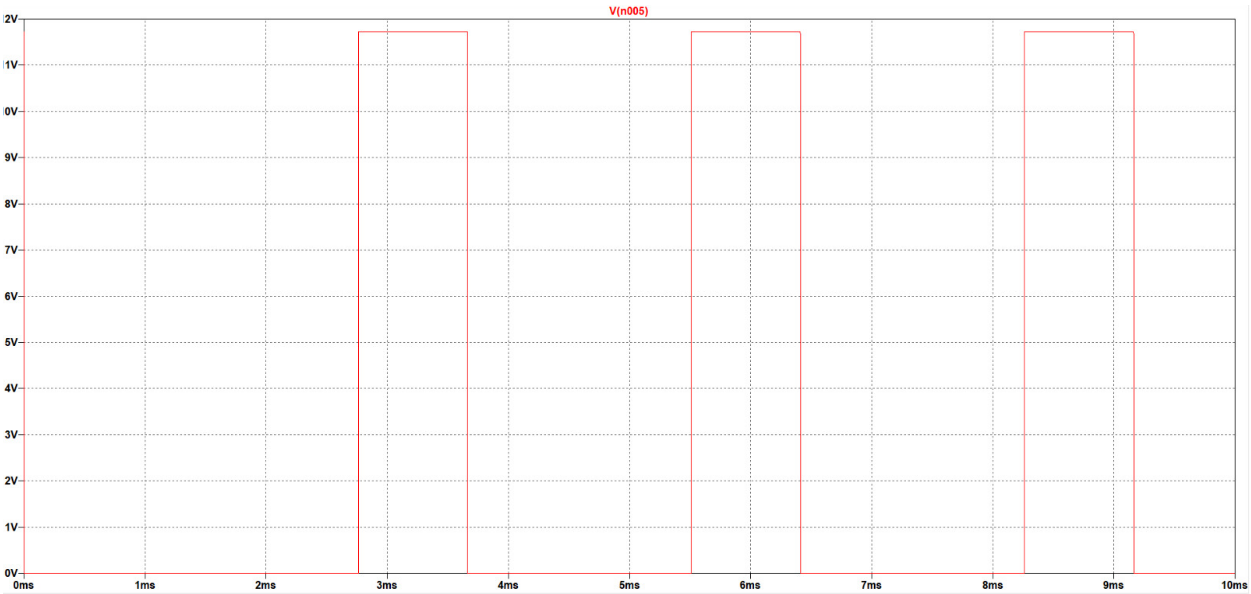
By using a gate driver, we have tried to operate IGBT properly without exceeding rating values. When we do not use a gate driver, the gate-emitter value can reach very high values. However, the rating value of gate-emitter voltage is about 20V for most IGBTs. Therefore, the gate driver provides the same duty cycle to the IGBT by keeping it in a safe region.

Design schematic of gate driver can be found in the following part:



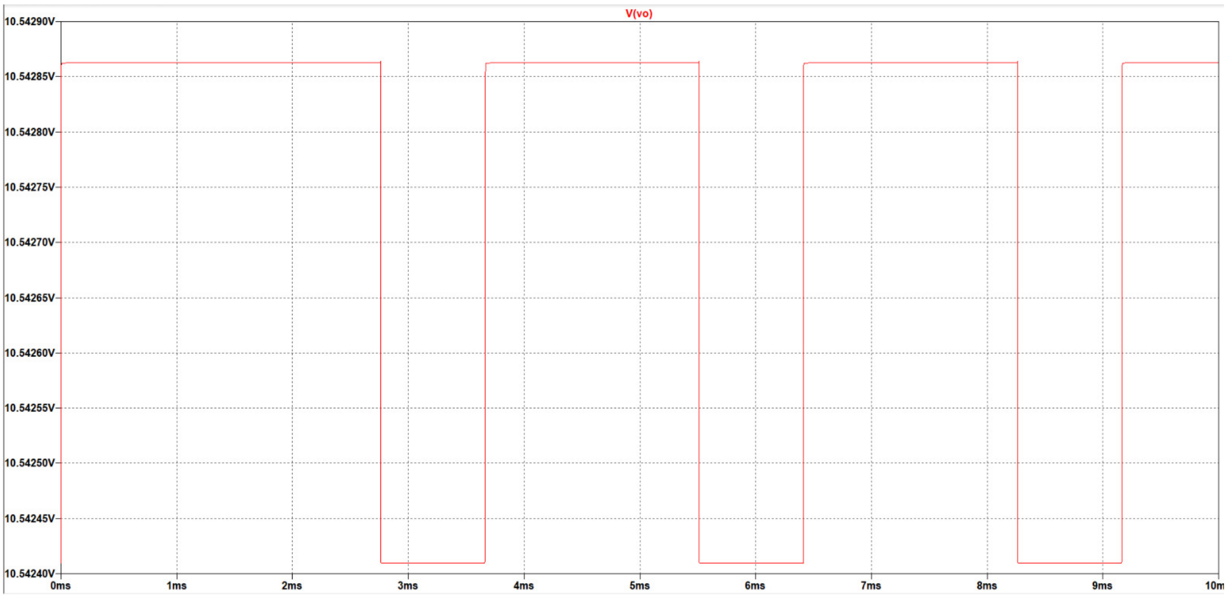
Gate Driver circuit model with its 555 timer connections modelled in LTspice

Output pwm obtained from 555 timer,



Plot of output voltage of NE555 vs. time

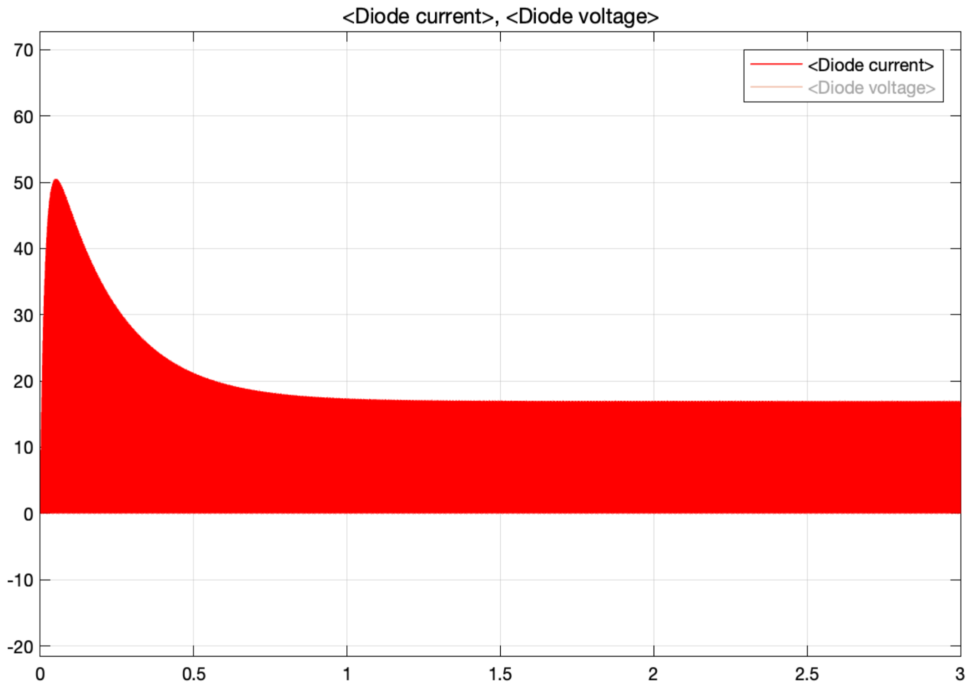
Output emitter voltage of IGBT,

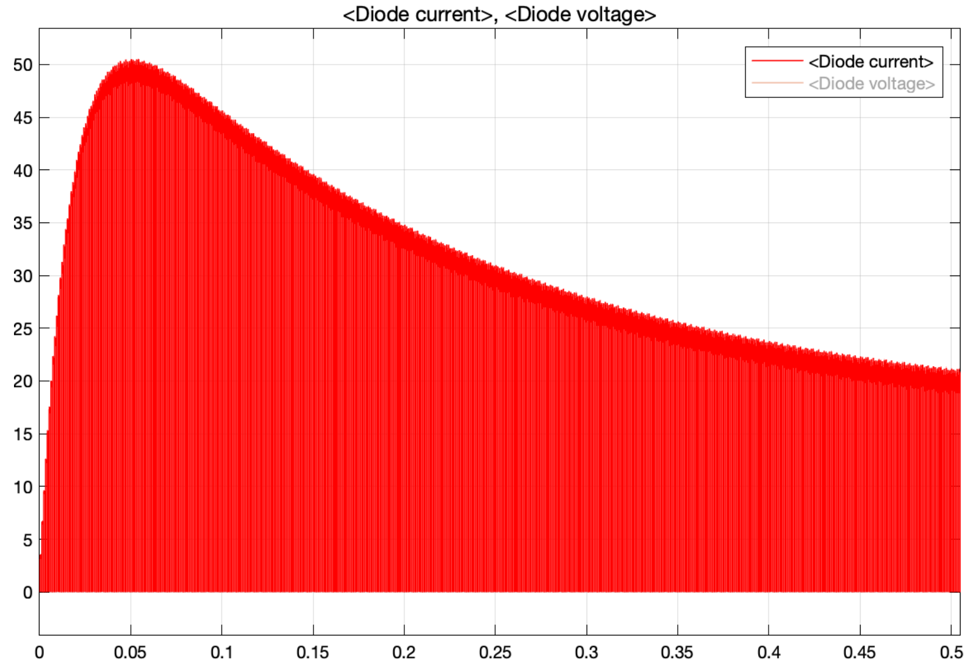


Plot of emitter voltage of IGBT vs. time

As seen from the figures, output voltage is a complement of PWM. To solve this problem, we decided to add the transistor to the input of the gate driver (pin 1 and 2). The transistor behaves like an inverter and when PWM is high, it gives output low and vice versa. Therefore, input PWM is inverted by transistor and output emitter voltage has a similar shape with the PWM obtained by NE555 timer.

Buck-Converter Diode

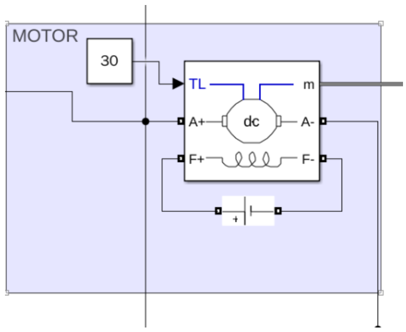




Plots of freewheeling diode current vs. time

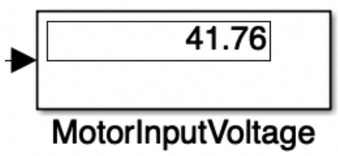
When the duty cycle of a buck converter is low, the mean current passing through the diode is high.). We measure the mean current is about 20A at duty cycle 20%. Therefore, we have chosen a diode accordingly. The details can be seen at the component selection part.

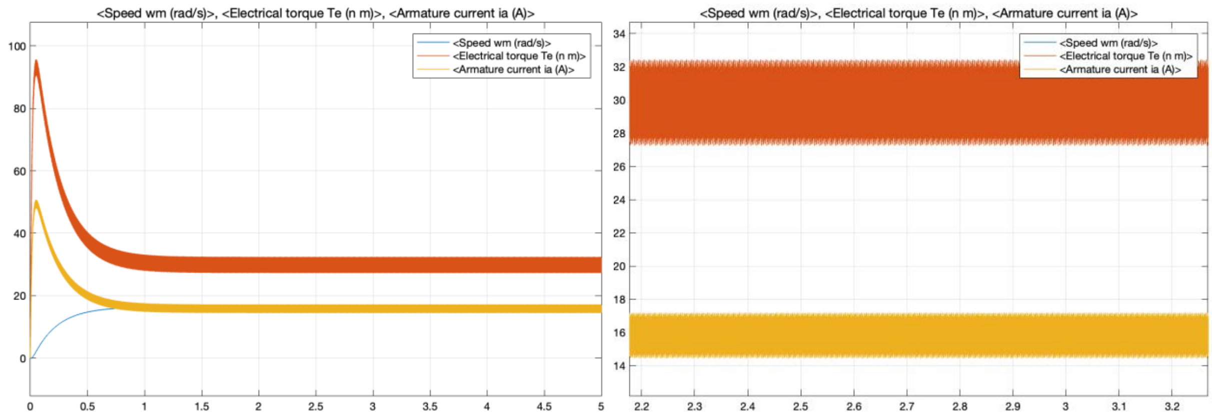
DC Machine:



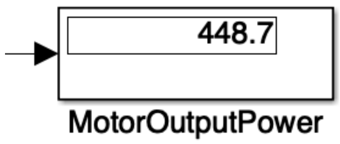
Schematic of motor side in Simulink

For 0.2 Duty Cycle Output Values

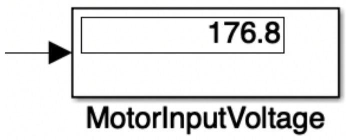


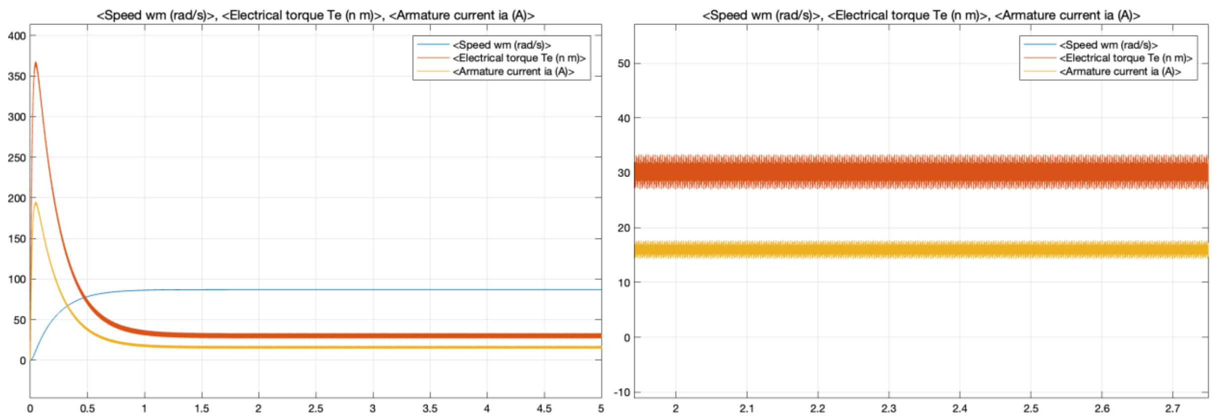


Waveforms of DC machine for D=20%

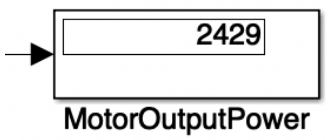


For 0.8 Duty Cycle Output Values





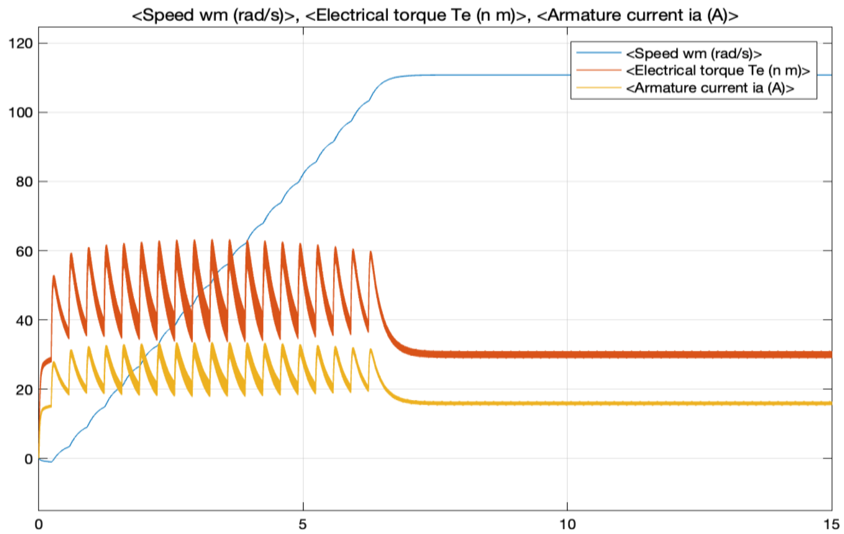
Waveforms of DC machine for D=80%



Since we don't want to reach the edges of 0 and 1, we determined the use 0.2-0.8 duty cycle values at min and max. Therefore, we added the related simulation results for the DC machine as can be seen above. Here, we see that only speed is changing when duty cycle is changed. The steady current is about 16A and this value meets our requirements. Also, we see a high inrush current for the 0.8 duty cycle. Since the motor speed is zero at the start-up, this inrush current is normal. In our demo day, we are allowed to do soft start using variac. Therefore, we expect that there is no high inrush currents observed.

Additional Simulation

We also obtain the duty-cycle vs. Torque-Current-Speed graph. If we will change the duty cycle %15 at each second, the Torque, Current, Speed vs time graph can be observed as in below:



Waveforms of DC machine while D is increasing

Component Selection

Table 1. All chosen components list

Component	Manufacturer Number	Quantity	Price(₺)	Total Price(₺)
Three phase bridge diode	SKBPC5016	1	38.5	38.5
Timer	NE555P DNSX19	1	2.6	2.6
IGBT	IXGH24N60C4D1	1	36.45	36.45
Diode	DSEI30-06A	1	40.03	40.03
Transistor	BC308B	1	1.33	1.33
Gate Driver	HCPL-3120	1	22.67	22.67
Fuses(30A 6*30mm ceramic fuse)	-	5	2.66	13.33
Capacitor(3.3uF 400V ceramic	-	1	0.888	0.888

capacitor)				
Capacitor(220nF 630Vdc)	-	1	1.13	1.13
Capacitor(10nF 50V ceramic capacitor)	-	1	0.752	0

Rectifier Diode

SKBPC5016 50A 1600V Three phase bridge diode
(More information can be found attached datasheet in our repository.)

Table 2. Critical parameter values of selected rectifier diode

PEAK REPETITIVE REVERSE VOLTAGE	1600V
AVERAGE RECTIFIED FORWARD CURRENT	50A
PEAK REVERSE CURRENT	10uA
NON-REPETITIVE PEAK SURGE CURRENT	500A
FORWARD VOLTAGE(I_{FM}=17A)	1.2V

According to our simulations and calculations, we see that we need a diode which can carry at least 30A. Since three-phase bridge diodes are cheaper than 6 diodes and they have a smaller size, as also the implementation is much easier. Thus, we choose three-phase bridge rectifier diode. It can carry 50A for 1600V.

Timer

NE555P DNSX19
(More information can be found attached datasheet in our repository.)

Since we generate a PWM by using only capacitors and resistors, we choose the NE555 Timer. This timer can generate PWM from microsecond to hour intervals. We are aiming to generate 1-5kHz square waves in our circuit.

IGBT

IXGH24N60C4D1 N Channel IGBT, High Gain 600V
(More information can be found here in our repository.)

Table 3. Critical parameter values of selected IGBT

COLLECTOR-EMITTER VOLTAGE	*600V*
GATE-EMITTER VOLTAGE	*+/- 20V*
COLLECTOR CURRENT	*56 A @ 25°*
POWER DISSAPATION	*190 W*
OPERATING TEMPERATURE	*-55°C / +150°C*

We calculated and measured that we will use at most 25A in our circuit at the steady state. Since the range of MOSFETs are not enough, we will use IGBT in our circuits. In our research, we couldn't find an IGBT that has higher current capability than **IXGH24N60C4D1.** Therefore, we decided to use this IGBT which also exists in the laboratory.

Freewheeling Diode

DSEI30-06A 37A 600V 35ns Ultrafast Diode
(More information can be found in here in our repository.)

Table 4. Critical parameter values of selected diode at buck converter side

RATED REPETITIVE REVERSE VOLTAGE	600V
AVERAGE RECTIFIED FORWARD CURRENT	37A
MAXIMUM REVERSE CURRENT	50uA
FORWARD VOLTAGE	1.6V
REVERSE RECOVERY TIME	50ns

For low duty cycles, the current through the buck converter's diode increases. Therefore, we have chosen the diode with the current rate accordingly. Also, since its recovery time is small, we eliminate the switching losses.

Capacitor & Resistor

We bought different capacitors and resistors for different purposes. Since we will use these capacitors in our controller, we don't consider currently for their voltage and power ratings at uppermost level since there is a still on-going process for our controller implementation. However, as we mentioned in previous parts, we bought some capacitors to connect the input terminals of the DC machine if it is needed. These capacitors are suitable for high voltage applications. Their voltage ratings are 400V.

Fuse

30A 6x30mm Ceramic Fuses

According to our calculations and circuit element current rates, current value should not exceed some limits. To prevent damage in the circuit, we bought ceramic fuses.

Gate Driver

HCPL-3120 2.5 Amp Output Current IGBT Gate Drive Optocoupler

To prevent high voltage drop on gate-emitter voltage of IGBT, we have added a gate driver to our design. The HCPL3120 has an insulation voltage of VIORM=630 V_{peak} and it provides 2.5A to the gate of IGBT. These values are very high among other gate drivers and suitable for our design.

Table 5. Critical parameter values of gate driver

MINIMUM PEAK OUTPUT CURRENT	2A
INSULATION VOLTAGE	630V
TEMPERATURE RANGE	40-100 $°C$
MAXIMUM SWITCHING SPEED	500ns

Thermal Calculations

In analysis part, there are 5 components that should be considered in thermal view. These are three-phase rectifier unit, the timer unit, gate driver unit, IGBT which is aimed to be used as the switch, and buck converter diode. At our on-going stage for the project, the losses for timer and gate driver unit were hold since the prototype and more experimental measurements are presumably needed.

IGBT

Over IGBT, there are 2 types of losses: switching losses and conduction losses. Switching losses are calculated by given section of the datasheet while taking into maximum frequency account:

$t_{d(on)}$	**Inductive Load, T_J = 25°C** $I_C = I_{C110}$, V_{GE} = 15V V_{CE} = 360V, R_G = 10Ω Note 2	21		ns
t_{ri}		33		ns
E_{on}		0.40		mJ
$t_{d(off)}$		143		ns
t_{fi}		68		ns
E_{off}		0.30	0.55	mJ
$t_{d(on)}$	**Inductive Load, T_J = 125°C** $I_C = I_{C110}$, V_{GE} = 15V V_{CE} = 360V, R_G = 10Ω Note 2	20		ns
t_{ri}		32		ns
E_{on}		0.63		mJ
$t_{d(off)}$		130		ns
t_{fi}		118		ns
E_{off}		0.50		mJ

For ON mode $with\ V_{GE} = 15V, V_{CE} = 360\ V, R_G = 10\Omega$:

$$E_{on} = 0.40\ mJ\ @25°C, and\ E_{on} = 0.63\ mJ\ @125°C,$$

For OFF mode $with\ V_{GE} = 15V, V_{CE} = 360\ V, R_G = 10\Omega$:

$$E_{off} = 0.30\ mJ\ @25°C, and\ E_{off} = 0.50\ mJ$$

As maximum frequency was limited at 5 kHz,

$$P_{switching} = f * \left(E_{on} + E_{off}\right) = 3.5\ W\ @25°C$$

$$P_{switching} = f * \left(E_{on} + E_{off}\right) = 4\ W\ @125°C$$

Conduction losses can be calculated for IGBT by given section of the datasheet:

Symbol	Test Conditions (T_J = 25°C, Unless Otherwise Specified)		Characteristic Values Min.	Typ.	Max.	
$V_{GE(th)}$	I_C = 250µA, $V_{CE} = V_{GE}$		4.0		6.5	V
I_{CES}	$V_{CE} = V_{CES}$, V_{GE} = 0V				10	µA
		T_J = 125°C			1.5	mA
I_{GES}	V_{CE} = 0V, V_{GE} = ±20V				±100	nA
$V_{CE(sat)}$	$I_C = I_{C110}$, V_{GE} = 15V, Note 1			2.28	2.70	V
		T_J = 125°C		1.95		V

$$as\ V_{GE} = 15V, V_{CE\,sat} = 1.95\ V\ with\ 125°C\ and\ V_{CE\,sat} = 2.7\ V\ with\ 25°C$$

$$I_{CES} = 1.5\ mA\ with\ 125°C\ and\ I_{CES} = 10\ \mu A\ with\ 25°C$$

$$P_{conduction}(125°C) = V_{CE_{sat}} * I_{CES} = 2.925\ mW$$

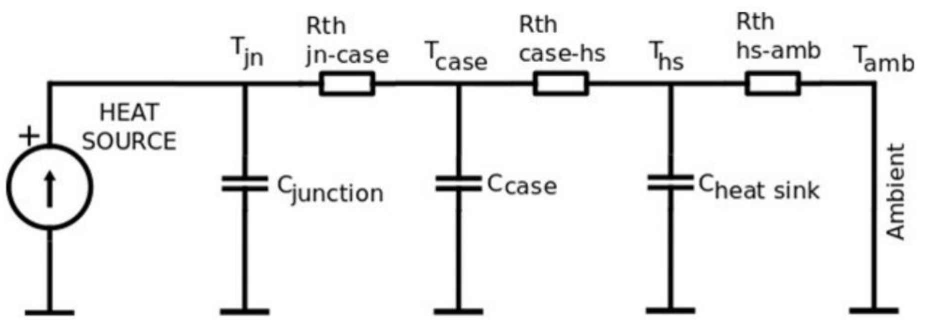
$$P_{conduction}(25°C) = V_{CE_{sat}} * I_{CES} = 27\ \ \mu W\ =\ 0.027\ mW$$

Overall, for our IGBT

$$P_{loss} = P_{switching} +\ P_{conduction}\ \cong 3.527\ W\ at\ 25°C$$

$$P_{loss} = P_{switching} +\ P_{conduction}\ \cong 6.925\ W\ at\ 125°C$$

Thermal circuit for IGBT



Typical thermal model in power electronics

Ignoring the capacitances for steady state,

$$P_{dissipated} = P_{loss} \cong 3.527\ W\ \ was\ found\ at\ 25\ °C.$$

R_{thJC}		0.65	°C/W
R_{thCS}	0.21		°C/W

$$R_{\theta junction-case} = 0.65\ °C\ /W\ and\ R_{\theta case-sink} = 0.21\ °C\ /W$$

And

$$R_{\theta heatsink-ambience} = 70\ °C/W\ for\ TO220\ [1]$$

Overall,

$$R_{\theta junction-ambience} = 70.86\ °C/W$$

Considering the changes in the parameters after 125 $°C$,

$$\frac{125\ °C - 25°C}{R_{\theta junction-ambience}} \approx 1.411\ W\ dissipated\ loss\ until\ temperature\ reaches\ to\ 125\ °C$$

$$T_{junction} = T_{ambient} + R_{\theta junction-ambience} * (P_{loss})$$

$$T_{junction} = 125 + 70.86\ °C/W * (3.527\ W - 1.411\ W\ ) \approx 236\ Celsius$$

Diodes

Rectifier Three-Phase Diode Losses

Conduction losses,

$$P_{loss} = V_F * I_F * D$$

@25°C

$$P_{loss} = 6 * 1.2 * 15 * 0.8 = 86.4W$$

Due to lack of data on datasheet, we could not calculate switching losses. (trr is not given). Also, we could not calculate temperature increase of diode since there is only R_{JA} value on datasheet.

Buck Converter Diode Losses

Conduction losses,

$$P_{loss} = V_F * I_F * D$$

@25°C

$$P_{loss} = 1.6 * 15 * 0.8 = 19.2W$$

Switching loss,

$$P_{sw_{loss}} = V_R * f_{sw} * t_{rr} * I_R$$

@25°C

$$P_{sw_{loss}} = 180V * 50Hz * 50ns * 50\mu A = 22.5nW$$

@125°C

$$P_{sw_{loss}} = 180V * 50Hz * 50ns * 7mA = 3.15\mu W$$

For temperature increase of diode,

$$T_{junction} = T_J + R_{JA} * (P_{loss})$$

$$T_{junction} = 298K + 35W/K * 51.8$$

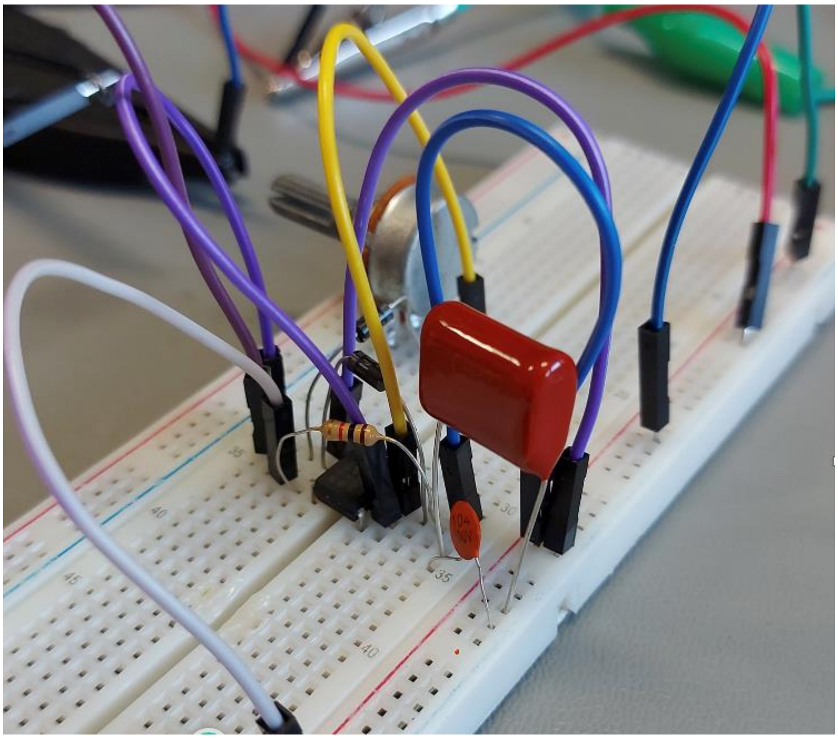
$$T_{junction} = 970K$$

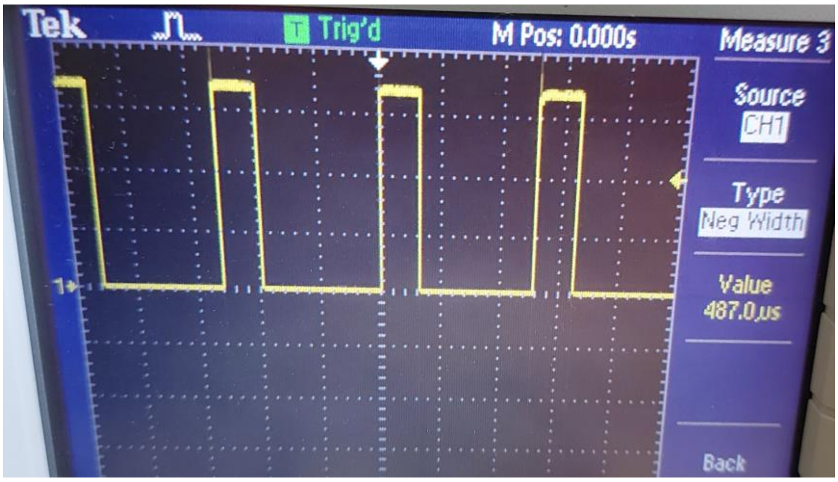
$$T_{junction} = 697°\text{C}$$

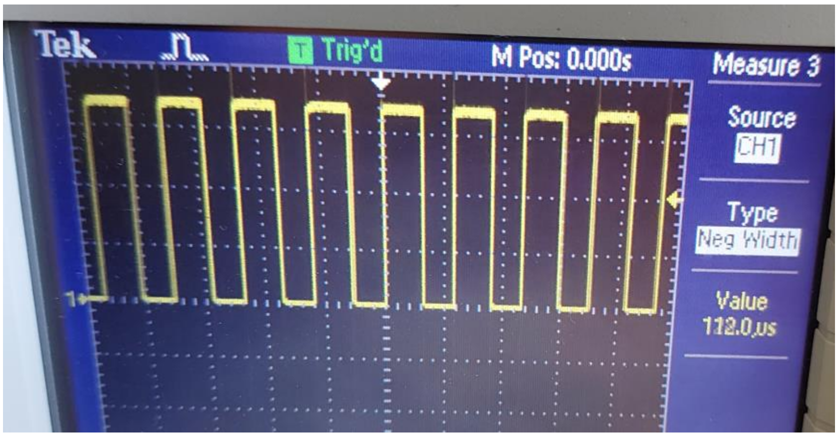
Implementation

555 Timer

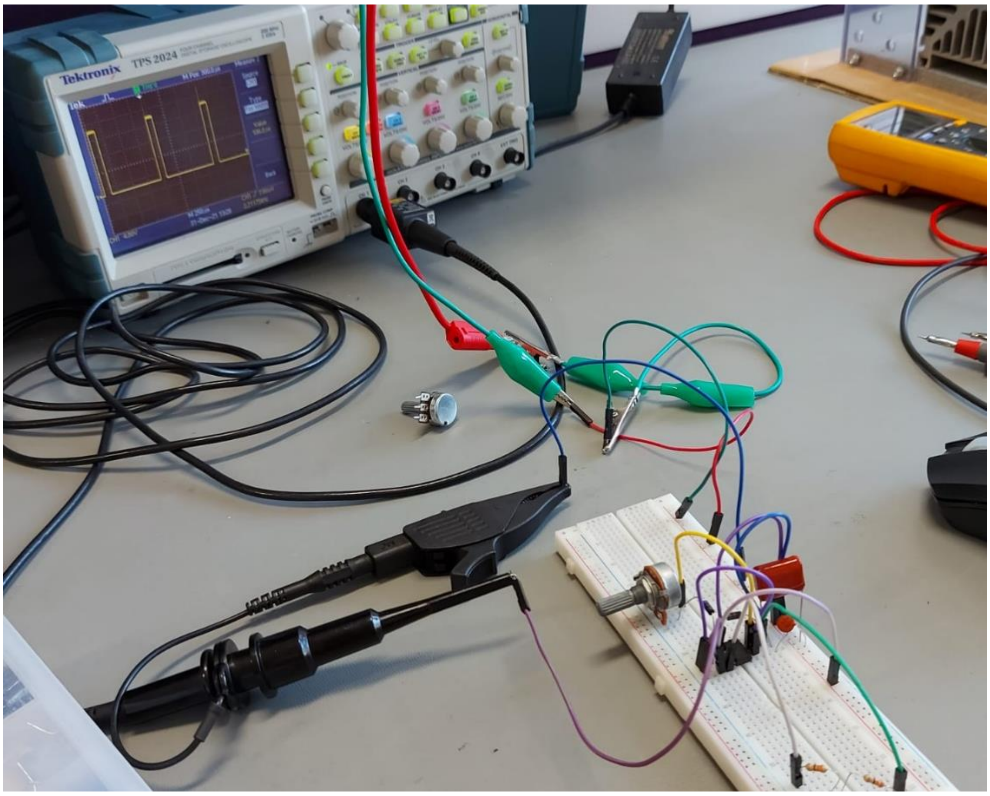
We have been 1 time in lab so far. At this session, we mainly focus on constructing the controller circuit. As we mentioned, we used a NE555 timer to generate the PWM. At first, we set this circuit by using only 1 POT. However, we observed that we could not obtain the required duty cycles with suitable frequency rates. Therefore, we added one more POT for the other resistive component in the circuit. Finally, we observed the needed duty cycles at the oscilloscope screen as can be seen below. (More recordings can be found in Lab Recordings file at Informative Pictures section in our repository.)



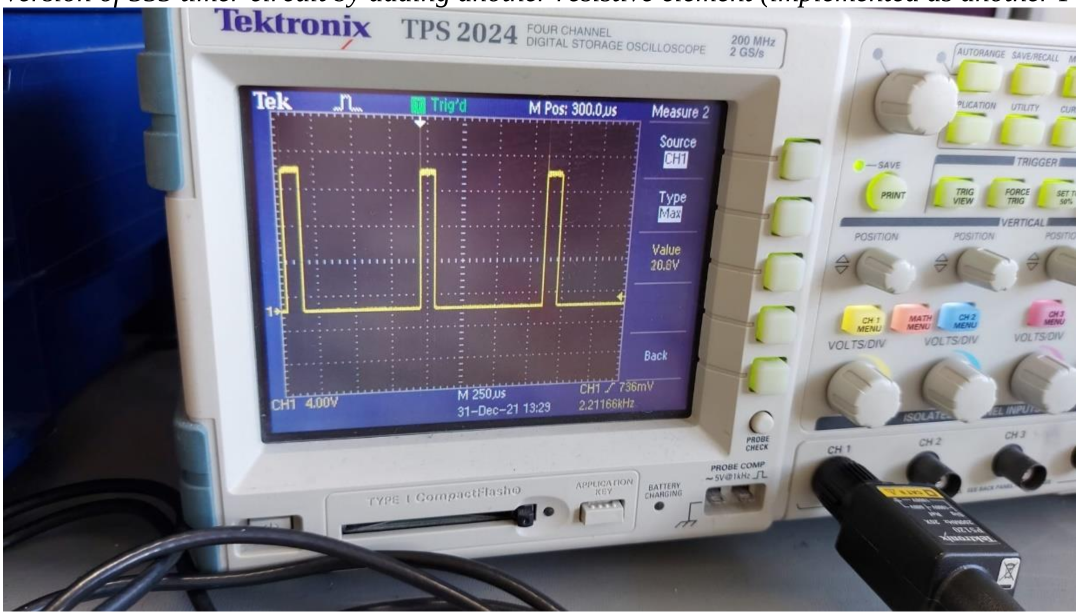




Recorded waveforms of NE555 timer at different frequency bands



Changed version of 555 timer circuit by adding another resistive element (implemented as another POT later)

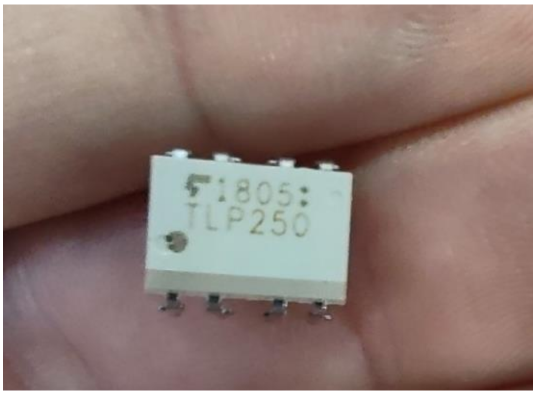


Recorded waveform of NE555 Timer circuit with two pots

As it can be observed by last recordings, we realized that by only using NE555 Timer as a control unit of our overall design, we were violating the given voltage limit of gate-emitter side for IGBT (indicated as 20 V in its datasheet) since we observed more than 20 V output at our timer. After these measurements, we had decided and understood that there was a requirement of gate driver for proper function of IGBT.

TLP250 Optocoupler

At first, we didn’t consider the importance of the gate-source voltage of IGBT. During the lab session, we realized that the gate-source voltage is one of the important things that we must consider. As we are thinking about how to solve this problem, our friend Samet (who is at another group, Son Motor Bükücüler) gave an idea about using an optocoupler to overcome this problem. Then, we determined to use TLP250. Since our time is limited, we couldn’t integrate the optocoupler part to our controller circuit. After the lab session, we are aiming to apply the necessary calculations and connections in LTSpice and we are planning that we will complete our controller circuit in the next lab session.



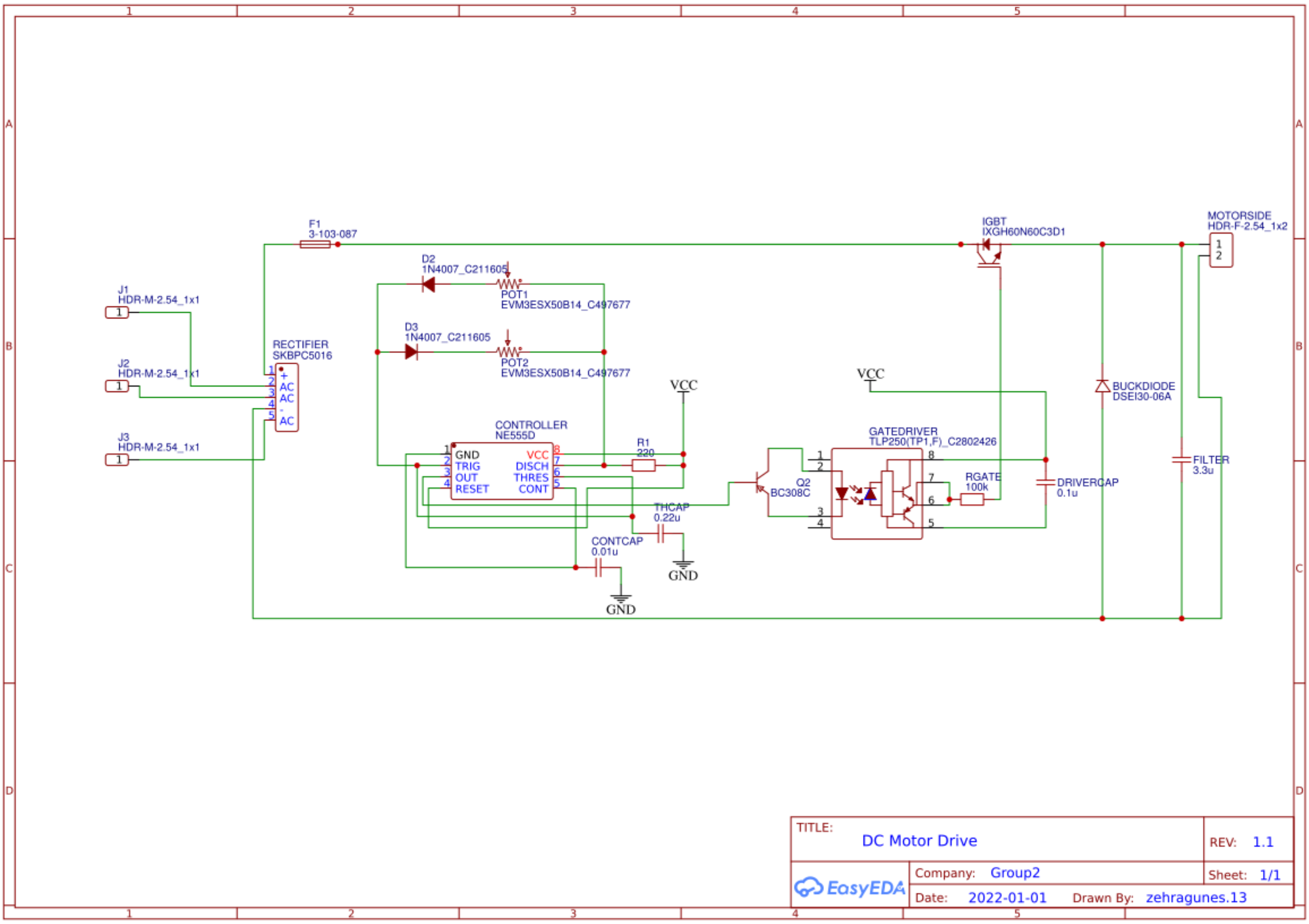
Measured component as a gate driver in lab session: TLP250 Optocoupler

Testing Our Equipment

Some equipment such as three-phase full-wave diode rectifiers may be broken. (Our friends in other groups have experienced this problem.). Therefore, we tested our equipment which we will use in next lab sessions during this test process. We did not observe any problem and we confirmed that all of them function properly.

PCB Implementation Studies

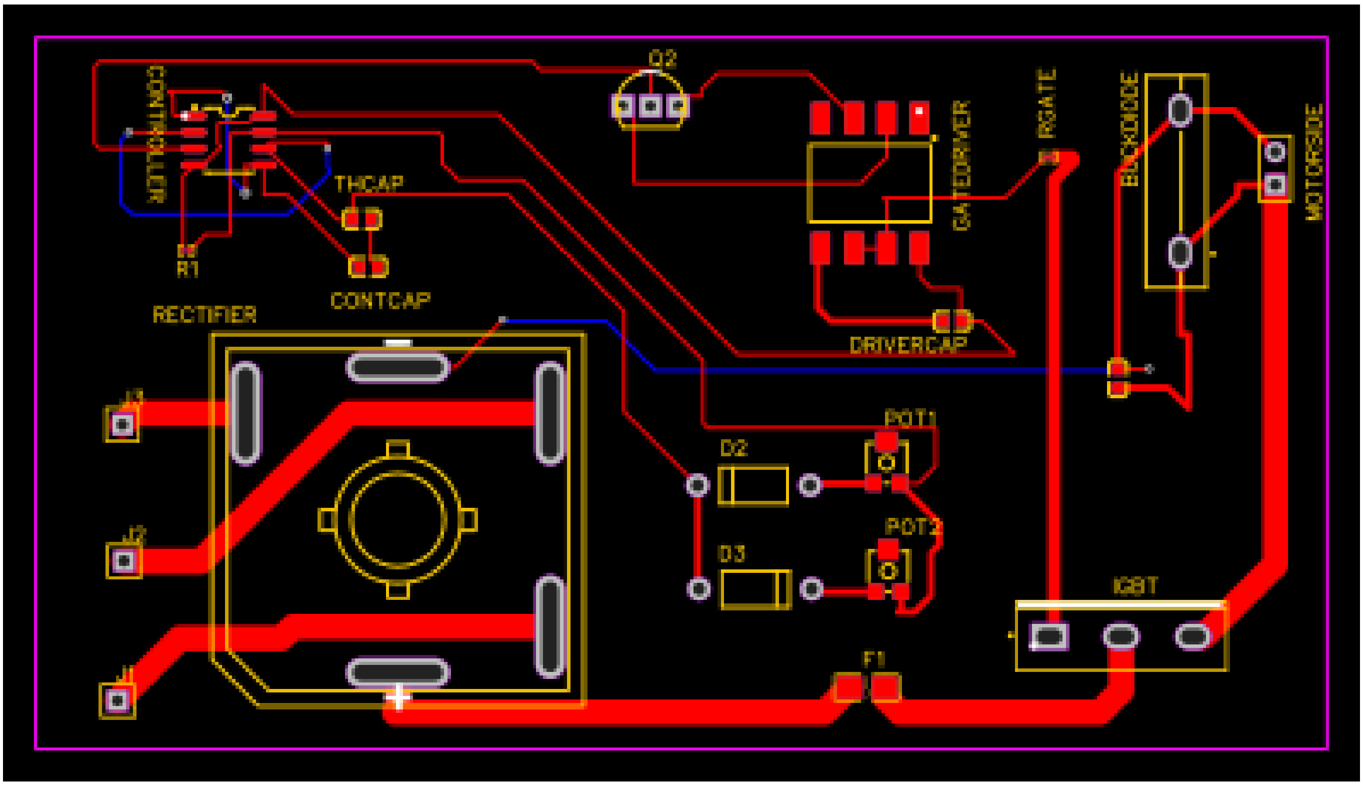
In addition to our laboratory testing and recordings, we have also tried to implement what we considered for our DC Motor Drive design. EasyEDA platform was chosen for PCB software as it is free and has simple structure without downloading for beginners. The related files can be found here in our repository. The planned circuit we explained so far was modelled as below:



The preliminary circuit model for DC Motor Drive designed in EasyEDA platform

As it can be observed that we implemented the actual components that we select or consider for PCB design. The input and output parts of the model can be updated later. Moreover, in case of a need, a filter capacitor with 3.3 µF was also implemented, this part can also be removed after more measurements will be recorded. It can also be noticed that currently, the optocoupler, TLP250 type, was selected since we did make experiments and recordings on it for now. Furthermore, a fuse component was also added on forward side of motor input side. The placement of it can be also discussed and changed if necessary.

After these connections were made, we transferred this circuit to PCB part to construct our board as a first version. It should be reminded that the connections can be debatable as this is our first experience with PCB Design.



The preliminary PCB Model of our considered design in EasyEDA

Early PCB Design can be observed in above. What we considered during this design was the temperature and resistance conditions of the components. Since a current at high level is planned to flow through IGBT as a switch, it will transfer the important part of given input thus a critical level of power will be transferred for the proper functioning of DC Motor. This will cause extra heat for IGBT as explained Thermal Analysis part. Thus, the placement of it in PCB Design carries a great importance. It was learned our research for PCB that this type of components should be implemented on board as far as possible from activated BJTs. Therefore, IGBT was placed at a corner with a strict distance between BJT (labelled as Q2) and optocoupler (labelled as Gate Driver) as we also learned by our assistant, TLP250 is a quite heat-sensitive component.
What was also considered for PCB is the designed wires. We tried to pay attention for the components such as IGBT while connecting its wires as thicker due to required higher power flow on it. Moreover, the length and width of the wires were also considered as much as possible in a limited area since longer wires cause more resistance at the same time thicker ones can cause undesired electromagnetic interactions.

Conclusion

The goal of this project is to demonstrate the lecture's outcomes on a broader level. We devised a circuit that rectifies three-phase AC voltage and lowers it to a DC Voltage Then we created the simulation of duty cycle cases. The concept here is that simulation is a method for selecting components to create a stable and effective solution So, after that, we picked the components for the simulations based on our analytical calculations and simulation results. Finally, we started our test and recordings our observations and measurements in an experimental environment at our lab while we also began using the design application EasyEDA to develop the schematics of our components and subsystems for this stage of the project.

For conclusion, we can say that we are about to complete our controller circuit. Also, we did a lot of simulations so far for the rest of the circuit. We can only say this is not a last day project because we are continuously returning to complete or overwrite to develop our solution or reduce the mistakes on our solution.