INDIAN INSTITUTE OF TECHNOLOGY PALAKKAD

DEPARTMENT OF ELECTRICAL ENGINEERING

Bidirectional DC-DC Battery Converter

ID3802:OPEN ENDED LAB PROJECT

OELP Final report

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1. ABSTRACT

The objective was to design a lightweight bidirectional buck/boost converter with constraints of limited components available in the market like smaller inductors . The glider is powered using a battery pack of 12 Li-ion cells producing an average voltage of 45V and delivering 200W at 24v to a DC bus which is connected to the BLDC motor and its driver circuits which are used to power the propeller.The open loop control of the converter portraying the buck and boost mode of converter within few intervals of simulation time was modeled in simulink and by performing simulations studies the behavior of the main inductor currents, LC filter, battery voltage were understood.

2. INTRODUCTION

A combination of solar energy conversion to electrical energy and storing part of energy in the battery for usage during times of changes in weather, day and night light conditions is critical for the elegant functioning of a solar glider. Electric energy provided by a solar cell will vary due to factors like intensity of light. Such a source of electric energy cannot be directly used to charge a battery. So, in a solar powered vehicle, like a glider, there should be a circuit to regulate the current and voltage with which the batteries are charged. Batteries are charged in 2 phases: a constant current phase and a constant voltage phase and the current and voltage in these phases should be precisely controlled.A single lithium ion cell voltage ranges from 3 to 4.2 V. The battery pack containing 12 cells can supply a voltage ranging from 36-50.4V. So, now during the day the onboard electronics is powered with the regulated voltage and current obtained from PV to constant DC circuit at 24V and the recharging of battery also takes place for which stepping up of DC voltage is required. During night time the battery pack has to power the electronics onboard for which stepping down of dc voltage is required. Hence, the objective is to design a circuit that can provide bidirectional flow of power that can charge the battery during the day while providing power to electronics with solar energy and utilize the stored energy at night to power the flight.

3. METHODOLOGY

A bidirectional buck/boost converter has been chosen as the DC-DC converter topology for the battery charger circuit as it is the most appropriate according to the required bus and battery voltages. The circuit acts as a buck converter when the battery is being discharged and as a boost converter when the battery is being charged.

The duty cycle when the battery is being discharged is $\frac{V_{bus}}{V_{battery}} = \frac{24}{V_{battery}}$ and the duty cycle when the battery is being charged is $1 - \frac{V_{bus}}{V_{battery}} = 1 - \frac{24}{V_{battery}}$. The mosfets in the circuit are operated at a switching frequency of 100KHz.

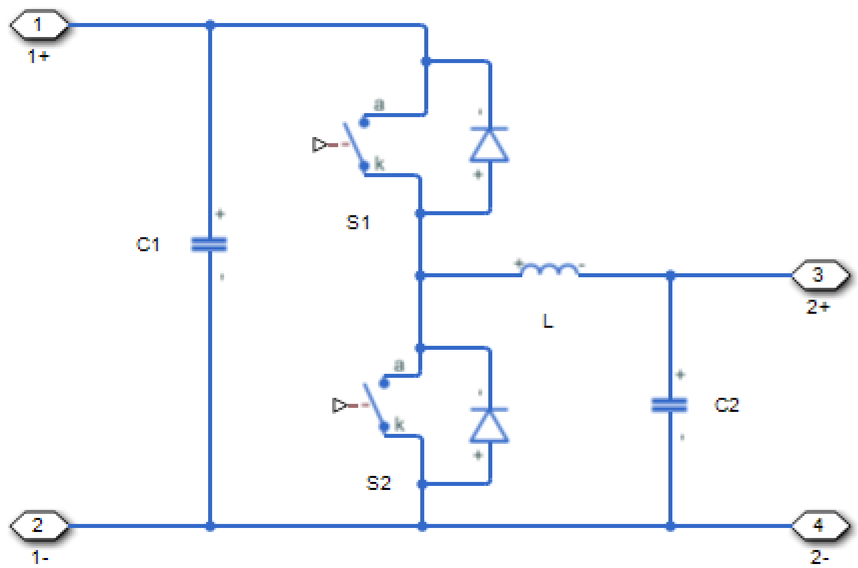


Fig: Bidirectional buck/boost converter

Mosfet Gate driver:

In order to turn on and off a mosfet in a controlled fashion we need a gate driver.A mosfet is turned on through 4 intervals. In the first interval the gate to source parasitic capacitance C_{GS} is charged from 0V to the threshold voltage.This is done so that the Mosfet is ready to conduct.This interval is called turn-on delay. During this interval there is no noticeable change in the drain current and drain voltage of the mosfet.Once the gate to source parasitic capacitance has been charged to the threshold voltage the second interval is underway. Here, the V_{GS} increases due to charge building up, the Drain to source current starts increasing meanwhile the V_{DS} remains constant.This goes on until it plateaus to a voltage known as miller voltage($V_{GS,Miller}$).Next during the third interval the gate is charged with respect to source to sufficient voltage of $V_{GS,Miller}$ which is enough to meet the load current requirements. As a result of which the V_{DS} starts to fall while V_{GS} remains constant.This region of operation is called as the miller plateau.The final step is to apply a V_{GS} so as to fully turn on the n-channel of the mosfet.This final voltage values of V_{GS} determines the on resistance ($R_{DS,On}$) of the device.This is achieved by charging both the parasitic capacitances C_{Gs} and C_{GD}.
Similarly for turning off the mosfet through 4 intervals the gate capacitors are to be discharged properly.First interval is the turn off delay during this period the drain voltage falls until it reaches the plateau. This discharge takes place through the input side capacitances C_{GS} and C_{GD} abbreviated as C_{ISS} as shown in Figure(2).The remaining 3

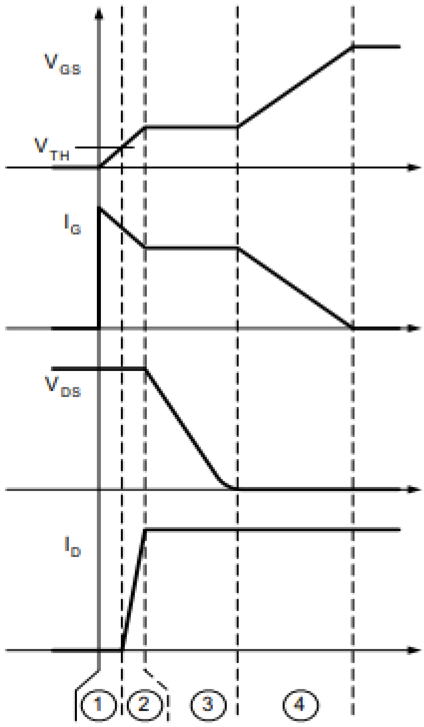
intervals are just the backtracked path of the turn off procedure. So it is evident that the switching action of MOSFET from high impedance to low impedance states can be controlled in 4 intervals and these intervals depend majorly on the gate drive current and parasitic capacitances.This highlights the requirement of a high speed gate driver. The Mosfet used in our application is IXTA130N15X4. This mosfet has a maximum value of threshold voltage VGT equal to 4.5V. We are supplying 12V unipolar pulses to power the mosfet. By driving the gate at a higher voltage, the turn on resistance as well as the switching losses can be minimised. The gate driver that was suitable for our application was the 175V/2A, High-Speed, Half-Bridge MOSFET Driver MAX1501CASA+.

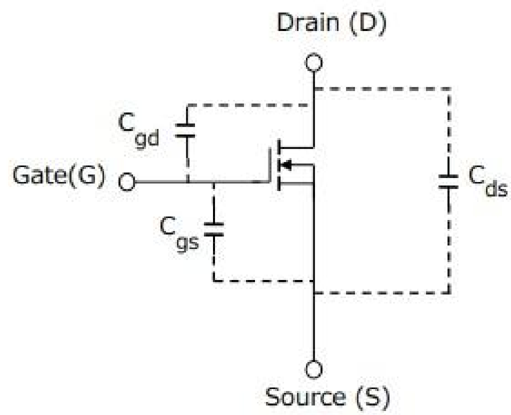
MAX1501CASA+:

- The gate driver receives an input signal from the microcontroller. This signal determines the timing and duration of the gate drive signal. The gate driver is powered by an external power supply, according to the data sheet it requires about 4-12V to operate.The input signal is level-shifted by the gate driver to match the voltage required to drive the MOSFET gate.This is necessary because the gate voltage required to fully turn on a MOSFET is often much higher than the input signal voltage.

- The most important feature of the driver that we will be leveraging is the Dead-Time Control.The gate driver includes a programmable dead-time control feature, which prevents the two mosfets in series from being turned on and off simultaneously which can short the battery or the bus. This prevents sudden surge of peak currents, which can damage the MOSFET or waste power.

- The MAX1503CASA+ gate driver provides a pulse current to the gate which provides an average value of gate current we calculated(shown in calculations section) to drive the gate of the MOSFET . This output signal has a rise and fall time of just a few nanoseconds, allowing for high-speed switching.
- When it comes to Protection, The gate driver includes various protection features, such as overcurrent and overtemperature protection, to prevent damage to the MOSFET.





Input capacitance $C_{iss} = C_{gd} + C_{gs}$

Output capacitance $C_{oss} = C_{ds} + C_{gd}$

Reverse Transfer capacitance $C_{rss} = C_{gd}$

Calculations:

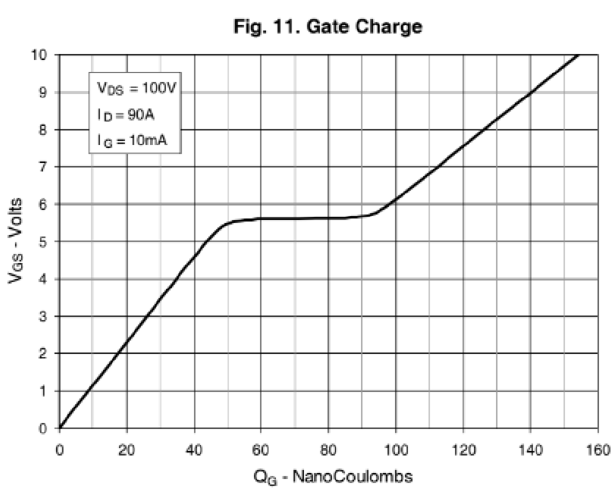


Fig: Gate voltage Vs Gate charge characteristics for our Mosfet.

Total charge $Q_G = I_G \times T_{rise}$

From the datasheet Q_G = 87nC and T_{rise} = 27ns

On solving we get,

Average gate current = 3.22 A

Power loss P = V_{GS} x Q x f_s

$= 12 \times 87 \times 10^{-9} \times 100 \times 10^{3}$

$= 0.1044$ W

CCM VS DCM analysis:

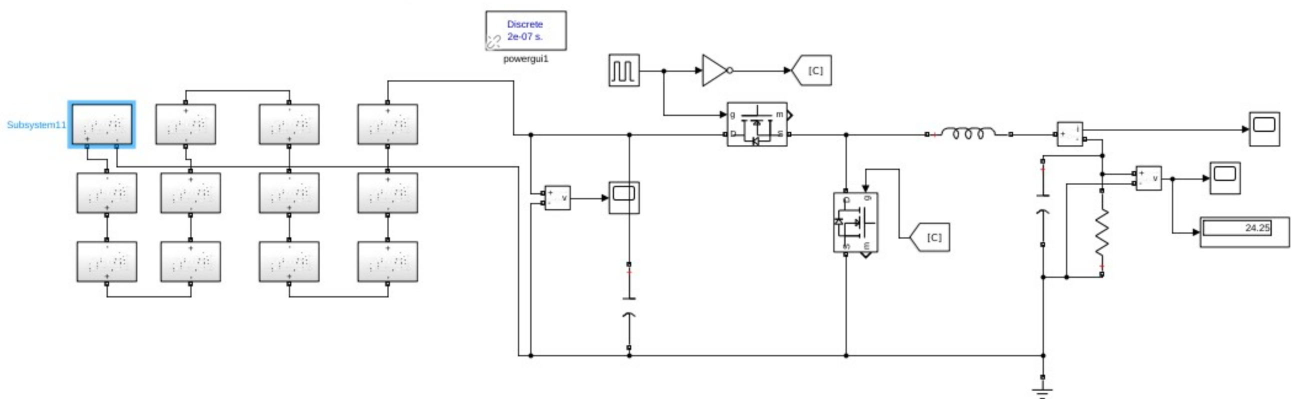


Fig: Simulink model of converter in buck mode alone.

The above model shows a complimentary switching implemented for the buck mode of the converter. The converter will work in Continuous charging mode or CCM.In this mode the inductor current can go positive or negative along with the ripple. We want to operate in CCM because in CCM the converter does not produce the desired output voltage of 24V. Sticking to our main goal of cutting down on the weight of the overall Circuit board.We reduced the size of the inductor by using a small inductor of 22μH to reduce weight but there is a tradeoff. By reducing the value of inductance the main inductor current ripple increases. A normal buck/boost converter with increased current ripple will go to discontinuous charging mode or DCM more easily. During DCM the inductor current will be zero for a finite interval of time even though this results in reduced switching losses. In this case we are going ahead with CCM.That is, we are doing a synchronous operation of the converter by switching devices in a complementary fashion.In synchronous operation we are using both the mosfets instead of mosfet and diode. This synchronous operation allows current including the ripple to be positive and negative. We are avoiding DCM through this operation and we are operating only in CCM this way.

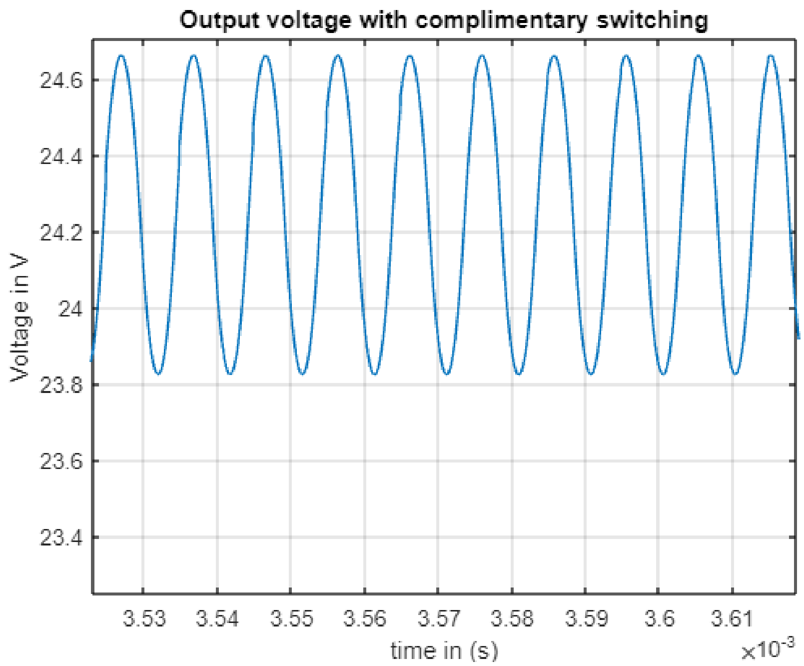


Fig: Output voltage at the DC bus for CCM/ synchronous operation.

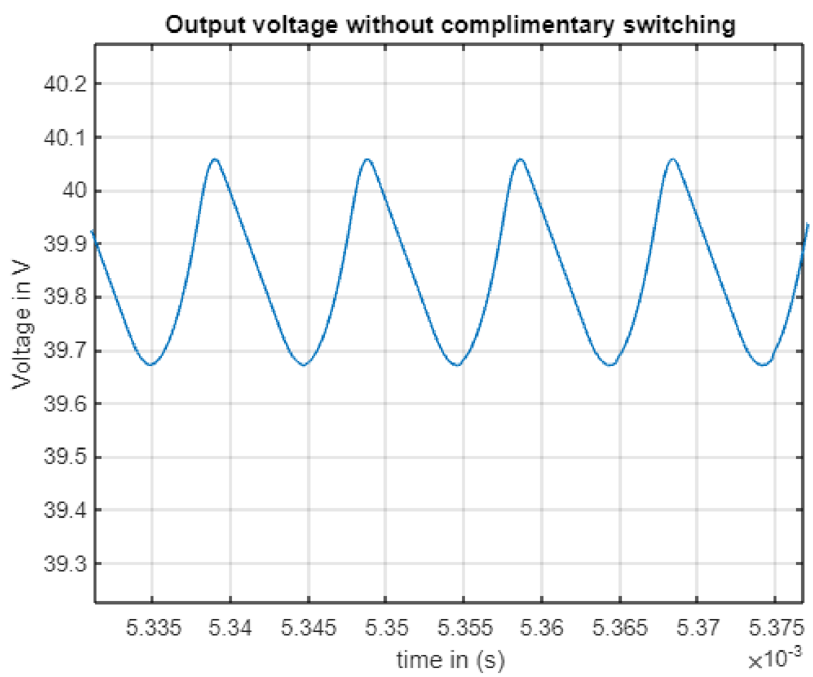


Fig: Output voltage at the DC bus for DCM operation.

Matlab simulation of open loop control of bidirectional mode:

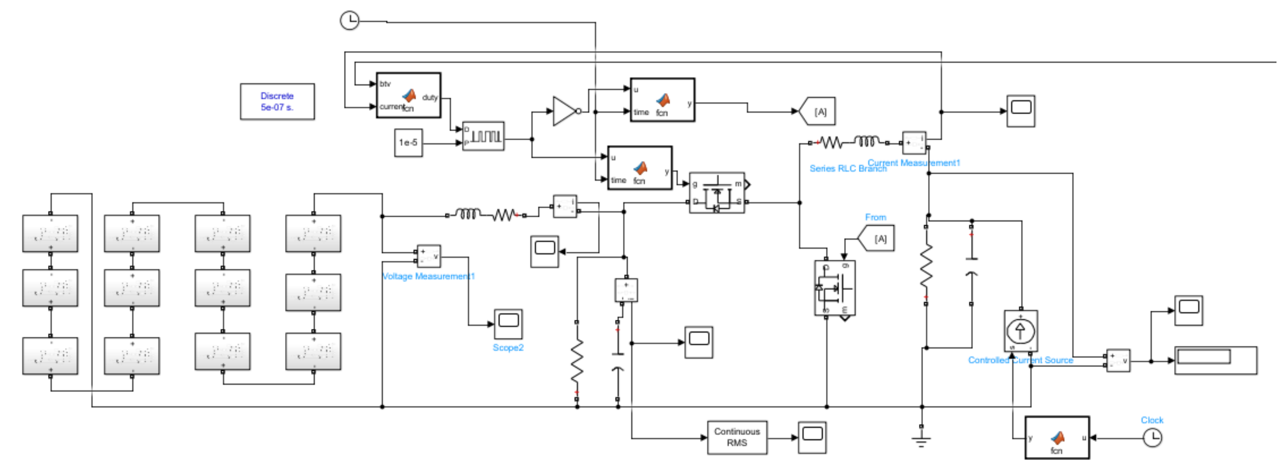
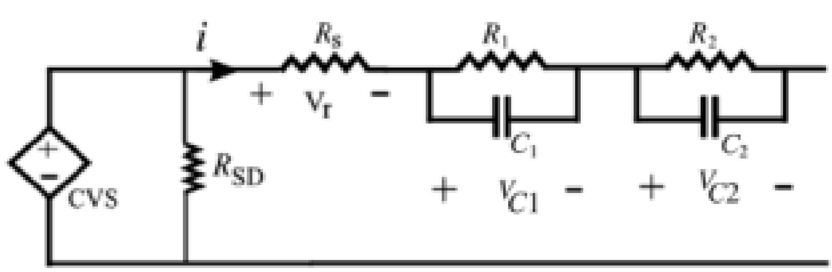


Fig: Simulink model bidirectional converter

A Simulink model has been designed to observe the transient and steady state voltage and current through different components of the converter. The constant voltage bus has been modeled as a current sink. The direction of current by the current source determines whether the battery is being charged or discharged. Since the converter is designed to give 200W of power at 24V, the current will be $\frac{200W}{24V} = 8.33A$. In our model, the battery is being charged with linearly increasing current for the first 0.002 seconds, then at a constant current of 8.33A for the next 0.002s, then charged with linearly decreasing current for the next 0.001s. The battery is then discharged with linearly increasing current till 0.006s and with a constant current till 0.008s and between 0.008s and 0.01s, the battery is discharging with a constant current of 8.33A.

To analyze and study about the bidirectional dc-dc converter , the Li-ion battery that is used to power the converter had to be studied. The steady-state and transient behavior of the battery was modeled using Thevenin-based circuit model. The circuit diagram of



the model is as shown below:

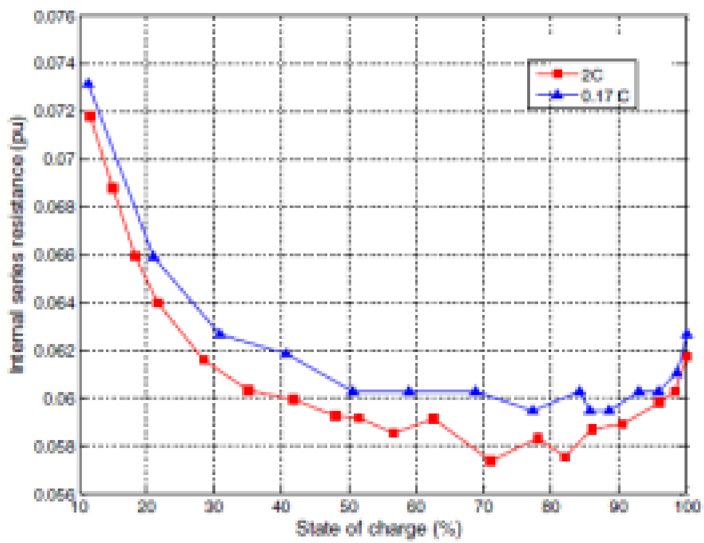
FIg: Thevenin-based circuit model of Li-ion cell

In the above model the lexicon used are as follows:

Rs represents the net resistance of the electrolyte, two electrodes and the contacts.The resistors and capacitors R1, R2, C1 and C2 are used for characterizing or mimicking the transient behavior of the battery.The voltage source which varies as a function of the charge remaining in the battery is modeled as a CVS(Controlled Voltage Source). The percentage of charge left in the battery is quantified using a quantity called State of Charge (SOC). It is given by the following equation:

$$SOC\% = 100 \times \frac{1-Q_{discharged}}{Q_n}$$

Here Qdis is the total charge removed from the battery after a period of discharge, Qn is the nominal capacity of the battery i.e the maximum charge it can hold. The variation of Rs with SOC after performing pulse discharge test using constant current sink are



obtained as shown below:

FIg: variation of Rs with SOC

To obtain a mathematical relationship between Rs and SOC curve fitting was done using the curve fitting tool in MATLAB. The resulting equating was obtained:

$$R_s = 2.29\times10^{-9}\times SOC^4 - 5.378\times10^{-7}\times SOC^3 + 4.791\times10^{-5}\times SOC^2 - 0.001908\times SOC + 0.08808$$

Since all the parameters such as R1, R2, C1 and C2 have increasing and decreasing trends over a full range of SOC for simplifying the model their values are taken to be fixed and equal to the mean value of the experimental readings. The CVS used in the model is given below:

$$\text{Voltage provided by Controlled Voltage Source,} CVS = 5.56\times10^{-5}\times SOC^2 + 0.001788\times SOC + 3.491$$

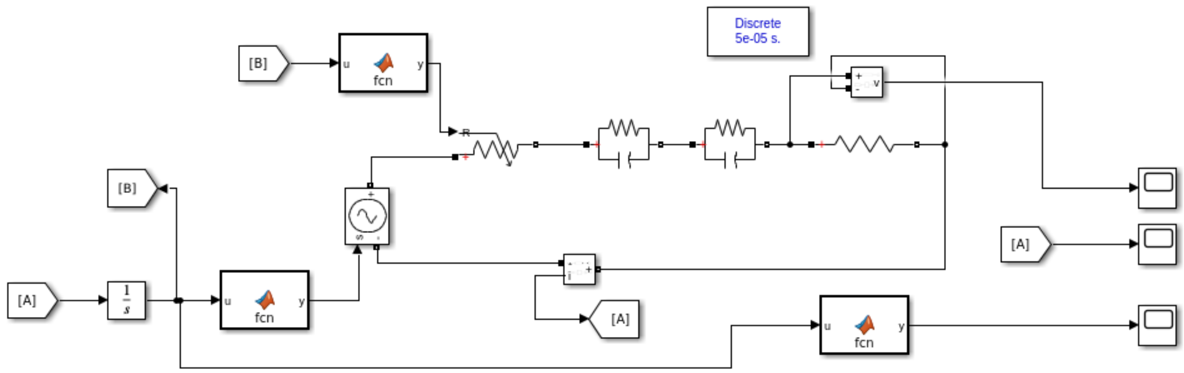


Fig: Li-ion cell model

The Li-ion cell model is taken as a subsystem and 12 Li-ion cell models are connected in series to make the Li-ion battery.

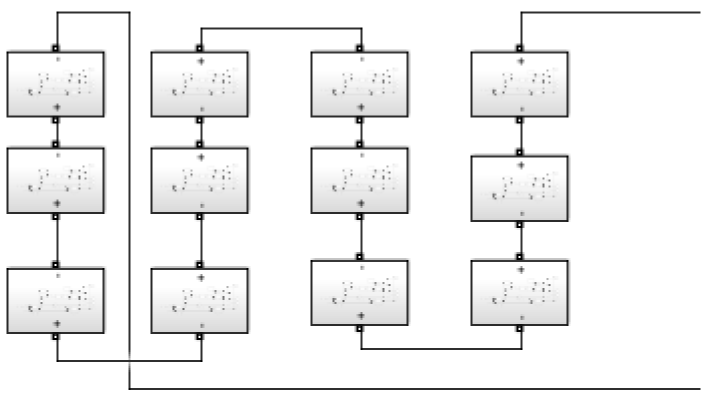


FIg: 12-cell Li-ion battery with Li-ion cell model as each one of the subsystems

The mosfet switching is controlled using a PWM signal whose duty cycle is controlled using a Matlab function which determines whether the battery is being charged or discharged based on the direction of current and sets the duty cycle accordingly. The battery has been set at an initial state of charge(SOC) of 60% to observe both charging and discharging.

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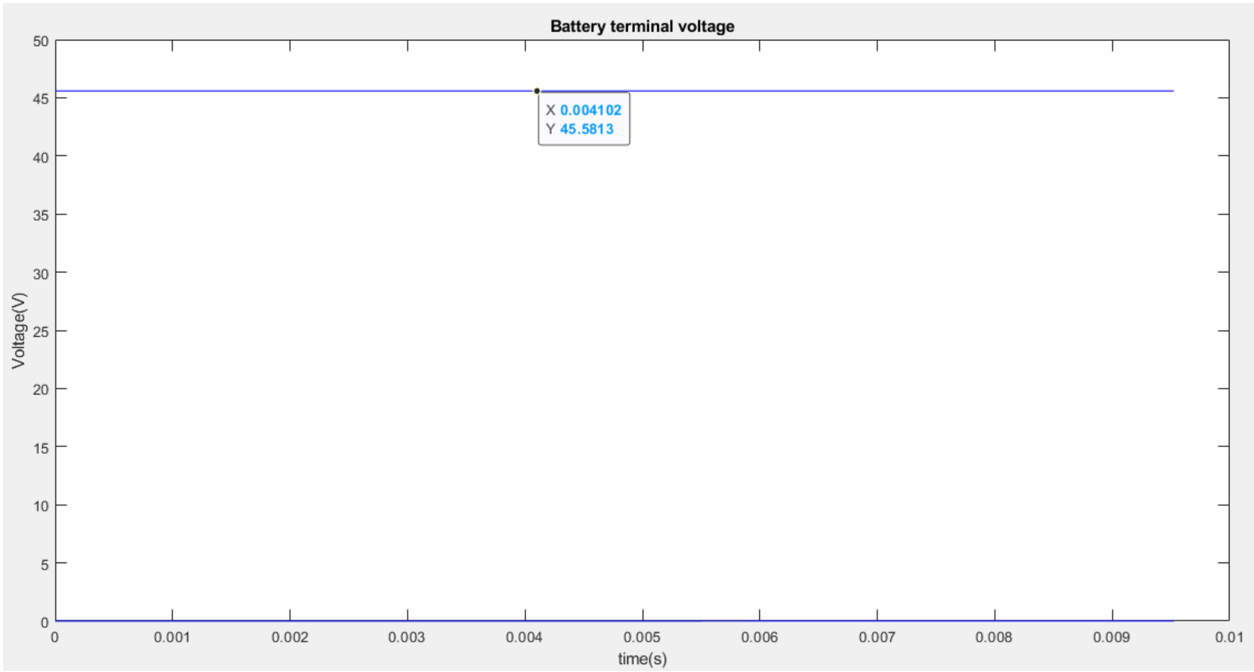


Fig: Battery terminal voltage

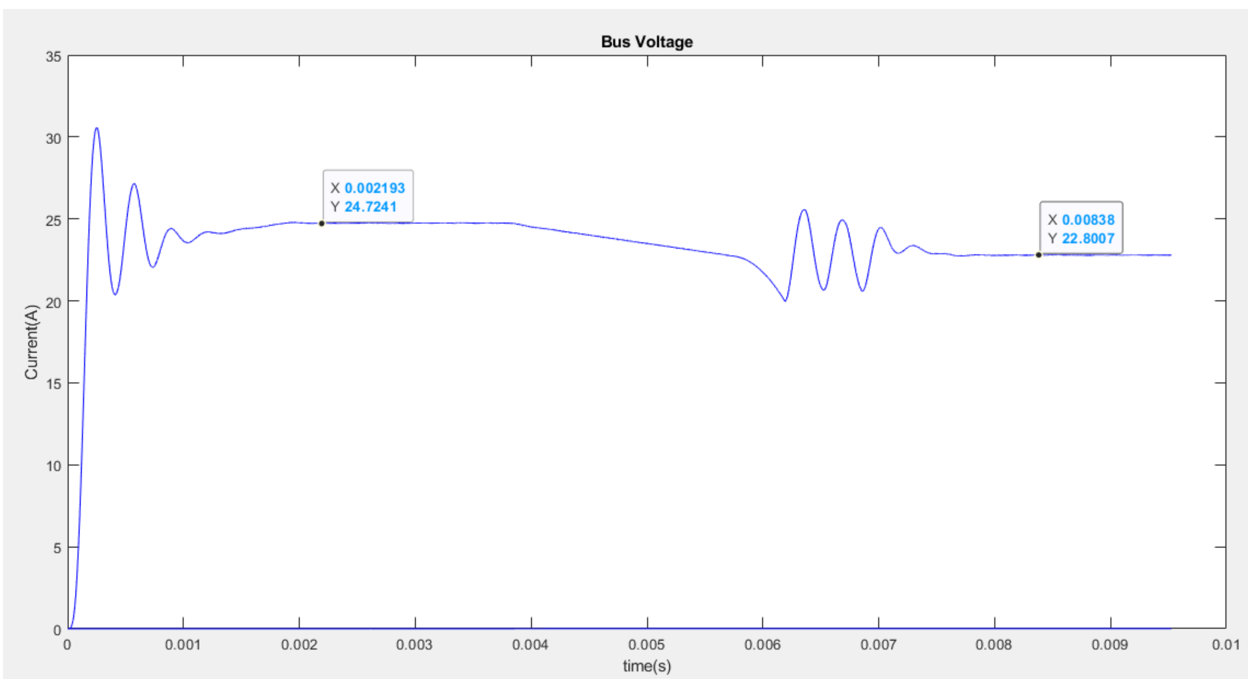


Fig: Bus Voltage

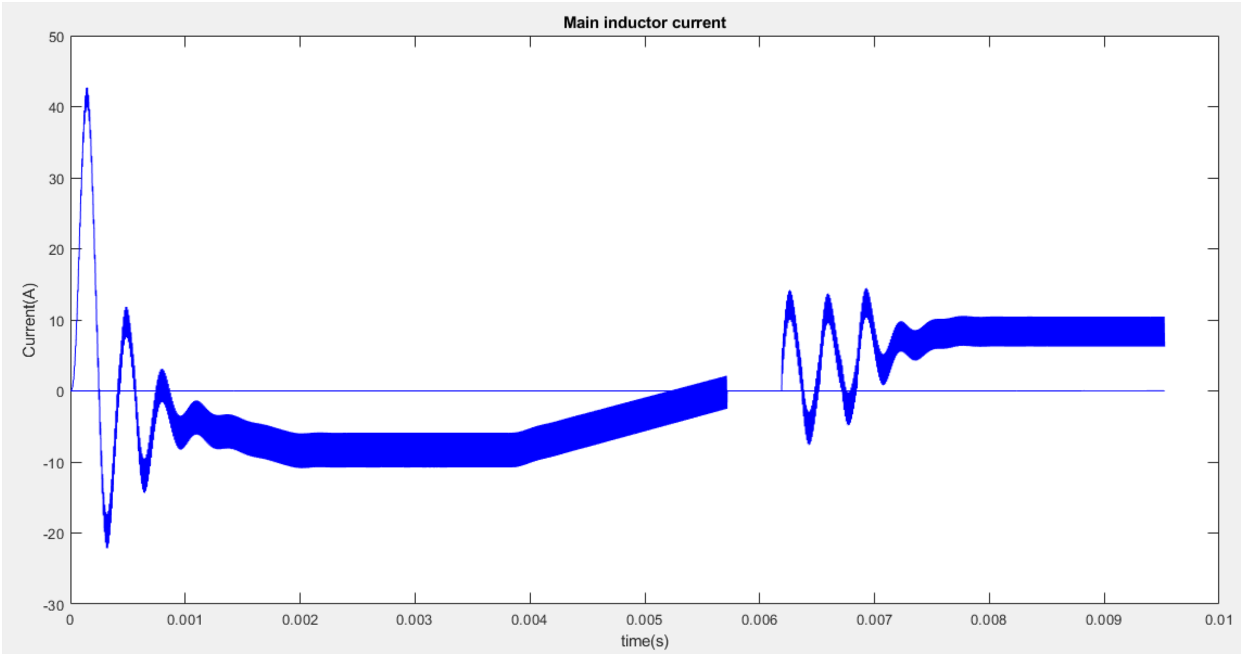


Fig: Main inductor current

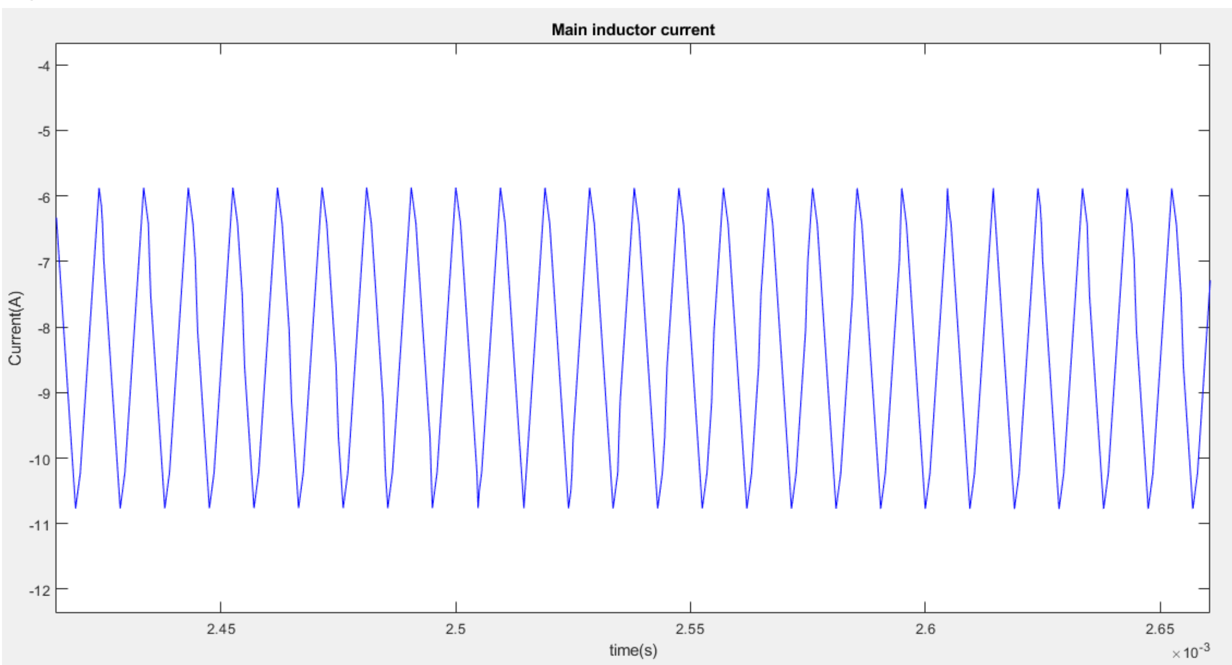


Fig: Main inductor current waveform shape

During the transient state, the inductor current can be seen to go to very high values. Thus an inductor with rated current of 40A must be chosen as the main inductor. At the instant where the battery changes from charging to discharging, both the switches so that the inductors and capacitors will discharge for the proper functioning when the converter changes its operation mode.

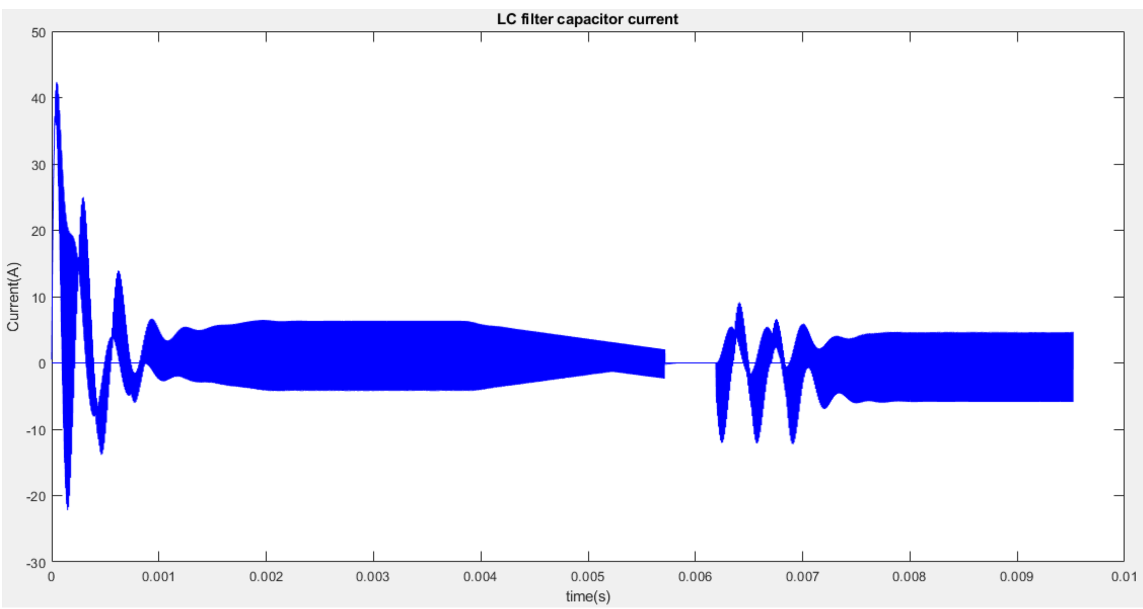
LC low pass filter:

In this bidirectional DC-DC converter, we have modified the design by adding two LC filters both on the input and output sides to mitigate the effects of peak currents that

occur during rapid transitions between charging and discharging. The capacitor in the LC filter acts as a storage element. During sudden current changes, such as when switching from charging to discharging or vice versa, the capacitor helps to stabilize the voltage by absorbing or releasing energy. It helps to smooth out the current ripple and reduce voltage fluctuations. On the other hand, the inductor in the LC filter helps to limit the rate of change of current. It resists rapid changes in current by storing energy in its magnetic field. By doing so, it prevents large and sudden current variations from flowing into the input or output circuits, reducing stress on the components and improving the converter's overall performance.
The corner frequency of the LC filter is given by the relation:

$$2\pi f_c = \frac{1}{\sqrt{LC}}$$

The switching frequency at which mosfets are operating is 100Khz. So we need to choose a cutoff frequency to be at least 1 decade from the switching switching frequency, this way higher frequency components that emerge during transitions can be filtered out. Since the inductor used is L = 22μH. For a cutoff frequency of 5 Khz we can find the capacitance required from the above equation. The capacitance required turns out to be 46μF.



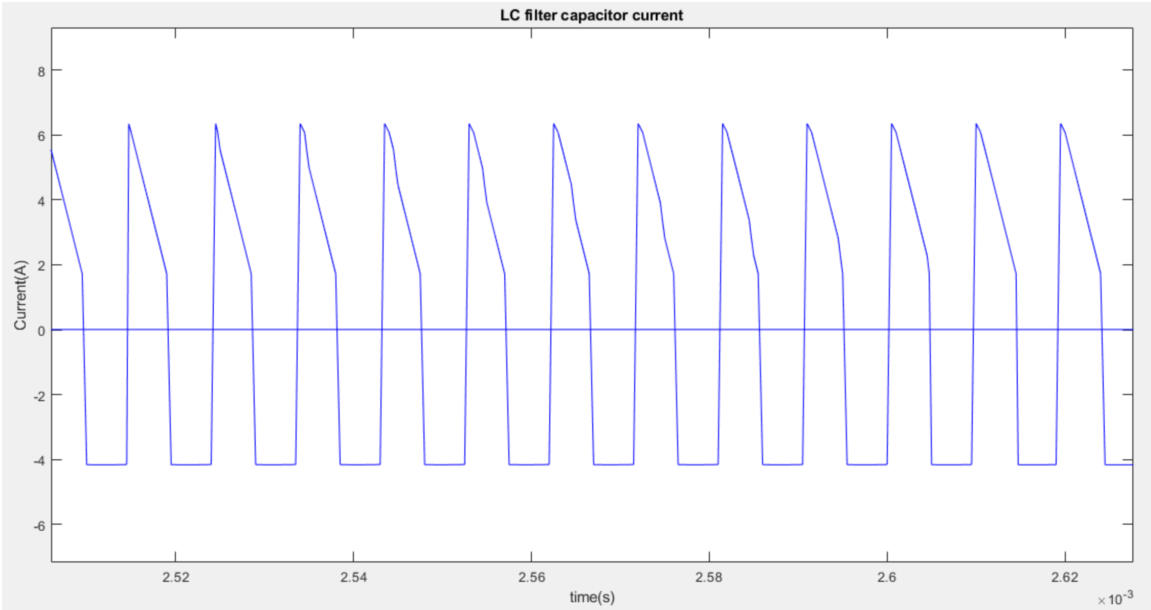


Fig: LC filter capacitor current
The above current plots shows how high the current in the capacitor goes which helps us choose an appropriate capacitor for the circuit.

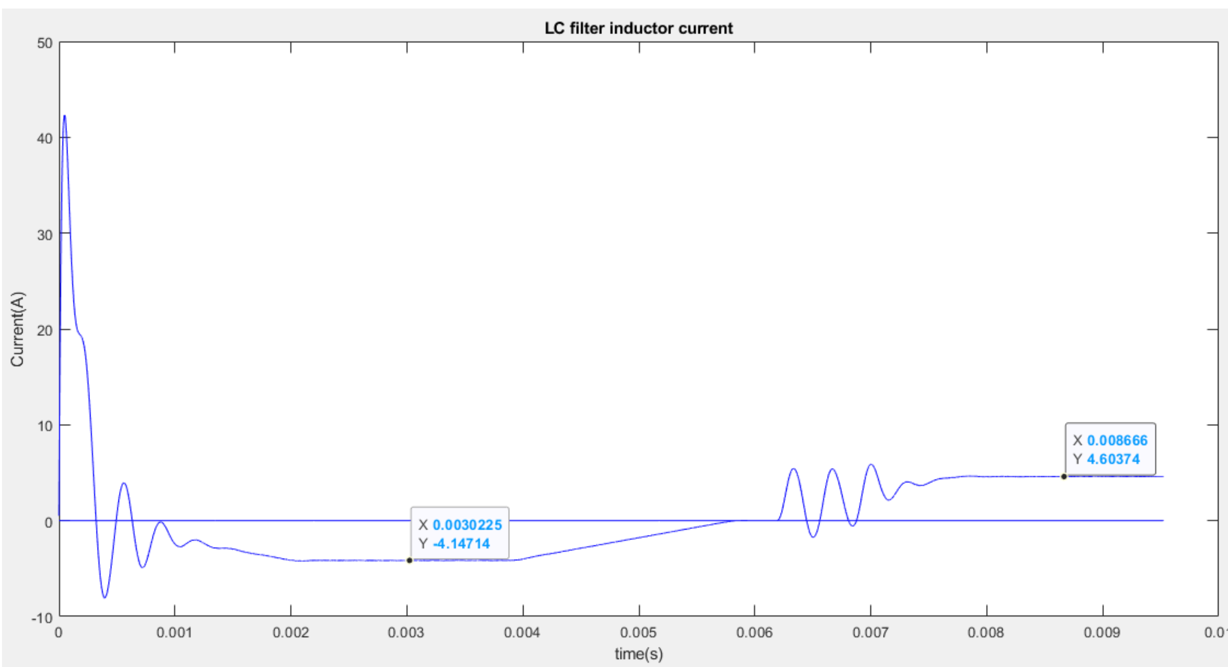
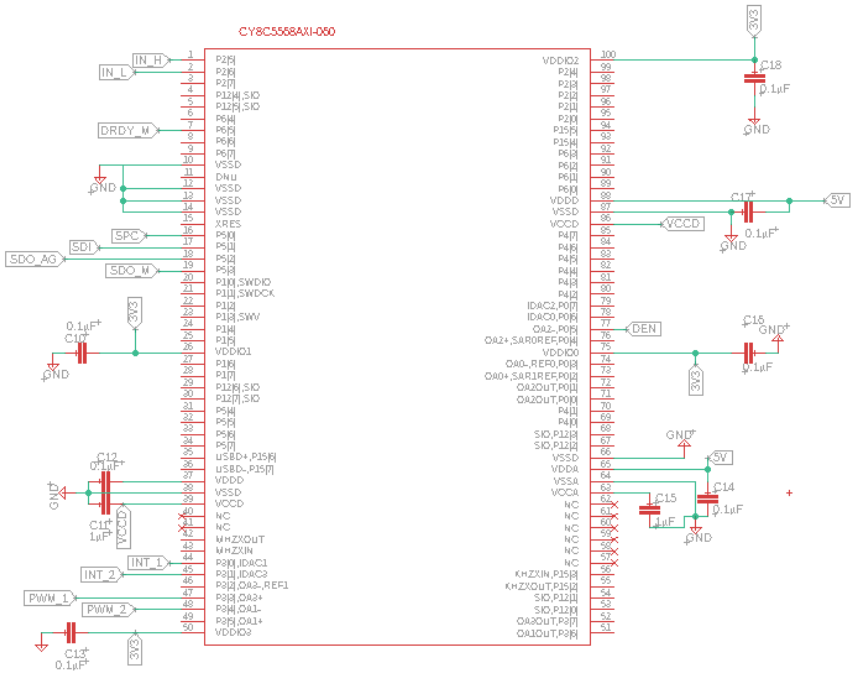


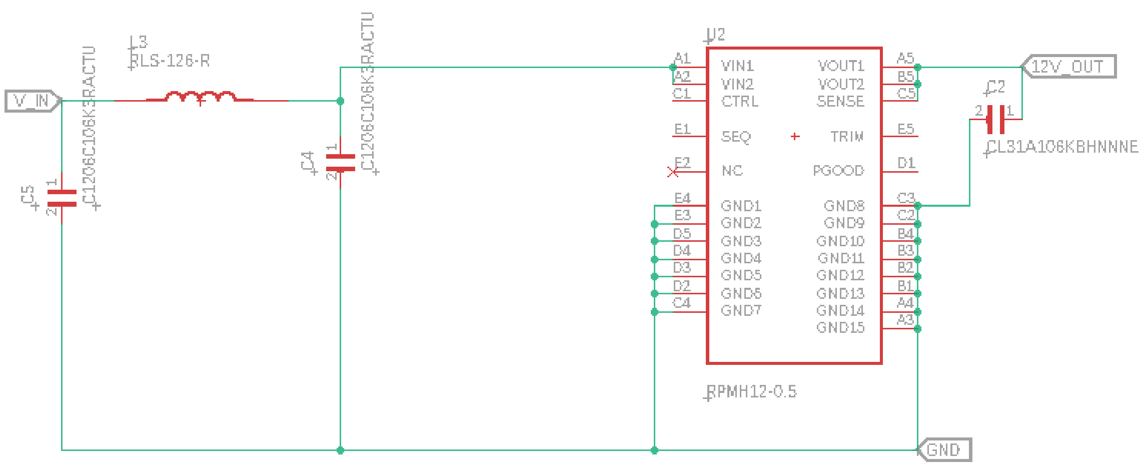
Fig: LC filter inductor current

Progress on PCB schematic:
1)Microcontroller:



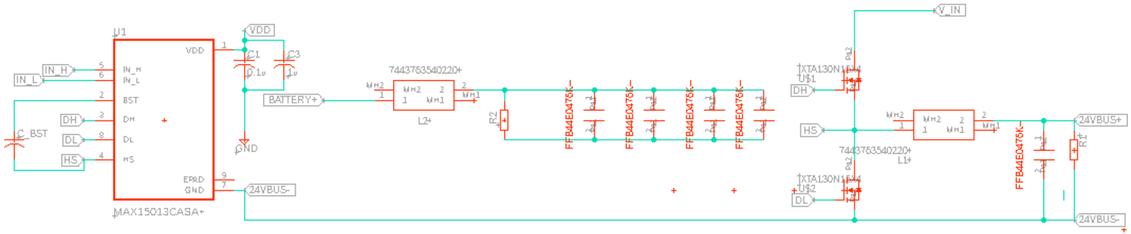
The cypress microcontroller CY8C5558AXI-060 is a 100 pin thin quad flat package used for generating the PWM signals for the gate driver. It is powered through 5V and 3.3 V supply.Left side consists of SPI communication pins along with GPIO pins used for generating the PWM signals for the gate driver.In future the current sensor are to be added to the design which actively monitors the average inductor current of the LC filter.

2)12V Voltage Regulator:



a 12v regulator is required to power the gate driver IC. At the input side we have a supply capacitor that supplies or takes care of the ripples in the input side.At the output side we have a decoupling capacitor, this acts as a charge reservoir, supplying excess current when needed and absorbing excess current when the load demands decrease. This helps maintain a steady and regulated value of 12V.

3) **Converter:**



The capacitor for the LC filter was 46μF. 47μF is available in the market so we chose that. The main capacitor is 47x4 = 188μF.The gate driver protection circuits are to be included in the future design.We are using the 40 A saturation current rated inductors because often due to duty cycle changes or transients the inductor current peak value can go up to 35-40 A so we chose the inductor [8].

Other component symbols and footprints designed:
Current sensor(MLX91221),
Voltage regulators(VX7805-500)
Mosfets (IXFT180N20X3HV)
Zener diodes(BZG05C3V3, BZD27B5V1P)

4. CONCLUSION

The results of the research and simulations provided us with crucial data that is essential for choosing the right components for the final circuit, which should be designed taking into account the rated voltages and currents. Voltages and currents in the transient state were observed, and it was found that they might rise significantly above steady state values. The output voltage of the buck-boost converter was also seen to be impacted by the effect of MOSFET resistance.

The battery charging and discharging circuit is essential to ensuring that the glider can run continuously and enables for the use of a renewable and sustainable energy source. The circuit may need additional testing and tweaking to increase its performance and dependability. Hence, as a whole the battery charging and discharging circuit is a major advancement in the development of the solar glider and has the potential to have a major impact on the field of renewable energy.

5. REFERENCES

[1] Saurabh Saxena, S Raghu Raman, B Saritha and Vinod John, “A novel approach for electrical circuit modeling of Li-ion battery for predicting the steady-state and dynamic I–V characteristics”, Department of Electrical Engineering, Indian Institute of Science, Bangalore.

[2] Dragan Maksimovic, Robert Warren Erickson,”Fundamentals of Power Electronics”

[3][Datasheet of microcontroller]

[4][Datasheet of capacitor]

V_{in} is the input voltage
V_{out} is the output voltage
Duty Cycle, D= $\frac{V_{out}}{V_{in}}$

[5]Datasheet of voltage regulator

[6]Datasheet of mosfet

[7]Datasheet of mosfet driver

[8]Datasheet of inductor(40A rated)

[9]Datasheet of inductor(30A rated)