Middle East Technical University

EE400 Summer Practice 2017-2018

TUBITAK-MAM Energy Institute

Converter Technologies

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Contents

1 Introduction

I have completed the internship that is assigned by the Electrical and Electronics Department in TUBITAK MAMS Ankara Research Centre, Power Electronics Section.

Energy Systems Department was established in 1992 by TUBITAK MAM. in February 1996, it was united with the Environmental Engineering Department to create the Energy Systems and Environmental Research Institute (ESÇAE). For 6 years, many prominent projects were conducted increasing the knowledge, experience, network and assessment evaluation capability of the unit to an international state in energy and environment areas.

TUBITAK MAM Energy Institute is a centre for Research and Development activities with the mission to be a leading centre for researching activities and with the vision to bring Turkey up to high levels in energy technologies and to research with modern information technologies since it was found in 1992. Institute targets to improve the energy technologies inside the country parallel with Turkey's development goals and to carry out projects in this direction together with the companies inside and outside of the country.

The Institute has two research centres one in Gebze and the other in Ankara. The centre in Ankara is located inside the Middle East Technical University Technocity campus. This is the centre where the summer practice which is subjected to this report is carried.

TUBITAK MAM Energy Institute has a wide cooperation network of project clients and project partners. They are shown in figure 1 explicitly.

Figure 1: Clients and partners [4]

Institute has the personnel profile shown in 2 and the organisation chart shown in 3.

Under Power Electronics and Control Technologies Section they have specialisations on vehicle technologies focusing on Railway vehicles,Special vehicle design and application,Hybrid and electric vehicle technologies,ICE technologies and tests; Battery Technologies and Power Electronics Technologies. These areas can be seen in chart 1 provided below.

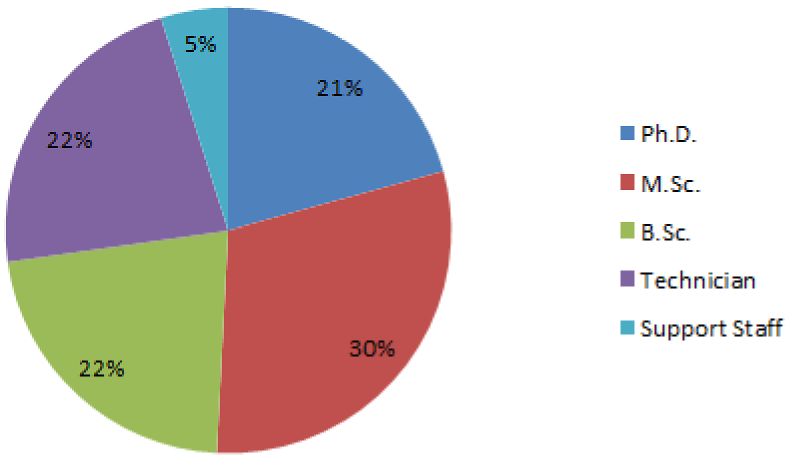

Figure 2: Personnel Profile

There are 250 employers of which approximately 150 are engineers in the institute. The employee profile is shown in 4

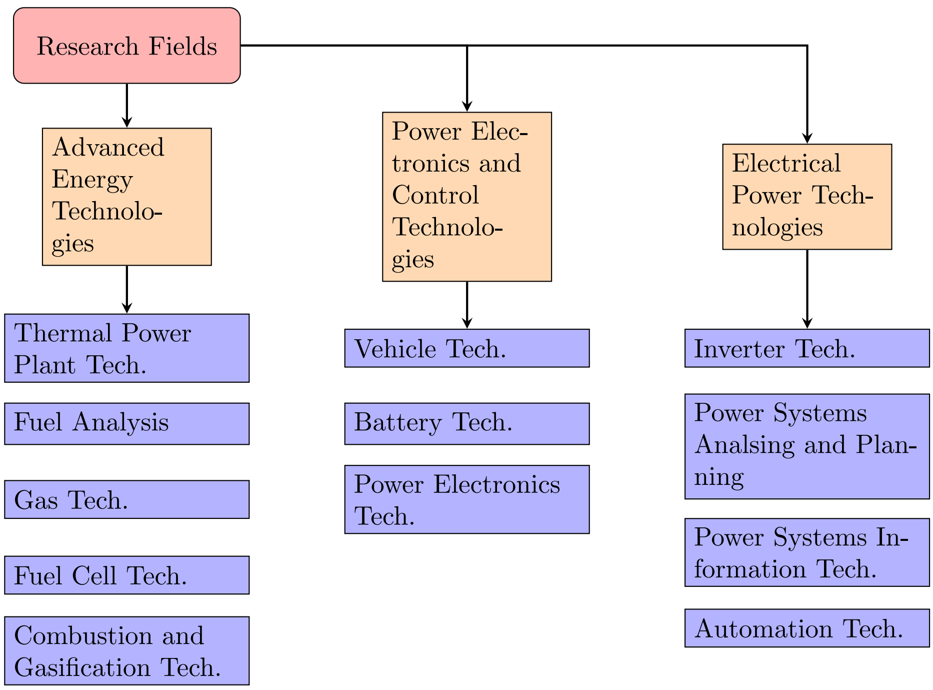

Figure 5: Research Areas Flowchart

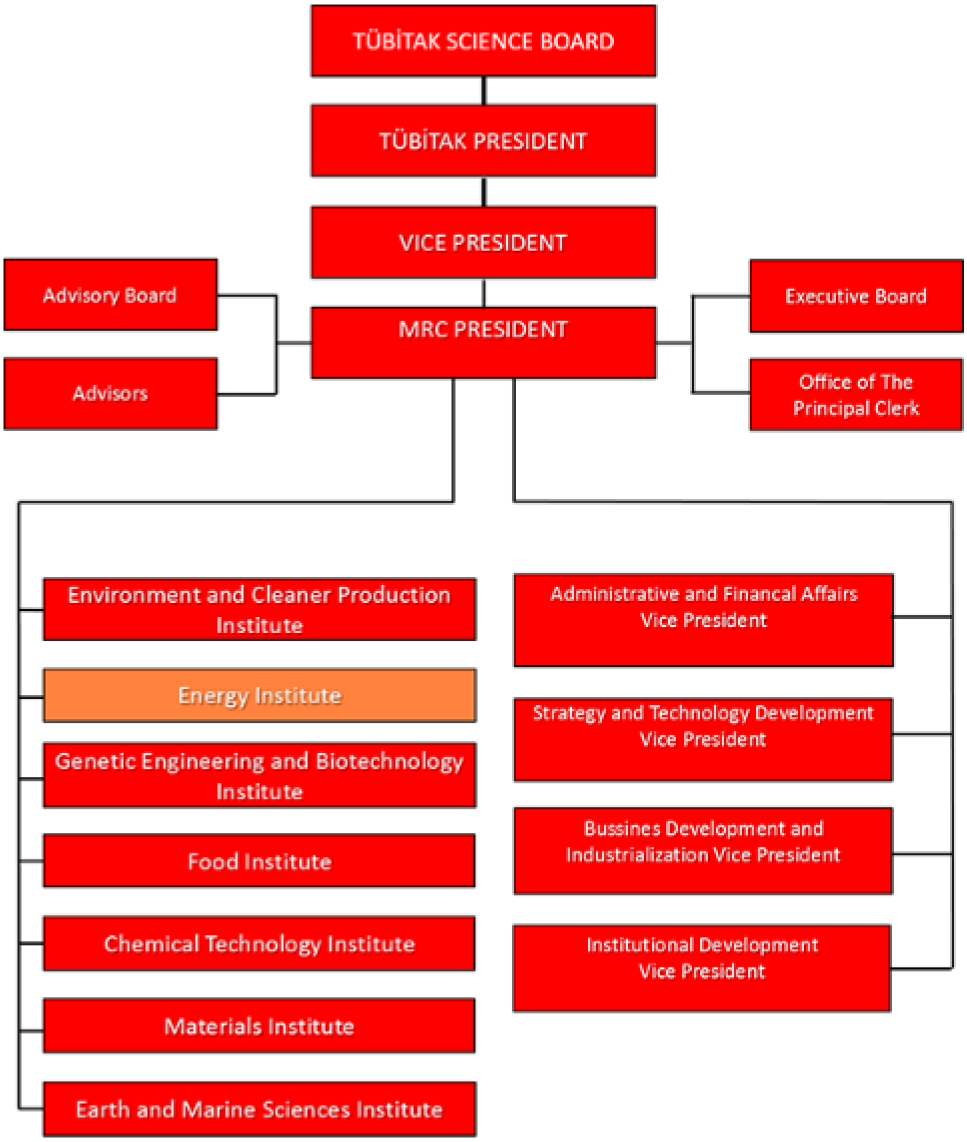

Figure 3: Organisation Chart

Figure 4: Employee Profile

2 Description of the Project

The project I was assigned was about designing a DC-DC converter for a small solar panel which will recharge a power bank battery. It was also aimed to make a controller controlled by a microcontroller to arrange the duty cycle of the converter so that the maximum power point will be achieved. That is, it was aimed to increase the effectiveness and efficiency of the converter.

For this project, first I was given the task of a background research on converter topologies and gate drivers. Some simulation tools like PSim and board design tools like Proteus was introduced and usage of MATLAB and Arduino Sketch was encouraged. Moreover, an introduction to ST was made as well at the beginning since most of the systems in the Energy Institute were designed with ST's microcontrollers for its effectiveness-price relation resulting in it being optimum choice.

Secondly, it was a necessity to learn PCB design. Hence, I made some readings and took video-lectures on the subject and talked about the specific needs for the design of this project. The next step was arranging the components on the board using this knowledge.

Then, it was assigned to me to make another research on the methods for maximum power point control, write a controlling code for this method and test it on the board.

Meanwhile, I had the chance to observe the process of the PCB manufacturing and adding the circuit components on the boards and making necessary changes later on due to some addition or distortions during testing procedure. I could learn and improve my ability to solder and to design a PCB.

Lastly, I could observe all the opportunities in a research center starting with the friendly working environment and relationships between the workers, including listening to the hot topics on the projects and getting advice on my upcoming studies as well.

3 Materials Used

The materials used in this project are shown below: (Figures are obtained from [3], datasheet information is supplied from [5].)

3.1 Solar Panel

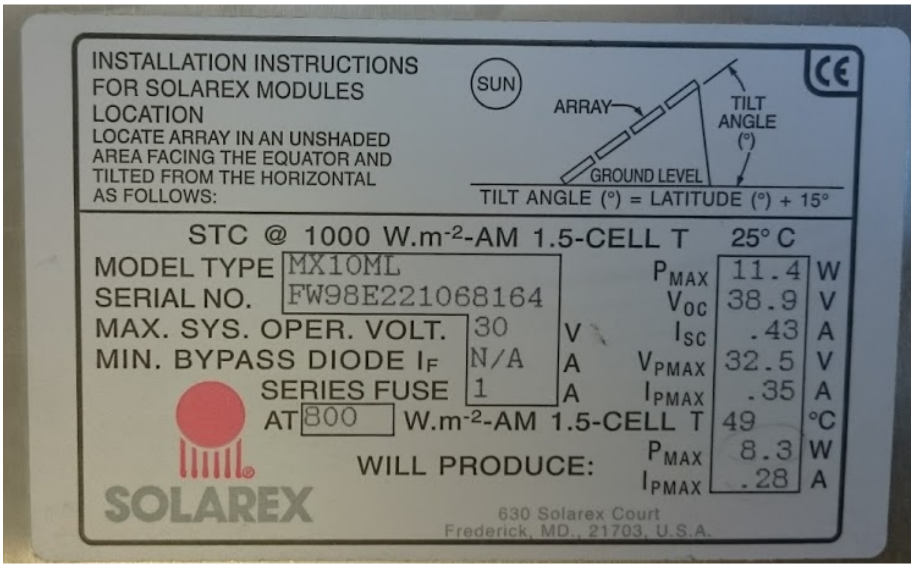

Figure 6: Solar Panel Specifications

The panel used in the project is shown in figure 6. It has the voltage-current and voltage power curve as shown in figure 7 , the plots are drawn in MATLAB using the Solar Panel as will be explained in MATLAB Design Section.

During designing, it is assumed that the panel is not under direct sunlight. Therefore, it is approximated that the receiving side which is modelled as battery collects 9 Watts power.

3.2 TLP250 Gate Driver

TLP250 Gate Driver is used to drive the MOSFET efficiently. The details about gate drivers will be provided in the next section.

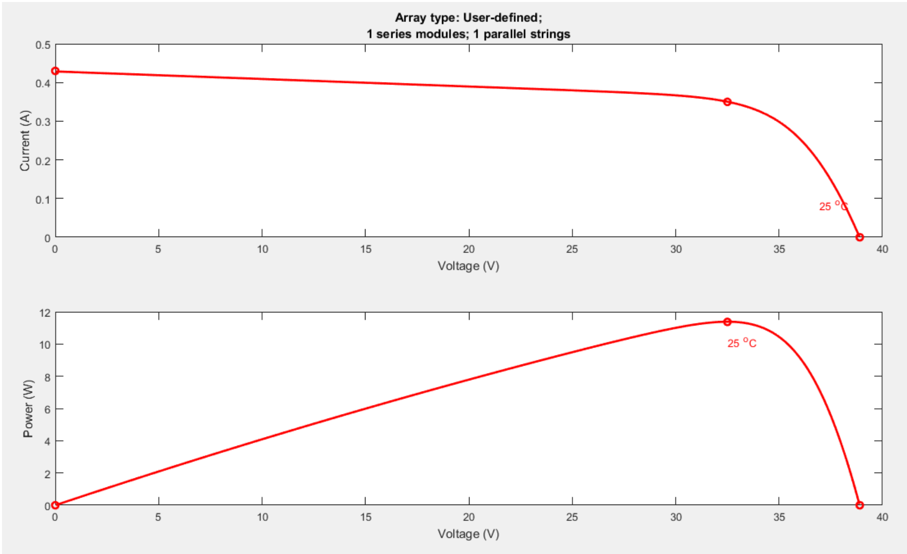

Figure 7: Solar Panel maximum Power Point Characteristics

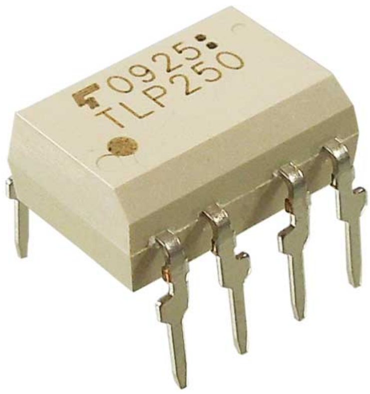

Figure 8: TLP250 Gate Driver

3.3 TMA0515S

Figure 9: TMA 0515S DC-DC Converter

TMA0515S is an electrically isolated DC-DC converter to provide 15 V gate voltage to the MOSFET.

3.4 IRF540N Power MOSFET

IRF540N is used for switching component. It has low on-resistance, high switching performance with advanced processing technologies. It is mostly preferred in industrial applications for its low cost, reliability and efficiency.

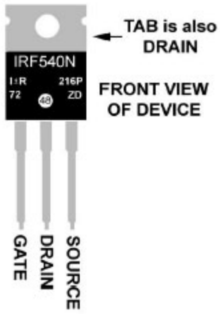

Figure 10: IRF540N Power MOSFET

3.5 MBR20100 Schottky Diode

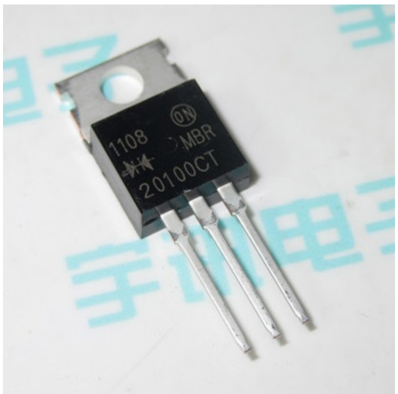

Figure 11: MBR20100 Schottky Diode

This schottky diode is selected due to its low on forward voltage which is shown in 12

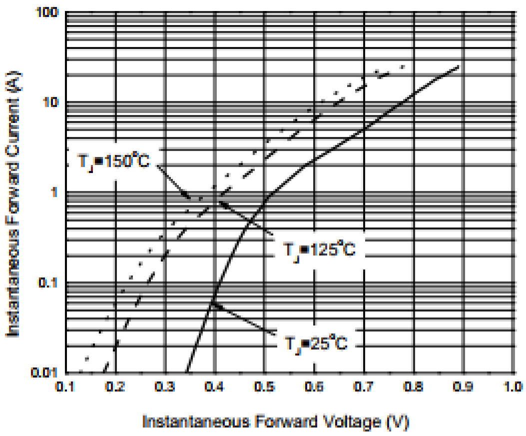

Figure 12: MBR20100 Schottky Diode Forward Voltage Characteristics

3.6 22 μH Handwinded Inductor

This inductor shown in figure 13 is a part of the buck converter and handwinded with the appropriate calculations which are explained distictly in DC-Dc Converters section. In the inductor an E shaped ferrite core is used, the material shown in 13 is ETD 39.

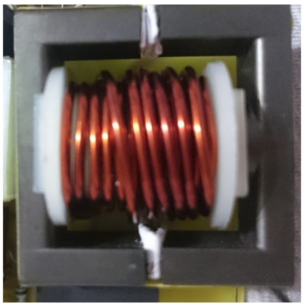

Figure 13: 22 μH Handwinded Inductor

3.7 AD8605ART SMD Opamp

Figure 14: AD8605ART SMD Opamp

AD8605ART SMD (Surface Mounted Device) Opamp in figure 14 is selected for voltage amplification in current reading. Since the value to be read and to be amplified was very small (in mV range), the opamp's offset voltage becomes relatively important at this point. AD8605ART SMD Opamp's offset voltage is 50 μV, not disturbing the measurement.

3.8 SMD 10 $m\Omega$ resistor

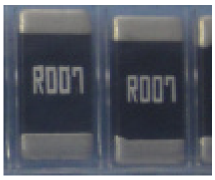

Figure 15: SMD 7 $m\Omega$ resistor

Since 10 $m\Omega$ resistor was not present, 7 $m\Omega$s are used (2 in parallel with another in series with them) for this purpose.

3.9 Atmega32u4 Arduino Leonardo Pro Mini

The Arduino used for the controlling process is shown in 16.

3.10 Other Packaged Components

There are additional components like 100 nF film capacitor as by-pass capacitor at the power entrance (V_{cc}) of the elements. 100 nF film and 100 μF electrolytic capacitors as filter capacitors, 22 μH inductor as filter component at the output of terminal, various resistors, sockets for solar panel and the battery, 7805 Regulator which is discarded afterwards since it caused undesired voltage drop at the output voltage.

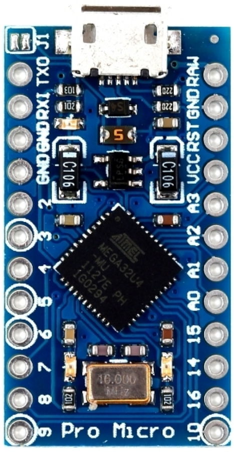

Figure 16: Arduino Leonardo Pro Mini

4 Theoretical Research Conducted During the Project

In this section, the theoretical background gained during the project will be provided. This knowledge is gained through the books, internet research and direct conversation with the engineers.

4.1 DC-DC Converters

In the project a buck converter is used. Before its selection, a detailed reading and simulation is performed to understand its operation well.

DC-DC converters are widely used in many applications covering the regulated dc power supplies and dc motor drives. There are 5 main topologies for these converters which are:

1. Step down (buck) converter
2. Step up (boost) converter
3. Step-down/step-up (buck-boost) converter
4. Cuk Converter
5. Full-bridge converter

Of these converters, only buck and boost are the basic topologies. And in this part, only the buck converter will be explained as it is the converter used in this project.

Buck converter produces a lower voltage at its output. The basic circuit for a buck converter is as shown in figure 17 with its output characteristic and frequency response graphics.

$$V_O = 1/T_s \int_0^{T_s} v_o(t)dt = 1/T_s(\int_0^{t_{on}} V_d dt + \int_{t_{on}}^{T_s} 0dt) = (t_{on}/T_s)V_d = DV \quad (1)$$

Using (1), the average output voltage is calculated in terms of the switching duty ratio.

While the switch is on, the diode is reverse biased and through the inductor the load is energised. When the switch is off, the inductor current flows through the diode and some of the energy on inductor is transferred to the load in this time. In this analysis, the filter capacitor used is assumed to be very large for a constant output voltage eliminating the ripples as much as possible. This is the case in real life applications as well. Moreover, in steady state, the voltage on the capacitor will be constant, meaning that its branch will be open circuit and the load current will be equal to the inductor current.

There are two important operation modes for the converter to be examined. These are continuous conduction mode and discontinuous conduction mode. Two modes are used in different situations. It is important to state that it is harder to control the current in continuous mode.

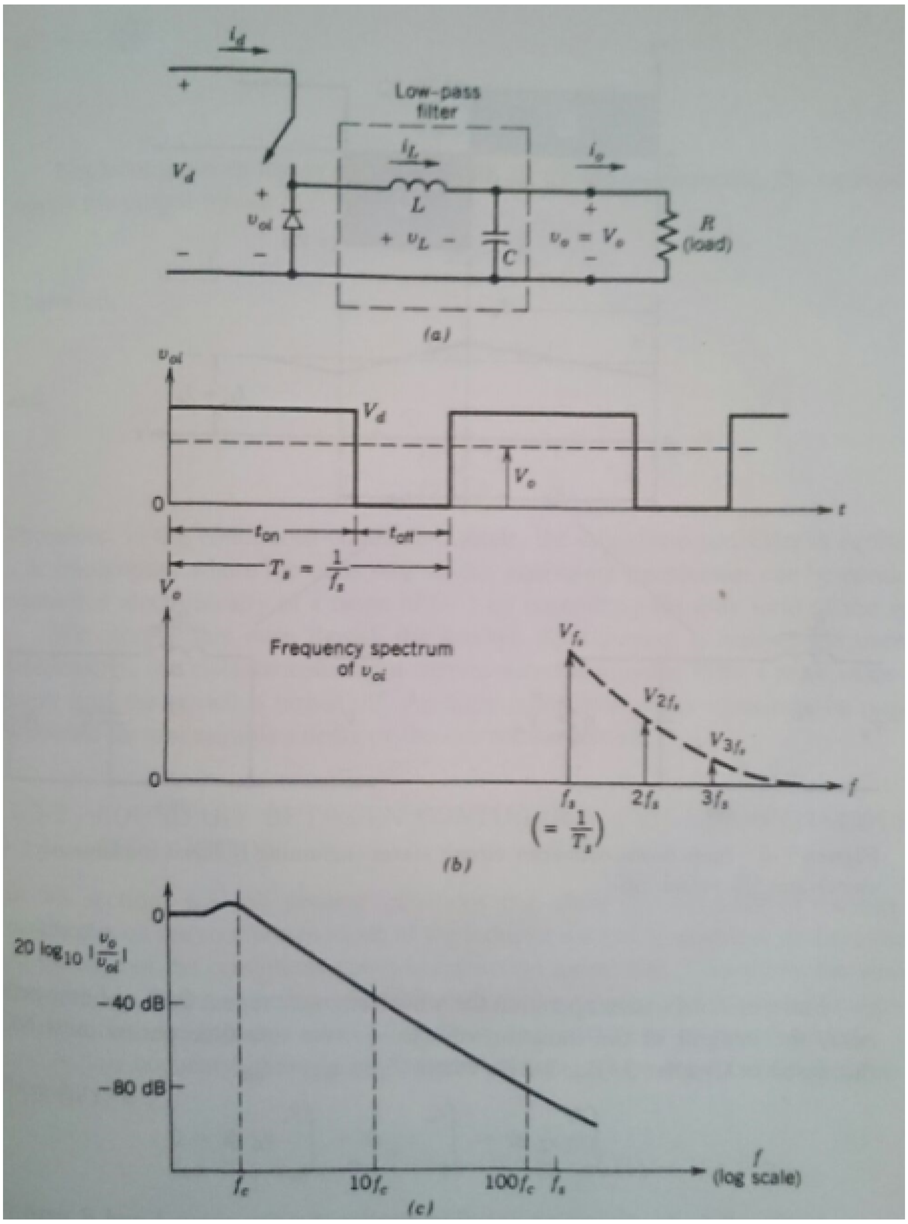

Figure 17: Buck Converter Circuit with Output Characteristic and Frequency Response

I. Continuous Conduction Mode of Operation

[7]

Figure 18 shows the waveforms for the continuous conduction mode of operation. In this mode, as seen in the figure, the inductor current flows continuously. During on time, the diode is reverse biased due to the current flow through the switch to inductor and during off time the inductive stored energy continuous to flow through the diode.

Using the (1), (2) is obtained.

$$V_0/V_d = t_{on}/Ts = D(dutyratio) \tag{2}$$

Therefore, in this mode the operation of the converter is equivalent to a transformer.

II. Boundary Between Continuous and Discontinuous Mode

Calculations for this boundary are made using figure 19 and using the continuation of the current

$$\Delta V = L^{-1}di/dt \tag{3}$$

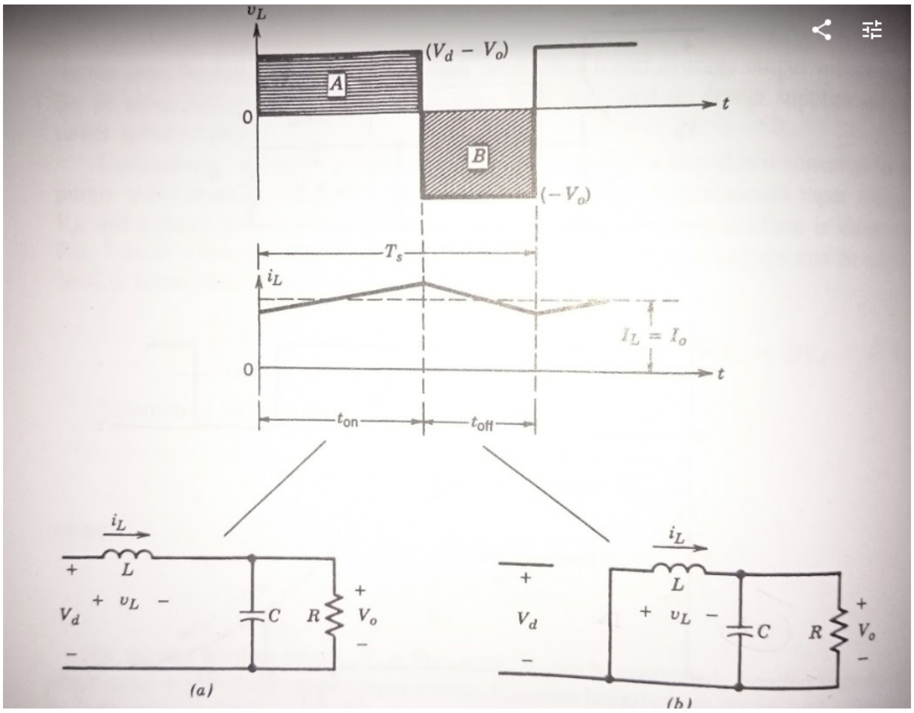

Figure 18: Continuous Conduction Mode of Operation on and off states

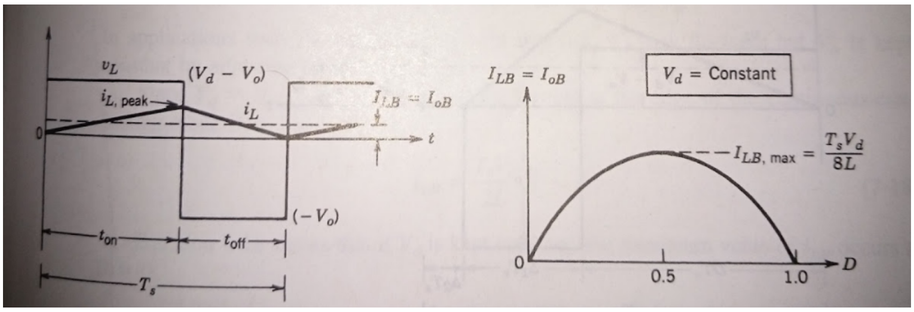

Figure 19: Current at the boundary and Inductor Current with respect to varying D

Using (3) the inductance we need for the operation is calculated. This inductance determines the slope for the falling curve in figure 19.

It is found appropriate that the overall system stays in discontinuous mode of operation for ease of control. For this a lower limit is calculated for the inductor. Assuming that the power received to the output side is 9 Watts and the battery voltage is 3 Volts, the current will be 3 Amps. An average of 3 Amps means that the current makes a peak at 6 Amps. We fix the frequency of the duty cycle to 20kHz. Lower frequencies create noice and larger ones increase the switching power losses. With this frequency we have 50 microseconds period and assuming a duty cycle to be 0.1:

$$\Delta I = L^{-1} * \Delta V * \Delta t \tag{4}$$

$$6A = L^{-1} * 3.4V * 45\mu sec \tag{5}$$

We obtain $L = 25.5\mu H$ from these equations. And we selected L to have $22\mu H$ in the design with approximately 3.44 Amps rms current.

III. Discontinuous Conduction Mode

This mode of operation is the region where we want to stay all the time in this recharging system. The calculations for the variables in this region are much more complicated and as long as we stay in this region, we will not be dealing with them. An increased falling slope in the current results in current reducing down to 0 and in the next cycle increase to the peak value. Since current reduces down to 0, this mode is called discontinuous.

It was stated that the output capacitor is selectively large so that the output voltage ripple is minimised. If we select this value such that at least the corner frequency of the system filter (L-C) meets or smaller than the output frequency $f_c = \frac{1}{2\pi\sqrt{LC}}$ which is the switching frequency 20 kHz. For this we have used 1200 μF electrolytic capacitor.

4.2 Gate Drivers

[8]

A drive circuit is used to switch a power semiconductor continuously. Usually, a power semiconductor spends too much time during that on-off state transition increasing the power loss. Gate driver circuits help to diminish the power dissipated reducing the time spent for the transition.

Drive circuits create the connection between the control circuit and the power MOSFETs and it amplifies the signal coming from the control circuit to the levels to drive the switching circuit. Moreover, they provide electrical isolation in various ways. There are many topologies for gate drivers but mainly they are created by three functional considerations which are output's polarity, isolation and connection. Unipolar output signals are simple whereas bipolars are needed for quick switching characteristics.

In this design, TLP250 Gate driver is used with light emitting diode isolation as illustrated in figure 20.

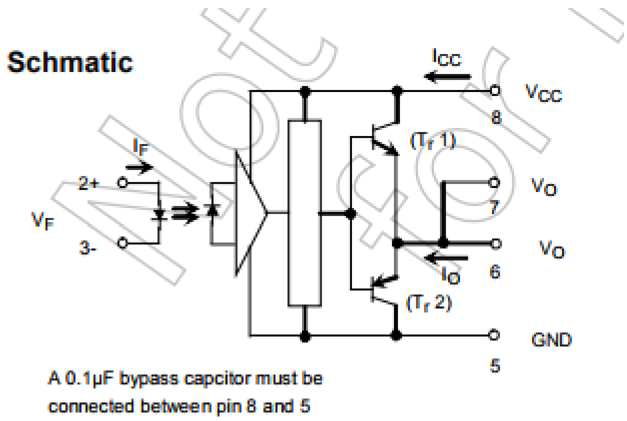

Figure 20: TLP250 Gate Driver

4.3 Inductor Material Choosing

For an inductor, there are different types of materials that can be used like air, ferrite, powdered core, amorph, M5/M18 steel. These materials have different magnetic characteristics and they are used for different ranges of operating frequencies. Air can be used for GHz ranges with linear magnetic characteristics while cast iron is used for DC.

In this project, ferrite core is used for 22 μH hand-winded inductor whose inductance is calculated in the previous section. Ferrite has low power loss in high frequency due to its high resistivity. The power loss associated with the inductor is given with 6. c is a constant depending on the material.

$$P_c = KfB^c \tag{6}$$

4.4 Primitive Design and Simulation

For a first-step design, PSim is used and some components for the real system are changed with their simple equivalent circuit components like solar panel is simply a current source and since the battery voltage will not be increasing rapidly, it is considered as a battery with constant voltage at 3 V. In figure 21, this configuration is shown, only the solar panel side is represented as a constant voltage source as well. This design is selected to show one situation of the system.

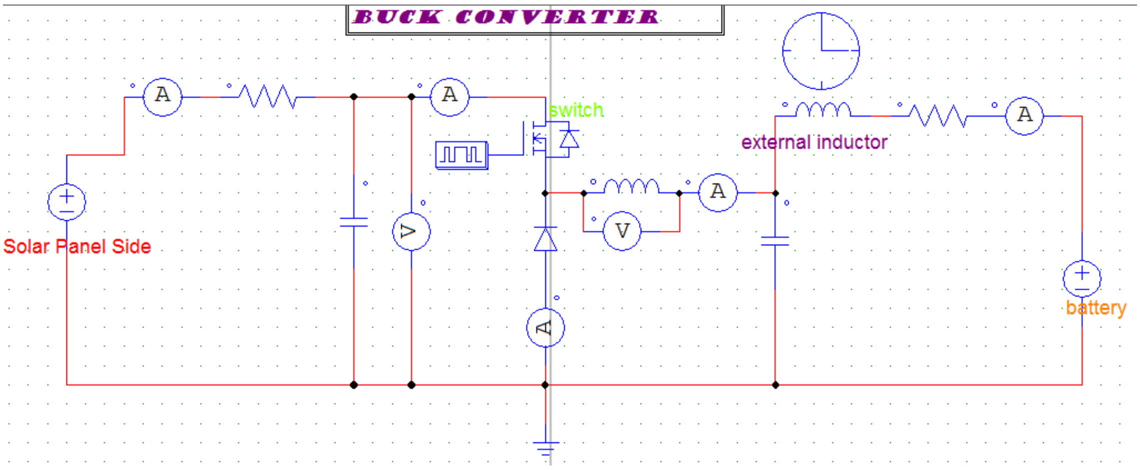

Figure 21: PSim Primitive Design of the System

Figure 22 shows panel's, inductor's and battery's current waveforms after a small time delay of operation with duty cycle 0.11. It is observed that the battery current does not swing too much as desired,it is in the range of 60 mA peak to peak and also the inductor is in discontinuous mode of operation as aimed. It can be said that approximately 0.11 duty cycle, the system is at the edge of continuous and discontinuous mode.

This system can be tested for various duty cycles and voltage values. A better system is simulated in MATLAB-Simulink Environment which is explained in the next section.

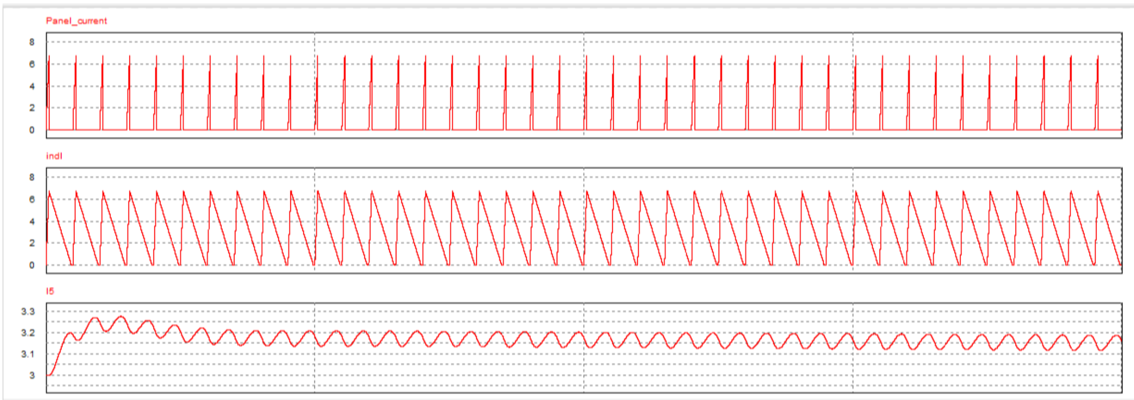

Figure 22: PSim Primitive Design Simulation Results for -from top to bottom- panel, inductor, battery currents

4.5 MATLAB-Simulink Design and Simulation

In Simulink, it is easier to implement a solar panel model and also create the system with electrical models adding a control algorithm with functional blocks. This is what is aimed in this section. For this purpose, a research in published articles on MATLAB Simulation for Solar Model and on Perturb and Observe Method is conducted. Before moving to the simulation model, some information will be given on Perturb and Observe Method.

Maximum Power Point Tracking (MPPT)

In the systems where the power varies, there is a need for a track method to catch the maximum power point for the system to pass the energy in the most efficient manner. These systems include PV solar panels, wind turbines etc.[10]

For a solar panel in our case, the characteristic of the power that the panel can supply change with regard to both the sunlight and the load that it is connected to. The sunlight limits the maximum power that the system can provide during a day time, while the load characteristics determine the power that can be transferred following the I-V curve that is shown in 6. The maximum point is the point which is one of the edges of the rectangular that can be drawn starting from the origin as another edge, gives the maximum area for this rectangular. To change this operating point, the load characteristic is changed such that the impedance that is seen by the solar panel side gives the maximum power point for the whole system. There are different methods for MMPT and many articles published on how to improve these methods.[1] The easiest and widely used one of these methods is Perturb and Observe Method.

Perturb and Observe Method

Widely used in MPPT, this method changes the voltage depending on the power that is read. Figure 23 gives a simple explanation for this method.

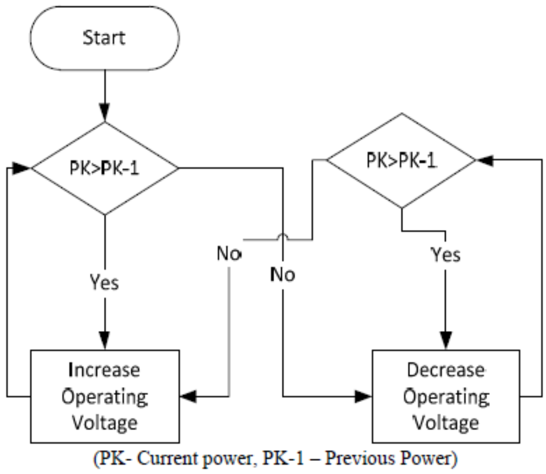

Figure 23: Block Diagram of Perturb and Observe Method
[11]

To change the voltage, the duty cycle of the signal that is controlling the switch is changed. This way, if the duty cycle is increased the voltage of the panel is increased as well. The same procedure applies when the duty cycle is decreased: a decrease in duty cycle results in a decrease in panel voltage. Starting from a small duty cycle, this voltage reading is fed to the controller as a feedback so that if the power corresponding to this voltage is bigger than the power read before, maximum power (P_{max}) is equated to this value until a decrease is detected in the power with increasing voltage following the curve. Due to this method's way looks similar to climbing a hill, it is also called "hill climbing" method. This enhanced description can be seen in figure 24.

Having covered the concept of maximum power point tracking with perturb and observe method, we can continue with the MATLAB design.

With the help of the models that are shown throughout the documents in [1] and [12], a MATLAB Simulink model is constructed. The model is shown in figure 25.

In this model, there is solar panel side on left with the proper current and voltage measurement taken using a demux and the rest of the electrical system on the right. The controller is shown with a rectangular subsystem box with scopes connected to it to see the D and the gate signal driving the MOSFET. Inside the subsystem, it looks like in figure 26, with unit delayed feedbacks and inside the function, there is **??** controlling the system.

The function block applies perturb and observe method. When the model is simulated though, there appears to be a problem with the delay command used in the feedback loop to synchronise with the rest of the system. Therefore, the model is left to be compared with the real model simulations.

4.6 PCB Design

For PCB design, Proteus is used. First, a schematic is drawn and the elements which will be used in the PCB are determined and if they do not have package in the program, their packages are also drawn. In figure 28 the overall system's last schematic is shown with the elements used in the real design.

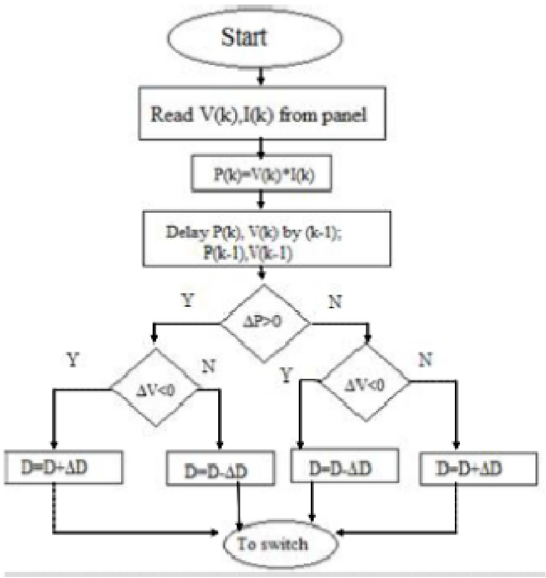

Figure 24: Explicit Diagram of Perturb and Observe Method[1]

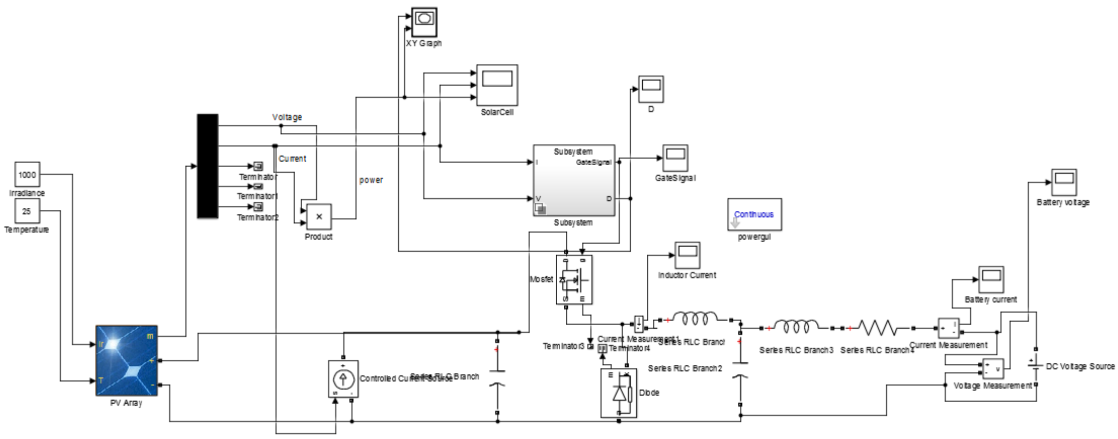

Figure 25: MATLAB Simulink Model of the Overall System

After schematic drawing, for an appropriate PCB design, document [6] was read and online seminar from Scott Nance [9] on the topic was watched.

Gaining valuable knowledge on the topic, I would like to highlight some of the significant points.

(i)During PCB design, it is important to notice that the top view is used while designing. Only when manufacturing, the board is looked at the bottom view.

(ii)Track size changes with respect to the electrical requirements of the design. Bigger tracks have lower DC resistance hence sometimes important for referencing points and bigger tracks are easy to manufacture. As a start it is found appropriate for the signals to have 25 thou, 50 thou for ground and power lines. In my case, 80-100 thou for ground and power lines were selected and the other tracks as large as possible between 30 and 60 thou thickness. Of course, the distance between the tracks are very important and the program shows the possible problems due to close packaging while designing. At least 1 mm distance is left between the tracks.

(iii) Copper used in the high current passing ways create resistance and due to this temperature rising. It is important to taking this to account and keeping the track thickness in the range of the temperature rise we can allow. For this calculation, [13] was used and around 50 thou thickness was used for 10-15 °C temperature rise.

(iv)Pad-hole ratio is also important for them not to cause problems in later times. A general rule of thumb is pad being 1.8 times larger than the hole diameter or at least 0.5 mm larger.

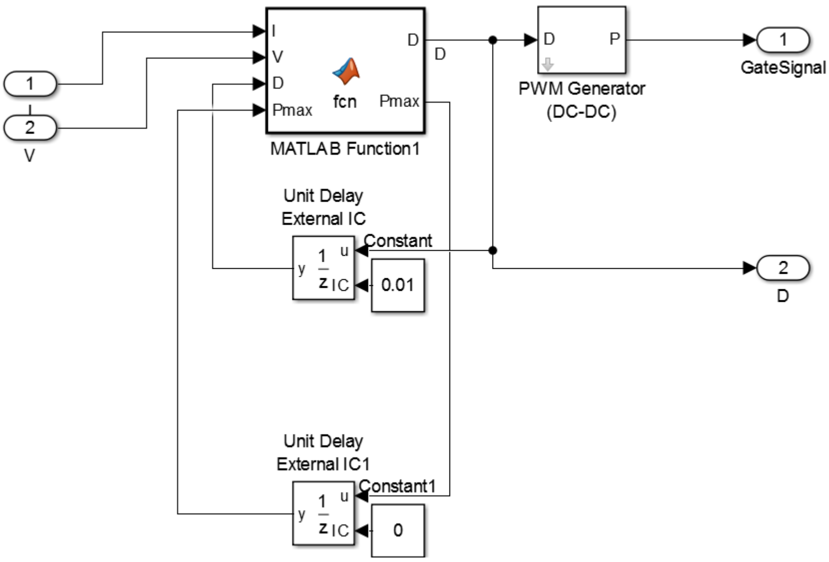

Figure 26: Subsystem for Control Block

```
function [D, Pmax] = fcn(I,V,D,Pmax)
    P=I*V;
    if (D<1) && (D>0)
        if (P>Pmax)
        D=D+0.01;
        Pmax=P;
        end
         if (P<Pmax)
            D=D-0.01;
         end
         if(P==Pmax)
            Pmax=P;
         end
    end
```

Figure 27: Subsystem Function Block

(v)It is important to design the whole system dividing it to subblocks such that digital and analogs do not mix, high frequency and high current does not mix with low frequency-low current sensitive circuits.The DC is what determines the output voltage. Hence, the current carrying DC information must be protected from the AC paths. And symmetry is a vital issue during design for easy an efficient tracking. It is better to keep 45 ° angles and not making right angles contrary to a common belief right angles do not introduce EMI.

(vi)There are different types of designs, from single sided to multilayered ones. Yet, it is easier and less cheap to design and manufacture a single layered board, which in our case as well applies.

After watching the seminar[9], there are few more issues which are important during designing in prefer to prevent some erroneous cases and interferences between circuits.

Design Considerations in Detail

The AC current loops are the most critical connections in any switching layout. Their placement and routing need to be planned first and they need to be routed with short, low inductance paths. This piece of information was introduced to me in the office as well. These paths 29 take the priority over all other paths.

Switch node which is denoted as out in figure 29 should be as short as possible in PCB since this part, with high switching frequency causes EMI radiation which can be denoted as the "antenna" of the converter. Moreover, the difference between the two AC loops, the blue and the purple paths in the

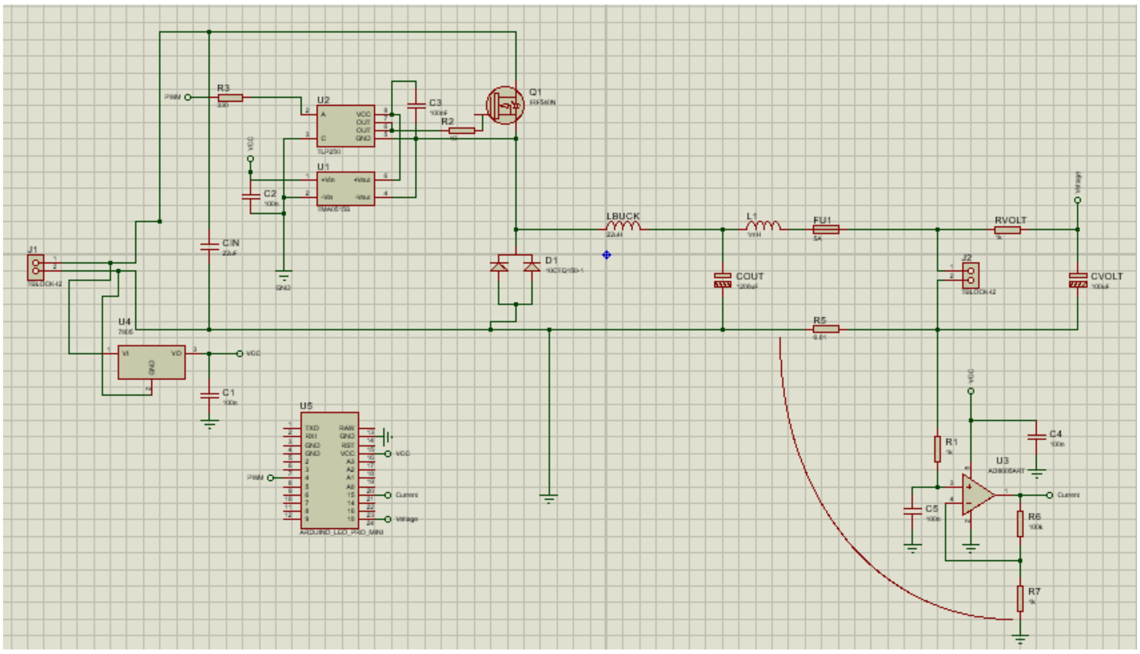

Figure 28: PCB Schematic Overall System Design

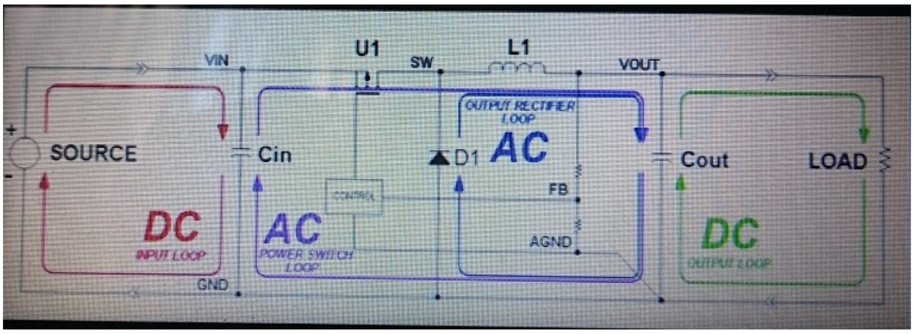

Figure 29: Current paths on buck converter

denoted figure, must also be short introducing a low impedance.

When MOSFET is closed we assume that its current is cut. However, because of the loop which is created due to the connection of the elements, there will be a stray inductance created (1cm of copper introduces 5 nH inductance.) The current that flows in the circuit and the inductor before the MOSFET will flow into the parasitic capacitor across the drain-source of the MOSFET. The current changes abruptly due to switching which will introduce a voltage ripple across the V_{ds} of MOSFET. This is not desired since it will damage the MOSFET.

We know from electromagnetics that, B created within a volume means energy storage. This energy will be stored in this inductance (stray). The more the current flows, the more the B will be present. $B^2V/(2\mu_0)$=LI^2/2 Here B and I are directly related, we can give their ratio a constant. This shows us that the inductance is related with the volume as well. If we can minimise this volume, we can minimise the L and also the energy stored in the loop. For this reason we need to put the components at the leftmost side terminal of the board as close as possible(giving enough space for the heatsinks). For the 2000 μF capacitor we are using electrolytic capacitor which has an inductance in itself due to the aluminium sheets that cylindrical packaging introduces. Not to add this inductance to the already existing loop, we are putting a film capacitor (100 nF) parallel to it across the panel output as close as possible.

Feedback coming from the circuit to the microcontroller on voltage and current reading is subject to noise. They are analog signals and need to be not corrupted by high current carrying paths. These voltage sensing components should not be placed near to where they are sensing but close to the microcontroller so that there will not be high impedance feedback track introducing noise to the signal. Additionally, we are amplifying a very small voltage to get current information which is once more very open to noise and the amplification is with respect to the ground of the negative input terminal of the amplifier not the grounded power terminal. This is very much important since otherwise, the path which will be between the input terminals will be extraordinarily long and this will create a very undesired noise in a very sensitive system.

One other important point is to put the output capacitor at the right place. To form an LC filter as desired at the output, it must be close to the 22 μF filter inductor.

With this information gained through reading, watching and listening from the engineers in TUBITAK, the PCB is designed. Before the manufacture process, it needed to be redesigned a few times additionally. The last version of it is shown in figure ??.

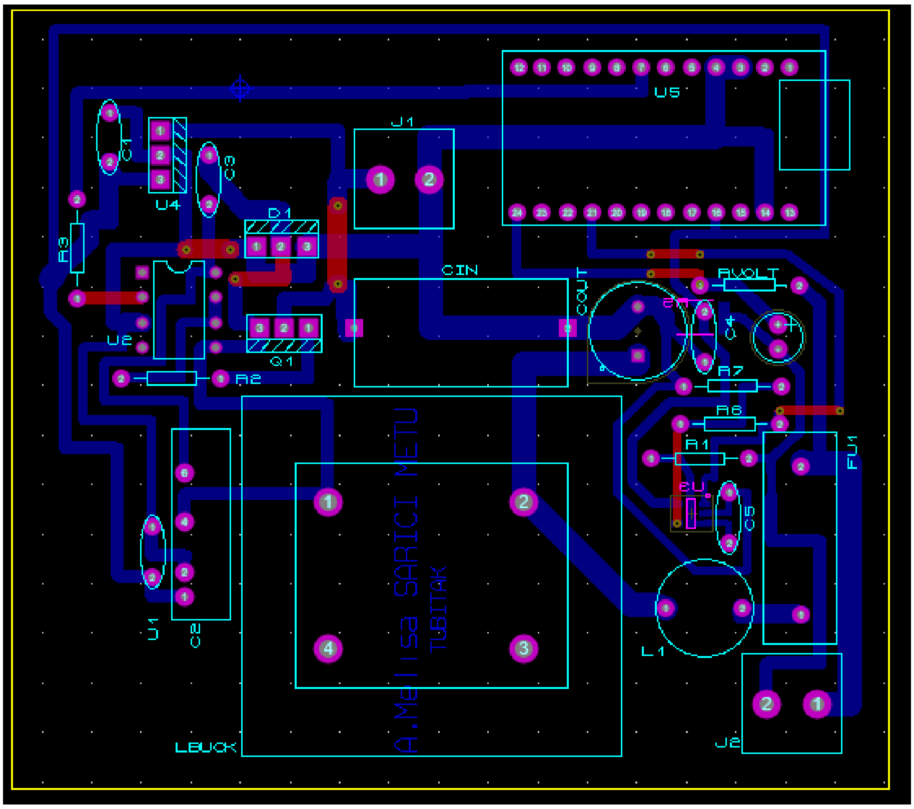

Figure 30: The PCB Layout of the manufactured board

After the design process,the board was printed on a one sided block using special paper, some heat process and after that washing the board with acidic chemicals (HCl and H_2O_2). The block after these steps looks like figure 31. Figure 31 also shows the PCB after the components are soldered.

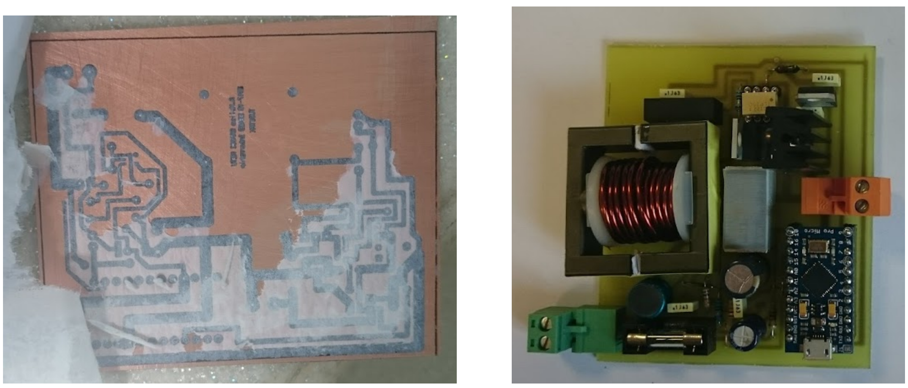

Figure 31: (a)Bare Board(Left) (b)Soldered Board(Right)

4.7 Inductor Winding Number Calculation

For the buck converter itself, we need 22 μH inductor which is the bulky rectangular in 13. Before winding it, we needed to calculate the winding number according to the current it will pass and the core we used. For the core we used ETD39 core with E shaped material having 125 mm^2 effective area.

Having the equations for the Energy Stored in Inductor as in 7 and putting the values(I_p=7 Amps, L=22 μH , $B_p = 0.1T$, Area=125 mm^2)in the equation 7, the gap distance which is denoted as length in the equation is found to be 1 mm. This distance is the total gap distance of the magnetic circuit that the core material creates. That is, single gap distance is 0.5 mm.

The winding area is given as 177 mm^2 and it needs to be multiplied with the fill factor to find the copper area. Fill factor is 0.3 and copper area is found to be 53 mm^2. If $I_{rms} \cong 4.5Amps$ is taken and the current density to be in the range of (2, 3) then the area of a single copper wire is in the range of (1.5, 2) mm^2 . With this rough calculation and using $\frac{CopperArea}{WireArea} = N \cong 17(windingnumber)$

$$E = \frac{L \cdot I^2}{2} = \frac{B_p^2 \cdot length \cdot Area}{2\mu_0 \cdot \mu_r} \tag{7}$$

Yet, the wire that was used in the real inductor had a larger wire area. Therefore, winding 18 times, we needed to measure the inductance using a program showing the angle-impedance relation of a material and according to this arrange the gap length. At the end, the inductance desired is obtained. A picture of the program while testing an element can be seen in the figure 32 .

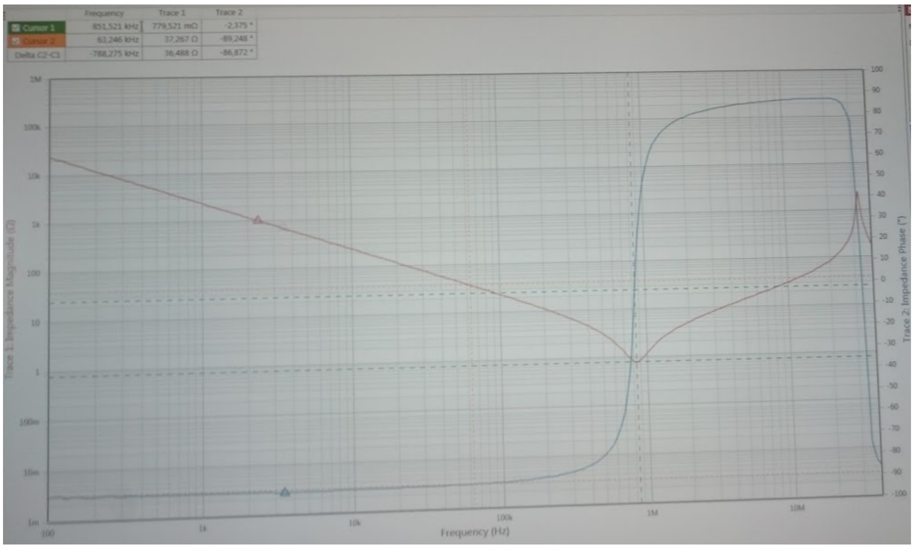

Figure 32: Impedance/Angle Graph

5 ST and Atmega32u4

At first, STMicrocontroller STM32F407 (33) was assigned for control part of the system. ST is mostly preferred due to its effectiveness and it being cheap at the same time creates a significant advantage. Yet, having a more complex system to learn while I had a limited time, it looked better to study with a microcontroller that I had already been familiar with. Therefore, STM32F407 was replaced with Arduino Leonardo Promini which has Atmega32u4 , Atler's microcontroller. For coding Arduino sketch is used and Arduino's own website [2] is used for getting help.

6 Control and Testing

6.1 Code for Control

Using Arduino Sketch, a code for Perturb and Observe Method is written. Before, using Arduino's own PWM structure, a PWM is supplied to the gate with specified duty cycle which gets this duty cycle as a feedback from the controlling part. The PWM Code is given in figure 34.

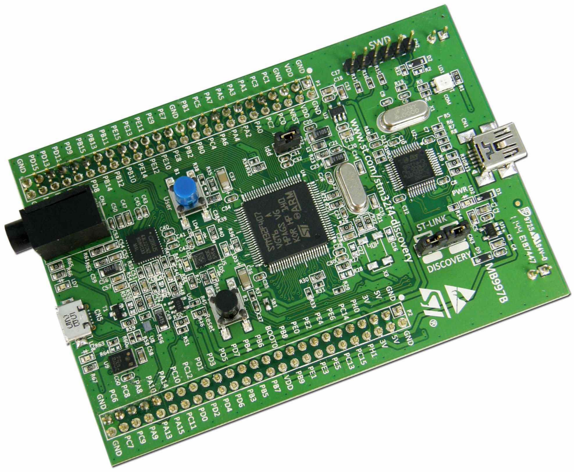

Figure 33: STMicrocontroller STM32F407

The rest of the code consists of the loop function and a function defined as power and called inside the loop function every T milliseconds that is defined at the beginning. This way, it is aimed to take the measurements for voltage and current in a period of T so that the system is has the time enough for settlement. Indeed, the gate frequency is 23 kHz and using 5τ rule. This corresponds to a 5 milliseconds of time. The time arranged in the code provided is more than this to ease the reading of the data that is printed on the port.

The code provided in 35 is for the perturb and observe method that is explained in the previous sections. The lines that are grey belong to an improved code where the power for the last 10 readings is stored and the current power reading is compared with these stored values to prevent an erroneous reading to be evaluated in the maximum data process. However, this part later on was taken out since the duty cycle increase can only be specified in integer values. Due to the fact that duty cycle can not take floating numbers on the contrary to the previous assumption, it was not a necessity to store the previous power data because for integer increase in duty cycle was already causing jumps in the power measurements eliminating the need for this piece of code. However, for the sake of showing the work and time spent on it, it is provided in figure 36 below.

6.2 Testing Results

23 kHz PWM Results

The PWM created using the code can be seen in figure 37.

Maximum Power Point Tracking

For maximum power point tracking, only the voltage and current reading from the battery side is taken since maximum power delivered to the system by the panel side is equivalent to the maximum power received by the battery side. Therefore, without adding extra components for measurements in the panel side, maximum power point tracking is carried out.

The readings are printed on the port, the power seen on the port is multiplied with a constant. The power measured is lower than the calculated one and the voltage measured on the panel side using a multimeter during the operation is approximately 18 V. Looking at the characteristics of the solar panel, this voltage is much smaller than the 25 $\circ C$ characteristic which is 38V. This is due to the environmental issues. That is, the place where the solar panel was placed was not a perfect place for the maximum light circumstances. Moreover, when the light was changed abruptly by obscuring with a piece of paper, the voltage provided by the panel side dropped dramatically to the level near to the battery voltage being unable to charge the battery.

Due to these, the measurements taken were considered on their own, trying different methods to get the system work better. During this time, the output for the maximum power point tracking was observed to be settling at the value of $D \cong (7-8)/255 \cong 0.03$. The result can be seen at figure 38

```
// Frequency modes for TIMER4
#define PWM187k 1   // 187500 Hz
#define PWM94k  2   //  93750 Hz
#define PWM47k  3   //  46875 Hz
#define PWM23k  4   //  23437 Hz
#define PWM12k  5   //  11719 Hz
#define PWM6k   6   //   5859 Hz
#define PWM3k   7   //   2930 Hz

// Direct PWM change variables
#define PWM6        OCR4D
#define PWM13       OCR4A

// Terminal count
#define PWM6_13_MAX OCR4C
```

```
// Configure the PWM clock
// The argument is one of the 7 previously defined modes
void pwm613configure(int mode)
{
// TCCR4A configuration
TCCR4A=0;
// TCCR4B configuration
TCCR4B=mode;
// TCCR4C configuration
TCCR4C=0;
// TCCR4D configuration
TCCR4D=0;
// TCCR4D configuration
TCCR4D=0;
// PLL Configuration
// Use 96MHz / 2 = 48MHz
PLLFRQ=(PLLFRQ&0xCF)|0x30;
// PLLFRQ=(PLLFRQ&0xCF)|0x10; // Will double all frequencies
// Terminal count for Timer 4 PWM
OCR4C=255;
}
```

```
        // Set PWM to D6 (Timer4 D)
        // Argument is PWM between 0 and 255
        void pwmSet6(int value)
        {
        OCR4D=value;   // Set PWM value
        DDRD|=1<<7;    // Set Output Mode D7
        TCCR4C|=0x09;  // Activate channel D
        }


void setup() {
  Serial.begin(9600);
   pwm613configure(PWM23k);

  pinMode(Current,INPUT);
  pinMode(Voltage,INPUT);
  pinMode(reset,INPUT);

}
```

Figure 34: Code for PWM with 23kHz using the internal commands of Arduino

Seeing this duty cycle and not being certain whether the system can not climb over this 7-8 point or not, another code to observe the maximum power point was written to test and find the point where the system is capable of providing the most energy. For this purpose, the code simply gives a ramp input for duty cycle with a period for increment such that the system is settled for sure. The code is provided in39. And the result was in favour of the existent control code meaning that, the system reaches the

```
void loop() {
  int D=power();

  if ((Pmax==0.00)||(D>=128)||(D<0)){
  initialize();
    }

    pwmSet6(D);

}

int power(){
      unsigned long T= 100;
      unsigned long last_t=millis();
      int call=0;
     if((last_t-start)>=T){
        start=last_t;
        I=analogRead(Current)*4.56/1023;
        V=analogRead(Voltage)*4.56/1023;
        A=I*V*1000;
        Serial.print("Power: ");
        Serial.print(A);
        Serial.print("      Battery Voltage: ");
        Serial.print(V);
        Serial.print("      Battery Current: ");
        Serial.println(I);

// Pnow=(int)A;

 //Pav= Compare_and_Store(Pnow,1);
      // if ((Pnow<=Pav*1.6)&&(Pnow>=Pnow*0.4)){
        if ((V<4.30)&&(I<0.55)){
               if ((D>=0)&&(D<128)){

                 if (A>=Pmax){
                   D=D+Increment_value;
                   Pmax=A;
                   Serial.println(D);
                   Serial.println("++++++ D is incremented ++++++");

               }
                 else {
                   D=D-Increment_value;
                   Pmax=A;
                   Serial.println(D);
                   Serial.println("----- D is decremented ------");
                   }
               }
         }
               //}
//        else {
//
//        call= Compare_and_Store(Pnow,0);
//        if (D==125) D=0;
//
//                    }

          Serial.print("Maximum Power of the system is ");
          Serial.println(Pmax);
          Serial.println(D);

          return D;

       }
}
```

Figure 35: Code for the Control Algorithm

maximum power at the $D = [7, 8]$ band for the duty cycle being swept from 0 to 255. (Later on, knowing that the system gets out of the discontinuous mode of operation for larger duty cycles, upper limit for D is declined to 121.)

Overall, the system worked well and the battery has been recharged.

Solar Panel and Battery Output

For testing, a 2.75 V power bank is used for charging. After using the code written in 6.1, the battery was charged up to 3.6 V successfully. These can be seen in figure 37(b).

```
//int Compare_and_Store (int Pnow, int validity){
//if (P[7]==0){
//  for (int m=0;m<=7;m=m+1){
//            P[m]=Pnow;
//        }
//  }
//  if (validity == 1){
//        Ptot=Pnow;
//        for (i=7;i>0;i=i-1){
//            Plost=P[7];
//            P[i]=P[i-1];
//            Ptot=P[i]+Ptot;
//            Serial.println(P[i]);
//        }
//            P[0]=Pnow;
//            Pav = Ptot >> 3;
//            Serial.println(P[0]);
//            Serial.println(Pav);
//            return Pav;
//    }
//        else if ((validity == 0)){
//          int k;
//          for (k=0;k<7;k=k+1){
//            P[k]=P[k+1];
//            }
//                 P[7]=Plost;
//                 Serial.println("%%%%%%%%%%%%%%%%%%");
//                 return 1;
//          }
//}
```

Figure 36: Additional but discarded code for improving

6.3 Results

In this project, it was aimed to build a charging system using solar energy. Using a buck converter design and simulation tools, a general circuitry is achieved and maximum power point was approximated at 1.11 duty cycle assuming that the solar panel operates under direct sunlight, at noon. Using these approximations and having the printed board at hand, the testing is operated. However, the testing was done inside the building, placing the solar panel in front of the window behind the glass and the sunlight was not coming directly but solar panel was operating with the brightness of the day and the light that was distributed in the sky. Hence, it was not expected from the system to give the calculated value for duty cycle but a much lower value, since there was not enough light.

As expected, duty cycle stabilised at 0.03 point with confirmed method (two different methods to confirm that it was the right point but a system fault.) Since the light was not sufficient, the voltage at the panel terminals were much lower than expected (16 V) during operation and was very vulnerable to light changes. This was another expectation.

With the system operating at this maximum power point in an environment described as above, the battery was recharged successfully. This system can be tested under direct sunlight to see that it will operate as expected under that condition as well. Since the microcontroller used was burnt and the ones to replace them had no USB connections (Using PL2303 which is a USB-TTL Converter, connecting the ProMini to Arduino was tried but without a success due to the component not being the original and hence requiring an outside reset system with a capacitor.) and due to the limited time, this was not accomplished.

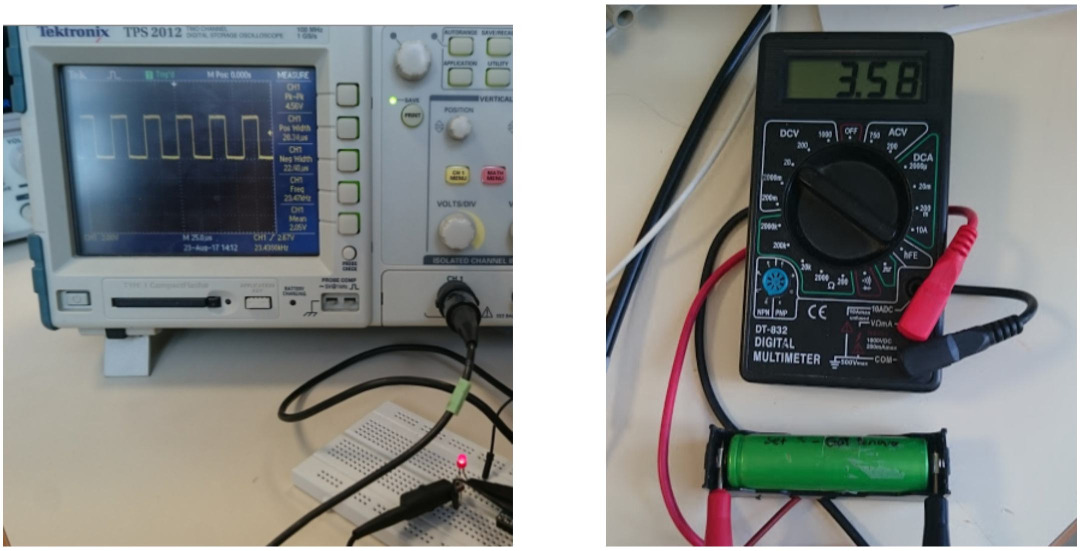

Figure 37: (a)PWM Output of Arduino(Left). (b)The battery charged(Right).

```
778

7
-------------------------------- D is decremented ----------------------------------
Maximum Power of the system is 735.85
Power: 816.62      Battery Voltage: 3.66      Battery Current: 0.22
750
831
734
815
717
815
735
816

776

8
++++++++++++++++++++++++++++++++ D is incremented +++++++++++++++++++++++++++++++++
Maximum Power of the system is 816.62
Power: 734.96      Battery Voltage: 3.66      Battery Current: 0.20
831
734
815
717
815
735
816
734

774

7
-------------------------------- D is decremented ----------------------------------
Maximum Power of the system is 734.96
```

Figure 38: Result of the MPPT with a constant duty cycle around 0.03

```
void loop() {
        if ((V<4.30)&&(I<0.55)&&(D<=120)){

                 pwmSet6(D);

                I=analogRead(Current)*4.56/1023;
                V=analogRead(Voltage)*4.56/1023;
                P=I*V*1000;
                if (P>=Pmax){
                  Pmax=P; Dmax=D;
                }


                D=D+1;
                delay(20);


        }
        if(D==121){
        Serial.println();
        Serial.println("Max Power Point: ");
        Serial.println(Pmax);
        Serial.print(Dmax);
        D=255;

      }
}
```

Figure 39: Code for reassuring whether the system outputs appropriately

7 Conclusion

In this summer internship, I have gained a very useful knowledge on power electronics and made a valuable practice. Having gained experience in soldering, PCB design rules, different simulation and design tools like PSim, Proteus, Arduino and MATLAB, basic control algorithms in solar systems (i.e. Maximum Power Point Tracking),I could revise and use the theoretical knowledge I had gained through the second and third year in the department mainly on Circuit Theory and Electromechanical Energy Conversion I - II. I have learned more about controlling with Arduino and programming.

During this summer practice, I could get help from very successful and insightful engineers who were glad to help me learning during all the process. Having faced some problems, I believe I have observed and learned how to think more practically, more like an engineer and work through the systems first with assuming then validating. I have had the chance to exercise on debugging as well. I could reach many resources to study, practice and learn. Furthermore, I have been able to ask and learn on power electronics area which is the specialisation field I am considering to choose the next year. Engineers who supervised me gave me great insight on the field clearing the doubts in my head and also giving me some advice on the practical things like the contents of some of the lectures that I am about to take and the ones that would be helpful to create a strong engineering background for myself.

In addition to the practical details, I believe considering the friendly environment and the extraordinary catering services is a must. People in my internship were very kind and helpful. The working environment is not only friendly but also comfortable and pleasant with the newly roasted and grounded coffee smell filling the entire room at noon and people having fun with powerball and chatting in the late afternoon, at the end of the day.

Believing that it was a very fulfilling internship for me and considering to continue it exceeding the official day requirement, I can definitely recommend TUBITAK-MAM-Energy Institute to a new intern.

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