EE 344
Electronic Design Lab
Final Report

15$^{\text{th}}$ April 2021

Solar-powered Street Light: Battery Management System

Project Objectives

We come up with a working design for a solar-powered street light equipped with an efficient battery management system, which has undervoltage and overvoltage protection capabilities. We also design a circuit to measure the State of Charge of the battery and display it, along with an estimate of the time remaining.

Group 12

Adway Girish 180070002
Saksham Gupta 180070049
Samar Jain 180010052

Faculty mentor: Prof. Joseph John

1 Block Diagram

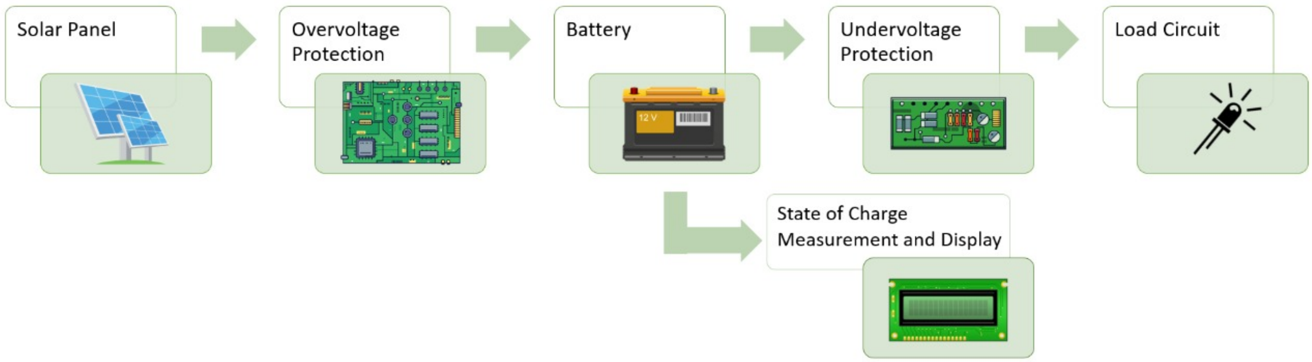

Figure 1: Block diagram

2 Design Approach

This project has four major subsystems, which are given below. We first describe the goal of each part, then explain how it is implemented.

1. Overvoltage protection : While charging the battery, we want to make sure that it does not overcharge - i.e. the voltage across it does not exceed 14.7 V - this is the maximum voltage that can be applied across the battery without damaging it in cycle use [2, Pg. 22], and to ensure that we get the fastest charging possible, we set the limit at this value and not any lower.
   For this, we need a circuit which monitors the voltage across the battery and disconnects the circuit if this voltage crosses 14.7 V. This is done by using an LM317 as an adjustable voltage regulator to generate 14.7 V. Along with the battery voltage, these are given as the inputs to an LM324 single supply opamp as a comparator to energize a relay which disconnects the battery from the solar panel when the voltage exceeds 14.7 V, and gives it the voltage regulator output instead.

2. Undervoltage protection : We must also prevent our battery voltage from falling below 10.5 V - the cutoff voltage for a discharge current of 0.42 A [1, Pg. 2] (the LED load is of 5 W and the battery voltage is 12 V, so the current is $\frac{5\,\mathrm{W}}{12\,\mathrm{V}} \approx 0.42\,\mathrm{A}$).
   To achieve this, we again make use of an LM324 as a comparator. The reference voltage here is generated using a Zener diode of appropriate breakdown voltage, which is one input of the comparator. The other input is the battery voltage (scaled appropriately using a voltage divider) such that the comparator energizes a relay which disconnects the LED load from the battery when the voltage drops below 10.5 V.

3. Load control circuit : We want the LED load to turn on once it gets sufficiently dark.
   This is done by using a light-dependent resistor (LDR) to control the base voltage of a transistor which is used as a switch with the LED at the collector.

4. State of Charge measurement : We also want a mechanism to view the State of Charge (SoC) of the battery, which we will display on an LCD screen interfaced using a Pt-51 microcontroller. To measure the SoC we make use of the open circuit voltage method, which

requires that we first disconnect the load from the battery for a while (around 5 minutes), then measure the open circuit voltage; a linear interpolation between 0% at 10.5 V and 100% at 12.6 V will give us the SoC as a percentage. We also use this to estimate the time remaining using a linear interpolation - the time left at full charge is nearly 20 hours [1, Pg. 2] at this value of discharge current (0.42 A).

We use a 555 timer in monostable multivibrator mode to disconnect the LED load for 5 minutes (again using the same relay as the one used to) and power the Pt-51 and an Analog to Digital Converter (ADC), which converts the analog battery voltage to a digital input that is fed to the microcontroller for calculation of SoC.

3 Details of Subsystems

Here we provide the circuit diagrams of each subsystem, explaining in detail the components used and relevant calculations.

3.1 Overvoltage protection

The aim of this part of the circuit is to ensure that the charging voltage across the battery remains at most 14.7 V - which is the maximum allowed charging voltage without damaging the battery. Any lower value of voltage would simply be inefficient and would take longer to charge the battery.

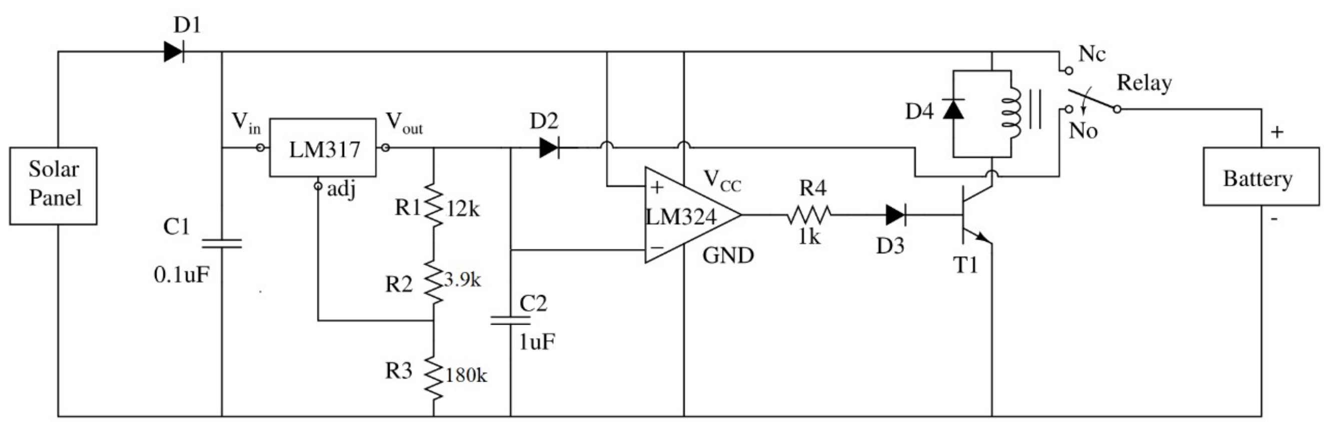

Figure 2: Overvoltage protection

Diodes D_1 and D_2 ensure that the battery does not discharge towards the solar panel. Since we want to compare with 14.7 V, we first generate a 14.7 V reference using an LM317 adjustable voltage regulator, which has 3 pins. Since the output of the LM317 then passes through a diode which will add a further voltage drop of 0.7 V, we design the LM317 to produce an output of $14.7\,\text{V} + 0.7\,\text{V} = 15.4\,\text{V}$. The internal circuitry of the LM317 is such that the voltage difference between pin 2 (output) and pin 1 (adjust) is 1.25 V [3]. The current output from pin 1 is of the order of microamperes and can be neglected. Hence we have the voltage at pin 2 (which we want as 15.4 V) given by

$$\begin{aligned} V_{\text{out}} &= 1.25\,\text{V}\left(1 + \frac{R_3}{R_1 + R_2}\right) \\ \implies 15.4\,\text{V} &= 1.25\,\text{V}\left(1 + \frac{R_3}{R_1 + R_2}\right) \\ \implies \frac{R_3}{R_1 + R_2} &= \frac{15.4}{1.25} - 1 = 11.32 \approx \frac{180}{12 + 3.9} \end{aligned}$$

Hence we choose $R_3 = 180\,\text{k}\Omega$, $R_2 = 3.9\,\text{k}\Omega$ and $R_1 = 12\,\text{k}\Omega$.

The relay is initially in the normally closed (NC) state, in which the battery is fed directly from the solar panel. The voltage regulator output is given as the inverting input to the LM324, and the output from the solar panel is given as the non-inverting input. Hence, if the voltage directly from the solar panel exceeds 14.7 V, the comparator produces a high output, which energizes the relay through the transistor. The diode and resistor are to protect the transistor from high or reverse base currents. When the relay is energized, it switches from the (NC) state to the normally open (NO) state in which the battery is charged by the voltage regulator output (through the diode) which gives it 14.7 V.

3.2 Undervoltage protection

This part of the circuit monitors the battery output voltage and checks that it remains over 10.5 V - the cut-off voltage at the required discharge current of 0.42 A.

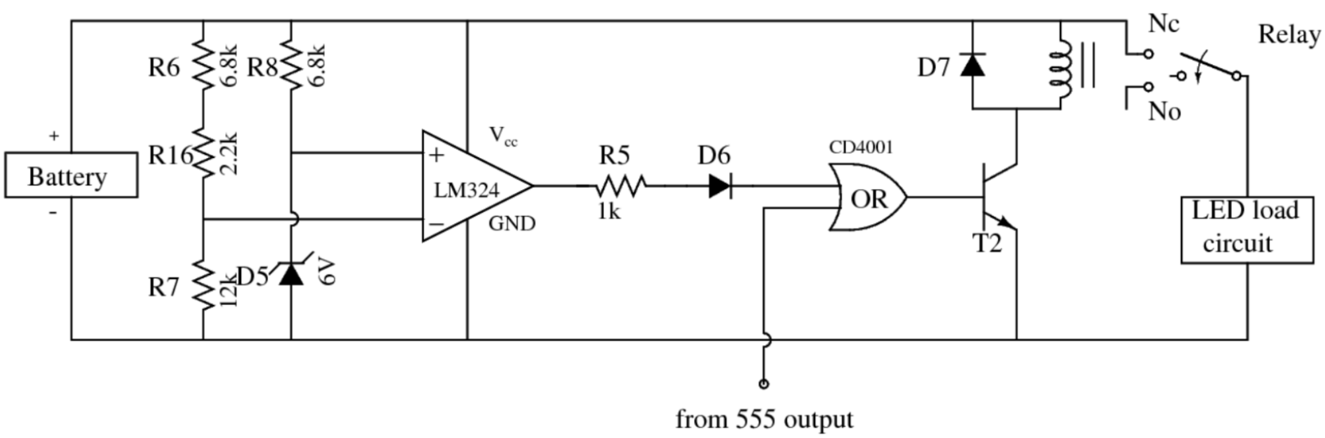

Figure 3: Undervoltage protection circuit

Once again, we make use of LM324 as a comparator. However, this time we use a Zener diode to generate the reference needed, since the LM317 requires a higher input voltage than the output, which makes checking undervoltage difficult. We choose a Zener diode of breakdown voltage 6 V and a voltage divider to scale the battery voltage and get 6 V when it is actually 10.5 V.

$$
\begin{aligned}
V_- &= V_{\text{Battery}} \frac{R_7}{R_7 + R_6 + R_{16}} \\
\implies 6\,\text{V} &= 10.5\,\text{V} \frac{R_7}{R_7 + R_6 + R_{16}} \\
\implies \frac{R_7}{R_7 + R_6 + R_{16}} &= \frac{6}{10.5} \approx \frac{12}{12 + 6.8 + 2.2}
\end{aligned}
$$

Hence we choose $R_7 = 12\,\text{k}\Omega$, $R_6 = 6.8\,\text{k}\Omega$ and $R_{16} = 2.2\,\text{k}\Omega$.

Now the Zener diode voltage is given to the non-inverting input and the (scaled) battery output is given to the inverting input. Hence when the battery output goes below 10.5 V, the comparator output becomes high and the relay is energized (through the OR gate, the other input coming from the SoC circuit) just as in the overvoltage protection case, disconnecting the load circuit from the battery.

3.3 Load circuit

This subsystem serves as a control to the LED load, allowing it to turn on only if it is dark (assuming that the battery has not been disconnected; if it has been disconnected then the LED will not turn on in any case).

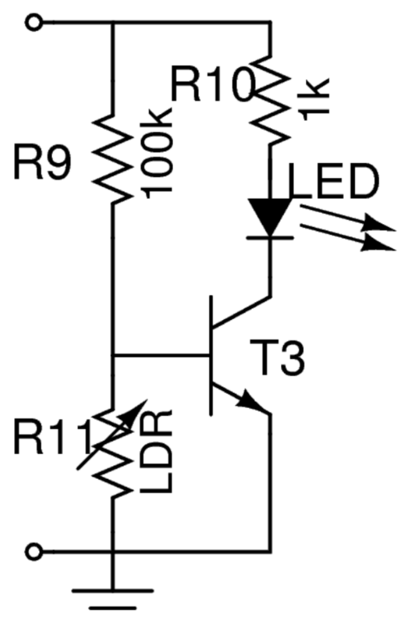

Figure 4: Load circuit

To achieve this, we make use of an LDR - this has a resistance of the order of a few kΩ when lit by ambient light, and a few MΩ in the dark. Hence to obtain a voltage that is high when dark and low when lit, we use a resistance that is in between these orders of magnitude - 100 kΩ - along with the LDR in a simple voltage divider circuit. The output of this serves as the control by providing the base voltage for a transistor with the LED at the collector, which turns on when the voltage divider output is high, i.e. when it is dark, which is exactly what is desired.

3.4 State of Charge measurement and display

We use the open circuit voltage method [6] to measure the SoC of the battery. For this, we require that the load be disconnected from the battery for some time (we do it for 5 minutes), and the open circuit voltage measured then gives us a way to calculate the SoC - we know that at full charge the battery voltage is 12.6 V, and 0% is taken at 10.5 V. A simple linear interpolation between these points will give us the charge for any value of open circuit voltage measured after 5 minutes.

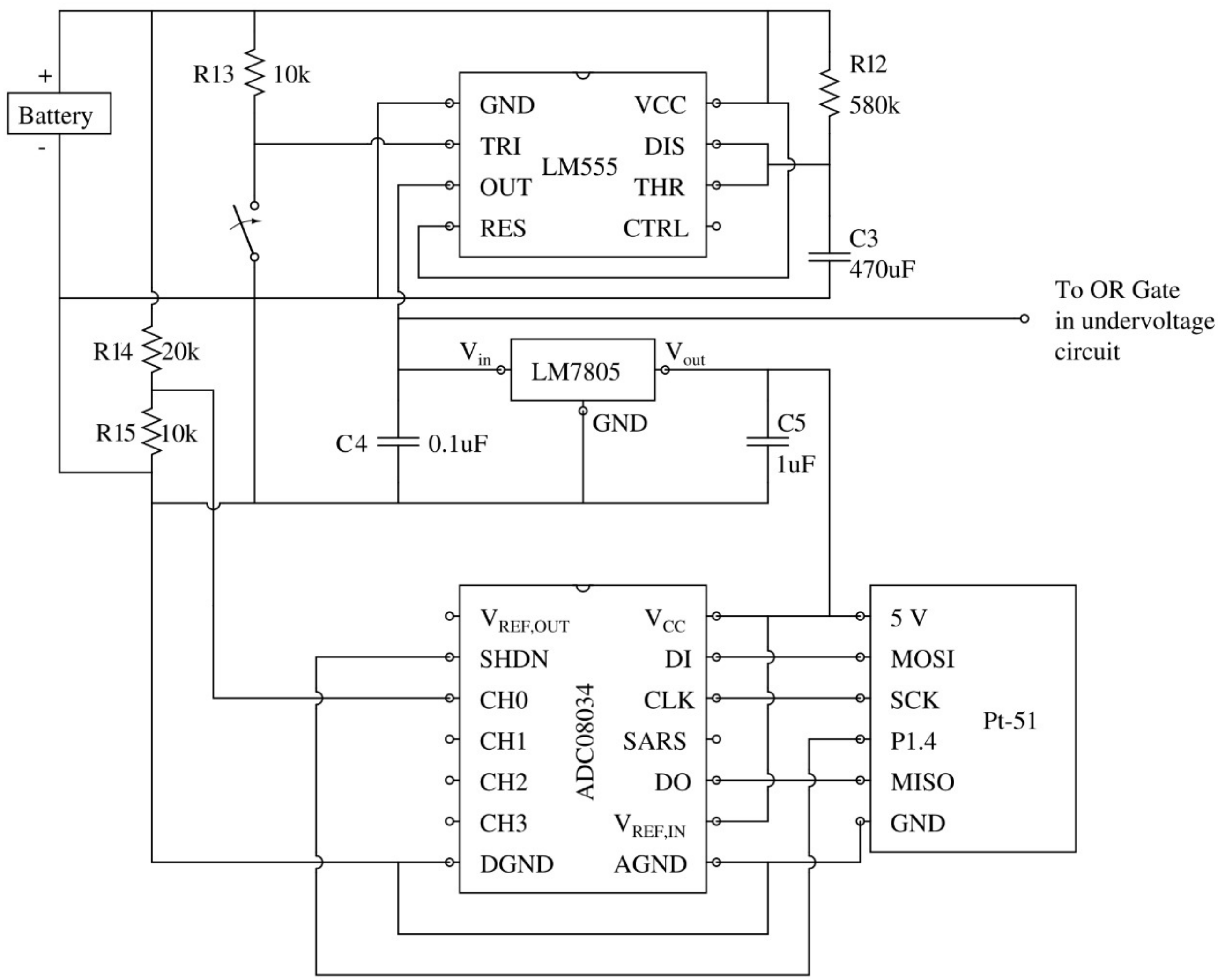

Figure 5: State of Charge measurement circuit

To make the battery disconnect from the load and power the Pt-51 and the ADC needed, we make use of a 555 timer in monostable multivibrator mode [4]. When we want to measure the SoC, we press the switch provided. This activates the monostable multivibrator circuit, and the output becomes high, where it will stay for 5 minutes (thanks to our carefully chosen values), after which it will go back low. The time for which it stays high is given by [4]

$$T = 1.1RC$$
$$\implies 5 \times 60\,\mathrm{s} = 1.1RC \approx 1.1 \times 480\,\mathrm{k\Omega} \times 470\,\mathrm{\mu F}$$

Hence we choose $R = 480\,\mathrm{k\Omega}$ and $C = 470\,\mathrm{\mu F}$.

Since the first thing we must do is disconnect the load, we connect this output to the other terminal of the OR gate in the undervoltage protection circuit. We also use this input to power the 8051 microcontroller and the ADC, ADC08034 [5]. Before we do that, we must first convert the output produced by the 555 (which is of a similar voltage as the battery output) to 5 V, using a 7805 voltage regulator (along with decoupling capacitors), which outputs a constant voltage of 5 V.

This 5 V turns on the microcontroller and the ADC, which are connected so that the digital output generated by the ADC is sent to the 8051, with the ADC reference voltage $V_{\mathrm{REF}} = 5\,\mathrm{V}$. Code is written for the microcontroller to take the input from here and perform calculations needed to obtain the SoC. For that, we require the battery voltage, which is between 10 V to 15 V. To make this manageable for the ADC to deal with, we pass this voltage through a voltage divider consisting of R_{14} and R_{15} which simply divides the voltage by 3. This gives us a voltage between 0 V to 5 V, which is converted into a digital form by the ADC and sent to the 8051. The range corresponding to 0% to 100% charge is 10.5 V to 12.6 V, which is equivalent to an ADC input of 3.5 V to 4.2 V (divided by 3). For an input voltage of V_{IN}, the ADC generates a digital value given by (since it is a 4-bit ADC)

$$V_{\mathrm{DO}} = \frac{256 \times V_{\mathrm{IN}}}{V_{\mathrm{REF}}}$$

V_{DO} is the value fed to the microcontroller, call this value V_{measured}. Hence in our code, we implement the SoC measurement by the formula

$$\begin{aligned} \mathrm{SoC} &= \frac{V_{\mathrm{IN}} - 3.5}{4.2 - 3.5} \times 100\% \\ &= \frac{V_{\mathrm{measured}} \frac{5}{256} - 3.5}{0.7} \times 100\% \end{aligned}$$

We also estimate the time remaining, using the information that at full charge, the time remaining is around 20 hours. Hence the time left is given by another linear interpolation

$$\text{Time remaining} = \frac{\mathrm{SoC}}{100\%} \times 20\,\mathrm{h}$$

This calculation is also done in the 8051, and we display the SoC and the time remaining on an LCD interfaced with the 8051.

4 PCB Design

The PCB designed includes all components except the solar panel, the battery, and the LED load; screw terminals have been provided to connect them to the PCB. The Pt-51 is also not included - pinheads are provided to make the connection to the microcontroller separately.

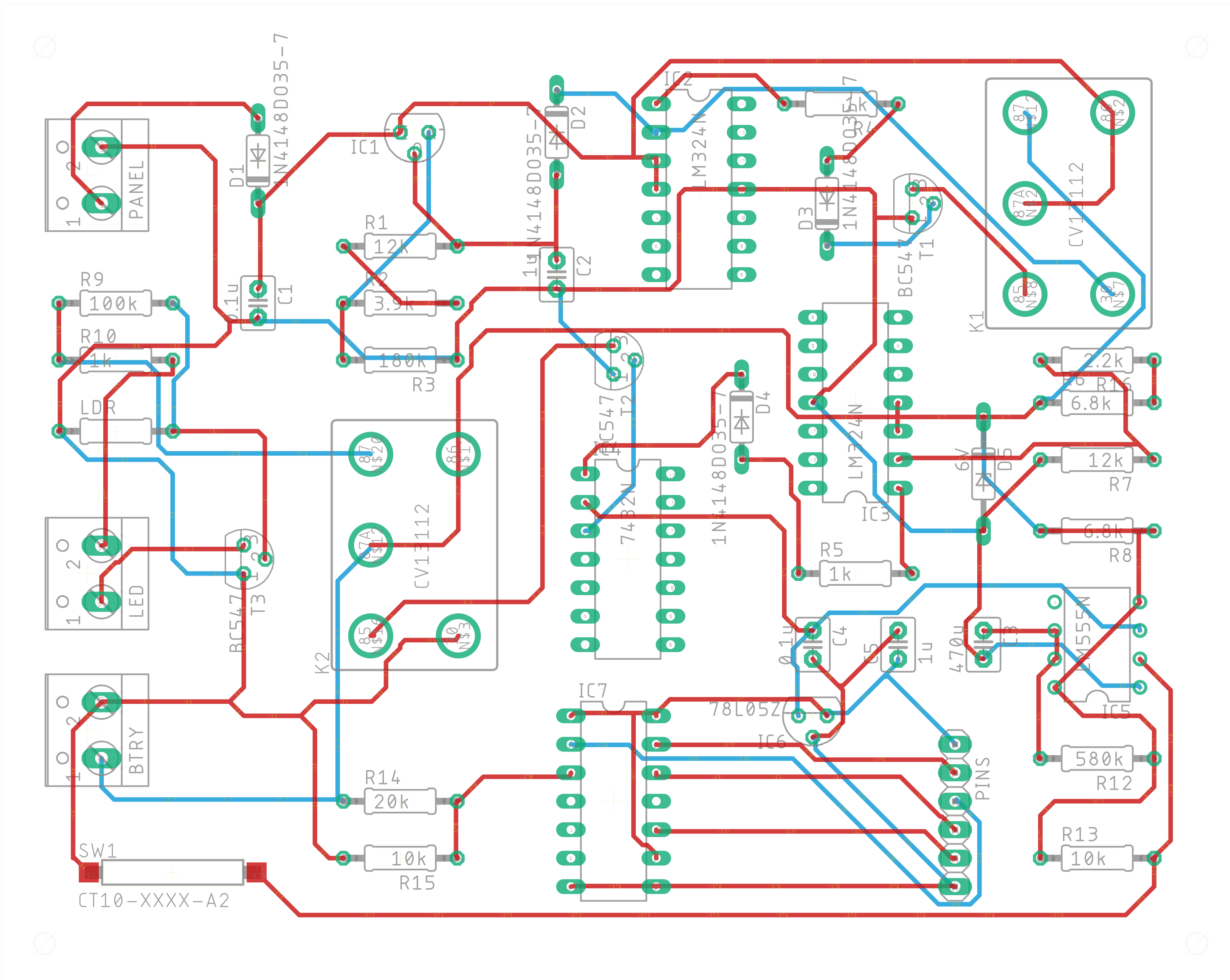

Figure 6: PCB designed

5 Bill of Materials

Qty	Value/Device	Parts	Description	Cost per Qty (in Rs.)
1	ADC08034N	IC7	A/D Converter	350
1	LM317L	IC1	Voltage Regulator	50
1	PINHD-1X6	PINS	Pin header	5
3	W237-102	BTRY, LED, PANEL	WAGO Screw clamp	15
2	0.1u	C1, C4	Capacitor	10
2	1u	C2, C5	Capacitor	10
1	470u	C3	Capacitor	50
1	100k	R9	Resistor	2
2	10k	R13, R15	Resistor	2
2	12k	R1, R7	Resistor	2
1	180k	R3	Resistor	3
3	1k	R4, R5, R10	Resistor	2
1	2.2k	R16	Resistor	2
1	20k	R14	Resistor	2
1	3.9k	R2	Resistor	2
1	580k	R12	Resistor	2
2	6.8k	R6, R8	Resistor	2
4	1N4148	D1, D2, D3, D4	Diode	10
1	6V	D5	6 volt Zener Diode	10
1	7432N	IC4	Quad 2-input OR gate	20
1	78L05Z	IC6	Positive Voltage Regulator	10
3	BC547	T1, T2, T3	NPN Transistor	10
1	CT10-XXXX-A2	SW1	CT10 Series Molded Switch	50
2	CV13112	K1, K2	Micro-280 Relay	150
1	LDR	R11	Light dependent resistor	100
2	LM324N	IC2, IC3	Single supply opamp	100
1	LM555N	IC5	Timer	10
			Total (on PCB) :	1,341
1	Pt-51 kit		8051 Microcontroller	500
1	10W, 18V		Solar panel	500
1	5W		LED load	50
1	12V		UP-PW1245P Battery	1500
1	16x2 with HD44780		LCD screen	100
			Total :	3,991

Table 1: Bill of Materials

References

[1] *UP-PW1245P Battery Datasheet.*
`https://www.omnitron.cz/_dokumenty/2982019204656944/up-pw1245p.pdf`

[2] *Panasonic VRLA Handbook, Industrial Batteries.*

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[3] *LM 317 Datasheet.*
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[4] *555 timer in monostable multivibrator mode.*
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https://datasheetspdf.com/pdf-file/166032/NationalSemiconductor/ADC08034/1

[6] *Open circuit voltage method to measure State of Charge.*
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