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MASTER'S DEGREE THESIS

MPPT Tracking Energy Harvesting System for Solar and Microbial Fuel Cell

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CB: Conduction Band 14
CREF: Sampled reference storage capacitance 18
CSTOR: VSTOR capacitor 19
DSCC: Dye Sensitize Solar Cell 4, 14
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MPP: Maximum power point 19
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OCV: Open Circuit Voltage 4
PEM: Proton Exchange Membrane 10
ROADM: Reconfigurable Optical Add/Drop Multiplexer 8
VBAT: Connection for storage element 19
VBAT_OK: Digital battery good indicator 19
VBAT_OV: User programmed over voltage 19
VBAT_OV_HYST: Internal battery over voltage threshold hysteresis 21
VBAT_UV: User programmed under voltage 19
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VIN(CS): Cold start starting voltage 19
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WSN: Wireless Sensor Network 9

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IV. Abstract

Energy harvesting is no more a new idea, due to over dependency of fossil fuel and its environmental hazards and higher prices engineers across the world are trying to find alternative ways of harvesting power. Due to abundant availability of wind as source and water as source and solar and microbe that produce energy and thermoelectric and vibration etc. Many researches are going on improvement and adaptation of harnessing these environment friendly free energy sources. Though availability of wind flow and water flow varies depending on geographical area but solar energy and microbial fuel energy profuse worldwide.

Motive of the thesis is to design and develop a Printed Circuit Board to harness maximum power available in Dye Sensitize Solar Cell (DSSC) and Microbial Fuel Cell (MFC) and to regulate the maximum available power such a way so that we can charge a high impedance batter or low voltage appliance. Dye sensitize solar cell is a relatively cheap solar cell based on a semiconductor thin film formed between a light sensitized anode and an electrolyte. MFC is based on bio-electrochemically conversion between chemical to electrical energy by interaction of microorganism. The work was done in three phases,

Firstly, selection of perfect IC for energy harvesting, there are more than one ICs available in market. However, for our purpose we have chosen BQ25504 a Texas Instruments IC which comes with maximum power point tracking (MPPT) options. Maximum power point achieved some fraction of Open Circuit Voltage (OCV) connected with harvesting sensors (approximately 80%), which is done using resistor divider with sensor OCV . To verify whether BQ25504 is viable or not we have done some experiments with BQ25504 development board and found quite enough for our harvesting application. As we know both DSSC and MFC output power are fluctuating DC and very low. We must design the circuits with minimum components possible so that we can use least power to run the board and supply more to output. According to ultra-low power requirements we have chosen necessary ICs.
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chosen necessary ICs likes switches, watchdog timer, flipflop, or gate, amplifier etc. The designed harvester board supposed to take two 3 port harvester inputs with each harvester input has 2 anode and common cathode (one harvester input for MFC and another harvester input for DSSC), Now by using switch and watch-dog timer combinations BQ25504 must measure open circuit voltage to find MPPT by using each harvester input's ports (1 anode + cathode) and another port for maintain supply power for itself through charge the VSTOR capacitor (CSTOR) and to maintain required supply power to other components.
The operations mentioned before can be achieved by using watchdog timer, flipflop and switches. Now Watch timer has capabilities of process DONE and WEAK signals, WEAK signal can be fed as input clock to toggled flipflop to process output Q and Q_BAR and then Q can be use as input logic to the switch to simultaneously connect harvester input ports (anodes) with BQ25504. Now it's not possible for harvester to provide proper voltage output always (for example, DSSC is light dependent) so we need to switch among harvesters depending on their output voltage. To do that good output level indicator signal (VBAT_OK) of BQ25504 can be used to switch among harvesters. Finally, the whole operations can be restarted by utilizing VBAT_OK signal of both harvester using or-gate to process a DONE signal and fed it to the watchdog timer.

Secondly, we have designed a primary schematic with minimum component possible so that the board can get supply primarily by charged battery or mimic battery made by lab power supply. Than the board were realized according to our schematic. We soldered all the components and test the board. With some exception the results were expected.

Finally, after gone through all experiments with the first board we find out some ground issue for using MFC and DSSC as input source, hence we modified the design to overcome the possible ground issue and proposed a final Schematic.

V. Acknowledgement

I am grateful to Mr. Prof. Danilo Dimarchi for letting me do my thesis under his supervision. I would like to thank Mr. Alesandro Sanjenario and Mr. Daniyal Ahmed for their guidance and belief in me throughout the work. Moreover, I would like to thank all those people for helping me with testing debugging the electronics boards. Finally, I would like to thank my parents for their endless support.

1 Introduction:

Nature bestowed us with ample amount of energy in different forms, as the Law of Energy Conversion states it's already there and neither created or destroyed rather transform and only transfer one form to another[1]. Contemporary times engineers throughout the world doing lots of experiment and research to tap different form of free energy to convert it in serviceable forms. We have different types of free energy sources likes radio wave, vibration, wind, water as hydraulic, solar, bio-microorganism as source etc. Normally we can use them to convert energy of different form to electricity. However, in this document we will deal with applications regarding solar and bio-microorganism to produce electricity.

1.1 Energy Harvesting

Energy harvesting can be termed as conversion of ambient energy into electrical energy. In other ways it allows electronic devices or appliances to operate under no conventional power source which nullify the need of wires or replacement batteries[2]. Energy harvesting normally uses unorthodox energy sources to the power up electronics. Typically, mini energy sources like piezoelectric sensor, thermoelectric generator, electromagnetic wave captured sensor, bio electrochemical sensor produces measurably small amount of electricity which feed through power circuitry and stored in heavy-duty cells like capacitor, super capacitor, micro energy cell or lithium solid state battery etc. The system usually encompasses with power regulation and protection circuits for storage devices and another circuitry that connected with it.

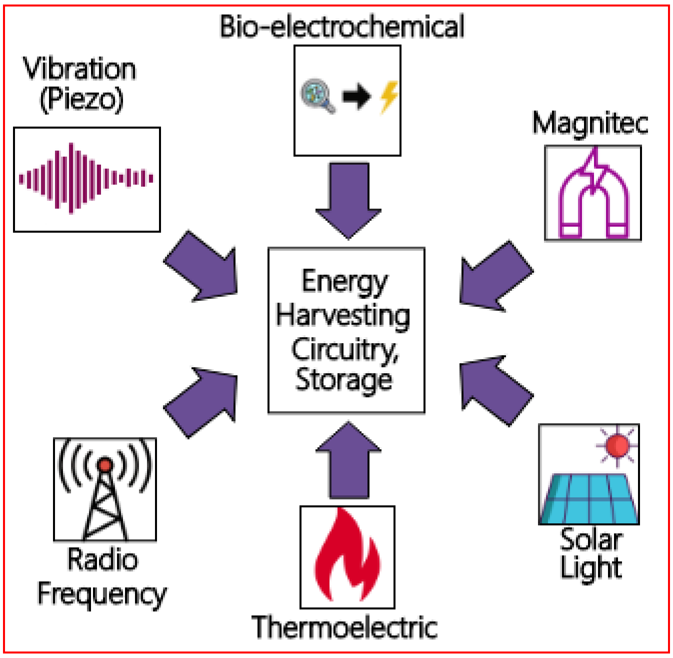

Figure 1: Example of different sources to harvesting energy

The diagram above shows us few of the free sources from which energy harvesting can be achieved. Energy harvester is the electronics or sensors by which harvesting system gets the electricity. All most all micro powered electronics used in houses, offices or factories such as remote sensors and embedded system devices are normally connect with battery. Though contemporarily long-lasting batteries are available still has a limited life span, hence must be replaced over time. However, while replacing hundreds of sensors in distinct locations can be troublesome and costly. Energy harvesting might come handy in situation like this and provide unlimited service in micro powered equipment and nullify the necessity of battery replacement which seems costly, impractical and hazardous. Most harvesting application normally designed to have self-sustainability, relatively cheap and need minimum services. The circuitry normally designed and kept closest to the sensors, as a matter of fact minimum loses can be achieved and the application or device can be feed power autonomously without use of battery[3].

Energy harvesting offers us to monitor and controlling at remote locations in sensitive ecological settings. There are handful applications that can be benefited by energy harvesting, for example remote sensors, remote sensing device, monitoring purpose, asset tracking and personal identification system for access control, security enhancing for remote location, auto lock door and light, equipment monitoring of gas and oil, monitoring forest, monitoring pipeline's valve in irrigation, tiny electronics attached with dresses and gear, smart card, even medical implanted device and more normally contains circuitry without power source.

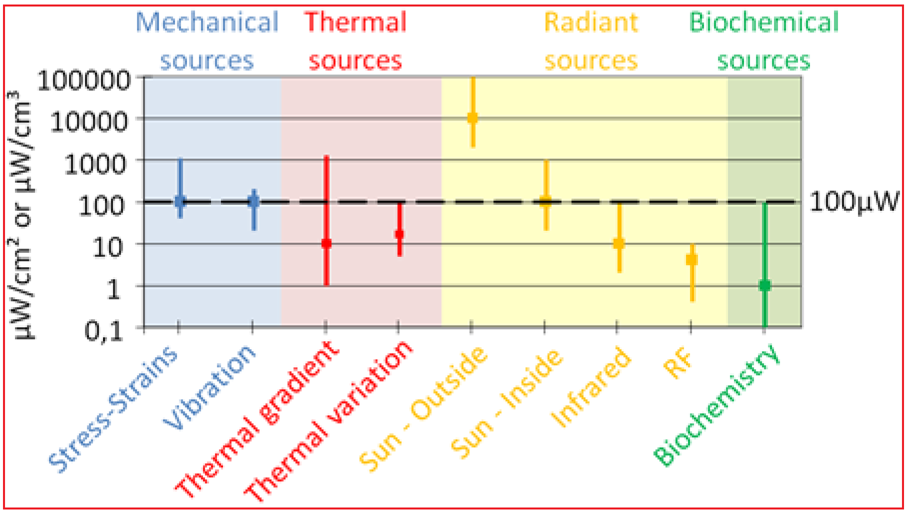

Figure 2: Natural power source density available to transform into electricity[4]

Figure 2 gives us an idea about various types of ambient sources available raw energy power density. Though, it also states that (10 to100) µW of power can be a good order of magnitude for a 1cm² or a 1cm³ energy harvester. However, (10 to 100) µW is not quite good enough, yet for many applications it is ok, Example: WSN[4].

Energy harvesting has much potentiality among us, though it comes with share challenges. Situation occurs when energy resources availability interrupted. For an example, using of solar panel in cloudy weather. Since supply of sources varies, need necessity for converting and regulating sources energy and storage elements.

1.2 Microbial Fuel Cell

The idea behind produce electricity using microbes was proposed in 1911 M.C. Potter. He manage to produce electricity from (Saccharomyces cerevisiae) which is a species of yeast[5]. Later in 1931 Branet Cohen creates first half Microbial Fuel Cell that produce 35 volts with 2 milliamps when arranged in series[6]. After that DelDuca et al. in his research use (Clostridium Butyricum an anaerobic organism) as reactant to anode of hydrogen and air fuel cell but the results were unreliable due to Clostridium Butyricum produce by fermentation of glucose[7]. In 1976 the issue resolved and first successful MFC was designed by Suzuki et al[8][9]. Robin M. Allen and later by H. Peter Bennetto research on understanding operation and principle of MFC makes the topic foremost authority. In 2007 University of Queensland with Foster's Brewing makes a 10L prototype MFC[10].

MFC is a bio-electrochemical system that produce electricity using bacteria by emulating bacterial interactions found in ecology. More precisely, it's an electrochemical cell that convert chemical energy present in organic or inorganic compounds into electricity under anaerobic condition which contained a bioanode and/or a biocathode.

Most cases microbial fuel cell is alike normal battery cell that comprise of membrane to separate anode (responsible of oxidation) and cathode (responsible of reduction). Oxidation reaction is responsible of production and movement of electrons in electrode or redox mediator species and current moved to cathode. The electrode connected by an external circuit while electrolyte solution facilitates to conduct electricity and the voltage difference between anode and cathode force the electron to flow within the circuit hence electrical power produced. The system's charge balance done through ionic movement normally by ionic membrane (PEM). Mostly MFC use organic electron donor which oxidized and produce CO_2, protons and electrons. Some cases other donor can be used. For an example, Sulphur compounds or hydrogen[11]. Cathode reaction utilize by verity of electron acceptors includes oxygen[12][13].

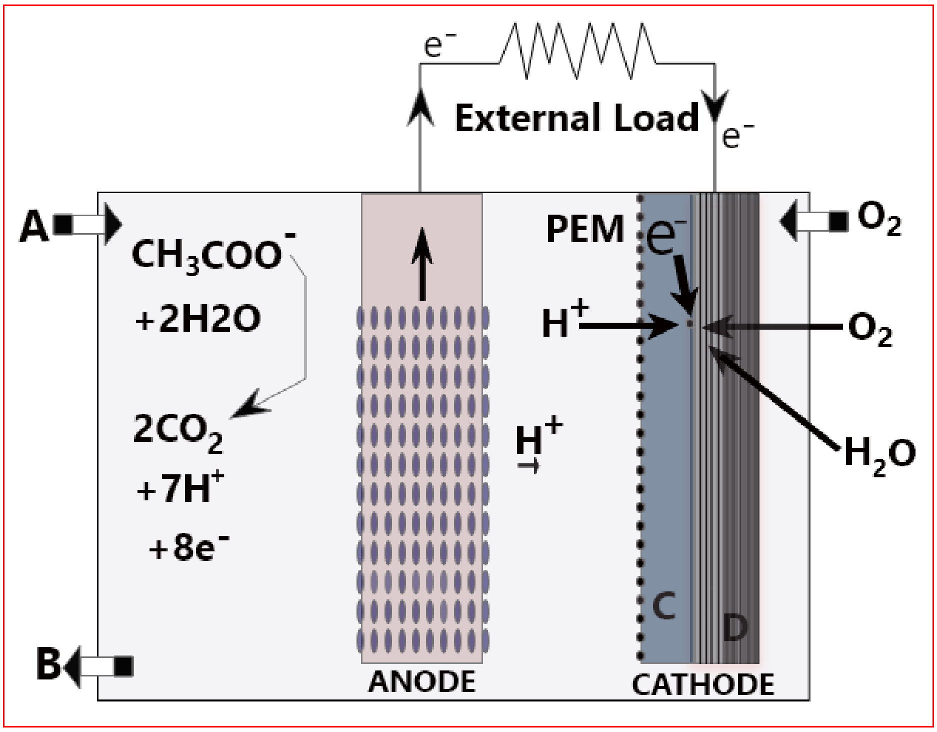

Figure 3: Typical single chamber MFC reactor with external load[14]

Above Figure 3 depicts a typical single chamber microbial fuel cell where anode and cathode placed and separated by proton exchange membrane (PEM) in reactor connected by external load. Where A, B, C and D are entrance, catalyst outlet, catalyst layer and diffusion layer respectively. Conventionally, microbial fuel cell has anode and cathode separated by proton exchange membrane such as Nafion and Poly-tetrafluoroethylene. The bacterial biofilm created at anode behaves as catalyst to occur reaction with organic molecules which transfer electrons and oxygen get reduced to form water at cathode. Organic molecules like acetate and glucose in the reactor above oxidize to produce electrons and electron travels through external circuit. Chemical equations for the oxidation reactions (sodium acetate) at anode and oxygen reduction at cathode occurred in MFC reactor above are given below respectively:

$$CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 7H^+ + 8e^-$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

organic molecules such as acetate and glucose are oxidized to produce electrons, which travel down to an external circuit, hence power produced[14].

Due to some key factors MFC efficiency of output power varies, such as

- Availability of organic matters in MFC reactor.
- Electron transfer rate of bacteria to the anode.
- Proton exchange membrane efficiency for hydrogen ions transfer.

In nature some microorganisms are available who transfer electrons from their oxidative pathways to their external environment whom are known as exoelectrogen. Two major families of bacteria are responsible of showing such abilities: Geobacter and Shewanella. Normally electrons transport to the electrode takes place in three ways. Such as

- Direct electron transfer.
- Electron transfer through mediator.
- Electron transfer through nanorire.

Direct electron transfer: Direct electron transfer can be seen in Shewanella and Geobacter species where electron directly transfer to electrode surface. The outer membrane cytochrome(C-Type) is involved in direct electron transfer produced from nicotinamide adenine dinucleotide (NADH)[14].

Electron transfer through mediators: This phenomenon can be seen in Shewanella and Pseudomonas genera get influenced in presence of chemical species like flavins known as shuttle molecules initiates transfer electron of bacteria outer membrane to electrodes[14].

Electron transfer through nanowires: Geobacter and Shewanella can also use conductive appendages to transfer electron outside the cell. These conductive network act like nanowires which conductivity reported much higher than metallic nanostructure. Forth mechanism can be seen sometimes transporting electron through oxidizing excreted catabolites by the bacteria[14].

Electrode Material Selections is another crucial factor in terms of bacterial adhesion, transfer of electron, electrochemical efficiency hence they impact on output power. Practically implementation purpose it is necessary to use easily available and relatively cheap materials and power density need to be as high as possible, for selection of anode materials carbon-based materials are widely used. For example, carbon paper, carbon felt, carbon fiber and carbon nanowire etc. For cathode materials selection catalytic property for oxygen reduction must be necessary. Generally, there are some criteria need to be taken care of while choosing electrode (precisely, anode and cathode). They are given below:

Surface area and porosity: Microbial fuel cell output power greatly influenced by surface area of electrode. Ohmic losses has directly proportionality with resistance of electrode, to decrease resistance need to be increased effective surface area while keeping the volume same, Surface area give more sites of reaction and electrode kinetics increase but porosity increase as well that decrease electrical conductivity[14].

Electrical Conductivity: Electrical conductivity need to be high so that electron released from microbe pass through anode with less resistance and travel to external circuit. Interfacial impedance needs to be low enough to help electron transfer. In case of cathode ionic conductivity needs to be more to triple phase boundary reactions[14].

Stability and durability: Reduction and oxidization in microbial fuel cell are responsible for swelling and decomposition of materials. Surface roughness increase durability of materials but Decrease long term performance of MFC. Material or electrode need to have durability as well as stability in acidic and basic environment[14].

Cost and accessibility: For commercialization of microbial fuel cell electrode material cost increase total cost of MFC. In shorts, selected material for electrode need to be cheap, sustainable and easily available. For an example, material like platinum are highly expensive, non-durable and non-sustainable. Composite material can be good alternative of expensive metal as electrode. Furthermore, anode needs to be biocompatible so that it enhances bacterial adhesion and usable life time of microbial fuel cell[14].

Different types of anode materials with pros and cons are given the Table 1 below:

Anode Material	Advantage	Disadvantage
Stainless Steel	Highly conductive, relatively cheaper, easily accessible	Low surface area, biocompatibility issues, corrosion
Graphite Rod	Highly conductive, chemically stable, relatively cheaper, easily accessible	Difficult to increase surface area
Graphite fiber brush	High specific area and easy construction	Clogging
Carbon Cloth	Large relative porosity	Relatively expensive
Carbon Paper	Easy wire connection	Fragile

Carbon Felt	Large surface area	High resistance
Reticulated Vitreous Carbon (RVC)	High electrically conductive	Large resistance, fragile

Table 1: Different anode materials used in MFC with their pros and cons[14]

Cathode Material: In microbial fuel cell reactor oxygen get reduced in gas interface, electrolyte and electrode to form water or hydrogen peroxide. It contains of three layers diffusion layer, conduction in support material and catalyst. To do the job perfectly MFC cathode must have following properties:

- Mechanical strength need to be high
- Need to have high catalytic characteristic
- Need to have good electron and ion conductivity

MFC performance reduce when oxygen reduction rate become low at neutral pH and low temperature. For graphite or carbon-based cathode with platinum-based catalyst oxygen reduction rate is inadequate. Catalyst need to be required of increase reduction process by decreasing activation barrier. Platinum can be used as catalyst most successfully due to having good oxygen reduction property due to its big surface area with low potential for cathode made of dual layer carbon/Polydimethylsiloxane packed with platinum. But hydrophobic material like PDMS has less water diffusion capabilities into single chamber MFC, though carbon nanotube (CNT)-Pt composite can increase catalyst activity up to extant. Normally, platinum contained catalyst widely used for MFC cathode, though due to its expensiveness, pH sensitiveness, hazardous property of sulfide and non-feasibility limits for commercial applications. Non-Pt based catalyst can be alternative of them. For example, transition metal-based catalyst like iron phthalocyanine shown rapid electron transfer due to π-π interaction between metal and carbon. Metal macrocyclic compounds such as cobalt tetramethoxyphenylporphyrin (CoTMPP) with ORR catalyst can be used too because of higher coulombic efficiency than platinum. Lead oxide can be used due to higher power density than Pt electrode. Biocathode can be another solution due to higher cost, non-environmentally friendly and complexity in fabrication of conventional catalysts lead to the development of biocathodes where microorganisms themselves act as the catalyst. The biofilm formed over the cathode catalyzes the reduction reaction[14].

1.3 Dye Sensitize Solar Cell

In contemporary time photovoltaics is one of the most promising and expected technology considering solution of future renewable power generation. In fact, in developed and developing countries one can find many solar cell-based power generation sites. Considering environmental hazards and rising cost of fossil fuels one can see it's as the most feasible alternatives. Different types of solar cell are available now a days, among them dye sensitize solar cell (DSSC) can be the most environment friendly candidate of photovoltaic technology because of being fabricated based on screen printing process with non-toxic materials and preferably low cost for clean energy harvesting sources of next generation which was first reported in 1991 by M.Grätzel [15].

DSSC is thin film solar cell where light absorbed by sensitizer attached to the surface of spacious semiconductor and charge get separated at the junction through photo induced electron injected through dye into CB. After that, carrier transferred in the CB of the semiconductor to the charge accumulator. Board absorption band sensitizer appended with crystalline oxide film permits to capture large amount of sunlight. Quantitively, amount of electrical current gets converted by incident photons achieved over a wide spectral range from ultra violet ray to near inferred ray region. One can achieved overall conversion efficiency over 10% using dye sensitize solar cell and can be manufactured with lower cost than conventional alternatives.

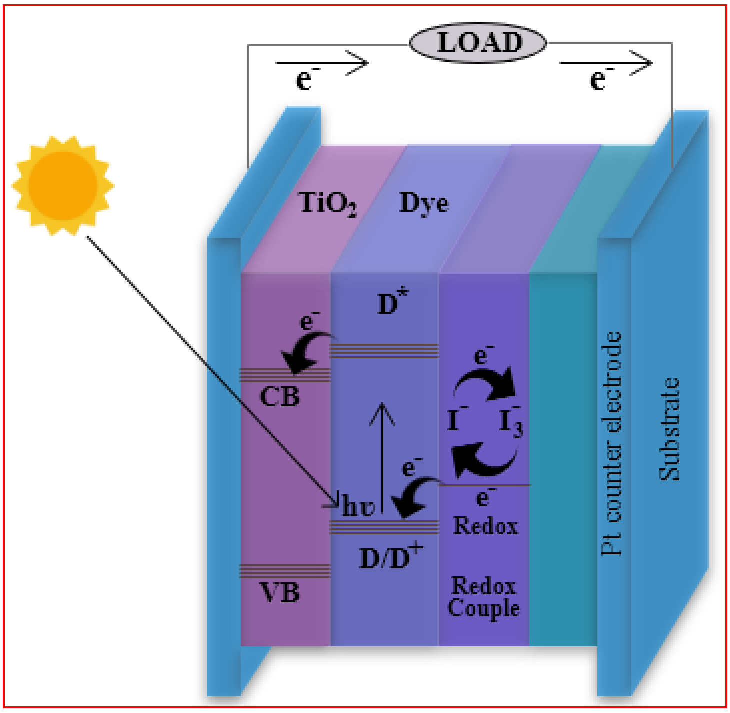

Figure 4: Typical TiO_2 based Dye Sensitize Solar Cell with external load

Working Principal of DSSC:

A schematic diagram of typical dye sensitize solar cell is given above in Figure: 4. The device left to first layer is transparent glass coated with conducting layer (Examples: Florine doped tin oxide $SnO_2: F$). After that, nanocrystalline TiO_2 that gives highly porous structure with large surface area which absorbs UV light region of solar spectrum. Then it immersed in dye solution of $Ru(II)$ polypyridyl complex which increase efficiency of conversion from solar light to current and thin layer of dye covalent bonded formed with another thin TiO_2 layer. After that, another conductive glass plate with thin layer of Pt attached with the structure which act as cathode or counter electrode. The both electrodes jointed one after another through heat with about 50 μm thick molten Surlyn film to keep both electrodes separated and electrolyte poured in the gap between then. At the time of light incidence, the sensitizer absorbed photon and the electron get energized and accelerated (metal-to-ligand charge transfer of sensitizer, MLCT) into CB of nanocrystalline TiO_2 and because of having nanocrystalline and high porosity property of TiO_2 add more dye on titanium oxide surface, as a result boost up its efficiency, same what does by chlorophyll in photo-synthesis of plants in nature. Now oxidized dye get reduced eventually by electron donation from electrolyte (typically I^-/I_3^-). Hence, organic electron passes through semiconductor network and reach at the back contact and accelerate through the external load then finally in counter electrode. While in counter electrode, triiodide get reduced and iodide regenerated which completes whole loop[16].

Main steps that involved in DSSC operations as shown above in Figure 4 are given below:

- Incident photon get absorbed by $Ru(II)$ polypyridyl complex photosensitizers on TiO_2 surface.
- The excited electron injected to CB of TiO_2 electrode which results to oxidation of photosensitizers from ground D to excited state D^*.

$$D + h\upsilon \rightarrow D^*$$
$$D^* \rightarrow D^* + e^-(TiO_2)$$

- Injected electron in the CB of TiO_2 get transported between TiO_2 nanoparticles with diffusion towards back contact, hence electron finally reached at counter electrode through the circuit.
- The oxidized D^* takes e^- to from redox mediator iodine ion I^- and leads to generate ground state D. Furthermore, two I^- ions get oxidized to primary iodine which becomes $I^-$to I_3^-.

$$D^* + e^- \rightarrow D$$

- The oxidized redox mediator I_3^- scatters toward counter electrode and after that get reduced to I^-.

$$I_3^- + 2e^- \rightarrow 3I^-$$

The efficiency of DSSC depends on D, D^*, photosensitizer, fermi level of TiO_2 electrode, redox potential mediator I^-/I_3^-in the electrolyte[16].

1.4 Maximum Power Point Tracking

Maximum power point tracking or MPPT is widely implemented in wind-turbine and photovoltaic-cell (PV) system to extract maximum possible power under all conditions. However, in this document point of view will be mostly regarding photovoltaic cell. How efficiently the power transferred by harvester cell depend on both amount of sun light falls or irradiance on the cell and electrical characteristic of the load that are connected to it. For an example, considering a non-MPPT based conventional charge controller that normally connect PV panel directly to the battery, when it charges the discharge battery what happens it force the module to operate at battery voltage which might not be the right voltage where the module is capable of provide its maximum power to load. Now MPPT plays an important role here in transferring best possible power to supply the loads.

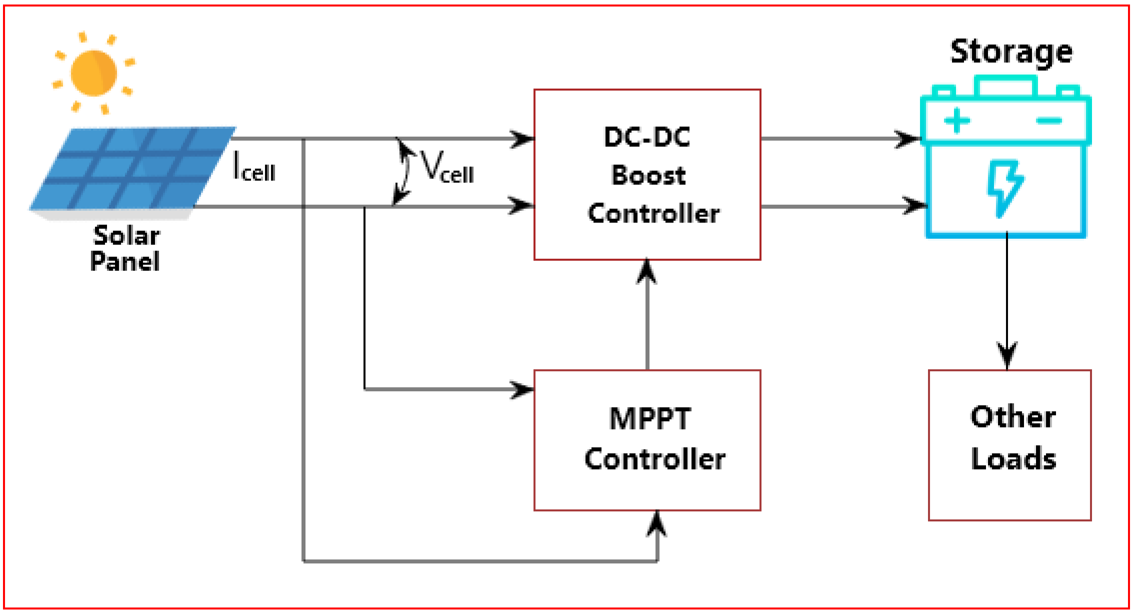

Figure 5: Typical MPPT System block diagram[17]

Now due to variation of sun light which leads to varying impedance, the load characteristic needs to change itself accordingly to get maximum power out from the harvester cell, this arbitrary load characteristic known as maximum power point MPP and the process to find this point where harvester cell can supply its maximum power at given time is called maximum power point tracking. PV cell has a complex I-V characteristic curve. MPPT system sample the PV cell output and induce necessary resistance to obtain maximum power. Normally, MPPT system incorporated with DC-DC power converter to convert current or voltage, regulate and filter to drive diverse loads. A basic block diagram regarding MPPT system are given above. When loads get connected operating point of solar cell will be rarely at its peak power. Now impedance that seen from the solar cell end can be translated to solar cell's the operating point and while changing the impedance this point can be moved towards the peak power point. As the solar cell is DC device and DC-DC converter may utilize for transforming source impedance to load impedance. Which can be achieve by varying duty cycle of DC-DC converter because change of duty cycle can change impedance that seen by the solar cell. In shorts, by changing duty cycle of solar converter we can shift operating point towards maximum power point. However, there are many algorithms able to sample cell current and voltage, then can be tuned the duty cycle. However, to do that microcontrollers are employed to implement these algorithms.

MPPT of BQ25504 DC-DC Boost Converter

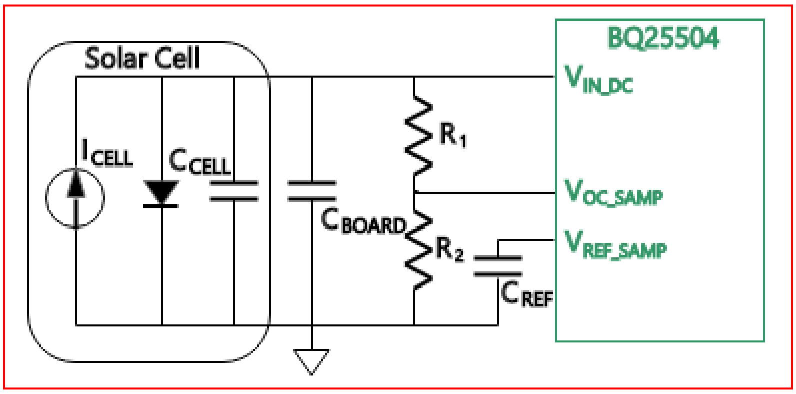

Figure 6: MPPT system of energy harvester BQ25504[18]

BQ25504 utilize open circuit voltage for adjusting of the solar cell power to its maximum power point which is normally fractions of OCV and same for all kinds of solar cell (typically 80%). Appropriate fraction of OCV can be found by utilizing resistors divider R1 and R2 as shown in Figure 6 above. In our board we use 50% MPPT using two 100K resistors. During normal operation, BQ25504 periodically turn off the charger so that panel can return to its OCV, now fractional voltage provides by the resistor's divider is sampled and stored in capacitor CREF which later used as reference voltage to maintain the panel's operating voltage. BQ25504 comes with preset 256 milliseconds of OCV sampling periods which get refreshed in every 16 seconds. This period is adequate for I_cell to charge C_cell and board capacitance C_board to settle the voltage at VIN_DC to the OCV of solar cell because of normally C_cell is small and I_cell is large (typically < 20 µA).

However, some solar cell has large C_cell and small I_cell, in such case 256 milliseconds sampling window isn't enough to settle VIN_DC to solar cell's OCV. Now in this case sampled voltage will be less than the target fraction of OCV sets to achieve by R1 and R2[18].

2 Prototyping

Once search through available option for energy harvester chip we come across many possible options, according to our need we choose BQ25504 which is an ultra-low power-based boost converter energy harvester with input as low as V_{IN} ≥80 millivolts and quiescent current $I_Q <$ 330 nanoamperes and has two stage undervoltage and over voltage protection. Furthermore, selecting other components our key concern was to choose component with minimum power consumption and capability of running under low voltage condition and as harvester output is low and we need to provide enough power to run additional components within the board as a matter of fact selecting minimum component as possible. Later in component section we will see in detail about components.

2.1 Components

The board supposed to take raw power from harvesters and mange itself to provide steady output to the battery or any low power appliance connect with it. The main component for doing such way to have a harvesting capable chip that is BQ25504, but we need some additional components like timer, switches, flipflop, or gate etc. Information regarding different components is given below:

2.1.1 DC-DC Boost charger/converter BQ25504

BQ25504 is 16 pins integrated circuit capable of acquire microwatts to milliwatts range of power from various type of sources like photovoltaic cell, thermal electric generator, bio fuel cell and more on. The design of the BQ25504 begins with a DC-DC boost charger or converter. That charger operating power requirement is merely microwatts to start its operation. The boost converter gets started at VIN less than 330 mV and when get started, it can maintain supplying energy up to as low as VIN of around 80 mV.

The bq25504 also implements a programmable maximum power point tracking sampling network to optimize power to supply the device. It sample the VIN_DC open circuit voltage which programmed by external resistors in addition to an external capacitor CREF. The available sources by which harvester chip extract source energy most often provide sporadic or time-varying DC voltage which troublesome in many ways. As a matter of fact, our system must need some sort of storage elements to maintain steady supply to the chip, for example conational capacitor or super capacitor or rechargeable battery must be added to ensure constant supply of power as far as possible when needed for the system and to avoids any unnecessary peak current from input source. It also provides protections or damage of storage element by monitoring maximum voltage and minimum voltages against the user defined under-voltage VBAT_UV and over-voltage VBAT_OV levels. It is also capable of toggling battery health signal to tell the microcontroller whether the voltage on an energy storage battery or capacitor has dropped below a previously set critical level. The VBAT_OV and battery health indicated voltage VBAT_OK thresholds can be programmed unconditionally. When CSTOR voltage goes above VSTOR_CHGEN (1.8V typical) main boost converter get started. When VSTOR and VBAT is less than 100mV, the cold start circuit must need to reach at least 330 mV or VIN(CS) to charge VSTOR by 1.8V. VIN_DC OCV are sampled by utilizing external resistors to control MPPT of harvester raw output which can be connected using additional external capacitor with VREF_SAMP pin. For example, todays solar cells has capability of operate at MPP of about 80% of their OCV, which are normally implemented by using resistor divider up to 80% of the available VIN_DC voltage and the network will maintain VIN_DC to be operate close to sampled voltage available at VOC_SAMP. Alternatively, more complex MPPT algorithm can be implemented by applying reference voltage to VREF_SAMP by using microcontroller unit externally. The figure below represents a typical application circuit with BQ25504.

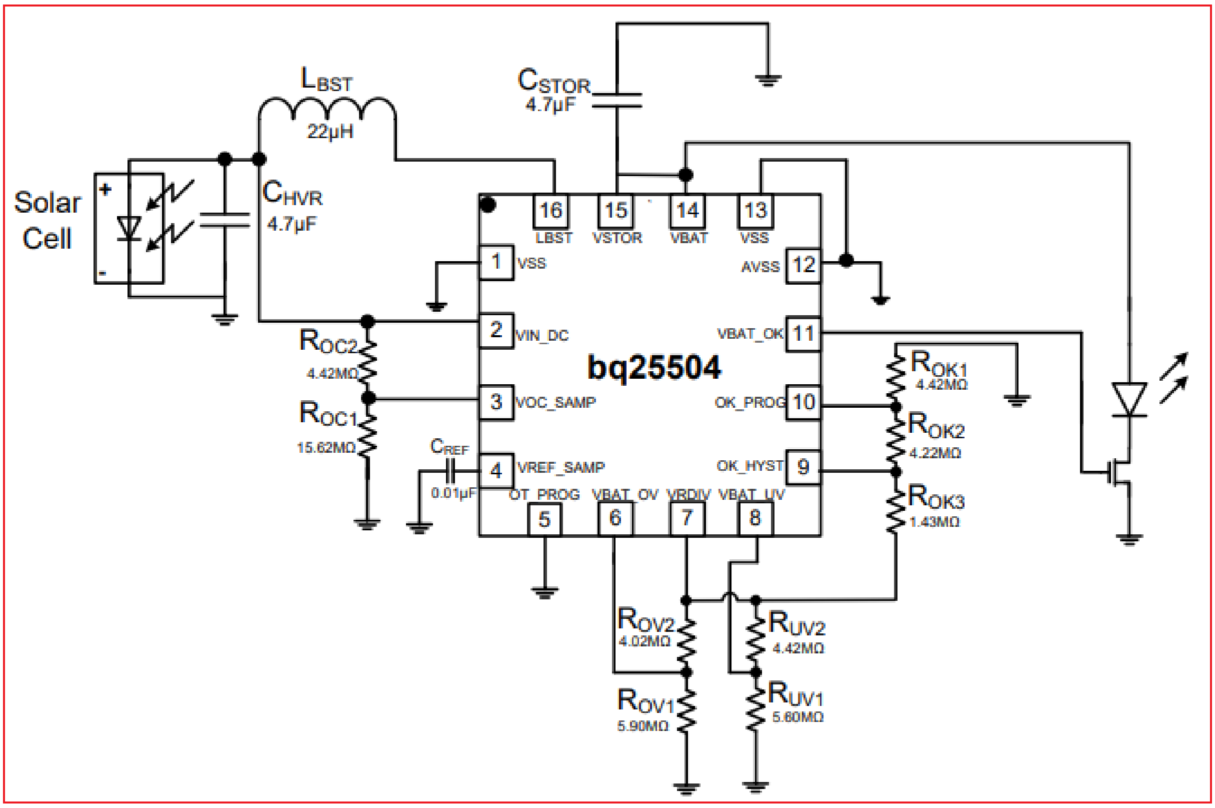

Figure 7: Typical application circuit with BQ25504[19]

2.1.1.1 Maximum Power Point Tracking of BQ25504

To get maximum raw power from the harvester source, by sensing voltage at VIN_DC and store in VREF SAMP pin, the boost converter can indirectly modulate input impedance of main boost charger. By periodically disabling the charger for around 256 milliseconds and sampling a fraction of harvester's open circuit voltage OCV and finally, the MPPT circuit obtain a new reference voltage around every 16 seconds. For an example, solar harvester has a maximum power point of around 70% to 80% of its OCV and for thermoelectric harvester it is around 50%. Exact ratio for MPPT can be optimized by connecting external resistors divider with input source. The input source should tie with resistor divider and connect to VIN_DC pin to get sampling reference voltage which should fed to VREF_SAMP pin.

$$VREF_{SAMP} = VIN_{DC}(Open_{Ckt})\left(\frac{R_{OC1}}{R_{OC1}+R_{OC2}}\right) \quad (1)$$

However, one can disable internal MPPT circuitry and periodic sampling of VIN_DC by tying VOC_SAMP pin to VSTOR pin and then can use an external reference voltage by directly giving the voltage to VREF_SAMP pin. Then boost converter will regulate VIN_DC by externally provided reference voltage. One can even disable input regulation by tying VREF_SAMP pin to GND. (i.e. Input source is low-impedance battery or power supply instead of a high impedance output energy harvester)[19].

2.1.1.2 Battery Undervoltage protection of BQ25504

VBAT_UV threshold must be set using external resistors for protect rechargeable battery or storage element available in the system from get damaged or discharged or totally depletion of charge from a capacitive storage element a under voltage. When the battery voltage is decreasing than VBAT_UV threshold voltage is given by,

$$VBAT_{UV} = \frac{3}{2}V_{BIAS}\left(1+\frac{R_{UV2}}{R_{UV1}}\right) \quad (2)$$

Resistors sum is recommended no higher than 10 MΩ, i.e. $R_{UV1} + R_{UV2}$ = 10 MΩ.

VBAT_UV_HYST is defined as VBAT_UV plus internal hysteresis voltage when the battery voltage is increasing . To work VBAT_UV feature properly, Load must be tied to VSTOR pin and storage or output battery must be tied to VBAT pin. Once VSTOR goes beyond the summation of VBAT_UV threshold and VBAT_UV_HYST threshold, the VSTOR get shorted or connected eternally with VBAT pins by utilizing PMOS FET and remain shorted unless

VSTOR becomes less compare to the VBAT_UV threshold. The system load remains connected or not truly based on the VBAT_OK threshold and that should be set more than threshold of VBAT_UV [19].

2.1.1.3 Battery Overvoltage Protection of BQ25504

To prevent rechargeable batteries from overcharged and over charging a capacitive storage element, the over-voltage VBAT_OV threshold need to be set using external resistors, which is also the voltage value level where the charger will regulate the VSTOR/VBAT pin when the input has enough power. The VBAT_OV threshold voltage when the battery voltage is increasing is given by,

$$VBAT_{OV} = V_{BIAS}\left(1 + \frac{R_{OV2}}{R_{OV1}}\right) \quad (3)$$

Resistors sum is recommended no higher than 10 MΩ, i.e. R_{OV1} + R_{OV2} = 10 MΩ.

When the battery voltage decreasing the VBAT_OV threshold becomes the voltage difference between VBAT_OV and VBAT_OV_HYST. Once the battery voltage become equals with VBAT_OV threshold voltage then boost converter become disabled. However, the charger will start again when the battery voltage dropped by VBAT_OV_HYST. When input energy become too high VBAT pin will start fluctuating in between VBAT_OV and the (VBAT_OV - VBAT_OV_HYST) levels. If situation occurs when VIN_DC>VISTOR>VBAT_OV, then it is recommended that VIN_DC should pull to ground through a small resistance to avoid charging more the storage and input source must be a high impedance one (typically higher than 20Ω).

2.1.1.4 Battery Voltage in Operating Range (VBAT_OK Output) of BQ25504

BQ25504 has programmable voltage in between overvoltage and undervoltage which can be set to indicate whether the VSTOR voltage is an acceptable level. When the battery voltage is decreasing the threshold is set by

$$VBAT_{OK\_PROG} = V_{BIAS}\left(1 + \frac{R_{OK2}}{R_{OK1}}\right) \quad (4)$$

When the battery voltage is increasing, the threshold is set by

$$VBAT_{OK\_HYST} = V_{BIAS}\left(1 + \frac{R_{OK2}+R_{OK3}}{R_{OK1}}\right) \quad (5)$$

Resistors sum is recommended no higher than 10 MΩ, i.e. R_{OK1} + R_{OK2} +R_{OK3}= 10 MΩ.

The logic high level signal defined as same as VSTOR voltage and the logic low level signal defined as same as GND voltage. To prevent MCU from damaging due to any excessive current flow a ~20KΩ resistor connected internally in series it powered up totally. VBAT_OK_PROG threshold must be set more the or equal to UV threshold[19].

2.1.2 Other Components

Excluding BQ25504 there are some other components that were used in the harvester board likes watchdog timer TPL5010, several switches, flipflop, or gate, instrumentation amplifier etc. All of them will be described as we further proceed on sections below.

2.1.2.1 TPL5010 Watchdog Timer

TPL5010 is an ultra-low power timer with watchdog features for weak up in duty cycle and has low current consumption around 35 nanoampere. Integrated timer while in sleep mode keep microcontroller consume power but TPL5010 being external timer with very low consumption allow microcontroller to save much power which makes it well suited for energy harvesting applications. In our board it supposed to check open circuit voltage OCV of different harvester connected with VIN_DC, to realize this we need a timer with WAKE and DONE signal so that we can send WAKE signal to an additional flipflop (SN74AUP1G74) and through flipflop via switch (TS3A24159) we can check maximum raw power available in different harvester which will finally get connected with VIN_DC pin of BQ25504. In our board we set the timer counting time for 30 munities by using resistor as shown in datasheet. However, later in this chapter we will briefly speaks about switches and other necessary components.

We can set the time interval by following equation,

$$R_{EXT} = 100\left(\frac{-b+\sqrt{b^2-4a(c-100T)}}{2a}\right) \quad (6)$$

Here, a, b, c are necessary coefficients depending on range of time intervals and T is desired time interval in second and finally, R_{EXT} is the required resistance value in Ω.

The coefficients value can be found by following table,

Set	Time interval range (s)	a	b	c
1	$1 < T \leq 5$	0.2253	-20.7654	570.5679
2	$5 < T \leq 10$	-0.1284	46.9861	-2651.8889
3	$10 < T \leq 100$	0.1972	-19.3450	692.1201
4	$100 < T \leq 1000$	0.2617	-56.2407	5957.7934
5	$T > 1000$	0.3177	-136.2571	34522.4680

Table 2: Required coefficients value necessary for equation (6)[20]

In our board we have utilized manual timer RESET option so that depending on necessity we can manually reset the system with timer and to do so we use a SPDT mechanical switch with two pin jumpers of that one pin connected to supply and another with DELAY/RESET pin of TPL5010 and the last pin connected with R_{EXT} .

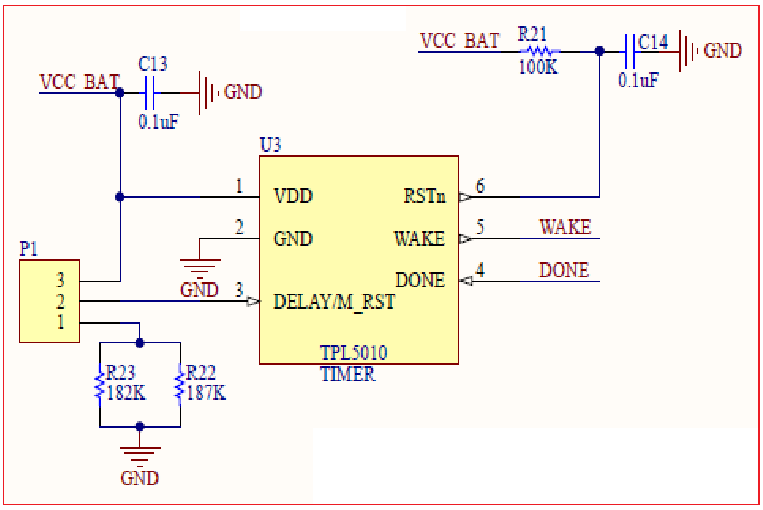

Figure 8: Manual RESET features of TPL5010

Figure 8 shows mechanical switch P1 in which if pin 3 and pin 2 get connected by jumper it will be regular configuration, but when pin 2 and pin 1 get connected by jumper it's manual reset.

2.1.2.2 Flipflop and Switch TS3A24159

As mentioned in chapter above we have used switches TS3A24159, TS5A3359 and flipflop SN74AUP1G74 and furthermore we used or gate SN74AUP1G32 and some 2 and 3 pin sockets with many passive elements and finally for 2nd schematic we used additional rail to rail output instrumentation amplifier INA827. All most all component has few common features which is ultra-low power consumptions capabilities. Our intention is to use 3 terminal based harvester (2 anode and 1 cathode) or two same type of harvester (1 anode and 1 cathode) with both the cathodes ties together and anode remain same for each input sockets (J1 and J2) of our board. Figure 9 below depicting connection of harvesters input in sockets J1, J2 and J3.

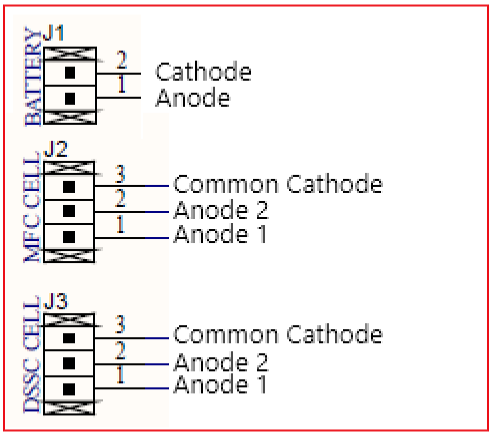

Figure 9: Main harvester input socket configuration

As we mentioned before, using of flipflop SN74AUP1G74 in our board is mainly gives us opportunities to control harvester inputs by controlling switching activities and to do that it supposed to get a WEAK signal from timer and apply output Q to each switch TS3A24159 which is common to both two version of schematics. Though switches connection and reason for using is different.

For 1st schematic once switch TS3A24159 get Q from flipflop, now harvesters two anode terminal directly connected through single pole double through SPDT switch with BQ25504 VREF_SAMP pin and VIN_DC pin such a way so that one anode can provide supply to BQ25504 through VIN_DC pin and another anode can take part to provide reference sample voltage to BQ25504 through VREF_SAMP pin for MPPT.

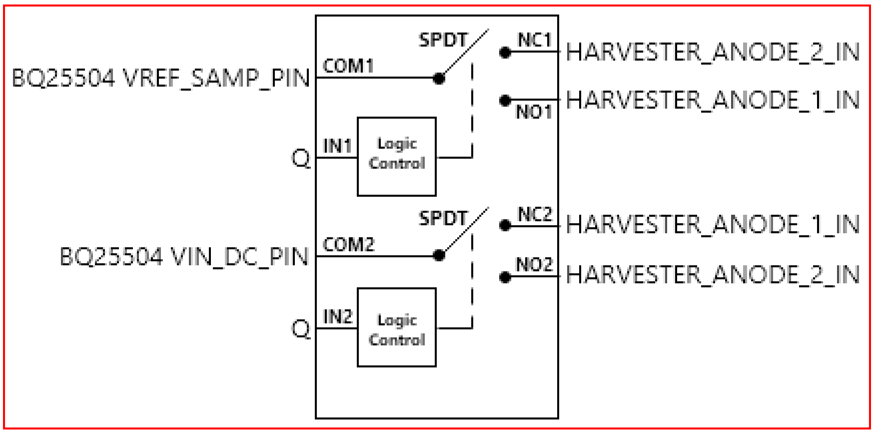

Figure 10: 1st Schematic version connection of switch TS3A24159

Figure 10 above shows the connection regarding 1st schematic switch TS3A24159 connections. Throughout truth table we find as we are giving Q(High) signal through flipflop, so harvester anode 2 will provide supply and harvester anode 1 will provide reference voltage.

Truth table for the TS3A24159 switch are given below,

IN	NC TO COM, COM TO NC	NO TO COM, COM TO NO
Q_BAR OR L	ON	OFF
Q OR H	OFF	ON

Table 3: Truth table of switch TS3A24159 [21]

For 2nd Schematic once switch TS3A24159 get Q from flipflop, now harvesters two anode terminal directly connected through single pole double through SPDT switch with BQ25504 VREF_SAMP pin and BQ25504 ground pin such a way so that one anode can grounded due get a known common ground and another anode can take part to provide reference sample voltage to BQ25504 through VREF_SAMP pin for MPPT.

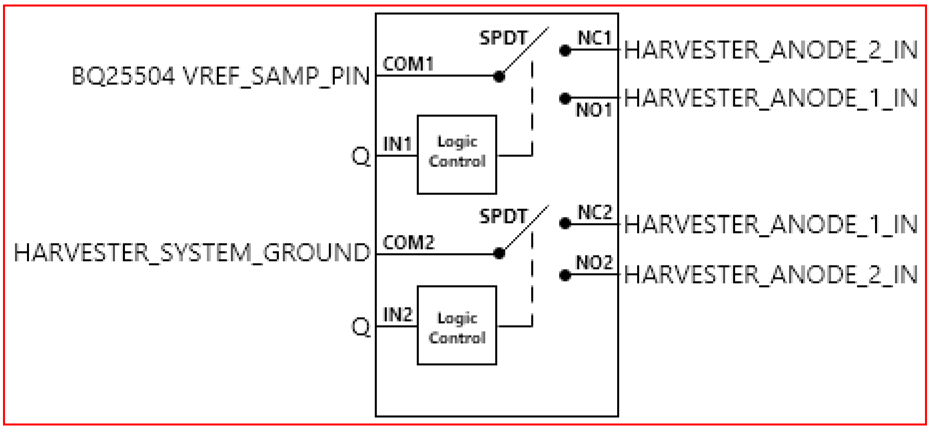

Figure 11: 2nd Schematic version connection of switch TS3A24159

Figure 11 above shows the connection regarding 2nd schematic switch TS3A24159 connections. Throughout truth table we find as we are giving Q(High) signal through flipflop, so harvester anode 2 will be grounded and harvester anode 1 will provide reference voltage.

2.1.2.3 Switch TS5A3359 for Supply and Ground

TS5A3359 is an ultra-low power, operating voltage 1.65 millivolts and 1Ω R_{ON} resistance single pole triple through SP3T switch. Once the BQ25504 boost converter get started and ready to supply the output battery before doing that it gives a safe output supply signal through VBAT_OK pin. For our board purpose we are going to use VBAT_OK signal to connect battery with BQ25504 boost converter output pin VBAT.

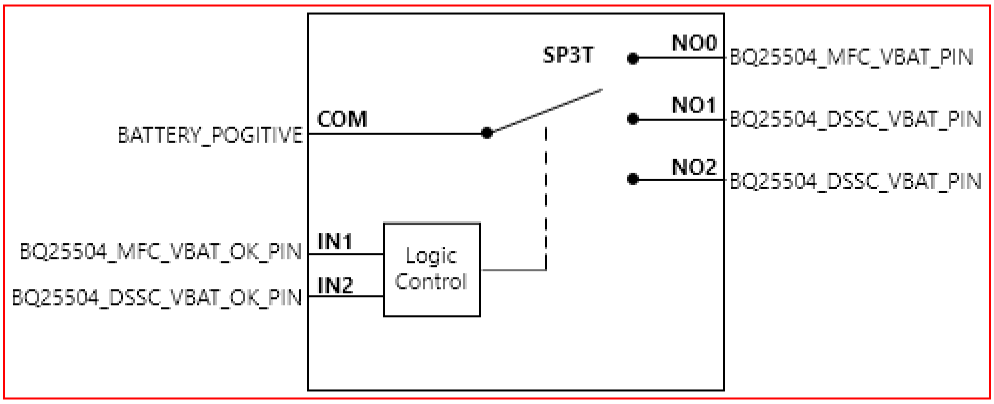

Figure 12: 1st Schematic version connection of switch TS5A3359

For 1st schematic Figure 12 shows above connection regarding switch TS5A3359 with boost converter and battery terminal depending on VBAT_OK signal. As we said before, Once BQ25504 finalize the harvester available with best output, it will boost it and send VBAT_OK signal and the switch will use it and connect battery with the best given output BQ25504 harvester chip.

Truth table for the TS5A3359 switch are given below,

IN1	IN2	COM TO NO, NO TOCOM
L	L	OFF
L	H	COM = NO0
H	L	COM = NO1
H	H	COM = NO2

Table 4: Truth table of switch TS5A3359 for system supply and ground [22]

Throughout the truth table given above in Table 4 we come to realize that when MFC harvester managing BQ25504 (VBAT_OK_MFC) is high then battery will get connect with BQ25504 MFC VBAT pin and when DSSC harvester managing BQ25504 (VBAT_OK_DSSC) is high then battery will get connect with BQ25504 DSSC VBAT pin but when both BQ25504's VBAT_OK is high then battery will get connect with BQ25504 DSSC VBAT pin.

For 2nd schematic we use two TS5A3359 switch for battery purpose and different harvester's ground switching purpose. Now connection regarding battery with boost converter VBAT pin exactly same with **1st schematic**. However, it is necessary that whichever harvester providing supply to the battery corresponding ground should be connect with loop otherwise it will lead to ground swing. For an example, if DSSC harvester power managing BQ25504's VBAT_OK is high than battery terminal will connect with its VBAT pin and system ground should connect with DSSC ground as shown below in Figure 13.

Throughout the truth table given above in Table 4 we come to realize that when MFC harvester managing BQ25504 (VBAT_OK_MFC) is high then system ground will get connect with BQ25504 MFC_GND pin and when DSSC harvester managing BQ25504 (VBAT_OK_DSSC) is high then battery will get connect with BQ25504 DSSC_GND pin but when both BQ25504's VBAT_OK is high then battery will get connect with BQ25504 DSSC_GND pin.

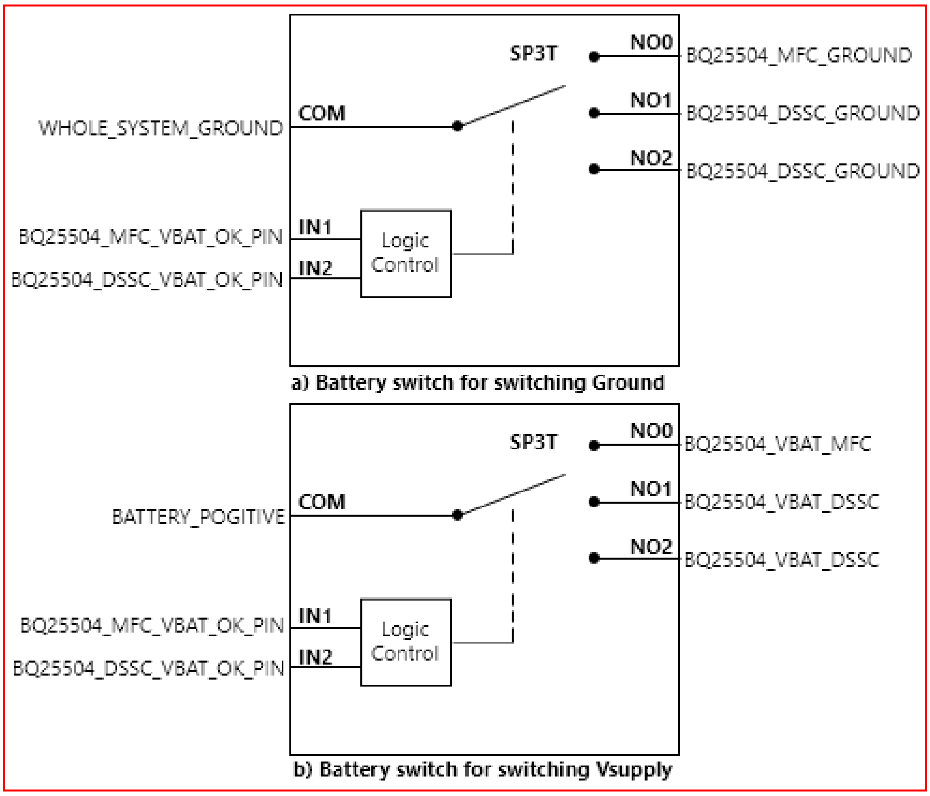

Figure 13: 2nd Schematic version connection of TS5A3359 for system ground and supply

Finally, there is one or gate we use in our board to utilize VBAT_OK signal of both BQ25504 boost converter so that we can process the timer DONE signal which initialize the timer counting time again.

2.1.3 BQ25504 Texas Instruments Evaluation Board

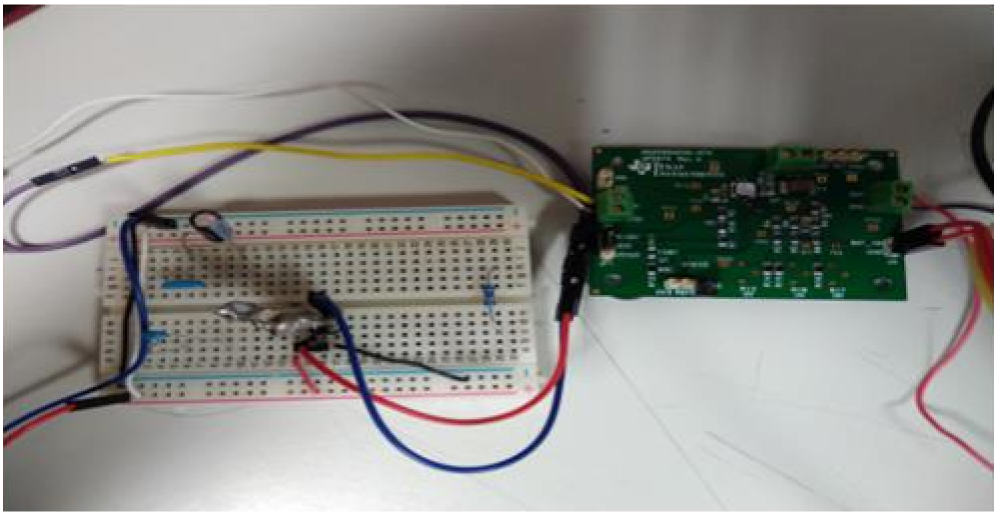

Figure 14: Texas Instruments Evaluation Board of BQ25504

2.2 Ground Problem

Our harvester (MFC or DSSC) that was arranged in a way that had 2 anode and 1 cathode, in a or in any fuel cell the anode is at the lower petential while cathode is at higher potential, so in nomal cases anode acts as a ground and cathode acts as pogitive terminal whenever we are going to extract power from harvester. In our case same harvester had 2 anode but 1 cathode, so the two configurations which we are extracting energy, we were thaking energy from (anode 1 to cathode) and (anode 2 nad cathode), now the cathode is always pigitive terminal while anode is negative terminal. Now the difference in the voltage for cathode and anode was always for the anode, so the cathode has always the same potentials, On the other hand anode had different potentials.

When we are going to connected our power extraction system, the problem was that we could not directly connect the anode to the ground, This was because we had two different anode which are in two different potential levels and different from ground potential level of the system. Since the ground level are suppose to be providing the ground for all the circuits, it was not a good idea to connect both anode as the gorund or even one anode as the ground.

So our main issue was energy etracted from the harvester at two different lower potential and there was no way to make the two anode at same potential, if connected them together with the ground we would have change the configurations from two anode into one anode(Means, if two anode shorted). Another issue was we could not deside that which of the two anode was lower in potential. For our case, what we needed was both the anode potential should have been higher than circuits gorund potentials because all the components we are using are expecting pogitive voltage supply in their terminals. So in case we had even one of the anode which was lower voltage than the circuit ground it would have caused negitive input at the BQ25504 harvester or even before that we were using switch and multiplexer, multiplexer can not take as input voltage lower than ground potetial of the circuits.

So it is necessary to have ground potential of the circuits lower than the two anode potentials. In our case, the cahlange was that, we could not say that which of the two anode has lower potential(In real experimant it shows that one time one anode was at lower potential after some time passed another anode was at lower potentials). Basically, it was the potential difference of the andode and cathode which mattered. But for developing electrical system the issue was that in our case the two voltage we were getting not due to the pogitive terminal but due to the nagitive terminal or the lower voltage of the system. Due to this issue we could not carrie on with the simple or straight forward solution.

In 1st schematic version we used use common ground due to testing in lab using lab power supply. But in case of real harvester output they are fluctuating dc and two harvester MFC and DSSC anodes or ground are in different potentials as described above. So, it is necessary to come up with some solution that provide a common ground, means when DSSC is providing power to the storage or battery then PCB and battery's common ground should have to be as same potential as DSSC cathode or ground. Similarly, MFC's ground or cathode must be in congruence with PCB and battery's common ground. To do that whoever providing the power it's ground must switched to PCB ground. Using a switch, we implement this in 2nd schematic versions.

2.3 Block Diagram and Flow Chart

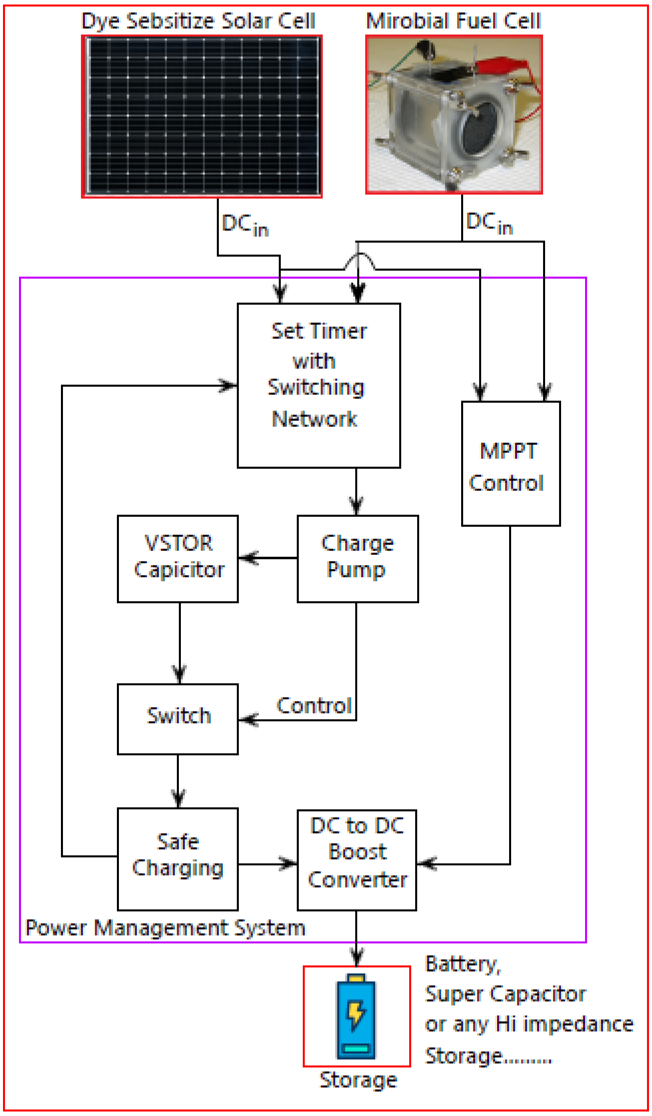

Figure 15: Block diagram of Energy Harvesting System

Figure 15 represent the general block of the harvesting board. The harvester inputs are fed to the power management system by switching network and after that passing through different block and get boosted by DC-DC converter and finally provide output to the storage or battery. The detailed description will be given later as we proceed further.

2.3.1 1st Version Flow Diagram

Common part of work flow:

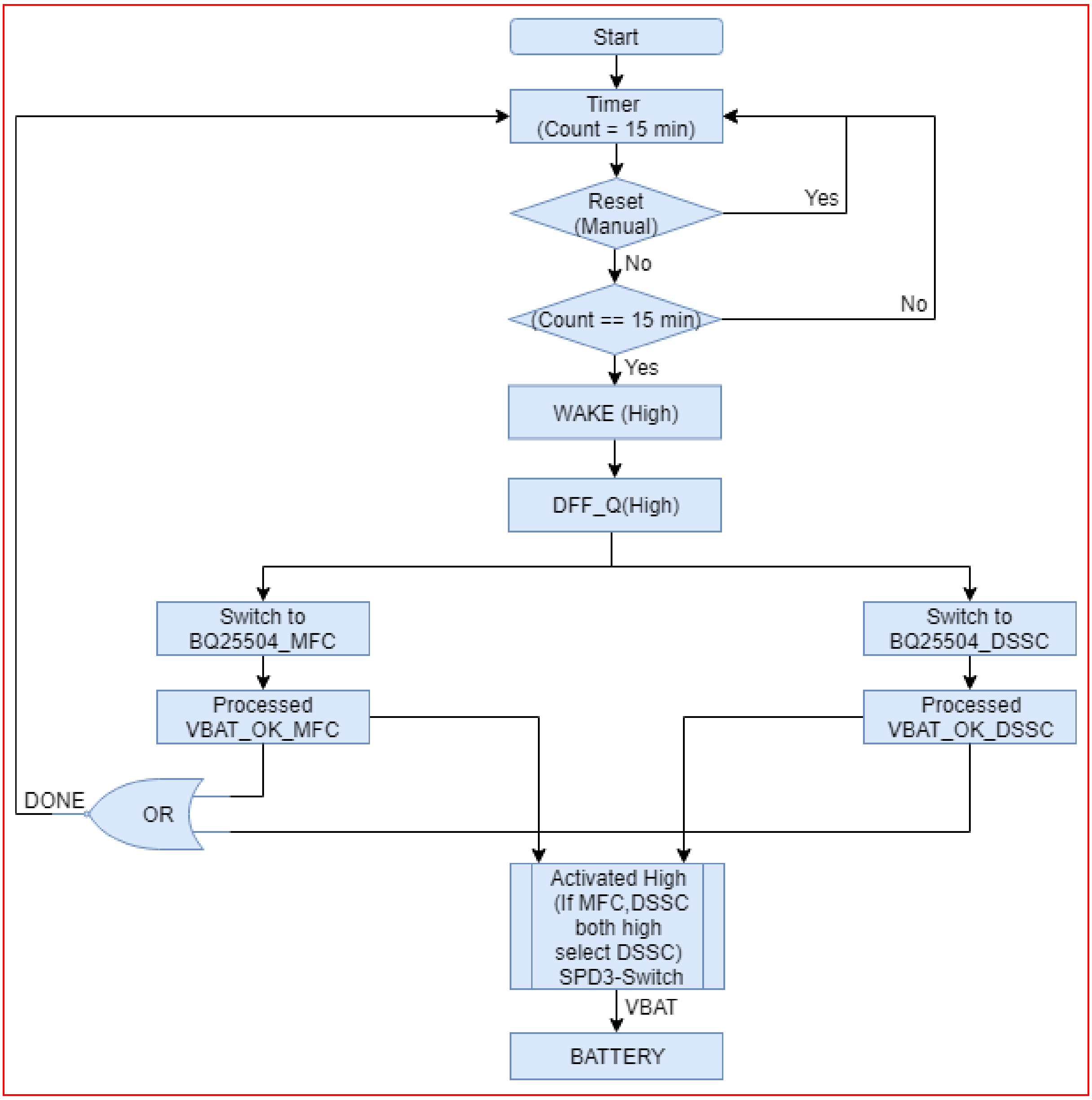

Figure 16: Flow diagram of schematic 1st version (without ground solution)

The electrical board that was developed with its components should follow the flow diagram given above in Figure 16. However, flow diagram above contains all the workflow of components except internal power management of the both boost converters BQ25504 due to lack of space though they will be shown below in the Figure 17.

When the system gets started the timer start counting to it's given period (approximately 30 munities) sets by the resistors unless manual reset pressed. Once the timer finish counting it supposed to send a WAKE signal to the flipflop and flipflop supposed to send high to switches TS3A24159 and TS3A24159 will connect VIN_DC pin of BQ25504 with harvester one anode and VREF_SAMP pin of BQ25504 with another harvester anode.

Now internal workflow regarding both BQ25504 will show later in Figure 17. Once BQ25504 processed VBAT_OK (acceptance signal regarding safe operating voltage to charge the battery) signal, whoever is eligible will charge the battery and DONE signal processed through or-gate using VBAT_OK signal will restart the counting of timer.

Internal work flow of BQ25504:

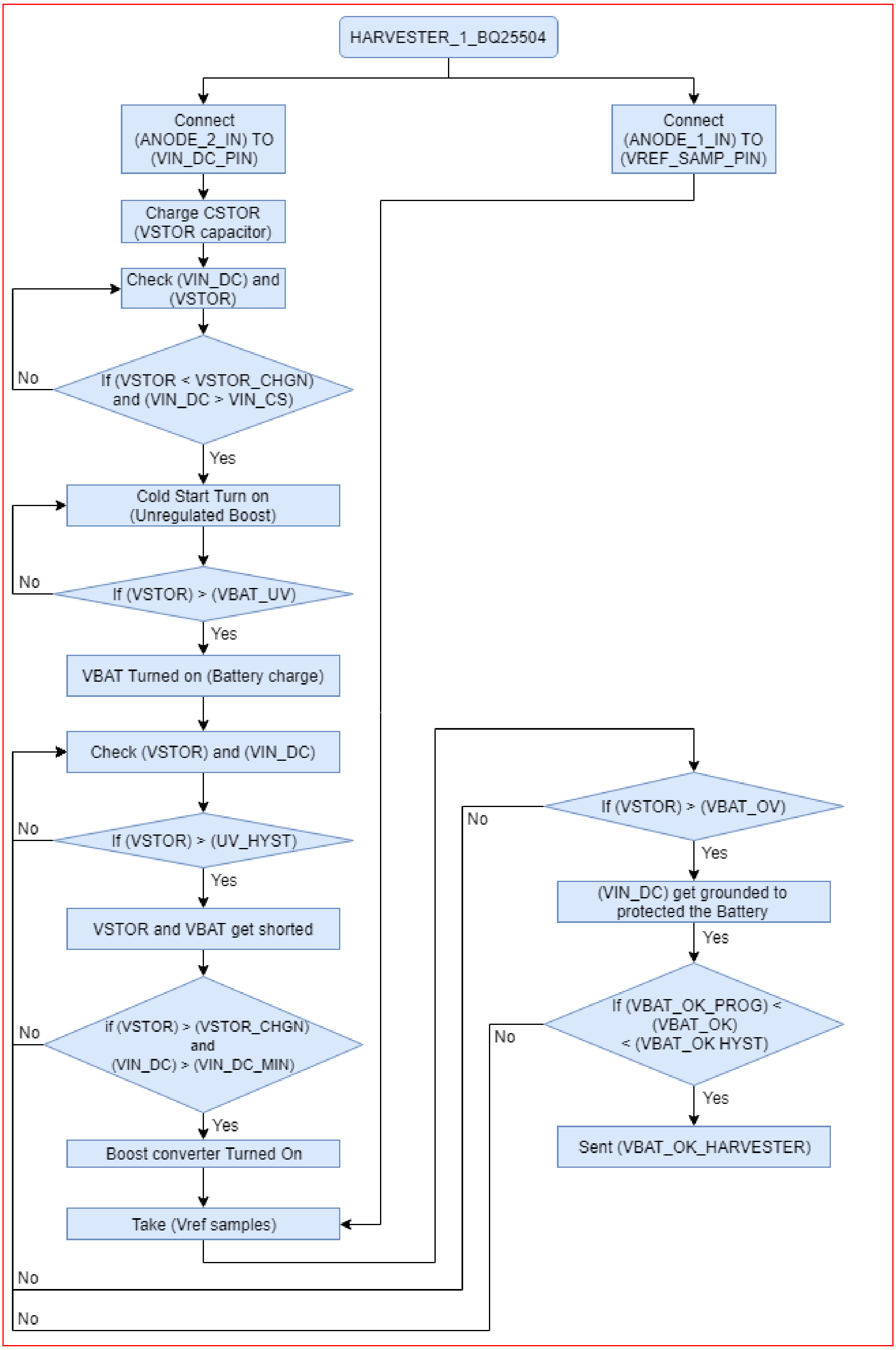

Figure 17: Internal work flow BQ25504 for Schematic 1st and 2nd versions

The main priority of BQ25504 is to charge VSTOR capacitor (CSTOR), then power additional circuitry from VSTOR and finally supply the storage connected through VBAT pin. Figure 17 shows internal work flow of BQ25504. In the board two BQ25504 were used and both has same internal work activities. After switching, once harvester get connected to BQ25504's VIN_DC pin and VREF_SAMP pin then BQ25504 sensed VIN_DC and when voltage at VIN_DC exceeds minimum input voltage with sufficient power then cold-start subsystem get started (Un regulated boost converter).

Now VSTOR get compared with VBAT_UV, when VSTOR reached to VBAT_UV threshold then internal PMOS between VSTOR and VBAT turned on and allow the battery to get charged. Now when VSTOR voltage reach to VBAT_UV_HYST then VSTOR and VBAT pin get shorted internally. When VSTOR reach to VSTOR_CHGEN and VIN_DC reach to VIN_DC_MIN then main boost converter get started.

Now when VSTOR reach to VBAT_OV the boost converter disabled and VIN_DC get grounded to protect battery from overcharging. Boost converter get started again when VSTOR voltage reach below VBAT_OV_HYST and VBAT enabled. As long as VSTOR and VIN_DC in operating voltage range VBAT_OK send to timer again and the whole process get started.

2.3.2 2nd Version Flow Diagram

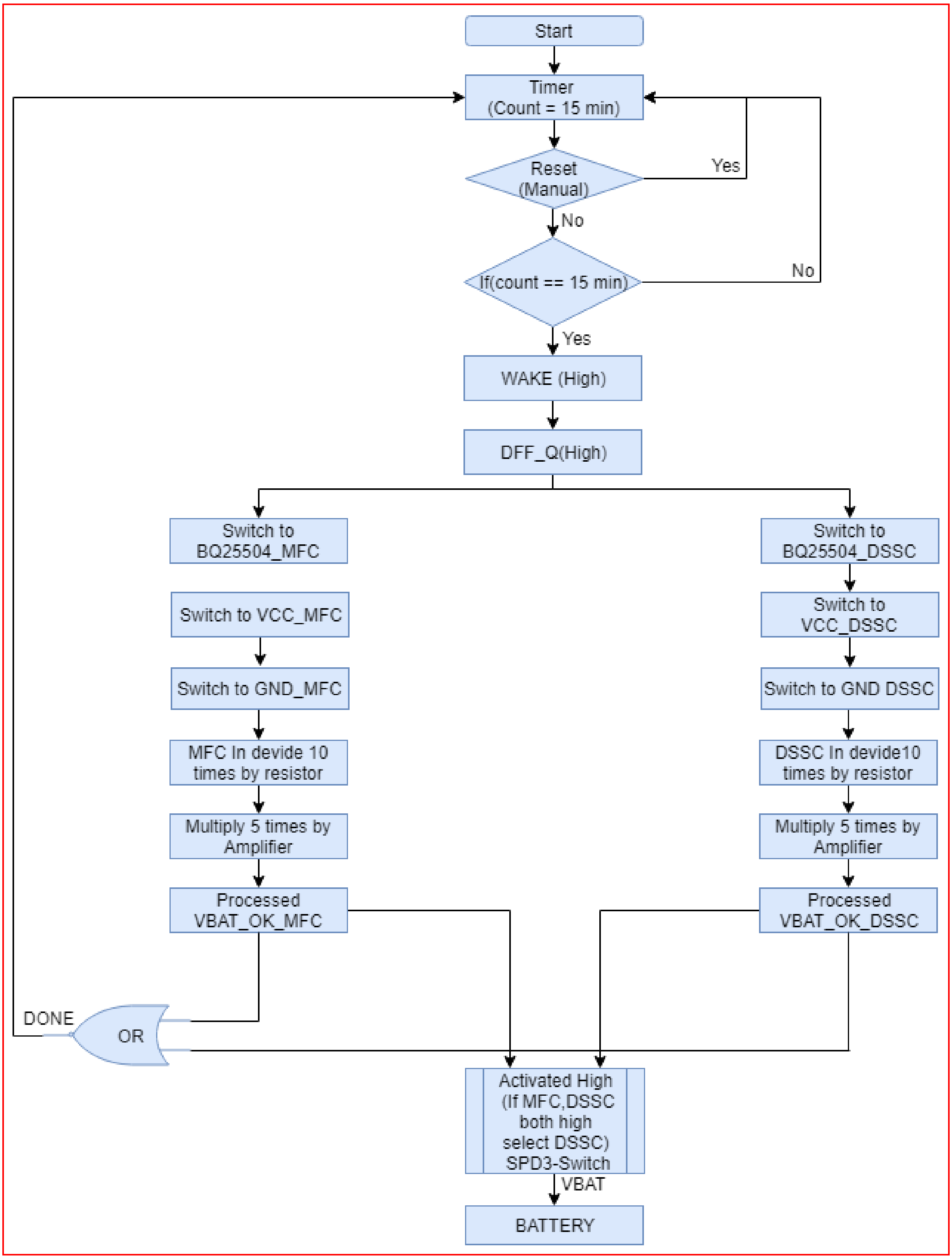

Figure 18: Flow diagram of schematic 2nd version (with ground solution)

The work flow of electrical board 2nd schematic after solving the ground issue that we have designed with its components should follow the flow diagram given above in Figure 18. However, flow diagram above contains all the workflow of components except power management of the both boost converters BQ25504 due to lack of space. The internal work flow of BQ25504 is same as described in 1st schematic version.

When the system gets started the timer start counting to it's given period (approximately 30 munities) sets by the resistors unless manual reset pressed. Once the timer finish counting it supposed to send a WAKE signal to the flipflop and flipflop supposed to send high to switches TS3A24159 and TS3A24159 will connect ground pin of BQ25504 with harvester one anode and VREF_SAMP pin of BQ25504 with another harvester anode.

Now harvester cathode connected through Instrumentation amplifier INA827 get divided by 10 times through resistor divider and multiply 5 times by INA827's internal gain and feed to VREF_SAMP pin of BQ25504. Once BQ25504 processed VBAT_OK (acceptance signal regarding safe operating voltage to charge the battery) signal, whoever is eligible will charge the battery and system supply and ground will connect to eligible harvester's supply and ground respectively. Finally, DONE signal processed through or-gate using VBAT_OK signal will restart the counting of timer.

3 PCB Design

Due to proper visibility both the schematic version is divided in three parts and represented below one after another, each of which contain one mutual part and two individual harvester part and descriptions mostly same as described above in chapter 2.3.

3.1 1st Schematic without Ground Solution

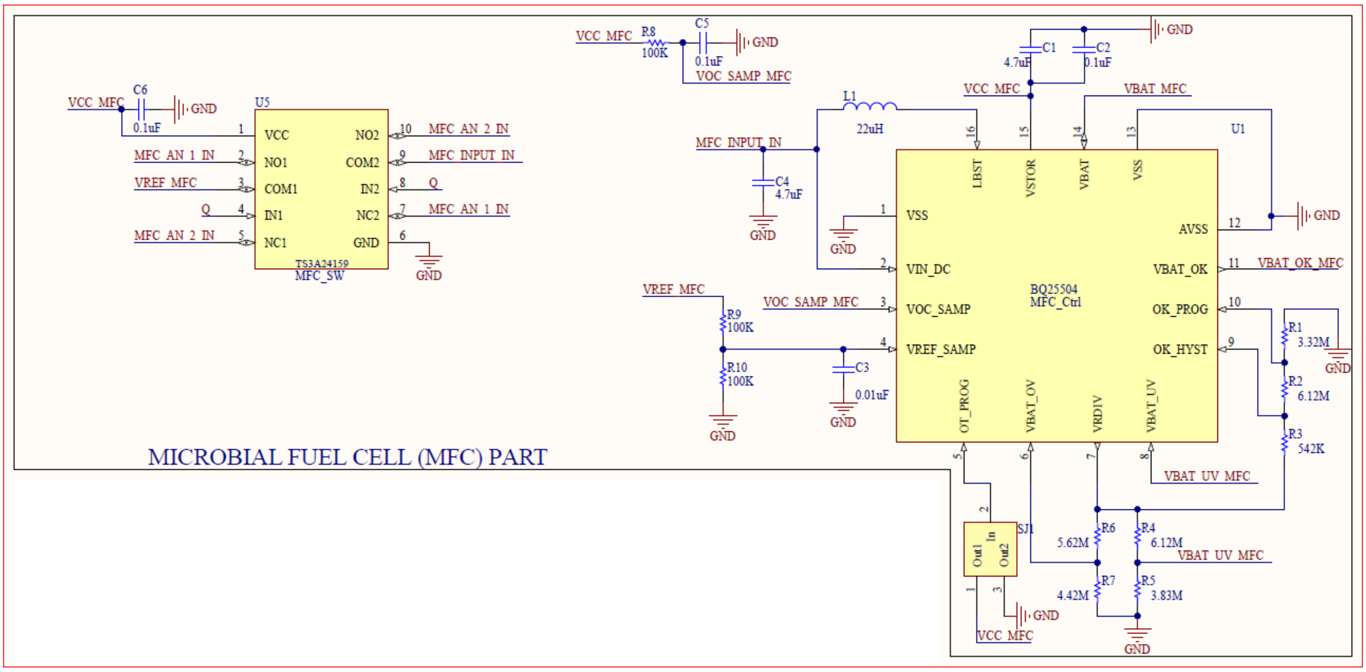

Figure 19: Schematic diagram of board without ground solution MFC part

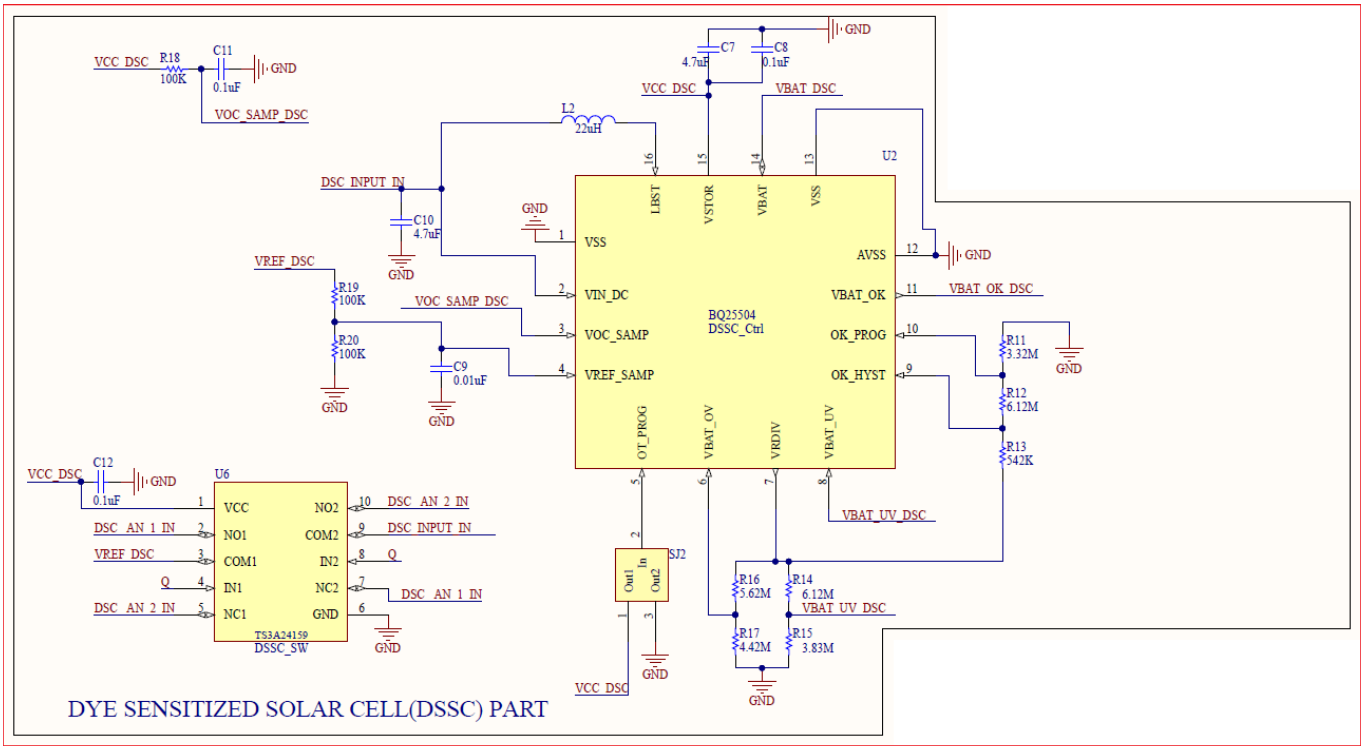

Figure 20: Schematic diagram of board without ground solution DSSC part

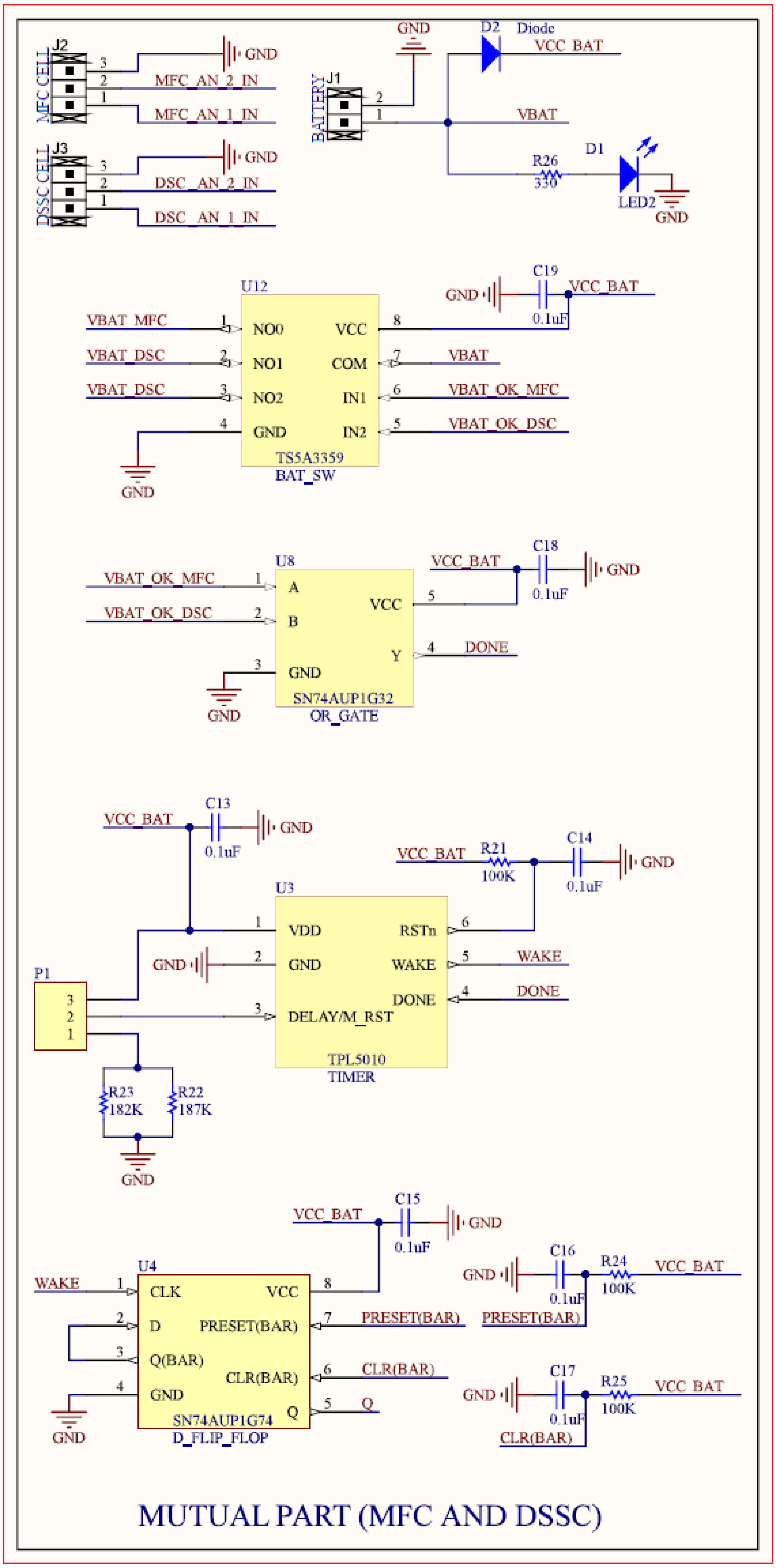

Figure 21: Schematic diagram of board without ground solution mutual part

3.2 2nd Schematic Version with Ground Solution

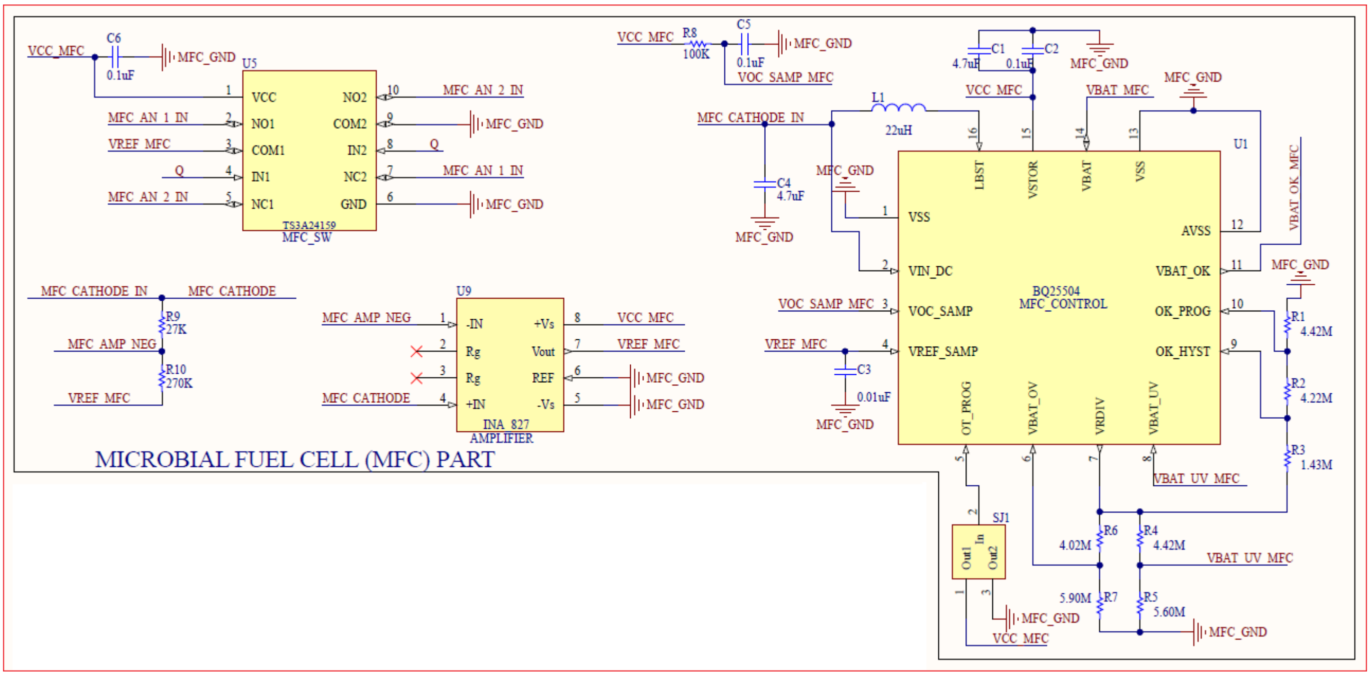

Figure 22: Schematic diagram of board with ground solution MFC part

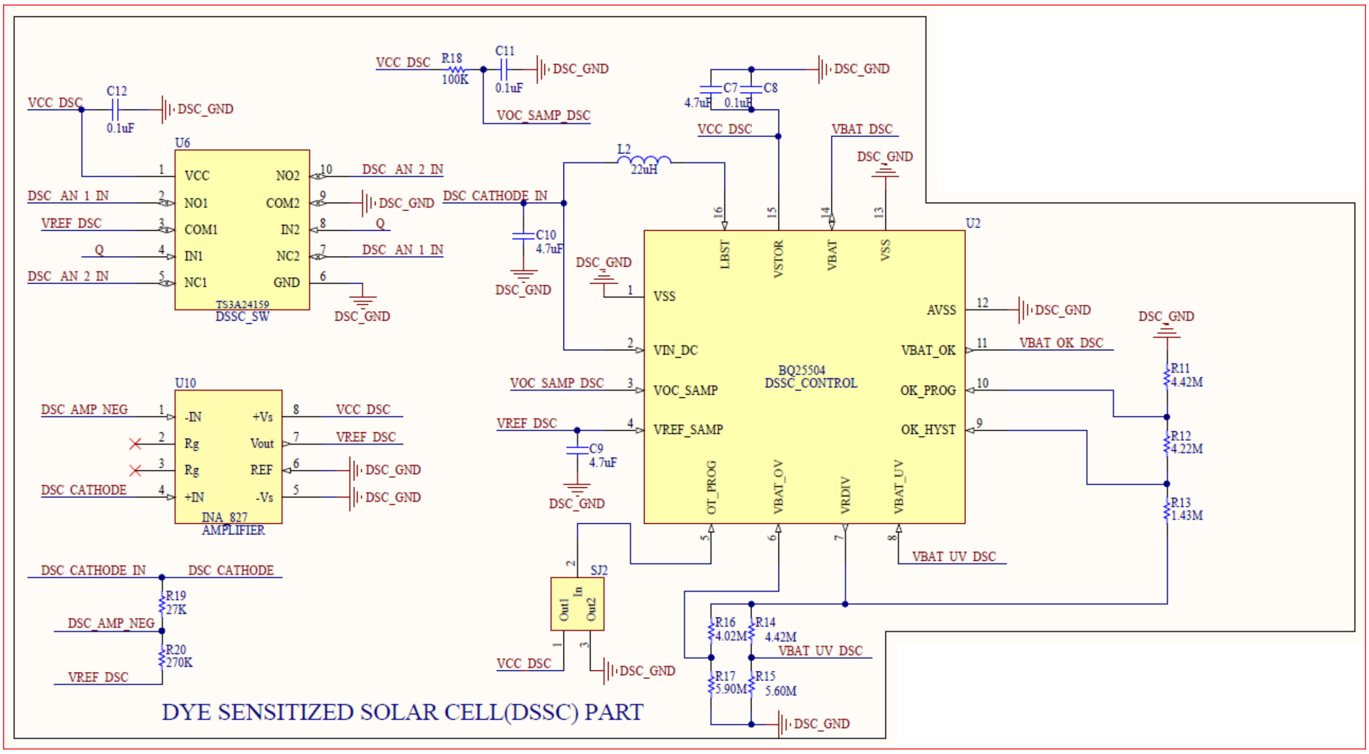

Figure 23: Schematic diagram of board with ground solution DSSC part

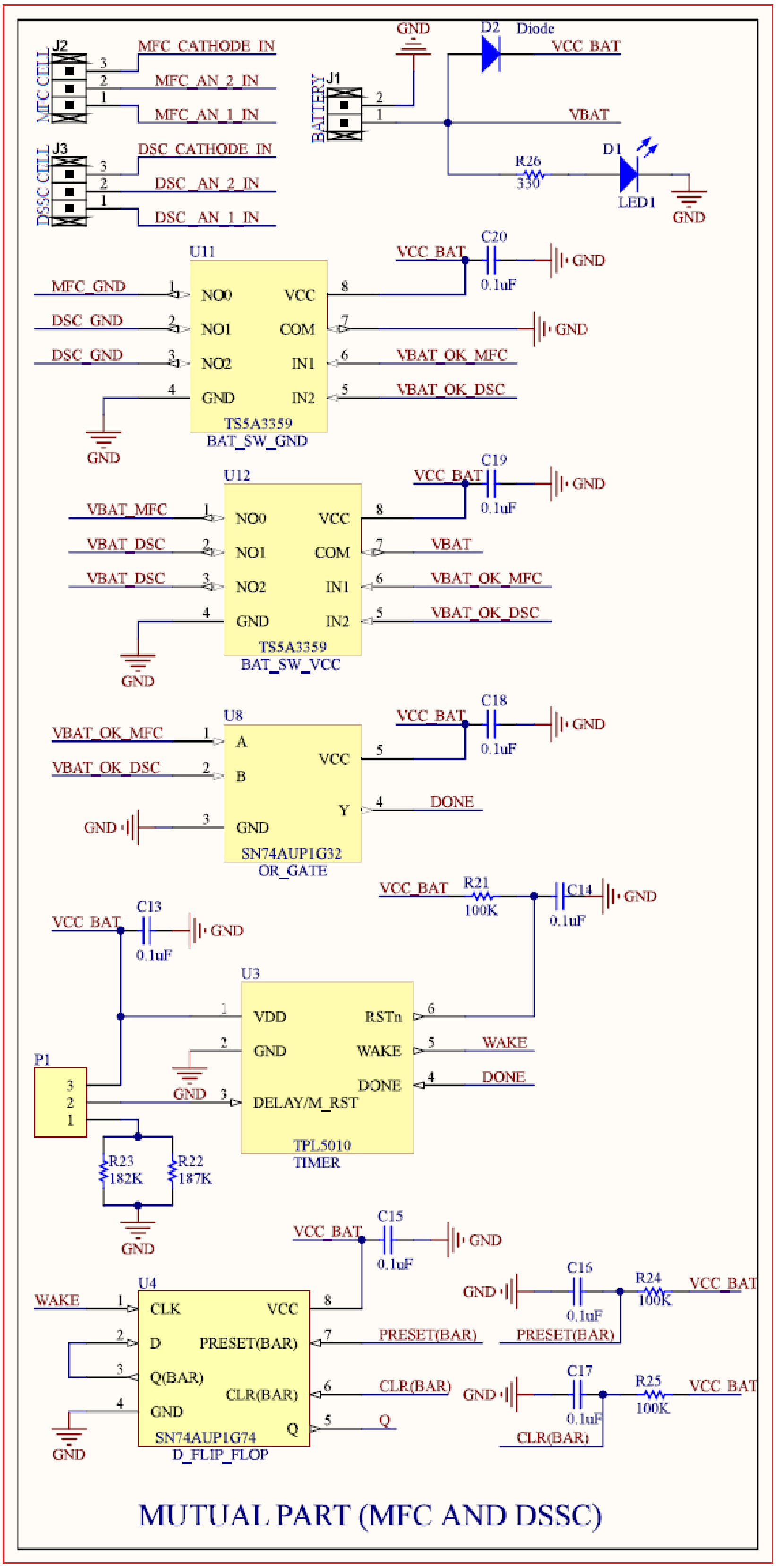

Figure 24: Schematic diagram of board with ground solution mutual part

3.3 Layout Diagram of Board

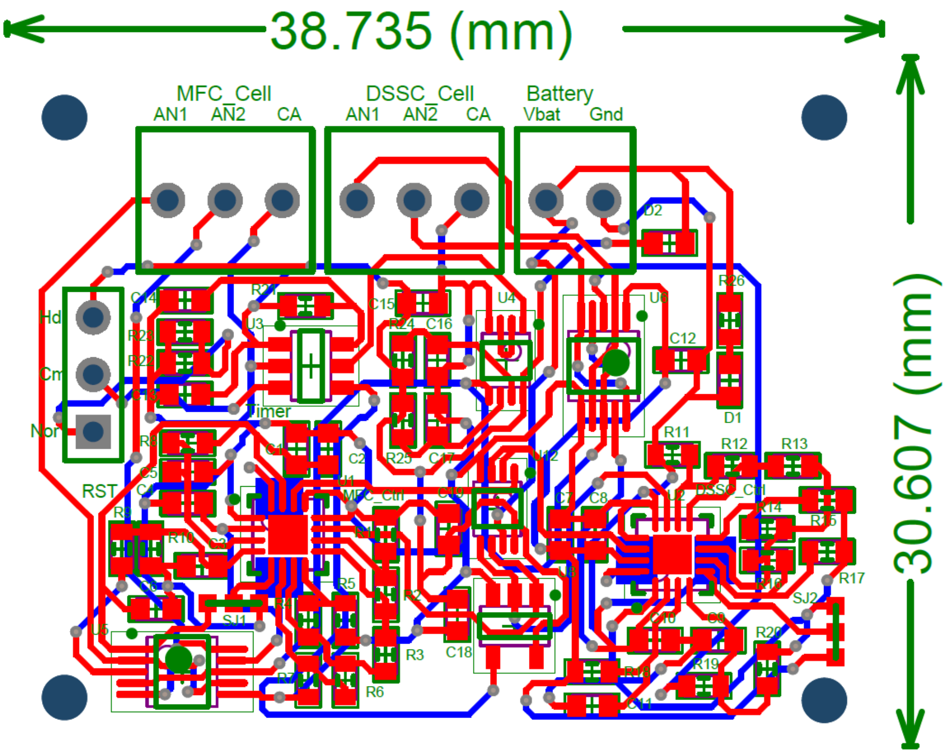

Figure 25 : Layout of board without ground solution

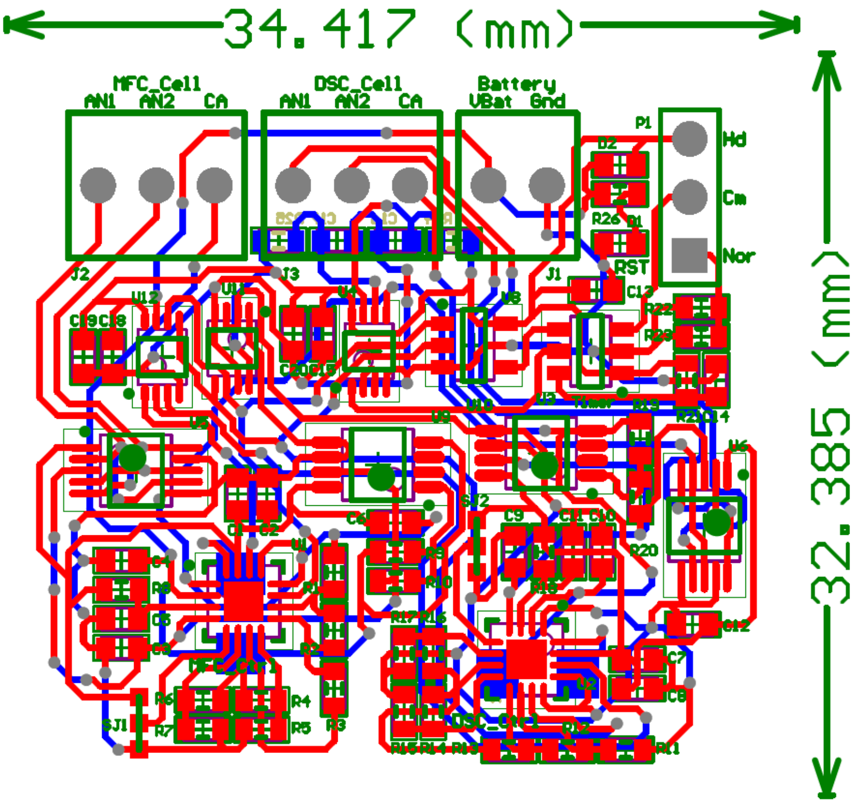

Figure 26: Layout diagram of board with ground solution

3.4 Realizing the Circuit Board

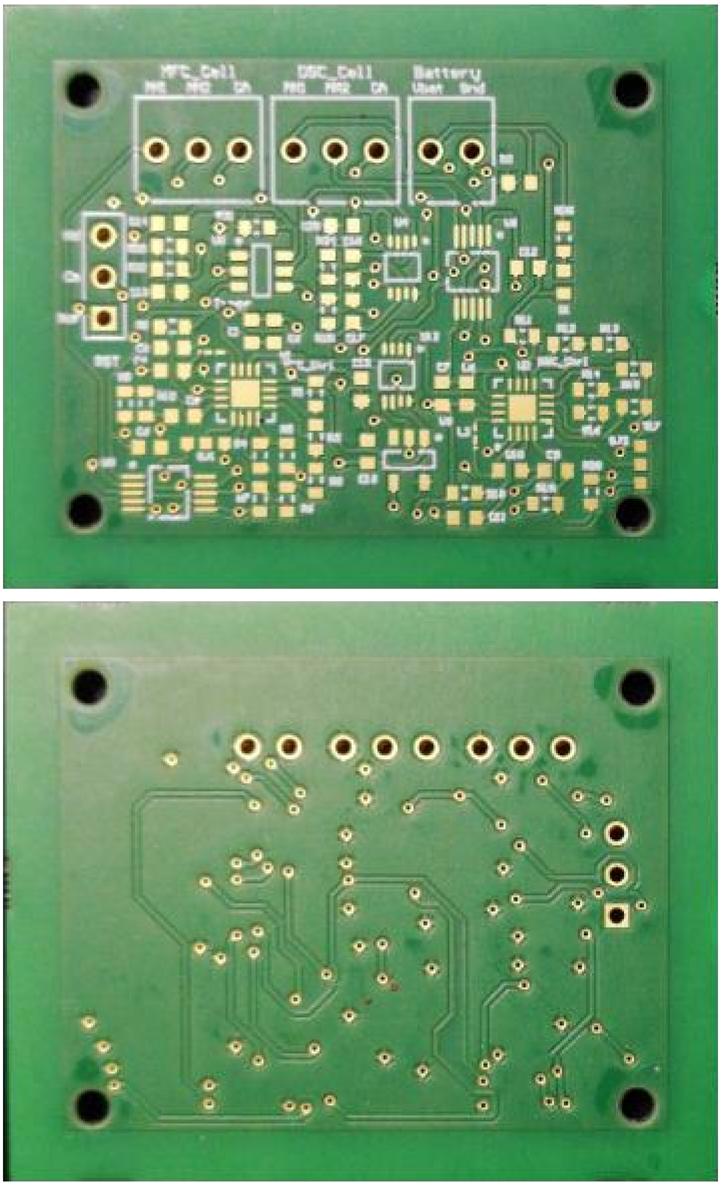

Figure 27: Top and bottom view of board after fabrication

Once the schematic version 1 design completed, it was sent for fabrication and finally after fabrication without component placement Figure 27 represents top and bottom view of printed circuit board.

3.4.1 Soldering

While in soldering phase two BQ25504 QFN chip were soldered by using hot plate first, then rest all main integrated circuits like timer, d-flipflop, or-gate, switches were soldered, after that all the 0603 size passive components, input and output socket were soldered carefully.

3.4.2 Debugging

While in debugging phase the board were thoroughly tested with using power supply to mimic battery as instructed in BQ25504 datasheet, at the time of schematic design few faults were made when choosing and placing of footprints and 0603 led were burnt at the time of soldering. However, all the problems were sorted out and solved.

3.4.3 Problem

While debugging phase one problem about choosing wrong footprints were found, as you can see the board is a tiny one and don't have enough free space in between components and the L_{BST} 22µF inductor was big enough to in place of 0603 size inductor. As a result, L_{BST} was placed at the board border and soldered it through tiny wire which shown by Figure 28 shown inside the red circles below.

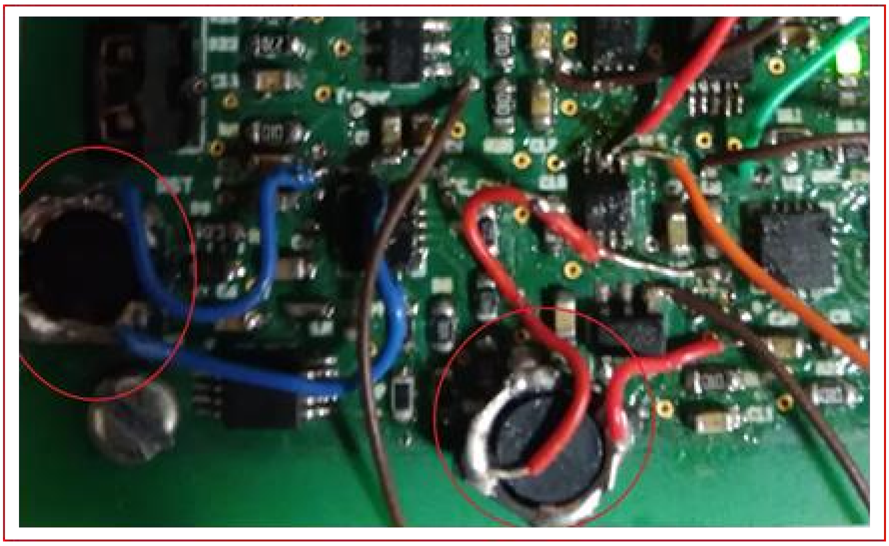

Figure 28: Placement of L_{BST} 22µF inductor

3.4.4 Testing

The first design was transferred to printed circuit board and mainly for experiment purpose by using lab power supply to mimic battery and as harvester's input. The PCB was tested in lab and found working ok. Figure 29 depicts PCB under test environments with flushing green led.

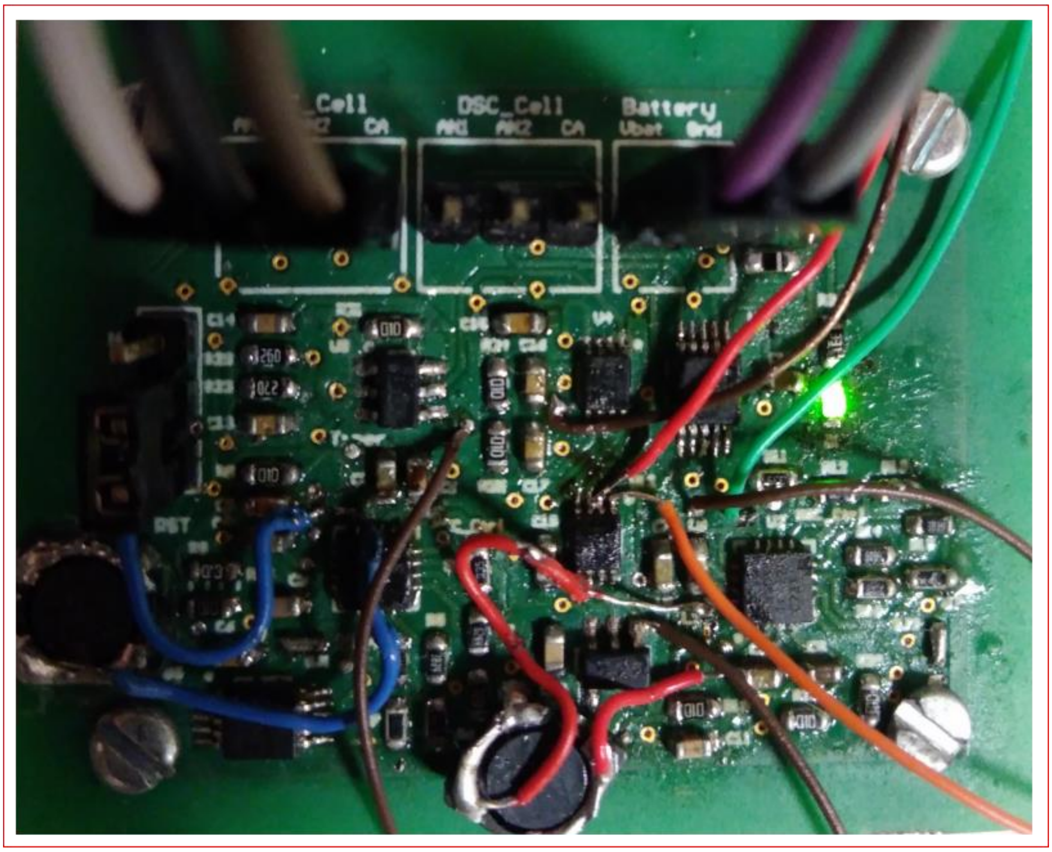

Figure 29: Designed printed circuit board under testing

From lab power supply range of voltage were given as harvester input and found approximately 370 millivolts DC-DC boost converter started and VBAT and VSTOR output was around 3.8 to 4.2 volt.

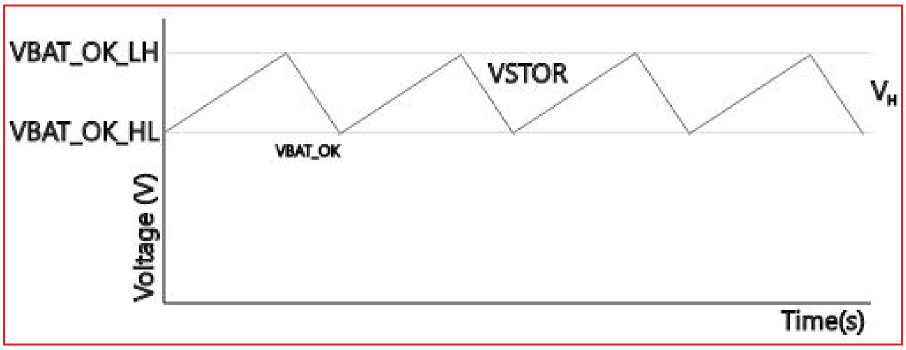

Figure 30: VBAT_OK theoretical pattern given in BQ25504 datasheet[19]

The VBAT_OK and VBAT found using oscilloscope while testing when boost converter turned on in different harvester input voltages are given below:

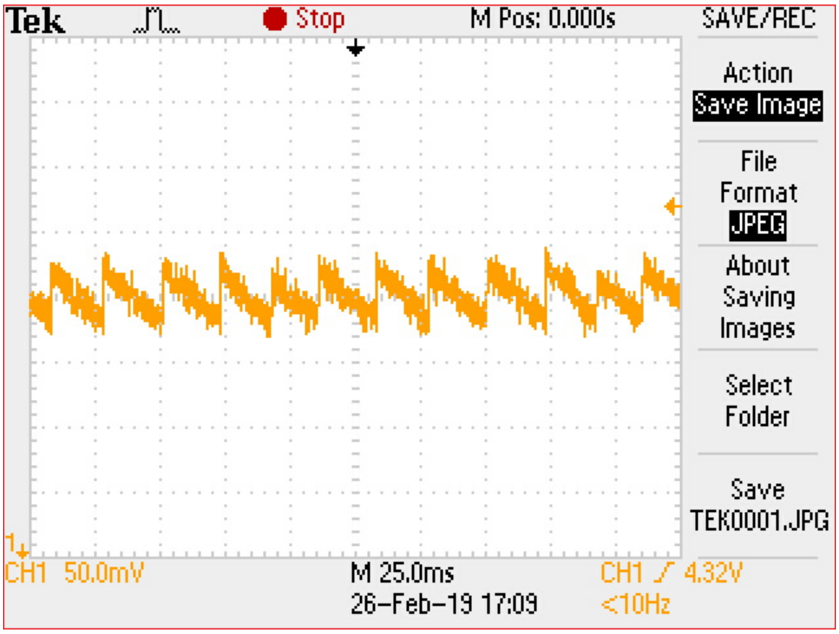

Figure 31: VBAT_DSSC oscilloscope plot

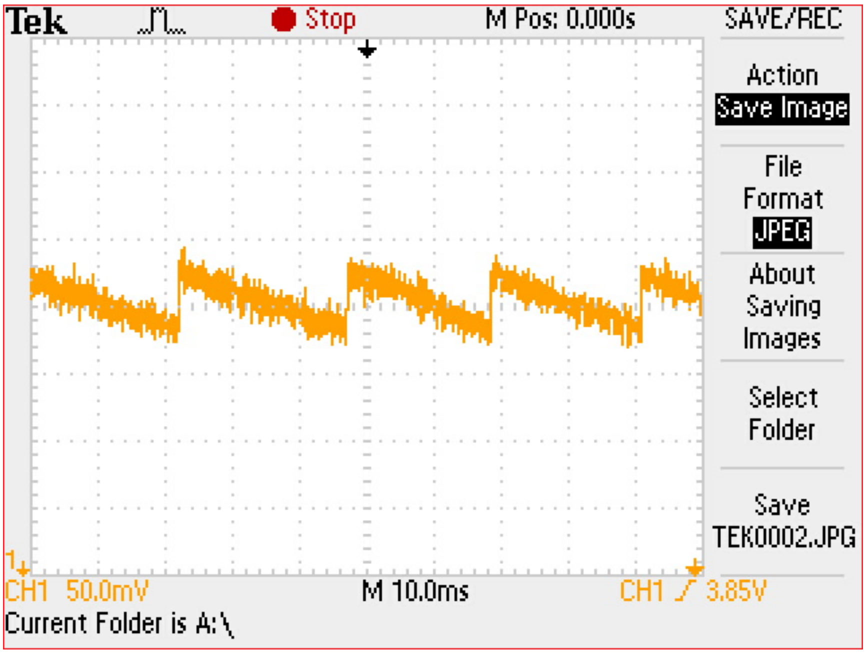

Figure 32: VBAT_OK_DSSC oscilloscope plot

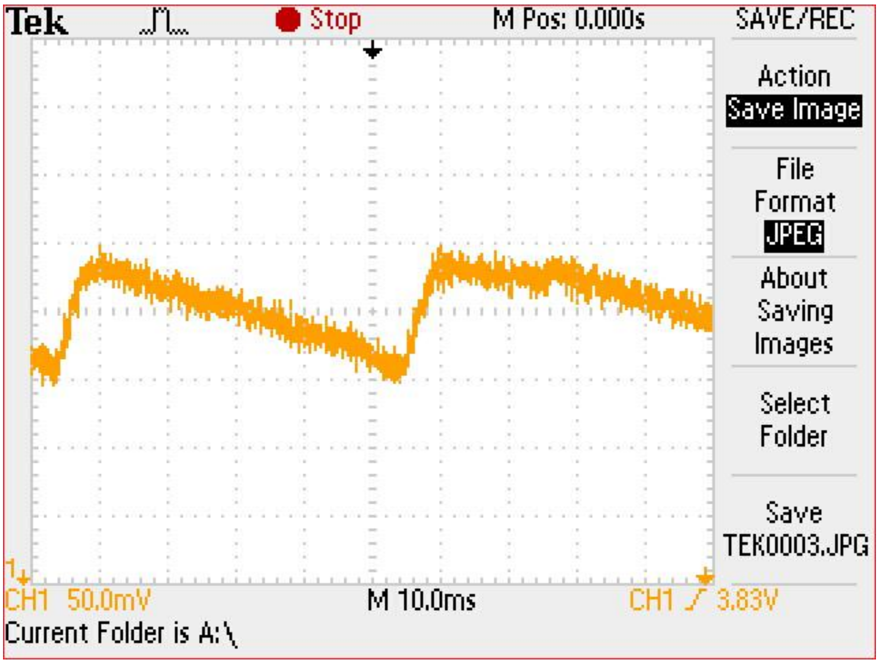

Figure 33: VBAT_MFC oscilloscope plot

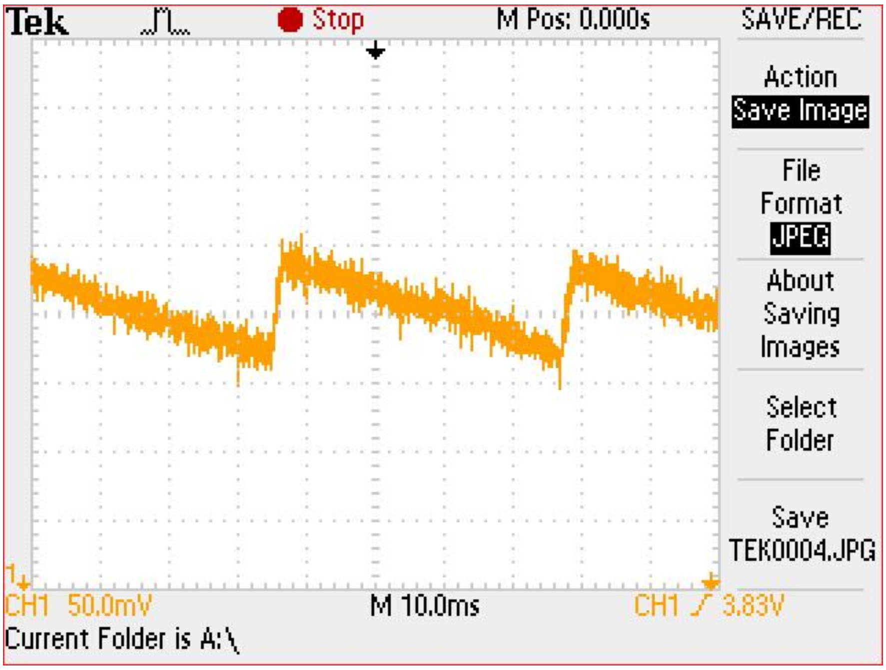

Figure 34: VBAT_MFC oscilloscope plot

4 Learning Outcomes

Throughout the thesis work phase i have learnt prototyping of whole system and using different schematic designing tool and designing schematic and designing specific component footprints and designing layout. Within this period i have worked with different simulation software. Moreover, I have learnt how to do soldering and its necessary equipment and get to know how to solder QFN integrated circuit package with hot plate and hot air gun. Abridgedly it was a huge learning experience for me till day one to now.

5 Future Work and Conclusion

Dew to contemporary fossil fuel high price and environmental issues people's view are approaching toward other available free sources and use of them efficiently as possible are getting popular day by day. Academics are searching new ways to tap free and environment friendly energies. More precisely, for running low power appliances or distinct monitoring system their use is getting popular. In this work, a low power energy harvesting board was designed and tested which worked under lab experiment and a real-time harvester power management system design were proposed. As future work this design can be implemented and furthermore, multiple types of harvester can be used for flexibility as expansions.

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