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Design and Development of a Maximum Power Point Tracking (MPPT) charge controller for Photo-Voltaic (PV) power generation system

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Abstract: - *This paper describes how to implement MPPT using the most popular switching power supply topology. There are many published works on this topic, but only a tiny portion of them show how to actually implement the algorithms in hardware, as well as state common problems and pitfalls. In our work to keep the design simple we have used Arduino Nano. It has features like: LCD display, Led Indication and it is equipped with various protections to protect the circuitry from abnormal condition. This design is suitable for a 50W solar panel to charge a commonly used 12V lead acid battery. As the maximum power point (MPP) of photovoltaic (PV) power generation systems changes with changing atmospheric conditions (e.g. solar radiation and temperature), an important consideration in the design of efficient PV systems is to track the MPP correctly. We have implemented the most common MPPT algorithm named Perturb and Observe (PO) to control the output of a synchronous buck-converter.*

Keywords: - *Photovoltaic systems, MPPT techniques, Perturb and Observe, Buck converter, Arduino*

I.   INTRODUCTION

Using a solar panel or an array of panels without a controller that can perform Maximum Power Point Tracking (MPPT) will often result in wasted power, which ultimately results in the need to install more panels for the same power requirement. For smaller/cheaper devices that have the battery connected directly to the panel, this will also result in premature battery failure or capacity loss, due to the lack of a proper end-of-charge procedure and higher voltage. In the short term, not using an MPPT controller will result in a higher installation cost and, in time, the costs will escalate due to eventual equipment failure. Even with a proper charge controller, the prospect of having to pay 30-50% more up front for additional solar panels makes the MPPT controller very attractive [1].The buck converter is used since it has a linear voltage transfer function when operating in Continuous Conduction Mode (CCM). This simplifies things a lot, and the MPPT controller can be implemented by operating directly on the converter duty cycle. The other topologies have a nonlinear voltage transfer function, and operating directly on the duty cycle will yield unpredictable results, especially at high duty cycles. In this case, the algorithm modifies the solar panel operating voltage by using a proportional integral (PI) control loop, which steers the voltage to the desired value [2-9]. In the subsequent part of this paper, the section 2 presents the basics of MPPT. In section 3 the PO algorithm is explained in brief. The Buck converter is discussed in section 4. The total hardware design procedure is illustrated in section 5and 6. The output results are presented in section 7. Finally concluding remarks are included in section 8.

II. MAXIMUM POWER POINT TRACKING

Maximum power point tracking (**MPPT**) is a technique used with wind turbines and photovoltaic (PV) solar systems to maximize power output. PV solar systems exist in several different configurations. The most basic

version sends power from collector panels directly to the DC-AC solar inverter, and from there directly to the electrical grid. A second version, called a hybrid inverter, might split the power at the inverter, where a percentage of the power goes to the grid and the remainder goes to a battery bank. The third version is not connected at all to the grid but employs a dedicated PV inverter that features the MPPT. In this configuration,

power flows directly to a battery bank. A variation on these configurations is that instead of only one single inverter, micro inverters are deployed, one for each PV panel. This allegedly increases PV solar efficiency by up to 20%. New MPPT equipped specialty inverters now exist that serve three functions: grid-connecting wind power as well as PV, and branching off power for battery charging. [10]

This paper is about the application of MPPT concerns itself only with PV solar. Solar cells have a complex relationship between temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve as shown in figure 1. It is the purpose of the MPPT system to sample the output of the PV cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. MPP (Maximum power point) is the product of the MPP voltage (Vmpp) and MPP current (Impp) [12].

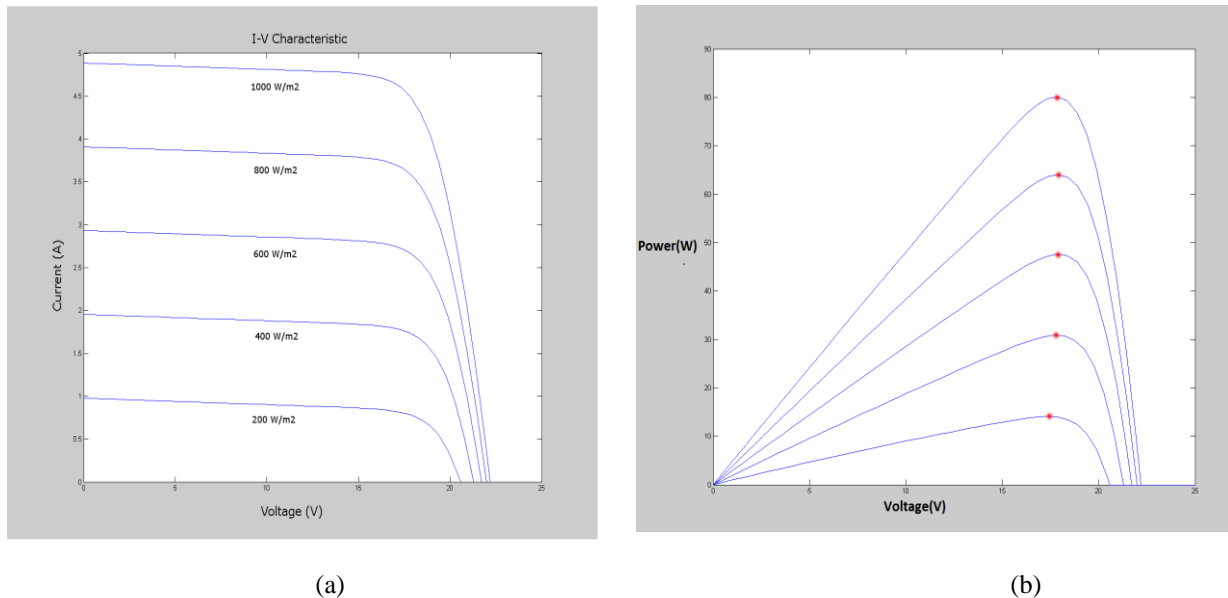(a)   (b)

Figure 1.(a) IV characteristics of PV panel for different irradiance level . (b) PV characteristics corresponding to IV characteristics in (a). Red dot shows the Maximum power point (MPP).

The author [10, 11] compares and evaluates the percentage of power extraction with MPPT and without MPPT.
It clearly shows that when we use MPPT with the PV system, the power extraction efficiency is increase to 97%. The study of developing a PV charging system for li-ion batteries by integrating MPPT and charging control for the battery is reviewed. The overall block diagram of PV panel with dc-dc converter and MPPT is shown in figure 2 [12].
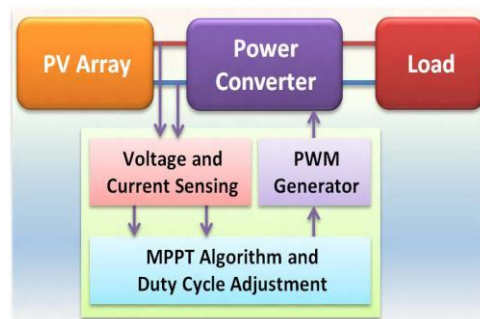

Figure 2. Block diagram of a MPPT controller.

III. PERTURB & OBSERVE ALGORITHM

The perturb & observe (P&O) algorithm, also known as the "hill climbing" method, is very popular and the most commonly used in practice because of its simplicity in algorithm and the ease of implementation. The most basic form of the P&O algorithm operates as follows. Figure 17 shows a PV module's output power curve as a function of voltage (*P-V* curve), at the constant irradiance and the constant module temperature, assuming the PV module is operating at a point which is away from the MPP. In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, ΔP, is observed. If the ΔP is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP [13]. Figure 3 shows the flowchart of this algorithm.
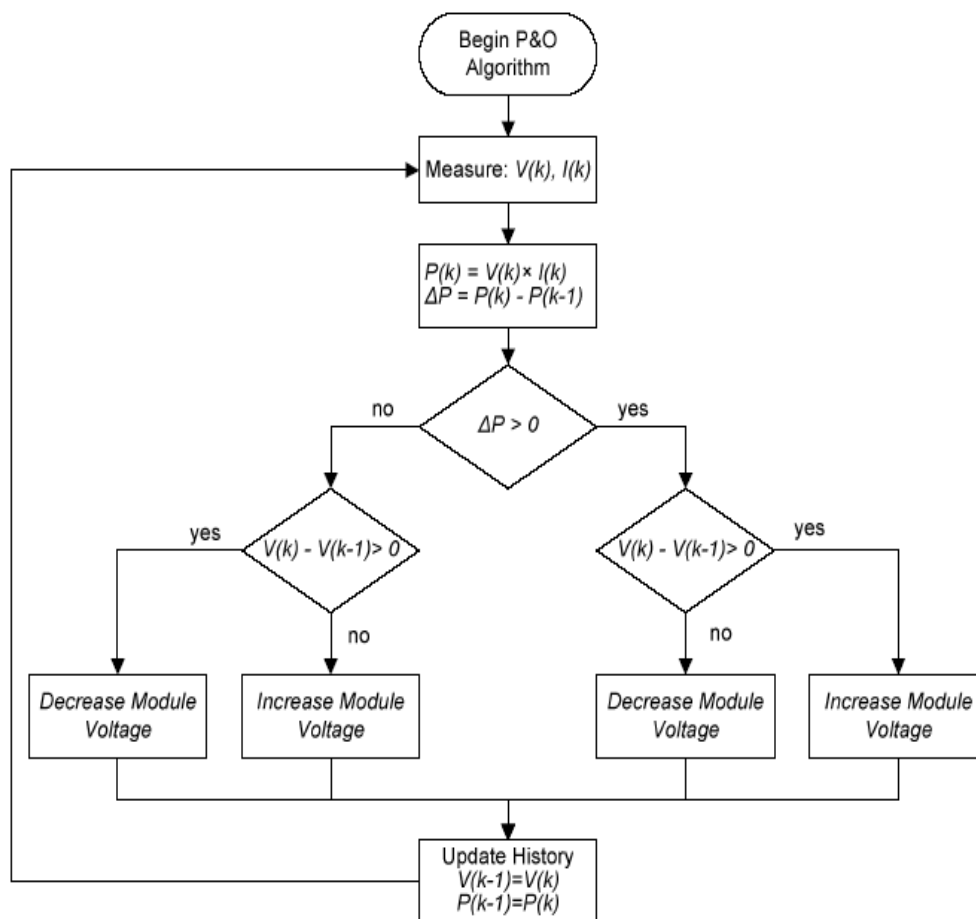
Figure 3. Flow Chart of PO algorithm used in our MPPT charge controller.

IV.SWITCHED MODE DC-DC CONVERTERS

The heart of MPPT hardware is a switch-mode DC-DC converter. It is widely used in DC power supplies and DC motor drives for the purpose of converting unregulated DC input into a controlled DC output at a desired voltage level. MPPT uses the same converter for a different purpose: regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer. As stated above, in our design we have used the buck converter. The principle of the buck converter is presented below.

4.1 The Buck Converter

A buck converter is a step-down DC to DC converter. it is a switched-mode power supply that uses two switches (a transistor and a diode), an inductor and a capacitor.

4.1.1 Theory of operation

The operation of the buck converter is fairly simple, with an inductor and two switches (usually a transistor and a diode) that control the inductor. It alternates between connecting the inductor to source voltage to store energy in the inductor and discharging   the inductor into the load.
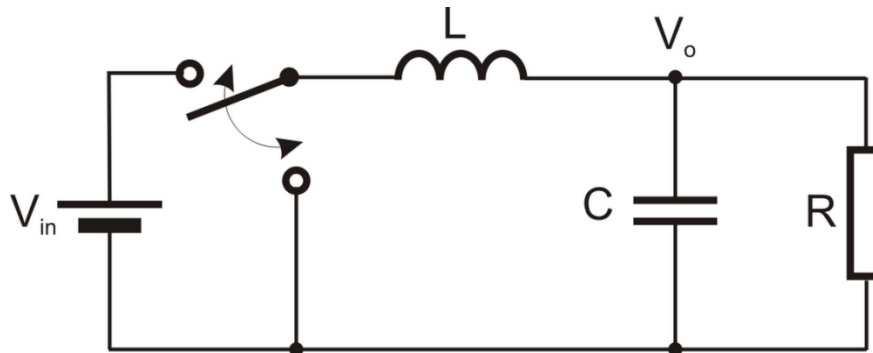

Figure 4. Buck Converter

For the purposes of analysis it is useful to consider an idealized buck converter. In the idealized converter all the components are considered to be perfect. Specifically the switch and the diode have zero voltage drop when on and zero current flow when off and the inductor has zero series resistance. Further it is assumed that the input and output voltages do not change over the course of a cycle (this would imply the output capacitance being infinitely large).

A buck converter operates in continuous mode if the current through the inductor (IL) never falls to zero during the commutation cycle. In this mode, the operating principle is described below:

- When the switch pictured above is closed (On-state, top of figure 2), the voltage across the inductor is $V_L = V_i - V_o$. The current through the inductor rises linearly. As the diode is reverse-biased by the voltage source V, no current flows through it;

- When the switch is opened (off state, bottom of figure 2), the diode is forward biased. The voltage across the inductor is $V_L = -V_o$ (neglecting diode drop). Current IL decreases.

The energy stored in inductor L is

$$E = \frac{1}{2} L \times I_L^2$$ $- -$ (1)

Therefore, it can be seen that the energy stored in L increases during On-time (as IL increases) and then decreases during the Off-state. L is used to transfer energy from the input to the output of the converter.

The rate of change of IL can be calculated from:

$$V_L = L \frac{dI_L}{dt}$$ $- -$ (2)

With VL equal to $V_i - V_o$ during the On-state and to $-V_o$ during the Off-state. Therefore, the increase in current during the On-state is given by:

$$\Delta I_{L_{on}} = \int_0^{t_{on}} \frac{V_L}{L}\, dt = \frac{(V_i - V_o)}{L} t_{on}$$ $- -$ (3)

, t{on} = DT

Identically, the decrease in current during the Off-state is given by:

$$\Delta I_{L_{off}} = \int_{t_{on}}^{T = t_{on} + t_{off}} \frac{V_L}{L}\, dt = -\frac{V_o}{L} t_{off}$$ $- -$ (4)

, t{off} = (1-D)T

If we assume that the converter operates in steady state, the energy stored in each component at the end of a commutation cycle T is equal to that at the beginning of the cycle. That means that the current IL is the same at t = 0 and at t = T (see figure 4).

So we can write from the above equations:

$$\frac{(V_i - V_o)}{L}t_{on} - \frac{V_o}{L}t_{off} = 0 \quad \text{---} \quad (5)$$

It is worth noting that the above integrations can be done graphically: In figure 4, is proportional to the area of the yellow surface, and $\Delta I_{L_{off}}$ to the area of the orange surface, as these surfaces are defined by the inductor voltage (red) curve. As these surfaces are simple rectangles, their areas can be found easily: $(V_i - V_o)\,t_{on}$ for the yellow rectangle and $-V_o t_{off}$ for the orange one. For steady state operation, these areas must be equal.

As can be seen on figure 4, $t_{on} = DT$ and $t_{off} = (1-D)T$. D is a scalar called the duty cycle with a value between 0 and 1. This yield:

$$(V_i - V_o)DT - V_o(1 - D)T = 0$$
$$\Rightarrow V_o - DV_i = 0$$
$$\Rightarrow D = \frac{V_o}{V_i} \quad \text{---} \quad (6)$$

From this equation, it can be seen that the output voltage of the converter varies linearly with the duty cycle for a given input voltage. As the duty cycle D is equal to the ratio between ton and the period T, it cannot be more than 1. Therefore, $V_o \leq V_i$. This is why this converter is referred to as step-down converter. So, for example, stepping 12 V down to 3 V (output voltage equal to a fourth of the input voltage) would require a duty cycle of 25%, in our theoretically ideal circuit.

V. SYSTEM OVERVIEW.

The overall system diagram can be viewed as in figure 5. The Required specifications are given in table 1.
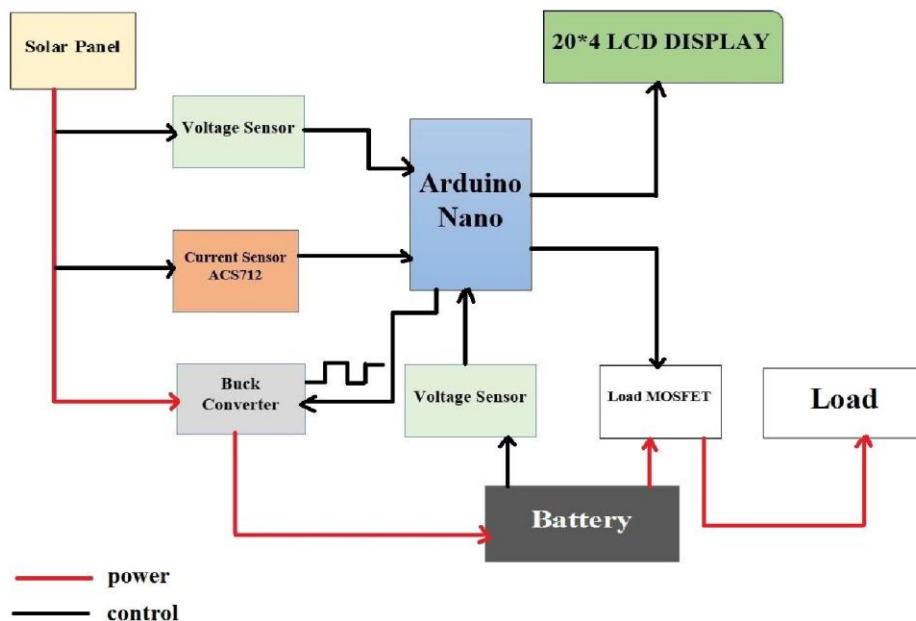

Figure 5. System block diagram.

Table 1. Features of the MPPRT controller

Specification of the prototype of solar charge controller	Electrical Specification of Buck converter
1. Based on Perturb and observe MPPT algorithm 2. LED indication for the state of charge 3. 20x4 character LCD display for displaying voltages, current, power etc. 4. Overvoltage / Lightning protection. 5. Reverse power flow protection. 6. Short Circuit and 7.Over load protection	1. Output Voltage =12 V 2. Max. Output Current = 5A. 3. Output Power = 50 W. 4. Input = 12-25V.

VI. IMPLEMENTION STAGE

In the implementation stage most important task was to get the component in accordance with the specification of the appliance. There are 2 main sub stages also: one is the hardware implementation and the other is implementation of the software. All the components with proper value are shown in the schematic below; the software is also implemented firstly in the simulation as we see in figure 6.

☐ The input power connector to the solar panels is the screw terminal JP1 and JP2 is the output screw terminal connector to the battery. The third connector JP3 is connection for the load.

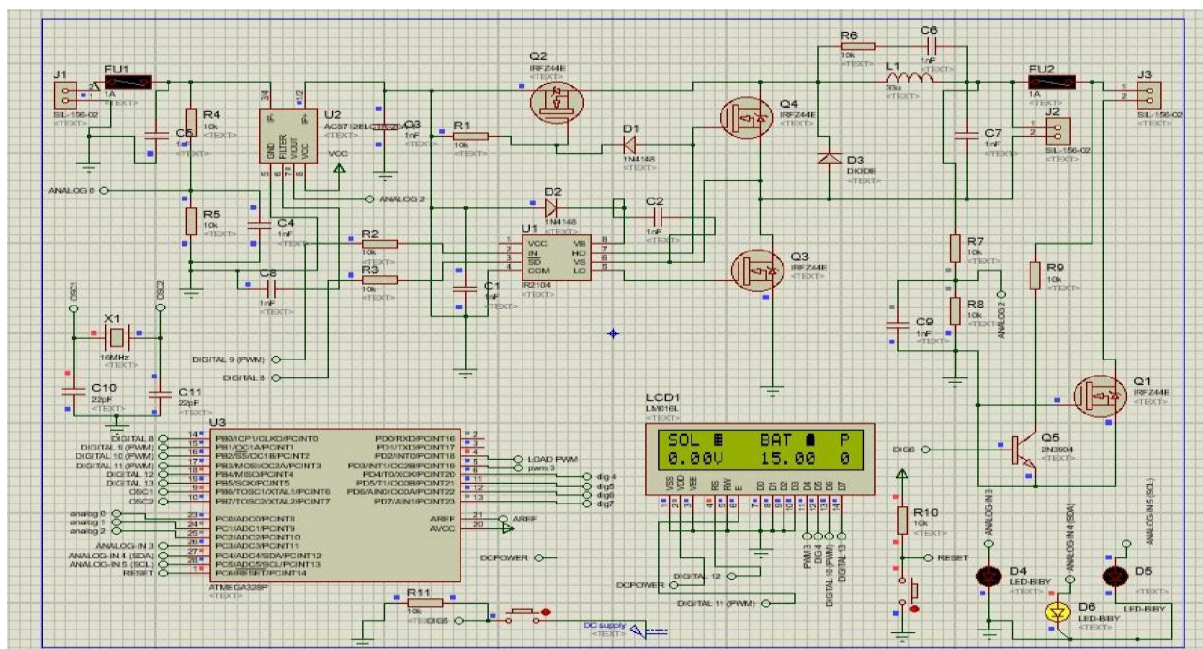☐ F1 and F2 are the 5A safety fuses.

Figure 6. Simulation of the system.

☐ The buck converter is made up of the synchronous MOSFET switches Q2 and Q3 and the energy storage devices inductor L1 and capacitors C1 and C2. The inductor smooths the switching current and along with C2 which smooths the output voltage.

☐ Capacitor C8 and R6 are a snubber network, used to cut down on the ringing of the inductor voltage generated by the switching current in the inductor.

☐ The third MOSFET Q1 is added to allow the system to block the battery power from flowing back into the solar panels at night. As all diodes have a voltage drop a MOSFET is much more efficient.Q1 turns on when Q2 is on from voltage through D1. R1 drains the voltage off the gate of Q1 so it turns off when Q2 turns off.

◻ The diode D3 (HER 507) is an ultra-fast diode that will start conducting current before Q3 turns on. It is supposed to make the converter more efficient.

◻ The IC IR2104 is a half bridge MOSFET gate driver. It drives the high and the low side MOSFETs using the PWM signal from the arduino (Pin -D9) .The IR2104 can also be shut down with the control signal (low on pin -D8) from the Arduino on pin 3.

◻ D2 and C7 are part of the bootstrap circuit that generates the high side gate drive voltage for Q1 and Q2. The software keeps track of the PWM duty cycle and never allows 100% or always on. It caps the PWM duty cycle at 99.9% to keep the charge pump working.

◻ There are two voltage divider circuits (R1, R2 and R3,R4) to measure the solar panel and battery voltages. The output from the dividers are feeds the voltage signal to Analog pin-0 and Analog pin-2 .

◻ The ceramic capacitors C3 and C4 are used to remove high frequency spikes.

◻ The MOSFET Q4 is used to control the load. The driver for this MOSFET is consists of a transistor and resistors R9 , R10.

◻ The diode D4 and D5 are TVS diodes used for over voltage protection from solar panel and load side.

◻ The current sensor ACS712 sense the current from the solar panel and feeds to the Arduino analog pin-1.

◻ The 3 LEDs are connected to the digital pins of the microcontroller and serve as an output interface to display the charging state.

◻ Reset switch is helpful if the code gets stuck.

◻ The back light switch is to control the back light of LCD display.

VII. HARDWARE TESTING STAGE

In this step especially the input and output of the buck converter is tested.
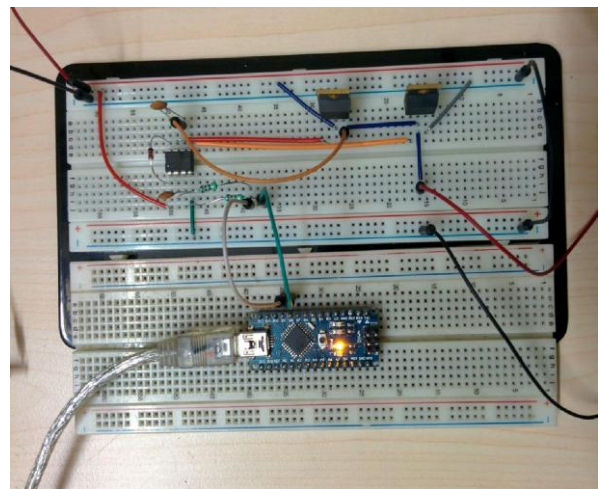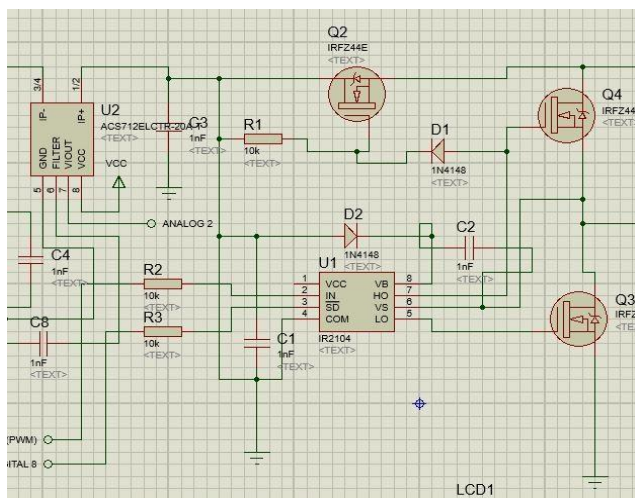

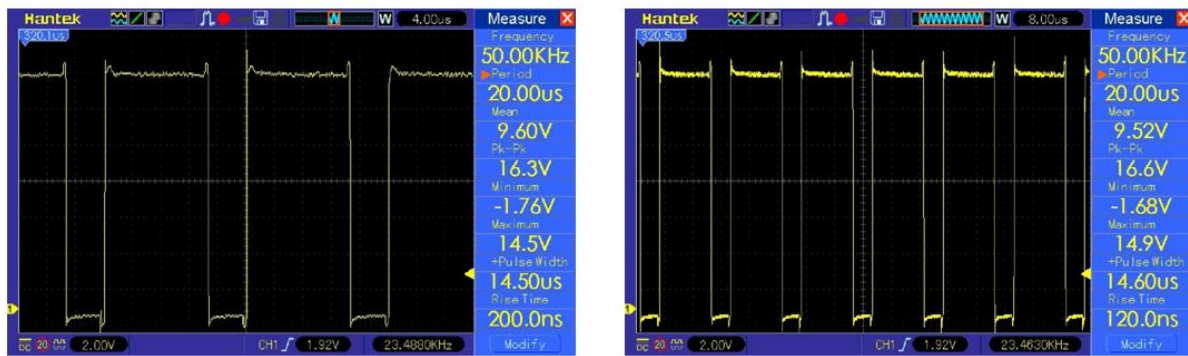Figure 7. Test schematic (Left) and Hardware prototype of the (Right) system.
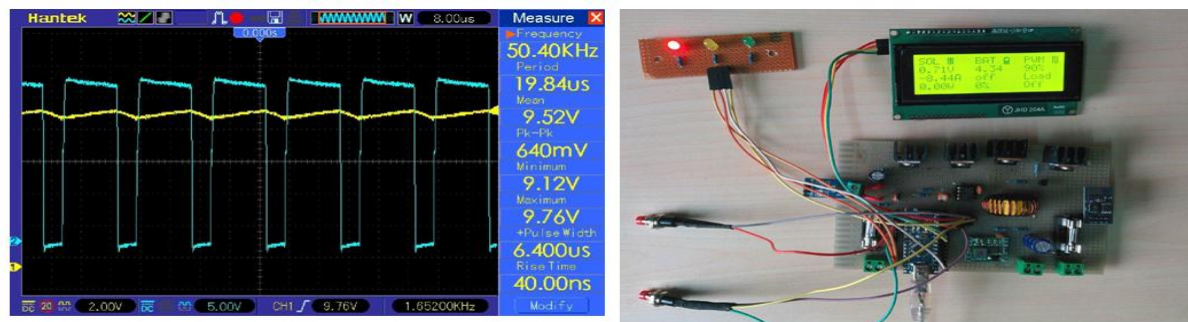
Figure 8. PWM output from the Arduino.

Figure 9. Output of the Buck converter (Left). The complete prototype sing Arduino.(Right)

VIII.   CONCLUSION

The Maximum Power Tracker uses an iterative approach to finding this constantly changing MPP. This iterative method is called hill climbing algorithm. To achieve MPPT, the controller adjusts the voltage by a small amount from the solar panel and measures power, if the power increases, further adjustments in the direction are tried until power no longer increases. The voltage to the solar panel is increased initially, if the output power increase, the voltage is continually increased until the output power starts decreasing. Once the output power starts decreasing, the voltage to the solar panel decreased until maximum power is reached. This process is continued until the MPPT is attained. This result is an oscillation of the output power around the MPP.

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