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An Efficient and Intelligent Solar Charge Controller: Design and Prototyping

M. Awais, I. Akram, and J. Iqbal

***Abstract*—Demand for alternative energy sources has increased incredibly due to the energy crisis in Pakistan. Photo voltaic system is one of the best solutions to cope with this crisis. Battery is a component of primary importance in these applications specifically in solar systems and it requires robust and efficient charging. This paper presents the design of Pulse Width Modulation (PWM) based solar charge controller that prevents battery from damage. It controls flow of charges to the battery and the load such that scenarios like battery over charging, under charging and over voltages are avoided while providing power to the load. It also prevents the system from abnormal conditions such as over-current. The proposed system also displays state of battery on a LCD with two LEDs indicating the position of the system. Furthermore, a data acquisition system is also built to view state of the system on a computer. Results collected from the in-house fabricated prototype demonstrate effectiveness of the proposed system.**

***Index Terms*— Charge controller, Cortex M3, Microcontroller, Solar battery, PWM.**

I. INTRODUCTION

DUE to the energy crisis in Pakistan, use of alternate energy sources like solar has increased to an extent. The battery is one of the main components used in these systems to store energy for later use. Every battery has a certain capacity to store the electricity. Also over charging, over voltage, over current and other conditions can reduce the lifetime of the battery and even cause damage. As the battery is one of the most expensive components of the system, its protection is important. In this paper, design of a charge controller is presented, that regulates the voltage of battery and source and prevents it from unwanted conditions. Overall system overview is shown in *Fig. 1.*

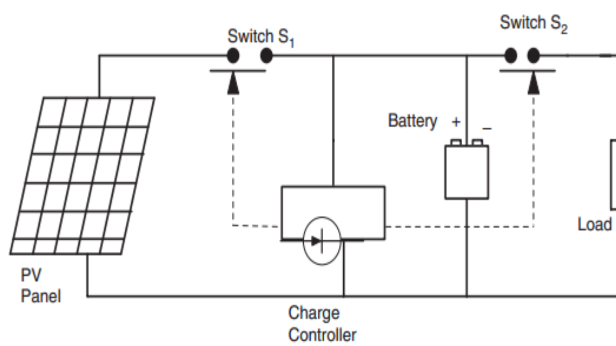

Fig. 1. System diagram of charge controller.

Developed charge controller prevents overcharging and may protect against over-voltage, which can reduce battery performance or life span, and may pose a safety risk. It may also prevent complete draining, i.e., 'Deep discharging' a battery, or can perform controlled discharges depending on the battery technology so as to protect battery life [1].

The battery storage in a PV system should be properly controlled to avoid catastrophic operating conditions like over charging or frequent deep discharging. Storage batteries account for most PV system failures and contribute significantly to both the initial and the eventual replacement costs. Charge controllers regulate the charge transfer and prevent the battery from being excessively charged and discharged [2].

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II. LITERATURE REVIEW

Several charge controllers have been reported in scientific community. Table I summarizes controller type, charge control technique used and its distinguished features.

Controller type	Technique used	Distinguished features
PWM	PWM based using buck DC-DC converter	Charging and discharging control of battery [3]
PWM	PWM based charging and discharging	Protection, Charging and discharging [4]
MPPT	MPPT technique	Charging and discharging control of battery, Reducing system power losses, Improving system efficiency, HVD & LVD (high voltage disconnect & low voltage disconnect) [5]
MPPT	PWM based controller by using buck DC-DC converter	Charging and discharging control of battery, Extract maximum power for battery charging [6]
MPPT	Constant Current Constant Voltage (CCCV) using DC-DC converter	Charging and discharging control of battery, CCCV technique used for reducing the battery charging time [7]
CUT-OFF	PV voltage directly used for charging and discharging purpose using MOSFET switches	Charging and discharging control of battery, Cost effective, Less complexity of the system, Easily modifiable system [8]
PWM	PWM based using shunt, series and DC-DC converter techniques	Charging and discharging control of battery, Over charging and deep discharging protection [9]
PWM	PWM based using DC-DC converter	Charging and discharging control of battery, Over charging and deep discharging protection, Over current and short circuit protection [10]
PWM	PWM based technique is used for charging and discharging purpose	Charging and discharging control of battery, Over charging and deep discharging protection, More efficiency of the system [11]
PWM	Charging and discharging of the car battery	Charging and discharging control of car battery [12]
PWM	Charging and discharging of the car battery	Charging and discharging control of car battery, Cost effective solution [13]
PWM	PWM based technique is used for charging and discharging purpose	Charging and discharging control of battery, Short circuit protection, HVD & LVD (high voltage disconnect & low voltage disconnect) [14]
PWM	PWM based technique used with ADC/DAC/DC-DC	Charging and discharging control of battery, Cost effective solution [15]
MPPT	MPPT by using buck-boost DC-DC converters	Charging and discharging control of battery, Over charging and deep discharging protection, Data acquisition [16]
PWM	PWM based shunt and series converter techniques	Charging and discharging control of battery, Over charging and deep discharging protection, Increasing battery life [17]
MPPT	MPPT by using inverters	Charging and discharging control of battery, Over charging and deep discharging protection [18]
MPPT	PWM based controller by using cuk converter along with MPPT	Charging and discharging control of battery, Maximum efficiency of the system [19]
PWM	PWM based technique is used for charging and discharging purpose	Charging and discharging control of battery, Charge controller module combined with data logging data transmitting option, V and I level control [20]
PWM	PWM based controller along with max power tracking by using product of V and I	Charging and discharging control of battery, Over charging and deep discharging protection, Increasing battery life [21]
PWM	PWM based controller by using buck DC-DC converter	Charging and discharging control of battery, Over charging and deep discharging protection [22]
MPPT	PWM based technique is used for charging and discharging purpose	Charging and discharging control of battery, Accurate results, CV and P&O algorithm implemented for good results [23]

III. SYSTEM MODEL

The output of the solar panel is initially checked for over-voltage and over-current condition for protection purpose. The voltage is then fed to the microcontroller. The controller keeps the battery fully charged without over-charging it. When the load is drawing power, the controller allows the charge to flow from the generation source into the battery and the load, or both using PWM and switch. When the controller senses that the battery is fully or nearly fully charged, it reduces or stops the flow of current from the generation source to the battery. It allows the load to connect with battery only when the source is not generating enough energy. The controller automatically disconnects the system once the battery is in the deep discharge position. An LCD and two LEDs are used to display the condition of the system as shown in *Fig. 2.* Protection is provided with Zener diode and fuse. A diode is used to prevent reverse current. The load is on or off using switch and battery is charged with PWM technique.

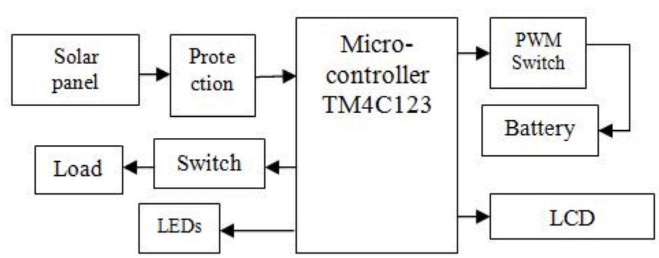

Fig. 2. Block diagram of the intelligent solar charge controller.

A. System protection

The solar input is passed through a protection block consisting of a Zener, a diode, and a capacitor. A 3A rated fuse protects from over-current. The components used in the designed circuit are rated above 3A. A Zener with 15V rating is used in reverse to protect the circuit from over-voltage. So any voltage above 15V will cause the system to shut down. The diode is used to block reverse current while a capacitor is used to protect the system from ripples that can cause damage to battery and microcontroller. The protection circuit is shown in *Fig. 3.*

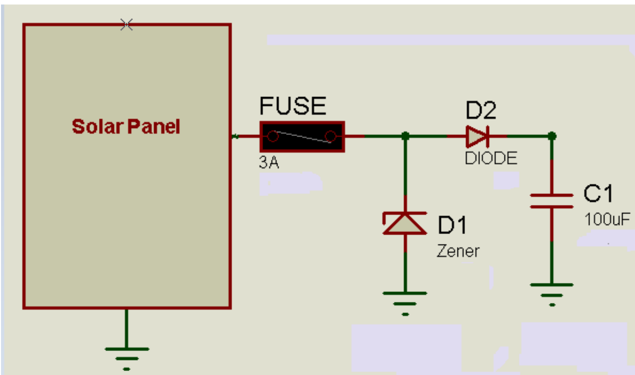

Fig. 3. Protection circuit for charge controller.

B. Voltage divider for sampling of voltage

Voltages are sampled by the controller at two places in the circuit for making a decision. Sampling is done for voltages from the solar panel and from the battery. TM4C123 microcontroller can bear at maximum 5V and it is a good practice to feed voltages less than 3.3V, so voltage divider circuit is designed with 10kΩ and 4.7kΩ which is placed near the battery and solar panel in a parallel fashion. The voltage divider circuit is shown in *Fig 4.*

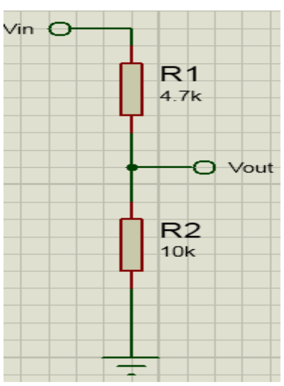

Fig. 4. Voltage divider for sampling.

The output voltage in Fig. 4 is given by,

$$V_{out} = V_{in}.\ R2/(R1+ R2) \quad (1)$$

With the opted values of R_1 and R_2 as shown in *Fig. 4,* the voltage dividing ratio is 0.3197. So maximum voltage that can appear at analog input of the microcontroller is,

$$V_{out}= 8.2 \times 0.3197$$
$$=2.62154V$$

In case of some fault occurring in the protection system, the microcontroller is safe for voltage up to 15.6396 V. Power consumed by this circuit is very small due to high resistance and is given by,

$$P = V^2/R \quad (2)$$

$$P = 8.2^2/14.7k = 0.00457W \text{ which is negligible.}$$

C. Switching

There are two points in the circuit where switching is used, one is battery and the other is a load. Both of them are in series hence the battery is charged by PWM based charge controller so that power can be provided to the load by the battery when solar power is not available. N-channel MOSFET is used for switching of load while P-Channel MOSFET for the battery as shown in *Fig. 5.* The load is simply switched on or off while battery needs PWM based charging. The duty cycle is controlled by the microcontroller based on the charging state of the battery.

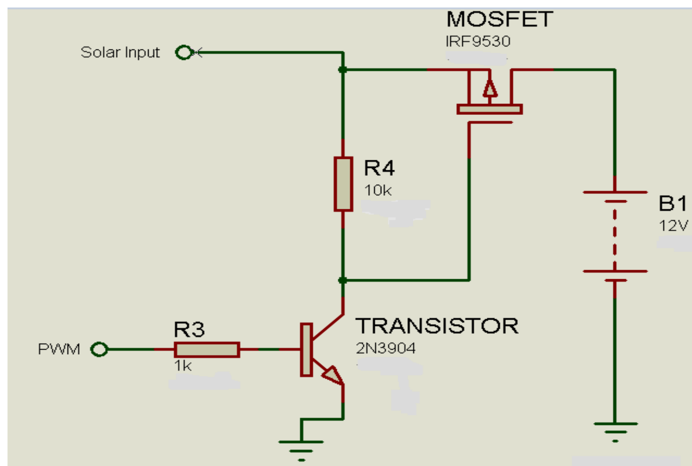

Fig. 5. Switching circuit for battery.

MOSFET driver is used here due to the fact that they have a large stray capacitance between the gate and other terminals, which must be charged or discharged each time the MOSFET is switched on or off. Since, a transistor requires a particular gate voltage in order to switch on, therefore the gate capacitor is charged adequately. Similarly, to switch the transistor off, charge is dissipated, i.e. the gate capacitor must be discharged.

IV. Results and Discussion

A. Circuit Design and Simulation

The complete circuit is first simulated on Proteus. The solar panel was simulated as a battery source for simulation purpose only. *Fig. 6* shows proteous design of the complete circuit. The input of solar panel is first passed through some protection block which checks for over-voltage, over-current and reverses current flow as discussed earlier. Further input is sampled with a voltage divider connected in parallel. The obtained voltage represents voltage of solar panel.

The solar panel voltage value is used in software to make certain decisions. A switching driver comprising of a MOSFET and a transistor is used for battery charging. PWM is generated on terminals of the transistor which then charges the battery based on the duty cycle of the PWM. Battery voltage is also sampled to see the present condition of the battery. The load is then connected in series with the battery. Another driver is used to switch on or off the load. These decisions are made by the software. Two LEDs are used to indicate system condition. When red LED is on, this means that the battery is fully discharged (<10%). Blinking of green LED indicates battery charging in progress while this LED if on implies that the battery is fully charged. LCD shows percentage charging of the battery and voltages of panel and battery. Serial communication is also kept for communication with a computer if needed.

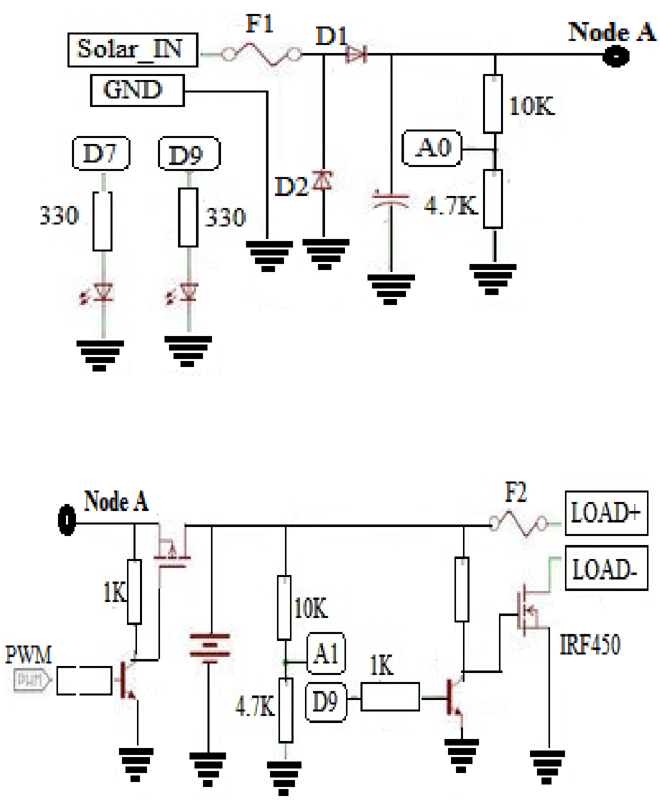

Fig. 6. Complete circuit of charge controller.

B. Experimental Results

It is the heart of the present research wok where all the developed logic is applied. Voltages are sampled from solar panel and battery and based on these two inputs, all the logic is applied. The primary task of the software is to make decisions about battery charging and to analyze on and off states of the load. Handling of display, LEDs and serial communication is also done by the software.

C. Battery and Solar Panel Voltages

Battery and solar voltages are two inputs of the system that decides states of the system. A resistance was placed after the solar panel to reduce the voltage and to increase the current at the same time for reducing charging time of the battery. For this system, logic given in Table II was used where V_B is the Battery voltage ($V_{Bmax} = 6.96V$) and V_S is Solar voltage ($V_{Smax} = 7.2V$)

TABLE II
SYSTEM MODELING RESULTS

Voltage condition	Status	PWM Duty cycle
$V_S > V_B$	Battery not charged	95%
$V_S > V_B$ & $V_B = V_{Bmax}$	Battery>80% charged	10%
$V_B>=7.2V$ (overcharging condition)	Battery not charged by solar panels	-
$V_B < 6V$ (deep discharging)	Red light will be on	-
$V_S < 3V$ and $V_B = 6.2V$ (battery is charged and solar light is not enough to produce power)	Load will be switched to battery	-

D. ADC Sampling

TM4C123 has two ADC modules with 12-bit resolution. In current application, software triggered conversion is used with busy-wait synchronization. As the speed of conversion does not matter much in developed application, so lowest sampling rate of 125k samples/sec was used. The output of ADC is in bits which are then converted to voltage level using following relationship;

$$V_{Measure} = (\text{ADC reading/ Resolution of ADC}) \times V_{System} \quad (3)$$

E. PWM generation

There are three modes related to PWM. If the battery is fully charged, then duty cycle will be 0%. If the battery is 80% charged, then PWM duty cycle will be 10% and if the battery is less than 80% charged, then PWM duty cycle is 80%. TM4C123 has two specific PWM modules with 16-bit counters. *Fig. 7* and *Fig. 8* show the PWM with 10% and 90% duty cycle respectively.

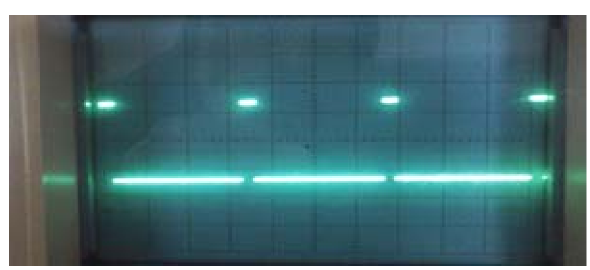

Fig. 7. 10.% PWM duty cycle.

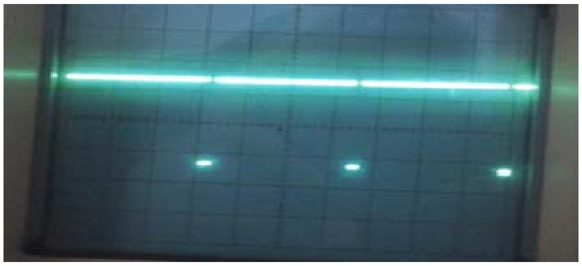

Fig. 8. 90% PWM duty cycle.

When the timer is initialized with the count value of zero, the reload value which is proportional to the frequency of PWM is immediately reloaded. Reloading also resets the output flip-flop as explained in *Fig. 9*. Now counter starts decrementing with each cycle and the current value is continuously compared against the value of duty cycle.

Initially, the counter value is higher than the duty cycle comparator. When current value becomes equal to the duty cycle value, flip-flop value goes high and it resets. Count continues decrementing untill it reaches 0 and underflow occurs resulting in reloading. Thus, PWM cycle ends and new cycle restarts [24].

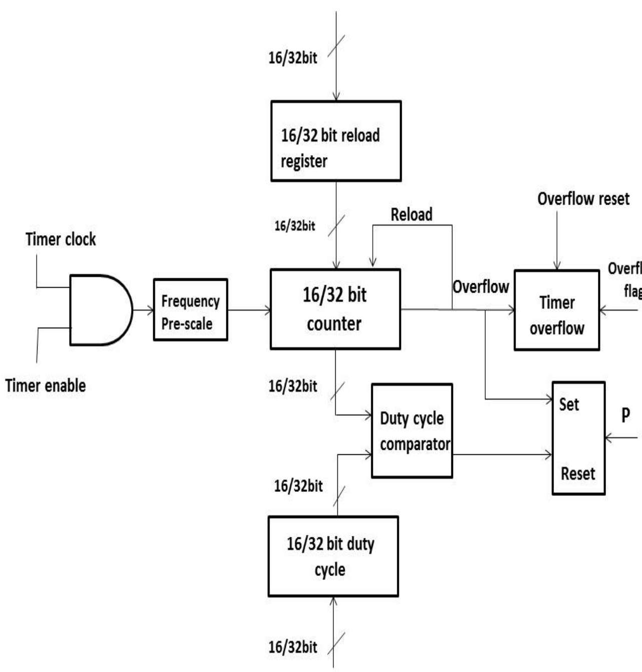

Fig. 9. PWM generation in TM4C123.

Two parameters are used for PWM generation. Developed system uses 100Hz PWM with a duty cycle of 90% and 10%. Reload value determines frequency of PWM with the relationship given as,

$$V_{Reload} = f_{clock}/f_{PWM} \quad (4)$$

Since, the counter is of 16 bit which can have a maximum value of 65,356, so, V_{Reload} will be 160,000. Hence, a pre-scalar is needed here. A pre-scalar of 16 is used resulting in new reload value of 10,000. For duty cycle, the value is subtracted from reload value. So, for 90% duty cycle, the comparator will have a value of 1, 000 and for 10% it will be 9,000. PWM charge controller increases charging efficiency, allowing for rapid recharging and maintaining healthy battery life. In overall, a PWM charge controller offers following advantages; Battery aging adjustments, Battery gassing and heating reductions, Charge acceptance increase, High battery capacity maintenance, lost battery recovery and Self-regulation with drops in voltage or temperature [25].

F. Algorithm

Overall functional flow chart of the system is shown in *Fig 10*.

G. Hardware

PCB of the circuit is designed in Proteus. The circuit is designed in two different modules; one is main controller circuit and the other is LCD interface for display.

H. Data Acquisition

Data is sent using serial communication with a baud rate of 9600 bps. An application using Labview is developed to get and display the obtained data as shown in *Fig. 11*.

The data corresponding to the current status of the system is sent using three values; battery voltage, solar voltage and % charging of battery. It is then separated using string function of Labview and converted into float value for display. In current application, USB cable is used for data communication. For practical purpose, Bluetooth Low Energy (BLE) or another appropriate device is used.

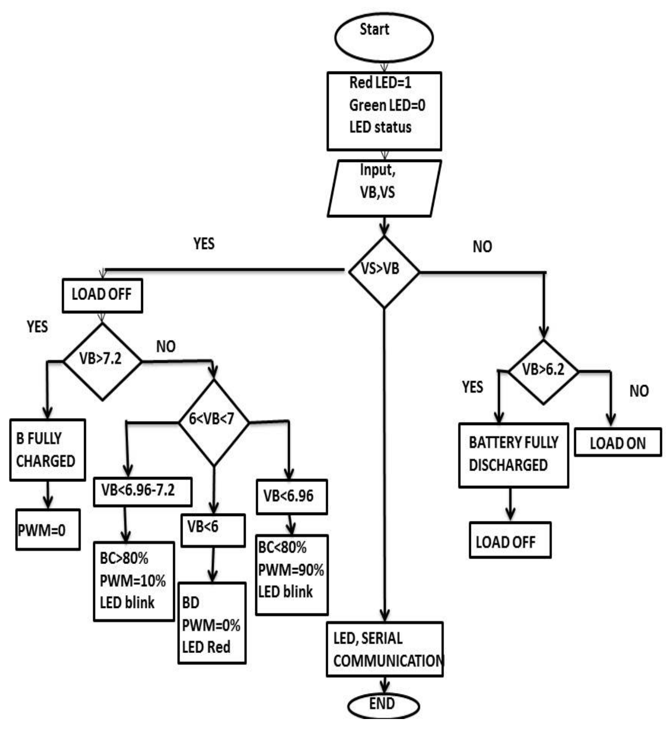

Fig. 10. Overall functional flow chart of the system.

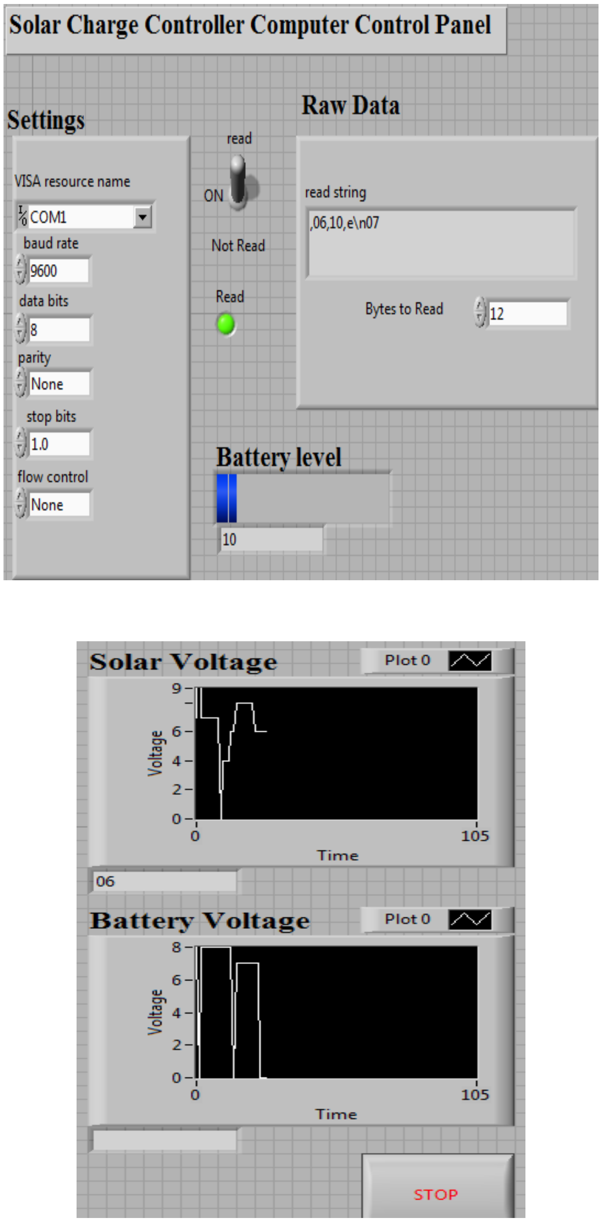

Fig. 11. Front panel of data acquisition system.

V. CONCLUSIONS

Energy crisis in Pakistan needs a reliable and quick source of energy. The renewables generation through solar offers comparatively more advantages and can be used to cope with the increasing energy demands. Generation from solar is only possible in day time when sun light is present. For night, stored energy in the battery is used. Developed system presents a low-cost and indigenously developed solar charge controller which is centered on ARM Cortex controller. PWM is used for switching since it is cheap and exhibits better performance compared to conventional on-off charge controller. A data acquisition system is also developed to view the data on computer. Developed charge controller can be used in small applications to increases battery life and to ensure efficient use of energy. So, life time of the battery increases with the developed protection circuit and overall system becomes efficient in term of cost and performance.

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