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# Design and Implementation of PV Fed Local UPS Inverter

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***Abstract-*** **Locally manufactured Uninterruptible Power Supply (UPS) units are purchased as an alternative to rolling blackouts and load shedding in underdeveloped and developing countries like Pakistan. These locally manufactured UPS units are energy-inefficient, causing stress on the national grid and cost-intensive for the residential consumer in the form of high utility bills of electricity. In this regard, the authors have proposed the PV fed local UPS inverter to make the existing UPS unit more efficient through photovoltaic (PV) energy without disrupting its function of providing uninterrupted supply during load-shedding hours. In order to validate the performance of the proposed PV fed local UPS inverter, the maximum power point tracking (MPPT) PV charge controller module is designed and implemented practically in a hardware setup and simulated in MATLAB/Simulink and Proteus environment, respectively. Moreover, the installation of an MPPT PV charge controller module in an existing locally manufactured UPS unit is also discussed. The practical results demonstrate the superiority of the proposed PV fed local UPS inverter with an average efficiency of 81.51% and a lowest total harmonic distortion (THD) of 1.29% as compared to existing UPS inverters.**

***Index Terms--*** **Maximum power point tracking, Uninterrupted power supply, PV charge controller, UPS inverter.**

## I. INTRODUCTION

With the rise in human population in underdeveloped and developing countries, the problem of the energy crisis has become a certainly not ending issue for these countries. In developing countries particularly Pakistan, every year the electricity demand increases by 5% which means approximately 1000 Mega Watt (MW) is added as a burden on the national grid [1]. The current electricity shortfall of Pakistan is almost 3000 MW that has given rise to rolling blackouts/load-shedding through the country. This situation of blackouts/load-shedding is worsened especially during summers due to the rise in electricity demand [2]. Electricity generators and UPS units are purchased as an alternative to counter the problem of rolling blackouts/load-shedding [3].

The electric generators burn fossil fuels like petrol, diesel, and natural gas to generate electricity. The burning process of the electric generator releases harmful greenhouse gases (GHG) that contribute to climate change [4]. Pakistan's overall GHG emissions are projected to increase from 347 million tons of $CO_2$ equivalents ($MTCO_2e$) in 2011 to 4621 $MTCO_2e$ in 2050 [5]. These emissions are responsible for raising the global temperature. According to [6], Pakistan's temperature is going to rise from 0.9 to 1.5 degrees Celsius by 2020 until 2050. Due to the rise in global temperature, an extreme risk of heat exposure is currently present in southern Pakistan [7]. Besides the climate change factor, the increase in CHG emissions is giving rise to air pollution in large metropolitan cities. According to the institute for health metrics and estimation, air pollution was categorized as the ultimate environmental/occupational cause for highest deaths and disabilities in Pakistan during 2017, and the 5th highest factor overall [8]. Moreover, electric generators are very uneconomical as their operating cost increases with the rise in the prices of fossil fuels [9]. The rise in fuel prices is directly associated with its resources in the region. The fossil fuel and oil demand in Pakistan will reach 131.8 MTOE and 29.9 MTOE in 2030, which is more than the present national refining capacity, while natural gas demand will be 85.8 MTOE, which will deplete known gas reserves of the country in a five-year time span [10].

On the other hand, the purchase of UPS units has increased as it charges the battery from the grid supply and provides uninterrupted power supply during load-shedding hours. The unpopularity of the electric generators is discussed in [11] by comparing the purchase ratio of the Pakistani users after every five years in Islamabad Electric Supply Company (IESCO) authority. This assessment of different backup supplies for the years 2005, 2010, and 2015 in IESCO authority is presented in Fig. 1. Although, this rising popularity of UPS units compared to electric generators has a positive influence on the environment, although these units are contributing to the enhancement of the energy crisis [12]. In the year 2017, the national utilization was 23,538 MW and the UPS wastage was 1647.7 MW (7%) as specified in [13].

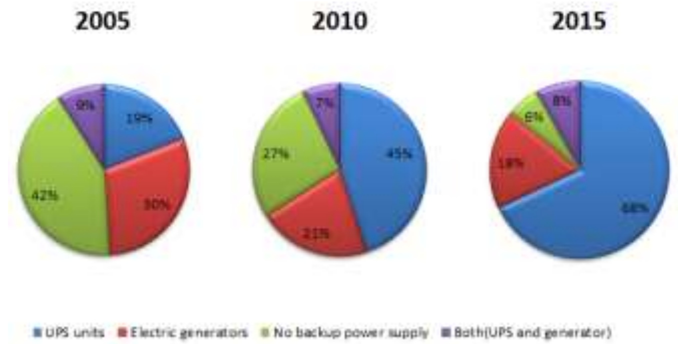


Figure 1. Comparison of different backup power supplies

The average efficiency of these UPS units is calculated to be between 50%-60% after the testing of multiple UPS units [14]. Moreover, half of the energy is wasted during the charging of the batteries (i.e., Alternating Current (AC) to Direct Current (DC) conversion) in these UPS units. In the context of the above-mentioned problem, the proposed system is the best solution to make these locally manufactured UPS more efficient by converting them into a PV fed UPS inverter. The system discussed in this paper is the design and installation of MPPT PV charge controller in the locally manufactured UPS. The system is designed such that it will prioritize the MPPT PV charge controller to charge the batteries during availability of sunlight, while during unavailability of sunlight (i.e., at night or on a cloudy day) the UPS will charge the batteries from the grid supply. In this aspect, the system improved the efficiency of the locally manufactured UPS without disrupting its function of providing uninterrupted power supply during blackouts/load-shedding hours.

Figure 2. Global Solar Atlas

As mentioned earlier, the UPS units locally manufactured in Pakistan wastes a lot of energy during the charging of batteries. One of the proposed solutions by [15] was the conversion of these UPS units into a solar UPS inverter. This is one of the best possible proposed solutions as Pakistan has a great potential of solar energy. According to [16], on average almost 1900-2200 kWh/m2 solar radiation intensity radiates on the country annually. Similarly, [17] presents an extensive assessment of the countries solar energy potential. To verify the countries solar energy potential, calculations were made using the global solar atlas an initiative by the World Bank under a project funded by the Energy Sector Management Assistance Program (ESMAP) as shown in Fig. 2 [34].

While it is evident by using the global solar atlas that the Pakistan has a good PV power output, direct normal irradiation (DNI), and Global horizontal irradiation (GHI) as can be seen in Fig. 2. Although, a survey conducted in southern Punjab in 2018 showed that 29% of the participants already used solar energy as an alternative energy source/backup power supply, 35% were using UPS units, and 10% were using electric generators, whereas 26% have no alternative energy source. According to [18], among the 29% of solar energy consumers, 40% reduced their electricity bills by 41-50%, and 33% reduced it by 26-40%. The significant reduction in electricity bills by shifting to solar energy and the wastage of energy in local manufactured UPS units especially during the charging of batteries as mentioned previously both highlights the importance of this work. Moreover, one of the reason that is preventing the adoption of solar energy as an alternative energy source mentioned by [18] is that the majority of the participants about 67% claim that the initial capital cost of the installation of solar system is the biggest hurdle in solar energy utilization. Therefore, by converting the existing local manufactured UPS unit into solar UPS inverter is more economical as compared to the costly imported solar inverters, which is not only attract more solar energy consumers although also shift the consumers using these UPS units to solar energy utilization.

In order to convert the UPS unit into a solar UPS system, a solar charge controller need to be designed. Two types of solar charge controllers are currently used, the pulse width modulation (PWM) and maximum power point tracking (MPPT) charge controller. The comparison between the two shows that the MPPT charge controllers are more superior to PWM charge controllers, and are 30% more efficient than the PWM charge controllers [19]. There are different algorithms for the maximum power point tracking (MPPT) of the solar charge controller. According to comparison of [20], MATLAB simulations reveals that the incremental conductance MPPT method have highest efficiency of 97.1%, and the fastest convergence as compared to the other two methods. Likewise, according to MATLAB simulations of [21], incremental conductance MPPT method has an efficiency of 99.5%. Consequently, in proposed system, the MPPT solar charge controller is designed by using incremental conductance algorithm. Subsequently, the MPPT solar charge controller module is installed in an existing UPS unit such that the function of providing an uninterruptable power supply is not disturbed. The [22]-[24] has suggested the system consists of a combined solar power system and UPS units. Many existing users of these

UPS units might consider investing in their solar power generation due to the lower lifetime cost of the installed system as compared to conventional stand-alone solar power system. This anticipated system matches the proposed local solar UPS inverter although they have made his UPS, while we convert the existing local manufactured UPS units into solar UPS inverter by installing a solar charge controller. Likewise, [25] has also developed a similar system through Proteus simulation, although not implemented the system practically. In [26], the authors have proposed a h-bridge PV inverter to drive the residential resistive load applications. However, the cost of the inverter increases due to the transformer utilized. Moreover, the efficiency of the inverter is not discussed as well. Asymmetrical cascaded multilevel inverter (ACMLI) has been designed and implemented in [27], however the output voltage total harmonic distortion (THD) is very high. In [28], the authors have proposed a PV and grid connected inverter which worked in two modes. During sunshine hours, PV energy fulfil the load demand while to charge the batteries both grid and PV module are utilized. However, the efficiency of the inverter is not specified and MPPT charge controller is not implemented. While [29] has converted a UPS unit into a solar UPS inverter, however, not specify the architecture of the UPS unit. The UPS unit used in the proposed system is locally manufactured having the same architecture throughout the country. The entire system of our solar UPS inverter is shown in Fig. 3.

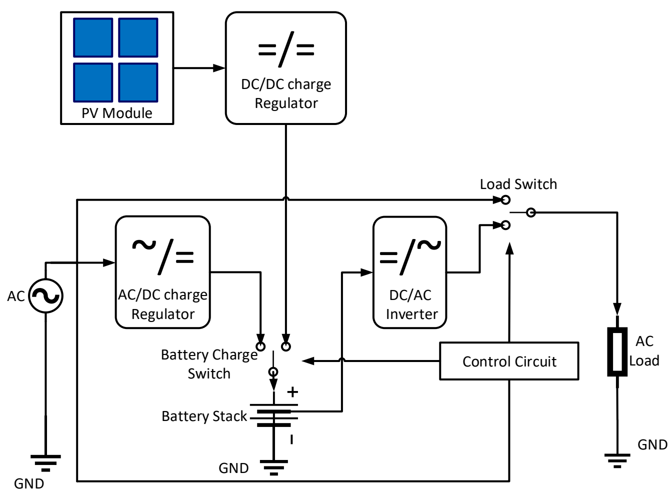


Figure 3. Design of our system in existing UPS

Based on the literature survey, in this paper, the authors claim the following contributions.

- The local PV fed local UPS inverter is designed and implemented practically and simulated in Proteus, and MATLAB/Simulink environment.
- The proposed system is design such that it will prioritize the MPPT PV charge controller to charge the batteries during availability of sunlight, while during unavailability of sunlight (i.e., at night or on a cloudy day) the UPS will charge the batteries conventionally from the grid supply. As a result, the large number of losses accounted from UPS units, and high electricity bills are reduced.
- The overall efficiency of a locally manufactured UPS unit is about 50-60% as declared in [11], [13], [20], and [21]. However, by converting these UPS units into proposed solar-based UPS, its charging efficiency is increased by 13.35%, resulting in the increase of its overall efficiency.
- Due to being locally manufactured, the proposed solar UPS inverter significantly reduces the capital cost of installation as compared to the costly imported solar inverters available in the market.

## II. IMPLEMENTATION OF MPPT BASED PV CHARGER

To develop a PV based local UPS, the first and major part of the system is the implementation of MPPT based PV charge controller. The implementation of the PV charge controller is divided into the following steps.

### A. MATLAB SIMULATION

Before going on to the practical implementation of the PV charge controller, the design is verified through the MATLAB/Simulink environment. The MATLAB simulation provided a better understanding of the working of a PV charge controller [30]. The overall operation and specifically the tracking of the maximum power point using the incremental conductance algorithm is visualized through MATLAB simulation. To analyze the actual working of the MPPT PV charge controller, the photovoltaic (PV) panel provided in MATLAB is utilized. Moreover, to analyze the actual efficiency of the PV charge controller, the PV panel is fed with irradiance and temperature input signals that are normally taken into consideration for PV panels, and a battery is employed at the output as shown in Fig. 4.

The PV module in Fig. 4 is used the incremental conductance algorithm for tracking the maximum power point. There are two methods for applying algorithms in MATLAB, by coding or state diagram. The incremental conductance algorithm in Fig. 4 is implemented through a state diagram that allows the visualization of the flow of an algorithm during the run time of the simulation. The state diagram, therefore, described about the insight and working of the algorithm. The measurements from the PV panel both input current and voltage are fed into the PV module as incremental conductance algorithm tracks the maximum power using short circuit (SC) current and open circuit (OC) voltage of PV panel. The SC current and OC voltage are required to obtain input power. Likewise, the charging current and output voltage of the battery are also required to acquire output power. Both the input and output power are fed into the oscilloscope which is used for observing the tracking of maximum power point.

### B. MICROCONTROLLER PROGRAMMING

The first step towards practical implementation is the coding for the PV charge controller. The code is divided into two parts, the MPPT algorithm, and battery charging program, respectively. The incremental conductance technique is selected for tracking the maximum power point as it works perfectly in unexpectedly

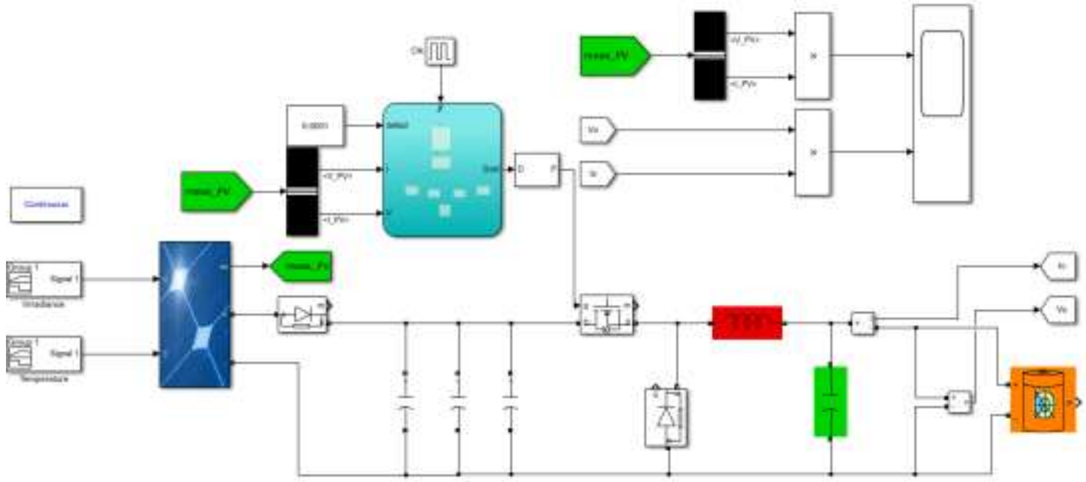

Figure 4. MATLAB simulation of MPPT PV charge controller using MATLAB/Simulink

changing atmospheric conditions, while the perturb and observe (P & O) technique fails under a rapidly changing atmosphere [20]. The incremental conductance method works by employing the (1)

$$(dI_{pv}/dV_{pv})=-(I_{pv}/V_{pv}) \quad (1)$$

Terms $I_{pv}$ and $V_{pv}$ are the SC current and OC voltage of PV panel. The maximum power point is tracked by comparing incremental conductance $dI_{pv}/dV_{pv}$ to the negative of instantaneous conductance $I_{pv}/V_{pv}$. When the condition becomes $(dI_{pv} / dV_{pv}) < - (I_{pv}/V_{pv})$, the operating point in P-V plane is at the right of maximum power point, while at $(dI_{pv}/ dV_{pv}) > - (I_{pv}/V_{pv})$, the operating point is at the left of maximum power point as shown in Fig. 5. Similarly, for battery charging, a two-stage charging technique is selected. The two-stage charging is divided into constant current (CC) mode and constant voltage (CV) mode, which can also be noticed in Fig. 6. The overall programming algorithm for charging the batteries through MPPT based PV charge controller is shown in Fig. 6. The first condition in the algorithm checks whether the batteries can be charged using PV panels. The condition ensures to turn off the PV charger during the unavailability of sunlight that is at night or on a cloudy day. The second condition applies CC mode by comparing the battery voltage with float voltage, which usually in the case of lead-acid battery is 13.5V. The charging current of the battery is 10% of total current rating of the battery. During this mode, the incremental conductance algorithm shown in Fig. 5 is implemented for about 80-90% of battery charging. As soon as the battery voltage crosses the float voltage threshold, the charging will enter CV mode, which will reduce the charging current to float current before turning off the charger. The PIC 16F877A was used for implementing the code.

C. PRACTICAL IMPLEMENTATION

To implement the incremental conductance technique of MPPT, a simple generic board for PIC microcontroller (MCU) is designed. The first stage in the practical implementation of the PV charging controller is the selection of the DC-DC converter topology. Meanwhile, the system is to be designed for a load of 300-500W, therefore, half-bridge topology seemed a great choice. The choice of optocoupler as MOSFET driver by [31]-[32] not to be a good option. It works perfectly at no load, however, didn’t drive high side MOSFET when connected to the battery. The practical implementation of the DC-DC charge controller is carried out according to the design flow showed in Fig. 7. Firstly, the Black box calculation for the DC-DC buck converter is calculated.

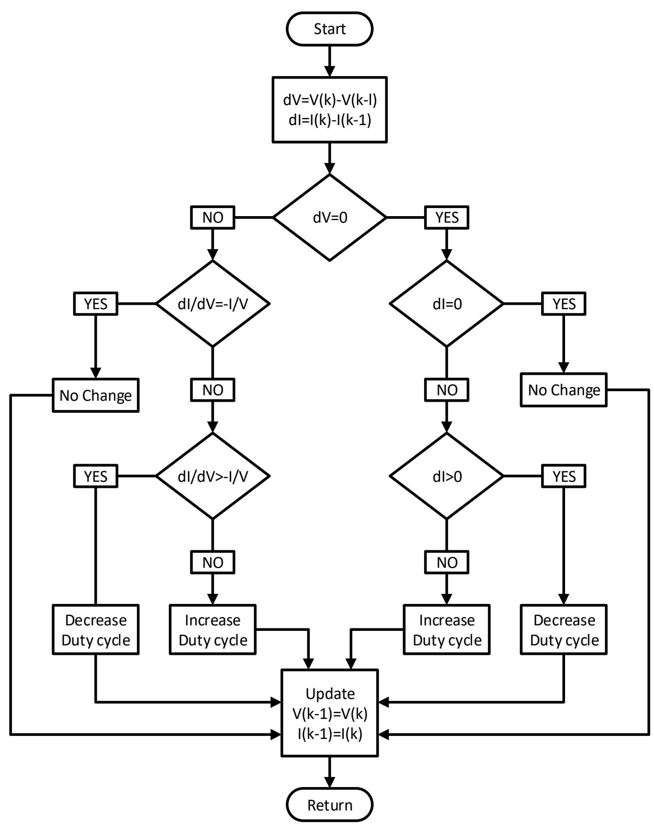


Figure 5. Algorithm for incremental conductance MPPT technique

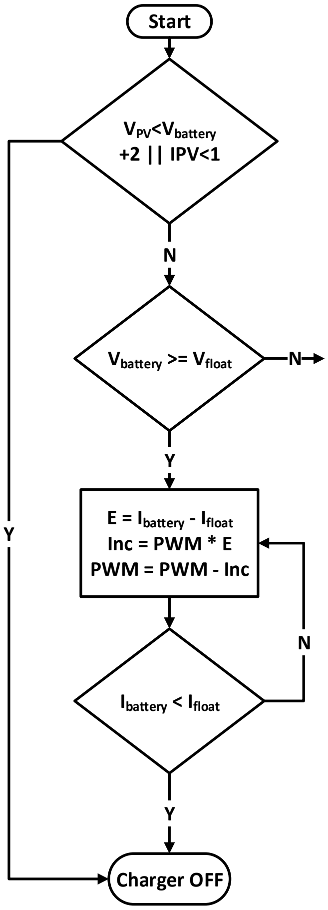


Figure 6.  Algorithm for PV charge controller

For continuous conduction mode, the required minimum value of inductance and capacitor are selected by using (2) [31] and (3) [36]

$$L=\frac{V_{out}(1-D)}{2I_{out}f_{pwm}} \tag{2}$$

$$C=\frac{I_{out}}{4\Delta V f_{pwm}} \tag{3}$$

Where, $I_{out}$, $f_{pwm}$, and $\Delta V$ represents the output current, switching frequency, and output voltage ripple, respectively. After calculating the black box value, the next step is the designing of filters. This step involved the designing of an inductor according to the calculated black box values. The core of the inductor is made of a toroid shaped iron powered core. Subsequently, the color-coding of the iron-powered core defines its resonant circuit frequency, therefore a yellow/white colored (type 26) core whose operating frequency is up to 50 kHz is best for LF filters and DC chokes. The inductor is winded according to the maximum chassis current of the board using the American Wire Gauge (AWG) table. The next step after the filter design is the selection of a power switch, and its driver. Both the p-channel and n-channel MOSFET used as power switch one after the other with each having its advantage and disadvantage over each other. The p-channel MOSFET IRF3205 utilized are almost 3/4 times more costly than its n-channel counterpart IRFZ44N. Besides the cost factor of p-channel MOSFET IRF3205, it dissipated more heat compared to n-channel MOSFET IRFZ44N, therefore making IRFZ44N an ideal choice for our efficient and cost-effective PV charge controller. The only advantage of p-channel MOSFET over n-channel MOSFET is that it can be easily driven using BJTs. While for n-channel MOSFETs, the optocoupler was used to drive the MOSFETs. Nevertheless, after optocoupler failure as MOSFET driver, the half-bridge MOSFET driver IC IR2104 used by [33] replaced in the design of the final PCB board shown in Fig. 8.

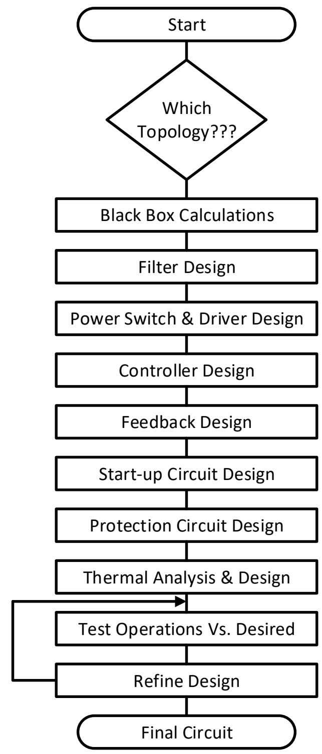


Figure 7. Design Flow of a DC-DC charge controller

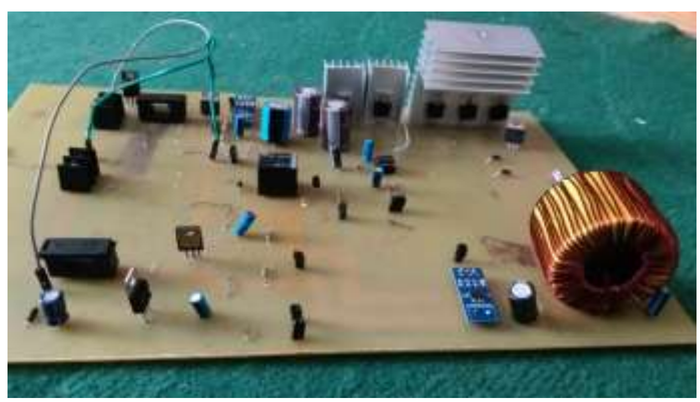

Figure 8.  Final PCB board of DC-DC charge controller

In order to run the charging algorithm shown in Fig. 6, the step feedback for the controller is to be designed using current and voltage sensors, both at the input and output side of the charge controller. The Hall Effect sensor ACS 712 is used as a current sensor, while the voltage divider as voltage sensor. The DC-DC charge controller is finally ready after adding the protection. The charge controller has three types of protections i.e., the reverse polarity, current protection, and voltage protection. The reverse polarity protection is necessary in the case of a DC source. While current protection is useful during short circuit, and the voltage protection protects the circuit from sudden surges in voltage. Moreover, the fuse is used for current protection, and the varistor for voltage protection.

## III. IMPLEMENTATION OF SOLAR UPS INVERTER USING EXISTING UPS UNIT

After designing and implementing the MPPT PV charge controller, the second part of our system is the development of a PV inverter. The PV inverter is developed by installing and interfacing the self-designed PV charge controller with an existing UPS unit available in the market. The MPPT PV charge controller is interfaced in such a way that the UPS original functionality is not disturbed and the new feature of charging batteries through PV energy is also added to it. Meanwhile, the main purpose of the paper is to develop a cost-effective and locally sustainable PV inverter, therefore a Pakistani manufactured UPS unit is selected to fully embed and properly interface the PV charge controller. The architecture of these UPS units is shown in Fig. 9.

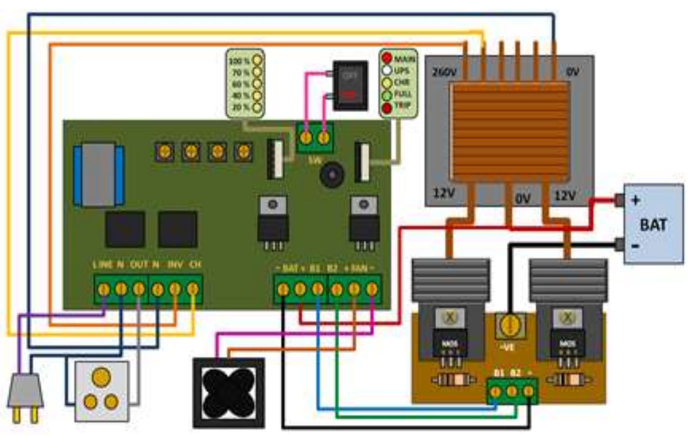


Figure 9. Architecture of locally manufactured UPS unit

The self-designed MPPT PV charge controller is interfaced with the UPS unit using a single pole double throw (SPDT) relay module. The relay module is connected between UPS charging wire, which is denoted by the yellow wire in Fig. 9. The relay module disconnected the yellow wire during sunshine hours when the batteries are charged using the MPPT PV charge controller. While during the unavailability of PV energy i.e., at night or on a cloudy day, the relay module is connected to the charging wire to charge the batteries using the grid supply of the house. The architecture of the proposed PV fed local UPS inverter is shown in Fig. 10. The PV inverter works in such a way that the PV panels are connected to the DC-DC converter. The sensors are used in the DC-DC converter to measure input/output voltage and current, which are fed to the PIC microcontroller. The PIC microcontroller utilizes the voltage and current values to generate the necessary PWM for charging the batteries by applying the algorithm shown in Fig. 6. Moreover, the PIC microcontroller also displays the voltage and current values on the LCD, and controls the relay module that is used for interfacing the PV charge controller and the UPS unit.

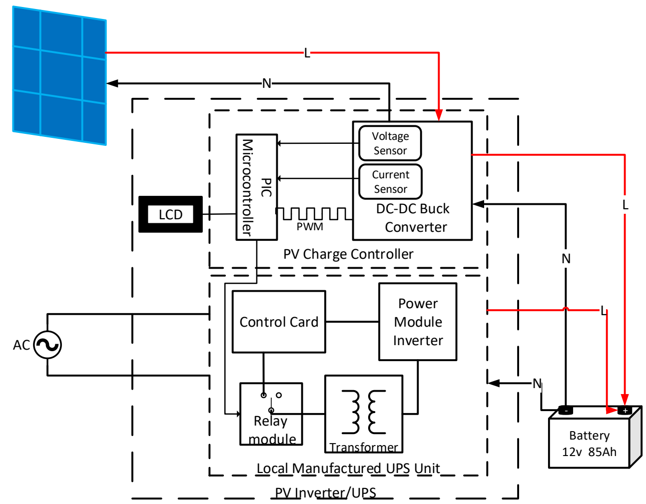


Figure 10. Architecture of the PV fed local UPS inverter

## IV. TESTING AND RESULTS

Tests are carried in different stages throughout the design and development of the system. Tests are first carried out on software simulations which are then followed by hardware testing to evaluate the PV inverter. Testing of the system contain three stages i.e., MATLAB simulation, Proteus simulation, and practical implementation.

### A. EVALUATION OF MATLAB SIMULATION

The MPPT PV charge controller simulation is developed on MATLAB/Simulink in an entire simulation of 10 seconds as shown in Fig. 4. The simulation is evaluated with different temperature and irradiance signals. The tracking of the maximum power point can be observed in Fig. 11, where output power is tracking the PV power. The electrical parameters of proposed system are described in TABLE 1 [35].

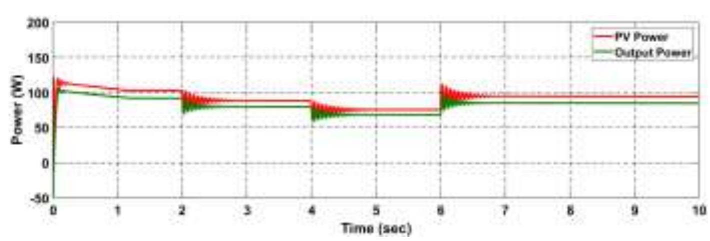


Figure 11. Output of MATLAB simulation

TABLE I
ELECTRICAL PARAMETERS OF PROPOSED MODEL

| Symbol | Parameter | Value |
|---|---|---|
| $L$ | Coupling Inductance | 6.2mH |
| $R_s$ | Coupling Capacitance | 450µF |
| $f_{pwm}$ | Switching Frequency | 5kHz |
| $Batt_{dc}$ | Battery Voltage | 12V |

B. Code Verification Using Proteus Simulation

After the MATLAB/Simulink simulation of the PV charge controller, a microcontroller simulation is developed using the Proteus software. The microcontroller simulation is used for testing the code. The MATLAB/Simulink simulation has a model-based design as shown in Fig. 4, while the Proteus simulation is schematic circuit design as shown in Fig. 12 making it best for evaluating an electronic circuit. The simulation works by adding the Hex file of the code to the schematic microcontroller.

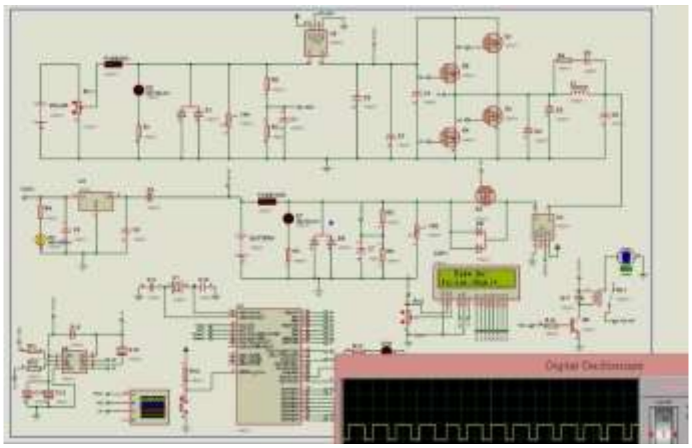

Figure 12. Proteus Simulation of MPPT PV charge controller

C. Practical Testing and Results

After testing the simulation models of both MATLAB and Proteus software, the next step is to carry out tests in a practical environment. The practical tests are carried throughout the development phase of our system. Tests are carried out both inside the laboratory and in an outdoor environment. After developing proposed solar UPS system, it is tested in an outdoor environment as seen in Fig. 13.

Figure 13. Practical testing of our PV inverter

The locally manufactured UPS unit is interfaced with the MPPT PV charge controller via relay module. The results of the practical tests carried on the system are noted down in the form of table, which can be observed in Table I. Where η represents the overall efficiency of UPS system. According to Islamabad Electric Supply Company (IESCO), the price for one electric unit (kWh) for the tariff category (residential) consuming 301-700 units per month is 19.55 PKR (for the year 2021). While the average efficiency of a 150W PV panel from the Table II is 81.51% and the annual mean sunshine duration is 8-10 hours across the country according to [15]. Consequently, the annual savings of proposed solar UPS system is revealed in TABLE III.

**TABLE II: Practical Result**

| Current (PV) (A) | Voltage (PV) (V) | Current (Battery) (A) | Voltage (Battery) (V) | Output Power (W) | PV Power (W) | η (%) |
|---|---|---|---|---|---|---|
| 3.5 | 20.9 | 4.76 | 12.56 | 59.79 | 73.15 | 81.74 |
| 3.33 | 20.4 | 4.22 | 12.65 | 53.51 | 67.9 | 78.77 |
| 2.58 | 19.4 | 3.01 | 12.7 | 38.32 | 50.05 | 76.56 |
| 2.95 | 19.8 | 3.52 | 12.74 | 44.84 | 58.41 | 76.77 |
| 1.58 | 17.8 | 1.9 | 12.77 | 24.26 | 28.1 | 86.26 |
| 0.9 | 16.4 | 1.03 | 12.77 | 13.15 | 14.76 | 89.11 |
| 0.26 | 16.3 | 0.27 | 12.77 | 3.45 | 4.238 | 81.4 |

**TABLE III: Financial and Energy Savings**

| Time | Power Produced (kWh) | Money saved (PKR) |
|---|---|---|
| One day | 1.1 | 21.51 |
| One month | 33 | 645.38 |
| One year | 396.14 | 7744.51 |

## V. CONCLUSION

In this paper, the authors have proposed a new idea about constructing a local manufactured UPS inverter more efficient through PV energy without disrupting its function of providing uninterrupted supply during load-shedding hours. The proposed PV fed local UPS inverter works in such a way that during the sunshine hours the batteries are charged through a PV charge controller, while at night or on a cloudy day the UPS unit charged the batteries conventionally from the national grid supply. The PV fed local UPS inverter then automatically supplies this stored power of the batteries to the house during the load shedding (rolling blackout) hours.

The design and implementation of an MPPT PV charge controller are performed practically in a hardware setup and simulated in MATLAB/Simulink and Proteus environment, respectively. The practical results demonstrate the superiority of the proposed PV fed local UPS inverter with an average efficiency of 81.51% as compared to existing UPS inverters and a lowest total harmonic distortion (THD) of 1.29% as compared to existing UPS inverters.

The objective behind the implementation of this idea is to promote the market of locally manufactured UPS units in Pakistan by upgrading them to solar UPS inverters. This conversion increases the efficiency of the system and results in the reduction of electricity bills. Consequently, the PV fed local UPS inverter presented in this paper will help the developing countries like Pakistan to achieve sustainable development goals (SDG) 7.

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