

SMART SOLAR ENERGY CONVERSION AND BATTERY CHARGING SYSTEM FOR ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT:

With the rise of electric vehicles (EVs) and renewable energy systems, there is a growing demand for effective and environment-friendly technologies for charging batteries. Solar photovoltaic (PV) energy is one of the most promising renewable energy technologies for EV charging applications owing to its environment-friendly and ubiquitous characteristics. But the traditional PV based battery charging system are facing several problems such as low energy utilization, inefficient charging of battery and fast degradation of battery when they are continuously charging. In the light of these challenges, this project has been come up with a Smart Photovoltaic Based Lithium-Ion Battery Charging System for Electric Vehicles using Adaptive Pulse-Ripple Current Control. The proposed system consists of photovoltaic (PV) array, two dual DC-DC boost converters, lithium-ion (Li-ion) battery banks, Maximum Power Point Tracking (MPPT) controller and adaptive Pulse-Ripple Current (PRC) charging strategy. Maximum power generation from PV array is taken by MPPT controller under different solar irradiation conditions to utilize the available solar power efficiently. The adaptive PRC charging technique comprises of charging pulses and rest periods, which keeps the battery from overheating and cuts down on lithium plating to ultimately prolong the battery life. In addition, the dual-converter design allows the solar power to be used at all times, switching between charging different bank arrays according to their State of Charge (SOC), and so avoiding wasted energy when one bank is being charged while the other is resting. The system is simulated and studied in MATLAB/Simulink for various operating scenarios. The simulations show that the charging efficiency can be improved, the usage of solar energy can be increased, stress on the batteries can be reduced, thermal performance can be enhanced, and the lifetime of the battery can be extended using the proposed charging methods. The proposed charging system is intelligent, reliable and environmental friendly, which can be applied to the charging infrastructure of the future electric vehicles and renewable power generation systems.

Keywords: Pulse-Ripple Current Charging, Maximum Power Point Tracking (MPPT), Lithium-Ion Battery, Electric Vehicle (EV), Dual DC-DC Converter, State of Charge (SOC), Renewable Energy, Solar Charging, Battery Management System, Energy Efficiency, Sustainable Transportation.

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I.INTRODUCTION

The demand for energy has increased significantly with the expansion of the world

population and the pollution of the environment has become an increasing concern which has led to the rapid growth of the renewable energy technologies and electric vehicles (EV). Solar

photovoltaic (PV) systems, as one of the renewable energy sources, have been highlighted because of its clean, sustainable and abundant nature. The EV has been gaining considerable traction as a means of cutting down GHG emissions and reliance on fossil fuels. But efficient battery charging systems are an essential component to the performance and reliability of EVs. The lithium-ion battery is a type of battery that is commonly used in electric vehicles due to its high energy density, long lifespan, and excellent charging capabilities. In spite of these benefits, traditional battery charging methods result in high battery temperature, loss of battery capacity, shortened battery life, and poor utilization of renewable energy sources. Traditional PV charging systems are not always optimally used the available solar energy, particularly for battery charging breaks and weather conditions. Thus it is one of the big research focuses to develop intelligent charging systems which can use the solar energy to the maximum extent, and at the same time ensure healthy battery condition. With the integration of renewable energy sources and advanced charging strategies, charging stations can be optimized to significantly enhance charging efficiency, improve battery performance, and contribute to the development of sustainable transportation systems. Therefore photovoltaic charging systems along with smart battery management technologies are becoming a great alternative for future mobility applications using electric vehicles and for renewable energy applications [1], [2].

There are a number of technical issues when using PV energy systems with lithium-ion battery charging systems, such as changing solar irradiances, changing battery operating conditions, and efficient power conversion. To overcome these limitations, advanced power electronic converters and intelligent control algorithms are used. Maximum Power Point Tracking (MPPT) techniques are widely used to harvest the maximum power from photovoltaic (PV) panels under varying environmental conditions. In addition, traditional constant current and constant voltage charging can expedite battery aging and exacerbate thermal stress, which shortens the battery life. The development of Pulse-Ripple Current (PRC)

charging techniques, which involve the application of controlled charging pulses and relaxation periods, have proven to be an effective alternative, offering benefits such as enhanced electrochemical stability and reduced internal battery stress. Multiple battery banks can also be charged efficiently thanks to the use of dual converter architectures, which help to maximize the utilization of solar energy to the greatest extent possible. Intelligent energy management systems keep track of battery State of Charge (SOC), charging current and available solar power for optimized charging operations. These advancements help to enhance charging efficiency, manage battery health, and optimize use of renewable energy. Thus, MPPT control and adaptive charging techniques and intelligent converter systems are essential to realize high performance PV battery charging system for EV application [3] [4].

The work proposes a smart photovoltaic (PV)-based charging system for electric vehicles (EVs) which is based on adaptive pulse-ripple current control (PRCC) to improve the charging efficiency, maximize PV energy utilization, and prolong the battery life. The proposed system comprises of a photovoltaic array, dual DC-DC boost converter, lithium ion battery banks, MPPT controller, and adaptive Pulse-Ripple Current charging mechanism. Under different irradiance conditions, the MPPT controller constantly monitors the MPPT point to ensure that the PV array can extract the maximum energy. The adaptive PRC charging strategy dynamically optimises charging pulses based on battery State of Charge and operating conditions, which helps to minimise lithium plating, battery degradation and temperature rise. Also, with the dual-converter configuration, it is possible to utilize the PV energy continuously by alternately charging the battery-banks during charging and relaxing periods. MATLAB/Simulink simulation is done to assess the system performance with varying environmental and load conditions. The findings revealed a significant boost in charging efficiency, battery health, and reduced charging losses, along with

improved temperature control and energy use over traditional charging systems. In the future, the proposed system promises to be an intelligent, reliable, and environmentally friendly system for EV charging infrastructure, renewable energy integration, and sustainable transportation development [5] and [6].

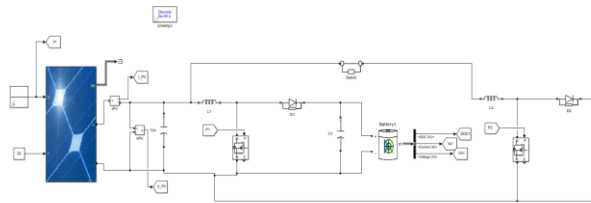


Fig 1 MATLAB/SIMULINK circuit of the system

In the Single Converter Operation (SCO) mode, converter C1 is the only converter used to charge the battery and the initial State of Charge (SOC1) of battery B1 is maintained at 50%. Table II lists the appropriate charging times and efficiencies for this operation and Figure 6.2(a) shows the pertinent PVs and battery waveforms for this operation. While the solar array produces almost 56.3 A of current, converter C1 transfers around 23.2 A to Battery B1 during the active charging time of 0.025 seconds. The PV system and battery stay dormant for the remaining period as a result of the Pulse-Ripple-Current (PRC) charging approach. Battery B1 needs about 49.7 minutes to get an extra 10% charge level due to this intermittent charging activity and partial usage of PV energy. Over the course of one minute of operation, the photovoltaic array generates around 238.08 kW-s of energy (E_{PV}), with almost 235.68 kW-s stored in Battery B1. This gives the system's energy conversion efficiency of 98.99% but only 49.6% PV utilization efficiency since the PV array is idle during rest times of PRC. At the start of Double Converter Synchronous Operation (DCSO) Battery B1 and Battery B2 are at 50% SOC. During the PRC charging pulse intervals, converters C1 and C2 work together. As the charging time is 0.025-seconds, as shown in figure 6.2(b), photovoltaic array will generate

total 56.3A, during the charging period each battery will take charging current from corresponding converter at the rate of about 11.6A. During the pulse rest periods, photovoltaic array and batteries are in dormant state which can allow them to consume partial solar energy just like the operation of SCOs. The charging current is shared between both batteries and will reach 10% increase of SOC in ~100.4 minutes for both batteries. When operating for a minute, the PV array produces 238.08 kW-s of energy (E_{PV}) and approximately 116.7 kW-s of it is stored in each of the B1 and B2 batteries. The PV utilization efficiency and overall energy conversion efficiency were determined to be around 49.55% and 98.12% for DCSO mode respectively. The use of PV energy is not possible due to the common idle time of the two converters, although DCSO can charge with two batteries at the same time.

II SURVEY OF RESEARCH

1. Esram and Chapman gave an in-depth comparison of Maximum Power Point Tracking (MPPT) techniques in PV energy systems. Different types of MPPT algorithms like Perturb and Observe (P&O), Incremental Conductance, Fractional Open Circuit Voltage and NN based algorithms were analyzed. The authors emphasised the importance of MPPT for the maximum extraction of energy from solar panels as the output of solar panels varies widely with the irradiance and temperature conditions. The experimental results indicated that the use of advanced MPPT techniques can enhance the efficiency of the photovoltaic systems by tracking the optimum operating point at all times. The study highlighted the importance of efficient MPPT control for improving energy harvesting and overall performance of battery charging system. In addition, the authors highlighted pros and cons of the various MPPT techniques for use in highly dynamic environments. The results of their work will become a base for developing intelligent photovoltaic charging systems in the cases of maximum utilization of renewable energy. The

findings of this research are a major step toward implementing effective solar powered electric vehicle charging networks.

2. The optimized Perturb and Observe (P&O) MPPT technique for photovoltaic applications was proposed by Femia et al. The study was directed towards the increase of tracking speed and minimising the power pulsations around the maximum power point. The authors proposed a modified algorithm that can track with high accuracy with fast response to the changing atmospheric conditions. It showed that the energy extraction efficiency was improved by simulation and experimental results in comparison to the conventional MPPT methods. The study further emphasized the importance of MPPT performance on battery charging systems, noting that higher efficiency in solar energy capture translates into more effective battery charging. Optimized algorithm minimized power losses and enhanced performance of the converter under different irradiance levels. The researchers concluded that the charging systems based on renewable energy sources require intelligent MPPT strategies. Their work will be helpful in the design of PV battery charging systems which demand maximum energy utilization with a stable charging performance.

3. An accurate electrical model of the lithium-ion battery was developed by Chen and Rincon-Mora that could predict the lithium-ion battery runtime performance and voltage-current characteristics. The model proposed included battery capacity variation, internal resistance and dynamic response characteristics under various charging and discharging conditions. Experimental validation showed the excellent agreement between simulated and real behaviour of the battery. The study highlighted the critical need for battery modelling for charging system design, battery management and lifetime prediction. With a precise battery model, the intelligent charging controllers can optimize the

charging current and voltage, and reduce the degradation of the batteries. The researchers also talked about how charging techniques can affect the lifespan and thermal performance of a battery. Their research has been adopted in electric vehicle battery management systems and renewable energy storage systems. This study offers valuable insights for the design of higher charging strategies to ensure the efficiency and reliability of battery operation.

4. For electric vehicle applications, Cao and Emadi suggested a hybrid energy storage system of a lithium ion battery with an ultracapacitor. The design was proposed to address the issues of energy management, battery life and system efficiency. The ultracapacitor was used to store energy during regenerative braking and provide quick bursts of power during acceleration, with the battery providing steady power needs. Experimental tests showed decreased battery current fluctuations, less thermal stress and higher energy utilization. The study emphasized the importance of intelligent charging strategies and power-sharing solutions to ensure the health and performance of batteries. Additionally, the hybrid system improved the efficiency of the regenerative braking and mitigated the impacts on battery ageing. The results are useful for developing new advanced energy storage devices to be used in conjunction with renewable energy sources feeding charging stations for electric vehicles.

5. Dusmez and Khaligh proposed a multifunctional compact power electronic interface for plug-in electric vehicles. All charging, propulsion and energy management functions were integrated in the converter. The goal was to minimize the number of components, increase efficiency and boost power density. The results showed that integrated converter structures would allow a tremendous reduction of hardware complexity with a high charging performance. Power flow control between renewable, batteries and vehicles loads was achieved through advanced

control algorithms. Experimental results demonstrated that the efficiency of the converter is enhanced, and it can work normally under different load conditions. The study emphasized the need for smart power electronics in the future of EV charging and renewable energy integration. Their results contribute to the design of smaller, more flexible battery charging stations powered by photovoltaics and enhance energy efficiency.

6. Mi, Masrur and Gao studied integration of renewable energy sources into electric vehicle charging infrastructures. The study focused on different charging architectures, battery technologies, power converter configurations, and energy management strategies. The authors highlighted the need for the use of renewable energy resources like solar PV system to minimize reliance on traditional mode of electricity generation. To enhance charging efficiency and battery lifetime, advanced battery charging techniques and intelligent control systems were discussed. The study also emphasized the importance of energy management algorithms to optimize power flow between renewable energy sources, energy storage devices, and electric vehicle loads. Analyses of simulated and practical data proved the viability of renewable energy powered EV charging stations. The researchers concluded that intelligent integration of renewable energy for the transportation sector is a must for sustainable transportation systems and environmental impact reduction. This work can be used to find insights for the design of PV charging stations for lithium-ion batteries for future EV applications.

III. WORKING METHODOLOGY

The aim of the proposed Smart Photovoltaic Based Lithium-Ion Battery Charging System for Electric Vehicles with Adaptive Pulse Ripple Current Control is to optimize the utilization of solar energy to improve the battery charging efficiency and prolong the life of the battery. It

is composed of a photovoltaic (PV) array, Maximum Power Point Tracking (MPPT) controller, two DC-DC boost converter, Lithium-Ion (Li-ion) battery banks and an adaptive Pulse-Ripple Current (PRC) charging controller. The PV array generates electrical energy from solar energy and the MPPT controller constantly extracts the maximum energy from the PV array in different environmental conditions. The power generated is sent to dual converters for efficient charging of multiple battery banks. The adaptive PRC charging technique offers charging pulses and controlled rest periods for reduced battery stress, minimized heat generation and increased electrochemical stability. The entire system is simulated and analyzed using MATLAB/Simulink for assessing charging efficiency, battery performance and energy utilization under various operating scenarios.

Photovoltaic Energy Generation

The charging process starts with the PV array which is used to convert solar radiation energy into electrical energy. The power generation from the PV panel is a function of sun's irradiance and temperature. The MPPT controller constantly searches for the MPP, thereby maximizing energy transfer from the solar panel.

The PV array output power is:

$$[P_{\{PV\}} = V_{\{PV\}} \times I_{\{PV\}}]$$

Where:

$(P_{\{PV\}})$ = Photovoltaic Output Power (W)

$(V_{\{PV\}})$ = PV Output Voltage (V)

$(I_{\{PV\}})$ = PV Output Current (A)

The solar power generated is used as the main power source for charging the battery.

Maximum Power Point Tracking (MPPT)

The PV array is connected to the converter stage and an MPPT algorithm is used for improving

the energy utilization. The MPPT controller continuously monitors the PV voltage and current, and adjusts the converter duty cycles to make the solar panel work at the maximum power point.

The PV conversion efficiency is given by:

$$[\eta_{PV} = \frac{P_{out}}{P_{in}} \times 100]$$

Where:

(η_{PV}) = PV Conversion Efficiency (%)

(P_{out}) = Electrical Output Power (W)

(P_{in}) = Solar Input Power (W)

This process is meant to extract available solar energy efficiently in different environment.

Dual DC-DC Converter Operation

The proposed system consists of two DC-DC boost converter to manage energy distribution efficiently among the multiple battery banks. Depending on the battery charging needs and the state of charge, the converters either provide synchronous or asynchronous operation. This architecture makes full use of the solar energy at all times even when one battery is in charging relaxation time.

The output voltage of the boost converter is:

$$[V_o = \frac{V_{in}}{1-D}]$$

Where:

V output = the output voltage of the transformer.

(V_{in}) = Input Voltage (V)

(D) = Duty Cycle

The boost converter raises the solar cell voltage to a desired battery charging voltage, and helps to ensure the converter operates at a steady state.

Adaptive Pulse-Ripple Current Charging Technique

The main feature of the proposed system is the adaptive charging strategy called Pulse-Ripple Current. Instead of charging using a constant current, PRC charging is done using a pulsed charging current and controlled rest intervals. The battery is charged during the pulse period and electrochemical stabilization takes place within the battery during the rest period.

The charging current is shown as:

$$[I_{charge} = I_p \times D_p]$$

Where:

Average Charging Current (A) (I_{charge})

(I_p) = Pulse Current (A)

Pulse Duty Ratio (D_p)

This method minimizes lithium plating, thermal stress and charging efficiency of the battery.

State of Charge Monitoring

Each battery bank is monitored by Battery Management System for State of Charge (SOC). To achieve an equal distribution of energy and efficient use of solar power, charging priority is given to the battery with the lowest SOC.

The battery SOC can be determined by:

$$[SOC = \frac{Q_{available}}{Q_{rated}} \times 100]$$

Where:

(SOC) = State of Charge (%)

$(Q_{available})$ = Available Battery Charge (Ah)

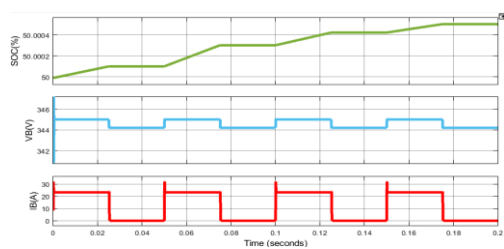
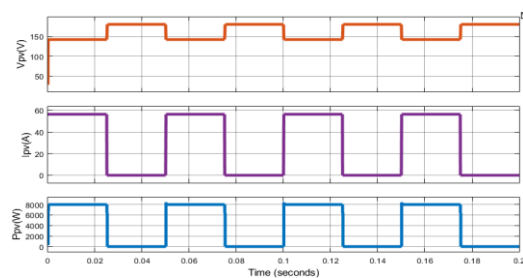
Units: (Q_{rated}) = Rated Battery Capacity (Ah)

SOC monitoring helps to avoid overcharging, making the batteries more reliable.

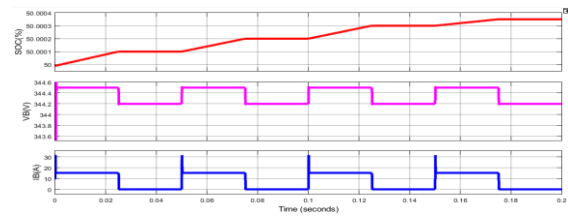
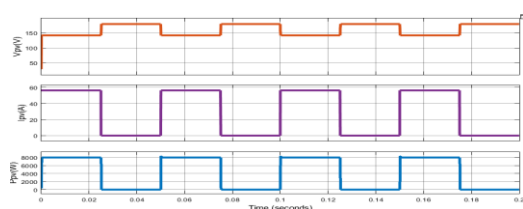
System Performance Evaluation

The entire system is modelled and simulated in MATLAB/Simulink in different conditions of solar radiation and battery loadings. PV output power, battery voltage, charging current, SOC variation, converter efficiency and charging efficiency are studied. The outcomes from the simulation show that the adaptive Pulse-Ripple Current charging strategy has a great effect on the utilization of solar energy, the battery degradation, the charging efficiency, and battery lifetime. Thanks to the dual-converter design, the energy transfer is continuous and there is no power loss during the charging rest periods. The proposed methodology is intelligent, reliable and sustainable for further development of renewable energy sources based electric vehicle charging systems.

IV RESULTS EXPLANATIONS



(a)



(b)

Fig. 2 The PV and battery results: (a) SCO and (b) DCSO.

Battery B1 and Battery B2 are initially kept at a 50% State of Charge ($SOC1 = SOC2 = 50\%$) in the first state of Double Converter Asynchronous Operation (DCAO). In order to have PV continuously working as in Figure 3(a), both the converters work in Pulse-Ripple-Current (PRC) mode. The first 0.025 seconds, Battery B2 is not charging, but Battery B1 is being charged with a current of approximately 23.2 A from the solar array (current approximately 56.3 A) through converter C1. As long as Battery B1 is not engaged, the solar array is providing 56.3 A, and the converter C2 starts to charge Battery B2 with 23.2 A between 0.025 and 0.05 seconds. This mode of operation of the alternating converter makes very efficient use of the solar energy as it eliminates periods of inactivity of the PV array. Both batteries need about 49.9 minutes to get a 10% improvement in state of charge, as seen in the performance data reported in Table II. The total energy generated by solar array ($E_{\{PV\}}$) is 477.48 kW-s at one minute working time while energy stored in Batteries B1 and B2 is 235.86 kW-s and 235.92 kW-s, respectively. It shows a very good utilization of the solar energy and charging performance with PV utilization efficiency

η_{PV} of about 99.48%, and energy conversion efficiency η_E of about 98.81%.

In DCAO state-2, the initial state of charge (SOC) of the batteries was intentionally set to different levels with an initial charge of 60% for SOC1, and 30% for SOC2, to test the adaptive charging feature of the proposed control strategy. The battery B2 is not doing anything between 0.0175 seconds until 0.035 seconds, while converter C1 charges the battery B1 at 23.2 A from the solar array which is approximately 56.3 A as shown in figure 6.3(b). From 0.0175s to 0.05s converter C2 charges Battery B2 with the same current that was charging Battery B1 and Battery B1 is idle. The control system can increase the pulse width of the PRC for Battery B2 because it has a low start of charge. Battery B2 will have more energy when charged than Battery B1 will. Performance study shows that Battery B2 has an extended charging interval that takes only 38.05 minutes to get the same 10% increase in charge as Battery B1. Battery B1, on the other hand, requires approximately 71.23 minutes. The solar array can produce about 477.6 kW-s of energy per minute (E_{PV}) while Batteries B1 and B2 can store about 165.12 kW-s and 306.84 kW-s of energy, respectively, when operational. The proposed Asynchronous charging system demonstrates that the adaptive pulse width control technique is suitable for a smart charging management of battery and efficient utilization of solar energy with 98.82% overall efficiency and with a good photovoltaic utilization efficiency of approximately 99.5%.

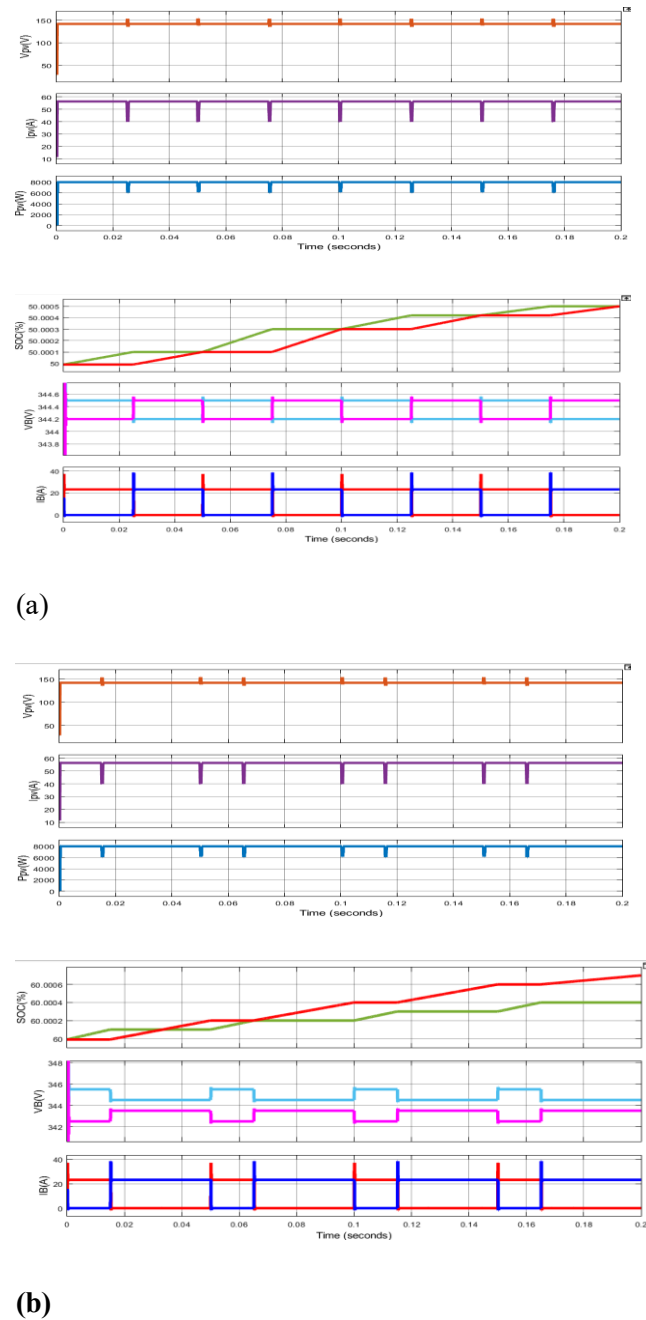


Fig. 3 The PV and battery results in DCAO: (a) state-1 and (b) state-2.

In Double Converter Asynchronous Operation (DCAO) state-3 the initial State of Charge (SOC) of Battery B1 is kept at 40% and Battery B2 at 80% intentionally. This is to see how resistance capabilities the proposed PV charging system can withstand with uneven battery charge. As shown in fig.6.4 during the initial

0.035 seconds, converter C1 is active and charges Battery B1 with the current of ~ 23.2 A, while the solar array is charging constantly with the current of ~ 56.3 A and Battery B2 is not doing anything. Between 0.035 and 0.05 seconds later, with Solar array still providing 56.3 A, Battery B1 is inactive and converter C2 starts charging Battery B2 at 23.2 A. The control system cleverly provides a longer charging pulse length to Battery B1 to ensure that it is charged first, as it is initially at a lower state of charge. The charging time of Batteries B1 and B2 are different, Battery B1 requires approximately 35.46 minutes for a 10 percent charge increase and Battery B2 requires approximately 83.33 minutes for the same charge increase. The total energy output (E_{PV}) from PV array is estimated 477.48 KW-s for one minute runtime and energy stored in battery B1 and B2 are estimated as 330.3 KW-s and 141.48 KW-s, respectively. The proposed asynchronously charging scheme achieves a remarkable solar usage efficiency (η_{PV}) of nearly 99.48% and a high energy conversion efficiency (η_E) of more than 98.81%. Results show that the adaptive DCAO control strategy can improve the efficiency and reliability of solar power charging system for EV, and maximize the PV energy utilization, balance the charging process and distribute the charging energy based on battery.

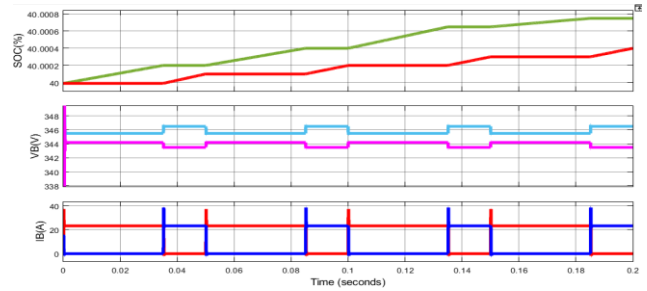
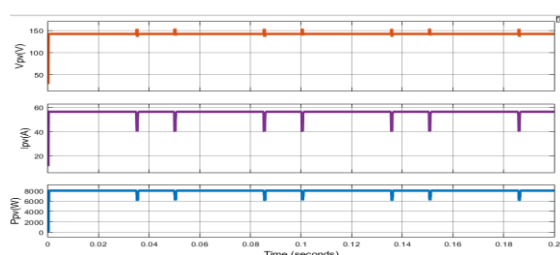


Fig. 4 The PV and battery results in DCAO-state-3.

Charging performance of the proposed system was tested in Double Converter Asynchronous Operation (DCAO) state-1 for different solar irradiation level and complete experimental study is carried out. The irradiance level was reduced to 800 W/m² and 300 W/m² at 0.3, 0.5 and 0.7 seconds respectively from the normal test irradiance of 1000 W/m² and excess irradiance of 1200 W/m². Waveforms in figure 5 illustrate the charging system response to different solar power levels on the photovoltaic side, and battery side. With these settings, the currents supplied to the batteries, B1, B2, were approximately 23.2 A, 27.8 A, 18.6 A and 7 A, respectively, and the currents supplied by the photovoltaic array were approximately 56.3 A, 67.6 A, 45 A and 16.9 A, respectively, and the State of Charge (SOC) increased at the rate of approximately 0.00335, 0.004, 0.002, and 0.001, respectively. All the lithium-ion batteries were charged at the same charge rate at all the irradiance levels, 0.25 C, 0.29 C, 0.2 C and 0.07 C, well below the recommended maximum charge rate (6C). The solar electricity available and the weather caused the charging rates of the batteries to differ. To make sure that the battery with the lowest State of Charge gets more charging energy during the pulse interval, the

suggested DCAO approach cleverly tweaks the Pulse-Ripple-Current (PRC) charging method. The overall charging time is decreased and the charge balance is much improved by this adaptive charging technique. Thus, in the DCAO charging mode, the charging time of Batteries B1 and B2 is about one half of that of DCSO. Furthermore, the utilization efficiency (η_{PV}) is 49.6% in SCO and DCSO modes, but in DCAO mode, the utilization efficiency of the PHV is increased to almost 99.5%. From these results, it can be discerned that the approach of asynchronous dual-converter has been effectively utilized solar energy, thus minimizing the losses and increasing the charging efficiency, the overall system performance and the charging efficacy of the battery.

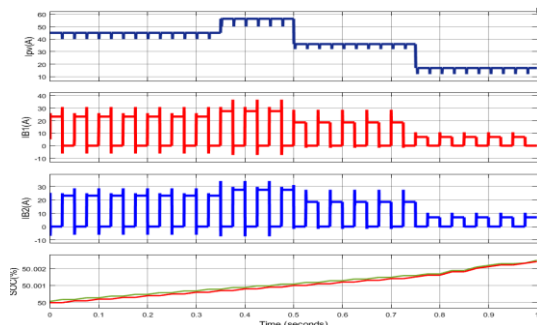


Fig. 5 The PV and battery waveforms with changes in solar irradiance.

V.CONCLUSION

In this research, a new energy conversion topology based on the double converter and a new charging method named Modified Pulse-Ripple-Current (PRC) charging method is proposed as a new energy conversion method and battery charging method for freestanding PV power driven lithium-ion battery systems. The proposed Double Converter Operation (DCO) system comprising of DCSO and DCAO

allowed the PV energy to be utilized more efficiently and also enhanced the charging efficiency than that of the conventional single converter charging system. The proposed system was able to charge multiple batteries simultaneously in an efficient and stable manner, irrespective of the irradiance level of the sun, by connecting two boost converters in parallel. Because the converters in the DCAO design were changed periodically, PV idle moments were eliminated, and virtually 100% PV energy consumption was achieved; this design proved to be the best of the operating modes investigated. The intelligent control strategy constantly measured the State of Charge (SOC) of the battery and dynamically adjusted the PRC pulse widths to provide more energy to the battery with the lowest SOC and to give priority of charging to this battery. The simulation and experimental results have shown that the method has higher energy conversion efficiency, PV utilization efficiency, charging balance and charging speed of the battery compared to conventional charging methods. The proposed PRC charging method also decreased the adverse effects of continuous charging like Constant Current and Constant Voltage charging on the batteries including thermal stress, lithium plating and battery degradation. The developed system resulted in the increase of the reliability of an e-car charging system, prolonging the lifetime of a lithium-ion battery, improving the overall system energy management as well as the operational efficiency.

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