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Design and Validation of Super-Capacitor Assisted Photovoltaic Array for Roof-Top Solar Powered Electric Vehicle Applications

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Abstract
Upkeeping the Battery State-Of-Charge (SoC) and its life are of great significance in Battery Electric Vehicle (BEV) & Hybrid Electric Vehicles (HEV). This is possible by integrating Solar Photovoltaic Panels (PPs) on the Roof-top of the BEVs & HEVs. However, unlike Solar Powered Vehicle Charging stations and other PV applications where the solar panels are installed in such a way to extract the maximum Photon energy incident on the panel, vehicle Roof-top mount Solar PPs face many challenges in extracting maximum Power due to partial shading issues especially under dynamic conditions when passing under trees, high rise buildings and cloud passages. This paper proposes a new strategy called "Super-capacitor Assisted Photovoltaic Array". In which Photovoltaic Modules are integrated with Super-capacitors to improve the transient performance of the Photovoltaic Array system. The design of proposed Super-capacitor Assisted PV array is validated & its performance is compared with conventional PV array in Matlab/ Simulink environment.

Keywords
Battery Electric Vehicle(BEC), Hybrid Electric Vehicles (HEV), Super-capacitor, Solar Powered Vehicle Charging stations

I. Introduction

The United Nations is focusing more on the sustainable development for the future generations in which one important goal is to reduce the carbon footprint by renewable energy generation for affordable & clean energy (SDG goal no. 7) [1, 2]. To meet this goal, Govt. of India and all other nations across the world pushing towards the technological developments in renewable energy power generation and Electric Vehicles. We know that solar energy is most promising renewable energy source, available abundant in nature. It can be harvested easily using Photovoltaic modules from anywhere of the world [3,4]. Also, integrating the Solar Photovoltaic system with the Electric Vehicle is not a big deal. However optimal utilization of radiant solar energy to enhance the driving range of the EV is of great significance. The Energy generated by the roof top PV modules may not be sufficient to provide full driving range, but it is sufficient to relieve the battery from additional burden of lighting loads, air conditioning and other accessories loads. Also, the excess energy can be utilized to charge the battery under static condition, which reduced the self-discharge rate of the battery and enhances its life. [5–7]

With the development of modern technologies, PV Modules can be easily installed on the roof-top of the Battery electric vehicles (Roof-top area-2 m2) (shown Fig. 1), Locomotive Rail coaches (30 m2), Electrical Buses (20 m2) and Heavy vehicles (15 m2) etc., These modern EVs and HEVs

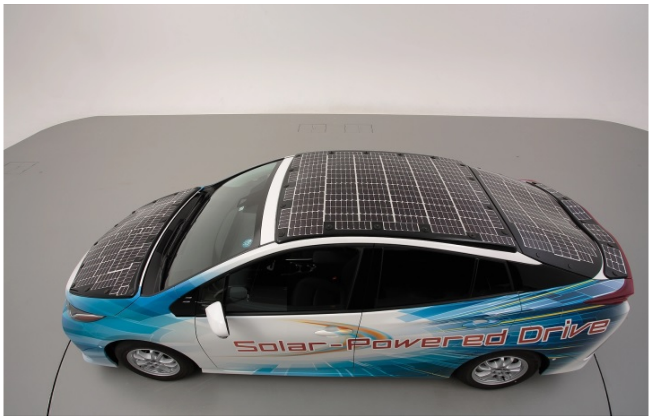


Fig. 1. Solar Power Electric Vehicle (PC: Toyota / TechCrunch / Google)

are already equipped with battery banks, Battery Management System, Bi-directional Converters & other necessary Power Electronics [8, 9].

The PV modules can generate an average amount 250W to 300W per square meter under normal solar radiation conditions. Hence, a minimal additional cost can be spared for the PV system to get the improved efficiency and performance of the Battery bank system.

II. Literature Survey

As per the authors knowledge many researchers made some attempts for optimally utilizing solar energy for Battery Life Enhancement, Drive Range Enhancement of the Electric Vehicles and realized a best state of art solar-powered EVs like Lightyear One, Sion Electric Car, etc., which are commercially available in the current market.

Maruthiparad and Krishnamoorthy proposed a Split Power Solar Source (SPSS) for Solar Powered Battery Electric vehicles for the drive range enhancement. In SPSS distributed array is used such that the PV Array is divided into multiple sections and each section is connected to a common DC bus. The DC bus is connected to 48V, 750Ah Battery through DC-DC converter. They concluded that during the real time simulations the variable irradiance, temperature and self-discharge effects reduced a 4% drop in desired operating performance [10].

Duan et al. proposed a Battery cell balancing system using the solar radiant energy. The proposed system uses balances the Battery cell during driving conditions also using a Switch Box Circuit controlled using Battery management system. They demonstrated that the proposed solar assisted battery balancing system enhances the battery capacity by 2.1% to 3.3% [11]. Wei et al. proposes a Battery Management System (BMS) for Solar powered BEVs. They used adaptive genetic algorithm based Multistage Constant Current Charging strategy for optimizing the battery temperature rise, charging time [12]. Yu et al. proposed Electric Drive Reconstructed Onboard Charger (EDROC) for solar powered electric vehicles. They demonstrated that using EDROC technology simultaneous charging & driving operations using vehicle-roof photovoltaics significantly increase the driving milage range [13].

Though many followed several different techniques for the optimal solar energy utilization using Conventional PV Array but all are facing a common problem of partial shading effects caused by high-rise buildings, trees and cloud passages especially under dynamic moving conditions.

The impacts of various conditions on the output power of the BEVs and HEVs roof top photovoltaic modules were investigates by Schuss et al. [14]. They also calculated the effective area available for PV installations on the curved surfaces of Electric Vehicles.

Madhu et al. investigated the effect of partial shading in maximum power extraction of PV arrays. They analysed a 4×4 PV array with different topologies such series, parallel, series-parallel configurations [15]. Nayak and Mohapatra proposed a Hybrid Array configuration for optimal power extracting and to reduce mismatch photovoltaic losses [16].

Singh et al. designed a solar PV array, battery energy storage, a diesel generator (DG) set and grid-based connected charging station which uses solar energy as a prime source of energy [17].

The novelty of this research work is authors proposed a novel strategy called as Supercapacitor Assisted Photovoltaic Array to address the problems faced during the dynamic moving conditions. It is particularly most important for EV applications with Solar PV system. When the vehicle moves it is subjected to irradiance variations, which leads to solar PV output power variations. This work proposed to the solution for this problems.

The paper work is organized as follows: Section I. presents the research motivation followed by literature survey in Section II. . Section III. discusses about the Conventional PV arrays and its limitations. The proposed Super-Capacitor Assisted PV Array presented along with its designing in Section IV. . In Section V. design validation with MATLAB/ Simulink environment is presented. Section VI. discusses the advantages of proposed system and conclusions.

III. Conventional Photovoltaic Array (CPVA)

The Photovoltaic Cells used to build PV modules as shown in the Fig. 2. To get the desired output power, voltage and current ratings, different configurations are made with series

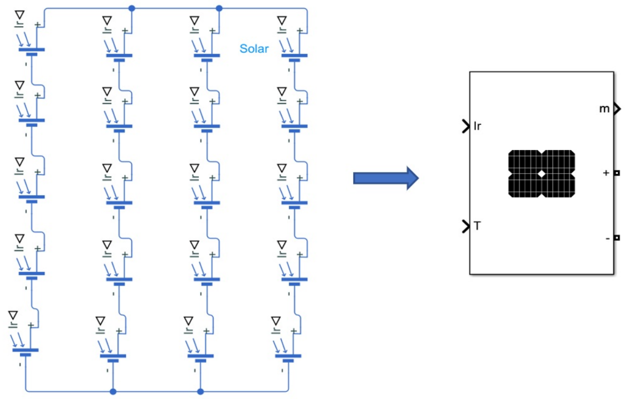


Fig. 2. Conventional PV Module & PV Array

and parallel connections using these PV modules forms an PV array. Usually, simulations will use PV array block, which will have one co-efficient for solar radiation and one for the temperature with the assumption that each cell in the PV panel is exposed to an equal amount of the solar radiation and operates at the same temperature level. This assumption is valid for the cases Roof of the house, Solar charging stations and other stationary PV installation applications [18]. In all these applications the PV panels are usually positioned at certain angle towards sun to get the maximum solar radiation all day equally across the panel [19]. However, if the PV panels are mounted on the roof-top of the vehicles, each cell will get a different amount solar radiation and operates at a different temperature in dynamic conditions especially when passing under clouds and proximity of trees and high-rise buildings. Also, an experimental study reveals that there will be a 24° difference in alignment of the far PV modules placed on the far ends of the curved surface of normal sedan car roof [14].

A. *Limitation of Conventional PV Array*

In conventional PV Arrays made of series and parallel connections of PV modules. The open circuit voltage (V_{OC}) increases with series connection. However, the short circuit current (I_{SC}) and maximum power point current (I_{MPP}) are limited by the weakest PV cell which receives the less radiation than the other ones. Conversely, the short circuit current (I_{SC}) increases with the parallel connection of PV modules. But the V_{OC} and maximum power point voltage (V_{MPP}) is limited by the weakest PV cell which receives less radiation.

The above conditions are simulated and verified in MATLAB/Simulink environment using 5 Nos. of solar array PV blocks (each rated with $V_{oc} = 5V$ and P = 40W) connected in series. Fig. 3 shows the Simulink model of 5×1 Series Connected PV Array.

From the waveform shown in Fig. 4, it can be concluded

TABLE I.
PV MODULE RATING

Maximum Power	42.63 Watts
V_{OC}	7.26 Volts
I_{SC}	7.84 Amps
V_{MPP}	5.8 Volts
I_{MPP}	7.35 Amps
Temperature coefficient of V_{oc} (%/deg.C)	−0.36099
Temperature coefficient of I_{sc} (%/deg.C)	0.102
Parallel strings per module	5

that the output voltage, current starts decreasing with radiation level of PV array-3 even the other PV array blocks are sufficiently radiated. This results in an undesirable voltage, current & power distortion at the output terminals of the PV array caused by intermittent partial shading effects, which needs to be regulated. To address this limitation Super-capacitor PV Array is proposed.

IV. Proposed Super-Capacitor Assisted PV Array (SCAPVA)

The proposed SCAPVA consists of super-capacitors connected across each PV modules. This integration of PV module with super-capacitor enhances the performance of the PV system. The Fig. 5 shows the arrangement of Super-capacitor assisted PV array (5×1) designed using PV modules connected in parallel to form 5 strings. Each string is connected with Super-capacitor across them through Power Diode. The Power Diode provides protection against the reverse conduction in the event of less solar radiation.

A. *Design of The SCAPVA*

A 1kW PV Array is designed using 5 Nos. PV modules, which can be accommodated on the Roof-top of the normal Sedan car (Approx. area- 2 square meter). Table I shows the rating of PV module and Table II shows the PV array rating.

B. *Design of The Superapacitor*

The voltage and power rating of the Super-capacitor is selected such that, when average solar radiation available is below the

TABLE II.
PV ARRAY RATING

Maximum Power	1065 Watts
V_{OC}	36.3 Volts
I_{SC}	39.2 Amps
V_{MPP}	29 Volts
I_{MPP}	36.75 Amps

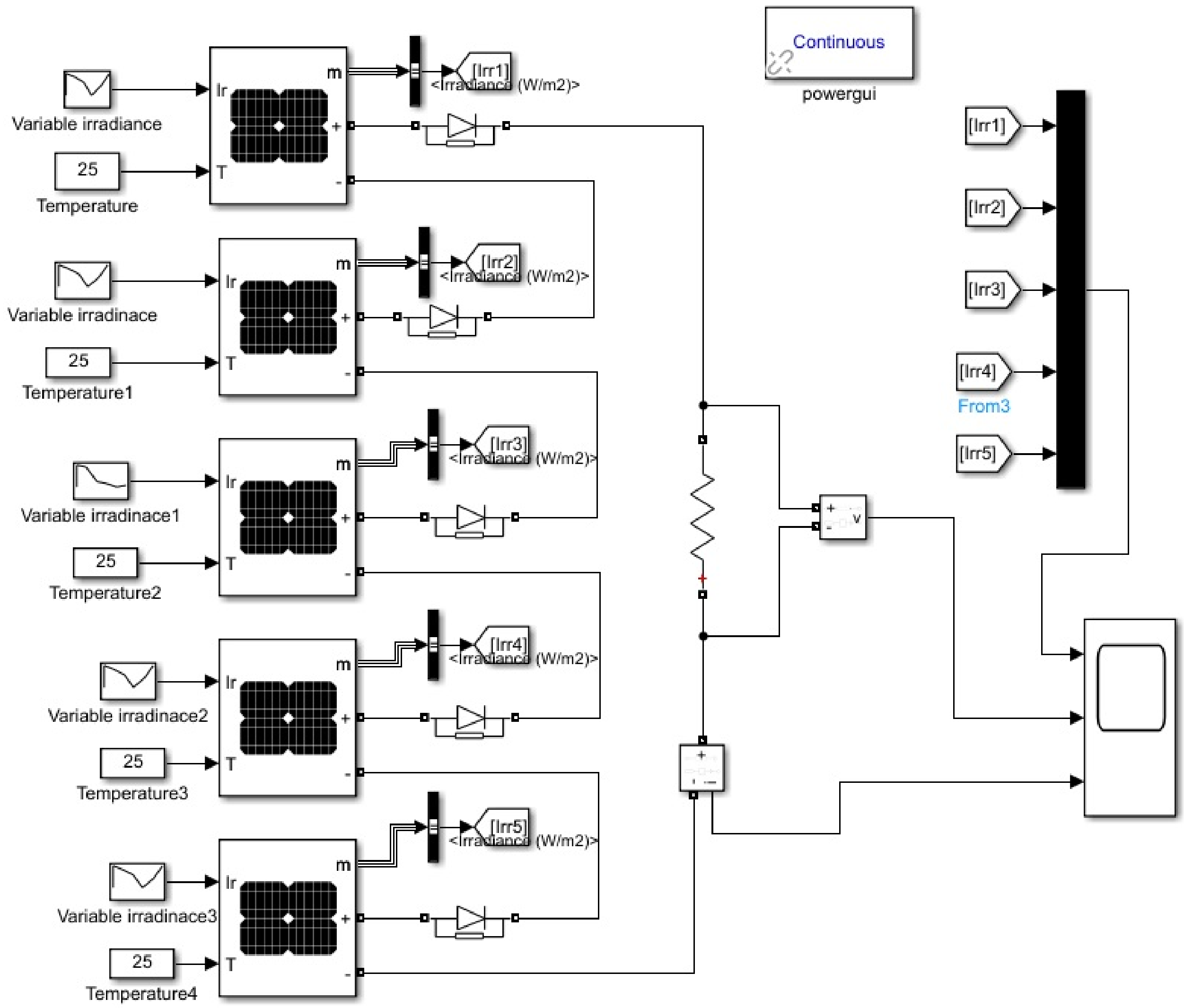


Fig. 3. 5×1 Series Connected PV Array

average solar radiation, the super-capacitor shall discharge and give excess power required by the load. And when the solar radiation available is above the average solar radiation, the PV module supplies power to charge the supercapacitor and supplies power demanded by the load [20]. For the simulation, a PV module block with maximum power point voltage of 5.8V at $1000W/m^2$ irradiance and 40 Farad, 5.5V rated super capacitor is selected. The typical voltage rating of Supercapacitor is 2.75V, the supercapacitor is composed of four individual supercapacitors [21]. The series capacitances double the rated voltage to 5.5V, but the capacitance reduces to half. The parallel capacitances increase the overall capacitance back to 40F. This configuration has allowed for an increase in rated voltage, without sacrifice of the total capacitance.

For the proposed application, i.e., one PV module can produce a 200W power and the supercapacitor has to deliver the energy for sufficient time (assume 60 sec) in the absence of PV energy.

Charging Voltage $(V_1) = 25V$

Lower cut-off voltage $(V_2) = 0V$

Energy required to be delivered by the supercapacitor,

$$E = P \times t = 1000W \times 60 = 60000 \text{ Joules} \quad (1)$$

Capacitance for total bank,

$$Cb = 2, \frac{E}{V_1^2 - V_w^2} \cong 200F2 \quad (2)$$

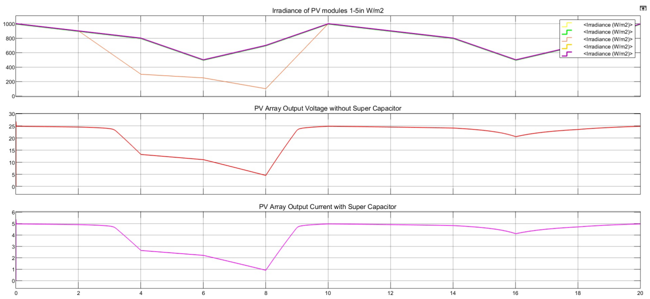


Fig. 4. Waveform of series connected PV array

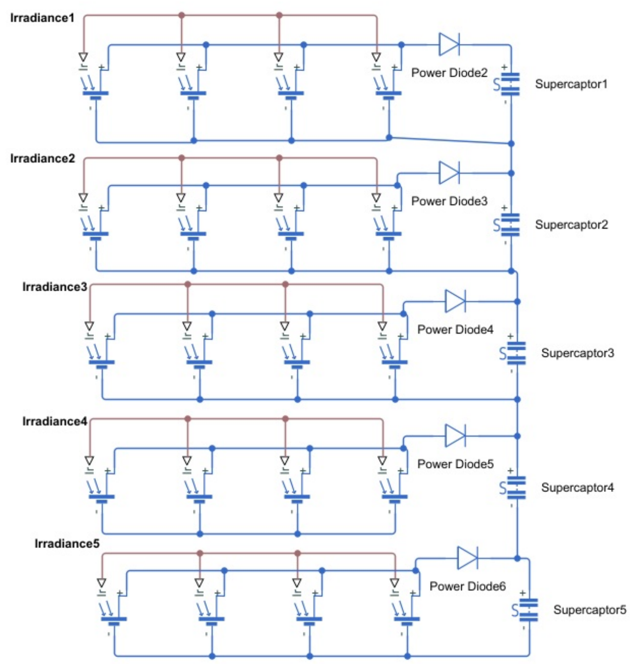


Fig. 5. Super-capacitor assisted PV Array

Capacitance for one module,

$$C = \frac{200}{5} = 40F \tag{3}$$

The simulation results of SCAPVA at different irradiation conditions are simulated and the charging & discharging cycles of the super-capacitor is shown in Fig. 6. At high values of irradiation, the Super-capacitor charges to its rated voltage and SoC building up. As soon as the irradiation (PV module-4) decreases and keeping other modules at high solar radiation, the supercapacitor-4 discharges and gives additional power required by the load. Hence the SoC of the supercapacitor-4 is coming down. The designed PV block & supercapacitor blocks will deliver power for 60sec in the event of partial shading or reduced solar radiation levels.

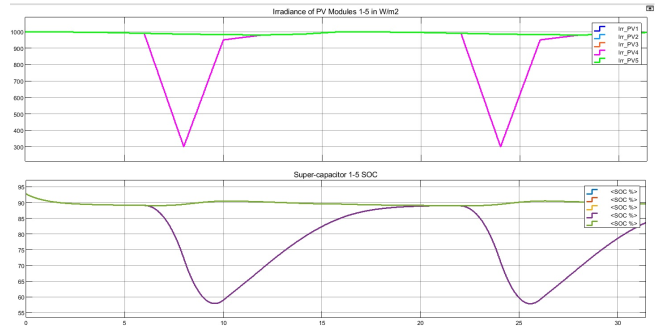


Fig. 6. Waveforms of the supercapacitor SoC under partial shading conditions.

C. Design Validation of The 5x1 Size Supercapacitor Assisted PV Array

For comparing the performance of the proposed SCAPVA (shown in Fig. 7) with CPVA (shown in Fig. 3) under different solar radiation levels and partial shading conditions, simulations are carried out with variable irradiance & temperature levels. The results are plotted and shown in Fig. 8. As shown in the waveforms in SCAPVA the voltage regulation is improved under partial shading conditions.

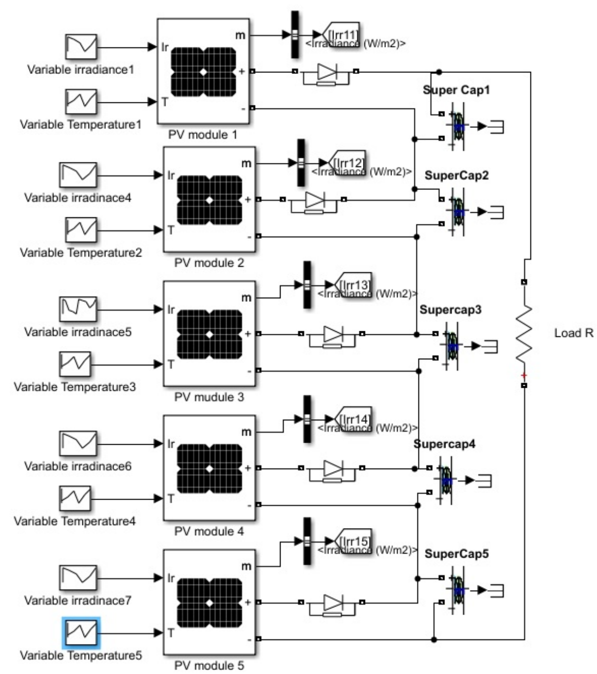


Fig. 7. 5 × 1 size Supercapacitor Assisted PV array in Simulink/ MATLAB

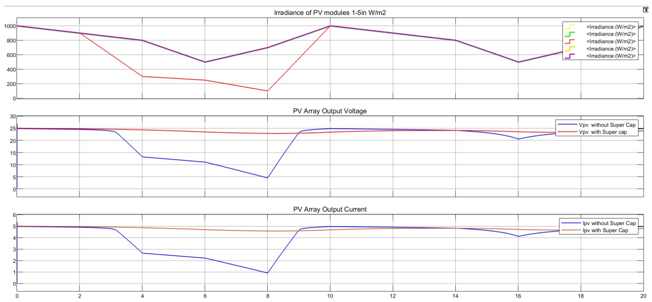


Fig. 8. Waveforms of the SC assisted PV Array vs Conventional PV Array

V. Advantages of The Super-Capacitor Assisted PV Array

The proposed Super-capacitor assisted PV Array offers the following advantages:

1. Improved voltage regulation under all irradiation levels, partial shading conditions.

2. Ripple free output voltage can be obtained resulted in reduction of the filter size at the output of the DC-DC converters.

3. Constant output power will be obtained under partial shading conditions.

4. No additional converter is required for charging and discharging the supercapacitors.

5. Efficiency of the overall PV array enhanced in the event of partial shading. Fig. 8 clearly indicates that the PV array output voltage and current is more or less maintained constant during the partial shading conditions in the Supercapacitor assisted PV array system, so we can conclude the efficiency reduction during the partial shading can be almost neutralized and hence the overall efficiency is improved.

A. Design validation for HEVS / BEVS

To validate the proposed optimal PV array in Hybrid Battery Electric Vehicles, the functional block diagram (shown in

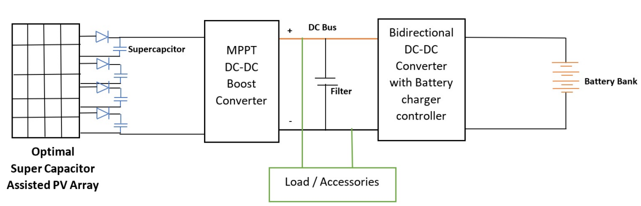


Fig. 9. Block diagram of the Simulation model

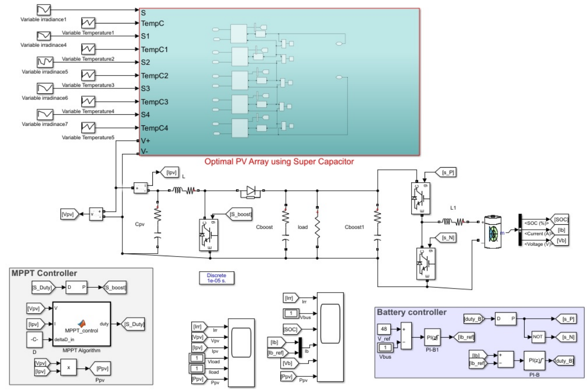


Fig. 10. Block diagram of the Simulation model

Fig. 9) is developed and validated in Matlab/Simulink environment (shown in Fig. 10). The optimal Super-capacitor assisted PV Array is connected to MPPT DC-DC boost converter, which is controlled by MPPT controller using perturb and observe algorithm developed on the functional block of the Simulink. The output of the boost converter is given the bidirectional DC-DC Converter with battery charge controller. Battery bank is connected to battery charger circuit. The Boost converter step-ups the PV voltage to DC bus voltage required by the load & battery. For the simulation purpose a 160Ah, 48V rated Li-Ion battery is used from the Simulink library and its performances is observed under various irradiance conditions. The battery is charged & discharged through the bidirectional DC-DC charger which is controlled using the PI Charge controller.

VI. Simulation & Results

The Fig. 11 & Fig. 12 show the simulation results of the HEV battery charging system with CPV & SCAPVA respectively. Here the irradiation level is varied in both cases from $300W/m^2$ to $1000W/m^2$ in 10sec & again to $200W/m^2$ in 10sec and various performance parameters are observed through waveforms. This can be treated as a result of intermittent change of solar radiation due to proximity of tree or high-rise building.

A. Case-1: HEV with CPV

As shown in Fig. 11, the CPV array power variation proportional to the solar radiation level ($300W@300W/m^2$ to $1050W@1000W/m^2$ and so on). Hence battery connected in system observed to be discharging during low solar radiation (power) level and charges during the high radiation (power) level to support the load shown in Fig. 11 battery current waveform. Hence this would cause the battery to charge & discharge very frequently along with level of irradiance. The State-of Charge of battery depicts the same.

B. Case-2: HEV with SCAPVA:

Conversely for the same solar radiation level as in case-1, the SCAPVA power will be maintained almost constant shown in Fig. 12, supported by Super-capacitor as explained in Sections 4.2 & 4.3. Hence the battery charging & discharging cycles will be contained for any intermittent changes in solar radiation or partial shading conditions. The battery current waveform shows that charging phenomena. Hence the SoC of battery keeps building when the system is idle or minimum load conditions.

VII. Conclusion

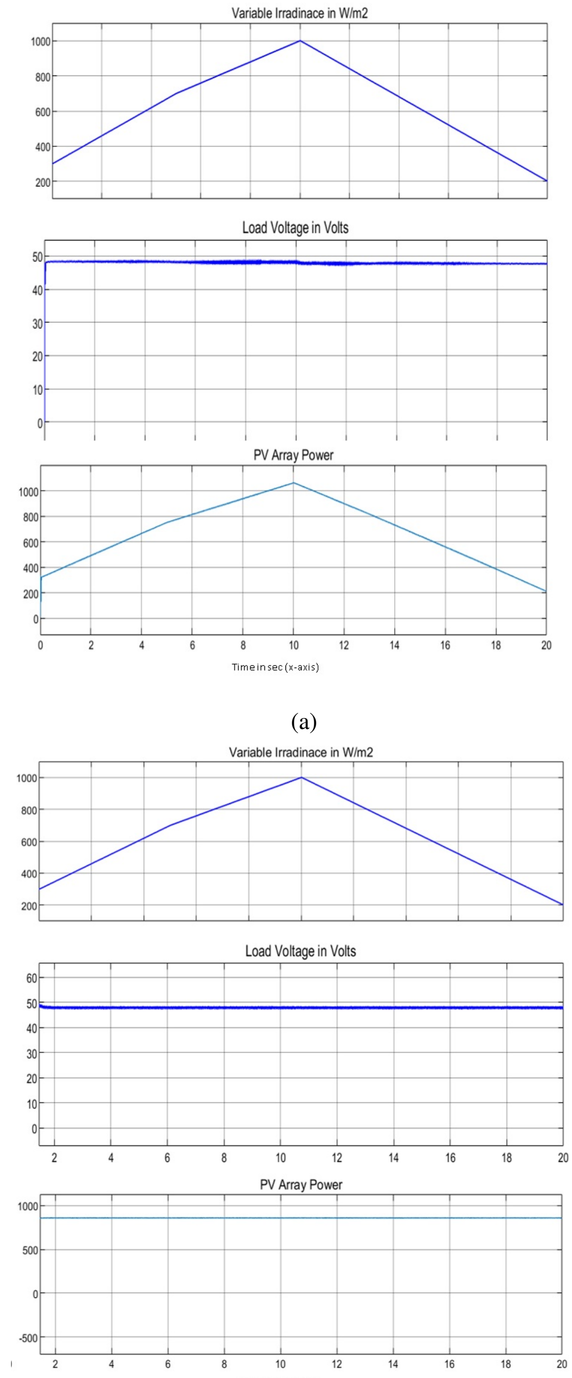
We could see that the compared fixed PV installations for Solar Powered charging stations and Solar Power Plants, vehicle roof mount Photovoltaic Panels face much challenges in dynamic conditions of vehicle movement. In this research work a novel Super-capacitor assisted PV Array is designed for optimal utilization of PV energy for Roof-top Solar Powered Electric vehicles. The simulation results for Conventional PV array and Super-capacitor assisted PV Array are presented and it shows that the proposed Super-capacitor assisted PV Array efficiently works under partial shading caused in dynamic conditions due to cloud passages, trees and high-rise buildings.

The following are the conclusions can be made from the simulations results:

- The Proposed Super-capacitor PV array can be easy to realize by inserting a suitable Super-capacitor across each PV module.
- The SCAPVA can supply the power to load and battery under partial shading for 60 sec. Also, the time duration can be increased by increasing the size of the Super-capacitor.
- It will benefit the Battery connected to the system by reducing the Depth of Discharge (DOD), and limits the frequent charging and discharging cycles caused by partial shading.
- The SoC of the Battery is enhanced using the proposed optimal PV array compared to conventional PV array.
- The ripple content is reduced greatly with the proposed method.

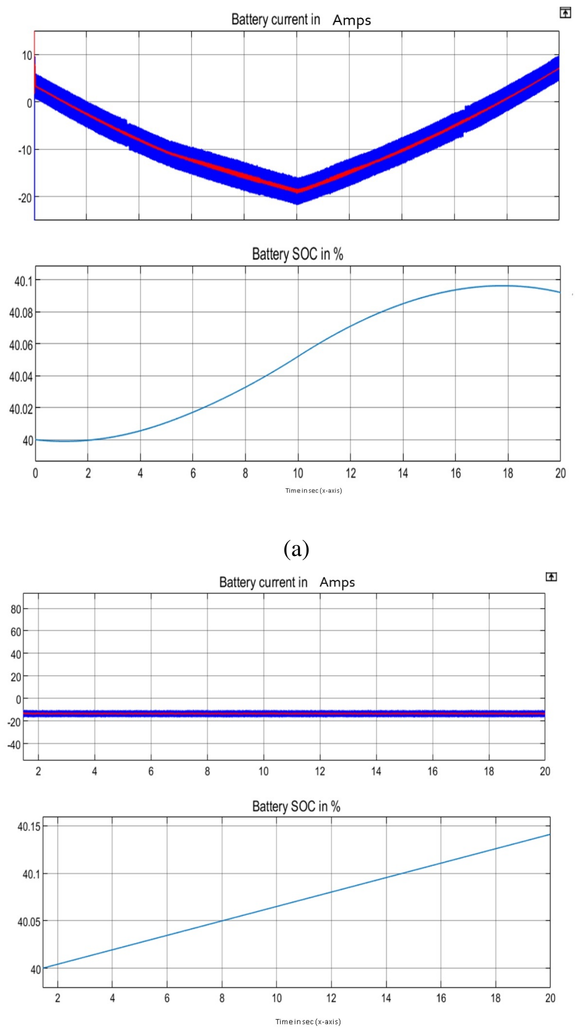
Conflict of Interest

The authors declare that there is no conflict of interest in the study.



(b)

Fig. 11. Waveforms of Irradiance, Load Voltage, PV Array Power, Battery Current, Battery SoC in % vs Time for CPV



(a)

(b)

Fig. 12. Waveforms of Irradiance, Load Voltage, PV Array Power, Battery Current, Battery SoC in % vs Time with SCAPVA

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