Photovoltaics Energy Storage for Standalone System in locomotives

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***Abstract*—The standalone/unconnected Photovoltaic (PV)-based systems for off-grid societies necessitates midway energy stowing policies/devices to stream/engross the sporadically generating power from Solar energy and to bring an equilibrium between generation and load consumption units. Storing energy in batteries as external source have been one of the key factors that upsurge the functioning cost of the standalone PV operated battery energy storing system which results in the faster let down by the unbalanced charging and discharging procedures. This paper recommends to install a capacitor segment in the presently working PV-battery systems in standalone conditions to lessen the charging/discharging traumas in battery by eradicating the strictly changing currents. Grounded on local solar isolation and projected load statistics of locomotive Himalayan Queen Train in MATLAB Simulink model is established to analyse the efficacy of the anticipated system in modifying battery strains. The projected Supercapacitor model was executed and tested with real Solar-battery energy system. Together simulation and investigational results demonstrates noteworthy drop in current flowing through batteries and the oscillation which has recommended for the upgrading in battery lifespan.**

Keywords--Supercapacitor, energy storage, Battery, Photovoltaics, standalone Systems.

I. INTRODUCTION

The knowledge consumption of biodegradable / renewable sources of energy, like wind, geothermal, solar energy ,biomass, hydropower, ocean tides, etc., can successfully assuage the global problems of atmospheric/environmental pollution, energy crisis ,global warming greenhouse effect.[5].Amongst these numerous naturally replaceable sources of energy for power generations, PV power system is realized to be the utmost speedy growing technology these years [2]. The progression of renewable energies also permits justifiable energy keys in isolated and countryside publics that are neither economically nor practically be linked to the grid systems .Standalone PV-battery systems are one of the widespread opportunities for providing electricity to the off-grid peoples. Fig. 1 demonstrates a distinctive standalone PV- energy system connected with batteries that generally entails of PV arrays, charge controlling unit, BESS(battery energy storage system) and load [8]. The charge controlling unit contains a charge regulator, is used to adjust the discharging/charging method and guard the battery from overcharging [6], [7]. Midst countless ESS (energy storage systems/devices), likewise Lead-Acid (LA) battery for residential load purpose and 2x65 AH SMF Tubular 24V Microtek battery for locomotive (In case Study) has been lengthily used and provides optimum solution due to the strong and steady electrical characteristics, and the striking low cost/KWhr [9]. However, the lifespan of LA battery is moderately petite, in the range of hundreds charging discharging cycles which ramblingly rises the effective rate of the system [1], [7].

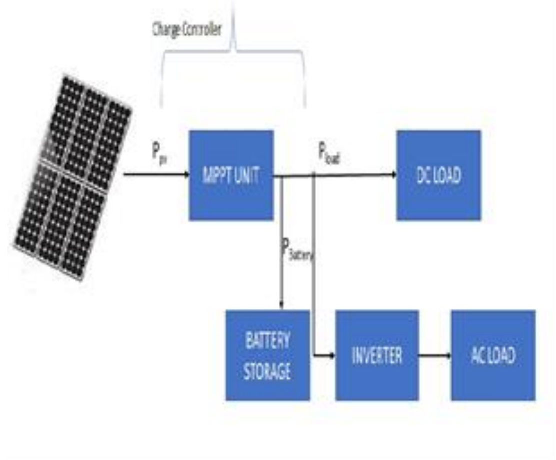

Fig 1. Distinctive standalone PV- energy system

A perfect energy storage device in standalone Photovoltaic energy system should be talented to streamed out both high energy and power demands to gratify the circumstances such as abrupt variations in solar isolations and loads that entail very high starting current. For illustration, air conditioner, heaters, refrigerators, blowers, and heavy electrical machines involve high starting/initial current that can be 10 times higher than standard current [3]. Supercapacitor (SC) supplies energy in the form of static/ motionless electric charges that delivers high power density as compared to LA battery which permits it to captivate or deliver huge power in a small period. The features of LA battery and Supercapacitor are itemized and related in Table 1.

TABLE I. FEATURES OF LA BATTERY AND SUPER CAPACITOR [1]

Features	*Lead Acid*	*Super Capacitor*
Life span	1000	<500000
Precise Power Density	10-100Wh/kg	1-10Wh/kg
Precise Energy Density	<1000W/kg	<10000W/kg
Precise discharging time	0.2-3hrs	0.3-30sec
Precise charging Time	1-6hrs	0.3-30sec

Done in the past eras, Super Capacitor based hybrid energy storage systems (HESS) have become a auspicious explanation for modifying the charge/discharge pressure on battery in numerous energy storage submissions like in electric locomotives/vehicles and housing energy storage solutions. The methodology of employing SC and battery has confirmed noteworthy suspension in battery weakening and enlightening the efficacy [11]–[15] and[22]. Yet, utmost of the HESS needs a comprehensive rearrangement of the battery storage outline in present PV system and segregating the key energy storage devices with vigorously controlled power electronic devices to attain favourite power exchange amongst dissimilar energy storage strategies [18]. These HESS organizations could possibly recover the lifespan of battery, but in the meantime forfeiting the robust electrical features of BESS.

This paper offers a new and fresh Super Capacitor-Battery HESS that provides the best explanation for modifying the charging/discharging pressure on battery without the desires of redesigning the battery energy storage portion [19].So as to plug-in module/component , the supplementary SC module can be installed to the conservative standalone PV BESS as depicted in in Fig. 2. The projected mix energy storage system is installed, and it works as a HESS that can be functioned autonomously to absorb/supply the unwanted charging/discharging currents owing to the alternating currents from Photovoltaic modules. The remaining part of the paper is arranged as: Section II offers the topology of the system and the proposed while Section III represents the model of the simulation with actual solar isolation data and load profiles. Section IV shows the example of the projected system and the related experimental case study results with thorough study and dialogues. To end, conclusion is summarized in Section V.

II. System Description

A. Planned System

Fig. 2 demonstrates a characteristic standalone PV-BESS with the proposed Supercapacitor module retrofitted to be installed in the present battery storage systems. The supplementary SC module is planned to grasp or stream the passing currents when undesired change in power of the battery storage system is sensed.

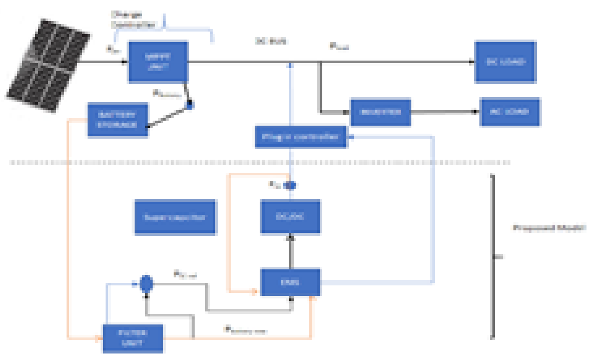

Fig. 2. Proposed standalone PV-BESS

The power managing and controlling units will direct the active power exchange to the Supercapacitor module while guaranteeing that the exchange of power in battery storage remains even in all conditions. Therefore, justifying the stresses on battery storage by lessening active power exchange and minutely changing cycles due to the presence of Photovoltaics energy sources.

B. Controlling and Managing Strategies (CMS)

Here Filtration based control (FBC) algorithm has been assumed to achieve the power distribution between battery energy storage system and SC module. The left power demand i.e. PBattery (PPV-Pload) is disintegrated into high frequency and low frequency components by using simple low-pass filter [3]. This humble application and power distributing approach needs fewer computational job which dropped the threshold for connecting HESS in distant countryside areas. Exclusively EMS, the SC is automated to answer vigorously to the very high frequency power exchange though the left part has the low frequency components of power demand side and it will be provided by the inactively associated battery storage.

Fig. 3(a) shows the filtration-based control algorithm used in the planned system while Fig. 3(b) illustrates the PI control system which is used for fire the PWM signals and to control the DC/DC converter that interconnects the SC module with DC busbar.

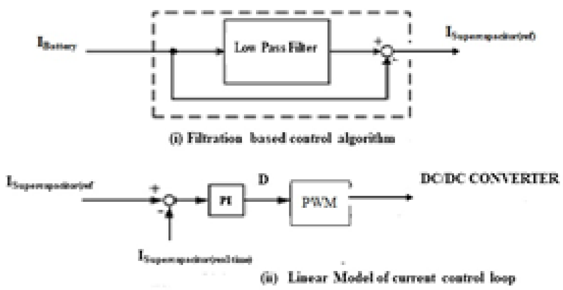

Fig. 3. Power distribution approach for battery SC-HESS

There occurs a trade-off amongst the SC size necessities and flatness of battery current profile for resolving the LPF cut-off frequency. For illustration, to attain comparatively evener battery current profile it wants moderately lower cut-off frequency, temporarily, the system desires higher SC dimensions and high-power rating of DC/DC converter to reimburse the inactive battery comebacks that ultimately control the cost exclusively. For this subject, some research works [12], [20] planned that the morals can be energetically improved via smart algorithms. But the mandatory complex regulator structure and heavy calculation competence has limited their applications in real world. In the projected system, the cut-off frequency will be sensibly resolute the simulation investigation to manage the cost and presentation and performance.

III. Numerical Investigation

A. *Pulse load retort*

The response/retort of the projected Supercapacitor-Battery HESS to pulsation load is simulated with MATLAB Simulink. The MATLAB/Simulink model established is portrayed in Fig. 4(a), whereas the results of the simulation model system when a pulse is given to the load is given away in Fig.4(b). The time period of the pulse load is customised to 10 secs and the amplitude to 5A with duty cycle set to 50% as represented in Fig. 4(b), when step change in current is in ON state then, capacitor module will discharge very quickly to achieve the unexpected change in current, meanwhile the battery expels the current slowly towards the demand side. If it is in OFF state, then Supercapacitor will captivate the extra current and permits the battery current to decrease slowly towards zero.

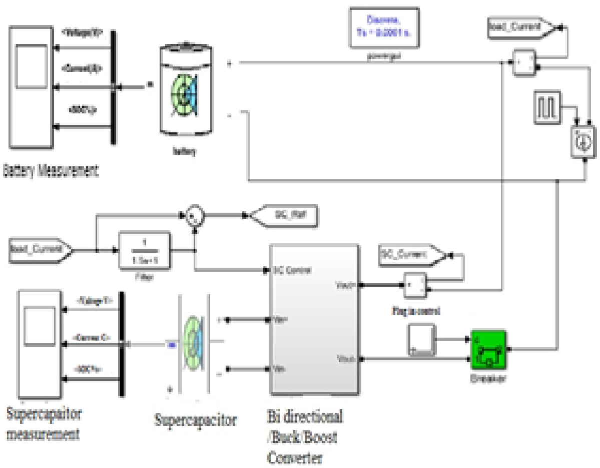

Fig. 4(a). Simulation Model in MATLAB/Simulink

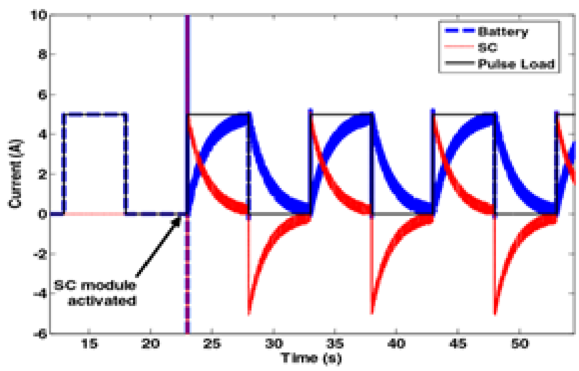

Fig. 4(b). Reaction of Supercapacitor to the pulse load and battery currents.

B. *Case Study*

To find out the effectiveness of the projected SC module introduced in justifying charging/discharging pressures on battery storage so check its efficiency a standalone PV-Battery operated housing energy system is established in MATLAB/Simulink as given away in Fig. 5. The projected Supercapacitor module is connected parallel to DC bus by a plug-in controller.

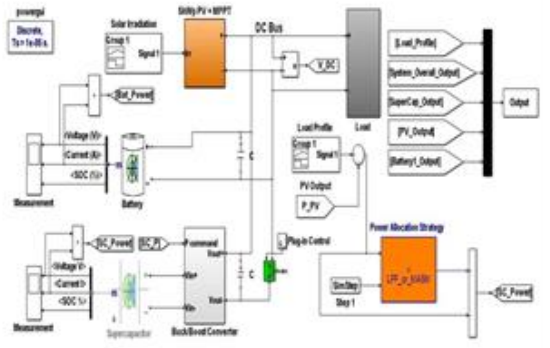

Fig. 5. PV-Battery operated housing energy system.

Grounded on Fig. 2 described in Section II of the paper, the model entails of a 5.0kWatt power PV arrays with Maximum Power Point Tracking charge controller, BES, load which is to be run by PV energy and the SC module linked with DC-DC buck/boost converter. A meek Ist order Low Pass Filter is hired to achieve the power allocationapproach with a time constant of 300000 milliseconds.

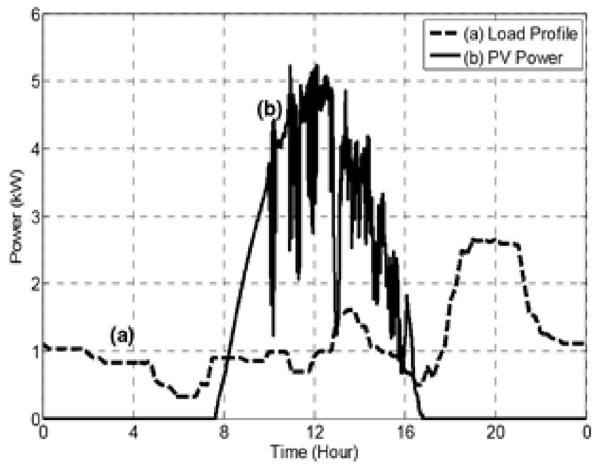

Fig. 6. 24-hrs statistics of local solar isolation for off-grid running the auxiliary load of Himalayan Queen Train (30˚51'8"N, 76˚56'15"E).

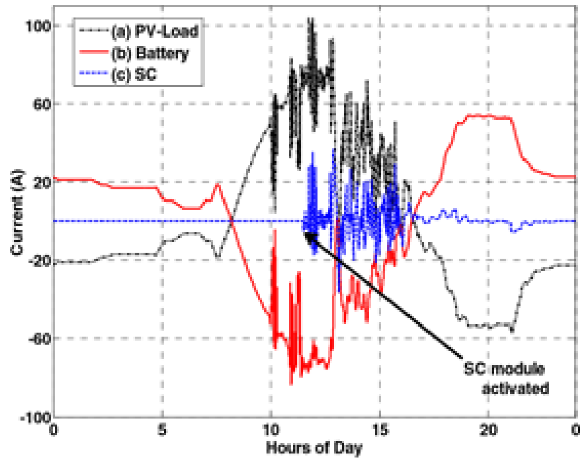

Fig. 7. Results of simulating the system in partial shading conditions.

Here Fig. 6 demonstrates the projected load profile based on data collected from an off-grid running the auxiliary load of Himalayan Queen Train (30˚51'8"N, 76˚56'15"E). The 24-hrs statistics of local solar isolation were collected together for the identical region in partial shading conditions i.e. in a cloudy day, while the Table 2 organized the constraints of the thoroughly analysed system in the simulation.

Fig. 7 exemplifies the simulation results of 24-hrs statistics of local solar isolation that were already represented in Fig.6. The arrangement was simulated with battery only settings for the Ist - 12 hours and later on SC module was triggered at 12:00 pm. During the first 12 hours when only battery was operating, it needs to absorb or supply the remaining power exchange i.e. PPV-Pload which was detected to be changing very fastly from 10 am to 12 pm. These extremely energetic changing currents possibly weaken the battery life span and also decreases the processes age too. When SC unit was triggered at 12:00 pm, some of the changing/fluctuating currents were rivetted by the SC module, which recommends a noticeable justifications for the battery operation strains.

TABLE II. SIMULATION MODEL CONSTRAINTS/PARAMETERS

Simulation model Constraints	*Battery*	*Supercapacitor Unit*
Capacity of Battery	1×103 Ah	--
Supercapacitor capacitance		500 F
Typical battery voltage	48V	--
Electricity consumption on daily basis	27.40 KWhr	--
PV array MPP	5.0 KW	--

To achieve an impartial evaluation, the proposed model is simulated with only battery setting and then with SC module which is proposed in the paper independently. The Photovoltaics power generation, total battery capacity and load/ electricity consumption is outlined for both the cases and is set under examination. While Fig. 8 displays the dissimilarities in the battery current over a period of 24-hrs for the above-mentioned case with identical data as represented in Fig.6.

A general battery can give along and better lifespan of many long years if it is fabricated, designed and maintained properly. The storage capability of any battery is never 100% but the storage value increases sluggishly during the first few years of actions. When peak is attained then the lifespan of the battery gradually starts deteriorating[21]. There are numerous aspects that may perhaps disturb the battery lifespan like:

- DoD (Depth of Discharge, a substitution to indicate battery's state of charge [16]),
- charging/discharging transition (higher the transitions bigger be the impact on battery life)
- dynamicity of battery current of operation, (It portrays at which frequency the surge power fluctuations occurs. Owing to the intermediate of the alteration among the Photovoltaics power and load demand, the battery continuously faces the effect of surge current that causes the charging/discharging of the battery which might harm the battery lifespan too).
- C-rate, etc [17]. The C-rate defines the amount of charging/discharging of a battery which estimates its operating speed whether reckless or sluggish.
- created on the popularizations of multifaceted phenomena in battery maturity, a battery's fitness function w.r.t cost i.e. Cost (Tff) as made known in eq. (1) is used to authenticate the efficacy of the projected system [15]

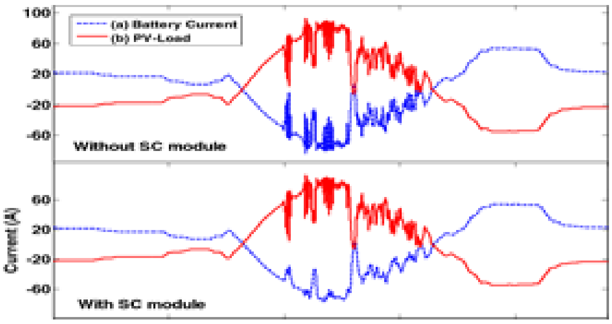

Fig. 8. Battery profiles w.r.t current with and without SC

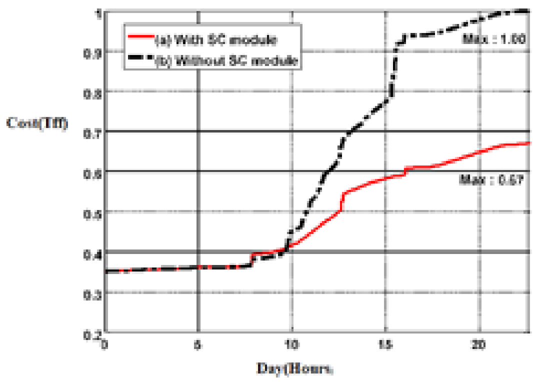

Fig. 9. Battery's fitness function with and without SC

$$Cost(T_{ff}) = \sum_{t=0}^{T'} m_1[i_c(t)^2] + m_2\left|\frac{di_c(t)}{dt}\right| + m_3[max\, e(t) - \min e\,(t)]^2 + m_4\begin{vmatrix}1 & [i_c(t) * i_c(t-1) < 0] \\ 0 & [i_c(t) * i_c(t-1) \geq 0]\end{vmatrix} + m_5$$

Here

T' is the total operating time.

$i_c(t)$ is the current flowing in the battery.

e(t) is the state of charge of the battery and m_1, m_2, m_3, m_4, m_5 are the +ve constants.

- m_1 defines C-rate, i.e. the amount of charging/discharging of a battery which estimates its operating speed whether reckless or sluggish.
- m_2 is dynamicity of battery current of operation, (It portrays at which frequency the surge power fluctuations occur. Owing to the intermediate of the alteration among the Photovoltaics power and load demand, the battery

continuously faces the effect of surge current that causes the charging/discharging of the battery which might harm the battery lifespan too).

- m_3 is the DoD (Depth of Discharge, a substitution to indicate battery's state of charge.
- m_4 is the charging/discharging transition (higher the transitions bigger be the impact on battery life)
- m_5 states about the almanac life of the battery.

To standardize the proposed system with Supercapacitor module to be installed with battery-alone system, the Cost (Tff) for both arrangements are standardized grounded on the cost of the battery-alone system. Fig. 9 depicts shows the standardized battery's fitness function for battery-operated alone system and system with SC module, respectively. The system with Supercapacitor module determines a 33% drop in battery strength cost which advises noteworthy interruption in battery response towards the fall and maturing procedure. Even though the battery maturing process is a complex process hence it is not easy to find out these parameters with battery fitness function Cost (Tff), but if SC module is installed then there a marvellous change in the battery lifespan.

IV. EXPERIMENT VERIFICATION

The Fig. 10 illustrates the experimental circuit for testing the load pulse. A programmable DC load is installed to generate the load pulse and basic parameters of the like duty cycle, time period and amplitude are to 50%,120seconds and 1A respectively. A 12V 6Ah Lead Acid battery is installed/placed with the supercapacitor with triggered duty cycles. The current flowing in the battery and supercapacitors is measured with current sensors and stored in ATMEGA328P Arduino. The battery and SC currents recorded in the pulsed experiment are represented in Fig. 11. The SC module of 50 F installed in the experiment tells us about the capability to react towards unexpected alteration in the current and also permits the battery to get charged and discharged accordingly.

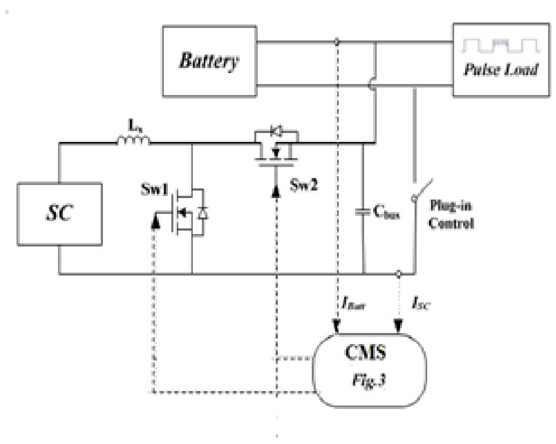

Fig. 10. Experimental circuit for testing the load pulse

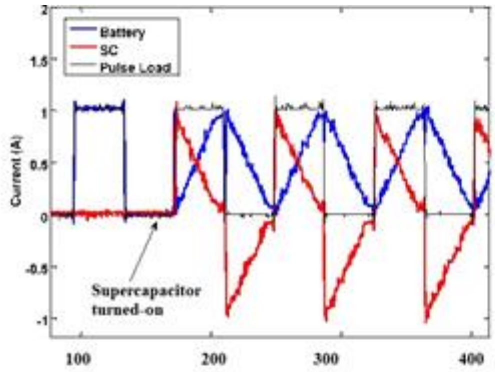

Fig. 11. Waveforms of Experimental circuit for testing the load pulse

Case Study

To authenticate the simulation results offered in preceding segments, PV energy system with Supercapacitor module was erected. Fig. 12 displays the tentative circuit diagram for the event/case study. The charge controller is linked Photovoltaics and battery. Initiative, first of its kind in world brought results and entire Himalayan Queen (52455/56) rake plying in UNESCO heritage KLK-SML section was converted to solar power train and started on 15/06/2012. Lot of engineering & technological efforts especially in design of complete system engineering, dynamic balancing of coaches, complete system integration, reliability enhancement has gone into this project to make it a success with support of CEGE, CEE & ML. The system consists of a 3KW generator provided in the underframe, driven by flat belt receiving power from Axle pulley. Regulator rectifier getting the feed from alternator, converts the energy to DC thus charging 210 AH flooded batteries at 24V. This was used to give power to the electrics of the coach. But the generator did not generate the power when the train speed is less than 15km/h.This will made battery hungry for the charge as the maximum sectional speed of the section is 25km/h.and about 50% of the time during the generator was not generating the power. The recorded currents for Photovoltaics module, power battery and Supercapacitor module are portrayed in Fig. 13. To illustrate the usefulness of the SC module in modifying battery charging/discharging, The arrangement was simulated with battery only settings for the I^{st} - 12 hours and later on SC module was triggered at 12:00 pm. During the first 12 hours when only battery was operating, it needs to absorb or supply the remaining power exchange i.e. P_{PV}-P_{load} which was detected to be changing very fastly from 10 am to 12 pm. These extremely energetic changing currents possibly weaken the battery life span and also decreases the processes age too. When SC unit was triggered at 12:00 pm, some of the changing/fluctuating currents were rivetted by the SC module, which recommends a noticeable justification for the battery operation strains. It is renowned that the battery current altered vividly by turning on the SC module. This is owing to the variance in potential difference at the DC bus terminals and SC module terminals. In actual practice, this process can be dodged by ending the system previously turning on the SC controller. The experimental case study is positively determines the efficacy of the proposed SC module in dropping the anxiety on battery in conservative PV-battery energy system deprived of the necessity to reshape the present energy storage system.

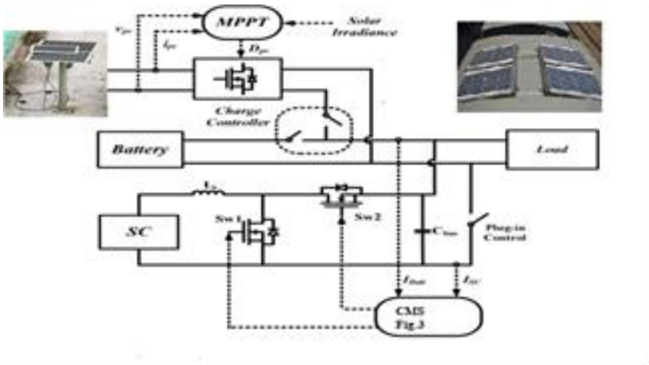

Fig. 12. Experimental Set up of the case study

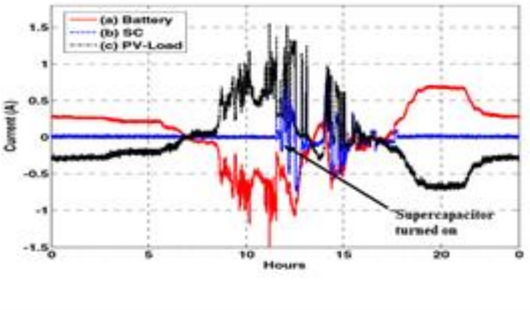

Fig. 13. Waveforms of the experimental data under partial shading conditions

V. Conclusion

This proposed paper boons a to introduce a SC module pointing to recover the battery storage lifespan in presently working conventional standalone PV-battery ESS. This new later on will be associated to DC bus by means of DC-DC converter and forms Hybrid Energy Storage System and then the battery which helps to lessen charging/discharging strains on battery storage system. The planned system can easily be installed in the prevailing PV-battery energy system without any requirements to restructure the conformation of energy storage part. Crumble demand side of the current in high and low frequency components by means of LPF, the projected Supercapacitor module grips/stores the high frequency shifting current in order to circumvent the damage of charging/discharging currents to flow to the BESS. Grounded on authentic data poised from Indian Railways, projected the system model in MATLAB/Simulink was created and the simulation is checked with the viability of the SC module. A battery fitness function w.r.t cost is also anticipated in the paper to assess the influence of battery current and pedalling pattern on the battery fitness function. The battery storage system installed with the SC represents a remarkable change or improvement in the battery fitness function when related to the traditional battery-alone system which submits a better-quality battery lifespan. Lastly, a standalone PV-BESS containing with Supercapacitor module as sample was raised. The experimental results have also coordinated with the simulation and confirmed the projected new SC module that can efficiently diminishes the charging/discharging strains on battery storage system in locomotives the present standalone Photovoltaics system deprived of redesigning the arrangement of energy storage part.

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