International Journal of Science, Strategic Management and Technology
Volume **02** Issue **05** May-**2026** | ISSN: **3108-1762 (Online)** | Impact Factor: 3.8
An International, Peer-Reviewed, Open Access Scholarly Journal Indexed in recognized academic databases

Photovoltaic Source with BESS and Energy Management Strategy

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https://doi.org/10.55041/ijsmt.v2i5.431

Cite this Article: Kushare, S. G. (2026). Photovoltaic Source with BESS and Energy Management Strategy. International Journal of Science, Strategic Management and Technology, *02*(05). https://doi.org/10.55041/ijsmt.v2i5.431

Abstract**—** This paper presents detailed investigation of a power management strategy for a a photovoltaic solar energy generation system integrated with a battery energy storage system (BESS). Battery due to the advantages of their respective energy and power density characteristics to enhance the reliability, operability and life of the system. PV systems with battery as an energy storage device where battery improves the firm capacity related to the irregular solar irradiance and unpredictable load demand, the effective supervision of a PV- Battery system is presented and discussed.

In order to address this problem, a simple and efficient control strategy is suggested to control charge-discharge operations of storage facilities according to the solar irradiance, load demand and the state of charge (SOC) levels of both energy storage components. Supervisory controller manages a correct power distribution between the battery system and the photovoltaic (PV) source and avoids overcharge and over-discharge. The system is modelled in MATLAB/Simulink, and an energy management algorithm with four switches and eleven operating modes is implemented. Simulation results demonstrate balanced battery operation under varying environmental conditions.

Keywords**—** Battery Control, Energy storage system (ESS), Photovoltaic (PV) system, Power Management, and Supervision and control

I. INTRODUCTION

There is a tremendous growing need for electric energy worldwide because of the growing population, fast industrialization and the technology progress. At the same time the increased concern for the environment and the diminishing stock of fossil fuels have brought about a much faster deployment of renewable technologies. Among the existing renewable energies, solar photovoltaic (PV) technology is under the spot light owing to the plenty of resources, no impact on the environment, modular and flexible structure of installing PV systems. These Photovoltaic (PV) systems are capable of being installed for connected to the utility grid or operated independently as standalone systems generation, hence suitable for distributed and decentralized energy generation.

Although the benefits are discussed, there are several operational problems for PV systems. Because the output power from PV array is extremely dependent on solar irradiance and environmental parameters, power generation is an inherently intermittent and fluctuating resource. Changes in in solar position, cloudy movements, and temperature variations can result in considerable fluctuation in the electrical power generated by the photovoltaic (PV) array. Also, the proposed problem statement of inconsistency between energy generation and energy demand exists. Both will cause unstable power supply and make system reliability suffer. To solve the problem, energy storage system (ESS) is widely integrated with PV.

Among different storage systems, batteries are widely applied for PV system. Batteries generally possess high density of energy and good capability for large time period energy storage. During the period of insufficient solar power (like cloudy weather or at night), batteries are capable of providing energy to compensate the difference. In PV system, repeated charge-discharge cycles can be triggered by fast solar fluctuation or rapid load changing. Batteries provide sustained energy and manage large time period storage with high charge-discharge cycles and long-life cycles. Battery and PV will complement each other in handling the energy from PV and power required by load. Several devices such as PV generator, battery, power converter, load need to work in integrated PV-based hybrid system.

An efficient control algorithm is therefore required to regulate power flow between these components while maintaining safe operating limits for the storage devices. Without proper supervision, several problems may occur, including imbalance in SOC of storage components, overcharging or deep discharging, excessive battery cycling, and inefficient utilization of solar energy. The control design of a smart Power Management Controller (PMC) should guarantee an efficient and intelligent power operation in these systems. The variable nature of the solar energy available stresses more the importance of an efficient supervisory controller. High solar energy is available and the excess must be efficiently stored to avoid any loss, low energy is available when needed and then, the stored energy must be efficient consumed to supply the load continuously. If there is not an appropriate control strategy between the battery, load and PV, imbalance of power or voltage level fluctuation, and the batteries will be degraded faster. Therefore, an adequate control strategy must be developed to regulate the power transfer among photovoltaic (PV) generators, battery storage systems, and the connected load.

The principal aims of the present work are thus to optimize the performance and the reliability of the PV system with battery storage. The behaviour of PV systems with battery storage under different working conditions is analysed to understand how power is shared between the battery and the supercapacitor. The design of the supervision and control strategy to efficiently manage power flows from PV generator to energy storage and load is one of the most important points in this research. Maximum power is achieved by PV system using MPPT, and SOC for the battery and the supercapacitor has to be regulated to avoid over-discharge and over-charge state. Moreover, a reduced battery stress is also achieved with abrupt and transient load variations with high power values. Finally, stability DC bus voltage and the global efficiency of power transfer are another one of the main goals and these will be validated under varied irradiance and load demand by MATLAB/Simulink simulations.

This paper addresses a standalone PV system with varying irradiance and load conditions. The system configuration includes an 80 W photovoltaic panel, and a 12 V/100 Ah battery.

II. LITERATURE REVIEW

The growing trend toward renewable energy system has led to emergence of various research works with respect to hybrid renewable energy systems (HRES). A HRES integrates number of renewable sources and a number of storage units so that to increase the dependability and efficiency of the system. When relying on a single source of renewable energy power output becomes irregular due to intermittency of solar and wind energy resources. Hybrid systems comprising several generating units and storage devices were proposed to facilitate constant and stable power generation [1], [3], [5].

Optimization techniques and advanced control schemes are generally applied in HRES to boost the operating performance of the system, decrease power losses and attain acceptable power quality. Energy management strategies were developed to coordinate and manage the power flow of different sources and storage devices in a hybrid system. Different control strategies were developed to maintain stable DC bus voltage and efficient utilization of stored energy [2], [6], [7], [11].

Energy storage devices compensate intermittent and fluctuating characteristics of renewable sources. The most common energy storage technologies in a HRES were the battery and supercapacitor systems. Batteries provide high energy density and capacity that is needed to store energy over a longer duration [8], [9]. Although batteries provide high energy storage capacity but their cycle life and efficiency is compromised due to prolonged charge and discharge cycles [9]. Therefore, in order to overcome the problems and challenges of battery-based energy storage system, hybrid storage system which uses both batteries and supercapacitors were suggested [8, 9].

Supercapacitors have the merits such as high density of power, short charge-discharge time and a large number of charge-discharge cycle life so it can be useful in transient power applications [14]. Supercapacitors were used in many systems such as hybrid storage system and electric vehicles to provide high power delivery and robust operation [10, 12, 15]. Hybrid storage systems that combine the strengths of batteries and supercapacitors with an advanced energy management strategy was a common design to overcome intermittency of renewable resources.

Hybrid systems comprising fuel cell and renewable energy sources also gained extensive attention [4]. A Proton Exchange Membrane Fuel Cell (PEMFC) is a clean energy source, which has high conversion efficiency and low emission. It is essential to develop models to predict the behaviour of fuel cell and to achieve optimum design [4].

Solar photovoltaic systems require effective control schemes to maximize power generation and control voltage. MPPT (Maximum Power Point Tracking) techniques are implemented to get maximum power from the solar arrays. Studies focus on characterizing MPPT algorithm with real time test system for improved accuracy [13]. In a HRES system, the coordination and control of different sources is important to achieve maximum power sharing and efficient performance. Efficient monitoring and control are required in each part of the system to obtain better efficiency and power quality of the hybrid system.

III. DESIGN, MATHEMATICAL MODELLING AND CONTROL

A. System Design

Fig 1 shows a standalone DC micro-grid made of a PV source feeding a bus and a load, with an energy storage composed of a battery. storage device is connected to the DC bus with its own DC-DC converter and is managed by a central supervisory control that issues current/charging references and protection actions.

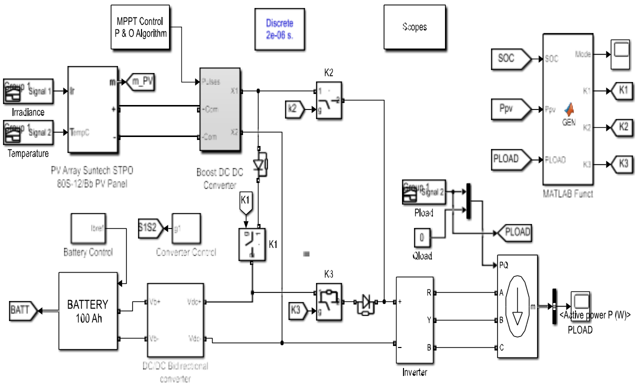

Fig. 1 MATLAB/Simulink model of the PV-battery system.

The system consists of:

1) *PV Source:* PV is primary energy source. In the figure it connects to MPPT converter (a DC-DC converter configured to perform MPPT) so PV operates at its optimum voltage/current point. The PV side is instrumented (measures I_{PV} , V_{PV} , irradiance, and temperature) so the MPPT can compute the maximum available power P_{PV}.
2) *DC-DC converters (buck-boost):* This boost (or generic DC-DC) converter both extracts maximum power from PV and steps PV voltage to DC-bus level when needed. The MPPT algorithm supplies the converter with a reference (voltage or current) to operate at V_{mpp}, I_{mpp}.
3) *DC bus:* The DC bus is a common supply node that feeds the DC load and connects the PV, battery converter, and SC converter. Its voltage is the regulated point V_{DC}(24 V). The controller regulates V_{DC} tightly (reference $V_{DC,ref}$) to ensure stable supply to the load and converters.
4) *Battery:* The battery is tied to the DC bus via a bidirectional DC-DC converter (buck-boost). This converter controls charge-discharge current of battery. Battery converter follows a current reference I_{Batt_ref} supplied by the Energy Management Controller (EMC). The converter is driven by a PWM signal to regulate current.
5) *Supervisory Control:* The central logic that monitors PV power P_{PV}, load power P_{Load}, battery SOC (SOC_{Batt}), and SC SOC (SOC_{SC}). It computes power or current references for both storage converters: I_{Batt_ref} and I_{SC_ref} . It also issues protection/disconnect actions when SOC limits are reached. It contains the decision logic that implements the 11 operation modes (charge, discharge, disconnect, transient compensation).
6) *DC load:* The DC load draws power P_{Load} from the DC bus. The controller must ensure P_{Load} is supplied by the sum of PV and storage devices.

A. Mathematical Modelling

The modelling involves deriving mathematical equations for each component to simulate real operating conditions.

1) *PV Array Model*

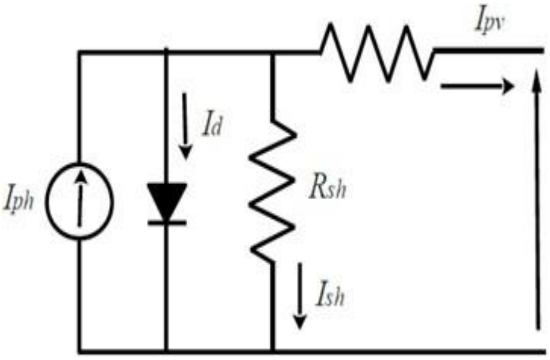

Fig. 2 One Diode Model of Solar Cell [9]

A single-diode model is used to characterize the PV panel:

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I_{PV} = I_{ph} - I_0\left[\exp\left(\frac{V_{PV}+I_{PV}R_S}{AV_T}\right) - 1\right] - \frac{V_{PV}+I_{PV}R_S}{R_{sh}} \tag{2}$$

2) *Battery Model*

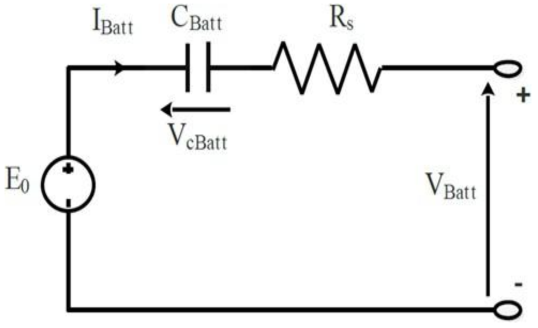

Fig. 3 Battery R-C Model [9]

The battery is represented by an R-C circuit with the following relations

$$V_{Batt} = E_0 - R_{Batt}I_{Batt} - k\int \frac{I_{Batt}}{Q}\,dt \tag{3}$$

$$SOC_{Batt} = 1 - \frac{I_{Batt}t}{C_{Batt}} \tag{4}$$

B. Proposed Supervision and Control Strategy

The power management control aims to regulate the DC bus voltage and maintain SOC within safe limits.

The fundamental power balance equation for the system is:

$$P_{Load} = P_{PV} + P_{Batt} \tag{5}$$

where:

P_{PV} : power from PV array
P_{Batt} : power from battery
P_{Load} : power consumed by load

The PV-battery energy management controller defines 5 distinct operating modes. These modes determine how energy flows between the PV array, battery and the load under different irradiance, load, and SOC conditions. Each mode specifies whether the battery is charging, discharging, or disconnected, and which DC-DC converter operates in buck (charging) or boost (discharging) configuration.

The primary decision-making parameters for the supervisory strategy include the power supplied by the photovoltaic (PV) generator and the state of charge (SOC) of the batteries. The implemented supervisory approach ensures maximum extraction of PV power, safeguards the batteries from overcharging and excessive discharge, and fulfills the required energy demand..

Depending on the different tests, the system operates in one of the following modes.

Mode 1: The available power from PV source ($P_{pv} \geq 0$) is sufficient to satisfy load demand and charge the batteries.

Mode 2: The power supplied by the PV generator is insufficient ($0 < P_{pv} < P_{load}$); in this case the power of batteries is added to satisfy the power demand. It's the compensation mode.

Mode 3: This mode is operated when no energy is provided from the PV generator ($P_{pv} < 0$), so, the batteries feed alone the load.

Mode 4: The power generated by PV source is sufficiently available and since batteries are charged to maximum level, batteries need to be disconnected for protecting them.

Mode 5: PV power is not available and the batteries are also discharged towards SOC level of 30 %. Hence load is to be disconnected.

The different modes depend on the three switches K_1, K_2 and K_3 (Table I).

TABLE I
SWITCHES AND MODE OF OPERATION

Modes	**K1**	**K2**	**K3**
Mode 1	On	On	Off
Mode 2	Off	On	On
Mode 3	Off	Off	On
Mode 4	Off	On	Off
Mode 5	Off	Off	Off

The DC bus voltage (V_{DC}) is regulated using PI controllers,

$$e(t) = V_{ref} - V_{DC} \tag{6}$$

$$I_{ref}(t) = K_p e(t) + K_i \int e(t)\, dt \tag{7}$$

Where, K_p and K_i are proportional and integral gains, respectively.

IV. SYSTEM PARAMETERS

1) PV Array Data

TABLE III
PARAMETERS OF A PV MODULE

Parameter	**Value**
Rated Power (P_{PV})	81.375 W
Voltage at MPP (V_{mpp})	17.5 V
Current at MPP (I_{mpp})	4.65 A
Open circuit (OC) voltage (V_{oc})	22 V
Short circuit (SC) current (I_{sc})	4.96 A
Temperature coefficient of SC current	3.00 mA/^{0}C
Voltage coefficient of SC Current	-150 mV/^{0}C
Number of cells per module	60
Series Connected modules	22

2) Battery parameters

For analysis purposes, the battery is modelled with equivalent impedance batt where is the resistive part and is the reactive part and represents the battery's response to the variations in the system. Parameters for internal impedance were estimated for a battery unit rated at 12V and 100Ah and calculated in Table III; however, these vary based on SOC state of the battery. Eight 12V 100Ah batteries in series were considered as the battery bank.

TABLE III
PV MODULE PARAMETERS

Parameter	**Value**
Battery Resistance R_{batt}	0.7 Ohm
Battery Reactance X_{batt}	0.07 Ohm
Battery capacitance C_{batt}	45.5 mF

3) *Study data*

- Irradiance levels: 0-1000 W/m²
- Ambient temperature: 21-35 °C
- Battery SOC range: 10-90% (initial SOC of 70%)

V. SIMULATION AND RESULTS

Preliminary test of the implemented control strategy and energy coordinating technique is done by performing the simulation under conditions with only electrical load supplied by the standalone system. In the produced simulation graphs, the validity of the control strategy to supply electrical energy and provide to the load in variable condition over 48h horizon is assessed. Under this system a full model of standalone system has been made in MATLAB/Simulink environment, where an amount of electricity generated by PV array is supplemented by battery storage system, which supply a variable three phase load. System sizing is done based on calculated load, where calculated daily energy consumption serves as design requirement for selecting adequate rating for PV modules, as well as to find total number of batteries to be used in autonomous mode of the system. Realistic climatic conditions are adopted for modelling PV modules by using variable solar radiation and ambient temperature, and plotted in Fig.5 and Fig.6, generation system is made of 22 units of 81-Watt PV modules in the span of roughly 60 m, while storage system is made of 8 of 12 Volt 100 Ampere-hour battery cells.

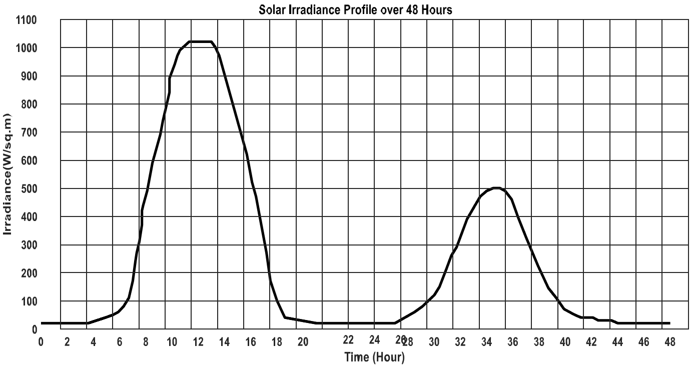

Fig. 4 Solar Irradiance Profile for PV Source Over 48 Hours

Fig. 4 displays the solar irradiance profile used for the PV source over a 48-hour simulation period. The profile shows two distinct solar cycles. First day (hours 0 to 24) with clear sky and solar peak of 1000 W/m^2 at hour 12, with availability around 12 hours, from 6 to 18 hours number. Second day (hours 24 to 48) represents a very cloudy or patchy day, with lower solar peak 480 W/m^2 around hour 34. The variation between the two days suggests the system is tested under highly variable weather conditions to validate the supervision and control strategy.

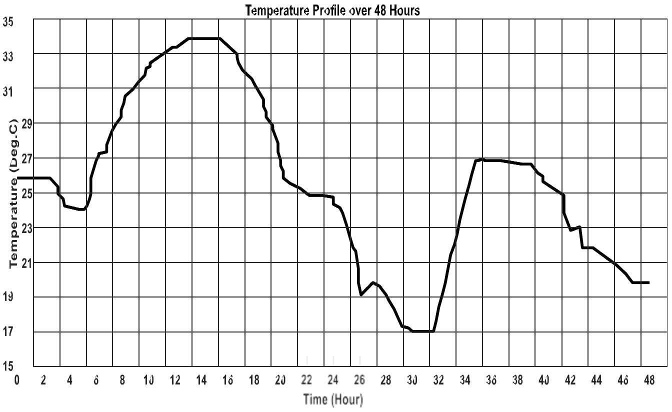

Fig. 5 Temperature Profile for PV Source Over 48 Hours

Fig. 5 represents the environmental (ambient) temperature over the 48-hour period, where it fluctuates between a minimum $17.3^\circ C$ and $34.5^\circ C$. The temperature profile clearly follows the irradiance. The peak is recorded on the first day at hour 14 (during maximum solar irradiance) whilst the second day has a lower, more flattened, peak as would be expected, this shows how closely the system is coupled with the environmental.

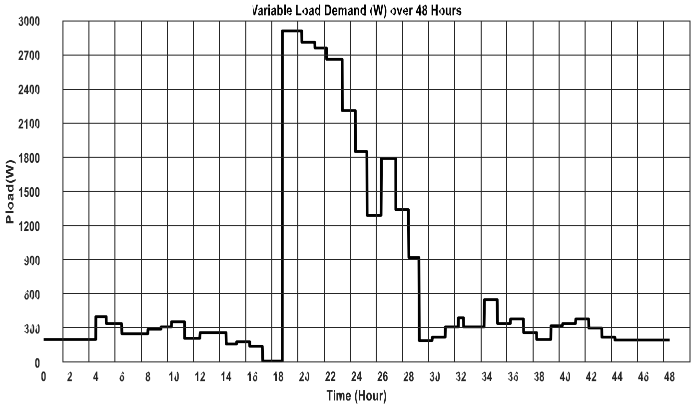

Fig. 6 Load Profile Over 48 Hours

Fig. 6 presents the 48-hour variable load profile, which has an average daily consumption of approximately 3300 Wh/day. The load is characterized by a high of nearly 2900 W occurring during the first night (Hours 18-24) and a significantly lower, intermittent baseline load (mostly 200-400 W) during daylight hours and the second day.

PV power output varies according to solar irradiance and temperature inputs considered as shown in Fig. 7. From 0-7 Hours PV output is unavailable, hence load is supplied by batteries. As PV output starts increasing from 7-18 Hours, load is getting supplied by PV source and excess power available after 7 Hours is used to charge the batteries. From 19-27 Hours as PV output goes down, total load gets supplied by battery power. From 29-48 Hours similar power management is observed from PV source, and batteries to supply continuously varying load.

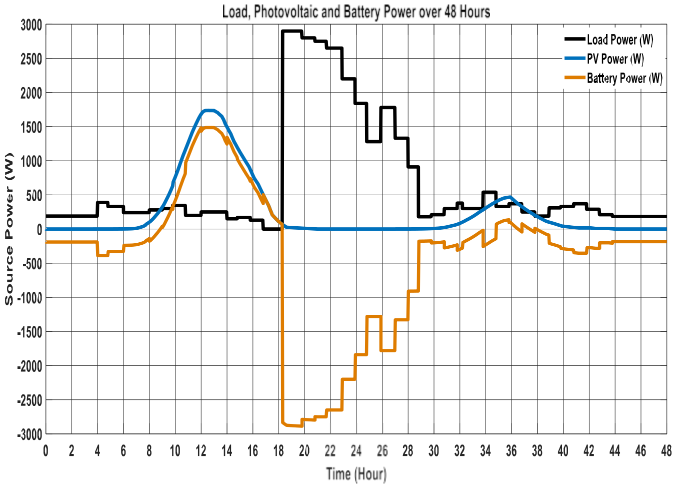

Fig. 7 Load, Photovoltaic and BESS Power (W) Variation Over 48 Hour Period

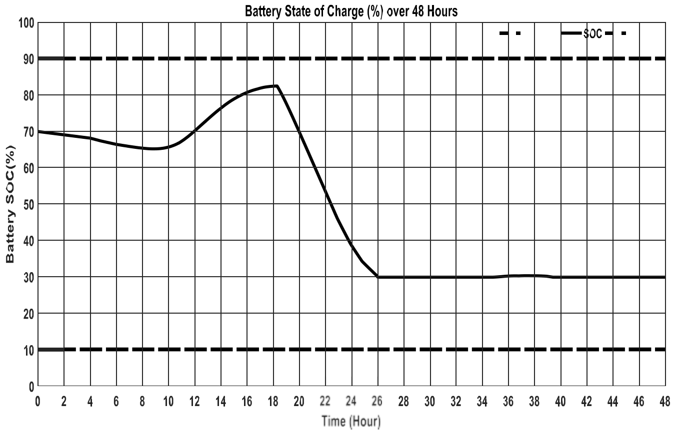

Fig. 8 Battery SOC and Limits Over 48 Hours

From 0-8 hours batteries are supplying the load, hence in discharge mode and SOC are decreasing from initial SOC value of 70% as shown in Fig. 7. From 8-16 hours, as excess power after supplying the load is available from PV source, battery starts charging. From 20-29 hours as total load gets supplied by battery power, batteries start discharging with gradual reduction in SOC.

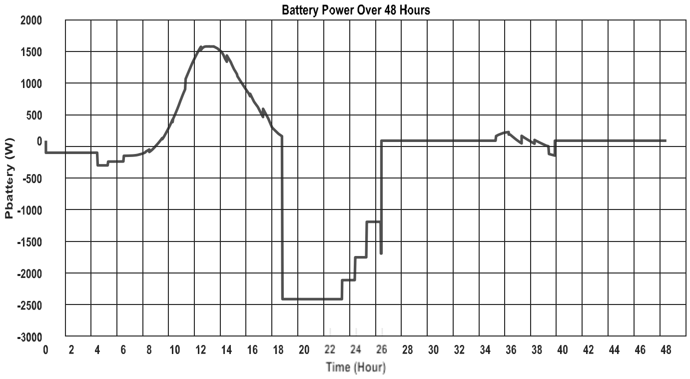

Fig. 9 Bi-directional Battery Power Flow Over 48 Hour Period

Fig. 9 illustrates the bi-directional power flow of the battery over 48 hours, where positive power indicates charging (maximum 1500 W around Hour 12) and negative power indicates discharging. The battery experiences its peak discharging events (maximum around 2500 W) during the high-load period of the first night (Hours 18-24) to satisfy the high demand when PV power is absent. Respective variation in SOC can be observed.

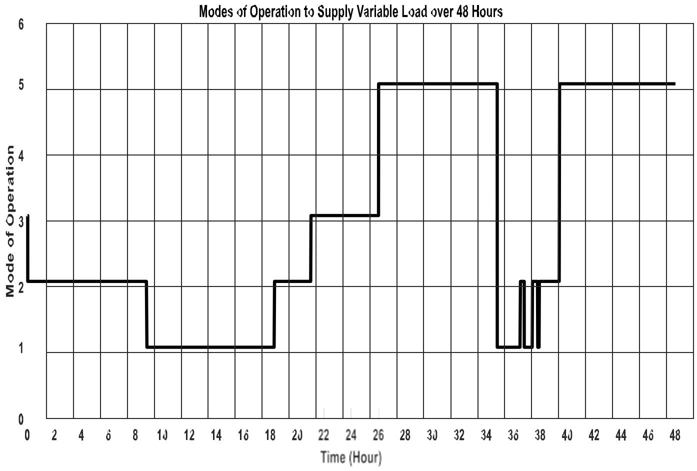

Fig. 10 Operating Modes for the Proposed System Over 48 Hour Period

Fig. 10 details the system's operational modes (1-5) over 48 hours, driven by the varying solar irradiance, load demand and SOC constraints.

VI. CONCLUSIONS

This paper presented a design, modelling, and simulation of a PV based energy storage system with battery storage and effective control strategy. In this paper, an attempt was made to analyse the behaviour of the PV energy storage system using battery and its control system for the changes in solar power and load, which is the initial step toward building a more effective BESS.

The introduced control system effectively controlled the flow of power between the PV source, battery, and load. Through simulation with MATLAB/Simulink, power equilibrium was maintained; load demand was fulfilled, and at the same time, battery is prevented from being over charged and over discharged. It is shown that simple supervisory logic used to switch between the different modes based on the level of sun light intensity and load power is able to cope with these changes and the power to load will be supplied without interruption.

Several aspects of the goals defined for this work are reached; such as optimal extracting of power from PV array without damaging the battery by keeping it within certain acceptable range for state of charge level and also ensuring power to load when either sun doesn't shine or load is heavy with suitable control structure which manages the power flow in an optimum way, for further stabilization purpose. It can be confirmed that the design structure of the supervisory control has enabled stabilization and robustness of PV-BESS.

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