# Integrating Battery Management Systems For Enhanced Energy Storage In Off-Grid Photovoltaic Systems

Devadharshini S
*Department of. Robotics and Automation*
PSG College of Technology
Coimbatore, Tamil Nadu, India

Nagalaxman G
*Department of Robotics and Automation*
PSG College of Technology
Coimbatore, Tamil Nadu, India

Dr. Anbarasi MP
*Department of Robotics and Automation*
PSG College of Technology
Coimbatore, Tamil Nadu, India

***Abstract***—Battery Management System (BMS) plays a critical role in Off-Grid Photovoltaic systems. BMS provides optimal battery performance and overall system reliability by monitoring and controlling key parameters. BMS also estimates System of Charge (SOC) to emphasize the impact of system efficiency sustainability to make the system independent from all the external common sources. The abstract also introduces modeling and simulation of integrating BMS in overall off-grid PV systems. This combination establishes a comprehensive approach to design and optimize sustainable energy solutions in remote areas)

***Keywords***—Battery Management System (BMS), System of Charge (SOC), Electric Vehicle (EVs)

## I. Introduction

The paragraph discusses the role of electricity supply in the development of world countries throughout the 20th century, emphasizing its impact on societal progress and well-being. Disparities in electricity supply expansion worldwide are noted, with some countries facing low electrification rates, per capita consumption, and poor service quality. Rural areas are particularly affected due to factors such as scattered population, isolation, high illiteracy rates, and limited access to healthcare and clean water. The high cost of grid extension exacerbates the challenge of rural electrification, prompting a focus on universal access to energy. The paragraph also introduces off-grid small-scale electricity generation as a viable option for rural electrification, highlighting its importance in achieving universal energy access. The International Energy Agency's forecasts suggest that 60% of additional electricity generation for universal access is expected to come from off-grid systems, with 90% relying on renewable-based systems and mini-grids. The second part of the paragraph outlines the need for a comprehensive framework and analytical overview of off-grid systems for rural electrification, covering areas such as the evolution of small-scale electricity generation, driving forces, typical energy uses in rural areas, and a new taxonomy for off-grid systems. The paper is organized into two main sections: the first presents the reference framework, while the second provides a comprehensive review of the literature, focusing on technology, simulation and sizing methods, techno-economic feasibility and sustainability analyses, case studies, and policy analyses [1]. This chapter provides an introduction to the guidelines and approaches employed in sizing and designing off-grid stand-alone solar PV systems. The complexity of the system can vary based on power requirements, load properties, and site-specific energy resources. The primary objective is to achieve maximum efficiency, reliability, and flexibility at an affordable cost. The subsequent sections delve into the design aspects of solar PV systems specifically tailored for off-grid electrification projects.

This passage emphasizes the significance of harnessing solar energy through photovoltaic (PV) systems, which directly convert solar energy into electricity. With fossil fuel resources expected to deplete, PV power systems offer a sustainable solution, especially for the 1.4 billion people worldwide lacking access to electricity, particularly in rural areas. The focus is on a decentralized off-grid extension in Nigeria, utilizing solar PV to address electricity challenges. Off-grid PV systems, relying on photovoltaic technology and battery storage, provide reliable electricity in areas with unreliable or nonexistent conventional grids. The geographical location of Government Technical College (GTC), Wedel, in Nigeria, known for its ample sunlight, makes it suitable for solar panel installation, with a minimum of 4.5 peak sun hours per day.

The growing electrification of transportation systems and the demand for portable electric products are driving a global surge in electric battery usage, making batteries a dominant force in total power storage. Maintaining high quality amid increasing demand is crucial. Battery performance is influenced by factors such as ambient temperature, charging methods, and battery composition. The state of charge (SoC) is a vital metric, impacting battery life, performance, and system safety. However, direct SoC estimation is challenging due to the nonlinearity, temperature, and time-dependent properties of batteries. Various techniques have been developed globally to measure SoC, with ongoing research for new approaches. SoC and cell balance serve as crucial indicators for assessing a battery's functionality and capabilities, providing an overview and comprehensive perspective. Additionally, cell balancing and charge limit calculation contribute significantly to battery health and efficient performance.

At last, In conclusion, the next step involves conducting MATLAB simulations by gathering key parameters to estimate the State of Charge (SoC) for electric batteries. This simulation aims to refine the understanding of battery performance, considering factors such as ambient temperature, charging methods, battery composition, and other critical indicators like cell balance and charge limit. MATLAB will be utilized to model and analyze the complex nonlinearity, temperature dependencies, and time-dependent properties of batteries. The simulation is crucial for improving accuracy in estimating SoC, extending battery life, enhancing performance, and ensuring the overall safety and reliability of the system.

## II. TYPES OF SOLAR PV SYSTEMS

PV systems are categorized into three primary types:

*Stand-alone Systems:*

Energy generation and consumption occur at the same location without interaction with the main grid. Devices using electricity are integral parts of the system, examples include solar home systems, solar street lighting systems, solar lanterns, and solar power plants.

*Grid-connected Systems:*

The solar PV system is connected to the main grid.

Subtypes include grid-tied systems, solely feeding power into the grid and unable to deliver local power during blackouts, as they must be completely disconnected as per safety standards. Some grid-connected PV systems with energy storage can offer local power during blackouts in an islanding mode.

*Solar PV Hybrid System:*

In a hybrid system, additional energy sources like wind, biomass, or diesel are combined with the solar PV system to meet the required demand. [2] The main goal of hybrid systems is to enhance overall system reliability cost-effectively by incorporating one or more additional energy sources. First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the Microsoft Word, Letter file.

For the above types, we use standalone PV modules with power backup to get efficiency in energy storage independently. We will further see about PV independent modules with the simulation of MATLAB after the brief theory of BMS systems with circuits.

## III. BATTERY MANAGEMENT SYSTEM (BMS)

The Battery Management System is essential to achieving battery performance and prolonging battery life in electric and hybrid vehicles. Government laws restricting CO2 emissions and promoting emission-free transportation have led to an increase in the popularity of electric vehicles. The main disadvantages of electric vehicles are their expensive price tag, limited driving range, battery issues, and irregular charging. This issue was resolved with the introduction of lithium-ion batteries. Because of their high-efficiency energy densities, battery packs have found widespread use in electric cars and portable electronic devices. They are now more widely used in many different applications, such as industrial equipment, trucks and buses, and small mobility vehicles [3]. When batteries are used improperly, they can cause fire and electric shock. Battery packs cannot be used safely or successfully without a Battery Management System (BMS)

## IV. SYSTEM OF CHARGE (SOC)

The State-of-Charge (SoC) is the percentage of charge that is present in a rechargeable battery. The State of Charge is affected by temperature and discharge rate. The State of Charge (SOC) of a battery is a percentage evaluation, stated in percentage, of the battery's available charge at any given time.

The user can find out from the SOC how long the battery might survive before needing to be updated or charged. With the right tools, battery properties like voltage and temperature may be immediately observed. SOC must be estimated due to its non-linearity and inability to be measured directly. [4] It is challenging to compute because there isn't a suitable sensor to measure the state of charge. SOC is a state parameter that changes in real time during the Hardware Design of BMS

Each BMS sub-module carries out tasks on its own, such as gathering battery cell data gathering and the energy balance of batteries. The sub-modules communicate voltage, current, and temperature data to the main control module in real time. The primary control module is in charge of analyzing battery data, calculating SOC, and doing other pertinent tasks. Moreover, the primary control module ascertains the battery's operating condition, offering temperature management, protection against overcharging and discharging, and alerting mechanisms against abnormal operations. abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

### A. *Design of voltage acquisition circuit*

In addition to providing a reference for charge and discharge management, voltage monitoring data tracks variations in voltage amongst individual battery cells, thereby minimizing inconsistency through the battery equalization circuit. Voltage readings are crucial for determining the battery state of charge simultaneously.

The common mode voltage between collection locations is considerable, but the voltage difference is tiny, necessitating appropriate monitoring and isolation when gathering voltage for power battery cells. Isolation can be seen in the distance between battery cell monitoring channels as well as the distance between the acquisition circuit and the power battery pack. This suggests that additional acquisition circuits should not be impacted by a single-cell acquisition circuit failure.

Voltage monitoring data not only serves as a standard for charge and discharge management, but it also monitors voltage fluctuations among individual battery cells, reducing inconsistency through the battery equalization circuit. Readings of the voltage are essential for concurrently determining the battery's state of charge.

When gathering voltage for power battery cells, proper monitoring and isolation are required due to the small voltage differential, despite the significant common mode voltage between collection points. The distance between the acquisition circuit and the power battery pack, as well as the distance between battery cell monitoring channels, both exhibit isolation as Fig.1. This implies that a single-cell acquisition circuit failure shouldn't affect other acquisition circuits [5]. The battery cell was isolated and sampled.

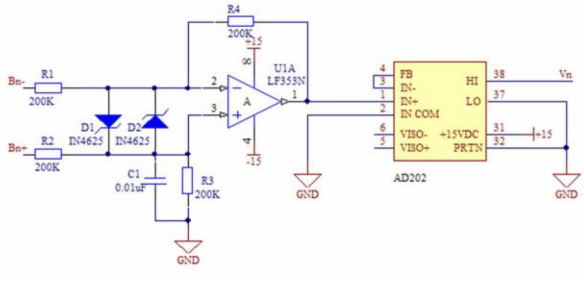


Fig.1. Isolation Voltage Circuit

### B. *Design of Analog Multiplex Switch*

A suitable multiplexer integrated circuit (IC) must be chosen and configured to satisfy system requirements to create an analog multiplexer switch within a Battery Management System (BMS). The multiplexer IC, an analog sensor for temperature and cell voltage monitoring, and a control signal source (such as a microcontroller) are crucial parts.

These sensors are coupled to the multiplexer, and to choose particular input channels, a control signal source provides binary signals. Important procedures include configuration, power supply provision, and appropriate BMS microcontroller interfacing. An analog-to-digital converter is attached to the system's output so that it can be processed further Fig.2.

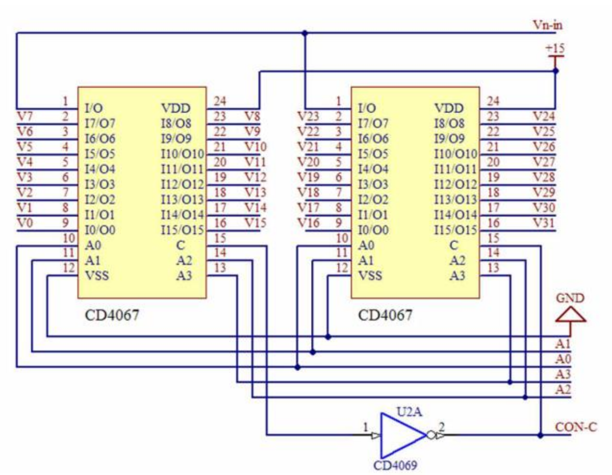


Fig.2. Voltage sampling analog multiplexer switch

Accuracy is guaranteed via testing, and safety features like defect detection systems can be put into place. For future reference and revisions, the design, connections, and safety measures must be documented. Compliance [5]. Accuracy is crucial for BMS system as this will emphasize the performance of off-grid independently

## V. IMPLEMENTATION OF BMS IN MATLAB SIMULINK

The implementation of BMS in MATLAB Simulink will discuss the components of an off-grid PV system and the importance of BMS functions.

### A. *Uses of battery backup in BMS*

Optimal performance and dependability are ensured in the design of a stand-alone solar PV and battery storage system by several important factors. First and foremost, choosing the right battery rating is crucial. It should consider variations in solar power generation as well as the connected load profile. The optimal configuration for solar power harvesting is t Fig.3. Then established, taking into account the number of strings that are connected in series as well as the number of panels in each string.

$$K_e(sT_e+1)/sT_e$$

Equation of PI controller

The purpose of a constant voltage single-phase AC supply is to give the connected load consistency and stability. The phase-lead constant and proportional gain define the PI controller, which is carefully chosen to control the solar PV and battery management system, affecting its stability and response.

### B. *Stand-Alone PV AC Power System*

With photovoltaic (PV) panels, the stand-alone PV AC power system model may generate electricity on its own without relying on the main electrical grid. PV panels in this self-sufficient system capture solar radiation and transform the resulting direct current (DC) into alternating current (AC) to power electrical loads as Fig.4.

The model consists of several parts, such as energy storage systems to effectively use power during times of low solar irradiance, charge controllers to regulate battery charging, and solar panels for DC to AC conversion as Fig.4. Because of the system's consistent and dependable AC power supply, [5,6] it can be used in rural areas or places with erratic grid connectivity. There is a monitoring panel to monitor the entire function in the simulation model

The model considers factors like battery storage and load demand [6].

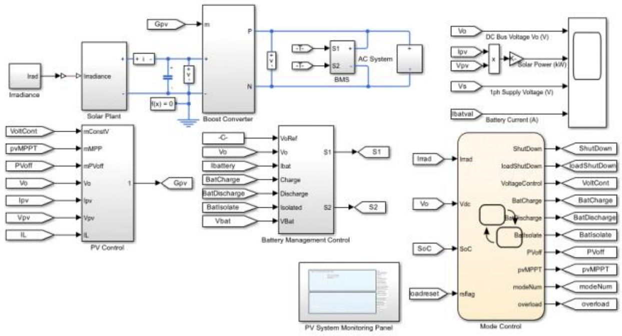

Fig.4. stand-alone PV AC power system model

*Stand-Alone PV AC Power System Panel Monitoring*

A standalone photovoltaic (PV) system producing alternating current (AC) power uses the stand-alone solar PV AC power system monitoring panel as a central hub for control and observation as Fig 5. This panel for monitoring is essential for supervising and controlling different parts of the system.

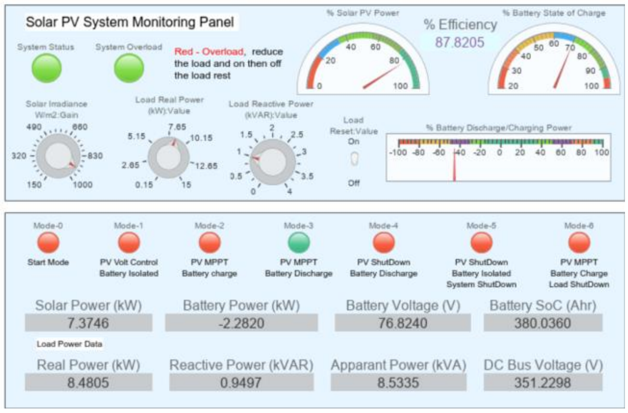


Fig.5.Monitor Panel

A user interface for displaying real-time data on energy production, battery health, and overall system performance is usually included. [7,9] This panel allows users to observe solar irradiance levels, evaluate the energy storage system's state of charge, and track the PV panels' efficiency. Furthermore, the monitoring panel facilitates the modification of system settings, guaranteeing peak efficiency in reaction to varying environmental circumstances or energy requirements. The dependability and effectiveness of standalone solar PV systems are improved by this centralized monitoring solution.

*Supervisory Control (Mode Control) Parameters*

Supervisory control parameters, also known as mode control parameters, are essential for managing and supervising the functioning of intricate systems. These settings guarantee that the system reacts to varied conditions by defining its behavior in distinct operating modes. Supervisory control parameters in the context of a stand-alone solar PV AC power system comprise the standards that specify when the system switches between modes, such as regular operation, battery charging, or standby as Fig.6.

These factors could include profiles of load demand, battery state of charge thresholds, and solar irradiance thresholds. [8,9] It is imperative to adjust these supervisory control settings to maximize system performance, improve energy economy, and guarantee a smooth transition between operating modes. The supervisory control system's efficacy is critical to obtaining dependability and sufficiency.

Operating modes of the stand-alone PV AC System are:

- Mode-0 - Start mode (Default simulation starting mode)
- Mode-1 - PV in output voltage control, battery fully charged and isolated
- Mode-2 - PV in maximum power point, the battery is charging
- Mode-3 - PV in maximum power point, the battery is discharging
- Mode-4 - Night mode, PV shutdown, battery is discharging
- Mode-5 - Total system shutdown
- Mode-6 - PV in maximum power point, the battery is charging, load is disconnected.

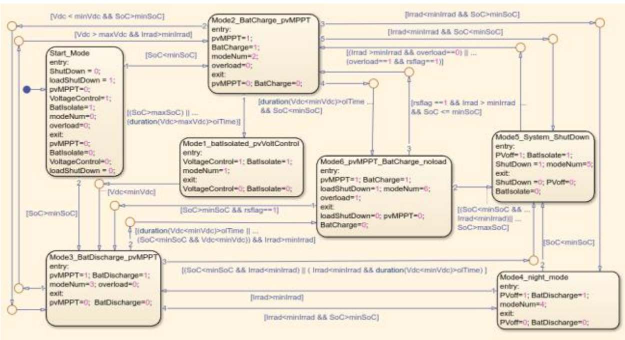


Fig.6. Mode Control Model

Together gathering information will lead to getting the output graphs which are displayed after pressing the "Run" button. The graph will show the characterization of voltage acquisition and monitoring control overall.

*MATLAB Simulation Output*

The output of the above circuit diagram is represented in MATLAB simulation using Simulink software and the output of the above circuits produces the result of the output graph which includes the output of DC Bus Voltage as Vo in volts, Solar power in kilowatts, Single phase supply voltage in volts, and also the Battery current in Amperes. These properties demonstrate how effective BMS energy storage is when used off-grid.

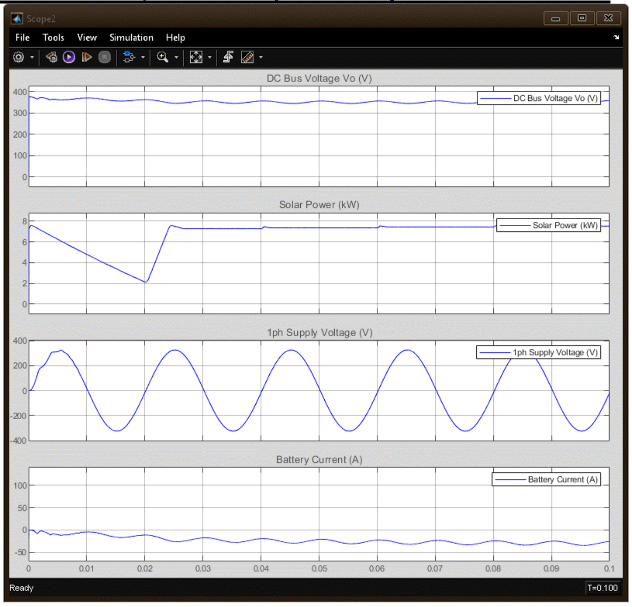


Fig.7. Output Graph

## VI. CONCLUSION

The integration of Battery Management Systems (BMS) in off-grid photovoltaic systems, modeled and simulated using MATLAB Simulink, presents a comprehensive approach to designing and optimizing sustainable energy solutions, particularly for remote areas. Through accurate modeling of battery nonlinearities, temperature dependencies, and time-dependent properties, Simulink enables precise estimation of the crucial State of Charge (SoC) parameter, vital for assessing battery functionality and extending operational life. The implementation of BMS functions such as cell balancing, charge limit calculation, and voltage monitoring contributes significantly to battery health, efficient performance, and overall system safety. The stand-alone PV AC power system model, incorporating energy storage systems, charge controllers, and solar panels, facilitates comprehensive simulation and analysis of various operating modes and scenarios. The monitoring panel allows real-time observation of energy production, battery health, and system performance, enabling adjustments for peak efficiency under varying conditions. Supervisory control parameters play a crucial role in managing system behavior and ensuring smooth transitions between operating modes based on factors like load demand, battery SoC thresholds, and solar irradiance levels. With continued research and innovation leveraging Simulink's adaptable features, off-grid renewable energy solutions will become increasingly viable and impactful, ensuring reliable and efficient electrification in remote areas worldwide.

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