A Smart Hybrid Solar–Grid DC Power Supply System with Automatic Source Selection

[1]Mrs. Varsha A. Bansod, [2]Prof. A. N. Mudiraj, [3]Prof. M. G. Aush

[1]PG Scholar, Electrical Engineering Department, Chhatrapati Shahu
[2]Head of Department, Electrical Engineering Department
[3]Associate Professor, Electrical Engineering Department, Chhatrapati Shahu College of Engineering, Chhatrapati Sambhajinagar, India.

Abstract: The rapid growth of renewable energy technologies has increased the need for efficient and reliable power management systems. Among various renewable sources, solar photovoltaic (PV) energy has gained significant attention due to its clean and sustainable nature. However, the power generated by a solar PV system depends on weather conditions and solar irradiation, making it difficult to ensure a continuous power supply. To overcome this limitation, integrating solar PV with the utility grid provides a practical solution for maintaining uninterrupted DC power to connected loads. This paper presents the design and simulation of an intelligent hybrid Solar PV–Grid power management system capable of automatically utilizing both energy sources according to power availability. The proposed system consists of a solar PV array, grid interface, isolated DC–DC converter, Maximum Power Point Tracking (MPPT), and PI-based control for regulating the DC bus voltage. Under normal conditions, the system gives priority to solar energy, while the grid supplies power whenever the available solar energy is insufficient. This strategy improves energy utilization and enhances the reliability of the overall system. The complete system is developed and analyzed in the MATLAB/Simulink environment under different operating conditions. Simulation results demonstrate stable DC bus voltage, smooth transition between solar and grid sources, effective maximum power extraction from the PV array, and satisfactory system performance. The proposed hybrid power management system offers a simple, reliable, and cost-effective solution for uninterrupted DC power applications and can be effectively used in residential, commercial, and small-scale industrial energy systems.

***IndexTerms* - Solar Photovoltaic (PV), Hybrid Solar–Grid System, Power Management, MPPT, DC–DC Converter, PI Controller, Renewable Energy, MATLAB/Simulink.**

I. INTRODUCTION

The increasing demand for electrical energy, together with growing environmental concerns and the depletion of conventional fossil fuel resources, has accelerated the adoption of renewable energy technologies worldwide. Among the available renewable energy sources, solar photovoltaic (PV) systems have become one of the most promising alternatives because they are clean, environmentally friendly, and require relatively low maintenance. Continuous improvements in PV technology have also made solar energy more accessible for residential, commercial, and industrial applications.

Despite these advantages, solar PV systems have an inherent limitation: the amount of power they generate depends on weather conditions, solar irradiance, and ambient temperature. As a result, the output power varies throughout the day and may not always be sufficient to meet the load demand. This variability can lead to interruptions in power supply, especially for applications requiring a stable DC output. To overcome this challenge, hybrid energy systems that combine solar PV with the utility grid have emerged as an effective solution. Such systems improve power reliability by automatically utilizing grid power whenever solar energy is insufficient while maximizing the use of renewable energy whenever it is available.

An efficient hybrid power management system not only ensures uninterrupted power delivery but also improves energy utilization and reduces dependence on conventional electricity sources. The integration of intelligent control algorithms and power electronic converters plays a significant role in maintaining stable voltage, minimizing switching losses, and ensuring smooth power transfer between multiple energy sources. In recent years, researchers have proposed various hybrid energy management techniques using different converter topologies and control strategies. Although these approaches have demonstrated improved system performance, many of them require multiple conversion stages, additional switching devices, or complex control circuits, which increase system cost and reduce overall efficiency.

To address these limitations, this paper presents the design and performance evaluation of an intelligent hybrid Solar PV–Grid power management system for reliable DC power supply. The proposed system integrates a solar PV array, grid interface, isolated DC–DC converter, Maximum Power Point Tracking (MPPT), and PI-based voltage control into a unified architecture. The control strategy gives priority to solar energy during normal operating conditions and automatically switches to grid power whenever the available solar energy becomes insufficient, thereby ensuring continuous operation without interrupting the DC load.

The complete system is developed and analyzed using the MATLAB/Simulink platform. Simulation studies are carried out under different operating conditions to evaluate voltage regulation, power flow, source transition, and overall system performance. The obtained results demonstrate that the proposed hybrid power management system provides stable DC output, effective utilization of solar energy, and reliable operation under varying environmental and load conditions. Owing to its simple configuration and efficient control strategy, the proposed system is suitable for renewable energy applications requiring continuous and dependable DC power.

Biomedical waste management defines waste management as the practices & procedures or the administration of activities that provide for the collection, source separation, storage, transportation, transfer, processing, treatment & disposal of waste. Biomedical waste management is a routine procedure of hospital administration as prescribed by law. Hospital waste, hospital acquired infection, transfusion transmitted diseases, rising incidence of hepatitis B, HIV & Other diseases, create potential threat of infection, contamination & serious health hazards to doctors, nurses, ward boys, support staff, sanitation workers, rag pickers & other health care workers. Who are regularly exposed to biomedical waste as an occupation hazards as well as general public in the surrounding area.

II. NEED OF THE STUDY

The growing demand for electrical energy and the increasing use of renewable energy sources have created a need for efficient and reliable power management systems. Solar photovoltaic (PV) energy is one of the most promising renewable energy sources because it is clean, abundant, and environmentally friendly. However, the power generated by solar PV systems varies with weather conditions, solar irradiance, and temperature, making it difficult to provide a continuous and stable power supply. This limitation highlights the need for a hybrid system that can intelligently combine solar PV and grid power.

A hybrid Solar PV–Grid power management system ensures uninterrupted DC power by automatically utilizing solar energy whenever it is available and switching to the utility grid when solar power becomes insufficient. Such an approach not only improves the reliability of the power supply but also increases the utilization of renewable energy, thereby reducing dependence on conventional electricity and lowering energy costs.

In addition, many existing hybrid systems require multiple converters and complex control strategies, which increase system cost, size, and maintenance requirements. Therefore, there is a need for a simple and efficient power management system that can maintain stable DC output, perform smooth source transition, and maximize solar energy utilization without increasing system complexity.

The present study addresses these challenges by developing an intelligent hybrid Solar PV–Grid power management system using MATLAB/Simulink. The proposed system incorporates MPPT and PI-based control to regulate the DC bus voltage and ensure reliable operation under varying solar and load conditions. The outcomes of this study can contribute to the development of efficient renewable energy systems for residential, commercial, and small-scale industrial applications, where uninterrupted and sustainable DC power is essential.

III. RESEARCH METHODOLOGY

3.1 System Design

The present study adopts a simulation-based research methodology to design, analyze, and evaluate an intelligent hybrid Solar PV–Grid power management system for reliable DC power supply. The proposed system is developed using the MATLAB/Simulink platform, where different operating conditions are simulated to investigate the performance of the hybrid energy management strategy. The methodology consists of system design, mathematical modeling, controller implementation, simulation, and performance evaluation. Initially, a solar photovoltaic (PV) array is modeled as the primary energy source. The PV module generates DC power based on solar irradiance and temperature conditions. The output of the PV array is continuously monitored, and a Maximum Power Point Tracking (MPPT) algorithm is employed to extract the maximum available power from the solar panels. This ensures efficient utilization of solar energy and improves the overall performance of the system. To provide uninterrupted power during low solar generation, the utility grid is integrated as a secondary energy source through an AC–DC rectifier. The proposed control strategy gives priority to solar energy whenever sufficient power is available. If the PV output decreases due to changing environmental conditions or increased load demand, the controller automatically transfers the load to the utility grid. This intelligent source selection maintains a continuous and reliable DC power supply. An isolated DC–DC converter is used to regulate the DC bus voltage and transfer power efficiently between the energy sources and the load. A closed-loop PI controller continuously compares the measured DC bus voltage with the reference voltage and generates appropriate PWM switching signals. The controller minimizes voltage fluctuations, improves transient response, and maintains stable output voltage during source transitions. The complete hybrid system is implemented in MATLAB/Simulink, where various operating scenarios are considered to evaluate system performance. The simulation records important electrical parameters, including PV voltage, PV current, output voltage, output current, output power, DC bus voltage, and converter efficiency. These parameters are analyzed to verify voltage regulation, automatic source switching, renewable energy utilization, and overall system stability.

3.2 Proposed System Architecture

The proposed hybrid Solar PV–Grid power management system consists of a solar photovoltaic (PV) array, utility grid interface, isolated DC–DC converter, control unit, DC-link capacitor, and DC load, as shown in Figure 1. The complete system is modeled and simulated in the MATLAB/Simulink environment to evaluate its performance under different operating conditions. The proposed architecture is designed to ensure uninterrupted DC power supply by intelligently utilizing solar energy as the primary source while employing the utility grid as a backup source whenever solar power is insufficient. A PI-based closed-loop control strategy regulates the converter operation and maintains a constant DC bus voltage.

3.2.1 Solar Photovoltaic (PV) Array: The solar PV array serves as the primary renewable energy source of the proposed system. It converts solar irradiance into electrical energy through the photovoltaic effect. In the simulation model, the PV array receives irradiance and temperature as input parameters. The generated DC voltage and current are continuously monitored and supplied to the power converter. The PV array is also connected to the MPPT controller to ensure maximum power extraction under varying environmental conditions.

3.2.2 Utility Grid Interface: The utility grid acts as the secondary power source whenever the available solar energy cannot satisfy the load demand. The AC supply is converted into DC using a diode bridge rectifier followed by a DC-link filter capacitor. The rectified DC voltage is supplied to the converter, thereby ensuring uninterrupted operation during periods of low solar irradiance.

3.2.3 Isolated DC–DC Converter: The proposed system employs an isolated DC–DC converter with a high-frequency transformer to transfer energy from the PV array or utility grid to the DC load. The converter provides galvanic isolation between the input and output sides, thereby improving electrical safety and system reliability. The converter also regulates the output voltage and operates efficiently over a wide range of operating conditions.

3.2.4 DC-Link Capacitor: A DC-link capacitor is connected across the converter output to reduce voltage ripple and maintain a constant DC bus voltage. It also provides temporary energy storage during sudden load variations and source transitions, thereby improving voltage stability and overall system performance.

3.2.5 PI-Based Control System: The proposed system utilizes a proportional–integral (PI) controller to regulate the converter output voltage. The controller continuously compares the measured DC bus voltage with the reference voltage and generates an error signal. Based on this error, the PI controller adjusts the converter duty cycle to maintain a stable output voltage.
The voltage error is expressed as

$$e(t) = V_{ref} - V_{dc}$$

where Vref is the reference DC voltage and Vdc is the measured DC bus voltage.

3.2.6 PWM Generation: The controller output is supplied to the PWM generator, which produces switching pulses for the semiconductor switches of the converter. The PWM technique regulates the duty cycle and controls the power transferred from the energy sources to the DC load.

3.2.7 Measurement and Monitoring: Voltage and current sensors are installed at the PV array, utility grid interface, converter output, and load terminals. These sensors continuously monitor the electrical parameters and provide feedback signals to the controller. The measured quantities include PV voltage, PV current, DC bus voltage, output voltage, output current, and output power.

3.2.8 Automatic Power Management: An intelligent energy management algorithm continuously monitors the available solar power and load demand. During normal operating conditions, the system prioritizes solar energy. Whenever the PV output becomes insufficient due to reduced irradiance or increased load demand, the controller automatically switches to the utility grid without interrupting the DC load. This strategy ensures reliable and uninterrupted operation while maximizing the utilization of renewable energy.

3.2.9 System Output: The regulated DC output is supplied to the connected load while maintaining constant voltage and current characteristics. The simulation results verify smooth source transition, stable DC bus voltage regulation, effective utilization of solar energy, and reliable operation under varying operating conditions.

The proposed hybrid Solar PV–Grid power management system was developed and evaluated in the MATLAB/Simulink environment. The PV array consists of 75 parallel strings, with 2 modules connected in series in each string. Each PV module has a rated maximum power of 200.143 W, an open-circuit voltage of 32.9 V, a maximum power voltage of 26.3 V, a short-circuit current of 8.21 A, and a maximum power current of 7.61 A. The PV model contains 60 cells per module and operates under a standard irradiance of 1000 W/m² and a cell temperature of 45°C. The utility grid is modeled with a 220 V AC input supply. The hybrid system is designed to maintain a 400 V DC bus voltage using an isolated DC–DC converter controlled by a PI controller. The reference charging power is set to 1.2 kW, while the battery nominal voltage is maintained at 300 V throughout the simulation. The switching signals for the converter are generated using PWM control to regulate the output voltage and ensure smooth power transfer between the solar PV source and the utility grid. The complete system is analyzed under different operating conditions to evaluate voltage regulation, power flow, source transition, and overall efficiency.

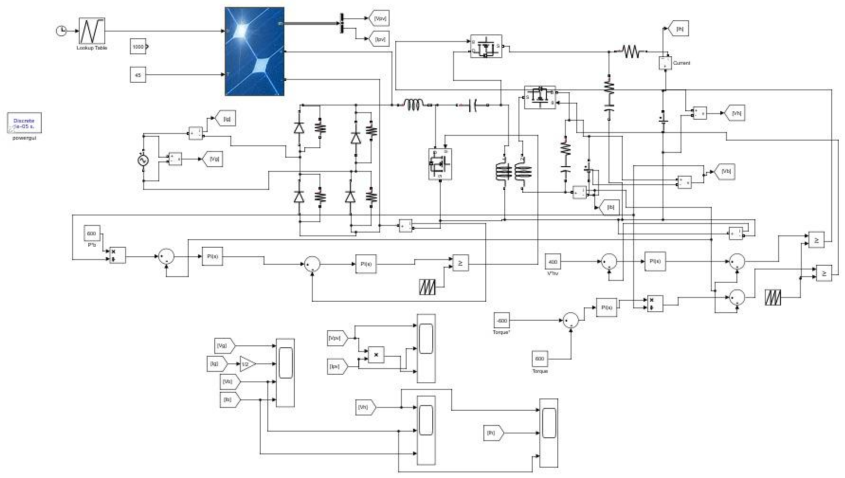

Fig.1: Proposed Hybrid Solar PV–Grid Power Management System Architecture.

3.3 Simulation Parameters

Parameter	Value
Grid Voltage	220 V AC
PV Module Maximum Power	200.143 W
Open-Circuit Voltage (Voc)	32.9 V
Maximum Power Voltage (Vmp)	26.3 V
Short-Circuit Current (Isc)	8.21 A
Maximum Power Current (Imp)	7.61 A
Cells per Module	60
Modules in Series	2
Parallel Strings	75
Solar Irradiance	1000 W/m²
Cell Temperature	45°C
Battery Voltage	300 V
DC Bus Voltage	400 V
Charging Power	1.2 kW
Control Technique	PI Controller
Switching Method	PWM
Converter Type	Isolated DC–DC Converter

Table 1: Simulation Parameters

3.4 Mathematical Modeling

The mathematical model of the proposed hybrid Solar PV–Grid power management system is developed to describe the electrical behavior of the photovoltaic array, DC–DC converter, and control system. The model provides the theoretical basis for analyzing system performance and validating the simulation results obtained from MATLAB/Simulink.

3.4.1 Photovoltaic (PV) Model

The output power generated by the photovoltaic array depends on the output voltage and current of the PV module. The electrical power generated by the PV array is expressed as

$$Ppv = Vpv\ X\ \ Ipv$$

Where, P_{PV} = PV output power (W)

V_{PV} = PV output voltage (V)

I_{PV} = PV output current (A)

The PV array operates under varying solar irradiance and temperature conditions. The MPPT controller continuously adjusts the operating point to extract the maximum available power from the PV array.

3.4.2 Load Power

The power supplied to the DC load is calculated as

$$P_{Load} = Vo \times Io$$

Where, Vo = Output voltage (V)

Io = Output current (A)

3.4.3 Converter Efficiency

The efficiency of the proposed converter is calculated using $\eta = \frac{Pout}{Pin} x\,100$ Where, Pout = Output power (W) , Pin = Input power (W)

A higher efficiency indicates better utilization of the available electrical energy.

3.4.4 PI Controller

The converter output voltage is regulated using a PI controller. The voltage error is calculated as

e(t) = Vref - Vdc Where, Vref = Reference DC bus voltage
Vdc = Measured DC bus voltage

The controller output is given by

$$u(t) = Kpe(t) + ki \int e(t)dt$$

Where, Kp = Proportional gain
Ki = Integral gain

The controller output is used to generate PWM switching pulses for the converter.

3.4.5 PWM Duty Cycle

The duty cycle of the converter is $D = \frac{Ton}{T}$ Where, T_{ON} = Switch ON time
T = Switching period

The duty cycle is continuously adjusted by the PI controller to regulate the DC bus voltage.

3.4.6 Maximum Power Point Tracking (MPPT)

The MPPT controller continuously tracks the operating point at which the PV array delivers maximum power.
The power generated by the PV array is

P = V x I

The maximum power point is obtained when

$$\frac{dP}{dV} = 0$$

This condition ensures that the PV system operates at its optimum efficiency under different irradiance levels.

IV. RESULTS AND DISCUSSION

The performance of the proposed hybrid Solar PV–Grid power management system was evaluated using MATLAB/Simulink under different operating conditions. The simulation was carried out to investigate the behavior of the PV array, converter, control system, and power management strategy. Various operating modes, including solar charging, grid charging, and propulsion (PP) mode, were analyzed to verify the effectiveness of the proposed converter and control algorithm. The obtained results demonstrate stable voltage regulation, efficient power transfer, and uninterrupted DC power supply under varying load and environmental conditions.

4.1. Characteristics of PV panel

The photovoltaic (PV) panel characteristics were analyzed to evaluate the electrical performance of the proposed system under standard operating conditions. The PV array generates output voltage and current according to the available solar irradiance and cell temperature. The simulation results show that the PV voltage, current, and output power vary smoothly with changes in environmental conditions. The MPPT controller continuously tracks the maximum power operating point and adjusts the converter duty cycle to maximize energy extraction from the PV array. As a result, the system achieves efficient utilization of available solar energy while maintaining stable operation. The smooth variation in PV electrical parameters confirms the effectiveness of the proposed MPPT control strategy.

4.2 Grid Charging mode

The grid charging mode was investigated to verify the charging performance of the proposed converter when solar energy is unavailable or insufficient. During this operating mode, the utility grid supplies power to the battery through the isolated DC–DC converter. The simulation results indicate that the grid voltage remains sinusoidal, while the converter draws a controlled current from the grid. The battery voltage is maintained close to its reference value throughout the charging process, and the charging current gradually decreases as the battery approaches its desired state of charge. The PI controller effectively regulates the converter output and minimizes voltage fluctuations during charging. These results demonstrate that the proposed system provides reliable battery charging with stable voltage regulation and smooth converter operation.

4.3 Solar charging mode

The solar charging mode was simulated to evaluate the capability of the proposed system to utilize renewable energy for battery charging. The PV array acts as the primary energy source, and the MPPT controller continuously extracts the maximum available power under varying irradiance conditions. The simulation results show that the battery is charged efficiently using solar energy while maintaining stable voltage and current characteristics. The converter operates smoothly throughout the charging process, and the PI controller ensures constant DC bus voltage. The proposed control strategy successfully reduces dependence on the utility grid and improves renewable energy utilization without affecting charging performance.

4.4 Propulsion mode

The propulsion (PP) mode was analyzed to evaluate the dynamic performance of the proposed converter under varying load conditions. During this mode, the battery supplies power to the DC load through the isolated converter. At **t = 1 s**, the converter supplies the required load power while maintaining stable DC bus voltage. At **t = 2 s**, the load demand changes, causing the controller to adjust the converter duty cycle to maintain the desired output voltage. At **t = 3 s**, the operating condition returns to a steady state, and the converter rapidly stabilizes the system with minimal transient oscillations. The simulation results confirm that the proposed controller provides fast dynamic response, stable voltage regulation, and reliable power delivery during propulsion operation.

4.5 Output Voltage and Current

The output voltage and current waveforms were analyzed to evaluate the voltage regulation capability of the proposed hybrid power management system. The simulation results indicate that the output voltage remains nearly constant despite changes in solar irradiance, source transition, and load demand. The PI controller effectively compensates for voltage variations and maintains the desired DC bus voltage. Similarly, the output current follows the load requirement with minimal ripple and smooth transient behavior. These results confirm the effectiveness of the proposed converter and control strategy in supplying stable and continuous DC power under different operating conditions.

Performance Analysis in Propulsion (PP) Mode

The propulsion mode (PP mode) is evaluated under different load conditions to verify the dynamic performance of the proposed hybrid power management system. During this mode, the battery supplies power to the load through the isolated DC–DC converter while the PI controller maintains stable operation.

- At t=1 s, the propulsion load is set to 1 kW**.** The converter responds quickly, and the battery delivers the required power while maintaining a stable DC bus voltage. No significant overshoot or oscillation is observed during the transition.
- At t=2 **s**, the propulsion load is increased (or maintained, depending on your simulation) to evaluate the transient response of the controller. The converter automatically adjusts its duty cycle to satisfy the increased power demand, while the battery voltage remains within the desired operating range. The current increases accordingly, demonstrating effective load sharing and fast controller response.
- At t=3 **s**, the operating condition changes again (such as a reduction in propulsion load or return to steady-state operation). The controller rapidly restores the system to a stable operating point with minimal voltage fluctuation. The battery current decreases smoothly and the DC bus voltage remains regulated, confirming the stability and robustness of the proposed control strategy.

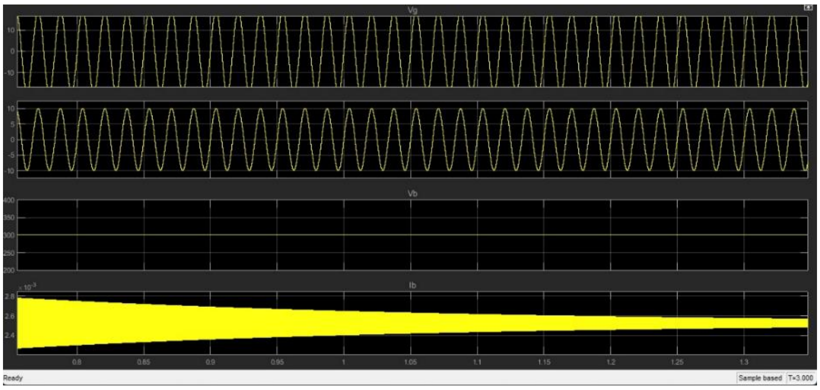

Fig.2: Output Voltage Characteristics of the Solar PV Array.

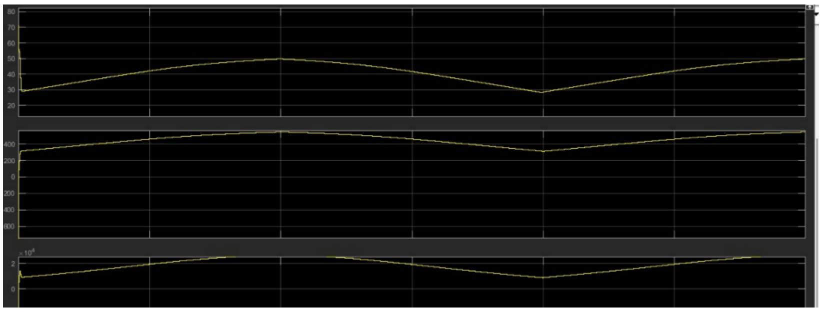

Fig 3: Power–Voltage (P–V) Characteristics of the PV Array

V. CONCLUSION

This paper presented the design and performance evaluation of an intelligent hybrid Solar PV–Grid power management system for providing a reliable and uninterrupted DC power supply. The proposed system integrates a solar photovoltaic (PV) array, utility grid interface, isolated DC–DC converter, MPPT algorithm, and PI-based closed-loop controller into a single energy management framework. The complete system was developed and analyzed using the MATLAB/Simulink platform under different operating conditions, including solar charging, grid charging, and propulsion (PP) mode. The simulation results demonstrate that the proposed control strategy effectively regulates the DC bus voltage and ensures smooth power transfer between the solar PV source and the utility grid. The MPPT controller continuously extracts the maximum available power from the PV array, improving renewable energy utilization, while the PI controller maintains stable output voltage with minimal fluctuations during changes in load and source conditions. The automatic source selection mechanism successfully prioritizes solar energy and switches to the utility grid whenever solar generation becomes insufficient, thereby ensuring continuous operation without interrupting the connected DC load. The performance analysis confirms that the proposed converter provides stable output voltage, efficient power conversion, reliable battery charging, and satisfactory dynamic response under varying operating conditions. Compared with conventional hybrid power management systems, the proposed approach offers improved voltage regulation, enhanced utilization of solar energy, reduced dependence on the utility grid, and increased system reliability. The use of an isolated DC–DC converter further improves electrical safety and operational stability.

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