Smart Hybrid Inverter Design Using Simulink and Solar Assistant

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Abstract— In this research paper, we introduce the design of a smart hybrid solar inverter. Key system components, such as AC/DC, DC/DC, and DC/AC converters, are described and presented. The innovation of the proposed system lies in its ability to accept a wide PV range of up to 15 kW and handle various load scenarios. The system was simulated to validate its operation under different load scenarios, programming parameters, and power priority configurations. The system is monitored and controlled via Solar Assistant software, which allows for the setting of various parameters to manage the different load scenarios effectively. Simulation results under different scenarios demonstrate the potential of the proposed system and its reliable operation with varying programming parameters and power priority configurations.

Keywords: Hybrid inverter, inverter design, converters, solar assistant, PV system

1. Introduction

The solar renewable energy sector has experienced significant advancements since 2008 [1], including the emergence of advanced technologies such as solar panels and charge controllers. Different solar system designs have been used to supply the energy needs of various residential, commercial, and industrial applications.

Previous research on solar inverters [1] highlights their vital role in converting the Direct Current (DC) output from solar panels into usable Alternating Current (AC) for diverse applications. Essential components of a solar inverter include the DC/DC, AC/DC, and DC/AC converters whose efficiency and quality can significantly impact the system's overall performance.

The study [1] also emphasizes the significance of solar inverters in various types of solar systems. Off-grid/hybrid and on-grid systems, the two common types of solar systems, rely on solar inverters for energy storage and distribution. The on-grid system [2] is utilized for net-metering and energy-saving solutions, while the off-grid/hybrid system is deployed in areas without grid connectivity.

The quality and power factor [1] of these components may vary depending on the type of systems deployed and their diverse range of applications. Therefore, choosing the right components for solar systems to maximize output power and ensure efficient performance is critical.

Other recent research [3] in solar inverters has focused on maximizing output power while monitoring all types of data within a given time frame.

The development of control strategies and algorithms for inverter operation has been crucial in optimizing their performance. Moreover, the focus of researchers extends to improving the cost-effectiveness and efficiency of solar inverters through the application of advanced technologies and materials.

Various studies [4] have designed and simulated solar inverters with different specifications. An inverter was designed [4] and used to provide power for a three-phase induction motor. The design used a charging algorithm based on Pulse-Width-Modulation (PWM).

Another inverter, designed using Simulink blocks [5], served only as a battery charger, simulating DC-to-DC conversion without incorporating the concept of an AC output algorithm.

The design considered in [6] was a 5-kW solar inverter with low frequency and large transformers, equipped with a maximum power point tracking (MPPT) algorithm. However, it only offered a single-phase output and had an 18 A short circuit current.

In practical applications, the use of low-frequency and low-voltage inverters [7] for small-scale applications is not feasible due to their high nominal operating voltage, limited efficiency, maximum power usage, low short circuit current, and restricted MPPT voltage range and startup voltage. Furthermore, many of these inverters are equipped with

PWM chargers, further diminishing their suitability for high-efficiency and maximum power utilization applications.

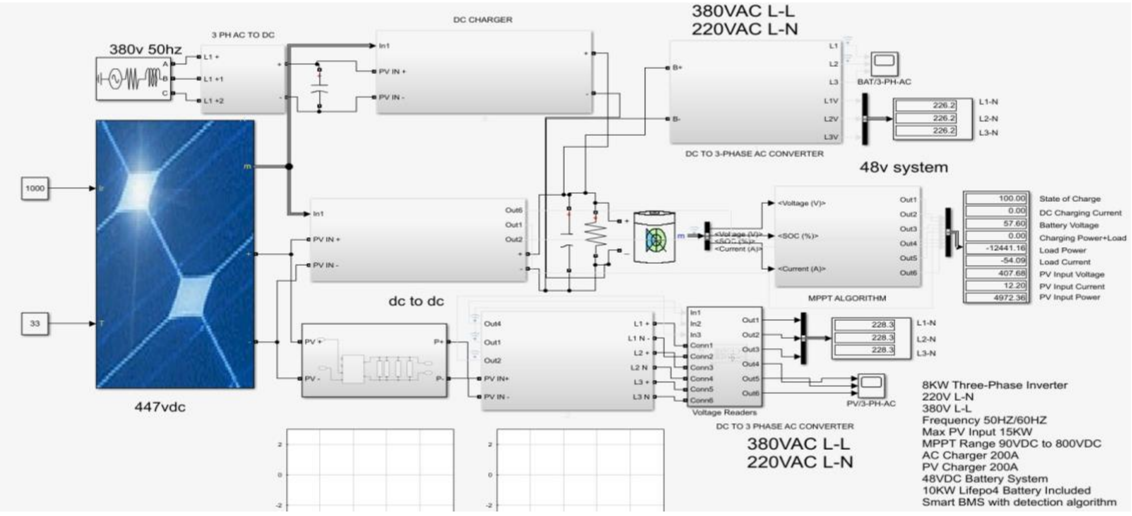

Figure 1. Architecture of the proposed system.

In this work, an inverter is introduced with a high-power factor, maximum power utilization, and real-time monitoring for residential and commercial use. It also addresses issues related to the circuit design in the inverter, like the short circuit current, the MPPT voltage range, and the startup voltage. This is especially pertinent for small inverters like low-frequency and low-voltage inverters [7,8], which often operate at a high nominal voltage. The innovation in this work lies in the inverter's ability to operate over a wide range of Maximum Power Point Tracking (MPPT) voltages, making it highly adaptable to varying solar conditions. Furthermore, this research aims to design and simulate a hybrid inverter system that can handle loads up to 8 kW while offering enhanced flexibility and efficiency in power management. The objective is to demonstrate the system's capability to manage different operational scenarios with user-defined power priorities.

After this introductory part, Section II describes the system architecture. Scenarios and simulated results are presented in section III, while a suitable conclusion is drawn in section IV.

2. System Implementation

a. *Overall Architecture*

Figure 1 shows the overall architecture of the proposed solution. The system consists of a 3-phase ac-to-dc converter, dc-dc converter, Photovoltaic (PV) dc-to-3 phase ac converter, battery dc-to 3 phase ac converter, MPPT circuit, and battery management system

To boost the efficiency of the system, the PV input range has been extended to 60-800 V, compared to the range 90V-425V used in [8].

The main equations used in the design of the system are explained.

1) Maximum power point tracker

The DC power derived from the solar panel is:

Real Power [14] $=VMPxImp$ (1)

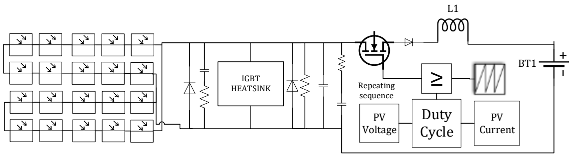

Figure 2. Solar Panel MPPT Side DC/DC Converter.

Ideal Power [14] = $Voc\ x\ Isc$ (2)

The definitions of the parameters used in equations (1) and (2) are:

1. I_{SC} = Short Circuit Current and can be measured by connecting the positive and negative terminals of the solar panel together and measuring but only for a short time.
2. I_{MP}= Maximum power current and it's usually less than the short circuit current while testing what is observed that this current value increases while a load is applied on the solar inverter powered by the panels.
3. V_{OC}= Open circuit voltage, this voltage is reached only at one case, zero load and the weather is appropriate for the solar panel to give its maximum output.
4. V_{MP}= Maximum power voltage, it is the normal operating voltage out by the solar panel at normal load and it decreases when a load is applied on the solar inverter powered by the panels.

The efficiency of the solar panel is also calculated by its area and power rating.

% Efficiency [15] = $\frac{Pmax}{Ax1000}\ x\ 100$ (3)

Where Pmax is the maximum panel power, and A is the panel area in m^2.

Now for the battery charging [10], the solar panel supplies a DC current which is set by the inverter parameters to match the battery and is calculated as follows:

$$\text{DC Charging Current [15]} = \frac{Charging\ power}{Battery\ Voltage} \qquad (4)$$

The system ensures the battery receives the maximum permissible current to elevate its charge state to approximately 80 to 90%. The float charging stage maintains the battery in a fully charged state without risking overcharging. Typically, the float charging voltage remains lower than the bulk charging voltage.

Due to the wide MPPT range of 15 kW [19], the inverter insures a straight 8 kW linear output to the end user load output, while the other remaining 7 kW is dedicated to charging the batteries.

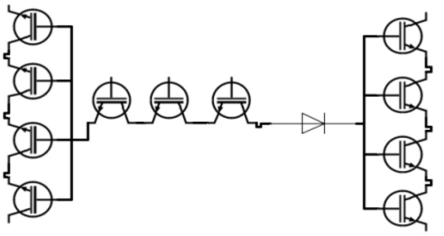

Figure 3. Heat Sink Containing SiC IGBTs.

This dual functionality not only maximizes the utilization of available solar power but also ensures a reliable power supply to the end-user while simultaneously maintaining optimal battery charge levels for future use.

The wide MPPT ensures optimized power extraction, adaptability to various panel configurations, and improved performance under variable conditions. Furthermore, this wide range ensures stability during fluctuations, providing consistent output with reduced grid dependency and extended battery life.

Figure 2 shows the architecture of the MPPT Side. Starting with 20 panels of 330 W each, connected to a diode, resistor, capacitor, and a set of transistors, connected to the buck converter module responsible for charging the battery through the Battey Management System (BMS).

Figure 3 shows the connection of the Silicon Carbide (SiC) Insulated Gate Bipolar Transistors IGBTs [18], [20] used in the MPPT algorithm. Employing SiC IGBTs on each MPPT tracker enhances overall system efficiency due to SiC's superior material properties, including higher breakdown voltage, lower switching losses, and improved thermal conductivity compared to traditional silicon-based devices. By utilizing SiC technology, these MPPT trackers can achieve higher switching frequencies, leading to reduced power losses, increased power density, and ultimately improved energy conversion efficiency in solar power generation systems.

Additionally, by integrating SiC IGBTs into the MPPT algorithm [20], the solar inverter can achieve more efficient power conversion, faster response times to changing environmental conditions, and greater overall reliability, thereby optimizing the energy output from the solar photovoltaic system.

In the proposed inverter system, a smart hybrid operation is established through relays, timers, and contactors. These devices sense whether the household load, combined with battery charging, still requires additional power. However, this is not always the case. The hybrid operation between the PV and grid implemented in the system supplies the load synchronously.

Figure 4 shows the battery management system and MPPT charging algorithm which is composed of three stages, battery mode, battery voltage, and battery state of charge.

Figure 5 presents the three-phase input to the six diodes connected to each phase terminal having an input [16] 85~440V connected to the buck converter module responsible for charging the battery through the BMS.

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Based on the BMS inside the battery, the maximum Solar/AC charging current is set, along with the programming parameters of the BMS, which include the number of cycles, state of charge (SOC), state of health (SOH), bulk, float and cutoff voltages. The controller operates in two modes. The first mode is set to prioritize the load over charging the battery, and the second mode is set to prioritize charging the battery over supplying the load.

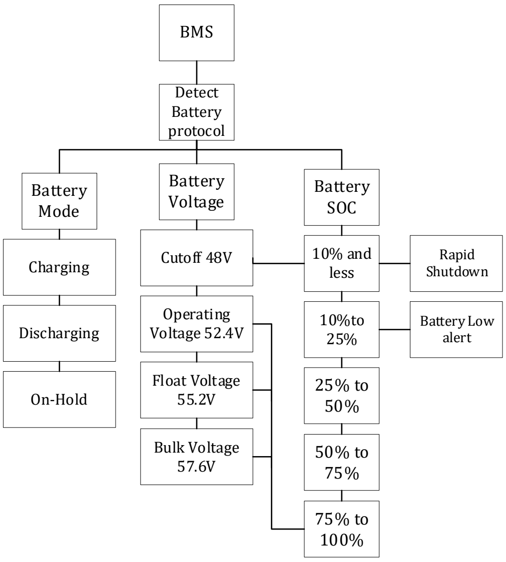

Figure 4. MPPT Algorithm.

Figure 6 shows the DC to AC converter used for PV to load and battery to load systems. However, the PV side uses a buck converter, whereas the battery side uses a boost converter. The converter has the capability of 8000VA power output with 16 IGBTs on the output, with 12 on the line phases and 4 responsible for switching. Furthermore, the system offers a wide range of input options, accepting battery DC voltages within the range of 12 to 250 volts.

Figure 7 shows the three-phase output waveform generated by two independent DC voltage sources. The first DC source is the PV side, employing a buck converter to step down the voltage with the necessary elements converting the signal. Similarly, the second DC source, obtained from the battery side, utilizes a boost converter to adjust voltage levels. The primary distinction between the two lies in the type of converter utilized.

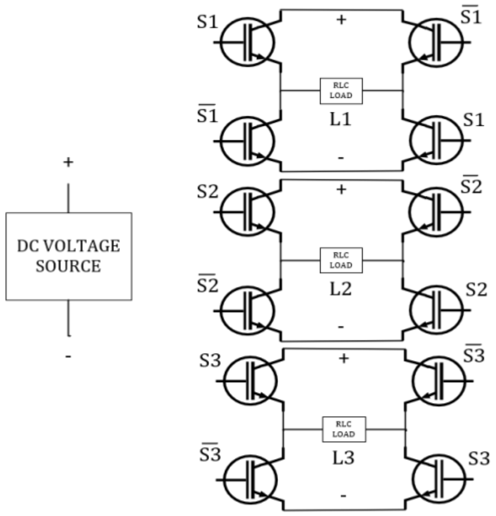

Figure 6. DC TO AC Converter.

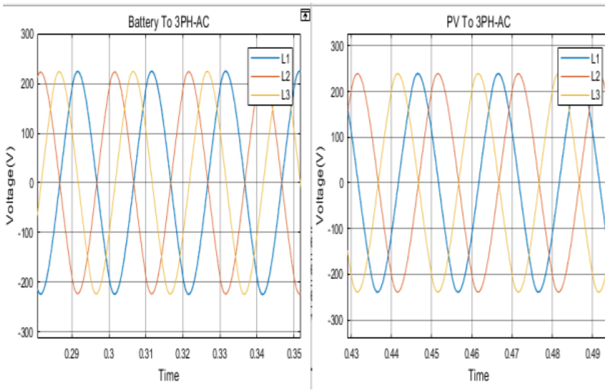

Figure 7. Three-Phase Output Waveform.

Moreover, a bypass mode is incorporated to prevent heavy loads on the inner contactor integrated within the inverter. This configuration ensures efficient power management and distribution within renewable energy systems.

4) Main Controller

Figure 8 illustrates the primary circuit responsible for power control [9]. It incorporates voltage and current sensing meters, which display various parameters such as voltage, current, and power readings from different sources like solar panels, the AC grid, and a generator.

Additionally, it shows the output power for house loads and battery charging power. The circuit includes a comprehensive configuration that allows users to set parameters, including voltage ranges, charger and MPPT power, DC and AC output voltage and frequency, as well as battery-related settings such as bulk [11], float, and cutoff voltages. Moreover, it provides various protocols for battery configuration, accommodating different battery types, along with an array of additional options.

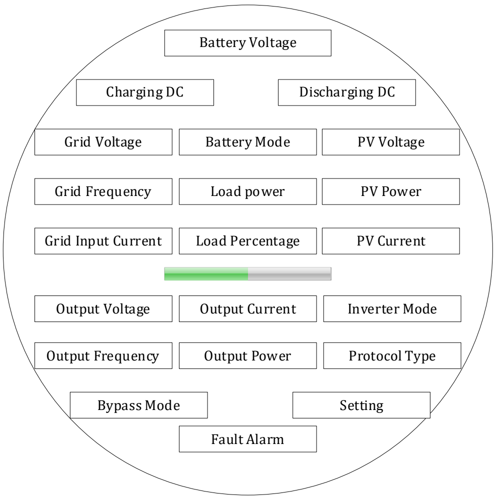

Figure 8. Controller Output.

5) Solar Assistant

Solar Assistant is a monitoring and control software used to send and receive all data and information from the inverter using an RS232 port. It monitors faults, SOC, SOH, and the temperatures of both inverter and batteries. In addition, the programming parameters of the controller can be adjusted using the Solar Assistant software [21].

Figure 9 shows the Solar Assistant [17] system used to provide the user with an enhanced monitoring solution to access a comprehensive set of details displayed on the inverter. This monitoring system allows for a deeper analysis of solar power generation, providing valuable insights into system performance and energy production.

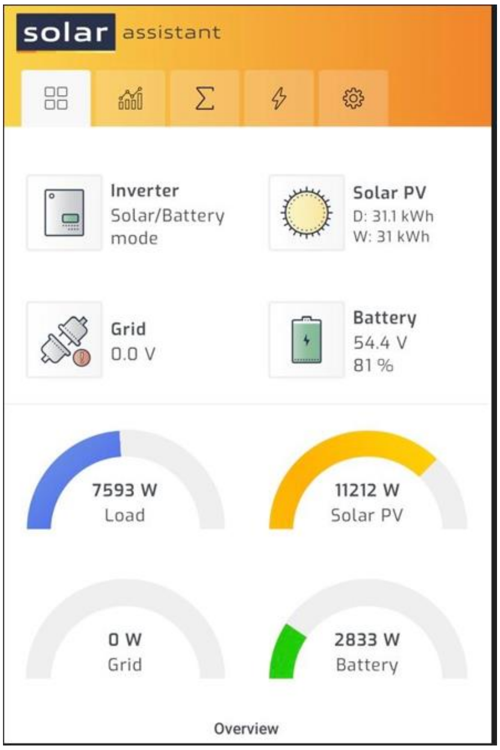

Figure 9. solar Assistant Dashboard.

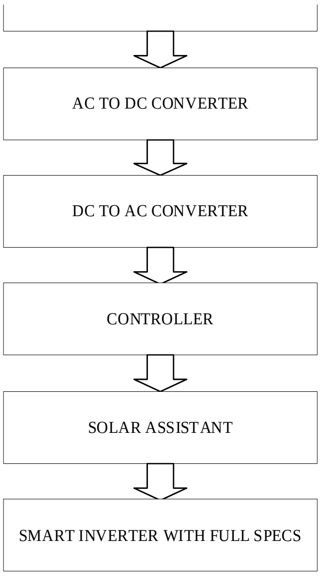

Figure 10. Inverter Diagram Flowchart.

b. Design Specifications

Figure 10 shows the flowchart of the inverter design process. This process of designing a solar inverter encompasses various stages: selecting an appropriate topology, choosing the right components, and implementing control strategies for efficient and safe operation. The flowchart provides a comprehensive overview of the steps involved in the solar inverter design process.

3. Simulated Results

To show the operation of the system, five different scenarios are presented. Each scenario has its parameter chosen by the user who programs the inverter to set priorities based on the demand and usage. Measuring devices, current transformers (CT) sensors, and AC contactors facilitate switching between different scenarios as programmed.

I. Scenario-1 UTI

In this scenario, the utility provides power to the loads as a priority. Solar and battery energy provide power to the loads, only when utility power is not available. The utility will supply the load needed at home and charge the battery at maximum charging current.

Figure 11 presents the utility priority scenario program which focuses mainly on the utility as the main supplier for the house load and battery charging; this is the bypass mode.

II. Scenario-2 SUB

In this mode, solar energy provides power to the loads as the priority. This is shown in Figure 12. If solar energy is not sufficient to power all connected loads, utility energy will step in to supply power to the load.

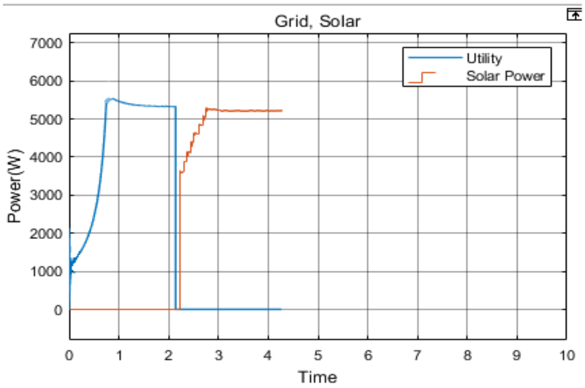

Figure 11. Utility Priority

III. Scenario-3 SBU

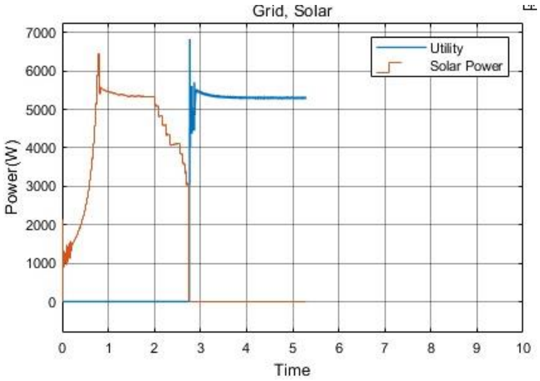

Figure 12. Solar Priority.

Solar energy provides power to the loads as a first priority [8,24]. If solar energy is not sufficient to power all connected loads, battery energy will supply power to the loads at the same time the battery is ready to supply up to a 200 A DC power at a rate of 10.24 kW. The utility provides power to the loads only when the battery voltage drops to either low-level warning voltage.

In this scenario, the solar power will be providing the load at its maximum capacity, with the battery covering any load shortage if needed until its capacity is low to 10%. When the battery's state of charge reaches this lower limit, a dry contact signal is sent to the relay controlling the AC input contactor causing the system to switch to grid mode to cover the shortage and charge the batteries.

Figure 13 presents the Solar/Battery priority scenario program which focuses mainly on Solar power and batteries as the main supplier for the house load called Battery mode. When the solar is unavailable, the utility enters the line of supply to cover the required load.

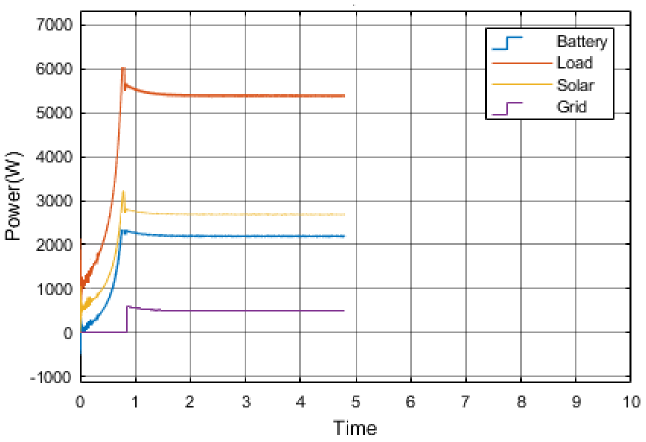

Figure 13. Solar Battery Priority.

IV. Scenario-4 SOL-NO grid

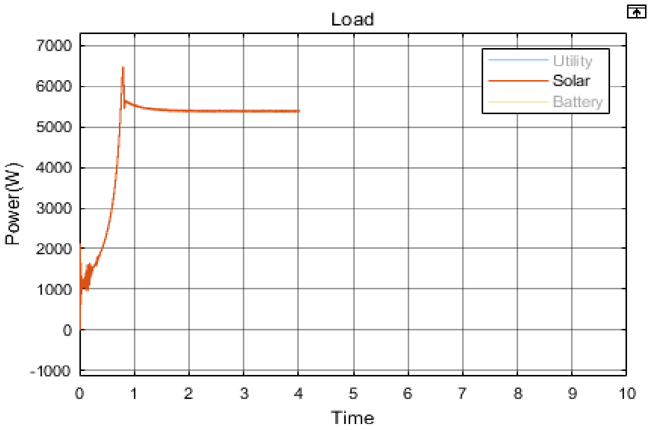

Figure 14. Solar No-Grid Priority.

Figure 14 shows the solar energy-only mode that will be supplying the load until the maximum panel power outage limit [12] [13]. If and only if capacitors are placed at the input of the batteries to activate the battery sensor as an input, the inverter will not permit the operation of any rapid surge device such as air conditioning ACs, electric heaters, and ovens.

V. Scenario-5 On-grid Operation

Solar energy will be supplying the load until it reaches the maximum panel's power outage limit [12,13]. No battery is installed and the grid will be covering the shortage of power resulting from excessive load.

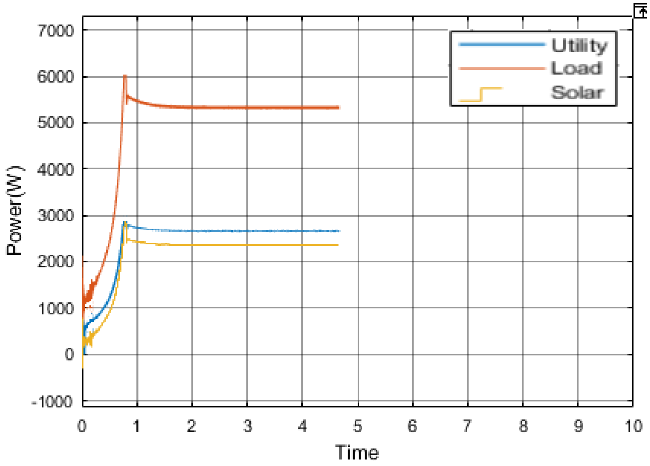

Figure 15. On-grid Operation Priority.

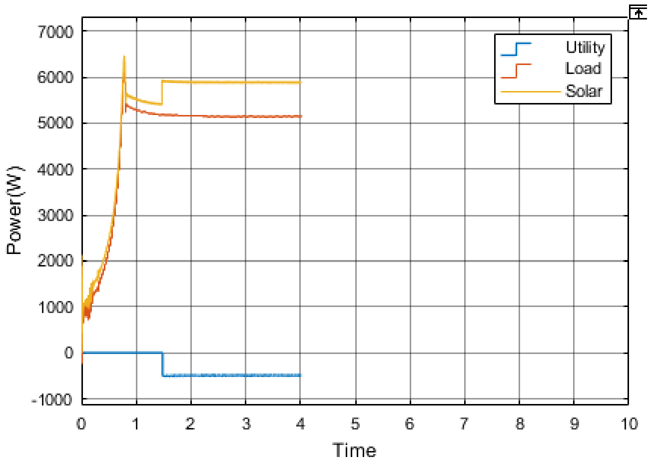

Figure 16. Net-Metering On-grid Priority.

Figure 16 presents the same programming parameter in Figure 15. However, in this scenario, as observed, the solar power was enough to supply the load, and the excessive power generated was returned to the grid.

4. Conclusion

In this paper, we propose a hybrid solar inverter with a wide range of MPPT voltages suitable for loads up to 8 kW. Simulated results showed that the system is capable of handling different scenarios with different power priorities set by the user. The hybrid inverter efficiently integrates solar, batteries, and grid power sources, ensuring reliable operation and optimal performance under varying load conditions. The flexibility to set power priorities allows users to maximize solar energy usage, reduce grid dependency, and maintain a stable power supply, making it an ideal solution for residential, commercial, and industrial applications. Overall, the proposed system enhances energy efficiency, offers greater control over energy consumption, and supports sustainable energy practices.

Future research can build on this work by exploring enhanced control algorithms, integrating the system with smart grids, and developing advanced battery management systems. Additionally, incorporating Internet of Things (IoT) technology, designing modular and scalable systems, and integrating multiple renewable energy sources such as wind energy and hydroelectric power can further optimize performance and flexibility.

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