Design of a Solar Inverter System for Off-Grid Solar Power Applications

Beatrice Anggitha Manurung, Zuraidah Tharo, Parlin Siagian

Abstract

The continuously increasing demand for electrical energy encourages the development of efficient and independent renewable energy solutions. This study aims to design a solar inverter system for off-grid solar power applications that can be used as an alternative electricity source, particularly in areas not yet connected to the national power grid (PLN). The designed system consists of a 100 Wp solar panel, a 12 V 100 Ah battery, a solar charge controller (SCC), and a 500 W inverter, and is equipped with an Internet of Things (IoT)–based monitoring system using NodeMCU and the Node-RED platform. The methods employed include power requirement calculations, system design, assembly, and performance testing of the solar panel, battery charging process, and response to a lighting load. The test results show that the system is capable of producing an average power of 76.26 W, charging the battery within 1.5 to 2 days, and maintaining voltage stability and capacity when subjected to a 16 W load. The IoT monitoring system also functions properly in monitoring voltage, current, temperature, and humidity in real time. It can be concluded that the designed off-grid solar inverter system is able to provide a stable and reliable power supply for light loads and can serve as an applicable and efficient renewable energy solution for small-scale needs in remote areas or public facilities.

Keywords: Solar Inverter, Off-Grid, Solar Energy, Solar Power Plant (PLTS), IoT, Renewable Energy.

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Introduction

The demand for electrical energy in Indonesia continues to increase along with population growth and rapidly expanding economic activities. In 2016, most of the electricity supply in the Java–Bali region was still dominated by fossil fuel–based power plants such as coal-fired power plants (PLTU), which contributed more than 50% of the total national electricity generation [1]. The use of fossil fuels is not only limited in availability but also has negative environmental impacts due to carbon emissions that accelerate global climate change [2].

As a solution to the energy crisis and environmental impacts, the utilization of renewable energy has become a key strategy in sustainable development. One of the most promising renewable energy sources is solar energy. Solar energy is abundant, environmentally friendly, and can be converted into electricity using solar cells or photovoltaic panels [3]. Solar panels generate direct current (DC), which must then be converted into alternating current (AC) so that it can be used by household and commercial electrical appliances [4].

The conversion process from DC to AC requires a device known as a solar inverter. The inverter not only functions as a current converter but also plays an important role in maintaining the stability, efficiency, and power quality of the electricity generated by a solar power system (PLTS), especially for off-grid systems that are not connected to the national electricity grid (PLN) [5]. In off-grid systems, the solar inverter must be capable of handling power fluctuations caused by changes in solar irradiance, module temperature, and environmental conditions such as panel cleanliness and orientation [6].

Off-grid solar power systems are highly relevant for implementation in remote areas that are not yet connected to the national electricity grid. In addition, these systems can also be utilized for specific applications such as electricity supply in boarding houses or educational facilities, which require lighting and cooling to create a more comfortable environment for users [7]. The use of off-grid solar power systems with high-performance solar inverters can serve as an efficient and sustainable solution to support electricity needs in such locations.

In this context, this research aims to design and develop an optimal solar inverter system for off-grid solar energy applications. The main focus of this study is to create an inverter with a stable and efficient pure sine wave output, capable of reliably supporting loads such as fans and lighting. Furthermore, the system is equipped with an Internet of Things (IoT)–based monitoring system using the Node-RED platform, enabling users to monitor system performance in real time [8].

It is expected that the results of this research will contribute to the development of appropriate technology to support the utilization of renewable energy, reduce dependence on fossil energy, and contribute to Indonesia's commitment to addressing the challenges of global climate change.

Literature Review

1. Solar Energy and Solar Panels (Solar PV)

Solar energy is one of the most promising forms of renewable energy due to its abundant availability and environmentally friendly nature. This energy can be converted into electricity through photovoltaic modules (solar panels) that transform solar radiation into direct current (DC) electricity [1]. The conversion efficiency of solar modules is influenced by various factors such as solar irradiance, module surface temperature, installation tilt angle, and panel surface cleanliness [2]. A study by Sukarno et al. (2020) shows that an increase in temperature of 1°C can cause a decrease in solar panel efficiency of approximately 0.4% [3].

2. Off-Grid Solar Power Systems

An off-grid system is a solar power system that operates independently and is not connected to the national electricity grid (PLN). This system is widely used in remote areas that have not yet been reached by the electricity grid or for local applications such as households, schools, and public facilities [4]. According to Nugroho et al. (2019), off-grid systems require good energy management because they rely entirely on renewable energy sources that are inherently fluctuating [5]. Off-grid systems typically consist of solar panels, a solar charge controller, battery storage, and an inverter.

3. Solar Inverter

An inverter is a device that converts direct current (DC) from solar panels into alternating current (AC) that can be used for common electrical loads. In off-grid systems, the inverter plays a crucial role not only in power conversion but also in maintaining voltage and frequency stability [6]. Pure sine wave solar inverters are considered more suitable for household applications and sensitive electronic equipment because they produce AC waveforms that closely resemble those of conventional utility grids [7]. In addition, modern inverters are equipped with protection features against over-voltage, under-voltage, and over-temperature, and offer high power conversion efficiency.

4. Internet of Things (IoT) for Solar Power System Monitoring

The application of Internet of Things (IoT) technology in solar power systems enables remote monitoring of system performance, such as voltage, current, battery status, and inverter output. One of the platforms commonly used for IoT implementation is Node-RED, which allows the integration of sensors and real-time monitoring dashboards [8]. Arief et al. (2022) successfully developed a Node-RED–based solar power system monitoring system for off-grid applications that provides real-time performance data via the internet [9]. The implementation of IoT adds value to the efficient and measurable operation and maintenance of solar power systems.

5. Off-Grid Solar Power Applications for Public Facilities

The utilization of off-grid solar power systems for public facilities such as campus or school canteens provides an energy-efficient and environmentally friendly solution. In addition to supporting electrification, these systems can also enhance user comfort through the provision of fans, lighting, and other electrical equipment [10].

Research Methodology

The research flowchart illustrates the systematic steps involved in designing a solar inverter system for off-grid solar energy applications, starting from problem identification to result evaluation. The following is a brief explanation of each stage:

1) Problem Identification: Identifying the need for an independent solar-based power generation system.
2) Literature Study: Reviewing references related to off-grid solar power systems, solar inverters, batteries, solar charge controllers (SCC), and IoT monitoring.
3) System Design: Designing a complete off-grid solar power system including solar panels, batteries, inverter, SCC, and protection systems.
4) Component Calculation: Calculating the required capacity of solar panels, batteries, inverter, and SCC based on load requirements and sunlight duration.
5) IoT Monitoring Design: Designing a monitoring system based on sensors (PZEM-004T, DHT11) and NodeMCU connected to the Node-RED platform.

6) Assembly and Implementation: Assembling and installing the system at the test location (canteen or public facility).
7) Testing and Evaluation: Testing system performance and monitoring accuracy, then comparing the results with the design targets.
8) Conclusion and Recommendations: Drawing conclusions and providing recommendations for further system development.

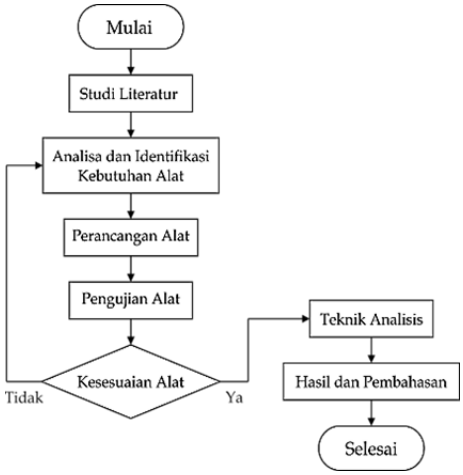

Figure 1. flowchart

Results 1. Off-Grid Solar Power System Design

The off-grid solar power system is designed to utilize solar energy as the primary source, which is converted into electrical energy. The system begins with a solar panel that receives solar radiation and converts it into direct current (DC). This energy is routed through a DC MCB (Miniature Circuit Breaker) as a protection device and then to a Solar Charge Controller (SCC), which regulates the battery charging process. The battery stores energy for use at night or when sunlight is unavailable. Subsequently, the DC energy from the battery is routed again through a DC MCB to the inverter, where it is converted into alternating current (AC). The AC output is then delivered to the load through an AC MCB and an AC watt meter to measure voltage and current parameters of the load

Figure 2. Process of the off-grid solar power system from input (sunlight) to output

2. Component Design of the Off-Grid Solar Power System Panel

The components of the solar power system are housed in a panel box with dimensions of 50 cm × 60 cm × 20 cm, which accommodates devices such as the SCC, inverter, battery, and MCB protection systems. This design was developed with the following considerations:

1. Space efficiency and component integration
    a) Installation safety
    b) Accessibility for maintenance
2. IoT-Based Off-Grid Solar Power Monitoring System Diagram
   This section presents the diagram of an Internet of Things (IoT)–based off-grid solar power system monitoring setup. The monitoring system is designed to observe key parameters such as current, voltage, temperature, and humidity, fully powered by the energy generated from the solar power system itself. The monitoring system consists of three main components:

1) Input Section

The input section includes sensors responsible for measuring physical parameters:

- PZEM-004T: Used to monitor electrical current and voltage from the inverter output to the load.
- DHT11: Used to monitor ambient temperature and humidity around the equipment, which can affect the efficiency of the solar power system.

2) Processing Section (Control and Communication)

Data from the sensors are processed by the NodeMCU ESP8266 microcontroller, which features Wi-Fi connectivity and supports communication via MQTT or HTTP protocols. The NodeMCU transmits data in real time to a server or user interface application.

3) Output Section

The monitoring results are displayed on a Node-RED dashboard, providing an interactive visual representation of system parameters such as AC voltage, current, power, temperature, and humidity. The system can also be connected to a relay module for automatic load control if required (for example, disconnecting the load when the battery voltage is low).

All monitoring components are powered directly by the solar power system, ensuring fully autonomous operation without reliance on the national electricity grid (PLN). The implementation of IoT in this off-grid solar power system aims to facilitate remote performance monitoring and to enhance efficiency and reliability in the management of renewable energy.

4. Off-Grid Solar Power System Performance Testing

This testing aims to evaluate the initial performance of the 100 Wp solar panel, which serves as the main energy source in the off-grid solar power system based on a solar inverter. The testing was conducted over seven consecutive days at a school canteen, within the time range of 10:00 to 15:00 WIB, with data collected every 30 minutes.

1) Solar Panel Test Results

Measurements were taken for three main parameters: voltage (V), current (I), and electrical power (W) generated by the panel. The daily data are summarized in Table 3.1 and generally indicate that the solar panel operates within an appropriate operational range in accordance with its specifications.

Figure 3. Off-Grid Solar Power System Testing

1. Off-Grid Solar Power System Characteristic Testing

This test aims to evaluate the initial performance of the 100 Wp solar panel, which serves as the main energy source in the off-grid solar power system based on a solar inverter. The testing was conducted for seven consecutive days at a school canteen, within the time range of 10:00 to 15:00 WIB, with data collected every 30 minutes.

2. Solar Panel Test Results

Measurements were taken for three main parameters: voltage (V), current (A), and electrical power (W) generated by the panel. The daily data are summarized in Table 3.1 and generally indicate that the solar panel operates within an operational range consistent with its specifications.

Table 1. Solar Panel Test Results

Day	Voltage (V)	Current (A)	Power (W)
First	21.28	3.63	77.13
Second	21.23	3.69	78.28
Third	21.22	3.38	71.69
Fourth	21.27	3.67	78.01
Fifth	21.36	3.64	77.75
Sixth	21.33	3.51	74.87
Seventh	21.33	3.57	76.09
Average	21.29	3.58	76.26

3. Analysis and Discussion

The average results show that the solar panel produces approximately 76.26 W of power per day under field test conditions. The average voltage recorded was 21.29 V, while the average current was around 3.58 A. The daily voltage values were relatively stable, ranging from 21.22 V to 21.36 V, and current fluctuations ranged between 3.38 A and 3.69 A.

The peak power output was recorded on the second day at 78.28 W, while the lowest power output occurred on the third day at 71.69 W. These fluctuations were caused by

environmental factors such as variations in solar irradiance, solar module temperature, and possible shading or dirt obstructing the panel surface.

4. Compatibility with the Off-Grid Solar Inverter System

The performance of the solar panel can be considered good and stable, with sufficient efficiency to charge the battery and support the planned loads such as lighting and fans in the school canteen. The obtained average power value (±76 W) is reasonably close to the nominal capacity of 100 Wp, considering system losses and natural variability. This power is then converted by the off-grid solar inverter to produce AC voltage that is directly used by the load. Output consistency is crucial in off-grid systems because there is no PLN grid as a backup power source. Therefore, stable panel performance supports the inverter's ability to maintain power stability and continuous load operation.

5. Influencing Factors

a) The performance of the solar panel is influenced by several factors:
b) Solar irradiance: Higher irradiance results in greater panel output.
c) Panel surface temperature: Efficiency decreases when the panel temperature becomes too high.

Panel cleanliness and orientation: Dirty panels or suboptimal positioning reduce power output. Based on the test results, it can be concluded that a 100 Wp solar panel is suitable for use in an off-grid solar inverter–based system for small-scale applications such as a canteen, especially when supported by proper system design and IoT-based monitoring.

6. Battery Charging Test

The battery charging test was conducted to determine the time required to charge the battery from a near-depleted condition to full capacity. The battery used has a capacity of 12 V, 100 Ah. The test was carried out over two days, from 10:00 to 15:00 WIB, during periods of optimal sunlight. Charging data were collected every 30 minutes, recording the voltage and current supplied to the battery through the solar charge controller (SCC).

The test results show that the battery voltage gradually increased from approximately 11.8 V to 13.8 V within one day. The average charging current ranged between 5 and 7 A, depending on sunlight conditions. Assuming an average current of 6 A for 5 hours, the energy delivered to the battery was approximately 360 Wh per day. This indicates that charging the battery from 50% to 100% state of charge requires approximately 1.5 to 2 days.

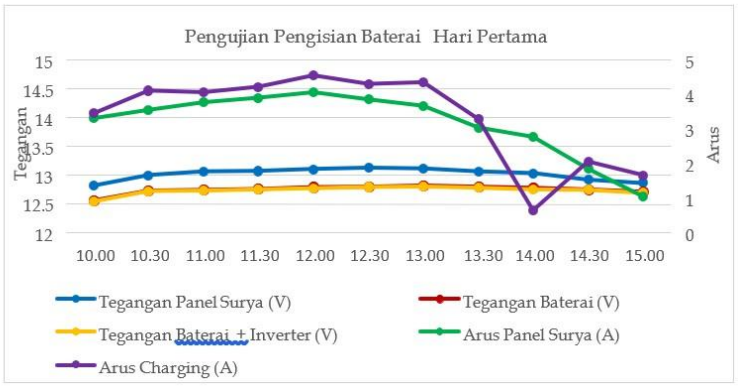

Figure 4. Battery Charging Test

The inverter used has a capacity of 500 W and operates stably. Although it is not directly involved in the charging process, the inverter contributes to maintaining overall system efficiency and ensuring proper energy distribution. Overall, the test results indicate that this

offgrid solar power system is capable of charging the battery effectively and is suitable for use as an independent power source.

7. Lamp Load Testing

The load test was conducted using a 16 W lamp as the primary load. The test results show that the off-grid solar power system is able to supply power stably and consistently during operation. The battery voltage remained within the range of 13.62 V to 13.82 V, indicating that the system maintained stable power delivery despite the presence of a load. During the test, the battery capacity remained at 100%, although a slight voltage drop from 13.47 V to 13.37 V was observed. This indicates that the battery responded normally to the applied load without significant capacity loss.

The input current to the battery also showed reasonable fluctuations, ranging from 0.14 A to 2.08 A, with an average value of 1.56 A. Overall, the tested solar power system and inverter demonstrated good performance in supporting the lighting load. These results confirm that the system can operate reliably for light-load applications such as lighting and has stable current and voltage management capabilities.

Discussion

This study demonstrates that a small-scale off-grid solar power system consisting of a 100 Wp solar panel, a 12 V 100 Ah battery, a solar charge controller, and a 500 W inverter can perform well in supporting light loads. The integration of IoT-based monitoring using NodeMCU and a Node-RED dashboard adds practical value, as users can monitor system conditions in real time and make operational decisions more quickly.

The performance of the solar panel during daily testing within effective sunlight hours showed relatively stable power output, with average daily values falling within a realistic range for a 100 Wp module under field conditions. The difference between the average field power output and the peak (Wp) rating can be explained by environmental factors such as solar irradiance intensity, module temperature, panel orientation and tilt, as well as potential shading and surface contamination. Such output fluctuations are normal characteristics of solar power systems; therefore, system success is determined not only by panel performance but also by effective energy management on the storage and load regulation sides.

On the battery side, the increase in charging voltage from the initial condition to full voltage indicates that the charging process operates in accordance with off-grid system principles. The estimated daily incoming energy and charging time of approximately one to two days for recovery from a half-charged state indicate that the panel and battery capacities are reasonably balanced for light-load usage scenarios. This finding is important because, in standalone systems, the battery functions as the primary buffer when solar radiation decreases or when loads are used outside peak sunlight hours. If load usage increases, the required battery capacity and panel power will also increase significantly; therefore, system design must consider the daily load profile and the targeted duration of nighttime power supply.

The 16 W lamp load test showed only a small battery voltage drop and no signs of power instability. This indicates that, for light loads, the system is capable of maintaining operating voltage and delivering consistent power. The presence of a 500 W inverter also provides flexibility for future expansion to other loads, such as fans or a combination of multiple devices. However, it should be emphasized that a high inverter capacity does not automatically mean the system can supply large loads for extended periods. The primary limiting factors remain the energy available from the solar panels and the effective battery capacity, including losses in the solar charge controller, inverter, and cabling.

The application of IoT in this study serves as a reliability-enhancing element. Monitoring electrical parameters through the PZEM-004T sensor and environmental conditions through the

DHT11 sensor helps users understand the relationship between weather or surrounding conditions and system performance. Real-time monitoring also opens opportunities for developing automatic control functions, such as disconnecting loads when battery voltage drops below a safe threshold, issuing alerts when charging current is abnormal, or scheduling loads based on battery conditions. Thus, the system functions not only as a power source but also as a smarter and more manageable energy system.

Although the test results indicate good system performance under the tested scenarios, there remains room for improvement to enhance the validity and practical applicability of the implementation. Testing can be expanded to include more representative load variations and longer observation periods covering diverse weather conditions. In addition, comprehensive system efficiency calculations and loss analysis of key components would help generate more precise design recommendations for field applications. Evaluating battery health, including state of charge (SoC) and state of health (SoH), is also important, as battery performance may change over time and affect supply stability.

Overall, the off-grid solar power system with IoT monitoring presented in this study is suitable as a basic electrification solution for public facilities or light-load applications, provided that load scale and usage duration are aligned with the daily energy harvest of the solar panels and the battery storage capacity. The integration of real-time monitoring is a key advantage, as it enhances operational safety, ease of maintenance, and the potential for automated energy management.

Conclusion

Based on the system design, implementation, and testing results, it can be concluded that the designed solar inverter system for off-grid solar energy applications functions effectively and meets the intended requirements. The 100 Wp solar panel demonstrated stable performance with an average daily power output of 76.26 W, which is sufficient to support light loads such as lighting and fans.

The 12 V 100 Ah battery used in the system can be charged effectively, with an estimated charging time of approximately 1.5–2 days under optimal sunlight conditions. The charging process operated smoothly and consistently with an average charging current of 5–7 A. The IoT-based monitoring system developed using the PZEM-004T sensor, DHT11 sensor, and NodeMCU microcontroller performed well, enabling real-time monitoring of voltage, current, temperature, and humidity through the NodeRED dashboard.

The 16 W lamp load test demonstrated that the system was able to maintain voltage stability and battery capacity effectively during loading conditions. The battery voltage experienced only a minor drop without affecting overall system performance.

In general, the designed off-grid solar power system successfully provides an environmentally friendly, efficient, and reliable independent energy solution, particularly for small-scale household or similar facilities that are not yet connected to the national electricity grid (PLN). These results indicate that off-grid solar inverter technology has strong potential for wider development across various regions in Indonesia as part of efforts to support the utilization of renewable energy.

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