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Assessment of Charging and Discharging Dynamics in Enhanced VRLA Battery Systems Using Solar Guardian

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ABSTRACT*The increasing demand for stable and sustainable renewable energy systems highlights the need for efficient energy storage in solar photovoltaic (PV) applications. This study investigates the impact of increasing VRLA (Valve Regulated Lead Acid) battery capacity on the performance of a rooftop solar power system monitored by the Solar Guardian Application. The system initially used two 100 Ah VRLA batteries and was upgraded to four 100 Ah batteries. Charging and discharging performance, voltage stability, and power supply duration were evaluated under a 350 W load. Experimental data on December 21, 2024, showed that the 2-battery system reached 100% SOC (State of Charge) at 11:36 with a peak current of 15.07 A and voltage of 13.84 V. During discharging, the SOC dropped to 50% in approximately 6 hours. On February 15, 2025, the upgraded 4-battery system reached full SOC earlier, at 10:30, with a peak current of 16 A and voltage stability around 14 V. The discharge duration increased to 10 hours before SOC dropped to 50%, with voltage remaining in the 12.3–12.6 V range. The results indicate that increasing battery capacity improves energy absorption speed, enhances voltage stability, and extends power supply duration. Real-time monitoring through the Solar Guardian App enables accurate performance tracking and effective energy management. This study demonstrates that combining higher storage capacity with digital monitoring significantly boosts the reliability and efficiency of rooftop PV systems in real-world conditions.*

KEYWORDS: *Battery capacity, Energy management, Rooftop solar system, Solar Guardian, VRLA battery.*

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I. INTRODUCTION

The increasing need for electrical energy drives innovation in renewable energy technology, one of which is solar power plants [1]. It is an environmentally friendly solution in reducing dependence on fossil fuels [2]. However, this system has challenges in terms of energy storage, especially when sun-light is not available [3]. To ensure a stable and sustainable power supply, the energy storage system used is a VRLA (Valve Regulated Lead Acid) battery [4].

VRLA batteries have advantages in terms of maintenance and reliability, but their limited capacity can reduce the efficiency of power supply [5], [6]. Therefore, increasing battery capacity is a potential solution in improving the performance of solar power plant systems. In this study, the Solar Guardian Application is used as a monitoring tool to measure key parameters such as voltage, current, and State of Charge (SOC) in real-time [7]. Accurate monitoring allows for a more in-depth analysis of the impact of increasing power capacity on solar power plant systems [8], [9].

This study was conducted by conducting experiments on a rooftop solar system using 2 VRLA batteries (100 Ah) as the initial configuration. After measurement and performance analysis, the system capacity was increased by adding 2 additional VRLA batteries, so that the total capacity became 4 VRLA batteries (100 Ah x 4) [10]-[12]. Comparison of results before and after capacity increase was analyzed using data from the Solar Guardian Application to evaluate changes in power storage efficiency and power supply stability [13].

The results showed that increasing the capacity of VRLA batteries had a positive impact on the duration of power supply and system stability. With monitoring through the Solar Guardian Application, changes in battery performance can be analyzed more effectively, enabling more efficient energy management [14]. Therefore, this study not only provides insight into optimizing power storage in solar power plant systems, but also emphasizes the importance of using monitoring technology in improving the reliability of renewable energy systems in the future [15], [16].

State of the Art, recent studies on photovoltaic systems have primarily focused on enhancing energy storage through increasing battery capacity or optimizing charge-discharge cycles of VRLA batteries. These efforts often include mathematical modeling or algorithmic solutions to improve storage performance and extend battery life. However, most existing literature lacks the implementation of continuous digital monitoring systems in practical environments. Research typically centers on theoretical efficiency improvements or simulations without deploying real-time applications in operational rooftop solar installations. Therefore, there remains a gap in integrating smart monitoring technologies that can provide live system diagnostics and performance data to guide energy management decisions more effectively in dynamic, real-world conditions.

Novelty, this study introduces a novel approach by integrating real-time digital monitoring through the Solar Guardian Application with the enhancement of VRLA battery capacity in rooftop photovoltaic systems. Unlike previous studies that only explored capacity expansion, this research uniquely combines capacity enhancement with continuous digital monitoring of voltage, current, and SOC parameters. This integration allows for a more precise and responsive assessment of system performance, enabling optimized energy storage management and improved power availability. The use of the Solar Guardian App sets a new benchmark in monitoring-based energy optimization, providing actionable insights that are directly applicable in real-world renewable energy deployments [17].

II. RESEARCH METHOD

This research employs an experimental approach to evaluate the impact of increasing VRLA battery capacity on the performance of a solar power plant system. The study consists of several key stages, including system installation, data collection, analysis, and performance evaluation [18]-[20].The experimental setup involves a solar power plant rooftop system equipped with 10 polycrystalline solar panels (100Wp each), connected to a solar charge controller (SCC), VRLA batteries, an inverter, and load appliances [21]. The experiment is conducted in two configurations: the initial setup with 2 VRLA batteries (100 Ah each) and an enhanced setup with 4 VRLA batteries (100 Ah each). The steps of the research methodology are as follows:

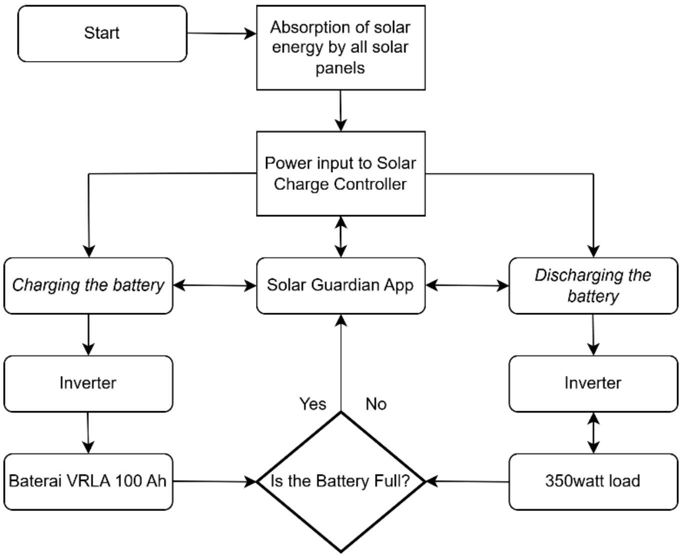

Fig.1. Research experimental design

Figure 1.show as this Research experimental design the workflow of a solar power system with a 100 Ah VRLA battery. The solar panel absorbs solar energy and channels it to the Solar Charge Controller to charge the battery.The Solar Guardian App is used to monitor the system. If the battery is not full, the charging process continues. If it is full, power from the battery is channel through an inverter to supply a 350watt load. The inverter functions to change the electric current to suit the needs of the device. This system ensures efficient use of solar energy for charging and using electric power.The solar power plant system is set up using two VRLA batteries (100 Ah each) as the baseline configuration [22], [23]. The system components are carefully integrated to ensure optimal func-tionality. These components include solar panels, a solar charge controller (SCC), an inverter, and monitoring tools [24], [25].

The solar panels, consisting of 10 polycrystalline modules (100Wp each), are installed on the roof-top to capture solar energy efficiently. The panels are wired in a combination of series and parallel connections to optimize voltage and current output [26], [27]. The SCC is connected to regulate the power flow from the solar panels to the batteries, preventing overcharging and deep discharging, thereby extending battery lifespan. The VRLA batteries act as the primary energy storage units, stor-ing the electricity generated during the daytime for later use when sunlight is unavailable. These batteries are connected in a parallel configuration, ensuring increased storage capacity and a stable power supply.

An inverter is integrated into the system to convert direct current (DC) from the batteries into al-ternating current (AC), which is compatible with household and industrial electrical appliances. The inverter is selected based on its efficiency and power handling capability to ensure stable energy conversion and supply to the connected loads.The system also includes monitoring tools, with the Solar Guardian Application playing a crucial role in real-time monitoring [28]. It continuously tracks key parameters such as voltage levels, cur-rent flow, and State of Charge (SOC), providing valuable insights into the performance and efficien-cy of the entire system. The Solar Guardian data logging feature allows for performance analysis over time, facilitating better decision-making in energy management and battery maintenance [29].To evaluate the performance of the system, data collection is conducted under controlled conditions to ensure consistency and accuracy. The system is operated under standard environmental conditions, where energy generation from the solar panels and energy consumption by the load appliances are continuously monitored [30]. During the data collection phase, key electrical parameters, including voltage, current, and SOC (State of Charge) of the VRLA batteries, are recorded at regular intervals using the Solar Guardian Application. The data logging capability of Solar Guardian allows for real-time tracking and long-term trend analysis.The duration of the power supply from the batteries to the loads is also assessed, providing insights into the overall efficiency of the energy storage system. The collected data is later used for comparative analysis to determine the impact of increasing battery capacity on system stability and reliability[31].

To enhance the energy storage capacity of the system, two additional VRLA batteries (100 Ah each) are added, increasing the total battery bank to four VRLA batteries (100 Ah x 4). This enhancement is carried out systematically to maintain system stability and prevent imbalances in charging and discharging cycles. he additional batteries are integrated into the existing parallel configuration, ensuring that the increased capacity does not negatively affect voltage stability. The connection points, cabling, and battery placement are carefully inspected to minimize resistance losses and optimize charge distribution. After the installation, the system is re-evaluated under the same operational conditions to ensure consistency in data comparison [32]. The Solar Guardian Application is used to monitor any changes in the charging and discharging behaviour, particularly in voltage regulation, current flow, and SOC fluctuations. This evaluation allows for the identification of improvements in energy storage efficiency and supply duration due to the increased capacity. Additionally, the impact of added storage on load handling capability is analyzed to determine the extent to which the expanded battery bank improves power availability and overall system reliability [33].

To evaluate the impact of increasing VRLA battery capacity, data collected from the two configurations (2-battery and 4-battery systems) are carefully analyzed and compared. The key parameters examined include charging time, discharging duration, voltage stability, and SOC retention.The analysis begins by comparing charging characteristics, examining the rate at which batteries in each configuration absorb energy from the solar panels. This includes monitoring the maximum charge acceptance rate and determining whether the increased capacity affects the charging efficiency.The discharging duration is then assessed by measuring how long the batteries can sustain power output under a defined load. This provides insights into how the additional battery capacity improves power availability and reliability, particularly during periods of low solar generation [34].Voltage stability is evaluated by observing fluctuations in voltage levels under varying load conditions. The presence of excessive voltage drops or spikes can indicate inefficiencies in power distribution. By comparing data from both configurations, it is possible to determine whether the increased storage capacity enhances system voltage regulation [35].Lastly, the SOC retention is analyzed by examining how effectively the system maintains charge over extended periods. A higher SOC retention rate in the 4-battery configuration would indicate improved energy storage efficiency, reducing the frequency of deep discharges and prolonging battery lifespan.The Solar Guardian Application plays a crucial role in this phase by providing real-time data visualization and historical trends, allowing for a more accurate assessment of performance differences between the two configurations. This analysis ultimately helps to determine the extent to which increasing battery capacity improves energy optimization and system efficiency [36].

The impact of increasing VRLA battery capacity on system stability and efficiency is concluded. The study determines the extent to which additional storage improves energy availability and system reliability. The research methodology provides a structured approach to understanding the role of increased battery capacity in enhancing energy storage efficiency. Through comprehensive data analysis facilitated by Solar Guardian, this study aims to offer valuable insights into the optimal management of solar power plant battery systems for improved energy sustainability.

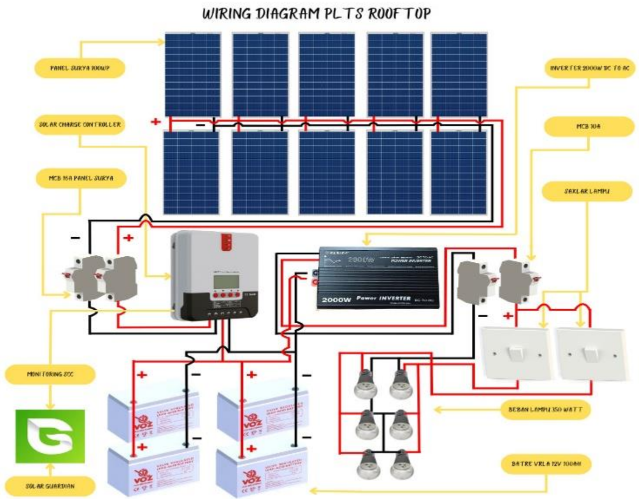

Fig. 2. Wiring Diagram

Fig.2. shows the workflow of the charging and discharging system on a rooftop solar power plant using VRLA batteries and Solar Guardian monitoring. Solar panels capture solar energy and convert it into DC current, which is then regulated by the Solar Charge Controller (SCC) before be-ing stored in the VRLA battery. The battery supplies power when there is no sunlight, with the voltage, current, and SOC status monitored by the Solar Guardian. The inverter (2000W) then con-verts the DC current to AC for use by the electrical load (350W). With automatic monitoring through the Solar Guardian, this system becomes more efficient and reliable in providing electrical energy.

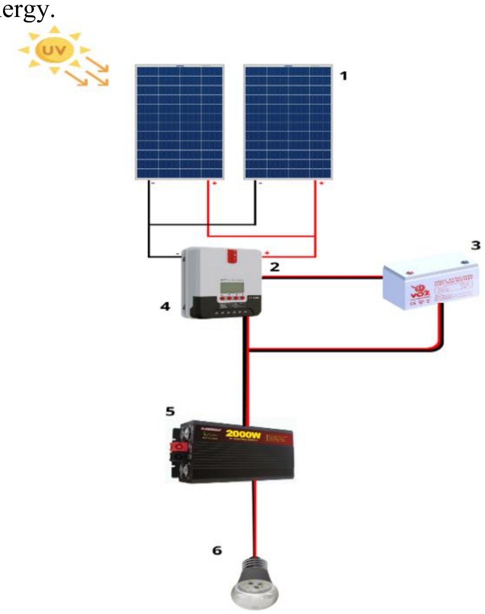

Fig. 3. Charging and Discharging System Workflow Using VRLA Batteries

Description:

1. Photovoltaic 100 Wp
2. Solar Charge Controller (SCC)
3. VRLA Battery 100 Ah
4. Solar Charge Controller (SCC)
5. Inverter 2000 Watt
6. Lamp

Fig.3. The described diagram illustrates the charging and discharging workflow of a VRLA battery in a solar power system. The process begins with solar panels that capture sunlight and convert it into direct current (DC) electricity. This energy is transmitted through electrical wiring to a charge controller, which regulates the power flow to ensure safe and efficient charging of the VRLA battery. The battery stores excess energy for later use, providing power when sunlight is unavailable. When power is needed, the stored DC energy is sent to an inverter, which converts it into alternating current (AC) suitable for household appliances. Finally, the electrical load, such as a light bulb, receives the converted AC power, ensuring continuous energy supply. This system optimizes renewable energy usage while protecting the battery from overcharging and deep discharging.

III. RESULT

The results of this study highlight the impact of increasing VRLA battery capacity on the performance of a rooftop solar power system.

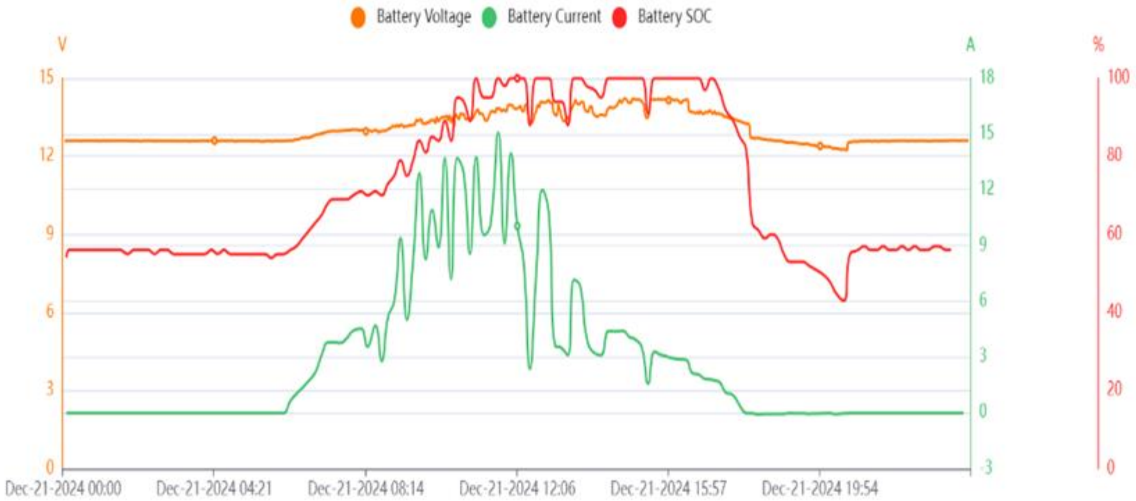

Fig. 4. Graph of Solar Guardian recording results in the form of Current, Voltage, and State of Charge (SOC) on December 21, 2024

Fig. 4.shows a graph of the recording results from the Solar Guardian application that records changes in current (A), voltage (V), and State of Charge (SOC) (%) on a rooftop solar power system with a configuration of 10 polycrystalline solar panels with a capacity of 100 Wp each on December 21, 2024. This graph is used to analyze system performance in the charging and discharging process on 2 100 Ah VRLA batteries. Based on the graph, the charging process began at 06:16 WIB with an initial voltage of 12.6V, a current of 0.63A, and a SOC of 56%. As the intensity of sunlight increases, the charging current gradually increases until it peaks at 15.07A at 11:36 WIB, with a voltage of 13.84V. In the time span of 11:06 – 11:36 WIB, the SOC reaches 100%, indicating that the battery is fully charged. After that, the charging current began to decrease, while the voltage remained stable at around 14V until the afternoon. The discharge process began at 17:56 WIB with an initial voltage of 13.24V and SOC of 82%. SOC decreased gradually until it reached 50% at around 20:06 WIB, indicating that the power was being used constantly by the load. The voltage remained in the range of 12.5V - 12.6V throughout the night, indicating that the discharge took place with good efficiency without any significant voltage fluctuations. From the results of this analysis, it can be concluded that with a configuration of 2 VRLA 100 Ah batteries, the rooftop PLTS system is able to charge quite well in about 5 hours, but still has limitations in terms of the duration of power supply at night, which is about 6 hours before the SOC drops to 50%. Although the voltage remains stable, the limited energy storage capacity prevents the system from supplying power for a longer duration. Therefore, increasing the battery capacity to 4 VRLA 100 Ah is a potential solution to increase energy storage efficiency and extend power supply time.

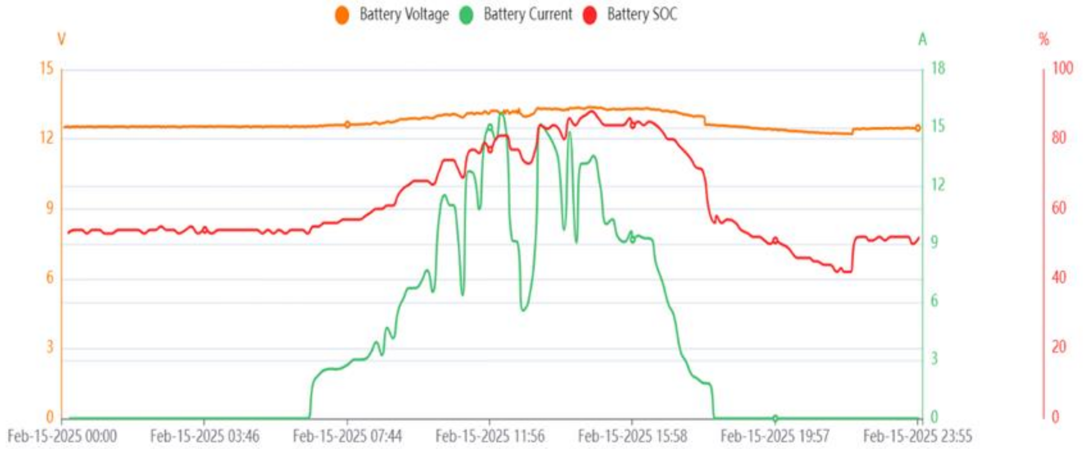

Fig.5. Graph of Solar Guardian recording results in the form of Current, Voltage, and State of Charge (SOC) on February 15, 2025

Fig. 6. displays a graph of the recording results from the Solar Guardian application that records changes in current (A), voltage (V), and State of Charge (SOC) (%) on a rooftop solar power system with a configuration of 10 polycrystalline solar panels with a capacity of 100 Wp each on February 15, 2025. This graph is used to analyze system performance in the charging and discharging process after increasing the battery capacity from 2 to 4 100 Ah VRLA batteries. Based on the graph, the charging process began at 06:16 WIB with an initial voltage of 12.56V, a current of 1.84A, and a SOC of 55%. The charging current increased faster than the previous configuration, with a peak val-ue reaching 16A at around 10:30 WIB, earlier than the system with 2 batteries which peaked at 11:36 WIB. The SOC also reached 100% faster, at around 10:30 WIB, indicating that the addition of battery capacity increases charging efficiency. The voltage remained stable at around 14V, indicating that the system could capture and store energy optimally. In the discharge process, discharging be-gan at 18:17 WIB with an initial voltage of 12.59V and SOC of 56%. The SOC decreased gradually, but at a slower rate than the previous configuration, indicating that the additional capacity helped extend the power supply time. The voltage remained stable at around 12.3V – 12.6V throughout the night, indicating a more even power discharge without a drastic drop. In addition, the power supply duration increased to ±10 hours, compared to only ±6 hours in the 2-battery configuration, so the system was able to last longer before reaching the minimum SOC limit.

IV. CONCLUSION

This study demonstrates that increasing the capacity of VRLA batteries in a rooftop solar power system significantly enhances charging efficiency, power supply duration, and system stability. The experimental results show that the initial configuration with 2 VRLA 100Ah batteries reached 100% State of Charge (SOC) at 11:36 WIB, whereas after increasing the capacity to 4 VRLA 100Ah batter-ies, the SOC reached 100% earlier at 10:30 WIB, indicating a more efficient energy absorption pro-cess. During the discharging phase, the 2-battery system sustained power for approximately 6 hours before reaching a 50% SOC, whereas the 4-battery system extended the supply duration to 10 hours, ensuring longer energy availability. Furthermore, the voltage remained more stable in the 4-battery system, reducing fluctuations and preventing deep discharge cycles, which helps to prolong battery lifespan. The integration of the Solar Guardian monitoring system provided real-time data tracking of voltage, current, and SOC, allowing for accurate performance evaluation and energy management optimization. This study confirms that increasing battery capacity is an effective solution to improve energy storage efficiency, enhance power availability, and ensure system reliability in renewable en-ergy applications. Future research could focus on integrating smart charging algorithms or hybrid energy management systems to further optimize performance and sustainability.

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