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EXPERIMENTAL STUDY OF SOLAR LEAD-ACID BATTERY CHARGING EFFICIENCY UNDER VARYING CONDITIONS

EKSPERIMENTALNA ŠTUDIJA UČINKOVITOSTI POLNJENJA SOLARNIH BATERIJSKIH HRANILNIKOV NA OSNOVI PbA PRI RAZLIČNIH POGOJIH

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This study presents an in-depth experimental investigation into the charging performance of 12-volt photovoltaic (PV) solar panels with lead-acid batteries under diverse atmospheric conditions. The research aims to evaluate how variations in solar irradiance, temperature, and cloud cover influence the charging efficiency and long-term stability of both functional and non-functional 12 V 130 Ah lead-acid batteries. A solar charging system was assembled using four 100 W panels connected in parallel and monitored under real outdoor conditions. Voltage data were recorded at thirty-minute intervals for both types of batteries, enabling a comparative assessment of their performance in clear and cloudy weather. The results demonstrated that the functional battery exhibited steady voltage growth and reached its target charge within two hours under clear skies, while cloudy conditions extended the charging duration to four hours. Conversely, the non-functional battery showed irregular voltage fluctuations and a pronounced decline in charging capacity, confirming its inability to store energy effectively. Mathematical models were formulated to describe the voltage–time relationships for each scenario, revealing charging rates of 0.644 V/h and 0.405 V/h under clear and cloudy skies, respectively. Additionally, post-charging relaxation analysis showed that the functional battery maintained voltage stability, whereas the non-functional battery experienced a continuous drop of 0.342 V/h, indicating internal degradation. The findings underscore the strong dependency of solar charging performance on meteorological conditions and battery health, highlighting the importance of effective charge control strategies and battery maintenance in optimizing solar energy storage and extending battery lifespan.

Keywords: solar, battery charging, atmospheric conditions, battery relaxation

V članku avtorji predstavljao eksperimentalno študijo učinkovitosti polnjenja svinčeno-kislinskih baterij oz. akumulatorjev (PbA; angl.: lead-acid batteries) z 12-voltnimi fotovoltaičnimi (PV) solarnimi paneli pri različnih atmosferskih pogojih. Raziskava se je osredotočala predvsem na ovrednotenje vpliva sončnega sevanja, temperature in oblačnosti na učinkovitost polnjenja ter dolgoročno stabilnost funkcionalnih in nefunkcionalnih 12V, 130Ah, PbA baterij. Raziskovalni solarni polnilni sistem je bil sestavljen iz medseboj paralelno vezanih 100 W sončnih panelov, ki so preko regulatorja polnjenja polnili obe izbrani bateriji. Avtorji so istočasno registrirali napetosti na obeh PbA baterijah v 30 minutnih intervalih pri realnih zunanjih okoljskih pogojih, kar je omogočalo njuno medsebojno primerjavo in oceno sposobnosti napajanja v jasnem in oblačnem vremenu. Rezultati meritev so pokazali, da je pri funkcionalni bateriji napetost enakomerno naraščala in dosegla ciljano napolnjenost v dveh urah pri jasnem vremenu, medtem ko je v oblačnem vremenu trajalo polnjenje te baterije do 4 ure. Nasprotno pa je nefunkcionalna baterija kazala tudi nepravilna nihanja napetosti in izrazit upad polnilne zmogljivosti, kar je potrdilo njeno nezmožnost učinkovitega shranjevanja energije. Avtorji so v okviru pričujoče študije oblikovali matematične modele za opis zveze med napetostjo in časom za vsak scenarij, ki je pokazal, da sta hitrosti polnjenja 0,644 V/h v jasnem vremenu in 0,405 V/h v oblačnem vremenu. Dodatno je analiza naknadne relaksacije pokazala, da je funkcionalna baterija ohranila stabilnost napetosti, medtem ko je pri nefunkcionalni bateriji prišlo do kontinuirnega padca napetosti 0,342 V/h, kar je potrdilo da je bila ta baterija že poškodovana (degradirana) v svoji notranjosti. Ugotovitve te študije so potrdile močno odvisnost sposobnosti polnjenja baterije od meteoroloških pogojev in »zdravja« baterije. S tem pa tudi osvetlilo pomembnost natančne strategije za kontrolo učinkovitosti polnjenja baterije in njenega vzdrževanja za optimizacijo shranjevanja sončne energije in podaljšanja njene življenske dobe.

Ključne besede: fotovoltaika, solarni sistemi, polnjenje baterij, atmosferski pogoji, relaksacija baterije

1 INTRODUCTION

Batteries are a necessary component for powering many advanced consumer electronics, which depend more and more on them to meet rising energy demands.[1,2] Although photovoltaic, or solar energy, offers a promising way to generate renewable energy, there are still many obstacles to overcome in terms of effectively storing this energy.[3] A significant challenge is the intrinsically variable character of solar energy production brought on by changes in solar irradiance, since the production of power is reliant on weather patterns. These variations impact the quality of the energy produced and make it more difficult to guarantee a steady power sup-

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ply.[4] Batteries are essential in this situation because they allow solar panels to store extra energy for later use. Nevertheless, photovoltaic energy storage in batteries currently has a limited efficiency, especially in overcast or low-light conditions.[5–7]

Many researchers have shown great interest in addressing these challenges and improving the efficiency of photovoltaic storage systems. For instance, Mohammed Gmal Osman et al.[8] developed a practical integrated system combining photovoltaic panels, battery storage, and electric vehicle charging with smart energy management, achieving over 92-% energy autonomy and significant CO_2 reduction. Stoica Dorel et al.[9] compared different charging strategies for off-grid PV systems, concluding that the optimal method depends on environmental and operational conditions to maximize efficiency. F. J. Sepúlveda et al.[10] showed that high-voltage battery systems outperform low-voltage ones by 3–10 % in energy efficiency and highlighted the importance of reducing inverter losses for better performance. Meanwhile, Ika Noer Syamsiana et al.[11] utilized a SEPIC converter with PI control and P&O MPPT to enhance battery charging efficiency in remote solar systems, achieving over 90-% efficiency even under low irradiance conditions, thus demonstrating strong potential for solar applications in challenging environments.

Short-term storage, in order to bridge the gap between generation and demand, electricity grid services employ three different types of energy storage technologies:[12,13] short-term storage, that focuses on the strength of energy and lasts for up to one minute; medium-term storage, which lasts between minutes and hours; and long-term storage, which offers energy distribution services for hours or days.[14] Inappropriate charging and discharging practices or prolonged periods of low solar energy availability shorten battery life. In order to guarantee a high state of charge and prolong the battery's lifespan, it is imperative to regulate the charging process, which necessitates the use of a suitable charging controller.[9,15,16]

In a stand-alone solar system, the battery charging controller's primary job is to charge the battery completely without allowing it to discharge, while simultaneously limiting reverse current flow at night and avoiding deep drain when the system is under load.[17,18] Variations in the flow of solar energy to the load, however, can result from shifting weather patterns and ongoing shifts in demand, which lower the efficiency of battery charging. The solar setup must run at its highest power point in order to overcome these obstacles and boost solar system efficiency.[19,20]

The main goal of this study is to examine how well 12-volt photovoltaic solar cells charge batteries utilizing a specially made system. A number of factors were looked at, starting with the analysis of how different cloud covers affected charging effectiveness. The system's performance was then examined using various solar battery capacities. Furthermore, the behavior of the voltage during the relaxation time of the battery after charging was investigated.

2 METHODOLOGY

This study's execution was greatly aided by materials, data gathering techniques, and system design. The selection of components and the procedure for obtaining precise data were given careful thought. To guarantee accurate measurements and a consistent performance analysis, the study used a variety of tools and supplies.

2.1 Used materials

The equipment utilized in this study is shown in **Figure 1**, including:

- Four photovoltaic solar panels (100 W, 12 V) connected in parallel
- Electrical wiring for interconnection
- A solar charge controller (12V-60A).
- Two deep-cycle, 12 V, 130 Ah lead-acid batteries: one operational and one non-functional. The

Figure 1: Equipment utilized in this study

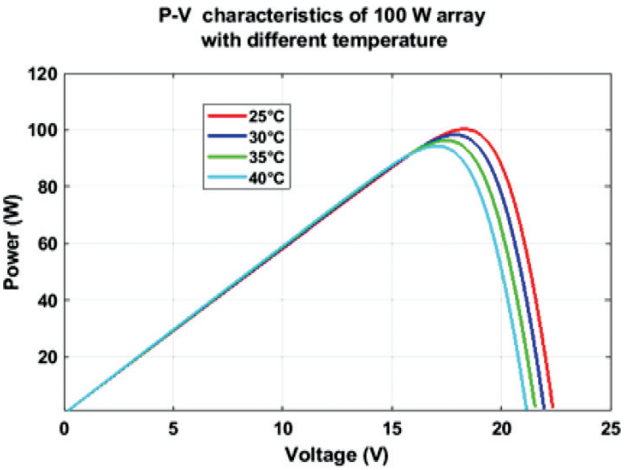

Figure 2: PV output characteristics at varying temperatures

non-functional battery exhibited sulfation, where inactive material accumulated on the plates, preventing normal charging and necessitating replacement.

- A digital multimeter used for measuring voltage

Figure 2 illustrates the output characteristics of a 100 Wp PV array under varying temperature levels.

Table 1: Electrical properties of the utilized devices

Mono solar panel 100 W 12 V	
P_{max}	100 Wp
V_{mpp}	18.3 V
I_{mpp}	5.48 A
V_{oc}	22.4
I_{sc}	5.87
PV charge controller	
Model	YJSS60
Nominal voltage	12 V
Nominal current	60 A
Max. PV voltage	50 V
Max. PV input power	780 W
Lead-acid GEL battery	
Model	Victron GEL 12 V 130 Ah
Voltage	12 V
Capacity	130 Ah
Reference	BAT412121104
Length (mm)	410
Width (mm)	176
Height (mm)	227

2.2 Data collection mechanism

In order to collect data, the voltage was measured in two different situations: first, the system was concurrently connected to both the non-functional and functional batteries. Throughout the observation period, voltage readings were taken every thirty minutes to guarantee consistency. The OCV was the basis for the technique used for these observations. When there is no current passing through an electrochemical cell, the voltage between its terminals is referred to as the OCV. The OCV is a vital sign of the health and charge level of a battery.[21]

We can evaluate a battery's performance in various scenarios by taking a direct measurement of this voltage.[22,23] By using the OCV as the control parameter, a system's energy storage capacities might be better understood, yielding insightful information.

2.3 Electrical design

To ensure a continuous power supply of 12 V, connecting the solar panels in parallel is crucial, as illustrated in **Figure 3**. This configuration allows for voltage stabilization; by doing this, the combined voltage of the linked panels is guaranteed to be the same as that of a single panel.[21,24] Additionally, this arrangement increases the system's overall capacity, as the power ratings of all panels combine to form a higher total capacity, thereby enhancing the system's overall efficiency.[25,26]

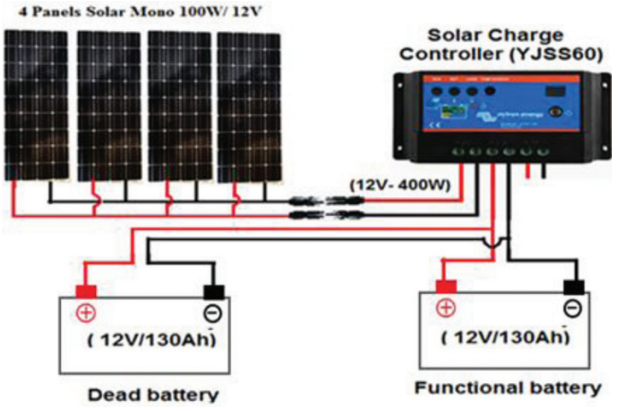

Figure 3: Simplified electrical design of the system

Moreover, the total current of the system is the total of the currents generated by all single panels, ensuring that the system can meet increasing energy demands. Connecting the panels in parallel is particularly advantageous in scenarios where some panels may experience shading or obstruction, as the overall performance of the system remains stable, allowing energy flow from the other panels to continue.[27] Based on this configuration, the previous quantities can be expressed with the following equations:

$$V_T = V_{p1} + V_{p2} + V_{p3} \quad (1)$$

$$I_T = I_{p1} + I_{p2} + I_{p3} \quad (2)$$

$$P_T = P_{p1} + P_{p2} + P_{p3} \quad (3)$$

Here, V_T, P_T, and I_T represent the total voltage, total power, and total current of the system, respectively, V_{p1}, V_{p2}, V_{p3}, indicate the voltages of the photovoltaic panels, while I_{p1}, I_{p2} and I_{p3} refer to the current generated by each panel. Finally, P_{p1}, P_{p2} and P_{p3} represent the power output of each photovoltaic panel. In theory, the system that was designed generated 400W and 12V. Important factors taken into account were the charging efficiency and battery relaxation voltage, and the outcomes were examined using mathematical modelling and differentiation.[28,29]

Table 2: Battery charging performance

Time (AM)	Non-functional battery in a clear environment			Functional battery in a cloudy environment			Functional battery in a clear environment	
	Voltage	ΔV	T (°C)	Voltage	ΔV	T (°C)	Voltage	T (°C)
7:00	7.99	0	30	9.69	0	20	10.50	30
7:30	8.59	0.6	32	11.15	+1.46	22	11.60	32
8:00	8.66	0.07	36	11.70	+0.55	23	11.60	33
8:30	7.86	-0.8	34	11.90	+0.2	24	11.58	35
9:00	7.85	-0.01	34	11.94	+0.04	23	12.12	36
9:30	7.83	-0.02	37	11.98	+0.04	25		
10:00	7.83	0	37	11.90	-0.08	22		
10:30	7.85	+0.02	39.50	11.95	+0.05	22		
11:00	7.86	+0.01	38	12.01	+0.06	23		

3 RESULTS AND DISCUSSION

3.1 Battery charging performance

The experimental findings for the charging performance of both the non-functional and functional batteries under various weather conditions are shown in **Table 2**, providing information on how variables such as temperature and cloud cover affect the charging process.

The non-functional battery voltage increased from 7.99 V at 7:00 AM to 8.66 V by 8:00 AM, indicating a positive charging trend at first. After that, though, the voltage began to fluctuate and even drop; this was especially apparent at 8:30 AM, when it dropped by 0.8 V. This suggests that the dead battery had trouble keeping a steady charge and that it got harder and harder to attain the desired voltage.[30]

A functional battery in a cloudy atmosphere showed a more consistent charging pattern even though it was running in overcast conditions. At 7:00 AM, the voltage was 9.69 V; at 8:30 AM, it improved to 11.90 V. Even though the voltage fluctuated slightly, particularly between 9:00 and 9:30 AM, the general trend was still good. Despite being slightly slower than ideal, the battery was able to charge steadily. Cloud cover decreased sunlight, which may have caused the slight voltage dips, but the working battery still functioned fairly well.

The best performance was exhibited by the operational battery under clear air conditions, which showed the steadiest and most notable voltage increase. The voltage increased gradually from 10.50 V at 7:00 AM to 12.12 V at 9:00 AM. The battery successfully reached the desired voltage, even though there was a slight levelling off between 8:00 and 8:30 AM.

This result demonstrates how maximum charging efficiency and faster achievement of the goal voltage are made possible by clear skies and ideal solar circumstances[7]. Voltage variations revealed the dead battery's degraded condition and diminished capacity to store energy as it tried to maintain a steady charge. The functioning battery, on the other hand, charged a little more slowly but still functioned well, especially in overcast weather. The functional battery performed best in clear conditions, exhibiting quick and consistent voltage rises, underscoring the need for ideal weather for effective charging[2,6]. It takes twice as long (four hours) in overcast weather to reach the target voltage as it does in clear weather. By drastically lowering sun irradiation, dense clouds minimize daily energy production. The model for the non-functional battery assumes voltage (V) on the Y-axis and charging time on the X-axis, represented by a straight-line equation:

$$y = -0.1477x + 9.3646 \tag{4}$$

The voltage drops when charging, as indicated by the negative sign. The equation's derivative is as follows:

$$\frac{dy}{dx} = -0.1477 \tag{5}$$

During charging, the non-functional battery voltage (ΔV) decreases by 0.1477V per hour. Without renewable energy, batteries can run out quickly, and they can be shortened in lifespan by overloading or high temperatures.

Self-discharge is more important in the case of the non-functional battery than energy gathering, and the rate of self-discharge is influenced by its thermal history.

3.2 Function of charging

The functional battery reached its target voltage within four hours under cloudy conditions. It started with an initial voltage of 9.69 V at 7:00 AM, which increased to 11.90 V by 8:30 AM, and eventually climbed to 12 V at 11:00 AM. This indicates that, even in the early morning under overcast skies, the battery was still capable of collecting and storing energy efficiently. The mathematical representation of the functional battery's charging behavior in cloudy conditions is captured by the following equation:

The functioning battery in a cloudy environment:

$$y = 0.4053x + 9.932 \tag{6}$$

The functioning battery in a clear environment:

$$y = 0.644x + 6.328 \tag{7}$$

The following is the derivative of the mathematical model for battery charging in overcast conditions:

$$\frac{dy}{dx} = 0.4053 \tag{8}$$

In clear conditions, we have:

$$\frac{dy}{dx} = 0.644 \tag{9}$$

Figure 4 illustrates voltage curves for both non-functional and functional batteries plotted against time in hours. The recorded voltage of the non-functional battery and functional battery was measured every half hour from 7:00 AM to 11:00 AM. The graph also displays the approximate equations representing these relationships.

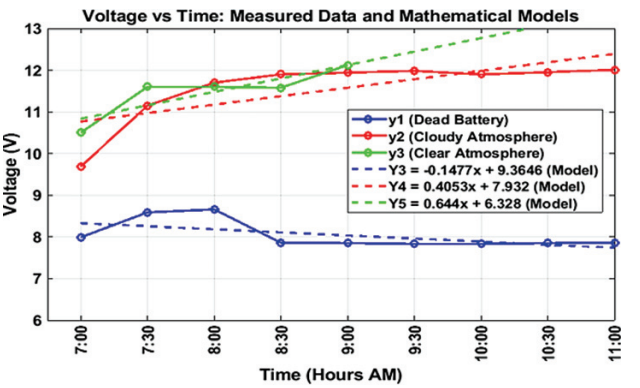

Figure 4: Voltage values for both non-functional and functional batteries over time

This visual representation allows for a comparative analysis of the battery performance under different conditions over time, while the accompanying equations provide a mathematical model of the voltage behavior.

The experimental data reveals intriguing disparities in battery charging performance across varying atmospheric conditions. In overcast environments, the battery exhibited a charging rate of 0.4053 V/Hr, while clear skies facilitated a more rapid charge accumulation of 0.644 V/Hr.

Despite initiating the charging process at the early hour of 7:00 AM, the results were noteworthy: under cloudy conditions, full charge was achieved within a four-hour window, whereas clear skies allowed for complete charging in merely two hours.

3.3 Post-charge battery behavior

After the battery undergoes charging or discharging, the voltage continues to change toward a stable value for hours or even days, even without a current exchange. This phenomenon is referred to as battery relaxation.[31,32] Battery relaxation exhibits distinct differences between non-functional and functional batteries. Monitoring revealed that after four hours, the voltage change (ΔV) in the dead battery decreased, likely due to charge loss, although full stabilization may take over 24 hours.[30,31] Conversely, the operational battery maintains stable voltage. **Table 3** shows the dead battery declining over four hours.

Table 3: Voltage recorded every 30 min during the battery relaxation

Time (Hr)	Non-functional battery		Functioning battery	
	Voltage	ΔV	Voltage	ΔV
0	10.80	0	12.01	0
0.5	9.3	1.50	12.01	0
1	9.1	0.20	12.01	0
1.5	9.06	0.04	12.01	0
2	9.03	0.03	12.01	0
2.5	8.98	0.05	12.01	0
3	8.96	0.02	12.01	0
3.5	8.89	0.07	12.01	0
4	8.63	0.26	12.01	0

Charge loss ultimately results in diminished capacity, which occurs due to ohmic leakage currents and electrochemical interactions among the components, including the active substances found in the plates, electrolyte, insulating layer, and current collector. Equation (10) is a straight-line equation, and Equation (11) shows the negative derivative indicating the voltage is decreasing.

$$y = -0.342x + 9.879 \tag{10}$$

$$\frac{dy}{dx} = -0.342 \tag{11}$$

This indicates that the battery loses charge at a rate of 0.342 V/h after four hours of rest (**Figure 5**). Although other performance metrics are sometimes used, charge

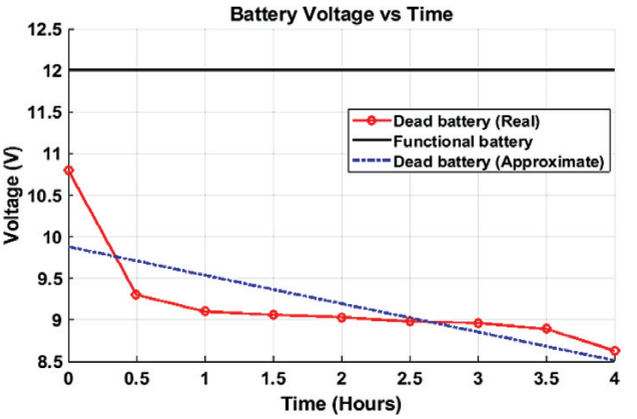

Figure 5: Voltage values of the battery recorded every 30 min during the relaxation period

loss is generally assessed regarding capacity reduction. During battery relaxation. this phenomenon may lead to reversible or non-reversible alterations within the battery system.[35] This might be brought on by charged active materials interacting with the grid, the electrolyte, or other cell constituents.

After four hours of observation, when the working battery is at rest, the voltage readout is horizontally straight. Equation (12) is used, and when deriving Equation (12), we obtain Equation (13).

$$y = 12.01 \tag{12}$$

$$\frac{dy}{dx} = 0 \tag{13}$$

This shows that the battery's voltage readout does not change during the four-hour observation period; it neither increases nor decreases. Several factors affect the self-discharge of lead-acid batteries, including voltage, temperature, and antimony concentration.[36]

Self-discharge rates depend on battery aging. The battery's new condition may explain its stable relaxation voltage. Quantifying this natural process in lead-acid batteries is crucial.

4 CONCLUSIONS

This study investigated the charging efficiency of deep-cycle, 12 V, 130 Ah lead-acid batteries under varying solar irradiation and temperature conditions. The results showed that operational batteries maintain higher efficiency, while non-functional batteries degrade significantly due to nonreactive substances coating the plates, directly addressing the study's objectives of assessing battery performance under real-world conditions. The findings highlight the importance of battery maintenance, careful selection, and monitoring in solar energy systems. Future developments could explore alternative battery chemistries or enhanced lead-acid designs, as well as predictive or real-time monitoring strategies to optimize charging and extend battery life. Potential ap-

plications include off-grid photovoltaic systems, solar energy storage solutions, and energy management in remote locations.

Overall, this study provides practical insights needed for improving the efficiency and performance of solar batteries through better maintenance, monitoring, and selection. It also offers guidance for future research, including the development of enhanced battery designs and intelligent charging strategies, and opens the way for applying the proposed approach in off-grid PV systems, solar storage solutions, and energy management in remote areas.

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