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# Design of Automatic Battery Charger using Forward DC-DC Converter for Solar Home Energy

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**ABSTRACT**

The utilization of solar energy as a renewable and environmentally friendly energy source, which is inexhaustible, is an ideal solution to meet the growing demand for electricity. Solar Home Energy refers to a house powered by solar energy. The solar energy is subsequently stored in batteries using a battery charger. This paper uses a forward DC-DC converter as a battery charger to supply power to a self-sufficient house from solar energy stored in a 96 V 45 Ah battery. A fuzzy logic controller is employed to regulate the output of the forward DC-DC converter, ensuring a constant charging voltage according to the set point. The production of this project is designed for 110 V 4.5 A; however, in practice, the forward DC-DC converter only achieved a charging voltage of 100.5 V, resulting in an error of 8.63% from the planned value. Additionally, the charging current reached 1.4 A, leading to a significant error of 63.89% from the planned charging current.



## 1. INTRODUCTION

As technological advancements accelerate, the global electricity demand has surged at an unprecedented rate. This growing demand necessitates the development of more efficient and large-scale power generation systems. Traditional electricity generation methods, which rely heavily on fossil fuels such as coal, natural gas, and oil, are not only limited in supply but also contribute significantly to environmental degradation through the emission of greenhouse gases. As fossil fuel resources become increasingly scarce and their negative ecological impact more pronounced, the shift towards renewable energy sources has become imperative [1]-[6]. Renewable energy, particularly solar power, has emerged as a vital solution to meet the rising global energy demand [7]-[10]. Solar energy is abundant, inexhaustible, and environmentally friendly, making it an ideal alternative to fossil fuels for electricity generation. The use of solar energy for power generation offers a sustainable and long-term solution to the energy crisis, reducing reliance on non-renewable resources and minimizing the carbon footprint of power generation [11]-[14]. One of the most significant advantages of solar energy is its ability to be harnessed at the household level, allowing individual homes to generate electricity through Solar Home Energy systems. Solar Home Energy systems typically consist of solar panels, inverters, and battery storage units, enabling households to generate, store, and utilize electricity without depending on the national grid. In countries like Indonesia, where the state-owned electricity company PLN (Perusahaan Listrik Negara) is the primary supplier, adopting solar energy can lead to substantial savings on electricity bills, as households become more self-sufficient in meeting their energy needs [15][16]. Moreover, solar energy systems help alleviate the strain on national power grids, particularly in areas with high energy demand or limited infrastructure, enhancing energy security and reliability [17]-[19]

The design and implementation of an automatic battery charger using many converters, including forward, boost, Swiss, and Vienna converters [20]. The boost converter is rarely used due to high conduction

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and diode recovery losses [21]. On the other hand, the Swiss and Vienna complex hardware topology [22]. However, A forward DC-DC converter is critical to optimizing solar energy systems for residential use. The forward DC-DC converter is an essential component that regulates the voltage and current supplied to the battery, ensuring efficient and safe charging. This type of converter is particularly suitable for applications where low input voltages must be converted to higher output voltages, as is often the case in solar energy systems [23]. By incorporating a fuzzy logic controller, the system can dynamically adjust the charging parameters based on the battery's state of charge and environmental conditions, ensuring optimal performance and prolonging battery life [24]-[27]. Furthermore, using fuzzy logic controllers with forward DC-DC converters allows for more precise control over the charging process. Unlike traditional controllers based on predefined rules, fuzzy logic controllers can adapt to changing conditions in real time, making them ideal for complex and non-linear systems like solar energy storage [28][29]. This advanced control methodology improves energy efficiency and ensures the battery receives a constant and stable charge, even under fluctuating solar radiation levels. By integrating these technologies, solar home energy systems can achieve greater autonomy and efficiency, reducing reliance on external power sources like PLN. As a result, households can reduce their energy costs and contribute to the broader goal of transitioning towards sustainable and renewable energy sources on a global scale.

Most research focuses on maximizing efficiency during peak solar radiation hours. However, one significant gap is the lack of studies on improving the efficiency of forward DC-DC converters during low solar irradiance (early morning, late afternoon, and cloudy days). This is especially important in tropical regions where fluctuating sunlight conditions prevail. Research is needed to enhance the converter’s performance under these less favorable conditions [30][31]. While fuzzy logic controllers have been integrated into DC-DC converters to optimize battery charging, relatively few studies focus on the long-term health of batteries in solar home systems. The impact of repeated charging cycles on battery longevity and the development of algorithms to prevent overcharging, undercharging, and thermal degradation are underexplored [32]-[34]. In [35]-[39], ZigBee and PLC integration are added. ZigBee-based energy measurement modules are employed to monitor the energy consumption of household appliances and lighting. Then, a PLC-based renewable energy gateway tracks the generation of renewable energy sources. In addition, [40], charging using a battery management system is the new era due to electric vehicle growth. The paper charging using a battery management system is the new era due to electric vehicle growth. The paper examines essential technologies in Battery Management Systems, focusing on battery modeling, state estimation, and charging processes. It comprehensively analyzes various battery models, such as electrical, thermal, and electro-thermal models.

Recently, integrating solar home systems with smart grids is an emerging area that has not been fully explored. Therefore, the outline of the main contributions of this paper: i) Forward DC-DC converters could be crucial in managing power flow between solar panels, battery storage, and the grid; ii) This converter can be adapted to facilitate bi-directional power flow and communicate with grid infrastructure in real time. The design and implementation have been rigorously validated through simulation and experimental results, making a substantial contribution to the field by addressing limitations noted in previous studies on photovoltaic (PV) systems and solar home energy applications [1]-[40]. This study proposes a novel solution that combines a forward DC-DC converter with fuzzy logic controller. The validation using experimental highlights its potential for practical application, marking an important step forward in renewable energy systems.

This article is arranged as follows: Section 2 discussed the Forward DC-DC Converter, voltage and current sensor, battery and PV design as well as parameter and controller design. Section 3 presented experimental results and analysis. The last is the conclusion in section 4.

## 2. METHOD

The block diagram system is shown in Figure 1. The overall design consists of six parts. The selection of the design in the simulation chosen based on the specification of the input and output. The first part includes the solar cell, which serves as the primary source of the system. The battery charging process is powered by a series of three 135 WP solar cells. These solar cells provide an input voltage of 160 V. The second part is the forward DC-DC converter, which functions to step down the voltage to a level suitable for charging the battery at 96 V. The third part consists of a current sensor and a voltage sensor. The voltage sensor is responsible for sensing the converter’s output voltage, which is then fed back to the microcontroller as input for the fuzzy logic control. Meanwhile, the current sensor is used to detect the charging current going to the battery. The fourth part includes the microcontroller. The microcontroller used is the STM32f4 Discovery minimum system with an ARM STM32F4 microcontroller. The microcontroller controls and adjusts the duty cycle. The duty cycle is regulated through the internal PWM of the microcontroller using the fuzzy logic controller method. The fifth part consists of an LCD TFT display and an alarm, which serve as the input/output interface for the microcontroller. The alarm functions as an indicator, sounding when the battery is fully charged. Additionally, the device is equipped with an auto shut-off feature that disconnects the battery from the power source when the output current approaches zero (indicating that the charging process is complete). Then, the sixth part is the battery load. The batteries used are rated at 12 V 45 Ah each, connected in series, resulting in a total battery capacity of 96 V 45 Ah.

### 2.1. Forward DC-DC Converter

A forward DC-DC converter generates an isolated power supply regulated by a DC voltage from a variable input DC source. The converter used in this paper reduces the solar cell's output voltage, which is intended to charge the battery. The forward converter includes several essential components, such as a transformer, inductor, and MOSFET. In designing the forward converter, two primary components require specialized design, including the high-frequency transformer and the inductor design. In addition, for the purpose of analysis, this converter is considered to be in steady-state operation with continuous inductor current. The duty cycle is determined as follows.

$$D_{dutyf} = \frac{V_{outf}}{V_{inf}^{max}} N_f \tag{1}$$

$$N_f = \frac{N_{secf}}{N_{primf}} \tag{2}$$

where $D_{dutyf}$ is the duty cycle of the converter, $V_{outf}$ and $V_{inf}^{max}$ are the output voltage and maximum voltage of the forward converter, and $N_f$ is the ratio winding between $N_{secf}$ secondary and $N_{primf}$ primary windings. The secondary and primary windings are obtained as

$$N_{primf} = \frac{D_{dutyf} T_f V_{inf}^{max}}{2B_{fluxf} A_{core}} 10^4 \tag{3}$$

Then, for the inductor and capacitor values for this converter are derived as follows

$$L_f = \frac{V_{outf}(1-D_{dutyf})T_f}{0.2 I_{Lf}} \tag{4}$$

$$C_f = \frac{V_{outf}(1-D_{dutyf})}{8L_f \Delta V_{outf} f_{switch}} \tag{5}$$

where $L_f$ and $C_f$ are the inductor and capacitor values, $T_f$ is the period, $f_{switch}$ is the switching frequency, $I_{Lf}$ is the inductor current, $B_{fluxf}$ is the flux density, and $A_{core}$ is the core cross-sectional area. Then, substitute (3) to (2) to obtain the secondary winding value.

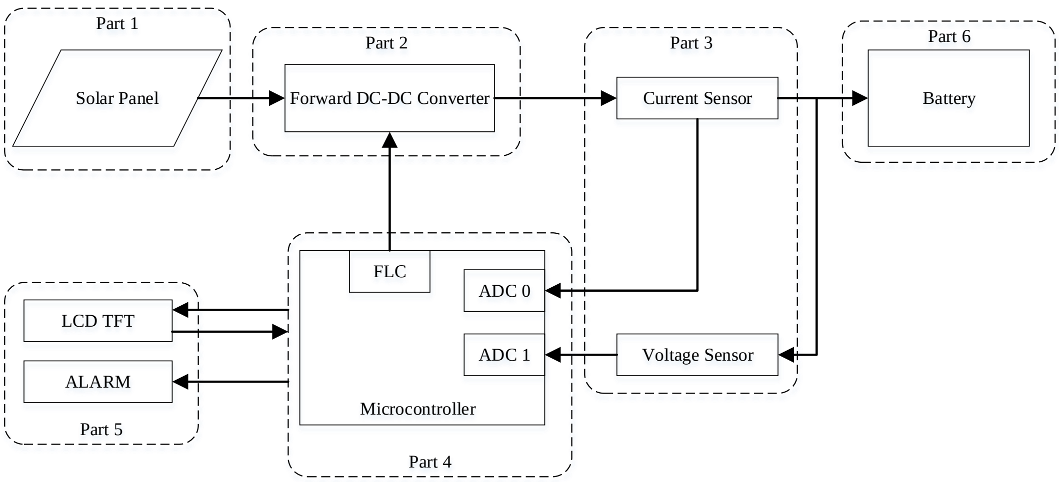



Figure 1. The block diagram system

### 2.2. Voltage and current sensor

The voltage sensor used in this system is a voltage divider. The sensor's input voltage corresponds to the output voltage on the forward converter's output side. Meanwhile, the sensor’s output voltage results from the voltage divider circuit, which is then fed into the ADC of the microcontroller. The maximum voltage to be measured is 120 volts, while the maximum input voltage for the microcontroller's ADC is 3 volts. The voltage divider circuit drawn by PSIM simulation is shown in Figure 2. The output voltage based on Figure 2 is derived as

$$V_{outf} = \frac{R_2}{R_1+R_2} V_{inADC} \tag{6}$$

where $V_{inADC}$ is the input voltage for the ADC microcontroller, $R_1$ and $R_2$ are the resistor values. Then, for current sensor, ACS 712 IC is implemented. This sensor is utilized to measure the output current from the forward converter, serving as feedback for the controller's response. The ACS-712ELCTR-20A-T sensor type is employed, which has a maximum current reading capacity of 20 amperes. This choice is due to the forward converter's maximum output of 7A.

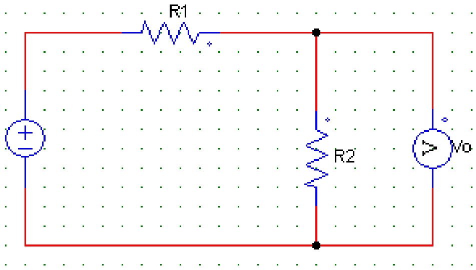


Figure 2. The voltage divider circuit

### 2.3. Battery and PV design

The battery is an essential part of the hardware in this system, and it is used for temporary storage. The fuzzy logic controller controls the current and voltage for the charging method. These parameters need to be counted precisely. The charging current is generally set to range between 10% and 30%. The maximum charging time and current are obtained as

$$I_{batt}^{charg} = 30\% \Upsilon_{cap} \tag{7}$$

$$T_{batt}^{charg} = \frac{\Upsilon_{cap}}{I_{batt}^{charg}} \tag{8}$$

where $I_{batt}^{charg}$ and $T_{batt}^{charg}$ are the charging current and time, $\Upsilon_{cap}$ is the battery capacity. The charging voltage is obtained from the output voltage of the forward DC-DC converter and needs to be calibrated based on the calculated battery capacity. The battery comprises 6 cells, each chargeable within a voltage range of 2.3V to 2.4V per cell, resulting in an overall charging voltage range of approximately 13.8V to 14.4V. The capacity of the photovoltaic (PV) system is defined by the converter's input parameters, which are derived as follows

$$PV_{capt} = P_{inf} \tag{9}$$

Then, the input and putput power are defined as

$$P_{inf} = \frac{P_{outf}}{\eta_{eff}} \tag{10}$$

$$P_{outf} = V_{outf} I_{outf} \tag{11}$$

Then, substitute (11) and (10) into (9), it is obtained as

$$PV_{capt} = \frac{V_{outf} I_{outf}}{\eta_{eff}} \tag{12}$$

where $PV_{capt}$ is the PV capacity, $\eta_{eff}$ is the efficiency of the forward converter, $P_{inf}$ and $P_{outf}$ are the input and output power.

### 2.4. Parameters and controller design

In this system, mathematical analysis is employed to find the value of each parameter. The parameters discussed in the paper are presented in Table 1.

Table 1. The system parameter

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $f_{switch}$ | 40kHz | $D_{dutyf}$ | 50% |
| $V_{inf}^{max}$ | 160V | $V_{outf}$ | 115V |
| $I_{outf}$ | 4.5A | $\eta_{eff}$ | 90% |

In the design of the fuzzy logic control system, the controlled variable is the output voltage of the forward converter, ensuring it aligns with the specified set point. The input of controller is error, $e(k)$ and delta error, $\Delta e(k)$ However, the output is duty cycle. The error represents the difference between the converter's output voltage and the reference voltage. Meanwhile, the delta error is obtained by subtracting the previous error from the current voltage. The equation of error and delta error are derived as

$$e(k) = V_{ref} - V_{outf} \tag{13}$$

$$\Delta e(k) = e(k) - e_{prev}(k) \tag{14}$$

where $V_{ref}$ is the reference voltage and $e_{prev}(k)$ is the previous error. The open-loop response of a forward converter plots the membership range of the input variables for fuzzy control. From this response, the maximum output voltage of the converter is determined, which serves as a reference for mapping the values of the error and delta error variables. In this system, the input error is classified into 5 types, which is NBE, NSE, ZE, PSE, and PBE. Furthermore, for $\Delta e(k)$ is NBD, NSD, ZD, PSD and PBD

## 3. RESULTS AND DISCUSSION

In this paper, several experimental results are presented. The input voltage of forward converter is shown in Figure 3. The responses of the input voltage are steady-state condition. The, the fuzzy logic is tested at the varying output voltage of forward converter, which is 100V, 110V, and 115 V. The purpose of this testing is to assess and validate the control performance of the system. In the Figure 4 shows the response of the fuzzy logic control. In Figure 4(a) set point is 100 V, it can be observed that the control operates effectively on the converter. The output voltage rises to reach the set point and then achieves a steady-state condition. In testing with a 100 V set point, the converter output reaches 96.9 V, indicating that the control successfully stabilizes the converter output near the set point. The error percentage at a 100 V set point is 3.1%. When the output voltage changes to 110V the responses have satisfactory performances, including small error 3.27% and tracked the setpoint well, which is presented in Figure 4(b). Then, small error increasing become 7.7% when output voltage is changed 115V, and shows in Figure 4(c). In Table 2 is the fuzzy logic controller used in the forward converter closed loop with varying reference voltage. It aims to test the robustness of the controller and the load for testing is DC load 100W, 220V. The experimental data describes the combination in the closed loop has as having good responses include can track the setpoint well and the error being small. The next stage of system integration testing was conducted using Fuzzy Logic Control, with the system provided a set point in line with the voltage references. Table 3 presents the results of the system integration for the charging process using fuzzy logic control when the battery's state of charge is at 60% or 98.5 V, with a set point of 110 V. This data was collected under bright sunlight between 11:30 a.m. and 12:10 p.m. In Table 3, it is evident that, with the use of fuzzy logic control, the output voltage of the forward DC-DC converter can be maintained at a constant level. Then for efficiency curves shows in Figure 5. Despite these benefits, the system's performance is constrained by material choices and design parameters. However, as previously mentioned, the charging voltage provided by the converter remains insufficient and does not reach the specified charging voltage set by the set point. The test results indicate a charging voltage of 100.5 V, resulting in an 8.63% error from the planned voltage. Additionally, the charging current measured was 1.4 A, with a 68.89% error from the planned charging current. The converter's inability to reach the specified charging voltage is attributed to saturation in the designed transformer. This transformer saturation is caused by various factors, one of which is the effect of the ferrite core used. Therefore, in transformer design, careful attention must be given to the choice of materials, particularly the ferrite core. Furthermore, limitations in the duty cycle of the converter also contribute to the converter's failure to reach the designated charging voltage. Transformer saturation limits the converter's ability to achieve the desired charging parameters, which could reduce efficiency and reliability. Furthermore, the high error in charging current suggests the need for improved design and calibration of the fuzzy logic controller and related components. These issues must be addressed to enhance the system's scalability and applicability. Addressing these limitations would involve exploring alternative materials for the transformer core, optimizing duty cycle ranges, and refining the fuzzy logic control algorithms. Additionally, research into integrating these converters with battery management systems and advanced monitoring tools could further improve performance and reliability. By tackling these challenges, the proposed design could have a broader impact, advancing sustainable energy solutions for residential and industrial applications. Environmental factors, particularly temperature variations and solar irradiance fluctuations, significantly influence the performance of the proposed forward DC-DC converter and fuzzy logic-controlled battery charger. These factors directly affect both the solar panels' output and the converter's operational efficiency. High temperatures can decrease the efficiency of photovoltaic cells, reducing their voltage output. As solar panels generate less voltage at higher temperatures, the input to the DC-DC converter might drop below optimal levels, leading to underperformance in maintaining the desired charging parameters. Then, Fluctuations in solar irradiance lead to inconsistent power input to the converter. The fuzzy logic controller is designed to adapt to these changes; however, rapid or extreme fluctuations might exceed the system's ability to maintain stable output, resulting in inefficiencies or intermittent performance.

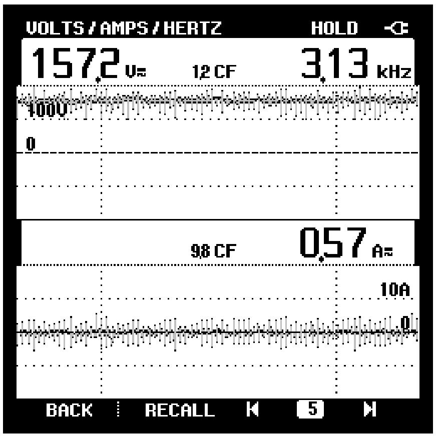
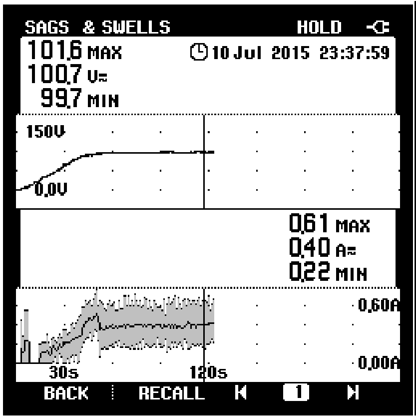
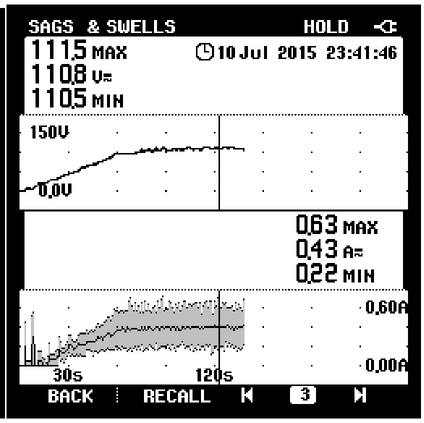


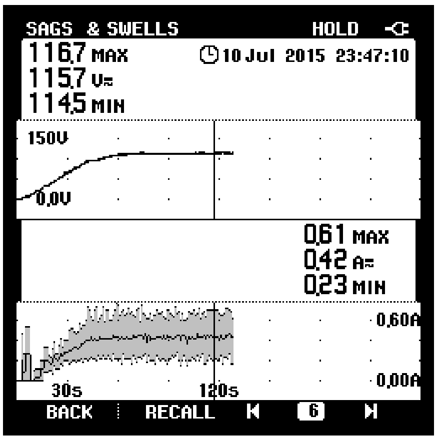

Figure 3. The input voltage of forward converter




(a)




(b)




(c)

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Figure 4. The fuzzy logic controller responses (a) 100V (b) 110V (c) 115V

Table 2. Closed Loop Forward Converter and Fuzzy Logic Controller

| $V_{ref}(V)$ | $V_{inf}(V)$ | $I_{inf}(A)$ | $V_{outf}(V)$ | $I_{outf}(A)$ |
|---|---|---|---|---|
| 120 | 155 | 0.4 | 119.4 | 0.3 |
| 110 | 154 | 0.38 | 110.8 | 0.3 |
| 100 | 155 | 0.3 | 99.3 | 0.29 |
| 90 | 156 | 0.24 | 89.8 | 0.25 |
| 80 | 156 | 0.22 | 79.6 | 0.24 |

Table 3. The integration system with Fuzzy logic controller

| $V_{ref}(V)$ | Time | $V_{inPV}(V)$ | $I_{inPV}(A)$ | $V_{charging}(V)$ | $I_{charging}(A)$ |
|---|---|---|---|---|---|
| 110 | 11.30 a.m. | 152 | 1.3 | 99.8 | 1.35 |
| | 11.40 a.m. | 151 | 1.35 | 100 | 1.4 |
| | 11.50 a.m. | 151 | 1.3 | 100.2 | 1.35 |
| | 12.00 p.m. | 151 | 1.35 | 100.3 | 1.4 |
| | 12.10 p.m. | 151 | 1.3 | 100.5 | 1.35 |

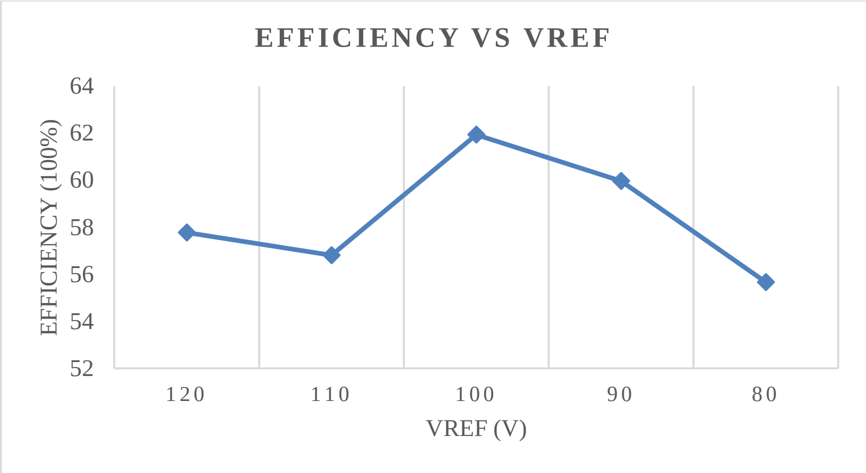


Figure 5. Efficiency curves

## 4. CONCLUSION

The paper demonstrates the design and implementation of an automatic battery charger using a forward DC-DC converter with a fuzzy logic controller aimed at optimizing solar home energy storage. The findings reveal that while the fuzzy logic control system maintains a stable output voltage, the charging voltage and current fall short of the set points, indicating a need for further optimization. The observed discrepancies, such as an 8.63% error in voltage and a significant 68.89% current error are primarily due to transformer saturation, likely influenced by the ferrite core and duty cycle limitations. This research underscores the importance of material selection, particularly in transformer design, to prevent saturation and enhance efficiency. Additionally, constraints in the converter's duty cycle contribute to its limited performance in meeting the desired charging parameters. Future work could explore alternative core materials and duty cycle adjustments, potentially improving charging performance and reducing errors, thereby advancing the effectiveness of renewable energy storage solutions for residential applications.

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