Adaptive Constant Current and Voltage Charging for Lead-Acid Battery Using Zeta Converter

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Abstract. In areas with unstable PLN electricity supply, the need for an energy storage system becomes very important, especially for charging devices such as mobile phones or laptops. Lead-acid batteries can be a solution, the energy storage process must be carried out with voltage settings that match the characteristics of the battery and do not damage the battery cells. This research develops a zeta converter-based charging system combined with FLC using CC-CV. During the charging process, the output voltage is used to charge the battery by setting a constant current of 3.6 A. This is done continuously until the charging system switches to CV. Testing for 200 minutes showed that charging in CC mode at 3.6 A was achieved for 80 minutes, starting from 50% to 85% SOC. Then, when the converter voltage reached 14.4V, the charging mode switched to CV with constant output voltage, but the current decreased as the battery SOC increased from 85% to 100%, and this process took up to 120 minutes. The system efficiency ranges from 74% to 80% during the CC process and 84% during the CV process. The CC-CV regulation processes are controlled by FLC.

1 Introduction

In some areas, especially in rural and remote areas, the reliability of electricity supply from conventional power grids such as PLN is still unreliable. This situation limits access to basic energy needs, including charging mobile phones, laptops, and other electronic devices [1]. As a result, the use of energy storage systems, especially battery-based energy storage, has become increasingly important. Batteries have emerged as an important alternative to ensure electricity availability during power outages and grid instability. As demand for smart and efficient energy systems grows, attention is increasingly focused on the development of battery charging and monitoring technologies, particularly in the context of household applications.

Among various types of batteries, lead-acid batteries remain widely used due to their low cost, proven reliability, and ease of implementation [2]. To address this issue, the constant current-constant voltage (cc-cv) charging strategy is often applied [3].

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This method begins with a constant current phase until the battery voltage reaches a predetermined threshold. Then, the method switches to the constant voltage phase, where the charging current gradually decreases until the battery is fully charged [4]. This approach aims to reduce the risk of overcharging and maintain the battery's longevity while minimizing thermal stress on the battery components.

To implement an accurate CC-CV method, a power converter that can be used for battery charging is required. This is especially important for effectively responding to changes in input conditions and load [5]. One suitable topology is the zeta converter, which is capable of regulating both rising and falling voltages while maintaining a non-inverting output. The zeta converter also offers low output ripple and better voltage stability, making it highly suitable for battery charging applications [6]. To improve the adaptability and precision of the charging process, a fuzzy logic controller (FLC) is used, which does not require complex prior data [7]. This differs from traditional PID controllers, which require accurate mathematical models [8].

Previous studies have applied battery charging management methods using various converter topologies such as buck, boost, or buck-boost [9]. However, these systems often have limitations in suppressing voltage ripple and require precise model adjustments to function optimally under dynamic load conditions [10]. Additionally, many studies have focused solely on single-stage control or lack critical integrated monitoring features essential for practical implementation. Fuzzy logic can address system nonlinearity and uncertainty by processing linguistic rules derived from human expertise [11, 12]. In this system, the FLC adjusts the zeta converter's duty cycle based on the error and the rate of change of error between the target and actual battery parameters. This enables smoother and more responsive transitions between constant current (CC) and constant voltage (CV) charging.

Through the integration of a zeta converter and fuzzy logic control, the proposed charging system offers an adaptive and intelligent solution for lead-acid battery charging. This study introduces an integrated system that combines the bidirectional capabilities of a zeta converter with adaptive fuzzy logic control to implement a CC-CV charging strategy [13]. This method provides a better response to input fluctuations and changes in battery conditions while simplifying control implementation [12]. This approach not only applies a real-time control scheme to stabilize the battery charging process but also makes a significant contribution to extending battery life and improving energy management efficiency. Therefore, this system is highly suitable for application in areas with unstable power supply from the main grid [14].

2 METHOD

This research was conducted through a structured and systematic sequence of stages. Initially, the system was designed through a comprehensive design process, which involved selecting essential components and determining the appropriate circuit layout. The main focus was placed on the configuration of the fuzzy logic control algorithm designed to manage the battery charging process adaptively, especially in ensuring a smooth transition between cc-cv modes. After completing the design and development phase of the control system, the system was physically built using STM32F4 microcontroller hardware integrated with various supporting sensors, including current and voltage measurement modules for real-time monitoring. This implementation aimed to evaluate the feasibility and robustness of the control system under varying electrical input and output loads. Performance evaluation is conducted through experimental testing in a controlled environment. Where key metrics such as output voltage stability, charging efficiency, and responsiveness to parameter fluctuations are carefully observed. Data collection is handled by an STM32 microcontroller, with further processing and analysis performed through supporting software, ensuring methodological consistency and reproducibility.

2.1 Block Diagram

The proposed system is designed to perform adaptive battery charging using a zeta converter controlled by a fuzzy logic controller. The output of the zeta converter is used to efficiently charge a 12V 18Ah VRLA battery by following the cc-cv charging method. The fuzzy logic controller generates a PWM signal based on error calculations and error delta between the actual voltage and current values and their reference values. This signal is used to regulate the duty cycle of the switch in the zeta converter, enabling the output voltage to be adaptively adjusted according to the charging conditions. The STM32F4 microprocessor serves as the central processing unit, responsible for reading data from the voltage divider and ACS712 current sensor through its ADC channel. In addition to processing control algorithms, the microcontroller outputs PWM signals and updates charging status information on a 16x2 character LCD display. This display provides real-time feedback on key parameters such as output voltage, current, and system status. As shown in Figure 1.

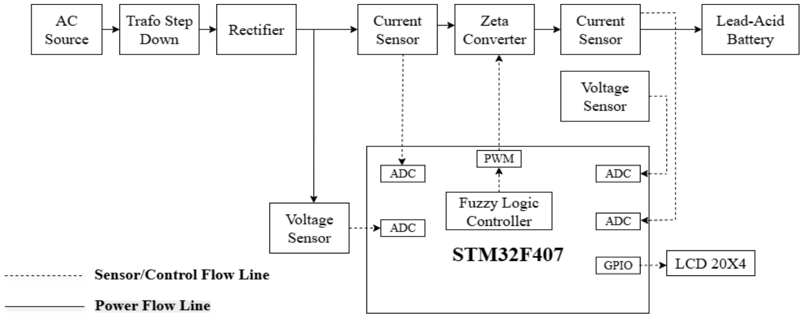

Fig 1. System block diagram

2.2 Hardware Components

The proposed system hardware configuration integrates several essential modules to support adaptive battery charging. Input comes from a 220 VAC power source, which is first converted to DC voltage using a rectifier. This converted DC voltage is then processed by a zeta converter, which uses MOSFET transistors as the main switching components for voltage regulation. Switching control of the converter is performed via PWM signals generated by the STM32F407VGT6 microcontroller. This microcontroller not only manages the fuzzy logic algorithm but also functions as a real-time data acquisition unit. As shown in Figure 2.

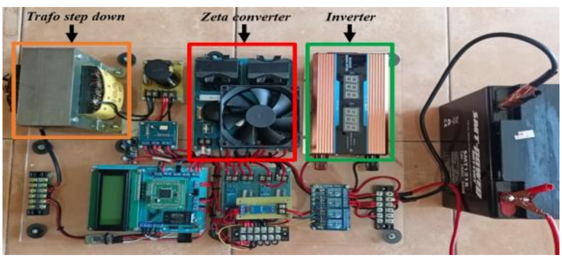

Fig 2. Hardware components

2.3 DC-DC Zeta Converter Topology for Battery Charging

Table 1 below shows the values of the components that make up the zeta converter.

Table 1. Zeta converter component parameter calculation

Component	Value	Units
$Inductor_a$	262μ	Henry
$Inductor_b$	236μ	Henry
Input Capacitor	105μ	Farad
Output Capacitor	297μ	Farad
Coupling Capacitor	347μ	Farad

The following steps were taken in the design and implementation of the zeta converter:

1. Simulation and testing of open loop systems without control (performed manually)

   The system is supplied with an input voltage of 16.8VDC from a step-down and rectified mains source. The potentiometer of the zeta converter is then turned or adjusted so that the current output from the converter reads 3.6A on the ammeter. The converter output voltage is then measured and the duty cycle at that moment is read. While charging the battery in constant current mode, after a while the battery voltage will increase because its SoC also increases, as indicated by the charging current starting to drop to less than 3.6A. Then the potentiometer is adjusted again so that the current remains at 3.6A and the converter voltage at that time is checked again.

   The job of adjusting the potentiometer to maintain a constant battery charging current of 3.6A occurs continuously by increasing the duty cycle, which automatically raises the converter voltage. This will stop when the converter output voltage reaches 14.4V or 120% of the battery's nominal voltage. At this point, the charging mode will switch to constant voltage because the voltage cannot be increased to 120% of the battery's nominal voltage. Doing so could damage the battery cells. When in constant voltage mode, the potentiometer, which is the duty cycle control device, is no longer adjusted. At this point, the voltage remains at 14.4V and the current decreases as the battery's State of Charge (SoC) increases. When the battery is fully charged at 100% SoC, the current drops to 0 and the charging system is disconnected using a relay.

2. Application of closed-loop systems with fuzzy logic controller

   All data obtained from measurements without the above controls were used as the basis for regulating the control system using a fuzzy logic controller in the CC-CV battery charging process. Finally, the test results data obtained are as shown in the CC charging and CV charging test tables. The results are shown in Tables 2 and 3.

Table 2. Charging with the constant current method

Time (Minutes)	Duty Cycle (%)	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Battery Voltage (V)	Eff (%)	SoC (%)
5	50.1	16.85	3.86	13.35	3.62	12.62	74.3	50
10	51.2	16.79	3.93	13.61	3.61	12.73	74.5	54.38
20	51.4	16.67	3.93	13.7	3.6	12.84	75.3	58.75
30	50.8	16.64	3.91	13.82	3.6	12.95	76.5	63.13
40	51.4	16.6	3.89	13.93	3.59	13.08	77.4	67.50
50	51.2	16.58	3.96	14.01	3.59	13.2	76.6	71.88
60	53	16.55	3.97	14.15	3.6	13.33	77.5	76.25
70	52.9	16.49	3.92	14.3	3.62	13.52	80.1	80.63

Table 3. Charging with the constant voltage method

Time (Minutes)	Duty Cycle (%)	Vin (V)	Iin (A)	Vout (V)	Iout (A)	Battery Voltage (V)	Eff (%)	SoC (%)
80	53.1	16.8	3.61	14.4	3.5	13.82	83.1	85
90	51.7	17.48	3.26	14.4	3.27	13.9	82.6	87.08
100	50	17.38	2.78	14.41	2.85	14.09	84.2	89.17
110	48	17.9	2.49	14.4	2.51	14.14	81.1	91.25
120	47	17.95	2.3	14.4	2.33	14.18	81.3	93.33
130	46	18.28	1.88	14.4	1.98	14.2	83	95.42
140	45.7	19.2	1.52	14.39	1.64	14.23	80.9	96.67
150	45	19.3	1.37	14.4	1.48	14.26	80.6	97.50
160	44.3	19.37	1.09	14.4	1.2	14.29	81.8	98.33
170	43.8	19.59	0.89	14.4	0.96	14.3	79.3	99.17
180	43.1	19.62	0.83	14.4	0.9	14.33	79.6	99.50
190	42.7	19.8	0.7	14.4	0.76	14.34	79	99.75
200	42	19.61	0.52	14,4	0.55	14.36	80.8	100

3. Current and voltage regulation process using fuzzy logic controller
   As explained at the beginning of this section, the duty cycle represented by the potentiometer is initially set so that the converter output current is 3.6A and the voltage is 12.66V, then left until the end when the current can no longer charge the battery. Then, all data from the beginning to the end is recorded and a curve is created, which is subtracted from the set value, resulting in an error curve that forms the basis for determining the membership function rule base of the fuzzy logic controller in constant current mode. The results are shown in Tables 4.

Table 4. Charging with CC-CV method

Vin (V)	Iin (A)	Vbattery (V)	Vout (V)	Iout (A)	SoC (%)
16.8	3.90	12.06	12.87	3.654	50
16.8	4.01	12.18	13.05	3.627	55
16.8	4.35	12.29	13.37	3.59	60
16.8	4.087	12.45	13.46	3.61	65
16.8	4.101	12.61	13.95	3.63	70
16.8	3.917	12.82	14.32	3.55	75
16.8	2. 87`	12.86	14.4	2.72	80
16.8	2.67	12.91	14.4	2.43	85
16.8	1.87	12.94	14.4	1.86	90
16.8	1.15	12.97	14.4	1.05	95
16.8	0.567	13	14.4	0.539	100

The error curve was created based on the data in Tables 4 below, then subtracted from the set point value. Next, the design and calculations for the application of fuzzy logic controllers in the system were carried out. In addition, the member functions are shown in Figures 3 and 4.

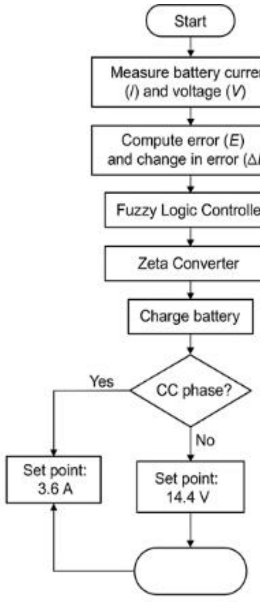

Fig 3. Flowchart system

3.1 Constant Current Method

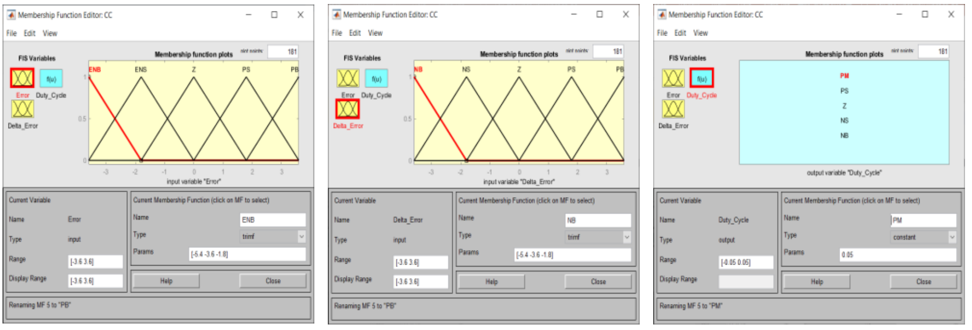

Fig 4. Membership function mode CC

3.2 Constant Voltage Method

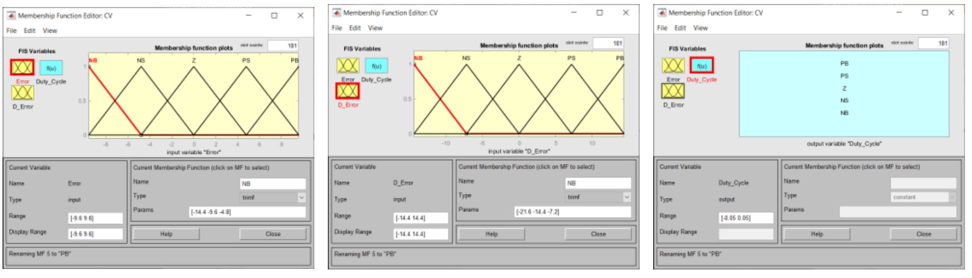

Fig 5. Membership function mode CV

Figure 5 is a zeta converter circuit for charging batteries using the CC CV method and the results have a curve as shown in Figure 6.

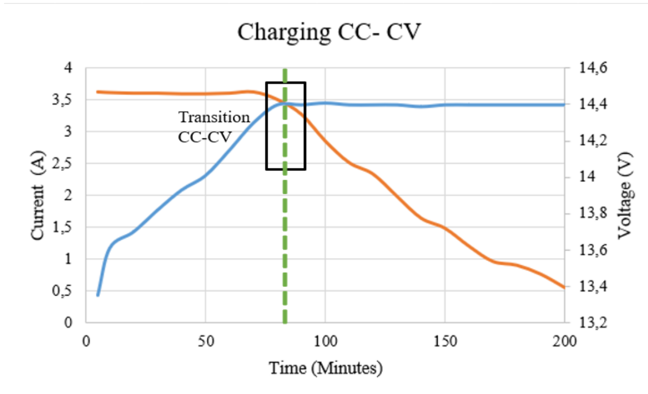

Fig 6. Voltage and current output on CC-CV battery charging

As shown in Figure 6, the battery charging curve using the CC-CV method is displayed. During the initial charging stage (0 to approximately 120 minutes), the current is maintained at a constant level of around 3.6 A, while the voltage gradually increases from 12.8 V to reach a maximum value of 14.4 V. Once the maximum voltage is reached, the system enters the constant voltage charging stage, where the voltage is maintained at 14.4 V and the current gradually decreases to 0.54 A. This pattern demonstrates the system's good charging characteristics and aligns with the operating principles of the CC-CV method, ensuring efficient and safe charging to extend the battery's lifespan. This charging behavior demonstrates the application of fuzzy logic in the system, which dynamically adapts to battery conditions. The gradual decrease in current during the constant voltage phase indicates that the system is equipped with a protection mechanism against overcharging risks. The stability of the voltage during this process also indicates that the voltage regulation is functioning optimally. Thus, the intelligently controlled CC-CV method not only enhances the reliability of the charging system but also helps extend the battery's lifespan. A 200-minute test showed that the 12V lead-acid battery charging system based on CC-CV with fuzzy control works effectively. In the initial stage, the current is maintained at a constant level of approximately 3.6 A, while the voltage increases gradually, indicating the CC charging mode. The duty cycle is dynamically adjusted by the fuzzy controller to maintain current stability, with efficiency ranging from 74% to 84%. When the voltage reaches 14.4 V, the system switches to CV mode, where the current decreases gradually as the battery capacity increases. The actual efficiency increases to 83% at low current, indicating optimal power conversion efficiency until the end of charging. These results demonstrate that the combination of a zeta converter and fuzzy control can manage charging adaptively and efficiently according to battery conditions.

3 RESULTS AND DISCUSSION

This section presents and explains the results of experiments obtained from the development of a smart battery charging system. The evaluation was carried out using two different testing schemes, namely open-loop and closed-loop configurations. These tests aimed to analyze the extent to which the system is able to maintain output voltage and current stability, manage the battery charging process, estimate the charging level, and its performance in terms of energy conversion efficiency. The focus of this analysis is to verify the reliability and flexibility of the implemented fuzzy logic controller, as well as to evaluate the performance of the zeta converter in applying a charging method that follows a constant current-constant voltage strategy. Through this approach, the system is expected to provide stable, accurate, and safe charging for lead-acid batteries under various operating conditions.

3.1 Charging System Efficiency

Power conversion efficiency is calculated based on the ratio between output power and input power. Tests show an average efficiency of 74% in CC mode and 84% in CV mode. This demonstrates the superior performance of the zeta converter in regulating voltage according to load characteristics.

3.1.1 CC-CV Battery Charging Algorithm

The battery charging strategy implemented in this system uses the (CC-CV) method, a commonly used approach to ensure efficient and safe charging of lead-acid batteries. This two-stage process is designed to combine the advantages of constant current and constant voltage charging while minimizing the disadvantages of each.

1. Constant Current (CC) Phase: At the initial stage of the charging process, the battery is charged with a constant current of 3.6A, which is equivalent to 20% of the battery's measured capacity of 18Ah, calculated as:

$$I_{charge} = C \; x \; r \tag{1}$$

$$I_{charge} = 18 \; Ah \; x \; 0.2 \; A \tag{2}$$

Where

I_{charge} = Battery Charging Current (A)
C = Battery Capacity (Ah)
r = Charging rate (C-rate), usually ranges from 0.1 to 0.3 for batteries VRLA.

2. Constant Voltage (CV) Phase: Once the battery reaches the target voltage of 14.4V, which is equivalent to 120% of the battery's nominal voltage (12V), the system switches to voltage regulation mode. In this phase, the voltage is kept constant, and the current is allowed to decrease gradually as the battery approaches full capacity.

$$V_{target} = 1.2 \; x \; 14.4 \; V \tag{3}$$

At this stage, the voltage is kept constant at 14.4 V, and the charging current gradually decreases as the battery approaches full capacity. This helps to avoid overcharging and reduces the risk of excessive heat generation. Charging is considered complete when the current drops below the specified cutoff level, typically set between 3% and 5% of the battery's rated capacity to prevent overcharging.

$$Cutoff \; Current = 1.2 \; x \; 14.4 \; V \tag{4}$$

By combining both phases, this strategy ensures high charging efficiency, protection against overvoltage, and increased battery life. The transition between phases is automatically managed by a fuzzy control system based on real-time feedback of battery voltage and current, without requiring an accurate battery model. This makes the CC–CV method ideal for dynamic charging applications. It prevents the risk of overcharging and extends battery life. The transition between phases is automatically handled by a control system based on real-time voltage and current feedback. This two-stage algorithm ensures the battery is charged within safe operational limits while optimizing charging duration.

3.1.2 Fuzzy Logic Based Charging Control

To achieve adaptive control in the battery charging process, a fuzzy logic controller (FLC) is used in the system. This controller operates based on two input variables: Error (E), defined as the difference between the desired value and the actual value (both current and voltage), and Error Change (ΔE), which represents how the error evolves over time. These inputs are processed to produce a single output: the PWM duty cycle that controls the switching of the Zeta converter's MOSFET. The fuzzy inference system is designed using triangular membership functions for simplicity and efficiency. Each input E and delta E is divided into five fuzzy sets. The same fuzzy sets are used for the output, which determines how the duty cycle should be adjusted. Basic structure of the Sugeno fuzzy method.

$$IF\ (X_1\ is\ A_1)\ AND\ \ (x_2\ is\ A_2)\ THEN\ z =\ \ f(X_{1,}X_2) \tag{5}$$

The Sugeno fuzzy logic method was chosen because it is capable of providing more accurate outputs with low computational load, making it ideal for application in microcontroller-based control systems. Unlike the Mamdani method, which uses fuzzy membership functions as outputs, the Sugeno method produces outputs in the form of constant or linear numerical values, which are simpler to calculate and faster in the inference process. This advantage is particularly important when used in embedded systems such as STM32, which require real-time control processes.

4 Conclusion

This study has **successfully** tested a battery charging system using a zeta converter with a constant current – constant voltage method and fuzzy logic controller as a regulated control. The charging process was carried out on a 12V battery with a capacity of 18Ah, starting from a state of charge of 50%. The constant current charging stage was carried out with a current of 3.6A maintained for 80 minutes. When the SoC reached 85%, the system automatically switched to the constant voltage stage at 14.4 V, which was maintained for 120 minutes. The test results showed that the system operated in accordance with the designed parameters and was able to maintain the stability of the charging process in line with the principles of the CC-CV method.

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