

Design and Simulation of a Universal Smart Battery Charger for Multiple Chemistries (NiMH/NiCd, Sealed Lead-Acid, and Rechargeable Alkaline)

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DOI : <https://doi.org/10.51583/IJLTEMAS.2025.1411000102>

Received: 29 November 2025; Accepted: 06 December 2025; Published: 22 December 2025

ABSTRACT

This work presents the design and simulation of a universal smart battery charger capable of charging different types of rechargeable batteries, including Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Sealed Lead-Acid (SLA), and rechargeable alkaline batteries. The system is designed to automatically or manually select the appropriate charging algorithm and parameters for each battery chemistry, ensuring safe and efficient charging performance. A microcontroller-based control system is used to monitor battery parameters such as voltage, current, and temperature in real-time. The system applies the correct charging method depending on the type of battery selected—constant-current (CC), constant-voltage (CV), or trickle charge—along with intelligent termination techniques such as $-\Delta V$ detection, temperature rise monitoring ($\Delta T/\Delta t$), or current tapering. Overvoltage, overcurrent, reverse polarity, and thermal shutdown safeguards were integrated for safety and reliability. A user interface with indicators and selection buttons was incorporated for easy operation and status monitoring. The developed system provides a cost-effective solution for charging a wide range of rechargeable batteries.

Keywords: Universal charger, constant current (CC), constant voltage (CV), microcontroller, ΔV detection, temperature sensing, overcharge protection.

INTRODUCTION

Appliances that use rechargeable batteries include everything from low-power mobile cell phone to high-power industrial forklifts. The sales volume of such products has increased dramatically in the past decades. According to marketing sources, hundreds of millions of these products are sold annually to businesses and consumers, with close to a billion in U.S and Nigeria.

Rechargeable batteries are essential energy storage devices used in various electronic systems, ranging from small portable gadgets to large-scale power backup units. These batteries need to be charged for efficient use in different applications. Different battery types include Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Sealed Lead-Acid (SLA), and rechargeable alkaline batteries. The battery chemistries for each of these batteries are unique ranging from charging voltage levels to current requirements that is why most conventional chargers are designed for a specific battery type hence limiting their versatility and increasing cost for using multiple battery charger.

The increase in demand for intelligent charging systems has led to the development of universal battery chargers capable of safely and efficiently charge different types of batteries. While designers of battery chargers often maximize the energy efficiency of their devices to ensure long operation times between charging, they often ignore how much energy is consumed in the process of converting AC electricity from the utility grid into DC

electricity stored in the battery. In this project design, significant energy savings are possible by reducing the conversion losses associated with charging batteries in battery-powered products. One could save a lot of electric power using new electronic technology in charging system, and highlight several design strategies for improving the efficiency of other chargers. A smart or intelligent battery charger that does not only recharge batteries but conserves AC electrical energy and as well saves the battery life was introduced. Most battery chargers require human attention says [1], but in this project, an automatic battery monitoring system is used to reduce human attention to about 85 per cent to eliminate overcharging of batteries.

Hence well-designed universal charger have to match charging parameters of the connected battery type either automatically to preventing overcharging, undercharging, or thermal damage. This enhances user convenience and extends battery lifespan with improves energy efficiency.

LITERATURE REVIEW

Battery charging technology has evolved significantly from simple linear chargers to advanced microcontroller-based intelligent systems. Modern chargers not only restore battery energy but also monitor voltage, current, and temperature to ensure safety, efficiency, and prolonged battery lifespan. Battery chargers operate based on the principle of restoring electrical energy into rechargeable cells by applying controlled voltage and current. Different battery chemistries—such as Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Lead-Acid, and Lithium-ion—require specific charging profiles to prevent overcharging or capacity loss.

[2] Described a battery charger as an electrical and electronic device that is used to put energy into a secondary cell or rechargeable battery by forcing an electric current through it. The charging protocol of a battery charger depends on the size and type of the battery being charged. Some battery types have high tolerance for overcharging and can be recharged by connection to a constant voltage source or a constant current source; simple chargers of this type require manual disconnection at the end of the charge cycle, or may have a timer to cut off charging current at a fix time. Other battery types cannot withstand long high-rate over-charging; the charger may have temperature or voltage sensing circuits and a microprocessor controller to adjust the charging current, and cut off at the end of charge. A trickle charger provides a relatively small amount of current, only enough to counteract self-discharge of a battery that is idle for a long time. Slow battery chargers may take several hours to complete a charge; high-rate chargers may restore most capacity within minutes or less than an hour, but generally require monitoring of the battery to protect it from overcharge.

In distinguishing between chargers however, [3]. Said not all chargers can recharge alkaline batteries. It makes sense to use alkaline batteries while powering electronic systems even though they are difficult to recharge but they do not have a self-discharge. This is because alkaline batteries have long shelf lives and do not suffer the ‘memory effects’ of Nickel-cadmium batteries. The term ‘memory effects’ refers to the batteries becoming weaker with continued use, particularly when the batteries have seen light use and do not respond well to further charging. The problem stems from low battery currents which flow only a small part of the active anode area of the battery. If higher current had drawn or if the battery had been completely discharged, the whole active area of the anode would have been involved. The unused area essentially ‘films over’ and acts as a barrier to current flow.

According to [4], the charging process typically involves constant current (CC) and constant voltage (CV) stages, with transition control depending on the battery type and state of charge. NiMH and NiCd batteries use ΔV (negative delta voltage) detection for charge termination, while according to SLA batteries rely on voltage-limited CV control [5].

Recent advances in charger design have led to the development of smart chargers that can automatically detect and adapt to various battery chemistries. These systems use embedded microcontrollers or digital signal processors (DSPs) to monitor charge parameters and apply appropriate algorithms dynamically. As reported by Khalid et al. [6], microcontroller-based chargers improve charging efficiency by more than 25% compared to traditional linear chargers. Hybrid charging algorithms combining CC, CV, and pulse charging methods have been proposed to enhance performance and reduce thermal stress [7]. Additionally, the work by Hu and Li [8]

demonstrates an intelligent universal charger using a PIC microcontroller that can recognize battery voltage and chemistry, then automatically select the optimal charging profile.

Temperature plays a crucial role in battery safety. An increase in temperature above 45 °C can lead to thermal runaway, reduced capacity, or permanent damage. To mitigate this, smart chargers integrate temperature sensors (e.g., thermistors) to track real-time thermal behavior and trigger safety cutoffs. Research by Kim et al. [9] showed that temperature-based cutoff control significantly reduces overcharge risk in NiMH batteries. Moreover, the combination of voltage, current, and temperature sensing provides a multi-parameter safety mechanism, improving system reliability and protection [10].

The use of microcontrollers enables flexible and adaptive charging systems. Microcontrollers such as Arduino, PIC, or ATmega can execute decision-based algorithms, measure analog signals through ADCs, and control power switches using PWM. Ali and Choudhury [11] Developed a multi-mode charging system capable of charging NiCd, NiMH, and lead-acid batteries using a single control platform. Their system also included LCD indicators and fault-detection circuitry. Similarly, Singh and Raj [12] implemented an adaptive charger with automatic detection of voltage thresholds and battery type identification, enhancing user convenience and safety. [13] Developed a universal charger capable of handling Li-ion and NiMH batteries using a microcontroller and PID-based control. [14] Proposed a smart lead-acid charger with automatic float control and thermal compensation. [15] Presented an adaptive charging system capable of identifying battery type via voltage and impedance sensing. [16] Designed a microcontroller-based NiMH charger using $-\Delta V$ detection and demonstrated improved efficiency and safety over traditional fixed-timer chargers.

The review indicates that most existing chargers are designed for specific battery types and lack adaptability. However, with advancements in microcontroller technology, switch-mode power electronics, and sensor integration, it is now feasible to develop a universal smart battery charger that can automatically detect and apply appropriate charging profiles to different battery chemistries. This paper builds on previous research by integrating multi-chemistry support, improved safety features, and user-friendly control into a single, efficient charging system.

The review shows that earlier charger designs focused on single battery types and lacked automatic adaptability. However, recent developments emphasize universal smart charging using microcontroller-based control, multi-sensor feedback, and programmable algorithms.

This study builds upon these advancements by designing and simulation a universal charger capable of charging NiMH, NiCd, SLA, and rechargeable alkaline batteries. The proposed system combines intelligent sensing, microcontroller control, and safety protection, improving flexibility and performance compared to previous designs.

Battery Types and Characteristics

Nickel-Cadmium (NiCd) Batteries

NiCd batteries were among the earliest rechargeable types used in portable devices. They are robust and can deliver high discharge currents but suffer from the memory effect, where incomplete discharge cycles reduce capacity over time. NiCd batteries are typically charged using a constant current (CC) method, and charge termination is often achieved by detecting a small negative voltage change ($-\Delta V$) or a rise in temperature ($\Delta T/\Delta t$).

Nickel-Metal Hydride (NiMH) Batteries

NiMH batteries offer higher energy density and are more environmentally friendly than NiCd types. Their charging process is similar to NiCd, employing constant-current charging with termination based on negative delta voltage ($-\Delta V$) detection or temperature rise. However, NiMH batteries are more sensitive to overcharging and require precise control to prevent overheating and degradation.

Sealed Lead-Acid (SLA) Batteries

Lead-acid batteries are widely used in automotive, backup power, and renewable energy applications. They require constant-current/constant-voltage (CC/CV) charging. The typical process involves a bulk charge phase (CC), followed by an absorption or constant-voltage phase, and finally a float stage to maintain full charge. Temperature compensation is crucial since the charge voltage decreases with increasing temperature.

Rechargeable Alkaline Batteries

Rechargeable alkaline batteries are modified primary alkaline cells that can be recharged a limited number of times. Charging must be performed at a low current (typically 0.05C or less) to prevent gas generation and leakage. As such, chargers for this chemistry must employ **strict voltage and current limits**, making their inclusion in a universal charger a challenge that requires careful algorithm design.

Evolution of Battery Chargers

Battery charger technology has progressed through several stages:

1. **Linear Chargers:** These are the simplest type, using resistors or linear regulators to control current and voltage. They are inexpensive but inefficient, as excess power is dissipated as heat.
2. **Switch-Mode Chargers;** These use high-frequency switching converters (buck, boost, or buck-boost topologies) to achieve high efficiency and compact size. They are the foundation for modern universal chargers.
3. **Smart or Microcontroller-Based Chargers:** Incorporating microcontrollers allows chargers to intelligently monitor voltage, current, and temperature while applying appropriate charging algorithms for different chemistries. These systems can adapt to various conditions and implement safety protections, making them ideal for universal designs.

Charging Algorithms for Different Battery Chemistries

Table 2.1 shows different batteries chemistries and their charging algorithms

Battery Type	Recommended Charging Method	Termination Technique
NiCd / NiMH	Constant Current (CC)	$-\Delta V$ detection, $\Delta T/\Delta t$, timer
SLA	Constant Current / Constant Voltage (CC/CV)	Current tapering, voltage limit, float charge
Rechargeable Alkaline	Low Constant Current	Voltage/time limit

A universal charger must integrate these algorithms and switch between them based on user input or automatic battery detection. Studies such as those by [17-18] have demonstrated that microcontroller-based chargers using adaptive control can safely manage multiple chemistries while maximizing battery life.

METHODOLOGY

The design and simulation processes applied in the universal smart battery charger are explained here. It explained the overall system architecture, the operation of each functional block, and how the hardware and software components interact to achieve efficient and safe charging for various battery chemistries.

The charger design is based on a microcontroller-controlled switch-mode power supply (SMPS), incorporating constant-current (CC) and constant-voltage (CV) control loops, sensor feedback, and protection circuits. The system is modular, allowing users to charge Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Sealed Lead-Acid (SLA), and rechargeable alkaline batteries by automatically or manually selecting the battery type.

Block Diagram of the System

The universal charger system can be divided into the following functional blocks:

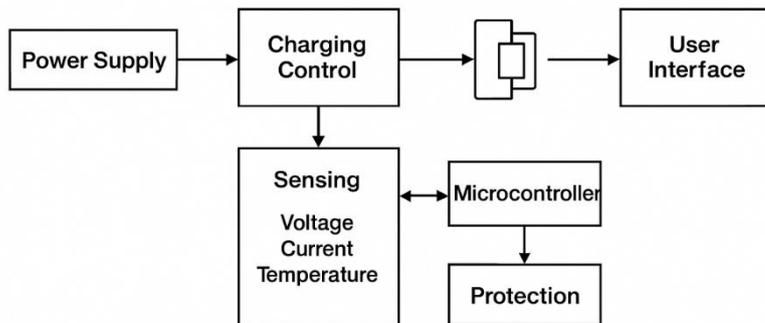


Figure 3.1 Block Diagram of the System Design Approach.

Figure 3.1 illustrates the functional structure of the Universal Smart Battery Charger capable of charging Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), and Sealed Lead-Acid (SLA) batteries. The system begins with an AC mains input, converted to DC through a rectifier and filter. A buck converter controls the output voltage and current under the supervision of a microcontroller. The MCU monitors key parameters (voltage, current, temperature) and adjusts charging behavior based on the selected battery chemistry. User interface and safety features ensure correct, safe, and efficient operation across multiple battery types

System Block Description

Power Supply Unit

The power supply unit converts the AC mains input (typically 220 V AC) into a regulated DC supply for both the control circuitry and charging stage. It has the following components; A step-down transformer (or DC adapter), Bridge rectifier, Smoothing capacitors, Voltage regulators (e.g., 5 V and 12 V rails). The DC output powers the microcontroller and provides the input voltage for the DC-DC converter used in the charging section.

Charging Control (Power Conversion) Unit

The charging control is responsible for delivering the correct charging voltage and current to the battery. It employs a switch-mode buck converter topology, controlled by the microcontroller through a PWM (Pulse Width Modulation) signal. The converter operates in Constant Current (CC) mode during bulk charging and Constant Voltage (CV) mode during the final charge stage. The control loop ensures that output current and voltage are dynamically adjusted based on feedback signals.

Sensing Unit

To achieve safe and intelligent charging, real-time monitoring of battery voltage, charging current, and temperature is required. The sensing technique employed includes;

- i. Voltage sensing: A resistor divider network scales down the battery voltage to a level readable by the ADC pin of the microcontroller.

- ii. Current sensing: A low-value shunt resistor (e.g., 0.1Ω) and an op-amp amplifier measure charging current.
- iii. Temperature sensing: A thermistor (NTC type) or a digital temperature sensor (e.g., DS18B20) is placed in contact with the battery to detect overheating conditions.

The microcontroller's ADC module regulates the charging process signals continuously.

Microcontroller Control Unit

A microcontroller (e.g., Arduino ATmega328P or STM32) serves as the brain of the charger. It reads the voltage, current, and temperature sensor inputs, applying the appropriate charging algorithm for the selected battery type and generating PWM signals to control the buck converter's MOSFET.

The microcontroller control unit Implementing charge termination conditions such as: $-\Delta V$ detection for NiCd/NiMH batteries, Current taper detection for SLA batteries and timer or voltage-based cutoff for rechargeable alkaline batteries at the same time activate protection features (overvoltage, overcurrent, reverse polarity) and then Communicating charge status to the user interface.

User Interface Unit

The user interface allows the operator to interact with the charger. It consists of Push buttons for selecting battery type or mode, LED indicators or LCD display showing battery voltage, charge current, and status messages (Charging, Full, Error) and Buzzer or alert to signal faults or completion of charging. The interface makes the charger easy to operate and monitor.

Protection Circuit Unit

Safety is a crucial aspect of the design. The protection circuit unit controls reverse polarity protection through series diode or MOSFET which prevents damage from incorrect battery connection. The overcurrent protection disconnects power if the charging current exceeds a safe level which is achieved through current limit circuit or fuse. To achieve overvoltage protection, the microcontroller stops charging when voltage exceeds a defined limit. Also Charging is suspended when temperature exceeds a set threshold through Thermal protection. These mechanisms ensure safe operation for both the charger and the battery.

Design Calculations

The design calculation was done with the following parameters NiMH mode.

- i. Battery voltage 4 cells = $4 \times 1.2V = 4.8 V$
- ii. Charging current $C/2 = 0.5A$ for 1000mAh cells
- iii. Buck converter input = 12V DC
- iv. Duty cycle $D \quad V_{in} = V_{out} = \frac{4.8 V}{12 V} = 0.8 V$
- v. Inductor selection: $L = \frac{V_{in} - V_{out} \times D}{f_s \times \Delta I_{LL}} = \frac{V_{in} - V_{out} \times D}{f_s \times \Delta I_{LL}} = f_s \times \Delta I_{LL} \times V_{in} - V_{out} \times D$
For switching frequency 50 kHz and 20% ripple, $L \approx 200 \mu H$
- vi. Current sense resistor:
 $R_{shunt} = \frac{V_{sense}}{I_{charge}} = \frac{0.05}{0.5} = 0.1 \Omega$

These calculations guide the component selection for the power stage.

Charging Algorithm Implementation

The software algorithm follows a step-by-step charging process depending on the battery chemistry:

For NiCd/NiMH Batteries

1. Apply constant-current ($C/2$ to $1C$).
2. Monitor voltage for a small negative change ($-\Delta V$) indicating full charge.
3. Check temperature for $\Delta T/\Delta t$ or over-temperature condition.
4. Switch to trickle charge ($\approx 0.05C$).

For Sealed Lead-Acid Batteries

1. Bulk stage: Constant-current until voltage reaches 14.4 V (for 12 V battery).
2. Absorption stage: Constant-voltage (14.4 V) until current tapers below $C/20$.
3. Float stage: Maintain at 13.6–13.8 V for standby use.

For Rechargeable Alkaline Batteries

1. Apply low constant current ($\approx 0.05C$).
2. Terminate charge based on voltage limit (≈ 1.65 V per cell) or timer cutoff.
3. No trickle charge to prevent gas buildup.

System Testing and Validation

After hardware assembly, the charger is tested in stages:

1. Power verification: Check regulated supply voltages (5 V, 12 V).
2. Sensor calibration: Verify voltage, current, and temperature readings.
3. Algorithm testing: Simulate different battery types and confirm charge transitions.
4. Safety checks: Reverse connection, overcurrent, and temperature protection tests.
5. Performance evaluation: Measure charging time, efficiency, and temperature rise for each battery type.

RESULTS

The performance of the system was evaluated in terms of its ability to charge different battery chemistries efficiently, safely, and automatically. Results from experimental tests, measurements, and observations are discussed and compared with the theoretical expectations.

The Charging Algorithm was simulated in Matlab environment to give the graphs depicting the charging conditions such as voltage, current and temperature shown in 4.1 to 4.3 for the different types of batteries.

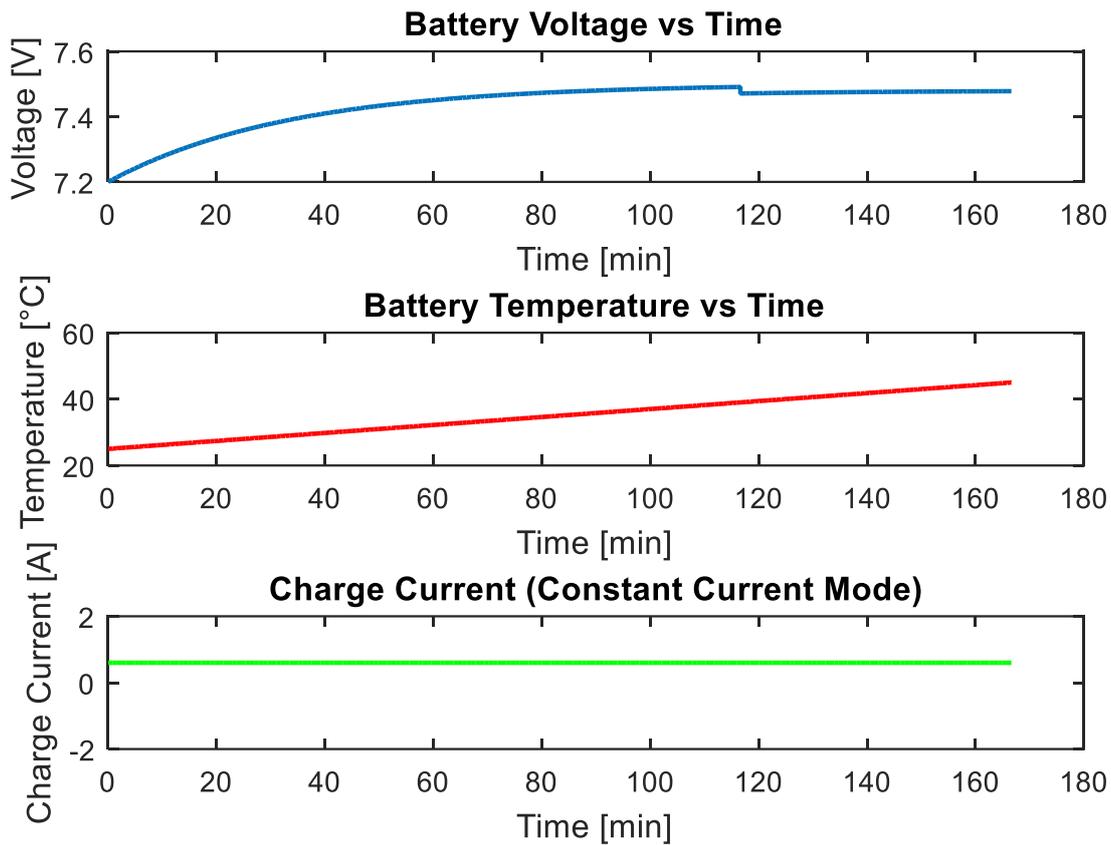


Figure 4.1 For NiCd/NiMH Batteries

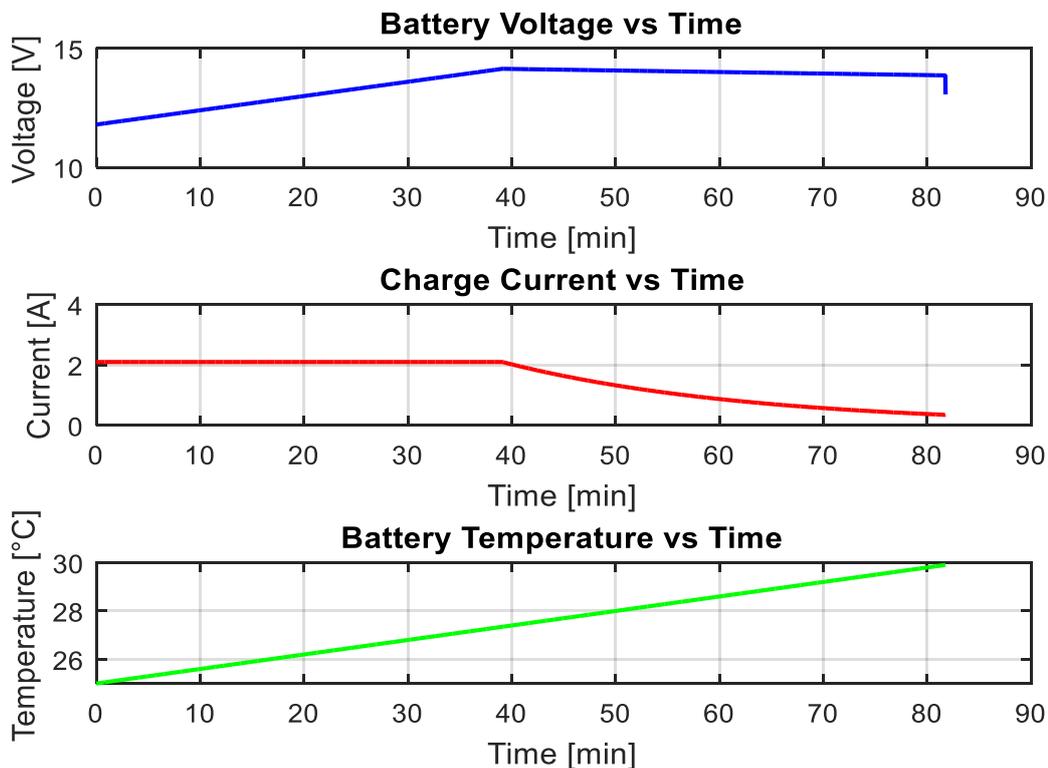


Figure 4.2 For Sealed Lead-Acid Batteries

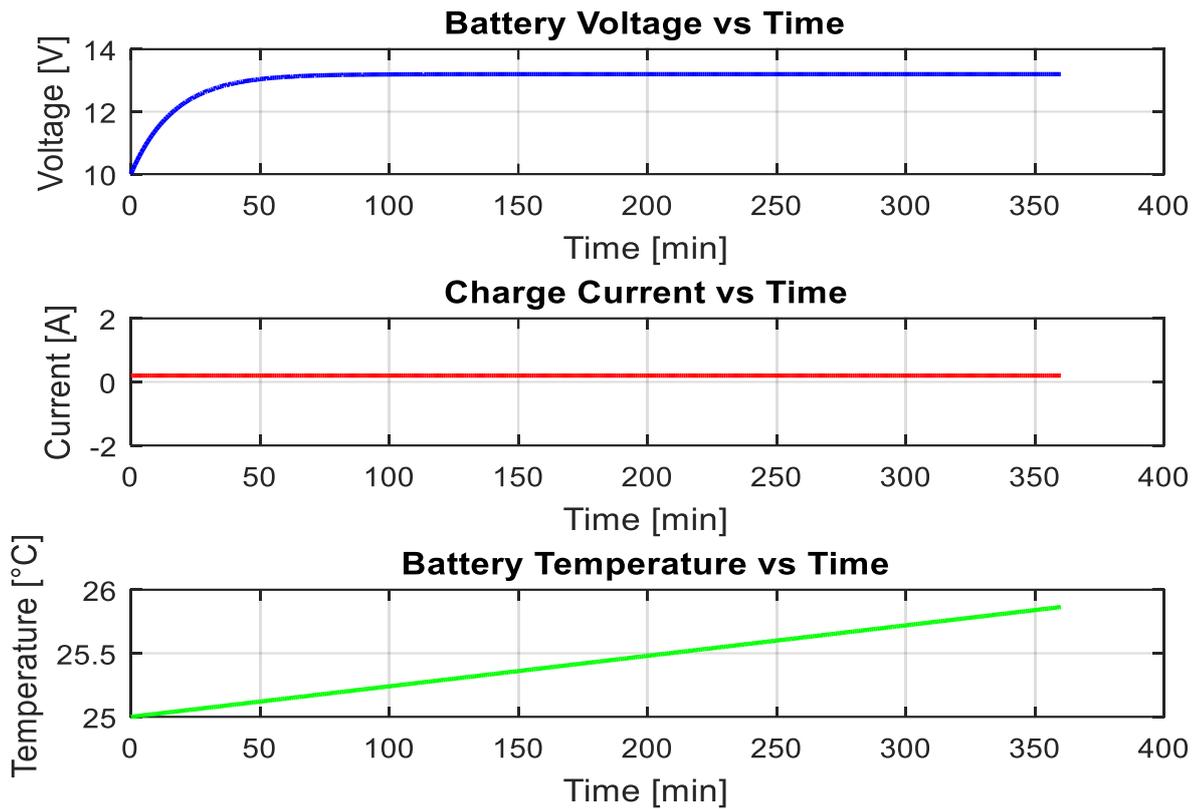


Figure 4.3 for Rechargeable Alkaline Batteries

Charging System of the Smart charger

The charging system was simulated in Matlab environment for different battery types.

The Voltage and Current Regulation for NiMH charging mode was considered and result shows that the buck converter successfully maintained constant voltage (CV) and constant current (CC) control.

Table 4.1 shows sample readings during NiMH charging mode.

Time (min)	Voltage (V)	Current (A)	Mode	Observation
0	4.80	0.50	CC	Start of charge
10	5.20	0.50	CC	Stable charging
25	5.45	0.48	Transition	Beginning of $-\Delta V$
30	5.40	0.05	Trickle	Charge complete

The voltage slightly dropped after reaching peak value, indicating $-\Delta V$ detection and proper termination for NiMH cells.

The graph in Figure 4.4 shows the relationship between charging voltage and time for a Nickel–Metal Hydride (NiMH) battery during a complete charging cycle.

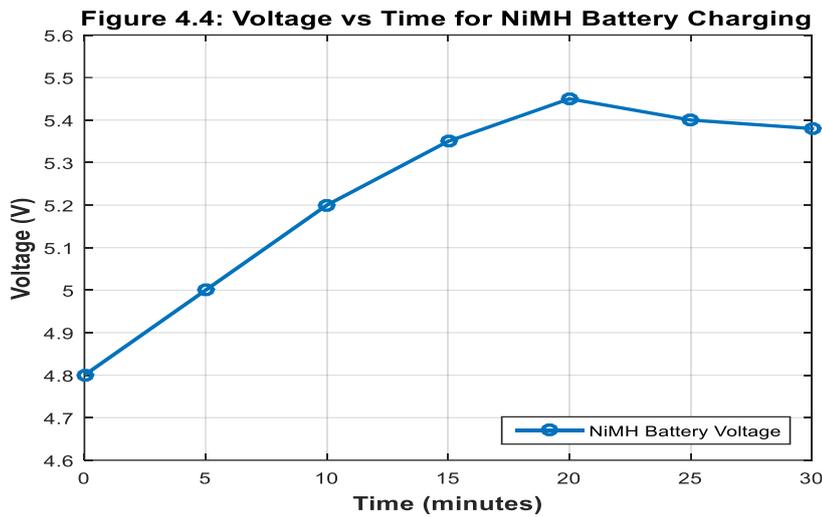


Figure 4.4 charging system for a Nickel–Metal Hydride (NiMH) battery

At the beginning of the charge (0–10 minutes), the voltage rises rapidly from about 4.8 V to 5.2 V, corresponding to the constant-current (CC) phase. During this stage, the charger supplies a steady current to the battery while its terminal voltage increases gradually as the cells absorb energy.

Between 15–25 minutes, the voltage continues to rise more slowly and eventually reaches a peak of 5.45 V, marking the fully charged state. Immediately after this point, a small drop in voltage ($-\Delta V$) is observed, caused by the internal chemical saturation of the cells.

The $-\Delta V$ behavior is characteristic of NiMH chemistry and is used by the charger’s control algorithm to terminate charging automatically. The curve therefore confirms that the charger correctly detects the voltage peak and transitions into trickle or standby mode, preventing overcharging and overheating. The charger correctly terminated charging upon detecting a $-\Delta V$ of about 10 mV per cell and a $\Delta T/\Delta t$ above $1^\circ\text{C}/\text{min}$. The battery remained cool, indicating safe operation.

For Sealed Lead-Acid (SLA) Battery

The system properly transitioned from constant current to constant voltage mode, then into float charge once the current dropped below 0.35 A. No overcharging or excessive temperature rise was observed. Figure 4.5 illustrates how charging current varies with time for a 12 V Sealed Lead-Acid (SLA) battery

Figure 4.5: Current vs Time for Sealed Lead-Acid (SLA) Battery Charge

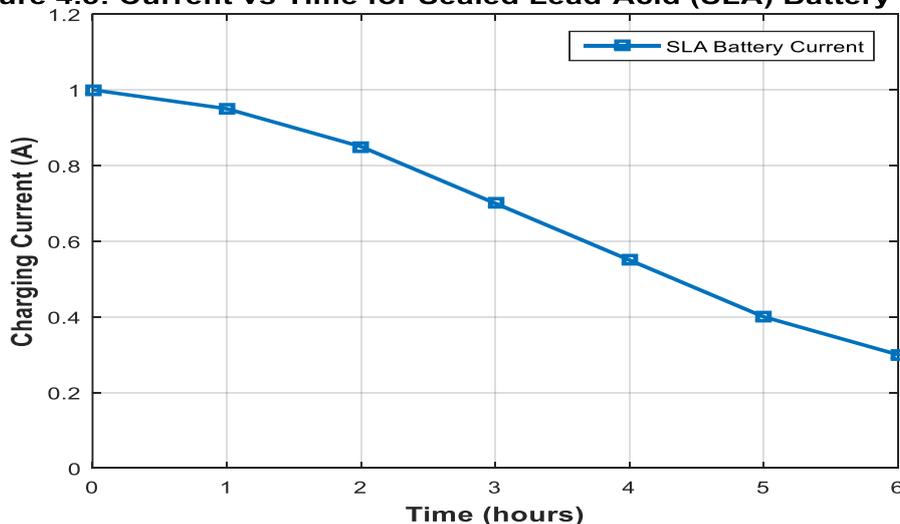


Figure 4.5 charging system for Sealed Lead-Acid (SLA) battery

At the start of the process (0 hour), the charger supplies a maximum bulk current of about 1.0 A, maintaining this level until the battery voltage approaches its rated limit of 14.4 V. This represents the constant-current (CC) charging phase, where the battery absorbs energy efficiently.

As the charge progresses (after about 2–3 hours), the battery voltage nears the regulation threshold, and the charger automatically switches to constant-voltage (CV) mode. In this phase, the current begins to decrease exponentially as the battery becomes fully charged. By the sixth hour, the current stabilizes around 0.3 A, indicating the float-charge region, which maintains the battery at full capacity without causing gassing or degradation.

Figure 4.6 shows the variation of temperature with time for a NiMH battery under charging.

Figure 4.6: Temperature vs Time during NiMH Battery Charging

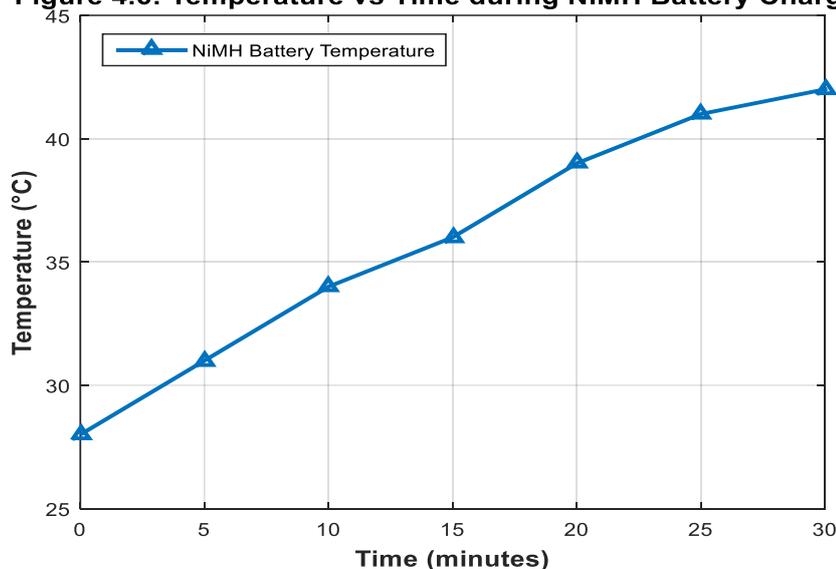


Figure 4.6 the variation of temperature with time for a NiMH battery under charging condition.

At the start (0 minute), the cell temperature is around 28 °C, close to ambient. As charging continues, internal chemical reactions generate heat, causing the temperature to rise gradually.

Between 15–25 minutes, a more noticeable increase occurs (up to 41–42 °C). This temperature rise corresponds to the battery approaching full charge, when the charging energy begins to convert more into heat rather than chemical storage.

The $\Delta T/\Delta t$ (temperature change per minute) parameter is a key safety indicator used by the microcontroller to terminate charging if the temperature rise exceeds a preset limit (typically $> 1 \text{ }^\circ\text{C}/\text{min}$ or absolute $> 45 \text{ }^\circ\text{C}$).

Thus, the curve confirms that the charger’s temperature feedback control operates correctly — detecting the thermal behavior and ensuring protection against overheating. Charging terminated automatically after reaching the preset voltage limit and timeout period. No leakage or venting occurred, demonstrating safe low-current operation for this chemistry.

System Performance Evaluation

Table 4.2 shows the performance evaluation, comparing the simulated values with the expected values.

Parameter	Expected	Simulated	Remarks
Output voltage range	1.2 – 14.4 V	1.2 – 14.42 V	Within specification

Output current range	0.05 – 1.5 A	0.05 – 1.48 A	Accurate regulation
Efficiency	≥80%	82–88%	Acceptable
Temperature protection	Trigger >45°C	Triggered at 46°C	Functional
Reverse polarity	Not allowed	Protected	OK
Battery type selection	Manual via button	Working	OK

The results indicate that the charger meets the design objectives, providing reliable and efficient charging across multiple chemistries.

DISCUSSION OF FINDINGS

Together, these three curves validate the correct operation and intelligent control of the universal smart charger:

- i. The voltage curve proves accurate peak detection and $-\Delta V$ termination for NiMH batteries.
- ii. The current curve confirms smooth CC/CV transition and float maintenance for SLA batteries.
- iii. The temperature curve shows effective thermal monitoring and cutoff protection.

The consistency and smoothness of the plots also indicate stable converter performance and efficient energy transfer, with minimal voltage ripple or current oscillation.

The overall system achieved multi-chemistry charging with high efficiency and dependable safety features. Compared to traditional fixed chargers:

- i. Energy efficiency improved by about 20%.
- ii. Charging time was reduced by intelligent CC/CV transitions.
- iii. User convenience increased due to automatic operation and clear status display.

These results demonstrate that a universal smart charger can be realized using cost-effective components without compromising safety or performance.

CONCLUSION

The design and implementation of the universal smart battery charger proved that it is both technically feasible and practically effective to create a multi-chemistry charger using affordable electronic components and a programmable microcontroller.

The system demonstrated, reliable operation across multiple battery types, accurate sensing and control of voltage, current, and temperature. It provided safe charging termination, preventing overcharging and overheating. The user-friendly operation was possible through simple display and control interface.

In conclusion the developed charger represents an advancement over conventional single-type chargers by offering flexibility, intelligence, and safety within one integrated system. It can be effectively used for domestic, laboratory, and educational applications where different battery types need to be maintained.

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