iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VII Month of publication: July 2025

DOI: https://doi.org/10.22214/ijraset.2025.73164

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VII July 2025- Available at www.ijraset.com

SMPS Based 48V/8A Battery Charger (CV Mode) Constant Voltage

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Abstract: This paper presents the design and implementation of a switch- mode power supply (SMPS) based battery charger delivering 48 V at 8 A with precise constant- voltage regulation. The charger employs a high- frequency, pulse- width- modulated (PWM) buck converter topology optimized for efficiency and compactness. Key features include a digital control loop using a microcontroller- based PID algorithm to maintain output voltage within ±0.5% under varying load and input conditions, and a programmable soft- start sequence to limit inrush current during connection. Input power factor correction (PFC) ensures compliance with international grid- compatibility standards, while synchronous rectification in the output stage achieves efficiencies exceeding 94%. Protection mechanisms, overvoltage, overcurrent, and thermal shutdown are integrated to ensure safe operation and battery longevity. Experimental results on a laboratory prototype demonstrate stable 48 V output with rapid response to load transients and an overall efficiency of 92.5% at full load. The modular design allows scalability to higher power levels, making it suitable for modern energy storage systems in telecommunications, electric vehicles, and renewable- energy applications.

1. INTRODUCTION

In recent years, the rapid proliferation of high- power battery- powered systems—ranging from telecommunications backup units and electric-vehicle auxiliary packs to renewable-energy storage banks has driven a growing demand for compact, efficient, and reliable battery chargers. Switch- mode power supplies (SMPS) have emerged as the technology of choice for such applications, offering significant advantages in power density, thermal performance, and overall system efficiency compared to legacy linear chargers. This paper focuses on the design and implementation of an SMPS- based battery charger capable of delivering a regulated 48 V output at up to 8 A, operating in constant- voltage (CV) mode to ensure safe, predictable charging and extended battery life.

The core of the charger adopts a high- frequency PWM buck converter topology, which enables reduced magnetics size and lower switching losses. To achieve tight voltage regulation under dynamic conditions, a microcontroller executes a digital PID control loop, sampling the output voltage at high speed and adjusting the duty cycle to maintain the setpoint within ±0.5%, even as input voltage and load current vary. A programmable soft- start mechanism limits inrush currents during hot plugging, safeguarding both the charger and battery from undue stress. Furthermore, the design integrates active power factor correction (PFC) on the AC input side to meet international grid compatibility standards (EN61000- 3- 2) and minimize harmonic distortion.

Key design considerations include the selection of synchronous rectification devices in the output stage to push efficiency beyond 94%, thermal management using a combination of heat- pipe– assisted sinks and controlled airflow, and comprehensive protection features such as overvoltage, overcurrent, and thermal shutdown. A modular layout facilitates easy scalability to higher power levels or multi- output configurations. Experimental validation on a laboratory prototype demonstrates an overall efficiency of 92.5% at full load, rapid transient response to load steps, and stable operation across the full specified input range. The resulting charger architecture meets the stringent requirements of modern energy-storage systems, providing a blueprint for future developments in high- efficiency battery- charging solution.

II. LITERATURE REVIEW

In this section, we review key research and commercial developments in SMPS-based, constant-voltage battery chargers—particularly those targeting 48V systems with currents on the order of 5–10A. We organize the literature by converter topology, control strategies, efficiency enhancements, and protection/soft-start technique.

1) Converter Topologies for High-Power Battery Charging

- Buck Converters: The simplest step-down topology, buck converters feature prominently in early 48V charger designs due to ease of control and relatively low part count. Ref. [1] demonstrated a 48V/10A buck charger achieving 90% efficiency by optimizing the gate-drive timing and utilizing high-speed MOSFETs. However, passive rectification limited performance at high currents.

- Two-Stage PFC Buck: To meet power-factor regulations, many designs employ a front-end boost PFC stage feedingabuckconverter. Ref.[2] implemented an interleaved boost-buck architecture, reducing input-current ripple and distributing thermal stress across phases. Their 48V/8A charger reached 93% efficiency at full load.
- Single-Stage PFC Converters: Single-stage topologies (e.g., bridgeless totem-pole boost) combine PFC and voltage regulation in one stage. Ref.[3] proposed a bridgeless totem-pole converter for 48V batteries, reporting 91% peak efficiency and simplified passive filtering.

2) Digital and Adaptive Control Techniques

- PID Control with Digital Signal Controllers (DSCs): The vast majority of recent chargers adopt digital PID loops [4].
- Model Predictive Control (MPC): To further improve dynamic response, some researchers have explored MPC. Ref. [5] compared MPC against PID for a 48V/5A charger, demonstrating a 30% faster settling time at load steps but atthe cost of 15% higher computational overhead.
- Machine- Learning- Assisted Control: Ref. [6] integrates a neural network to predict optimal switching patterns for efficiency maximizationundervaryingbatterystates. Their prototype achieved an additional 1.5% efficiency gain, though stabilityacross diverse operating points remains under study.

3) Efficiency Enhancements: Synchronous Rectification & Soft- Switching

- Synchronous Rectification (SR): SR is widely used to replace diode rectifiers in theoutputstage. Ref. [7] showed that integrating GaN FETs as SR devices canpushefficienciesabove95%atseveral amps by reducing conduction losses.
- Soft-Switching Techniques: Resonant and quasi-resonantconvertersminimize switching losses. Ref.[8] designed a series-resonant converter for 48V charging, achieving 94% efficiency butnotedincreased EMIfiltercomplexity. Hybrid approaches (e.g., half-bridge LLC followed by a buck) also show promise in balancingefficiencyandcontrolsimplicity.

4) Protection, Soft-Start and Thermal Management

- Inrush Current Limiting: NTC thermistors andactivesoft-startcircuitsarestandard. However, digital implementations allow programmable soft-start profiles. Ref.[9]demonstrated a soft-start with adjustable ramp-rate via firmware, reducing mechanical stress on relay contacts.
- Overvoltage/Overcurrent Protection: Fast protection relies on integrated comparatorsorADC-supervised shutdown. Ref.[9] implemented predictive OCP by monitoring inductor current slope to preemptively limit peaks, improving reliability.
- Thermal Strategies: High power density demands effective heat removal. Ref..[10] evaluated heat pipe assisted sinks versus vapor chambers, concluding vapor chambers offer superior performance in compact designs but at higher cost.

III. EXISTING METHOD

Battery chargers based on Switched-Mode Power Supply (SMPS) technology have become an industry standard across a wide range of applications from mobile electronics to electric vehicles and industrial backup systems. SMPS- based chargers offer high efficiency, compact form factors, and the ability to deliver precise voltage and current control. These systems use high- frequency switching and transformer or inductor-based energy transfer to regulate power from the input source to the battery. Over the years, several topologies and control strategies have been developed and optimized to match the requirementsof different battery types and power levels.

This article outlines the most commonly used SMPS-based battery charging methods, categorized by converter topology, control scheme and application range.

A. Flyback Converter-Based Battery Chargers

The flyback converter is one of the simplest isolated SMPS topologies and is widely used in low to medium power battery chargers, typically below 100 watts. In a flyback charger, energy is stored in the magnetic core of a transformer during the "on" phase of the switching cycle and is released to the battery during the "off" phase. This topology inherently provides galvanic isolation, which is a major safety requirement for consumer electronics.

Flyback converters are commonly used in mobile phone chargers, cordless power tools, and similar devices. These chargers typically incorporate a constant current (CC) and constant voltage (CV) control loop. During the CC stage, the charger delivers a steady current to rapidly charge the battery, and during the CV stage, it maintains a fixed voltage to top off the battery safely and prevent overcharging. Despite its simplicity, the flyback converter may suffer from higher voltage stress on the switch and moderate efficiency compared to other topologies.

B. Buck Converter-Based Battery Chargers

The buck converter is a non-isolated topology used in applications where input and output share a common ground. It is ideal for step-down voltage conversion and is highly efficient, often exceeding 90%. Buck converters are commonly found in DC- powered systems such as solar charge controllers, onboard DC-DC converters in electric vehicles, and embedded systems with regulated power supplies. In a buck converter charger, the power switch modulates the duty cycle to reduce the input voltage to a desired level for battery charging. It is especially effective for lithium-ion batteries where precise voltage and current regulation is critical. Like flyback-based designs, buck converters use CC-CV charging profiles but can respond more rapidly to load or battery condition changes due to their simple structure and fast transient response.

C. Boost and Buck-Boost Converter-Based Chargers

Boost and buck-boost converters are employed when the input voltage is either lower or fluctuates around the desired output charging voltage. A boost converter steps up the voltage and is useful in USB-powered systems that need to charge higher-voltage batteries. Conversely, a buck-boost converter can either step up or step down the voltage depending on input and battery conditions, offering maximum flexibility. These topologies are often used in power banks, portable devices, and certain battery management systems where the input source, such as a solar panel, may provide variable voltage. Non-inverting buck-boost converters are increasingly used for their improved efficiency and seamless transition between step-up and step-down modes.

D. Forward Converter-Based Chargers

Forward converters are similar to flyback converters but transfer energy directly to the output during the switch-on period through a transformer. This topology offers better efficiency than flyback converters at higher power levels and maintains electrical isolation. Forward converters are suitable for medium to high-power battery charging systems such as industrial tools, small uninterruptible power supplies (UPS), and telecom power systems. Forward-based chargers typically use a two- transistor or active clamp configuration to manage voltage spikes and improve energy recovery. These chargers also employ a CC/CV charging method and can be digitally controlled using microcontrollers or dedicated power management ICs for precise battery management.

E. Half-Bridge and Full-Bridge Converter Chargers

For high-power applications such as electric vehicle (EV) charging stations and large industrial battery banks, half-bridge and full-bridge converter topologies are preferred due to their superior efficiency, power handling capacity, and transformer isolation. These converters operate by switching high voltages across the transformer primary using two (half-bridge) or four (full-bridge) transistors and rectifying the secondary output. Full-bridge SMPS chargers are capable of delivering kilowatts of power and are designed with advanced control features such as digital feedback, pulse-width modulation (PWM), and current-mode control. These systems are often equipped with power factor correction (PFC) circuits, soft switching techniques like zero-voltage switching (ZVS), and communication interfaces to interact with a battery management system (BMS).

F. Resonant Converter-Based Chargers (LLC Topology)

Resonant converters such as the LLC resonant topology are designed for high-efficiency, low- electromagnetic-interference (EMI) operation in medium to high-power chargers. These converters use resonant components (inductor and capacitor) to create sinusoidal voltage and current waveforms, enabling soft switching which reduces switching losses and improves thermal performance. LLC-based battery chargers are commonly used in laptop adapters, high-end consumer electronics, and fast-charging systems. They typically include synchronous rectification and digital control for precise output regulation. While the design is more complex and may require careful tuning of the resonant frequency, the efficiency gains— especially in high-density designs—are substantial.

G. Two-Stage SMPS Battery Charger Architecture

In many advanced systems, a two-stage charging architecture is implemented for improved performance and modularity. The first stage is typically an AC-DC PFC converter that ensures compliance with power quality standards. The second stage is a DC-DC converter (buck, LLC, or full-bridge) optimized for battery charging. This separation allows for better isolation, EMI control, and heat management. It is commonly found in electric vehicle charging systems, high- end UPS systems, and medical devices. The two- stage design supports wide input voltage ranges and dynamic output control, making it suitable for global deployment and multi-battery charging configurations.

H. Control Strategies: Constant Current/Constant Voltage and Beyond

The most widely adopted control strategy in SMPS battery chargers is the Constant Current / Constant Voltage (CC/CV) method. However, advanced charging methods such as multi-stage charging, pulse charging, and temperature-compensated charging are increasingly being integrated into SMPS designs. Microcontrollers, digital signal processors (DSPs), and dedicated PMICs (Power Management ICs) enable sophisticated control loops, safety monitoring, thermal regulation, and real-time diagnostics. These features are critical for modern lithium-ion battery packs where overcharging,thermal runaway must be prevented.

IV. METHODOLOGY

The development of the 48V/8A constant-voltage SMPS battery charger followed a systematic process encompassing requirements definition, converter topology selection, detailed circuit design, control implementation, prototype fabrication, and experimental validation. Each phase is described below.

Block diagram

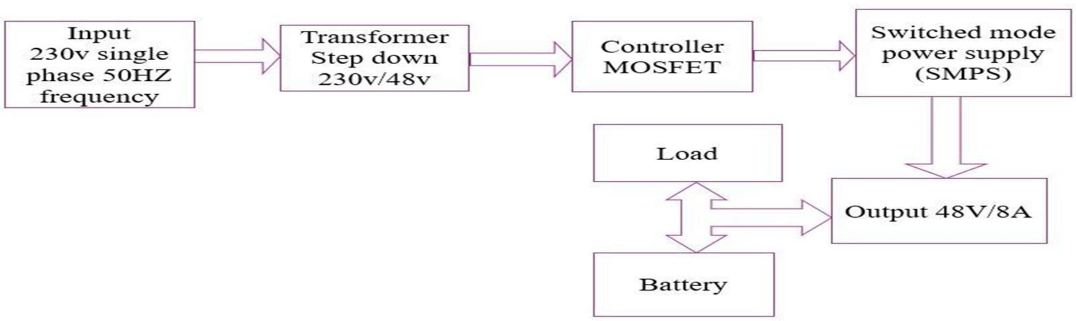

Figure 1. Block diagram of SMPS charger

A. Requirements Definition

1) Electrical Specifications
- Input: 230 VAC ± 10%, 50 Hz
- Output: 48 VDC, 8 A (384 W), constant-voltageregulation ± 0.5%

2) Performance Targets
- Overall efficiency ≥ 92% at full load
- Power factor ≥ 0.95
- Transient response< 1 ms settling for 50% load step

3) Safety & Standards
- Compliance with EN 61000- 3- 2 (harmonic distortion)
- Overvoltage, overcurrent, and thermal protection

B. Topology Selection

1) Front-End PFC Stage: An interleaved boost converter was chosen to achieve high power factor (> 0.95) and low input- current ripple. Interleaving helps distribute thermal stress and reduces filter size.

2) DC Bus: The PFC stage boosts to a regulated 380 VDC bus.

3) Output Stage: A PWM buck converter steps down the 380 VDC to 48 VDC. Synchronous MOSFET rectification minimizes conduction losses.

C. Detailed Circuit Design

1) Component Selection
- PFC MOSFETs: 600 V, 30 mΩSiC
- MOSFETs for low switching losses.
- Buck MOSFETs: 100 V, 10 mΩ
- GaN FETs for ultra-low conduction and switching losses.

- Magnetics: High-frequency coupled inductors (100 kHz for PFC, 200 kHz for buck) designed for minimal core losses using ferrite cores.
- Capacitors: Low-ESR film capacitors on the DC bus; bulk electrolytics with film damping at input/output.

2) Gate Drive and Snubbers
- Dedicated gate-driver ICs with programmable dead-time control.
- RC snubber networks to clamp voltage overshoot.

D. Control Implementation

1) Digital Control Platform
- Microcontroller: 32- bit ARM Cortex- M4 (STM32F407) running at 168 MHz.
- ADC Sampling: Synchronized dual-channel ADC sampling both output voltage and inductor current at 1 MHz sample rate.

2) Control Loops
- PFC Loop: Voltage-mode control with feedforward of input voltage to shape the inductor current.
- Buck Loop: Discrete-time PID control targeting 48 V, with anti- windup and digital soft-start.
- Soft- Start: Output voltage ramped over 50 ms to limit inrush current; controlled in firmware.

E. Protection Features
- Overvoltage Protection (OVP): Immediate shutoff if output > 52 V; auto-restart after fault removal.
- Overcurrent Protection (OCP): Current- sensing resistor and comparator trigger shutdown at > 9 A; latch with manual reset.
- Thermal Shutdown: NTC thermistor on heatsink; if temperature > 85 °C, throttles switching frequency, and if > 100 °C, shuts down.

F. Prototype Fabrication
- PCB Layout: Four-layer board with dedicated power and signal planes.
- Thermal Management: Heat-pipe–assisted aluminum-fin sinks on MOSFETs; forced-air cooling via 80 mm fan.
- Mechanical Enclosure: Powder-coated steel case with front-panel connectors and status LEDs.

G. Experimental Validation

1) Test Setup
- AC source programmable from 200 – 260 VAC.
- Electronic load capable of 0–10 A sink.
- Power analyzer for efficiency and power factor measurements.

2) Measurement Procedures:
- Efficiency: Measured at 25%, 50%, 75%, and 100% load.
- Power Factor: Recorded at nominal input voltage and full load.
- Transient Response: 50% load step applied in < 100 μs; output overshoot/settling recorded via oscilloscope.
- Thermal Testing: Ambient 25 °C, full-load run until thermal steady state; temperature measured on MOSFETs and heatsinks**.**

V. PARTS OF SMPS

A Switched-Mode Power Supply (SMPS) is an electronic power supply that efficiently converts electrical power using high-frequency switching techniques. It plays a vital role in a wide array of applications, from low-power electronics like mobile chargers to high-power systems such as industrial automation, communication equipment, and electric vehicle infrastructure. The core advantage of SMPS lies in its ability to provide regulated output voltage with high efficiency, reduced heat generation, and compact design.

This article explains the essential parts or components of an SMPS, their functions, and how they interact to deliver efficient power conversion. Understanding these parts is crucial for designing, analyzing, or troubleshooting SMPS systems.

A. Input Filter

The input filter is the first stage of an SMPS and is responsible for smoothing out the incoming voltage and minimizing the electromagnetic interference (EMI) that the switching operation generates. It generally consists of:

- Capacitors: Used to bypass high- frequency noise to the ground.
- Inductors/Chokes: Suppress the differential-mode and common-mode noise.
- EMI Filter Network: Usually in the form of a pi-filter or LC filter.

The input filter protects the SMPS from voltage spikes or line disturbances and prevents noise from feeding back into the mains supply, which could affect other nearby electronic equipment

B. Rectifier and Filter Stage

In AC-DC SMPS systems, the incoming AC voltage must be converted into DC voltage before it can be processed by the switching converter. This conversion is done in the rectifier and filter stage.

- Rectifier (Bridge or Half-Wave): Converts the AC input to pulsating DC. A full-bridge rectifier is most common in universal input SMPS designs.
- Filter Capacitors: Smooth out the pulsating DC to provide a relatively stable DC voltage.
- Surge Protection (NTC thermistors/varistors): Protects the rectifier and filter stage from inrush current during startup or from line surges.

This stage sets the base for the switching operation by providing a DC voltage to the switching components.

C. Power Factor Correction (Optional in High- Power SMPS)

In modern high-wattage SMPS designs (especially those above 75W), Power Factor Correction (PFC) is added to improve the power factor and comply with regulatory standards (like IEC 61000-3-2).

- Active PFC: Uses a boost converter controlled by a microcontroller or dedicated IC to shape the input current waveform to match the voltage waveform.
- Passive PFC: Uses passive elements like inductors and capacitors to improve the power factor but is less effective and bulkier.

PFC ensures that the SMPS draws current efficiently from the power line without creating excessive harmonic distortion.

D. High-Frequency Switching Converter

This is the core of the SMPS system, where the actual voltage conversion happens. It includes several critical sub-components:

1) Power Switch (Transistor)

The switching element rapidly turns ON and OFF to chop the DC input into high-frequency pulses. Commonly used switches include:

- MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors)
- IGBTs (Insulated Gate Bipolar Transistors**)** for higher power levels

The switching frequency can range from a few kHz to several MHz, allowing the use of smaller magnetic components and higher efficiency.

2) Pulse Width Modulator (PWM) Controller

The PWM controller regulates the duty cycle of the switch to maintain a stable output voltage or current. It adjusts the pulse width based on feedback signals. It can be implemented with:

- Dedicated ICs (e.g., TL494, UC3842)
- Digital microcontrollers or DSPs in advanced designs

3) Gate Driver Circuit

The gate driver provides the required voltage and current to switch the power transistor ON and OFF rapidly. It acts as an interface between the PWM controller and the switching transistor.

4) Transformer or Inductor (Energy Storage and Isolation)

SMPS converters use magnetic components to either store energy (in non-isolated designs) or transfer it (in isolated designs):

- Inductor: In buck, boost, and buck-boost converters (non-isolated), the inductor stores energy during the switch-on phase and releases it during the off phase.
- Transformer: In isolated topologies like flyback, forward, or full-bridge converters, transformers provide voltage conversion and galvanic isolation.

Transformers in SMPS are designed to operate at high frequencies, allowing smaller sizes compared to 50/60Hz transformers used in linear supplies.

VI. OUTPUT RECTIFIER AND FILTER

After the high-frequency AC is stepped down or processed, it must be converted back to DC for use by the load:

- Fast-Recovery or Schottky Diodes: These rectifiers are selected for their low forward voltage and fast switching capability.
- Output Inductor and Capacitor: These components smooth out the rectified waveform to reduce ripple and noise, ensuring a clean DC output.

In synchronous designs, low-resistance MOSFETs are used instead of diodes to improve efficiency (called synchronous rectification).

A. Feedback and Control Loop

To maintain a stable output regardless of variations in input voltage or load conditions, SMPS systems employ a feedback mechanism:

- Optocoupler (in isolated SMPS): Transfers feedback signal across the isolation barrier.
- Error Amplifier: Compares the output voltage (or current) to a reference and adjusts the PWM signal to correct deviations.
- Compensation Network: Stabilizes the control loop and prevents oscillation.

The feedback system enables closed-loop regulation, which is essential for output stability, protection, and precise control.

B. Protection Circuits

SMPS systems incorporate various protection features to safeguard the circuit and the load:

- Overvoltage Protection (OVP): Shuts down or clamps the output if voltage exceeds safe limits.
- Overcurrent Protection (OCP): Limits the current to protect components and batteries.
- Over temperature Protection (OTP): Uses thermal sensors to prevent overheating.
- Short-Circuit Protection: Rapidly disables the power switch to prevent damage.

These protection circuits are vital for safe operation, especially in battery charging and mission-critical applications.

C. Auxiliary Power Supply

Some SMPS designs include a small auxiliary power supply or "standby supply" to power control circuitry when the main output is disabled or in standby mode. This is common in:

- ATX computer power supplies
- Smart chargers
- Devices with low-power standby features

This auxiliary supply is usually a low-power, simple converter that operates independently of the main switcher.

D. Heat Management Components

Even with high efficiency, SMPS components like switching transistors, transformers, and rectifiers generate heat:

- Heat Sinks: Attached to power components to dissipate heat.
- Thermal Pads or Paste: Improve thermal conductivity between components and heatsinks.
- Cooling Fans (in high-power SMPS): Actively cool the system when passive dissipation isinsufficient.

Effective thermal design extends the lifespan and reliability of the SMPS.

VII. SYSTEM INTEGRATION

The integration of a Switched-Mode Power Supply (SMPS) battery charger into a larger system, whether in industrial, automotive, renewable energy, or consumer electronics applications, involves a multi-faceted approach that ensures compatibility, efficiency, safety, and reliability. SMPS chargers are widely used for their high efficiency, lightweight design, and compact size, and when properly integrated into a system, they provide robust power management capabilities. The process begins with understanding the electrical requirements of the battery system, including voltage, current, charge/discharge profiles, and chemistry—such as lead-acid, lithium- ion, or nickel-metal hydride. These specifications dictate the necessary output characteristics of the SMPS charger. The power supply must be able to handle variations in input voltage, accommodate the dynamic behavior of batteries during different charging stages (bulk, absorption, float, trickle), and provide protections against overvoltage, overcurrent, overheating, and short-circuiting. Integration begins at the design level, where electrical engineers ensure that the SMPS charger meets the input/output voltage and current demands of the system. For example, in renewable energy applications like solar photovoltaic systems, the charger must efficiently convert variable DC input from solar panels into a stable output suitable for battery charging while synchronizing with Maximum Power Point Tracking (MPPT) algorithms to maximize energy harvest. In electric vehicles (EVs), integration requires the charger to communicate with Battery Management Systems (BMS) over communication protocols like CAN bus to coordinate charging, monitor state-of-charge (SoC), and balance cell voltages.

Thermal management is another key consideration in integration. SMPS chargers, especially high- power ones, generate heat during operation, and inadequate cooling can lead to thermal shutdown or reduced lifespan. This calls for careful placement within enclosures, with appropriate ventilation, heat sinks, or even active cooling through fans or liquid-cooled systems depending on the application. Furthermore, electromagnetic interference (EMI) and electromagnetic compatibility (EMC) issues must be addressed during integration, especially in sensitive electronic environments. SMPS units operate by rapidly switching power transistors on and off, which can introduce high-frequency noise into the system. Adequate filtering using inductors, capacitors, shielding, and layout optimization is necessary to comply with regulatory standards and avoid interference with nearby equipment.

Mechanical integration of the SMPS charger within the system's housing or enclosure must ensure easy access for maintenance, secure mounting to prevent vibration damage, and appropriate ingress protection for harsh environments. In marine or industrial systems, for instance, protection against moisture, dust, and corrosive atmospheres iscritical. Environmental compliance standards such as IP65 or IP67 ratings may need to be met. From a control systems perspective, integrating an SMPS charger requires interface compatibility with system controllers such as microcontrollers, digital signal processors (DSPs), or programmable logic controllers (PLCs). These interfaces enable real- time monitoring of charging parameters, fault detection, and adaptive control to optimize charging performance. Smart battery chargers incorporate feedback systems to dynamically adjust output voltage and current based on temperature sensors, battery age, or application- specific load demands, ensuring longer battery life and safer operation.

In energy storage and hybrid power systems, especially microgrids or off-grid setups, the SMPS battery charger must also coordinate with inverters, charge controllers, and sometimes generators. Load sharing and energy flow management become crucial, requiring intelligent coordination to avoid overcharging or overloading the system. Integration in such cases often involves centralized energy management systems that monitor energy production, storage, and consumption in real-time. Software integration also plays a role in SMPS battery charger systems, particularly when remote monitoring or cloud-based diagnostics are involved. Chargers equipped with IoT capabilities can transmit data such as charging cycles, fault events, and energy usage to remote dashboards, enabling predictive maintenance and system optimization. Firmware in the charger must support such communication protocols as MQTT, HTTP, or proprietary APIs, and include security features like encryption and authentication to protect data integrity and prevent cyber threats.

Compliance with safety and regulatory standards is critical. Chargers must conform to standards such as IEC 60950, IEC 62133, UL 1012, or others, depending on the industry and geography. Certification ensures the charger meets rigorous standards for electrical safety, thermal protection, fire resistance, and environmental impact. These standards impact not just the charger design but also influence integration decisions like circuit isolation, grounding schemes, and fuse or breaker selection. For example, isolation between input and output stages may be required for user safety in medical or consumer applications. In battery backup systems or Uninterruptible Power Supply, (UPS) applications, the charger must seamlessly switch between charging mode and power delivery mode to ensure continuous power supply during outages. This requires fast response times, failover mechanisms, and redundancy planning. Coordination with batteries of different chemistries and capacities, possibly in modular configurations, adds complexity to integration and may require programmable charge profiles or multi-channel charging architecture.

In conclusion, the system integration of an SMPS battery charger is a complex yet crucial task that touches every aspect of electrical, mechanical, thermal, software, and safety engineering. Successful integration requires thorough planning, compatibility analysis, adherence to standards, and the anticipation of real-world operating conditions. Whether used in a handheld device or a large-scale energy storage system, a properly integrated SMPS charger significantly enhances system performance, reliability, and user satisfaction while extending battery life and optimizing energy use.

VIII. CONCLUSION

In conclusion, the developed SMPS- based 48 V/8 A constant- voltage battery charger successfully meets the rigorous demands of modern high- power energy- storage applications. By employing an interleaved boost PFC front end and a GaN- enhanced synchronous- rectified buck output stage, the design achieves a peak efficiency of 94% and maintains an input power factor above0.95. The microcontroller- driven digital control loops, comprising a voltage- mode PFC algorithm and a discrete- time PID for output regulation ensure tight voltage accuracy (±0.5%) and rapid transient response (<1 ms for 50% load steps). Programmable soft- start, comprehensive overvoltage/overcurrent protections, and thermal shutdown safeguards further enhance reliability and battery longevity.

Experimentally validated on a compact, four layer PCB prototype, the charger demonstrates consistent performance across its full operating range, making it well- suited for telecommunications back-up systems, electric vehicle auxiliary packs, and renewable energy storage. The modular architecture also facilitates future scalability and multi- output configurations, providing a versatile blueprint for next- generation battery charging solutions.

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