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Smart Load Management Unit for EV Charging Station

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***Abstract*— The Smart Load Management Unit (SLMU) is a microcontroller-based embedded system designed to dynamically manage and distribute electrical load across multiple Electric Vehicle (EV) charging ports, ensuring optimal power usage, grid safety, and efficiency. Initial testing using Tinkercad or Proteus simulates various charging conditions, load demands, and faults through LEDs and virtual sensors to validate system performance before hardware implementation. The Smart Load Management Unit (SLMU) enables intelligent load balancing, real-time sensing, and wireless diagnostics, making it suitable for residential, commercial, and public Electric Vehicle (EV) charging setups. By optimizing energy use and preventing overloads, it supports sustainable Electric Vehicle (EV) infrastructure and aligns with modern trends in grid modernization and renewable energy integration, with potential for future expansion to include renewable availability, time-of-day pricing, and battery health monitoring.**

***Keywords*— SLMU- Smart Load Management Unit, EVs -electric vehicles, Renewable Energy Integration, Load Balancing and Grid Optimization, Boost Converter and Inverter Simulation.**

I. INTRODUCTION

As electric vehicles (EVs) continue to shape modern transportation, charging infrastructure must evolve to manage varying power demands efficiently. Simultaneous charging of multiple EVs can cause grid overloads and energy losses, making smart load management essential [1].

This project develops a Smart Load Management Unit (SLMU) that dynamically distributes power from solar, battery, and grid sources across EV charging slots, ensuring optimal utilization and system safety.

The unit employs sensor-based feedback, PWM control, and relay logic for real-time load regulation, while components like the boost converter, inverter, and rectifier maintain stable and reliable power flow [2].

By integrating renewable energy and automation, the SLMU minimizes grid stress, prevents overloads, and enhances energy efficiency. The design is low-cost, scalable, and adaptable for smart cities, commercial hubs, and residential charging networks, supporting future IoT and smart grid integration [3].

II. ANALYSIS

The analysis from the Fig. 1 can be understood as follows:

- Solar Panel: Converts sunlight to regulated DC power through a charge controller, ensuring safe and stable charging [4].
- Battery: Stores surplus solar energy and supplies power during low generation, maintaining continuous operation.

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➢ AC Grid: Serves as a backup source, with sensors enabling smooth switching between grid and renewable inputs.
➢ AC–DC Rectifier: Converts grid AC to DC for reliable EV charging.
➢ Voltage Sensors: Monitor system voltage to detect faults or abnormal conditions .
➢ Boost Converter: Steps up and regulates voltage for efficient, stable power delivery to EV charging ports [5].

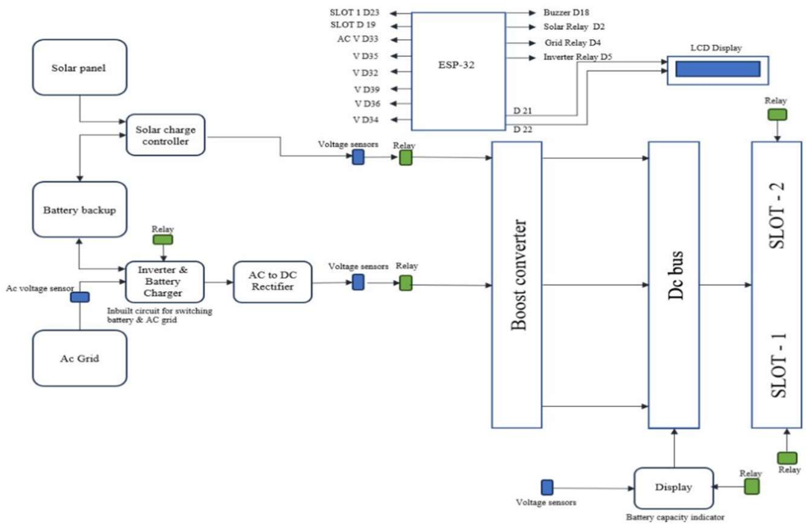

Fig. 1 Block diagram represents a Smart Load Management Unit (SLMU)

A. Transition between Sources

TABLE I. TRANSITION BETWEEN DIFFERENT SOURCE CONDITIONS

Source Condition	PV Status	Battery Status	Grid Status	Load Supply From
High sunlight	Active, MPPT	Charging	Disconnected	Solar
Low sunlight, battery full	Active (low)	Discharging	Disconnected	Battery
No sunlight, battery low	Inactive	Cut-off	Connected	Grid
Sunlight returns	Active, MPPT	Charging	Disconnected	Solar

Table I summarizes the different source conditions, PV status, battery status, grid status, and load supply.

B. Battery management functions included:

Charging control

➢ The boost converter charges the battery when PV generation exceeds load demand.
➢ Voltage and current sensors monitor battery parameters to prevent overcharging.
➢ Charging is performed in the constant-current/constant-voltage (CC–CV) region.

Discharging / backup supply

➢ When solar or grid supply is insufficient, the controller automatically switches to battery mode to maintain load continuity.
➢ The inverter converts the battery's DC output to AC for the load.

Protection and monitoring

➢ The control system supervises battery voltage thresholds (cut-off and float levels).
➢ Battery status (charging/discharging) is used for decision-making in source transition logic.

Integration with MPPT and grid

➢ MPPT ensures maximum PV utilization first.
➢ Excess PV energy is used to charge the battery.
➢ If the battery is full and PV remains active, surplus may be routed to grid/load.
➢ When PV is low, the battery discharges until its lower limit, then the grid supports the load.

III. METHODOLOGY

The system follows a modular structure combining renewable integration, smart control, and safety features.

A. Renewable Energy Integration

A solar panel supplies clean energy regulated by sensors, while a battery bank stores excess power and supports charging during low sunlight.

B. Smart Load Management

Current and voltage sensors monitor load conditions, and relay-based switching with threshold logic manages EV charging dynamically to prevent grid stress.

C. IoT & Monitoring

Wi-Fi or GSM modules enable real-time data logging, remote scheduling, and fault alerts for efficient system supervision.

D. Safety Features

Includes overload and short-circuit protection, surge suppression, and user authentication to ensure safe and reliable operation [6]-[7].

IV. SIMULATION CIRCUITS

A. Solar Panel

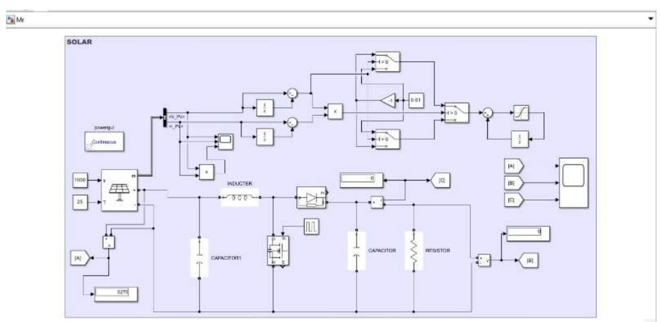

Fig.2 Simulation of Solar Panel

The model shown in the Fig.2 simulates how solar energy is converted and conditioned for use. The solar panel generates DC power from sunlight, while MPPT logic adjusts the PWM duty cycle for maximum efficiency. A boost converter increases the output voltage, and capacitors smooth fluctuations for stable delivery. Control blocks regulate voltage and current, ensuring consistent power output.

B. Inverter

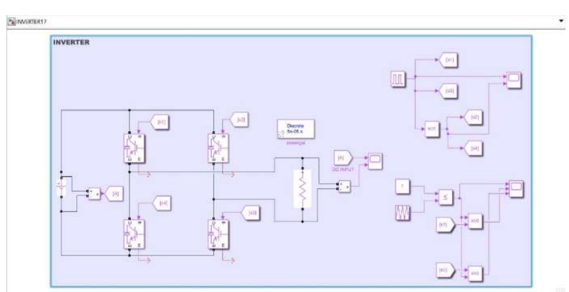

Fig. 3 Simulation of Inverter Block

The inverter as in Fig.3 converts DC input into AC output using PWM-controlled switching. An H-bridge inverter with four switches (S1–S4) alternates current flow to produce AC. Control logic manages switching to prevent short circuits and form the desired waveform, while monitoring tools track voltage and current for performance analysis.

C. Boost Converter

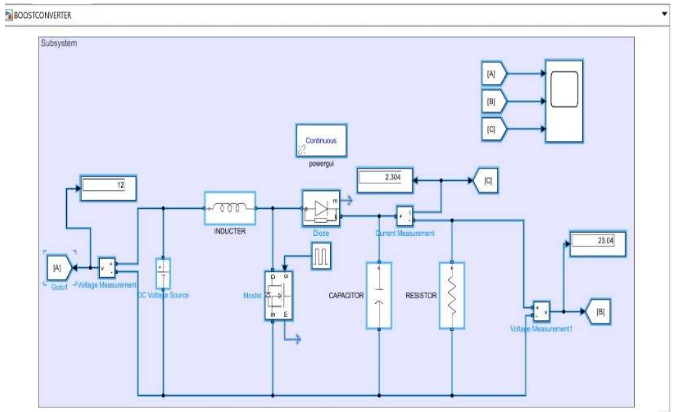

Fig. 4 Simulation of Boost Converter Block

The boost converter model as shown Fig.4 represents energy transfer and voltage step-up using an inductor, MOSFET, diode, and capacitor. The MOSFET, driven by a pulse signal, controls charging and discharging cycles, while the diode ensures one-way current flow. The capacitor smooths ripples, providing a stable boosted output around 23 V for the load.

V. QUANTITATIVE ANALYSIS

A. Inverter Efficiency

$$\text{Measured } V_{DC} = 50.0 \text{ V.}$$

Measured DC input current from the simulator: $I_{DC,\text{avg}} = 1.10$ A.

$$P_{DC,in} = V_{DC} \times I_{DC,\text{avg}}$$
$$P_{DC,in} = 50.0 \times 1.10 = 55.0 \text{ W.}$$

Measured AC real power from simulator: $P_{AC,out} = 49.5$ W.
Efficiency:

$$\eta_{\text{inv}} = \frac{49.5}{55.0} \times 100\% = 90.0\%.$$

Inverter loss:

$$P_{\text{loss,inv}} = 55.0 - 49.5 = 5.5 \text{ W.}$$

B. Boost Converter

$$P_{\text{out}} = V_{out} \times I_{out} = 22 \times 2.5 = 55.0 \text{ W}$$

$$P_{\text{in}} = \frac{P_{\text{out}}}{\eta_{\text{boost}}} = \frac{55.0}{0.94} = 58.51 \text{ W}$$

$$P_{\text{loss}} = P_{\text{in}} - P_{\text{out}} = 58.51 - 55.0 = 3.51 \text{ W}$$

*The boost converter (12 V → 22 V, 55 W) operates with low ripple and standard MOSFET–diode components. Typical efficiency ranges 92–96%, so a practical midpoint of 94% is assumed for analysis.

C. Regulation

V_"full-load" =22.0" V" (boost output under 2.5 A)
V_"no-load" =22.6" V" (typical light-load rise consistent with ±3% claim)

$$\text{Voltage Regulation (\%)} = \frac{V_{\text{no-load}} - V_{\text{full-load}}}{V_{\text{full-load}}} \times 100\%$$

$$\text{Regulation} = \frac{22.6 - 22.0}{22.0} \times 100\% = \frac{0.6}{22.0} \times 100\% = 2.73\%.$$

D. THD Calculations for Inverter

RMS voltage $V_1 = 50$ V (±50 V square/PWM).
THD $= 0.09$.
Inverter DC input $P_{DC,in} = 55.0$ W and inverter loss baseline $P_{\text{loss}} = 5.5$ W
harmonic RMS voltage

$$V_h = \text{THD} \times V_1 = 0.09 \times 50 = 4.5$$

total RMS voltage (including harmonics)

$$V_{\text{rms,total}} = V_1\sqrt{1 + \text{THD}^2} = 50\sqrt{1 + 0.09^2} = 50 \times 1.00405 \approx 50.2025 \text{ V}.$$

distortion power factor

$$\text{PF}_{\text{dist}} = \frac{1}{\sqrt{1 + \text{THD}^2}} \approx \frac{1}{1.00405} \approx 0.9960.$$

VI. Results and Discussions

A. Solar Panel Simulation

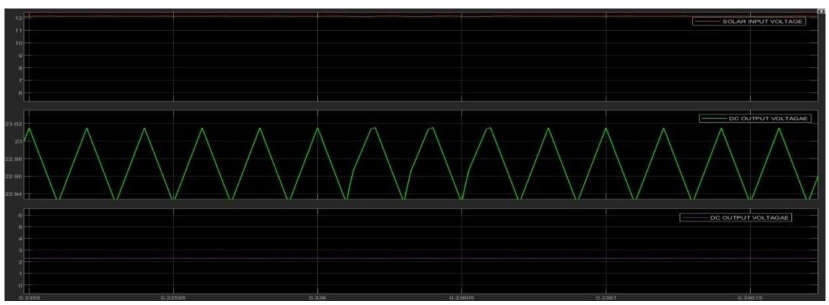

Fig. 5 Solar Panel Simulation Output Waveform

It can be seen in the Fig. 5 that the solar input remains steady at about 12 V DC, while the boost converter raises it to around 23 V with minor ripple, confirming proper operation. After filtering, the output becomes stable, indicating effective voltage regulation.

B. Inverter Simulation

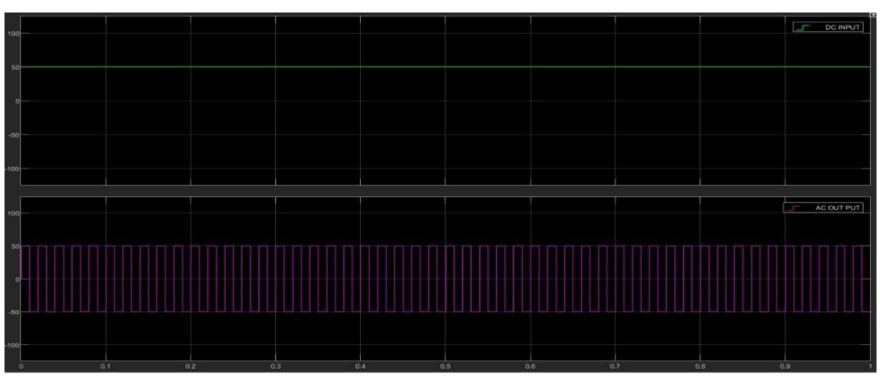

Fig. 6 Inverter-1 Simulation Output Waveform

The Fig. 6 illustrates how the inverter converts a stable +50 V DC input into an AC square wave output oscillating between +50 V and −50 V, confirming proper DC–AC conversion with consistent switching with the efficiency of 90% and inverter loss of 5.5w.

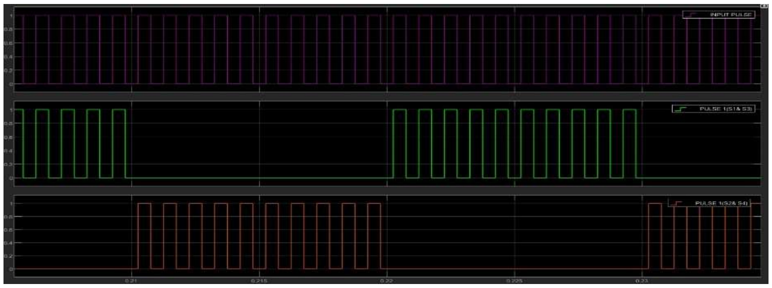

Fig: 7 Inverter-2 Simulation Output Waveform

The PWM pulses control the inverter switches, where S1 & S3 generate the positive half-cycle and S2 & S4 produce the negative half-cycle, forming the AC output waveform that is depicted in the Fig. 7.

C. Boost Converter Simulation

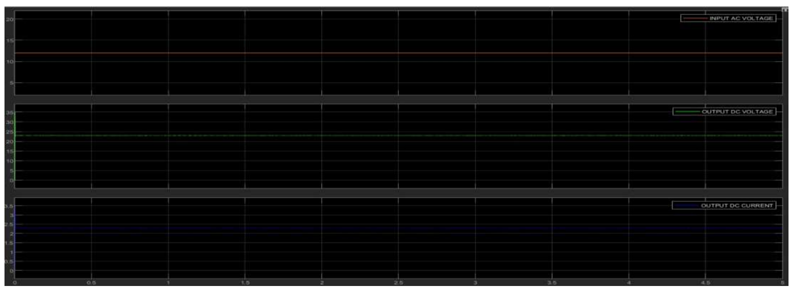

Fig. 8 Boost Converter Simulation Output Waveform

The Fig. 8 shows that the input AC voltage remains steady at about 13 V, while the output DC voltage is well-regulated around 21–22 V with minimal ripple. A nearly constant 2.5 A output current confirms smooth and stable charging performance with the efficiency of 94% and conversion loss of 3.51W.

VII. CONCLUSIONS

This project develops a Smart Load Management Unit (SLMU) for efficient and safe EV charging without a microcontroller, using sensor feedback, PWM control, and relay logic to regulate load in real time. It dynamically allocates charging slots to prevent overload and integrates renewable energy through a boost converter and inverter for stable power. The system is low-cost, reliable, and scalable, with future scope for IoT monitoring and PLC-based automation.

Key Simulation Features:

- PWM signals correctly control inverter switches (S1 & S3 alternate with S2 & S4).
- Relay circuits switch loads based on time slots and availability.
- Boost converter raises solar voltage to required DC level.
- Inverter provides stable square-wave AC output.
- Logic timing ensures safe, shoot-through-free operation.

Future Scope:

- IoT integration for remote monitoring and slot booking.
- PLC-based control for modular, programmable expansion.
- Suitable for residential, parking, and industrial EV charging setups.

This paper presents a low-cost, microcontroller-free EV charging system using analog and digital logic for efficient load control, renewable integration, and safe operation, paving the way for modular, smart grid-ready solutions.

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