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Review Article

ANALYSIS AND DESIGN OF A STANDALONE ELECTRIC VEHICLE CHARGING STATION SUPPLIED BY PHOTOVOLTIAC ENERGY

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ABSTRACT
Independently of the power grid, drawing clean energy directly from sunlight while ensuring uninterrupted charging even when solar energy is unavailable. This project demonstrates a compact, standalone photovoltaic-based electric vehicle (EV) charging station that integrates direct solar charging and battery-assisted charging within a single system. The design showcases how solar energy can be efficiently captured, stored, and utilized to supply EV loads in a controlled and reliable manner. The complete energy flow and operation of the system are explained through the following stages.

Keywords: *Photovoltaic Charging, Solar EV Infrastructure, Battery Energy Storage, Off-Grid Power System, Renewable Energy Integration, Sustainable Transportation.*

1. INTRODUCTION

In an era where sustainable transportation and clean energy solutions are no longer optional but essential, the development of renewable-powered electric vehicle (EV) charging infrastructure has become a critical research focus. As EV adoption accelerates globally, the demand for reliable, environmentally friendly, and grid-independent charging systems continues to grow. This project explores the design and implementation of a standalone electric vehicle charging station powered exclusively by photovoltaic (PV) energy.

The proposed system is designed to harness solar energy and utilize it efficiently for EV charging through both direct and stored energy pathways. The process begins with the conversion of solar radiation into electrical energy using a photovoltaic panel, which serves as the primary energy source. During periods of sufficient sunlight, the generated power is supplied directly to the load, representing real-time EV charging. Simultaneously, excess solar energy is stored in a lithium-ion battery through a regulated charging process.

To ensure uninterrupted operation during low or no sunlight conditions, the stored energy is later supplied to the load through a battery-assisted charging path. The integration of direct solar utilization and energy storage within a single system enhances reliability, efficiency, and adaptability. This compact and scalable approach demonstrates the fundamental working principles of real-world standalone EV charging stations while promoting sustainable energy utilization.

2. LITERATURE

The development of electric vehicle (EV) charging infrastructure has evolved alongside the rapid growth of electric mobility. Early EV charging solutions were predominantly grid-connected, relying on conventional electrical networks to supply power for vehicle charging. These grid-based charging stations offered reliability and ease of deployment in urban areas; however, they significantly increased grid load and indirectly depended on fossil fuel–based electricity generation. To reduce grid dependency, researchers explored renewable energy–assisted EV charging stations, particularly those powered by photovoltaic (PV) systems. Initial implementations focused on grid-tied PV charging stations, where solar panels supplemented grid power during daylight hours. While these systems reduced operational costs and emissions, they remained vulnerable to grid outages and did not fully eliminate reliance on conventional power sources.

Standalone photovoltaic-based EV charging stations emerged as an alternative solution, especially for remote and off-grid regions. These systems utilize solar panels combined with energy storage units to supply EV charging power independently. However, many early standalone designs were complex, incorporating multiple power electronic converters, sophisticated control algorithms, and high-capacity energy storage systems, making them costly and difficult to maintain.

Small-scale and experimental models have also been proposed for educational and research purposes. These prototypes demonstrated the feasibility of solar-powered EV charging using simplified architectures. Nevertheless, limitations such as inefficient energy utilization, inadequate storage integration, and lack of seamless transition between direct and stored energy modes were commonly observed.

Previous solutions often suffer from the following limitations:

Intermittent Energy Availability: Solar power generation varies with irradiation levels, leading to unstable charging performance without proper energy management.

Limited Energy Storage Integration: Inadequate or inefficient storage systems restrict charging continuity during low sunlight conditions.

Conversion Losses: Multiple power conversion stages introduce losses, reducing overall system efficiency.

High Complexity and Cost: Advanced systems with sophisticated converters and controllers increase cost and reduce accessibility for small-scale deployment.

Poor Scalability for Educational Use: Many designs are unsuitable for academic demonstration due to complexity or high-power ratings.

TECHNOLOGICAL TRENDS

Recent advancements in renewable energy systems and power electronics have significantly improved the feasibility and performance of standalone photovoltaic-based EV charging stations.

1. Advancements in Photovoltaic Technology

Modern photovoltaic panels offer higher conversion efficiencies, improved durability, and reduced costs. The use of monocrystalline and polycrystalline PV modules has enhanced energy harvesting capabilities, making solar-powered charging more practical even at small scales.

2. Solar Charge Controllers and Battery Management

The development of dedicated solar charge controllers for lithium-ion batteries has simplified energy storage integration. Controllers such as constant current–constant voltage (CC-CV) chargers provide regulated charging, overcharge protection, and reverse current prevention, ensuring battery safety and longevity.

3. Lithium-Ion Energy Storage Systems

Lithium-ion batteries have become the preferred choice for EV-related applications due to their high energy density, fast charging capability, and long cycle life. Compact battery configurations enable efficient storage of solar energy for later use, ensuring uninterrupted charging operation.

4. Direct and Indirect Energy Utilization

A growing trend in system design is the dual-mode operation of EV charging stations. Direct utilization of solar energy during peak sunlight hours minimizes storage losses, while battery-assisted charging ensures continuity during reduced solar availability. This hybrid operational strategy improves overall efficiency and reliability.

5. Efficient DC Power Distribution

Modern EV charging architectures emphasize DC-based power distribution to minimize conversion losses. Supplying DC loads directly from solar panels or batteries eliminates unnecessary DC–AC–DC conversion stages, improving system efficiency.

6. Modular and Scalable Designs

There is an increasing emphasis on modular system architectures that allow easy scaling and customization. Modular PV panels, batteries, and load sections enable system expansion based on demand and simplify maintenance and upgrades.

7. Integration of Smart Monitoring

Although optional in small-scale systems, microcontrollers and IoT platforms are increasingly used for monitoring voltage, current, and system status. Features such as data logging, fault detection, and remote monitoring enhance reliability and user awareness.

RELEVANT STUDIES

Numerous studies have contributed to the advancement of photovoltaic-based EV charging technologies.

1. Standalone Photovoltaic EV Charging Systems

Several researchers have analyzed and implemented standalone PV-powered EV charging stations, focusing on energy balance, storage sizing, and charging reliability. Studies highlight the importance of proper coordination between solar generation, energy storage, and load demand to ensure stable charging performance.

2. Energy Storage Sizing and Management

Research has shown that optimal sizing of energy storage systems significantly improves charging station performance. Studies emphasize balancing storage capacity with solar availability to reduce cost while maintaining reliability.

3. Power Flow and Energy Management Analysis

Analytical approaches have been proposed to model power flow between PV panels, storage batteries, and EV loads. These analyses help determine system efficiency, charging duration, and energy availability under varying solar conditions.

4. Simplified Charging Station Architectures

Recent academic work has focused on simplifying EV charging station designs for educational and low-power applications. These studies demonstrate that even small-scale prototypes can effectively illustrate real-world charging principles when designed appropriately.

5. Experimental and Laboratory Prototypes

Universities and research institutions have developed laboratory-scale PV-based EV charging models to validate theoretical concepts. These prototypes use LEDs, DC motors, or resistive loads to represent EV batteries and auxiliary loads, providing valuable experimental insights.

6. Reliability and Safety Considerations

Studies on lithium-ion battery integration emphasize the importance of regulated charging, thermal management, and protection mechanisms. Proper charge control significantly reduces battery degradation and enhances system safety.

7. Applications in Remote and Off-Grid Areas

Research consistently highlights the suitability of standalone PV EV charging stations for rural electrification, remote transportation hubs, and emergency power scenarios. These systems reduce reliance on fossil fuels and improve energy accessibility.

RESEARCH GAP AND PROJECT MOTIVATION

Despite extensive research on photovoltaic-based EV charging stations, most existing solutions focus on high-power, grid-scale implementations. Limited attention has been given to compact, low-cost, and educationally oriented prototypes that clearly demonstrate both direct solar charging and battery-assisted charging within a single system.

Additionally, many experimental models lack clear operational transparency, making it difficult for students and researchers to understand real-world charging behaviour. There is a need for a simplified yet realistic standalone PV EV charging system that balances technical accuracy with practical implementation.

This project builds upon existing research by presenting a low-power, laboratory-scale standalone photovoltaic EV charging station that integrates direct and stored energy operation. By focusing on simplicity, clarity, and efficiency, the proposed system addresses key limitations of previous solutions while serving as an effective educational and experimental platform.

SYSTEM DESIGN AND ARCHITECTURE

The proposed system is a standalone photovoltaic-based electric vehicle (EV) charging station designed to operate independently of the electrical grid. The system harnesses solar energy as the primary power source and efficiently manages energy flow to support both direct charging and battery-assisted charging modes. The architecture integrates renewable energy generation, regulated energy storage, and controlled load operation to ensure reliable and continuous charging performance.

At the core of the system is a photovoltaic (PV) solar panel that converts solar radiation into direct current (DC) electrical energy. Since solar energy availability is inherently variable due to environmental conditions, the system incorporates an energy storage unit to ensure uninterrupted operation. A solar charge controller regulates the charging process of a lithium-ion battery, protecting it from overcharging and reverse current flow while maximizing energy utilization.

During periods of sufficient solar irradiation, the generated power is supplied directly to the load through a controlled switching arrangement, representing real-time EV charging. Simultaneously, excess solar energy is stored in the battery. When solar power is unavailable or insufficient, the stored energy is delivered to the load through the battery-assisted charging path. LEDs and a DC fan are used as representative EV and auxiliary loads to demonstrate system behaviour.

The integration of direct solar utilization and battery-based energy supply creates a seamless energy flow from generation to consumption. The system is designed to be modular and scalable, allowing future expansion in terms of power capacity, monitoring features, or real EV battery charging applications.

HARDWARE COMPONENTS

1. Photovoltaic (PV) Solar Panel

Function: Converts solar energy into DC electrical power.

Specifications:

Power Rating: 5 W

Output Type: DC

Considerations:

- Acts as the primary energy source for the system.
- Output varies with solar irradiation and environmental conditions.
- Supplies power for both direct load operation and battery charging.

2. Solar Charge Controller (CN3065)

Function: Regulates the charging of the lithium-ion battery using solar power.

Specifications:

- Designed for lithium-ion battery charging
- Constant current–constant voltage (CC–CV) charging profile

Features

- Overcharge protection
- Reverse current protection
- Efficient energy transfer from solar panel to battery

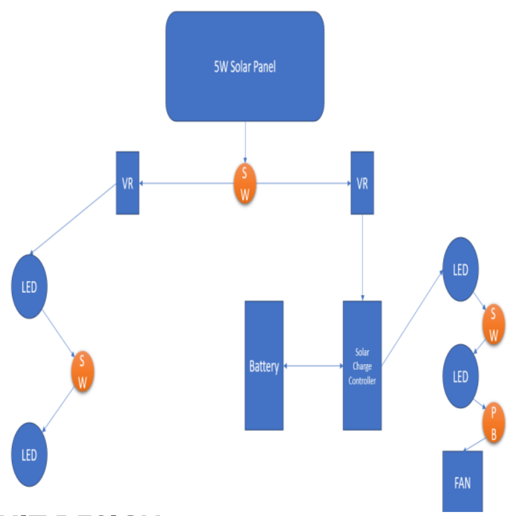
Considerations

Ensures battery safety and long operational life.

3. Lithium-Ion Battery (18650 Cell)
Function: Stores electrical energy for use during low or no sunlight conditions.
Specifications:
Nominal Voltage: 3.7 V
Capacity: 2500 mAh
Considerations:
Acts as an energy buffer to ensure uninterrupted charging.
A permanently connected LED serves as a power indicator, confirming battery availability.
4. Direct Load Section
Function: Demonstrates real-time utilization of solar energy.
Components:
2 × 1 W LEDs
Control Switch (SW)
Operation:
Powered directly from the solar panel during sufficient sunlight.
Advantages:
Eliminates storage-related energy losses.
Improves overall system efficiency.
5. Indirect Load (Battery-Assisted) Section
Function: Represents EV charging and auxiliary loads powered from stored energy.
Components:
2 × 1 W LEDs
1 × 1 W DC Fan
Switches (SW) and Push Button (PB)
Operation:
Powered by the lithium-ion battery during insufficient solar availability.
Purpose:
Demonstrates continuity of operation using stored solar energy.
6. Switching and Control Elements
Switches (SW):
Used to control direct and indirect load operation.
Push Button (PB):
Enables momentary control of selected loads.
Purpose:
Simulates real-world EV charging control and user interaction.
7. Indicator Elements
Power Indicator LED:
Turns ON immediately upon battery insertion.
Confirms system readiness and battery presence.
Load Indicator LEDs:
Visually represent power flow and operational modes.

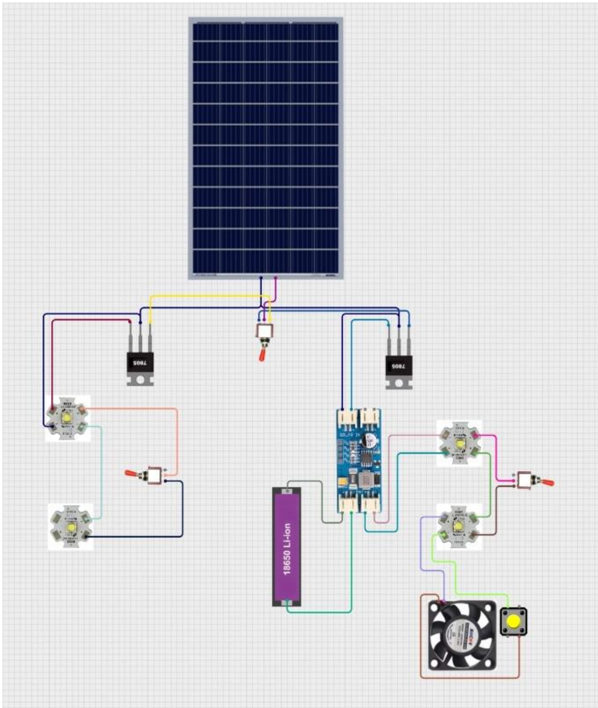
BLOCK DIAGRAM OF THE PROPOSED SYSTEM

[Solar Energy]
↓
[Photovoltaic Panel]
↓
┌──────────────────────┐
│ Direct Load Path │
│ (Solar → SW → 2×1W LEDs) │
└──────────────────────┘
↓
[CN3065 Solar Charge Controller]
↓
[18650 Li-ion Battery, 2500 mAh]
↓
┌──────────────────────┐
│ Indirect Load Section │
│ (2×1W LEDs + 1W DC Fan) │
│ Controlled by SW & PB │
└──────────────────────┘



CIRCUIT DESIGN

The circuit design integrates the photovoltaic panel, solar charge controller, lithium-ion battery, and load sections into a unified system. The design enables two operational modes: direct solar-powered load operation and battery-based load operation. Proper switching elements are .incorporated to control power flow and simulate real-world EV charging behaviour.



Future Enhancements

This section outlines possible improvements and extensions to the proposed standalone photovoltaic-based electric vehicle (EV) charging station. These enhancements aim to improve efficiency, scalability, reliability, and practical applicability while building upon the existing system architecture.

1. Integration of Maximum Power Point Tracking (MPPT)

Future versions of the system can incorporate a Maximum Power Point Tracking (MPPT) controller to improve solar energy harvesting efficiency. MPPT allows the photovoltaic panel to operate at its optimal voltage and current point under varying irradiation conditions, thereby maximizing energy extraction and reducing charging time.

2 Increased Power and Energy Storage Capacity

The system can be scaled by:

- Using higher wattage photovoltaic panels
- Adding multiple lithium-ion batteries in series or parallel
- This enhancement would allow the charging station to handle higher loads and operate for longer durations during low sunlight conditions, bringing it closer to real EV charging applications.

3 Real EV Battery Charging Interface

Future implementation may include:

- Dedicated EV charging connectors
- Proper voltage and current regulation suitable for EV batteries

This would enable direct charging of light electric vehicles such as e-bikes or electric scooters.

4. Smart Monitoring and Data Logging

The integration of a microcontroller and sensors would enable:

- Real-time monitoring of voltage, current, and battery state of charge
- Data logging for performance analysis
- Display or mobile-based system status indication
- Such enhancements improve system visibility and operational control.

5. IoT-Based Remote Monitoring

- By incorporating IoT platforms, the system can support:
- Remote monitoring of charging status
- Fault detection and alert notifications
- Cloud-based data storage and analysis
- This is particularly useful for unattended or remote installations.

6.Automated Load Management

- Future designs may include:
- Automatic load switching based on battery voltage levels
- Protection-based load disconnection during low battery conditions
- This would enhance system reliability and battery protection.

7. Improved Safety and Protection Features

- Additional safety mechanisms such as:
- Fuses and circuit breakers
- Thermal sensors
- Enhanced enclosure designcan be implemented to support higher power levels and long-term operation.

8. Modular and Portable Design

The system can be redesigned into a compact, modular unit that is:

- Easy to transport
- Suitable for rural and emergency applications
- Expandable based on energy demand

CONCLUSION

This project successfully demonstrates the analysis, design, and implementation of a standalone electric vehicle charging station powered by photovoltaic energy. The developed prototype effectively integrates solar energy generation, regulated energy storage, and controlled load operation within simple and reliable system architecture. The system operates in both direct solar charging and battery-assisted charging modes, ensuring efficient utilization of renewable energy and uninterrupted power availability under varying sunlight conditions. The use of a solar charge controller and lithium-ion battery ensures safe and stable energy storage, while visual indicators and controlled loads provide clear demonstration of system operation.

Although the system is implemented at a low power level, it accurately represents the working principles of real-world standalone EV charging stations. The experimental results validate the feasibility of using solar energy as a sustainable and grid-independent source for EV charging applications.

The project serves as an effective educational and experimental platform for understanding renewable energy integration, energy storage management, and dual-mode charging operation. With further enhancements such as MPPT integration, increased capacity, and smart monitoring, the proposed system can be extended toward practical EV charging solutions suitable for rural, off-grid, and sustainable mobility applications.

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