INDIAN INSTITUTE OF INFORMATION TECHNOLOGY

Topic:

ELECTRIC VEICHLE CHARGING USING SOLAR CELLS

SUBMITTED BY-

1. OM TAMBE(IEC2023125)
2. ABHINAV KUMAR(IEC2023119)
3. VISHAL PANDEY(IEC2023114)
4. HARSH MARKAM(IEC2023116)
5. MOHIT RATHWA(IEC2023098)

SUBMITTED TO-

DR. ASHUTOSH KUMAR SINGH

ABSTRACT

Air pollution continues to pose a severe threat to public health and the environment, as emphasized by the World Health Organization (WHO), which attributes millions of premature deaths annually to poor air quality. In response, the global transportation sector is witnessing a paradigm shift toward emission-free and environmentally sustainable mobility solutions. Electric vehicles (EVs) have emerged as a viable alternative to internal combustion engine (ICE) vehicles, offering zero tailpipe emissions and enhanced energy efficiency. This transition is evident from the 43% surge in EV sales between 2019 and 2020, with forecasts estimating global sales to reach 14 million units by 2025.

However, widespread adoption of EVs still faces several challenges. These include high battery costs, limited driving range, long charging times, and concerns regarding the overall reliability and life cycle of EV systems. To address these limitations and promote cleaner energy ecosystems, the integration of renewable energy sources (RESs)—notably solar, wind, and biomass—into EV charging infrastructure is gaining momentum. Among these, **photovoltaic (PV) solar energy** stands out due to its abundance, scalability, declining installation costs, and low maintenance requirements.

This paper focuses on the role of **PV solar-based charging systems for EVs**, evaluating ONLY **standalone (off-grid)** configuration. It highlights the advantages of solar EV charging systems, such as lower operational costs, reduced load on electrical grids during peak hours, and improved environmental performance.

In addition, **battery modeling and power electronic interfaces**—such as DC-DC converters with MPPT (Maximum Power Point Tracking), AC-DC rectifiers, and bidirectional inverters—are analysed for their roles in optimizing system performance and ensuring seamless power exchange. The paper underscores the need for **advanced charging management systems** that can intelligently regulate charging schedules, extend battery life, and adapt to variable PV output and grid conditions.

Finally, the paper outlines **future research directions**, which include the development of **AI-based control algorithms**, **wireless charging integration**, **fast-charging infrastructure expansion**, **material innovation for power electronics**, and **multi-vehicle compatibility enhancements**. These advancements are crucial to achieving a reliable, efficient, and user-friendly EV charging ecosystem powered by renewable energy.

By consolidating recent technological developments and proposing future improvements, this comprehensive review serves as a valuable resource for researchers, engineers, and policymakers aiming to accelerate the deployment of sustainable EV charging systems integrated with PV solar technology.

LITERATURE REVIEW

The accelerating adoption of electric vehicles (EVs) across the globe has prompted a critical need for innovative, scalable, and sustainable charging infrastructure. One of the most promising pathways identified by recent research is the integration of solar energy into EV charging systems. Solar-based EV charging stations not only support environmental sustainability but also contribute to energy independence by reducing dependence on fossil fuel-based grid electricity. The reviewed literature reflects a convergence of technological advancement, control strategies, feasibility planning, and policy implications, all pointing toward a smarter and greener future for EV mobility.

Early studies on solar-powered EV stations emphasize the importance of clean and renewable energy sources in minimizing the carbon footprint of transportation. System architectures commonly feature photovoltaic (PV) panels coupled with DC-DC boost converters, energy storage units, and smart grid interfaces. For instance, several prototypes have demonstrated the efficacy of using 250W–500W solar modules connected via voltage regulation and auto-cutoff circuits to maintain a steady, safe, and efficient charging process. These designs often include digital monitoring components to enhance operational reliability and user awareness.

A major advancement in the field is the use of **multiport DC-DC converters**, which enable seamless power flow from multiple sources such as solar PV, battery energy storage systems (BESS), and the utility grid. Research highlights that these converters, when equipped with closed-loop Proportional-Integral (PI) control and Maximum Power Point Tracking (MPPT) algorithms, can intelligently manage energy distribution based on real-time conditions. For example, power is primarily drawn from solar panels during peak irradiance, while the BESS supports EV charging under cloudy conditions or at night. In critical grid-stress scenarios, the converter can route excess energy back to the grid, demonstrating bidirectional functionality and flexible energy management.

The control optimization of power conversion systems further enhances charging station performance. In particular, **Dual Active Bridge (DAB)** converters are receiving attention for their high efficiency, low harmonic distortion, and modular design. Studies demonstrate that careful tuning of voltage and current control loops, supported by simulation and experimental validation, significantly improves the system's dynamic response and waveform quality. Moreover, the integration of flywheel storage and advanced harmonic mitigation strategies offers additional resilience against fluctuations in load and power supply.

In the Indian context, the feasibility of large-scale deployment of EV charging infrastructure has been analysed with respect to existing grid limitations, economic factors, and urban planning constraints. The literature stresses the importance of **strategic location planning** to minimize power system losses and optimize user accessibility. Tools such as Genetic Algorithms and Particle Swarm Optimization are used to identify optimal sites for public and semi-private charging stations. Cost estimation studies reveal that while DC fast chargers require higher initial investment, economies of scale and growing market competition are expected to bring costs down over time. Moreover, multi-charger installations can significantly reduce labour and infrastructure overheads .

As EV penetration increases, **smart energy management** becomes indispensable for maintaining grid stability. Research suggests leveraging off-peak charging windows, typically during night or midday low-demand periods, to reduce stress on the distribution network. Smart grid frameworks enable two-way communication between utilities and consumers, facilitating real-time demand-side management. Additionally, **Vehicle-to-GRID (V2G)** capabilities allow EVs to act as distributed energy resources, supporting frequency regulation and grid resilience. Aggregators managing charging stations or battery swapping stations can optimize their participation in day-ahead markets and ancillary services, maximizing both operational efficiency and economic returns.

Case Study: Solar-Powered Charging in Indian Cities

EV Charging Infrastructure in Prayagraj

Prayagraj hosts several EV charging stations, catering to both two-wheelers and four-wheelers. Notable charging stations include:

- **IOCL - Airport Charging Station**: Located near the airport, this station offers AC Type 2 charging facilities.
- **Tata Power - Zikra Hotels & Restaurants, Civil Lines**: A private charger providing AC Type 2 charging, situated in the Civil Lines area.
- **HPCL - Prabhavati Charging Station**: Located in Post-Khunta, Tehsil-Meja, this station offers Bharat AC001 charging.
- **HPCL - Hamara Charging Station**: Situated in Purushottampur Urf Garapur, Tehsil - Phulpur, providing Bharat AC001 charging.
- **Ather-Prayagraj Charging Station**: Located at 4, Sardar Patel Marg, Behind SBI Bank, Civil Lines, this station caters to Ather electric scooters.

Electric Vehicle Registrations in Prayagraj

The adoption of electric vehicles in Prayagraj has been on the rise:

- **Total EV Registrations**: In 2021, 2,686 electric vehicles were registered. This number more than doubled in the first 10 months of 2022, reaching 5,417 registrations.
- **E-Rickshaws**: Private e-rickshaws dominate the EV segment, with 7,222 registered between 2021 and October 2022. Government e-rickshaw registrations also increased from 59 in 2021 to 145 in the first 10 months of 2022.
- **Electric Two-Wheelers**: Registrations of electric bikes and scooters saw a significant increase, from 39 in 2021 to 491 in the first 10 months of 2022.

A 2021 study by Singh et al. designed an off-grid PV-EV station for six Indian cities, revealing key insights:

City	Annual Energy (kWh)	CO_2 Reduction (tons/year)
Bengaluru	14,410	7.95
Delhi	13,200	7.30
Tawang	10,920	6.15

- **Economic Analysis**:
  - Lifetime cost: ₹4.05/km (monocrystalline) vs. ₹5–7/km for gasoline[1].
  - Payback period: 6–8 years, driven by fuel savings and low maintenance[1][2].
- **Challenges**:
  - Space requirements: Off-grid systems need 16× more area than grid-tied alternatives[1].
  - Intermittency: Cloud cover in cities like Tawang reduces efficiency by 15–20%[1].

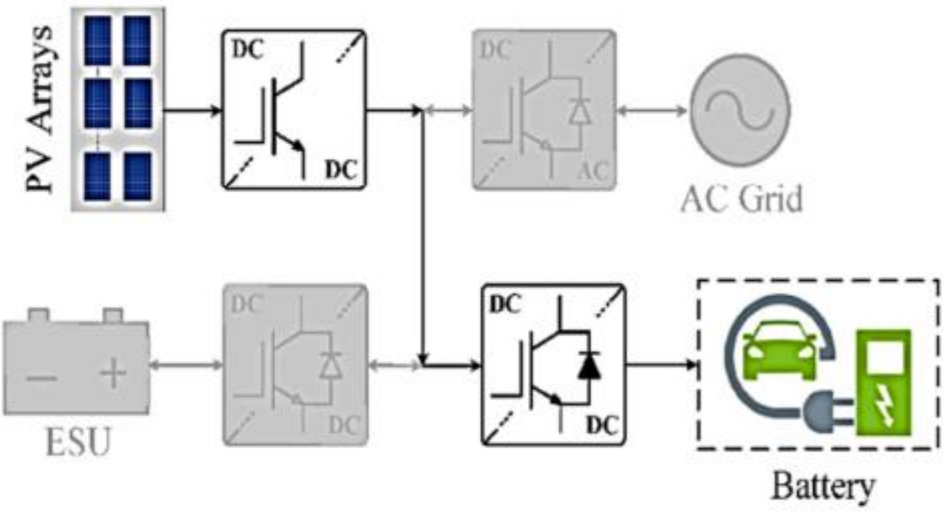
Cost-Benefit Analysis

Component	Cost (INR)
8.1 kWp PV Array	3,00,000
Lithium-ion Battery	5,00,000
Installation	1,50,000

- **Savings**: Avoided fuel costs (₹7–10/km) and grid electricity (₹6–8/kWh) offset upfront investments[1][2].

• Off-Board Charging Systems: 1. Public Charging Stations: These are publicly accessible charging stations and are often located in places such as gas stations, public parking lots, shopping malls, and other public areas. Public charging stations usually provide high-power direct current (DC) charging and low-power alternating current (AC) charging. 2. Rapid Charging Stations: These stations provide high-power DC charging, allowing vehicles to recharge much more quickly than standard charging stations. They are ideal for long trips and are often located along highways. 3. Induction Charging: This technology allows an electric vehicle to be recharged wireless, using electromagnetic fields. The vehicle must be placed on top of a special charging plate installed in the ground. Induction charging is still under development but promises greater convenience. 4. Home Charging Stations: These stations are installed in private homes and allow electric vehicle owners to charge their vehicles at night or when they are at home. They can offer alternating current (AC) or direct current (DC) charging, depending on the needs of the vehicle.

BLOCK DIAGRAM



The **PV (photovoltaic) system** will handle the entire charging process as long as it generates enough solar energy to meet the electric vehicle's (EV's) charging needs. In this situation, **grid electricity is not required** at all. The power flows through a **DC–DC converter**, which is a device that regulates and adjusts the direct current (DC) voltage coming from the solar panels before it reaches the EV battery. At the EV side, a **DC charger** ensures that the energy is delivered at the correct voltage and current to safely charge the battery. The charging process continues until the **state-of-charge (SOC)**—which indicates how full the battery is—reaches its maximum limit. If the solar panels continue to generate more energy after the EV is fully charged, the **grid-interfaced DC–AC converter** (a device that converts DC electricity from the solar system into alternating current or AC suitable for the grid) sends this **excess electricity** back to the utility grid.

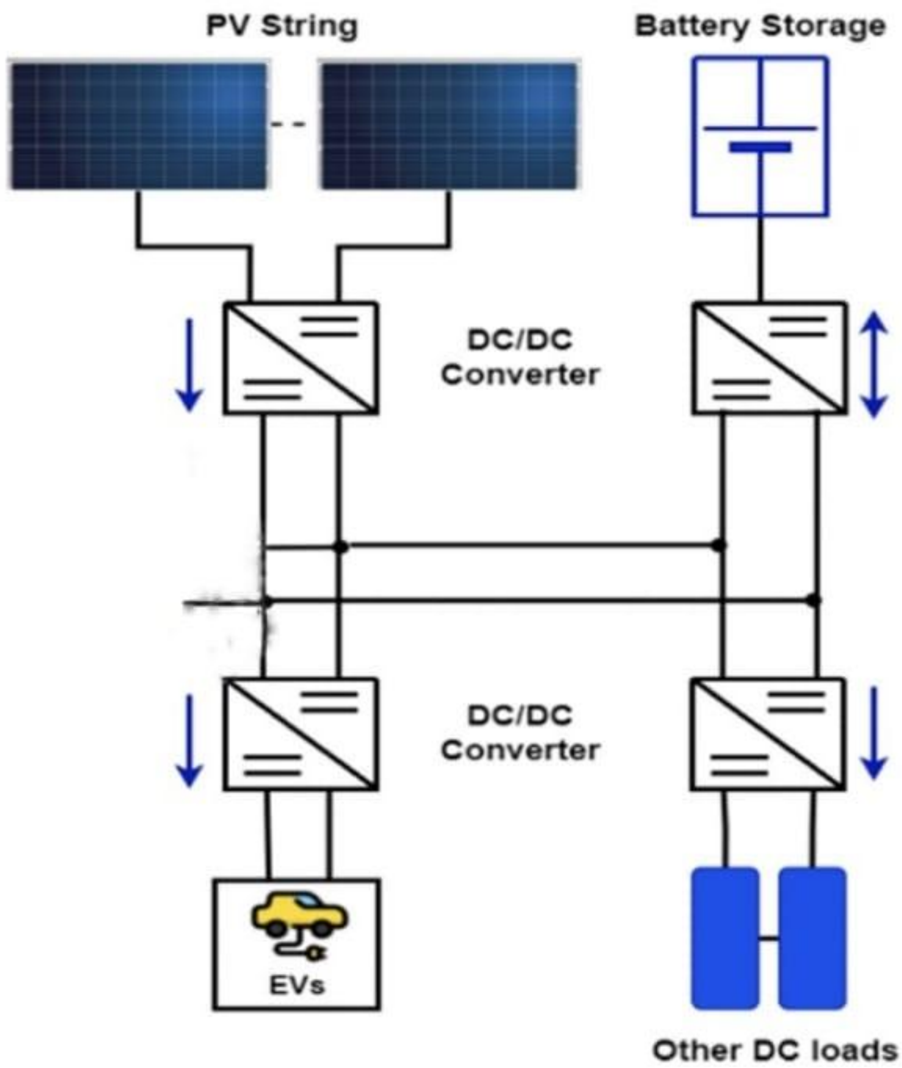


FIGURE 1 BLOCK DIAGRAM

The image shows an off-grid DC microgrid system for charging electric vehicles (EVs) using solar power. Solar energy from the PV panels is regulated by DC/DC converters and directed to charge EVs, power other DC loads, or store excess energy in batteries. The battery storage uses a bidirectional converter to charge or discharge as needed, ensuring stable operation even when solar power is inconsistent. This setup offers a sustainable, grid-independent charging solution ideal for remote or renewable-focused environments.

MODELLING

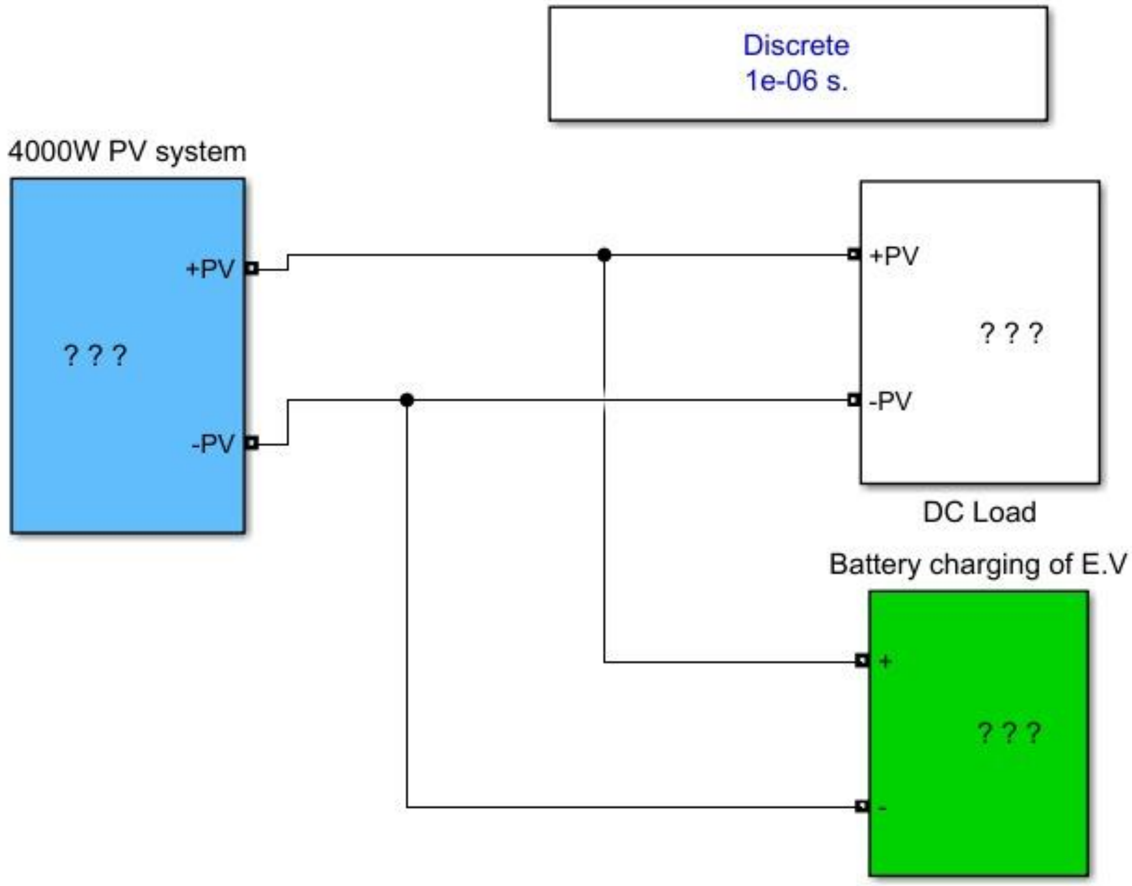


FIGURE 2 SIMULINK DIAGRAM

1. Power Generation (PV System)

Component: The 4000W PV system (first image, blue box) converts sunlight into DC electricity.

Inputs: Solar irradiance (G, e.g., 500 W/m^2) and temperature (T, e.g., 25°C) determine the PV output voltage (+PV, -PV) and current.

Process: The PV array generates a variable output depending on environmental conditions. This power is fed into the MPPT controller and distributed via the discrete switch.

Role: Provides the primary energy source for the system, with a maximum capacity of 4000W under optimal conditions.

2. DC Load

Component: DC load (first image, white box) represents external devices powered by the PV system.

Process: Receives excess PV power when the battery is fully charged or when the load demand exceeds the battery's charging needs.

Role: Utilizes surplus energy, ensuring no power is wasted.

3. EV Battery Charging Circuit

Component: Battery charging system (third image, green box) regulates the charging of the EV battery.

Sub-Components:

EV Controller: Monitors battery voltage (Vdc) and desired SOC (e.g., 98%), generating a PWM signal to control charging.

Inductor (L) and Capacitor (C): Smooth the charging current to prevent damage to the battery.

Process:

The EV controller receives Vdc and SOC feedback. Initially, the battery starts at a low SOC (e.g., 51.6439% in the scope graph).

The PWM signal adjusts the duty cycle of the DC-DC converter, regulating the charging current (Ich).

The system operates in two phases:

Constant Current (CC) Phase: Early in charging, the current is maintained (e.g., oscillating between 2–4 A), and the voltage rises (from 0 V to 350 V in the graph).

Constant Voltage (CV) Phase: As the voltage approaches 350 V and SOC nears the target, the current decreases (stabilizing near 0 A), preventing overcharging.

The inductor and capacitor filter the current, reducing ripple.

Output: The battery charges, with SOC increasing (e.g., to 51.64425% in 0.7 seconds).

Role: Safely charges the EV battery while protecting it from overvoltage or overcurrent conditions.

WORKING OF MODEL

PV SYSTEM

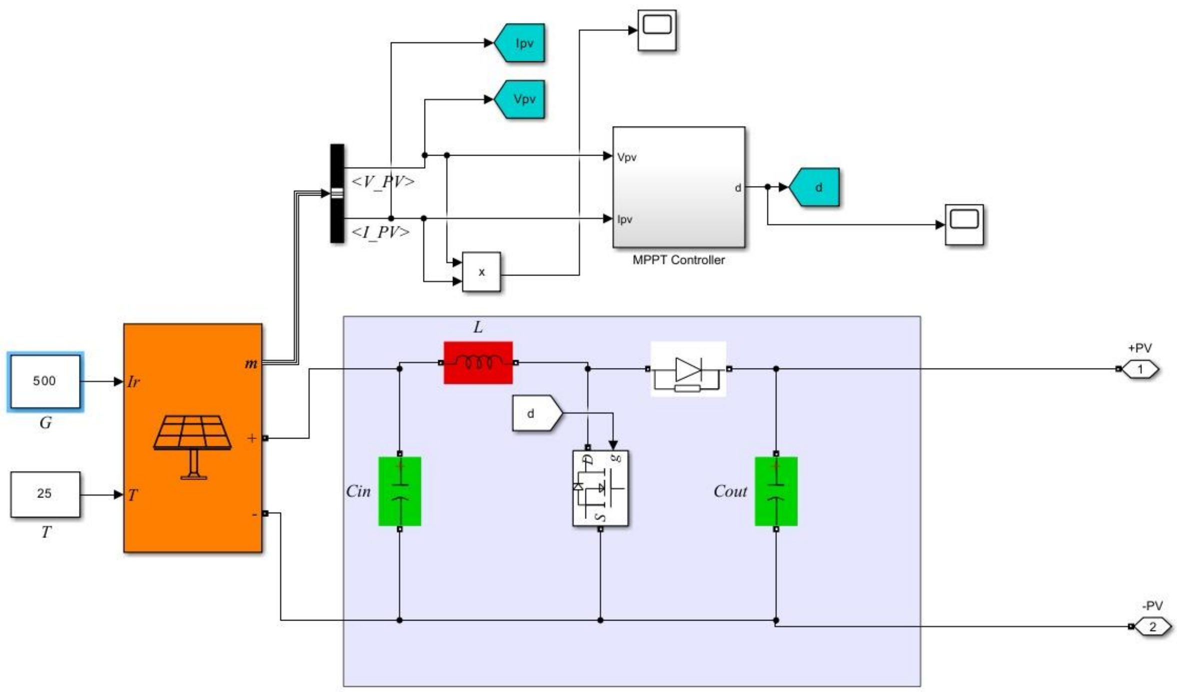


FIGURE 3 PV SYSTEM

1. Maximum Power Point Tracking (MPPT)

Component: MPPT controller (second image, central block) optimizes PV output.

Sub-Components:

RefGen: Generates a reference voltage (Vref) corresponding to the maximum power point (MPP) based on PV voltage (Vpv) and current (Ipv).

PI Controller: Compares Vref with actual Vpv, adjusts the error, and outputs a duty cycle (d) to control the DC-DC converter.

DC-DC Converter: Includes an inductor (L), capacitor (Cin, Cout), and switch (S) to step up or step down the PV voltage for efficient power transfer.

Process:

The MPPT continuously monitors Vpv and Ipv to track the MPP using a Perturb and Observe or similar algorithm.

The PI controller fine-tunes the duty cycle, which modulates the switch (S) in the converter.

The converter adjusts the PV output to match the load and battery requirements, maximizing power extraction (e.g., up to 4000W under ideal conditions).

Output: Optimized DC power (+PV, -PV) is sent to the discrete switch for distribution.

Role: Ensures the PV system operates at its maximum efficiency, adapting to changing irradiance and temperature.

DC LOAD

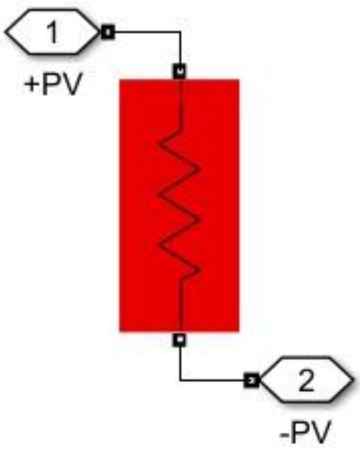


FIGURE 4 DC LOAD

A **basic electrical circuit component — a resistor —** connected to a **photovoltaic (PV) power source**. Here's a breakdown of the diagram:

Components:

1. **Red Block with Zigzag Line**:
    - This represents a **resistor**, which is a passive electrical component that resists the flow of electric current.
    - The zigzag line is the standard symbol for resistance in circuit diagrams.
2. **PV Source Connections**:
    - **Terminal 1 (+PV)**: This is the **positive terminal** of the photovoltaic (solar) power source.
    - **Terminal 2 (-PV)**: This is the **negative terminal** of the photovoltaic source.

Function:

- The resistor is connected across the **positive and negative terminals** of the **PV source**.
- This configuration forms a **simple resistive load** powered by a solar cell or PV panel.
- When the PV source generates voltage, **current flows through the resistor**, causing it to dissipate power as **heat**.

BATTERY CHARGING CIRCUIT OF E.V.

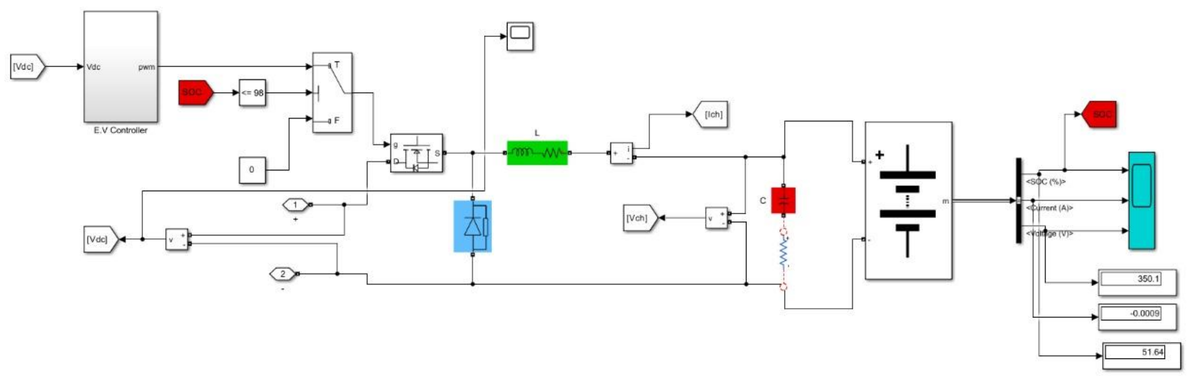


FIGURE 5 EV SYSTEM

The figure represents a **Photovoltaic (PV)-based Electric Vehicle (EV) battery charging system**. It integrates PV voltage input, a controller, power electronics (DC-DC converter), current measurement, and a battery storage system. Let's explain the major components:

◇ 1. PV Source Input ([Vdc])

- A **DC voltage input** representing the **output of a photovoltaic (PV) panel**.
- This voltage is supplied to the EV controller.

◇ 2. E.V Controller Block

- Takes Vdc as input and generates a **PWM (Pulse Width Modulation)** signal.
- Controls the switching behaviour of the DC-DC converter (likely a buck or boost converter).
- Ensures optimal charging based on SOC or charging algorithm.

◇ 3. SOC Logic Block

- Red hexagonal block: Checks if **SOC (State of Charge) ≤ 98%**.

If true, charging continues; otherwise, charging is stopped.

- **4. Power Electronics Block (Switching)**
  - Consists of a **MOSFET/IGBT switch (T)** and a **diode (F)**.
  - Controlled by the PWM signal.
  - Forms part of a **DC-DC converter** for regulating charging current and voltage.
- **5. Inductor (L) - Green Block**
  - Stores energy when the switch is ON and releases it when OFF.
  - Typical part of a **buck/boost converter**.
  - Smoothens the current.
- **6. Current Measurement Block ([Ich])**
  - Measures the **charging current (Ich)** flowing to the battery.
  - Useful for feedback control and monitoring.
- **7. Diode - Blue Block**
  - Allows current to flow in one direction only.
  - Protects the system and works as a **freewheeling diode** during switching.
- **8. Capacitor & Load Resistor - Red Block**
  - Acts as a **filter** to smooth out voltage ripple before reaching the battery.
  - The **resistor** may simulate load or battery charging resistance.
- **9. Battery Model**
  - Represented by a **series of capacitors**.
  - Models the behaviour of a **rechargeable battery**.
- **10. SOC Calculation & Display**
  - Calculates **SOC, charging current, and battery voltage**.

    SOC (%) is shown using a battery icon and numeric displays.

- Three values displayed:

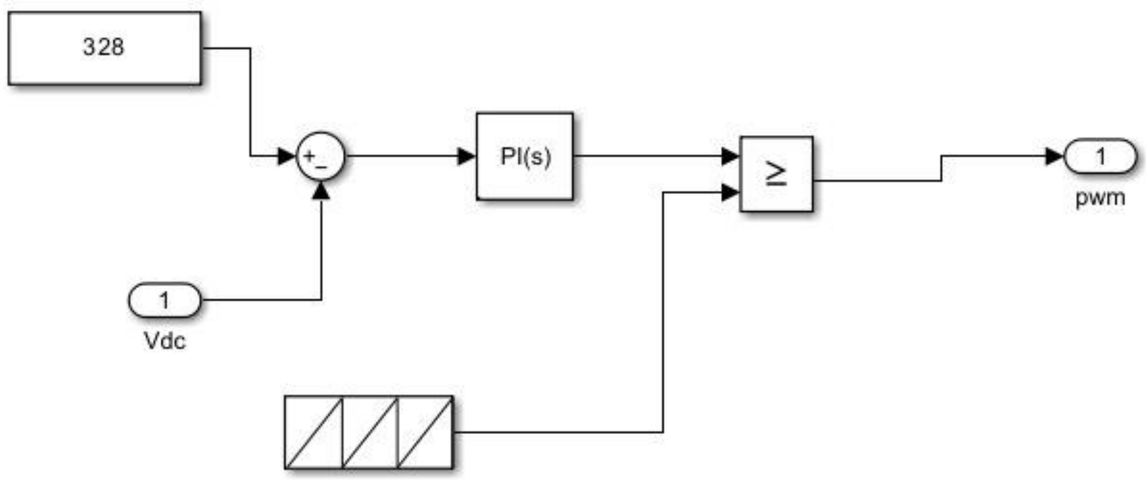
  350.1 V — Battery voltage

  - **-0.0009 A** — Charging/discharging current (negative may indicate discharging)
  - **51.64%** — State of Charge

◇ **Overall Flow Summary:**

PV Input (Vdc) → Controller (PWM) → DC-DC Converter → Inductor & Diode → Battery Charging Circuit → SOC Monitoring

EV CONTROLLER



Block-by-Block Explanation of the EV Controller

◇ **1. Reference Voltage (328)**

- A constant block set to **328 V**.
- This is the **desired PV voltage** level or **setpoint** for the controller.

- The controller will try to regulate the PV voltage to this value (usually the MPP of the panel or desired charging voltage).

2. Measured PV Voltage (Vdc)

- This input comes from the PV panel in real-time.

It's compared to the setpoint (328 V).

3. Error Calculation (Subtraction Block)

- Calculates the **difference (error)** between the reference voltage (328 V) and the actual PV voltage (Vdc):

$$e(t)=V_{ref}-V_{dc}$$

This error signal is passed to the PI controller.

4. PI Controller [PI(s)]

- A **Proportional-Integral controller** block.
- It processes the error signal to determine the corrective action:

$$u(t)=K_p e(t)+K_i \int e(t)dt.\ u(t)$$

- Output is the control signal that determines **duty cycle** for the PWM.

5. Sawtooth Wave Generator (Triangle Block)

- Generates a **sawtooth or triangular waveform**, typically at a fixed frequency (e.g., 10 kHz).
- Used for **PWM generation**.

6. Comparator Block (≥)

- Compares the PI controller output with the sawtooth waveform.
- **If PI output > sawtooth**, output is HIGH (1); otherwise, LOW (0).
- This creates a **PWM signal**.

◇ 7. PWM Output

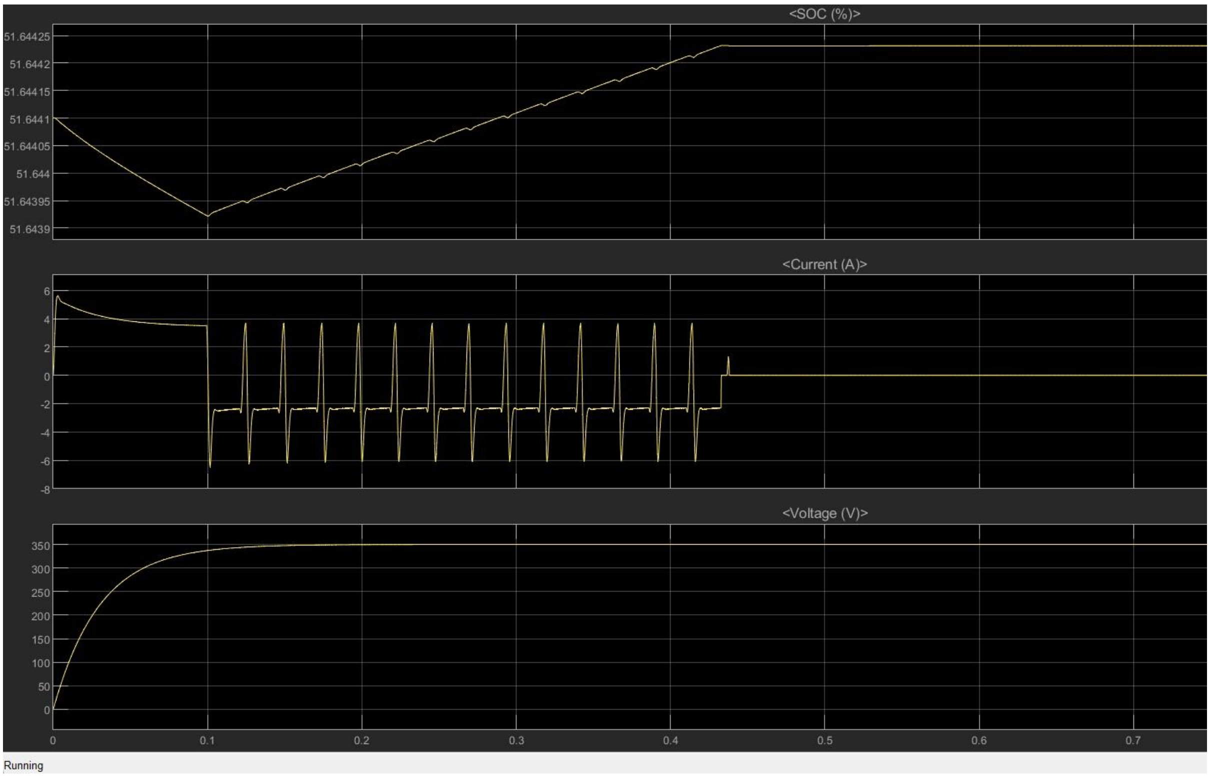
- Final output is the **PWM signal** used to control the **DC-DC converter's switch (e.g., MOSFET)** in the main charging circuit.

Purpose of This Controller

This is a **classic voltage-mode PI control with PWM generation**. It:

- Regulates the PV output voltage (or tracks maximum power point).
- Ensures efficient and stable charging by modulating the DC-DC converter via PWM.

RESULTS



Initialization (0 to 0.1 seconds):

The PV system begins generating power based on G and T.

The MPPT controller adjusts the duty cycle to find the MPP, causing initial current spikes (negative at -8 A).

The EV controller starts PWM, leading to a brief SOC dip (51.64405% to 51.6439%) due to discharge or transient load.

Voltage rises rapidly from 0 V to 300 V.

Charging Phase (0.1 to 0.5 seconds):

The MPPT optimizes PV output, and the discrete switch directs power to the battery.

The EV controller maintains a CC phase with oscillating current (2–4 A positive, -2 A negative), filtered by L and C.

SOC increases gradually (to 51.64425%) as net charging occurs despite fluctuations.

Voltage continues rising toward 350 V.

Stabilization Phase (0.5 to 0.7 seconds):

The battery enters the CV phase as voltage reaches 350 V.

Current stabilizes near 0 A, indicating reduced charging as SOC nears the target.

Excess power, if any, is routed to the DC load.

FUTURE SCOPE

The EV charging system faces challenges when PV-based EV chargers are integrated into the system. EV batteries are usually used to decrease the problems associated with the PV variable nature, which can result in unwanted charging or discharging of EV batteries. This can shorten the lifespan of EV batteries. Therefore, there is an essential requirement for a reliable, effective, and uncomplicated controller capable of meeting

EV user requirements, dealing with the intermittent nature of renewables, and charging the EVs from RES with seamless transitions between operating modes. Various control algorithms with their pros and cons have been proposed in the literature, such as model predictive control (MPC), heuristic optimizations, fuzzy logic control (FLC), and particle swarm optimization (PSO). A comprehensive study representing the associated control methods could provide a better direction for future research.

There are several exciting avenues for future research and development in the field of OBCs. These include:

• Advanced control algorithms: Exploring AI-based control algorithms to further enhance OBC efficiency and user experience.

• Wireless charging integration: Investigating seamless wireless charging integration for enhanced convenience and user adoption.

• Fast-charging infrastructure expansion: Addressing the growing need for high-power OBCs to support ultra-fast charging stations.

• Materials innovation: Continuing to explore novel materials for improved power electronics and thermal management.

• Multi-vehicle compatibility: Developing OBCs that can efficiently charge various EV models with different specifications.

CONCLUSION

The rising concerns about air pollution and environmental degradation have significantly increased the popularity of **emission-free and eco-friendly transportation options**, particularly **electric vehicles (EVs)**. These vehicles offer a sustainable alternative to traditional internal combustion engine vehicles by reducing greenhouse gas emissions and contributing to cleaner urban environments.

To ensure the **long-term sustainability** of EV adoption, the integration of **renewable energy sources (RES)** such as **solar photovoltaic (PV)**, **wind**, and **biomass** into EV charging infrastructure is gaining momentum. Among these, **solar PV-based EV charging** stands out due to its numerous benefits:

- It ensures **financial savings** by minimizing reliance on conventional energy sources.
- It offers **simpler and flexible installation**, especially in rural or remote locations with limited energy infrastructure.
- It reduces operational costs by eliminating or reducing dependence on fossil fuels.

This paper highlights the various **types of EV chargers**, applicable **standards**, and key aspects of **battery modeling** relevant to PV-based EV charging. It specifically focuses on **stand-alone (off-grid) PV-EV charging systems**, which operate independently of any utility grid and are ideal for settings where grid access is limited or unavailable.

Off-grid PV charging infrastructure involves fewer power conversion stages compared to traditional charging systems, leading to increased efficiency and cost-effectiveness. These systems typically incorporate **battery energy storage**, allowing EVs to be charged even during periods of low solar generation, such as cloudy days or nighttime.

A particularly effective solution in off-grid setups is the use of **off-board charging systems**, where the charger is installed externally from the vehicle. This approach enables:

- **Faster charging speeds** due to fewer constraints on charger size and thermal management,
- **Reduced weight** in the vehicle, improving EV performance, and

  Enhanced communication and safety protocols with the external charger.

Future research should concentrate on the development of **smart and adaptive charging management techniques** for off-grid systems.

These may include predictive solar power algorithms, battery state-of-charge estimation, and energy optimization strategies to enhance the efficiency and reliability of PV-based EV charging without relying on any grid infrastructure.

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