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Development Of A Sustainable EV Fast Charging Infrastructure Using A Hybrid Solar-Battery System

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Abstract–*The growing adoption of electric vehicles (EVs) has significantly increased the demand for electricity, leading to greater reliance on the conventional power grid. This increased dependency poses challenges for sustainable EV charging, especially when the grid is powered by non-renewable energy sources. To address this, a grid-integrated solar-based EV charging system is proposed in this work. The system utilizes photovoltaic (PV) panels as the primary energy source, supported by backup battery unit to ensure continuous charging availability during periods of solar irradiance. Moreover, the system is interfaced with the utility grid to enable bidirectional power exchange, thereby improving system reliability and operational adaptability. An advanced Maximum Power Point Tracking (MPPT) technique is utilized to ensure optimal energy harvesting from the photovoltaic (PV) array under dynamically changing irradiance and temperature conditions. The integration of renewable energy, backup battery, and grid connectively ensure efficient, reliable, and environmentally friendly charging, while reducing the overall dependency on the grid.*
Keywords–*Backup Battery, Grid, Solar System, Grid Power, Solar power, Electric Vehicle, Common DC link, Backup Battery power, Charging, Discharging*

INTRODUCTION

Electric Vehicles (EVs) are gaining wide spread adoption as the global focus shifts toward sustainable, low-emission, and energy-efficient transportation technologies. This shift is largely motivated by the urgent need to minimise carbon emissions and minimize the use of fossil fuels. However, as the count of EVs on the road grows, so does the demand for electricity to charge them. Most existing EV charging infrastructures are primarily dependent on the conventional utility grid, which predominantly derives its energy from non-renewable sources such as coal and natural gas. This growing reliance not only puts pressure on the grid but also limits the environmental benefits that EVs are intended to provide.To make EV charging more sustainable, incorporating renewable energy into the charging infrastructure is essential. Among various renewable options, solar energy stands out due to its wide availability and rapid technological progress in photovoltaic (PV) systems (1). Solar energy alone is not sufficient, as it depends on sunlight, which is variable and unpredictable. To maintain a stable power supply, an energy storage system (ESS) comprising battery backup is employed to store excess energy generated by the photovoltaic array during peak solar irradiance, enabling power delivery during periods of low or no solar availability.Additionally, connecting the system to the utility grid adds another layer of reliability. The grid can supplement power when both solar generation and battery storage are insufficient. On the other hand, excess solar energy can be fed back into the grid, improving overall energy efficiency and supporting grid stability.To enhance the effective use of solar energy captured by the system, a Maximum Power Point Tracking (MPPT) technique is integrated. This method actively regulates the operating conditions of the photovoltaic (PV) array, ensuring it consistently operates at its peak power output.By adapting to fluctuations in sunlight and temperature, MPPT significantly improves the overall energy conversion performance of the solar system.
This proposed system works in three different cases.
1)Case-1: In the presence of both solar power and battery backup, the electric vehicle is charged using the available renewable energy, and any extra power available is exported to the utility grid.
2)Case-2: In the absence of both solar generation and battery backup, the entire power required for EV charging is drawn from the utility grid.

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3) Case-3: In the absence of EV charging demand, the solar-generated power is utilized to charge the backup battery, and any surplus energy is exported to the utility grid.

CONFIGURATION OF THE MODEL

Electric vehicle (EV) charging systems are generally classified into different levels based on input voltage, power capacity, and charging speed. Level-1 chargers use a standard 110V AC household outlet and deliver a low charging power of around 1–2 kW. As a result, they require a long duration—often exceeding 10 hours—to fully charge an EV battery. Level-2 chargers, operating at 220–240V AC, can provide 7–22 kW of power and offer significantly faster charging times,typically between 3 to 8 hours depending on battery size and charger rating.

In the proposed system, an 8 kW DC charger is used to charge a 32-kWh battery. Based on the energy-to-power ratio, the theoretical charging time is calculated as:

$$\text{Charging Time} = \frac{\text{Battery Rating}}{\text{Charger Capacity}} = \frac{32\text{kwh}}{8\text{kw}} = 4\text{hours}$$

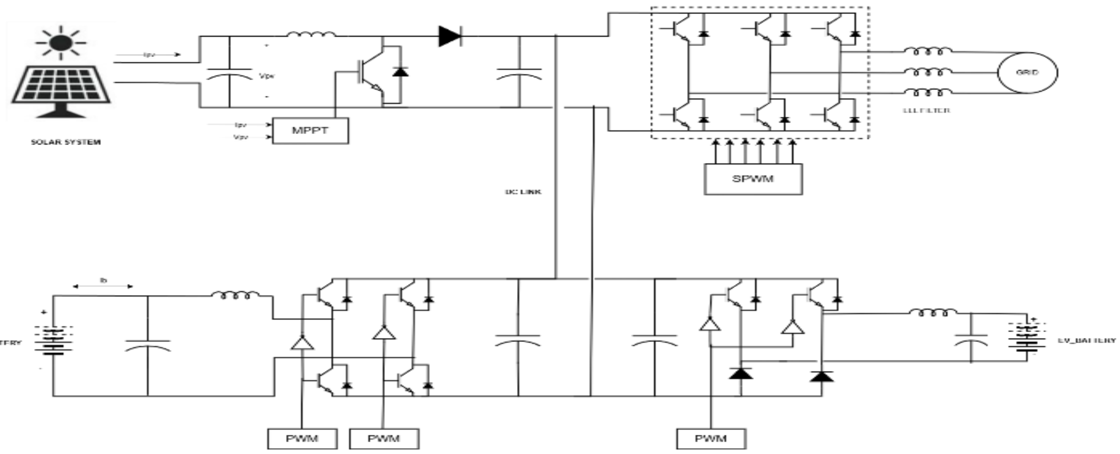


Fig 1. Schematic diagram of the system

Level-3 DC fast chargers are capable of delivering high power outputs, typically 50 kW or more, enabling electric vehicles to reach up to 80% state of charge within approximately 30 minutes.The proposed DC charging station is primarily powered by a 6-kW solar photovoltaic (PV) array, supplemented by a backup battery storage system (BBSS) and integrated with the utility grid to ensure operational reliability. To maximize energy harvesting from the photovoltaic (PV) array amidst varying environmental conditions, an incremental conductance MPPT algorithm is employed alongside a DC–DC boost converter. This setup ensures that the PV system consistently operates at its optimal power point. Furthermore, an interleaved bidirectional DC–DC converter (BDDC) manages the two-way energy exchange between the battery-based storage system (BBSS) and the electric vehicle (EV), facilitating efficient charging and discharging operations.The converter functions in buck mode during EV charging and switches to boost mode for charging the battery using surplus solar energy. The system does not support vehicle-to-grid (V2G) operation; energy flows only from the solar panels, battery storage, or grid to the EV for charging.The hybrid renewable energy system consists of a 6-kW solar photovoltaic (PV) array and a 10-kWh backup battery storage system (BBSS) with a nominal voltage of 200 V and a capacity of 50 Ah, capable of delivering up to 4 kW of continuous power. This battery acts as a backup energy source, allowing the charging station to function even during periods of low solar generation, thus reducing dependency on the grid.To improve power quality, an inductive filter is placed after the inverter to reduce harmonic distortion. The electric vehicle is charged via an integrated system comprising a solar PV array, battery energy storage, and grid interface, Together these components contribute to the development of a sustainable and energy-efficient electric vehicle (EV) charging infrastructure. A comprehensive overview of the system configuration is illustrated in Fig. 1.

A. A. Solar Energy System

A solar panel is a device that generates electrical energy by converting sunlight into electricity using multiple photovoltaic (PV) cells. These solar cells are typically interconnected in series and/or parallel configurations to form a photovoltaic (PV) module, which is encapsulated within a protective enclosure featuring a tempered glass cover to endure various environmental conditions.

Solar panels are widely deployed in both grid-connected and off-grid applications, ranging from residential rooftop systems to utility-scale solar power plants. They play a critical role in accelerating the adoption of renewable energy and mitigating carbon emissions, thereby contributing to a more sustainable and low-carbon energy future. The technical specifications of the solar panel utilized in this system are detailed in the table below.

Table1. Ratings of solar panel

Parameters	**Rating**
Input Irradiance	1000W/M
Input Temperature	25 C
No of parallel strings	2
No of modules in series	12
Maximum power	6000W
Shirt circuit current (Ish)	9A
Open circuit voltage (Voc)	35V
Cells per module	60
Current at MPP	8.17A
Voltage at MPP	31V

The voltage of solar panels will be added in series placement current will remain same, in parallel connection of solar panels current will be added and voltage will remain same.

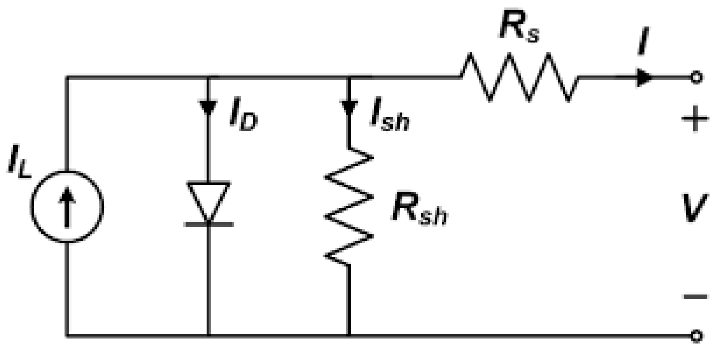


Fig 2. Single diode model of photovoltaic cell

$$I = I_L - I_O\left(e^{\frac{V+IR_{se}}{nV_t}} - 1\right) - \frac{V+IR_{se}}{R_{sh}} \qquad (1)$$

$$V_t = \frac{kT}{q} \qquad (2)$$

$$I_L = [I_{sc} + \alpha(T - T_{ref})] * \frac{G}{G_{ref}} \quad (3)$$

$$I_{pv} = \frac{R_{sh} + R_{se}}{R_{sh}} * I_{sc} \quad (4)$$

$$I_o = \frac{I_{sc}}{e^{(\frac{V_{oc}}{nV_t})} - 1} \quad (5)$$

B. EV battery and backup battery

Lithium-ion (Li-ion) batteries are rechargeable electrochemical energy storage devices extensively utilized in portable electronics, electric vehicles, and renewable energy applications. Lithium-ion batteries are favored for their high energy density, low weight, and long operational lifespan compared to traditional battery technologies. Their exceptional efficiency and dependability make them a cornerstone in the evolution of modern technologies and the shift toward cleaner energy systems. These batteries are widely utilized across diverse applications, from portable electronic devices to large-scale energy storage systems supporting renewable integration.

$$Energy(kwh) = \frac{Ah \times Voltage}{1000} \quad (6)$$

$$Capacity(Ah) = \frac{Energy \times 1000}{Voltage} \quad (7)$$

A 200 V, 50 Ah backup battery and a 320 V, 100 Ah EV battery are interconnected via a common DC bus through an interleaved bidirectional DC-DC converter (BDDC). When the electric vehicle (EV) is disconnected, the backup battery is charged by the solar photovoltaic (PV) system.When the EV is present, the backup batteryalong with the solar sourcesupplies power to charge the EV battery. This bidirectional energy flowensures efficient energy utilization from the solar system and provides a reliable and continuous power supply for EV charging.

C. Grid

The electrical utility grid functions as an auxiliary power source to guarantee continuous EV charging. Although the primary energy is supplied by the 6-kW solar PV system and the 72 V backup battery, the grid provides power during periods of low solar irradiance such as night time or overcast conditions and when the battery state of charge is insufficient. Although the system is primarily designed for autonomous operation utilizing solar generation and battery storage, the grid connection enhances the reliability of the EV charging station by:

- Providing auxiliary power when renewable sources are insufficient.
- Maintaining voltage and frequency stability on the DC link through controlled interfacing circuits.
- Supporting peak load demands when the EV battery charging current exceeds the available renewable power.

This integration ensures a stable, flexible, and reliable charging system that supports continuous operation regardless of solar availability.

COMPONENTS DESIGN

D. Filter design

Inbetweeninverterandgrid,there'saninductive filter.It smoothingoutanyroughedgesandreducinghigh-frequency noise. This guarantees that the power injected into the grid is clean and stable, safeguarding equipment and complying with regulatory standards. The inductance value is calculated using Equation

(8), where *V* represents the grid-side voltage, *P* denotes the nominal power per phase, and *f* is the grid frequency.

$$L = \frac{0.2 \times V^2}{2\pi f P} \quad (8)$$

E. Boost converter

A boost converter is a type of DC–DC converter designed to increase the input voltage to a higher level at the output. During the on-state of the switching cycle, the inductor accumulates energy from the input source. When the switch turns off, this stored energy is released to the output through the diode, effectively raising the output voltage above the input level. This switching operation enables efficient voltage conversion from low-voltage sources to higher-voltage loads. Boost converters are commonly employed in power supplies, battery management systems, and renewable energy applications to achieve stable voltage regulation and optimized power transfer.

1) Inductor

The inductor is a critical component in a boost converter, responsible for energy storage during the switch-on interval and energy transfer to the output during the switch-off interval. This operation enables the elevation of the input voltage to a higher output level. Moreover, the inductor plays a crucial role in minimizing current ripple, thereby enhancing the stability and efficiency of the power conversion process.

$$L = \frac{V_{in} \times D}{\Delta I_L \times f_s} \quad (9)$$

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (10)$$

$$\Delta I_L = \frac{V_{in} \times D}{L \times f_s} \quad (11)$$

Where L represents the inductance in Henries (H), Vin is the input voltage in volts (V), D denotes the duty cycle (dimensionless), ΔIL is the peak-to-peak inductor current ripple in amperes (A), and fs is the switching frequency in hertz (Hz).

2) Input capacitor

The input capacitor in a boost converter is essential for stabilizing the input voltage by filtering out high-frequency voltage ripple generated during the switching process.It provides a low-impedance path for high-frequency currents, reducing stress on the input power source and improving overall converter performance. A properly sized input capacitor helps ensure smooth and reliable power delivery to the converter.

$$C_{in} = \frac{I_{out} \times D}{\Delta V_{in} \times f_s} \quad (12)$$

Where Cin is the input capacitance (F), $Iout$ is the converter's output current (A), D is the duty cycle (unitless), ΔVin is the allowable input voltage ripple (V), and fs is the switching frequency (Hz).

3) Output Capacitor

The output capacitor in a boost converter functions to filter and smooth the output voltage by minimizing voltage ripple generated during switching. It delivers current to the load during the switch-on interval and stores excess energy during the switch-off interval, thereby maintaining a stable and continuous output voltage.

$$C_{out} = \frac{I_{out} \times D}{\Delta V_{out} \times f_s} \quad (13)$$

Where $Cout$ is the output capacitance (F), $Iout$ is the output current (A), D is the duty cycle (unitless), $\Delta Vout$ is the allowable output voltage ripple (V), and fs is the switching frequency (Hz).

F. Buck boost converter

An interleaved buck-boost converter enables bidirectional power transfer between two voltage levels—such as a battery system and a DC link or grid—by combining the functionalities of both buck (stepdown) and boost (step-up) conversion within a single integrated topology. This topology enables efficient voltage regulation and power transfer in both directions. The interleaved structure reduces input and output current ripple, which helps improve overall efficiency, reduces losses, and extends component lifespan. The sizing of key components like the boost inductor and output capacitor is done using Equations (9) and (13), based on voltage, current, and switching frequency.

$$D = 1 - \frac{V_{in}}{V_{out}} \qquad (14)$$

In buck mode operation, the duty cycle (*D*) is less than 0.5, whereas in boost mode operation, the duty cycle (*D*) exceeds 0.5.

II. CONTROL METHODOLOGY

A. Incremental conductance method for solar system

The Incremental Conductance (IC) algorithm is a popular MPPT method in PV systems that optimizes energy extraction by continuously adjusting voltage and current to track the Maximum Power Point (MPP) under changing irradiance and temperature. Unlike the Perturb and Observe (P&O) method, which can lose accuracy during rapid environmental changes, IC compares the incremental conductance (dI/dV) with the instantaneous conductance (I/V). When these are equal but opposite in sign, the MPP is reached. This allows IC to track the MPP more accurately and with less oscillation, improving the efficiency and stability of PV systems, especially in fluctuating conditions.

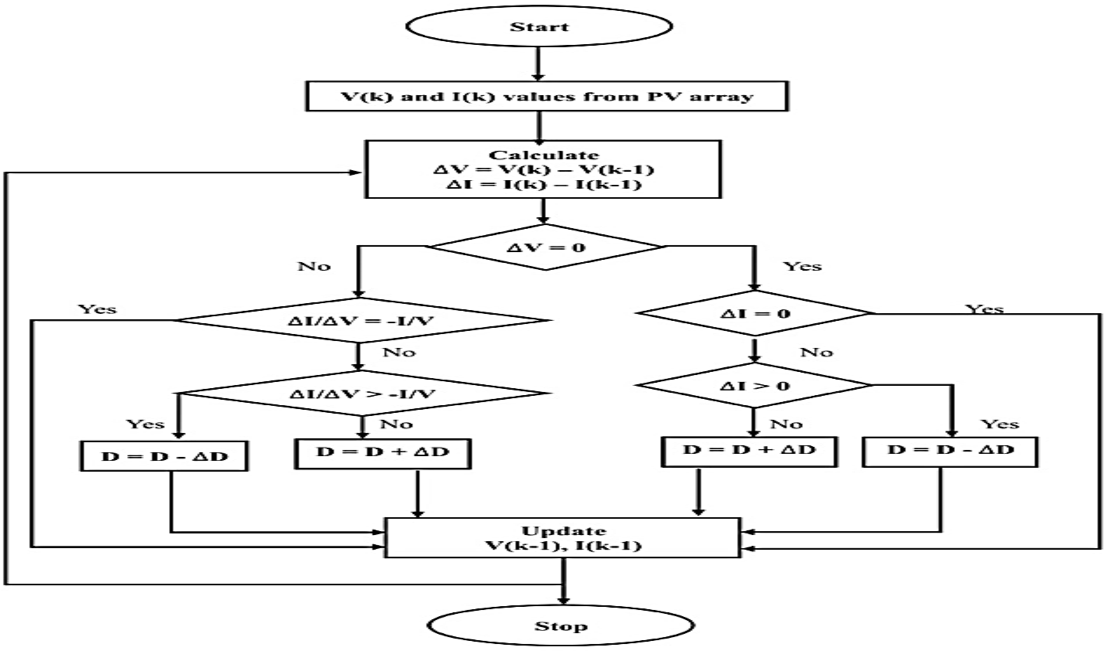
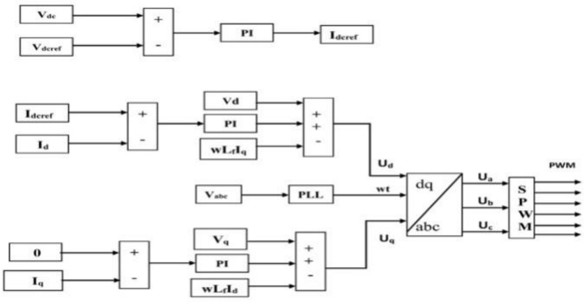


Fig 3. Incremental conductance MPPT for solar system

B. Grid side converter control

The d–q control technique is essential for controlling active and reactive power in grid-tied inverter systems. It relies on voltage measurements at the Point of Common Coupling (PCC) to perform control actions within the synchronous reference frame (d–q). The d-axis component manages active power flow either to fulfill grid requirements or to stabilize the DC link voltage while the q-axis component regulates reactive power, allowing for power factor correction and maintaining operation close to unity power factor. This approach ensures efficient power exchange between the renewable energy source and the grid, contributing to improved energy flow, voltage stability, andsystem performance. A Proportional-Integral (PI) controller is employed within the d-axis control loop to accurately track the current reference, enabling precise active power regulation and enhancing the inverter system's overall



efficiency and reliability.

Fig 4. Grid side converter control

C. DC-DC bidirectional converter control

The bidirectional converter functions in grid-connected mode to manage and optimize power exchange among the solar PV system, backup battery, and the grid. When no Electric Vehicle (EV) is connected, the backup battery is charged by the solar PV array, and any excess energy is fed back into the grid. Upon EV connection, power from both the solar PV and backup battery is allocated to charge the EV's battery. The system keeps the DC link voltage stable to ensure consistent power transfer between the inverter's DC and AC sides. During periods of low solar irradiance or increased load demand, supplementary power is drawn from the grid to maintain a continuous supply. The control scheme employs inner current control loops and outer power control loops to produce the necessary switching signals for the bidirectional converter, optimizing solar power harvesting while preserving DC link voltage stability. This approach supports efficient renewable energy utilization and smooth integration of EV charging into the grid-connected setup.

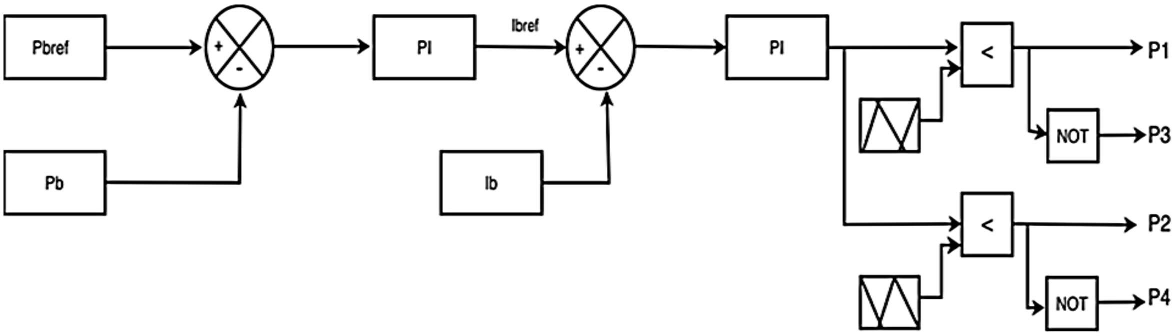


Fig 5. Bidirectional DC-DC converter

D. Unidirectional converter for EV charging

A unidirectional DC-DC converter is employed on the EV side to manage the battery charging process. It permits power flow solely from the DC link to the EV battery, ensuring safe, controlled, and efficient charging without the risk of reverse current flow. The converter regulates the charging current and voltage according to battery specifications, protecting against overcharging and enhancing battery life. Since energy flows in one direction only, this setup is simple, cost-effective, and suitable for systems where vehicle-to-grid (V2G) functionality is not required.

SIMULATION AND RESULTS

The proposed system operates under three distinct scenarios, determined by the availability of energy sources:

- Case 1: When the EV is connected and both solar and battery sources are available, it is charged from both. Excess solar power is fed to the grid.
- Case 2: If both the solar PV system and the backup battery are unavailable, the entire charging power required by the EV is supplied directly from the utility grid.

- Case 3: When the EV is not connected, the energy generated by the solar PV system is utilized to charge the backup battery. Any excess solar energy is exported to the utility grid.

Case-1

In this scenario, the solar PV array produces 6 kW of power, while the backup battery contributes 4 kW, providing a total available power of 10 kW. From this, 8 kW is effectively used to charge the Electric Vehicle (EV), and the remaining 2 kW is fed back to the grid, preventing any energy wastage. This setup not only ensures optimal utilization of renewable energy but also enhances overall system efficiency by balancing power flow between the EV, grid, and energy sources. By prioritizing solar energy and supplementing it with battery support, the system reduces dependence on the grid and promotes a sustainable and reliable charging infrastructure.

Fig 6. And Fig 7. Shows the powers of the individual systems and charging of EV and discharging of backup battery. Fig 8 and Fig 9 shows the DC link voltage and grid voltage and current.

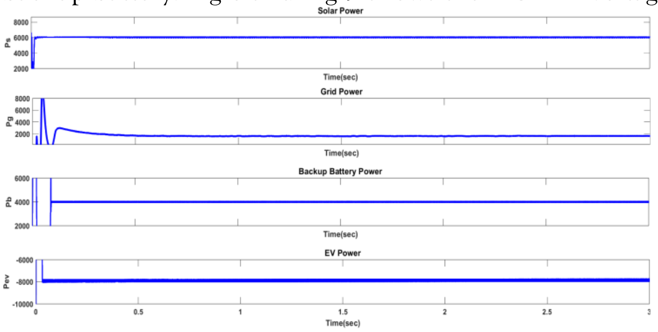


Fig 6. Powers of the solar (Ps), grid (Pg), BB (Pb), and EV (Pev)

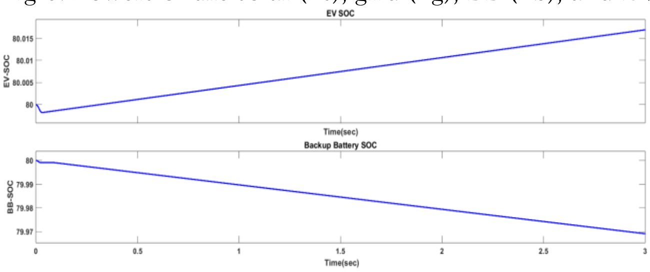


Fig 7. Charging of EV and discharging of BB

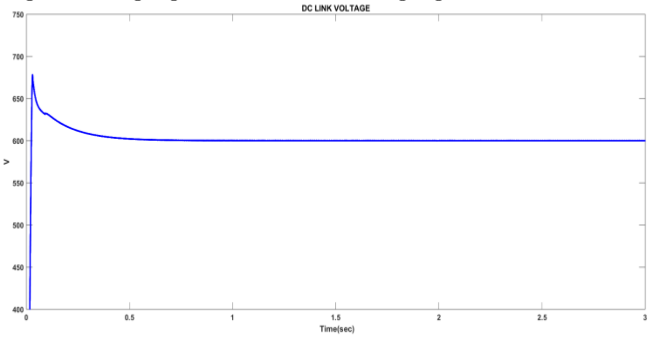


Fig 8. DC link voltage

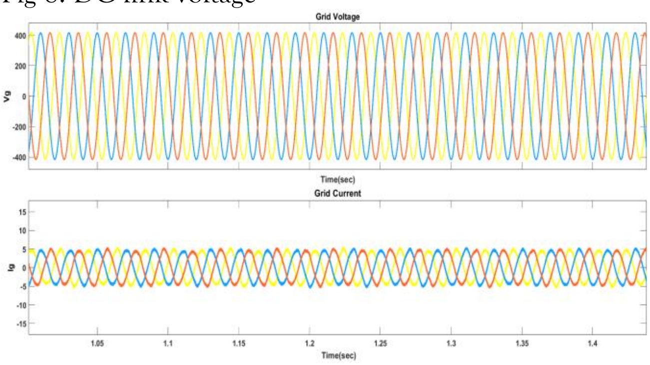


Fig 9. Grid voltage & current

Case-2

In this case, when both the solar panels and the backup battery are not availablesuch as at night or during cloudy weather when the backup battery is emptythe full 8 kW needed to charge the Electric Vehicle (EV) is supplied by the utility grid. This ensures that the EV can still be charged without any interruption. While grid power is used in this situation, the system is designed to mainly rely on solar energy and battery storage whenever they are available. This helps reduce the use of conventional electricity and supports a more sustainable way of charging. Even when solar and battery are offline, the system continues to provide reliable charging while encouraging the use of clean energy during normal operation.

Fig 10. And Fig 11. Shows the powers of the individual systems and charging of EV and discharging of backup battery. Fig 12 and Fig 13 shows the DC link voltage and grid voltage and current.

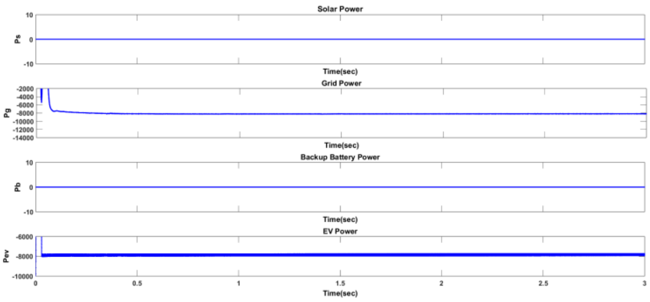


Fig 10. Powers of the solar (Ps), grid (Pg), BB (Pb), and EV (Pev)

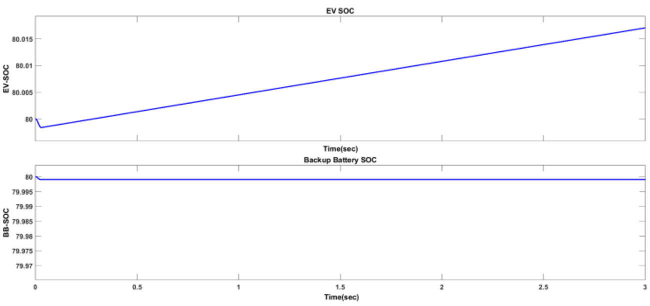


Fig 11. Charging of EV and discharging of BB

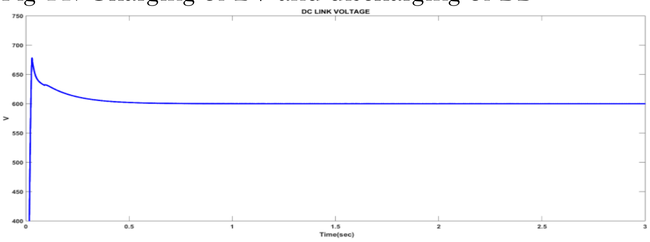


Fig 12. DC link voltage

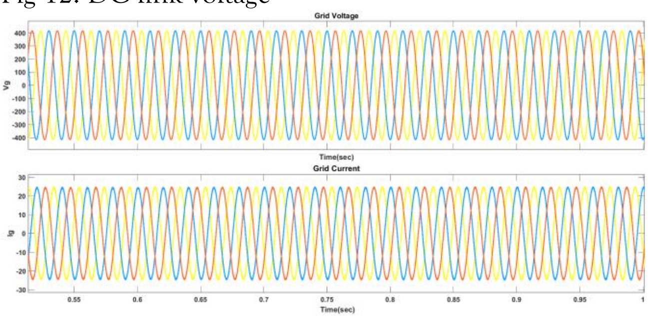


Fig 13. Grid voltage & current

Case-3

In this case, when the EV is absent, the 6-kW generated by the solar system is used to charge the 4-kW backup battery, while the excess 2 kW of clean renewable energy is supplied to the grid. This maximizes the utilization of solar energy, reduces wastage, and promotes a sustainable and efficient energy management system.

Fig 14. And Fig 15. Shows the powers of the individual systems and charging of EV and discharging of backup battery. Fig 16 and Fig 17 shows the DC link voltage and grid voltage and current.

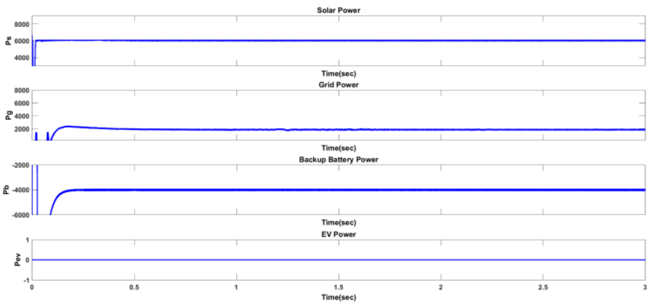


Fig 14. Powers of the solar (Ps), grid (Pg), BB (Pb), and EV (Pev)

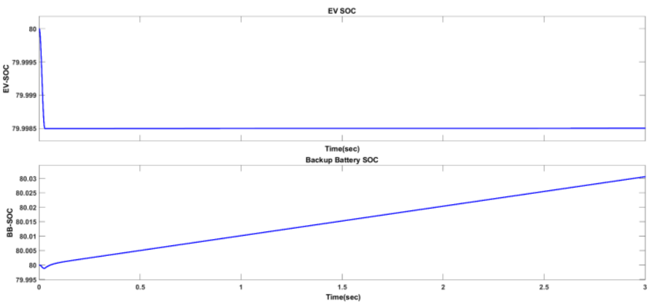


Fig 15. Charging of EV and discharging of BB

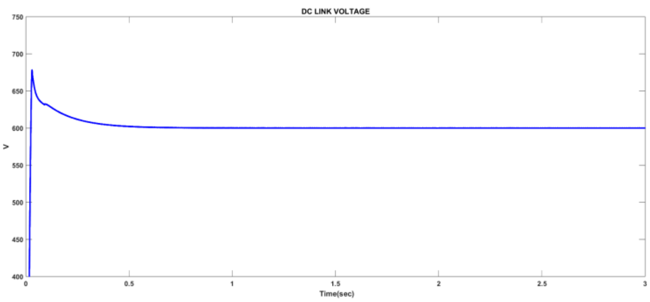


Fig 16. DC link voltage

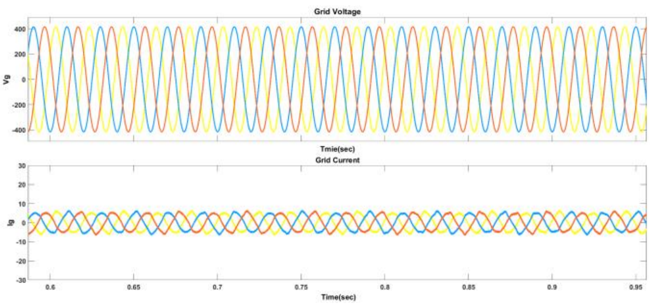


Fig 17. Grid voltage & current

CONCLUSION & FUTURE ENHANCEMENTS

This paper presents a grid-integrated electric vehicle (EV) charging system powered by a hybrid renewable energy source, consisting of a 6-kW solar photovoltaic (PV) array and a 10-kWh battery (200 V, 50 Ah). The system was modeled and simulated in MATLAB/Simulink to assess its performance under various operating conditions. An incremental conductance-based Maximum Power Point Tracking (MPPT) algorithm was employed to optimize solar energy extraction. A bidirectional DC–DC converter managed battery charging and discharging, supporting the EV charger when solar energy was insufficient. The system employed a dq-axis control strategy to regulate active and reactive power flow and maintain a stable DC-link voltage. The 8 kW DC EV charger was able to charge a 32-kWh battery. The results demonstrate that the proposed system effectively reduces grid dependency, enhances energy efficiency, and promotes a sustainable and reliable EV charging infrastructure through the optimal utilization of renewable energy sources. The THD in case-1 is 5.48% and in case-3 is 5.66%. The Proposed system has been implemented by using hybrid solar– battery system. Existing work may be enhanced further for the reduction of THD below 5 % by utilizing other Renewable sources along with hardware implementation.

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