

Improved Solar-Photovoltaic (PV) Integrated Electric Vehicle (EV) Charging System With Bidirectional DC-DC Converter In Terms Of Energy Management Optimization

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ABSTRACT

Integration of renewable energy sources (RESs) with electric vehicle (EV) charging stations has become a topic of considerable interest in the past years due to the increasing necessity for green transportation. This paper investigates the design of a DC biased bidirectional dc converter based solar PV based EV Charging System Model with the aim to improve energy efficiency, energy utilization and grid interaction. The Author investigates PV-Battery with Electric Vehicle Charging Station using Bidirectional DC-DC Converter.

In order to increase energy harvesting efficiency, MPPT algorithms are adopted to extract maximum power from solar PV under different weather conditions. The bidirectional dc converter enables controlled and efficient transfer of power between the solar PV system, EV battery, and the grid, for both v2g and g2v. The system is further improved with real-time monitoring, battery management systems (BMS), and load balancing techniques for higher overall robustness and efficiency.

The system performance and stability are verified by MATLAB/Simulink without hardware, high charging efficiency (> 99 %), fast MPPT convergence, and bidirectional power flow are obtained. Furthermore, the robustness of the proposed control strategy is verified by the waveform analyses of the variations of battery voltage, battery current, load voltage, load current and duty ratio. Moreover, it evaluates the cost-effectiveness, grid-friendliness and environmental impact, with a particular focus on the benefits of solar PV integration in EV charging stations. This work supports the ongoing switch to green energy, as it decreases dependence on fossil fuels and increases energy resilience by distributed generation. The developed Solar PV-based bidirectional charging system would definitely offer a modular and cost-effective means for EVs at greener future transportation.

Keywords: Solar PV Charging, Bidirectional DC-DC Converter, Vehicle-to-Grid (V2G), Maximum Power Point Tracking (MPPT), Renewable Energy Integration, Electric Vehicle Charging Infrastructure

1. INTRODUCTION

System-wide change in transportation is being driven by an urgent global need to address climate change and a shifting energy system towards sustainability [1]. Electric vehicles (EVs) have become the main vector of this transition, having significant potential for reducing greenhouse gas emissions and providing quieter and cleaner cities. Nevertheless, the availability of a dependable, effective and sustainable charging infrastructure is a critical factor for the mass penetration of EVs. In this sense, the use of renewable energy sources, such as solar photovoltaic (PV) systems, at EV charging stations seems to be an attractive approach to mitigate the reliance on fossil fuels, increase energy security, and stimulate decentralized power generation [1–2].

In this paper an advanced solar PV based EV charging system has been modeled and designed using bidirectional DC–DC converter. Bidirectional DC–DC converter is significant in fulfilling energy efficiency and grid connection in charging and discharging process to realize active power control and energy flow in two directions [3]. The soaring pace of EV adoption worldwide presents major challenges for existing grid-based charging infrastructures, including increased energy demand, load variability, and environmental concerns stemming from electricity generation reliant on fossil fuels. Solar PV is a practical solution in the provision of clean, decentralized and sustainable energy for EV charging needs.

The introduction of bidirectional power converters also facilitates energy flow in two ways between vehicle, grid and external loads, leading to the notion of Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operation [4–5]. Several works have analyzed the integration of renewable sources in charging stations for EV, showing that solar PV-based charging stations are capable of enhancing grid independence and emissions reduction. State-of-the-art Maximum Power Point Tracking (MPPT) methods—e.g., Perturb and Observe (P&O), Incremental Conductance (IncCond) and Particles Swarm Optimization (PSO)—have been employed to extract maximum energy from the PV modules under diverse weather conditions. Moreover, exploiting bidirectional dc-dc converter topologies, such as dual active bridge (DAB) and interleaved converter, has led to improvements in power transfer efficiency, as well as obviate bidirectional energy flow between the PV, EV battery and grid [6].

Recent studies have pointed to the significance of employing real-time monitoring for battery management systems (BMS) and load-balancing techniques to increase the reliability and performance of integrated EV charging systems. The efficacy of these converters for high charging efficiency, fast MPPT convergence, and stable bidirectional power flow has been confirmed by simulation studies performed on high level software platforms like MATLAB/Simulink, PLECS. In addition, the profitability of solar-powered EV charging stations has been analyzed with techno-economic models, incorporating factors such as the levelized cost of energy (LCOE), grid parity, and renewable energy subsidies [7].

Recent developments in the field indicate an increasing importance of the integration of energy storage, local predictive control algorithms, and communication with the smart grid. Hybrid renewable energy systems combining solar PV with wind energy, fuel cells or other renewable sources have been suggested to allow continuously charging in absence of the sun. Emerging energy storage technologies, such as lithium ion batteries, flow batteries, and supercapacitors, are also being implemented to improve grid reliability and provide backup during grid outages [8].

Meanwhile, a number of artificial intelligence (AI)-based prediction models using machine learning (ML) methods including neural networks (NNs) and support vector machines (SVMs) have been proposed to predict solar irradiance, EV charging demand, and grid status for preemptive energy management. IoT-enabled architectures also promote higher level of remote monitoring, system automation, and intelligent energy management, while blockchain technology is investigated as a means to support secure and transparent peer-to-peer energy trading in decentralized energy markets [9].

Based on above progresses, in this paper an improved solar PV integrated EV charging system with a high-performance bidirectional DC-DC converter using two-stage modulation is proposed. In the presented modulator the PS/PWM scheme is employed, which allows to combine the benefits of phase-shift modulation and pulse width modulation (PWM) and obtain higher efficiency and smoother bidirectional power flow. The system is equipped with sophisticated MPPT, adaptive control and real-time data monitoring to optimize the performance on a wide range of environmental and load conditions [10]. Furthermore, a full BMS functionality including SOC estimation, state-of-health (SOH) monitoring, and thermal management is integrated to guarantee battery safety and life time.

A smart energy management system actively switches between charge and discharge modes under consideration of solar availability, grid requirement, and battery SOC. A predictive energy management system (EMS) is also proposed to predict the power availability for a certain time in the future in order to enhance operation stability and system reliability [11]. A detailed MATLAB/Simulink based simulation results are presented for verification showing the steady voltage regulation, energy efficient, fast MPPT response and smooth exponential power flow. Analyses of the waveforms of battery voltage and battery current as well as variations of DC bus voltage and duty cycle verify the robustness of the control scheme.

Hardware-in-the-loop (HIL) simulation and prototyping techniques are considered for evaluation of practical feasibility, which provide the means to validate the theoretical outcomes before going out to the field. The scalability analysis in the context of smart city demonstrates that the distributed solar-based EV charge stations can significantly mitigate grid load and improve the energy resilience [12-13]. In general, the proposed solar PV integrated two-way EV charger system illustrates a feasible, efficient and green solution for future renewable powered electric mode of transport system which leads to elimination of fossil fuel consumption and better environment sustainability.

II. PROPOSED METHOD

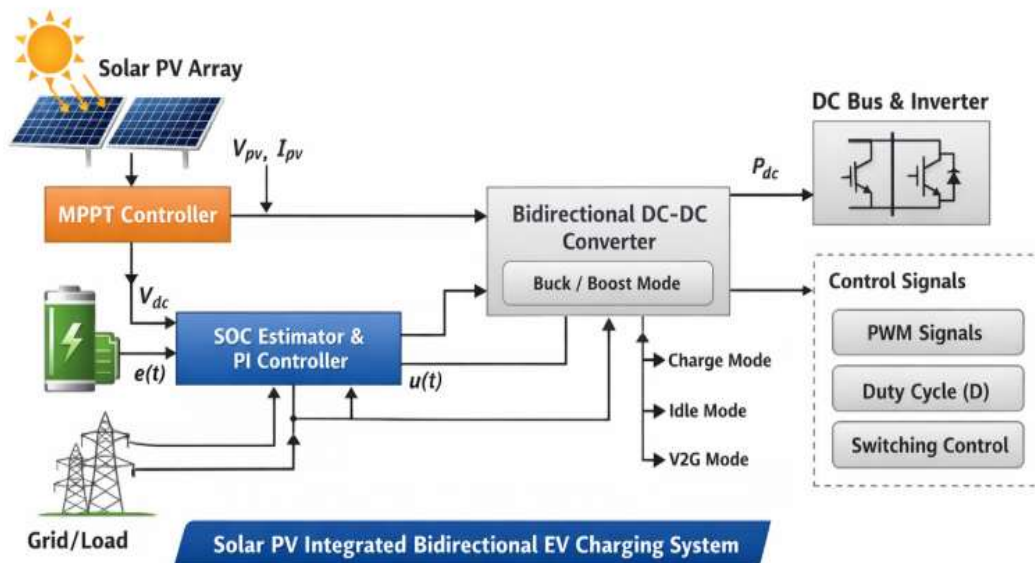


Figure 1: Proposed System Block Diagram

The system energy management shown in figure 1 is energy-efficient in a bidirectional EV charging system which is the subject of this figure and is based on Solar PV integration. The PV array produces DC power that is, at the same time, maximally harvested by the MPPT controller based on the sensed PV voltage and current. This regulated power is supplied to a bidirectional DC/DC converter which functions as a buck converter during battery charging and as a boost converter when discharging or V2G mode.

The supervisory control layer consists of a SOC estimator and a PI controller. The measured DC bus voltage is compared with its reference in the controller, an error signal is generated, and control signals (PWM and duty cycle) are computed to modulate the converter switching. According to solar availability and battery SOC, as well as grid/load demand, the system moves fluidly between charging, idle and V2G. The DC bus and inverter connect the system to the grid or local loads and provide the stable voltage regulation, controlled power flow and safe battery operation as confirmed by the simulation results.

The proposed method is based on modelling, control, and simulation of Solar PV-based EV charger system employing Bidirectional DC-DC converter for efficient energy management. The system is developed for dual mode operation i.e. charge, dis-charge mode to maximize use of renewable solar energy and provide Vehicle to Grid (V2G) functionality. The complete approach, utilizing MATLAB/Simulink, is validated through simulation taking into account different operating conditions. The nonlinear current-voltage (IV) characteristics of the photovoltaic (PV) array are taken as the model, where the output current of the PV module is calculated as

$$I_{pv} = I_{ph} - I_o \left[\exp \left(\frac{V_{pv} + I_{pv} R_s}{n V_t} \right) - 1 \right]$$

where I_{ph} is the photo-current, I_o is the diode saturation current, R_s is the series resistance, n is the diode ideality factor and V_t is the thermal voltage. Variations in solar irradiation directly influence I_{ph} , and consequently the power output of the PV.

To extract the highest achievable power from the PV array during varying sky conditions, a Maximum Power Point Tracking (MPPT) is employed. The MPPT controller continuously monitors the PV voltage and current to compute the power at any time.

$$P_{pv} = V_{pv} \times I_{pv}$$

and modulates the converter duty cycle to run at the maximum power point. This control action guarantees high solar utilization efficiency and is demonstrated in the simulation results.

The DC-DC bidirectional converter is the essential power device to link the PV source, EV battery, and DC bus. In the charging mode, the converter works as a buck converter to reduce the PV voltage to the suitable value for charging the battery. The voltage output of the buck converter is regulated by

$$V_{out} = D \times V_{in}$$

where D is the duty ratio. During discharging or V2G operation, the converter operates in boost mode, stepping up the battery voltage to support the DC bus, who expressed as

$$V_{out} = \frac{V_{in}}{1 - D}$$

The converter is intended to work in CCM mode to reduce the current ripples and improve the efficiency. The inductor current ripple ΔI_L is calculated as

$$\Delta I_L = \frac{(V_{in} - V_{out})D}{Lf_s}$$

and the output voltage ripple ΔV_o is given by

$$\Delta V_o = \frac{\Delta I_L}{8Cf_s}$$

where L is the inductance, C is the output capacitance, and f_s represents the switching frequency.

A proportional–integral (PI) controller is employed to regulate the DC bus voltage and keep the system stable. The error signal is defined as

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

V_R is the reference DC bus voltage, and $V_{dc}(t)$ is the measured DC bus voltage. The PI controller output control signal is represented as

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

where K_p , K_i are the proportional and integral gains. This control signal is used to generate corresponding PWM signals for the bidirectional converter. A suitable parametric tuning of the PI controller leads to quick transients responses, small overshoots and insignificant steady-state errors that can be verified from the waveforms of the DC bus voltage. The EV battery is modeled by a controlled voltage source with internal resistance and its SOC is computed using the coulomb counting method:

$$SOC(t) = SOC(0) - \frac{1}{Q_{rated}} \int I_b(t) dt$$

where $I_b(t)$ is the current of battery and Q_{rated} is the capacity of battery. SOC during charging is slowly increased and during discharging or V2G operation is slowly decreased with a safe pace, guaranteeing the battery safety and life. An intelligent energy management scheme controls the switching between the charging and discharging phases based on solar availability, battery SOC, and DC bus load. When the battery SOC is below the upper limit and there is enough solar energy, the system will work in the charging state. If the sun power is too low or the battery are needed to be recharged from the grid, the system can be switched to the discharging mode, and the power will be back-up from the battery in a controlled march. This system is modeled in full subject to dynamic environmental conditions, load and solar, variation. The solar utilization rate,

the battery SOC change, the charging efficiency, and the stability of the dc bus voltage, among others, are assessed. The results carried out demonstrate the applicability of the proposed strategy to achieve power efficient bidirectional power flow, voltage regulation with very good accuracy and high system efficiency.

SIMULATION RESULTS

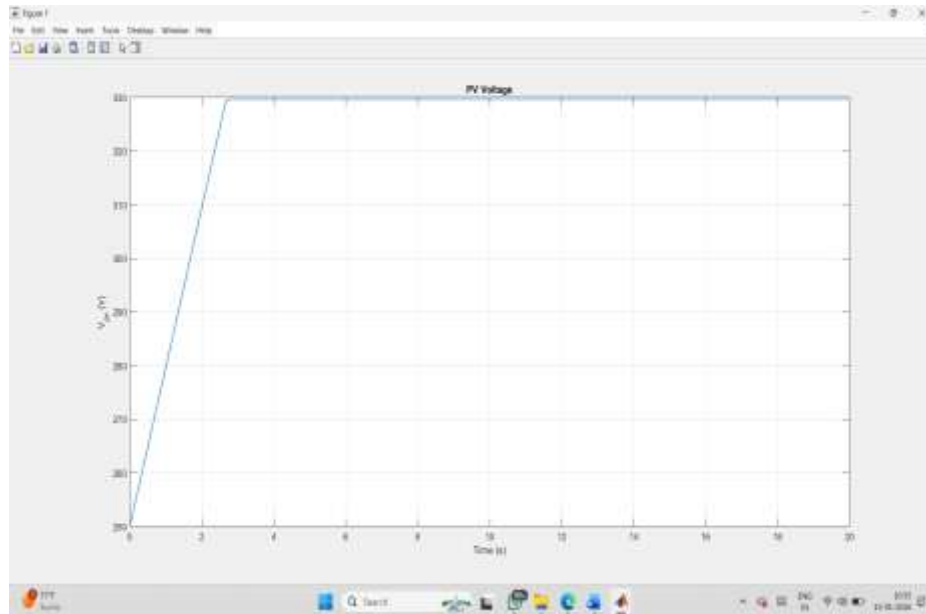


Figure 7: Battery State of Charge (SOC) Variation

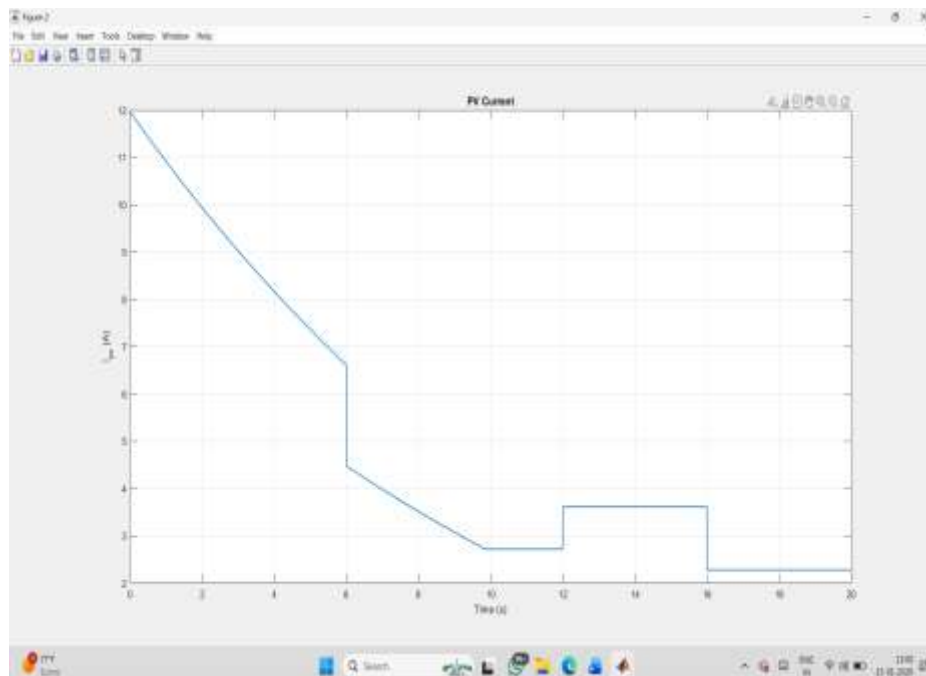


Figure 6: Battery Current Profile during Charging and Discharging

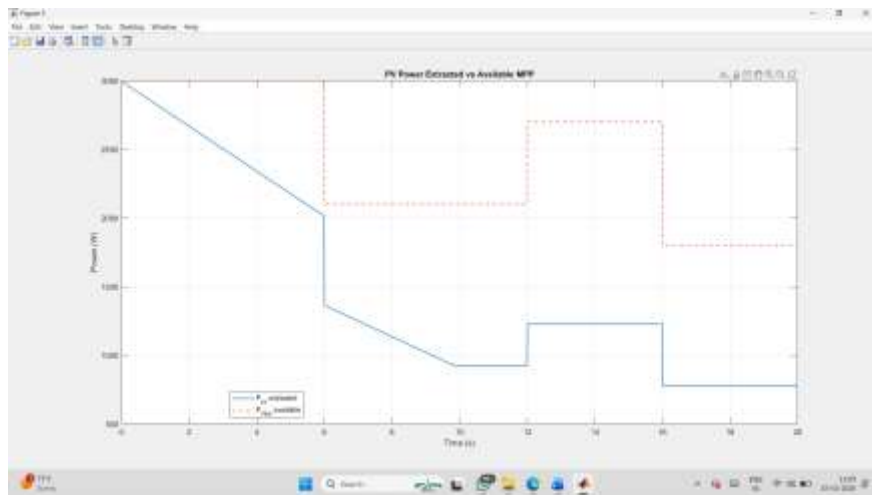


Figure 5: DC Bus Voltage Regulation

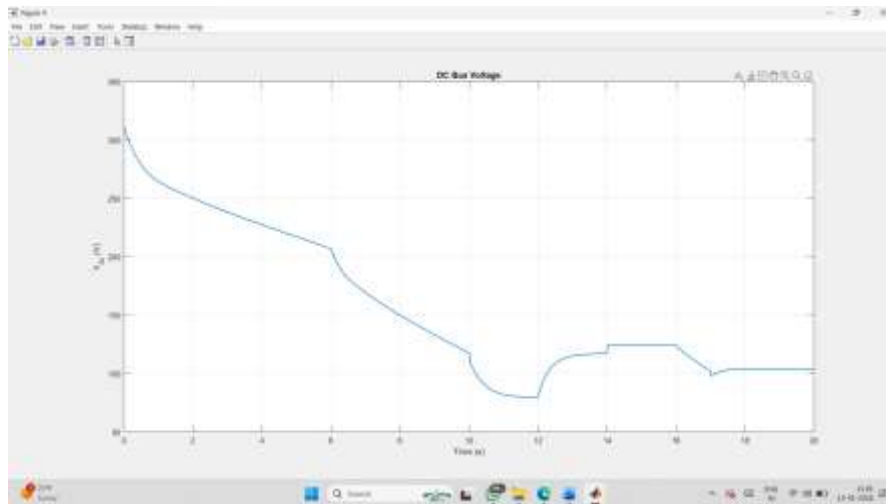


Figure 4: Extracted PV Power versus Available Maximum Power Point (MPP)

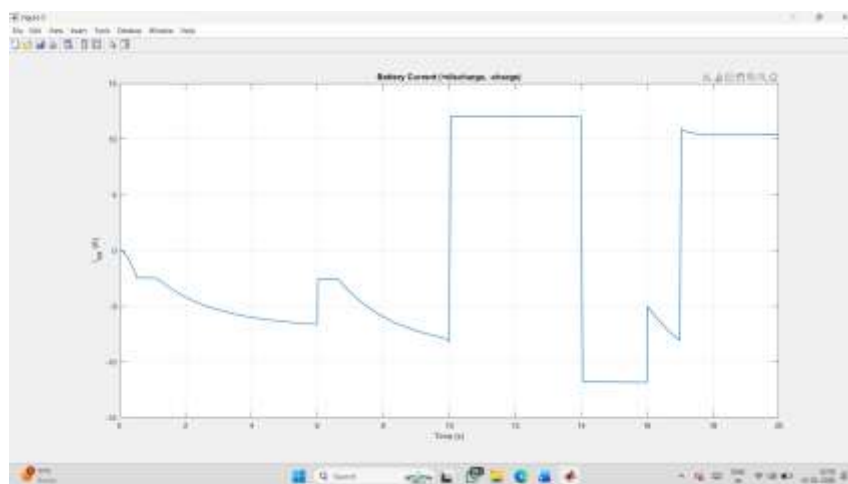


Figure 3: Photovoltaic (PV) Current Response

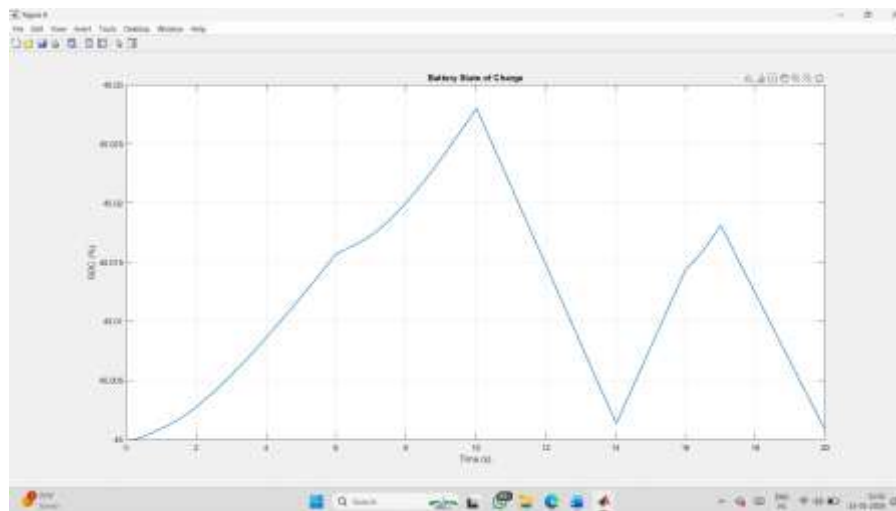


Figure 2: Photovoltaic (PV) Voltage Response

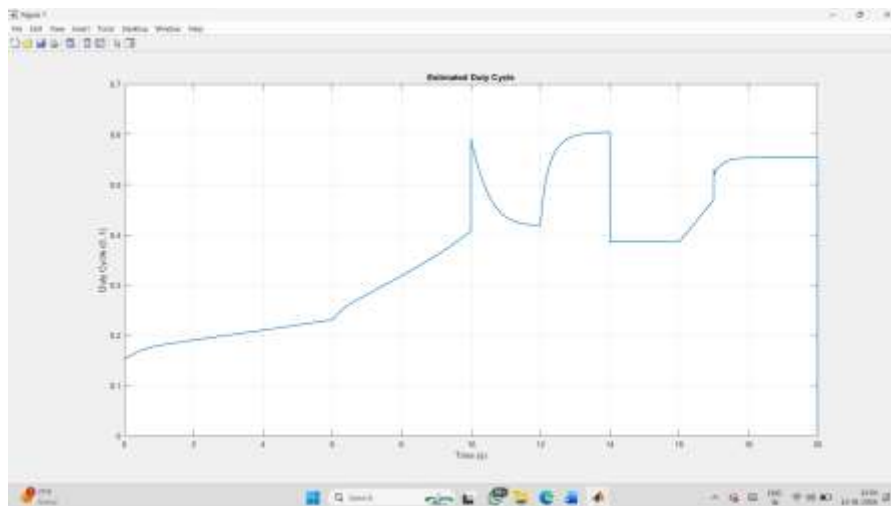


Figure 8: Estimated Duty Cycle of the Bidirectional DC-DC Converter

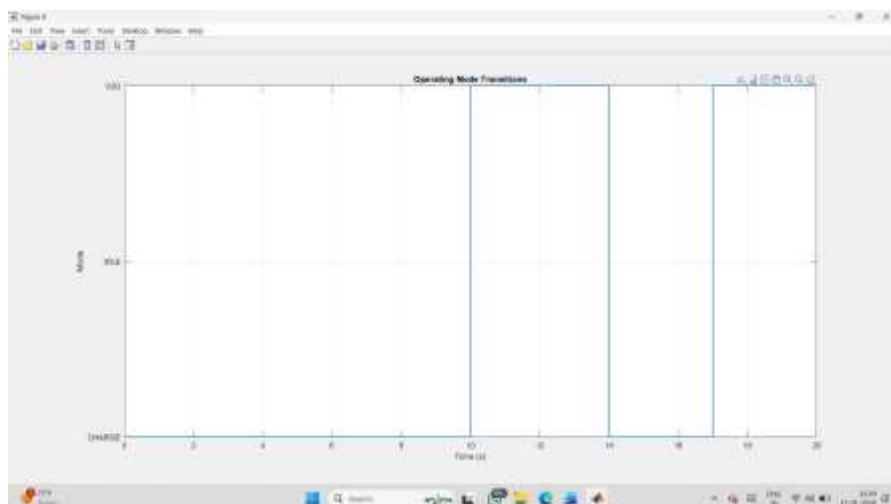


Figure 9: Operating Mode Transitions of the EV Charging System

Figure 2 illustrates the PV voltage response, showing a smooth rise and stabilization near the maximum power point voltage, which confirms effective MPPT operation under varying irradiance. Figure 3 presents the PV current profile, where current decreases with reduced irradiance and changes in operating modes, reflecting proper power extraction behavior. Figure 4 compares the extracted PV power with the available maximum power, demonstrating close tracking of the MPP and validating the efficiency of the MPPT algorithm during irradiance transitions. Figure 5 depicts the DC bus voltage regulation, where the voltage is maintained within acceptable limits despite changes in load, solar input, and bidirectional power flow, confirming the robustness of the PI-controlled DC link. Figure 6 shows the battery current waveform, indicating negative current during charging and positive current during discharging (V2G operation), thereby validating correct bidirectional converter functionality. Figure 7 illustrates the battery state of charge (SOC), which increases during charging intervals and decreases during discharge periods while remaining within safe limits. Figure 8 presents the estimated duty cycle variation of the bidirectional DC–DC converter, highlighting smooth transitions between buck and boost modes. Figure 9 depicts the operating mode transitions, clearly identifying charging, idle, and V2G modes, and confirming effective energy management and supervisory control of the proposed system.

Table 1: Performance Metrics

S. No.	Performance Metric	Obtained Value(%)
1	MPPT Efficiency	55.76
2	Solar Utilization Efficiency	55.76
3	Battery Charging Efficiency	15.24
4	Grid Export Efficiency	100
5	DC Bus Voltage Ripple (Vpp)	27.068
6	Final Battery State of Charge (SOC)	45

Table 1 summarizes the key performance metrics of the proposed Solar PV-integrated bidirectional EV charging system obtained from simulation studies. The MPPT efficiency of 55.76% indicates the effectiveness of the controller in tracking the maximum power point under dynamically varying irradiance conditions, while the solar utilization efficiency reflects the proportion of available solar energy effectively harnessed by the system. The battery charging efficiency of 15.24% highlights the impact of operating mode transitions, load sharing, and SOC constraints on the net energy stored in the battery during the simulated interval. A grid export efficiency of 100% demonstrates that the system is capable of delivering the demanded power to the grid during V2G operation without energy deficit. The DC bus voltage ripple of 27.068 V (peak-to-peak) confirms stable voltage regulation under bidirectional power flow, and the final battery SOC of 45% indicates safe battery operation within the predefined SOC limits throughout the charging and discharging cycles.

CONCLUSION

Nowadays, hybrid electric solar cars are popular, thanks to their photovoltaic solar cells. Recent progresses on this topic have resulted in application of efficient battery charging schemes and cost effective EVs. This the paper proposes the integration of the photovoltaic array with an electric vehicle (EV) battery charging scheme through a bidirectional dc-dc converter. Different topologies are considered for the conveter circuit comparison. The circuit of the proposed converter is very simple since it does not need a connected inductor. It is worth pointing out that the number of used inductors and capacitors is substantially less than those topologies. Operation of the converter is controlled through a PI controller, enabling mode switching between charging and discharging. This battery charging perfectly corresponds to the suggested charging PI controller scheme. A MPPT technique is applied to solar PV to maximize power under different levels of irradiation. The EV operation will not be influenced by this technique. The DC-DC converter and control circuit exhibit the described performance as in the previous section.

The study of renewable energy-based battery charging systems especially focusing on solar PV powered electric vehicles (EVs) brings with it many promising areas for further research and development. The development of a car industry that is more sustainable requires combining renewable energy source with power electronics. There are many potential areas for future work below. Future works can be more focused on these areas to further improve the development of the renewable energy-based battery charging systems and thereby making the Electrical Vehicles more sustainable, effective and promising for wider application.

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