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Design of High Gain Active Balancing Multi Port Converter for PV Based EV Battery Charging System

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ABSTRACT: Electric Vehicles (EVs) are emerging as a sustainable alternative in transportation sector, leading to the shift away from fossil fuel-based vehicles. This paper presents a high gain DC-DC multi-port converter for EV charging applications, enabling efficient integration of multiple energy sources such as Photovoltaic (PV) systems, batteries, supercapacitors and other DC sources. To step up the High-Gain DC-DC active balancing multi-port converter for PV-based EV charging applications. The proposed system enhances voltage gain, optimizes power balancing among multiple energy sources, and improves energy conversion efficiency by integrating advanced converter and PI controller. The multi-port converter ensures continuous power flow, reducing ripple current, and improving overall power quality. The developed system is evaluated through MATLAB simulations, demonstrating stable operation, reduced switching losses and improved battery performance. The presented converter achieves the highest efficiency of 93%, outperforming traditional methods. This research work contributes to the advancement of clean energy-driven transportation, promoting widespread EV adoption while reducing dependence on fossil fuels. The proposed system ensures efficient and sustainable EV charging, supporting the transition towards a greener future.

Keywords: Renewable Energy Sources (RES), Photovoltaic (PV), Electric Vehicle (EV), Multi-Port Converter, Battery.

1. Introduction

RES are substituting conventional fossil fuel-based energy sources due to rising global energy demand and environmental concerns. Coal, oil, and natural gas are instances of fossil fuels that have long served as the foundation for economic and industrial growth. Its drawbacks include air pollution, greenhouse gas emissions, global climate change, and limited supplies. A continued dependence on fossil fuels contributes to rising Carbon Dioxide (CO_2) levels, which accelerate global warming and environmental degradation [1]. Additionally, geopolitical tensions and fluctuating fuel prices create instability in energy markets. To address these challenges, RES such as solar, wind, hydro, and biomass have gained prominence due to their sustainability and minimal environmental impact. Since PV energy is readily available, produces clean energy, and is suitable for decentralized energy generation, it has become one of the most promising and extensively used renewable energy sources [2].

Solar energy is available in almost every region of the world, making it an excellent solution for off-grid and on-grid power generation. The advancements in PV technology, along with decreasing costs of solar panels and energy storage systems, have accelerated the adoption of solar power in residential, industrial, and transportation sectors. An intermittent nature of PV energy, however, is a major problem because solar power generation is dependent on the availability of sunlight, which fluctuates during day and it is influenced by meteorological factors. Thus, effective power management and storage solutions are necessary for integrating PV energy into power systems to provide a steady and dependable power supply. EV charging infrastructure is one of the main uses for PV energy. With global push toward sustainable transportation, EVs are rapidly replacing traditional internal combustion engine (ICE) vehicles, significantly reducing carbon emissions and dependence on fossil fuels [3-4]. However, conventional EV charging stations are often connected to the electrical grid, which, in many regions, is still powered by fossil fuel based power plants [5].

A PV-based EV battery charging system offers a sustainable solution by directly utilizing solar energy for charging, reducing the load on conventional power grids and ensuring a cleaner energy supply. To ensure efficient energy conversion in PV-based EV charging systems, a power management system is required to regulate voltage and current flow [6-7]. In power electronics, proportional-integral (PI) controllers are frequently used because of their straightforward design, simplicity in implementation, and efficiency in steady-state operation. PI controller regulates the charging voltage and current, ensuring stable operation [8]. However, it has several drawbacks, including poor dynamic response, difficulty in handling sudden load variations, sensitivity to parameter changes, and inefficiency in nonlinear systems [9-10]. These limitations make PI controllers less suitable for applications where fast response and adaptability to changing conditions are required. In addition to control strategies, the choice of DC-DC converters is crucial in PV-based EV charging systems. Conventional DC-DC converters such as buck [11], boost [12], buck-boost [13], and bidirectional converters [14-15] are commonly used due to their high efficiency, compact size, and ability to step up or step down voltage as required. Though, these converters face significant drawbacks, including limited voltage gain, high switching losses, reduced efficiency under varying loads, and inadequate power balancing in multi-port configurations. These issues result in inefficient power transfer, increased heat dissipation, and reduced lifespan of system components.

To address these limitations, this paper proposes a high-gain active balancing multi-port converter designed specifically for PV-based EV battery charging applications. The proposed converter aims to enhance voltage gain, improve power balancing among multiple energy sources, and optimize energy conversion efficiency. The proposed system contributes to the development of next-generation PV-based EV charging solutions, enabling the widespread adoption of clean energy-driven transportation systems and reducing dependency on fossil fuel-based power grids.

2. Recent Works

Binxin Zhu *et al* (2020) [16] have proposed a single switch high step-up Zeta converter for a productive grid-connected renewable energy management system. By reducing the losses usually associated with isolated converters, the non-isolated architecture of the Zeta converter enables it to function with high efficiency. This converter is ideal for grid-tied renewable energy systems where optimal energy delivery requires reducing losses. Nonetheless, it experiences significant voltage stress, which impairs system performance.

Yao *et al* (2021) [17] have demonstrated grid-connected PV systems with buck converters. A buck converter's main function is to effectively lower voltage In grid connected PV systems, a buck converter reduces voltage with a minimal power loss, even when output voltage of the PV array surpasses load or grid demand.. Applications where DC connection voltage must be kept within specific bounds for grid compliance benefit greatly from this efficiency. Nevertheless, it produces switching noise and Electromagnetic Interference (EMI).

Yanhui Huang *et al* (2021) [18] have preesnted a bidirectional buck boost converter that integrates with a PV system's grid interface. An adaptability of this conveter makes it possible to manage variations in solar irradiance and guarantees that the system will function effectively in a range of environmental circumstances. Additionally, especially in systems with significant PV penetration, this converter enhances the overall power quality of the electricity fed into the grid. However, it cannot increase the magnitude of fluctuations or the converter's efficiency.

Shawky*et al* (2021) [19] have developed three-phase SEPIC converter to lower order harmonics in RES powered grid tied applications. For higher-power applications, a three-phase SEPIC converter is more appropriate than a single-phase one. In addition to improving power quality and reducing harmonics, the converter also minimizes needless switching losses in other power system components, such as transformers and inverters. On the other hand, high peak currents put the power transistor in a converter under more stress and raise the possibility of failure.

Arshad Mahmood et al (2021) [20] have proposed a high gain, non-inverting DC to DC boost converter with a constant input current. With just one switch, the developed converter lessens the voltage load on switching devices. Because it achieves a higher gain at a shorter duty cycle and maintains a constant input current, it is suitable for applications like solar PV systems. Constant input current is maintained in order to improve RES performance and minimize ripple. Because the converter operates across a wider duty cycle range, it provides greater control flexibility. The large voltage gain causes considerable stress on other components even when the voltage stress on switching devices is decreased.

3. Proposed Work Explanation

To provide a steady and effective power supply for EV charging and other load applications, the proposed system incorporates a High-Gain DC-DC Multi-Port Converter that integrates several energy sources, such as a PV system, battery, super capacitor, and DC source. To maintain stable operation, the battery and super capacitor are integrated to store excess energy and provide backup power during low solar energy periods. The DC source acts as an auxiliary power supply, ensuring seamless energy availability in case of extreme variations in renewable energy generation. All these energy sources are connected to the High-Gain DC-DC Multi-Port Converter, which performs voltage boosting and power balancing functions. The converter efficiently steps up DC voltage from PV system and other sources to the required level (V_{DC}) before supplying it to the load. This high-gain converter ensures that the system meet the power demand of EV charging or other applications while minimizing losses and improving energy conversion efficiency. Figure 1 presents the proposed work block diagram.

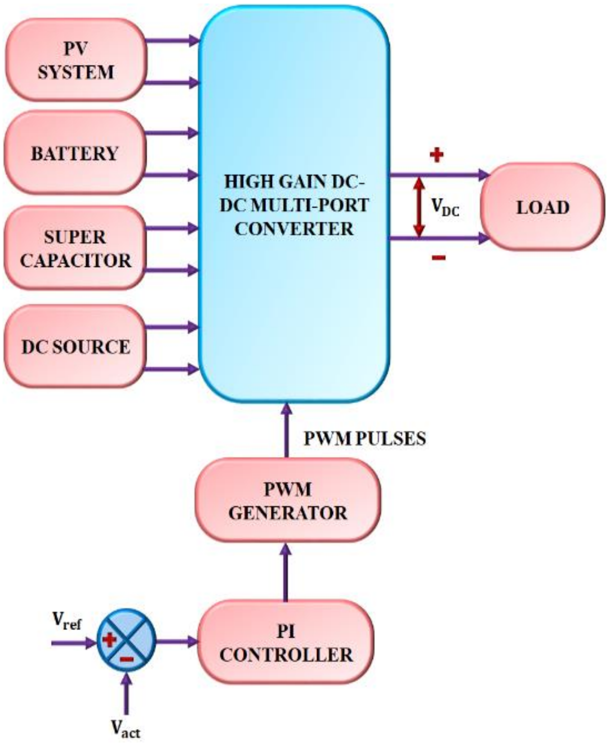

Figure 1: *Proposed Work Block Diagram*

To achieve accurate voltage regulation and system stability, a PI Controller is implemented. The PI controller continuously monitors system by comparing the reference voltage (V_{ref}) with an actual output voltage (V_{act}). The difference (error signal) is processed to adjust duty cycle of the converter, ensuring that output voltage remains stable under varying load and input conditions. The error signal from the PI controller is fed into PWM Generator, which generates PWM pulses to control the switching of the converter. These pulses regulate the switching operation of power semiconductor devices inside the multi-port converter, dynamically adjusting the power transfer and voltage levels. By precisely controlling the switching process, the system minimizes power losses, enhances energy efficiency, and maintains continuous power delivery to the load.

3.1 PV system

When the PV system is exposed to solar radiation (G), it generates a current (I_{pv}). The corresponding circuit for PV system is shown in Figure 2(a), which shows that the output terminal has both voltage (V_{pv}) and current (I_{pv}). The current-voltage (I-V) characteristics are be expressed through the use of Kirchhoff's current law.

$$i_{pv} = I_{pv} - I_0\left[exp\left(\frac{v_{pv}+i_{pv}R_s}{N_sV_t}\right) - 1\right] - \frac{v_{pv}+i_{pv}R_s}{R_{sh}} \tag{1}$$

PV system parameters include dark-saturation current (I_0), the number of series cells in the PV panel (N_s), the series resistance (R_s), and the shunt resistance (R_{sh}). The PV system's thermal voltage, represented byV_t, is determined by

$$V_t = \frac{aK_bT}{e} \tag{2}$$

The diode ideality factor is expressed as (a) in Equation (2), with the contributions of junction temperature (T), Boltzmann's constant (k_b), and electron charge (e). PV system circuit diagram is presented in Figure 2.

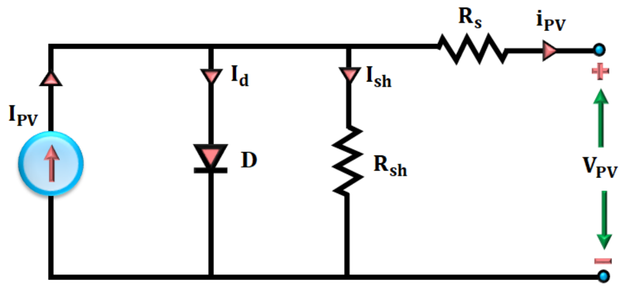

Figure 2: *Equivalent circuit for a PV system*

The PV system power output is determined by,

$$P_{pv} = v_{pv} \times i_{pv} \tag{3}$$

MPP is a single point that exists for all sun irradiation levels. At this point, the PV system reaches its maximum value. To increase the voltage generated by PV converter operation is crucial.

3.2 High-Gain DC-DC Multi-Port Converter

Figure 3 illustrates the proposed multiport DC-DC converter, which uses just four IGBT switches to connect two distinct loads and three separate DC sources. Port 1 has a PV attached, Port 2 has a battery, and Port 4 has a super capacitor. A DC link V_0in the proposed architecture has two ports for loads with two distinct voltage levels. The inductors L_{dw} and L_{up} power buffering function helps to transfer energy across ports. The capacitors for PV, battery, Port-3 load, fuel cell, and DC link are denoted by C_1,C_2 ,C_3 ,C_4 and C_5respectively. The corresponding currents for the port-3 load, fuel cell, and DC link are V_1 =V_{PV}, V_2 =V_{bat}, V_3 =V_{R3}, V_4 =V_{FC}. DC link and Port-3 loads are denoted by $R_O$andR_3, respectively. Even in the event that the PV is unavailable, the proposed topology may accomplish PV MPPT, battery charging and discharging, and DC link voltage regulation.

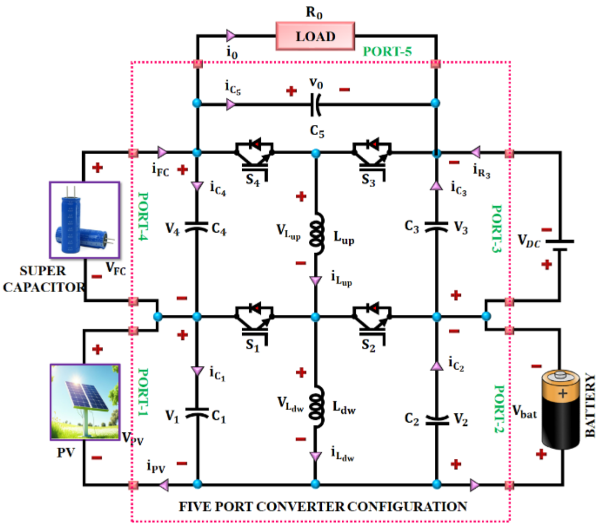

Figure 3: *Multiport DC-DC converter*

There are two possible modes of operation for the proposed multiport topology, depending on the PV's availability.

Mode-I (available PV and Supercapacitor): The loading state determines whether the battery charges or discharges.

Mode-II (no PV): The battery and Supercapacitor are both managed to satisfy the load demand. The top switches S_3 and S_4(duty cycle d_4) govern DC link voltage in all operating modes, while the bottom switches S_1 and S_2 (duty cycle d1) regulate the power generated by the PV or the battery. Duty cycle, denoted by the slight letter, is a time-varying variable. D_1 is controlled to achieve MPPT, or perturb and observe technique (P&O), when PV is available; otherwise, it regulates battery power. Port-1 and port-2 are lower ports and upper ports (port-3, port-4, and port-5) are thus individually controlled by d_1 and d_4, respectively. Three operating scenarios be identified based on the values of d_1 and d_4: (1) d_1> d_4, (2) d_4> d_1, and (3) d_4 = d_1.Furthermore, only three of these states are feasible when d_1 is greater than or less than d_4, according to the operational situations listed above. There are only two conceivable states when d_1 = d_4. To maintain power balance between sources and loads, a battery is charged when PV power exceeds demand of the loads.

3.3 PI controller

As a voltage controller, the PI controller lowers voltage error and determines the optimal solution using the current signal. To modify the PI controller, the proportional and integral gains, Kp and Ki, are displayed in Figure 4.

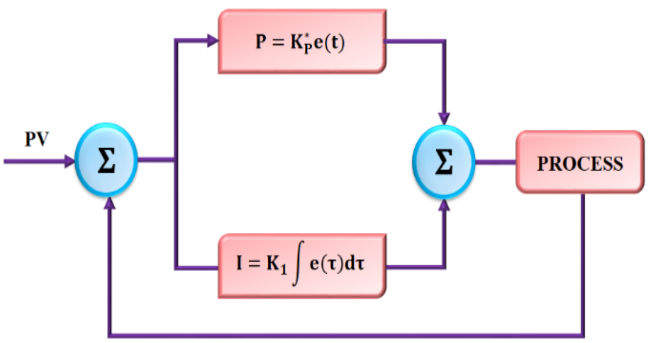

Figure 4: *Modelling of PI controller*

$$u(t) = k_p.e(t) + K_i.\int_0^t e(t)dt \tag{4}$$

Because it depends on only a few of the integral conditions of the actuating signal, the output response acts as an integral error compensator. The PI controller proposes two terms for the compensation type, one of which is proportional to the actuating signal and the other integral to it. This controller is known as a proportional plus integral controller, or PI controller.

4. Results and Discussion

This section discusses an overall results of the Matlab/Simulink thorough overview for the proposed system. Furthermore, the comparative analysis is made over with the traditional methods and obtained outcome of the proposed work are examined to expose the significance of the developed work. Following Table 1 illustrates parameter specification for the proposed topology

Table 1: *Parameter specifications*

Parameter	Rating
Peak power	$10kW$
$Open\ circuit\ voltage\ V_{OC}$	$37.25V$
Number of cells connected in series N_s	36
$Short\ circuit\ current\ I_{SC}$	$8.95A$
Multiport DC-DC converter	
Inductor (L_{up}, L_{dw})	$1mH$
Capacitor (C_1, C_2, C_3, C_4)	100µF
Switching Frequency	$10kHz$
Duty cycle	0.5

Figure 5: *Hardware setup*

Figure 5 shows a high-gain active balancing multi-port converter for a PV-based EV battery charging system implemented on hardware. To guarantee effective energy conversion and steady power delivery, the system is made up of several interconnected circuit boards, such as DC-DC converters, PI controllers, super capacitors, and battery management systems. To verify the system's functionality, real-time voltage waveforms are monitored using an oscilloscope. The prototype shows that designed system is feasible in practice and highlights its potential to optimize voltage regulation, improve power quality, and increase overall energy efficiency in renewable energy applications.

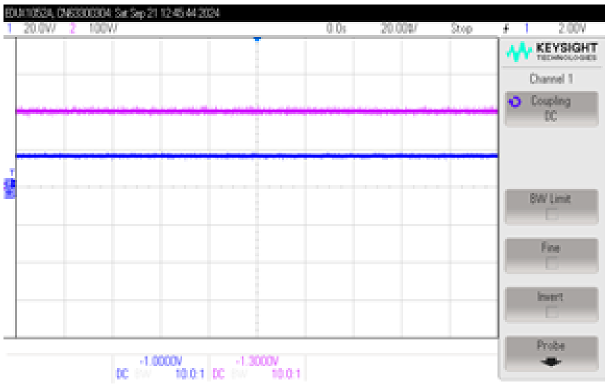

Figure 6: *Converter Input and Output Voltage Waveform*

The waveform demonstrating voltage characteristics of proposed converter is presented in Figure 6. It is seen that with respect to input voltage of 12V, the proposed converter responds with boosted voltage measuring 24V.

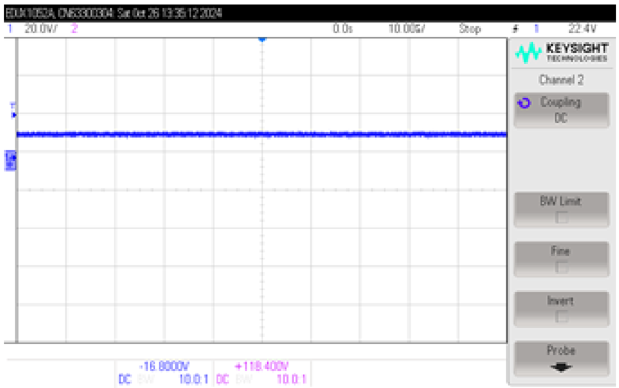

Figure 7: *Super capacitor Voltage Waveform*

The proposed converter utilizes supercapacitor with one of the source and the corresponding output is presented in Figure 7. It is seen that, voltage of supercapacitor is noticed to be maintaining at 12V constantly.

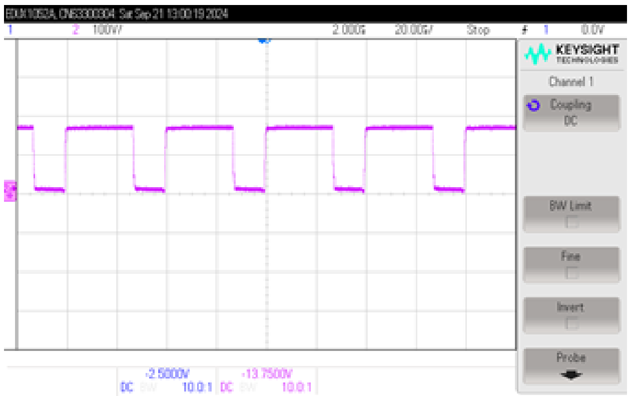

Figure 8: *Converter Pulse Waveform*

The proposed converter utilizes PI controller for regulation of converter operation. The generated pulses by PWM generator is presented in Figure 8. According, to the pulses generated the converter function is performed.

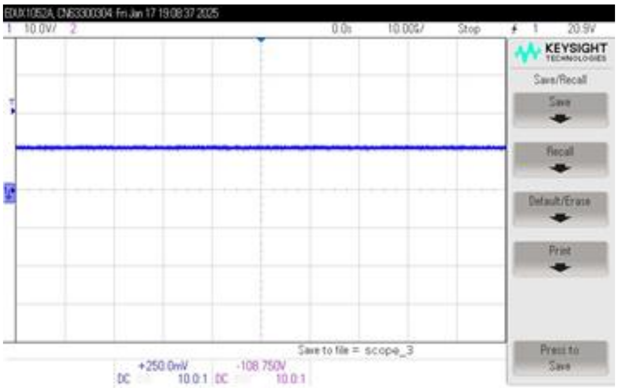

Figure 9: *Battery Voltage Waveform*

The voltage utilizing from battery to the proposed multiport converter is presented in Figure 9. It is noticed that, a stabilized voltage of 12V is fed as input to the converter, which is boosted and fed to load.

Table 2: *Analysis of converter Efficiency with existing*

Converter Reference	Efficiency (%)
Interleaved DC–DC SEPIC PFC converter	90
Interleaved landsman converter	91.5
Non-isolated high gain quadratic boost converter	92
Proposed Converter	93

Table 2 shows various converter types and their corresponding efficiency percentages in a comparative analysis of converter efficiency. The Interleaved Landsman converter has an efficiency of 91.5%, while the Interleaved DC-DC SEPIC PFC converter has an efficiency of 90%. At 92%, the non-isolated high gain quadratic boost converter has a slight greater efficiency. Additionally, the Proposed Converter outperforms an existing system with the highest efficiency of 93%. The proposed converter's ability to outperform conventional designs is demonstrated by this comparison, which also shows the gradual increases in converter efficiency.

5. Conclusions

The proposed high-gain active balancing multi-port converter effectively addresses the challenges associated with PV-based EV battery charging systems, ensuring enhanced voltage regulation, efficient power distribution, and improved system stability. By integrating the proposed converter designs and intelligent control mechanisms, the system effectively manages power fluctuations caused by the intermittent nature of solar energy. The inclusion of a PI controller further refines voltage control, minimizing fluctuations and ensuring a steady and reliable power supply to the battery and grid. The simulation results show increased battery performance, less switching losses, and stable operation, confirming the efficacy of the proposed approach. The converter outperforms conventional techniques with a high energy conversion efficiency of 93%. The findings of multi-port converter design are a scalable and adaptable solution for integrating RES into modern EV charging networks. Ultimately, this research supports the global transition towards clean energy-driven transportation, reducing dependence on fossil fuel-based power grids and promoting a more sustainable and eco-friendly energy ecosystem.

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