

Chapter 7

Solar-Integrated Interleaved Direct Current Charging System for Electric Vehicles

7.1 Introduction

The increasing interest in solar-to-vehicle (S2V) charging systems is driven by the growing adoption of EVs and the demand for sustainable energy solutions. Recently, there has been a significant increase in the focus on renewable energy sources due to environmental concerns and the escalating costs of fossil fuels. The most widely used renewable energy source nowadays is photovoltaic systems, which use solar radiation to generate electrical energy [118,190]. A photovoltaic array's MPP (maximum power point) can be monitored by varying duty cycles of the DC/DC converter using MPPT techniques. The MPPT algorithm identifies the optimal duty cycle by comparing the voltage and current of the PV panel up to the reference value. This reference value is generated using a specific MPPT algorithm. Consequently, designing efficient MPPT techniques is crucial to extracting the maximum available power, especially in large solar PV setups. Various MPPT techniques, including the incremental conductance (INC) and perturb and observe (P&O) algorithms, have been extensively studied in the literature. The P&O algorithm is a popular MPPT method recognized for its simplicity and computational efficiency [191,192].

Research on EV systems goes beyond analyzing the components and driving mechanisms found in cars. Charging strategies are also vital for enhancing the sustainability of EVs in the transportation sector. A DC/DC converter, a bidirectional or boost converter, is essential to energy systems. It helps control the flow of harvested energy from sources like solar panels or wind turbines. This means the energy can be used efficiently in EVs, renewable energy systems, and industrial power supplies. The converters ensure the energy is managed well and can be integrated into different power systems to meet specific needs [193,194]. These converters are essential for harnessing these energy sources. In the past, SCRs were used to regulate these converters. Modern switches like MOSFETs and IGBTs can operate across various frequencies [195]. Increasing the operating frequency can reduce the size and cost of inductors and capacitors [196]. Fast battery charging is essential for electric vehicles to compete with petrol stations. This research illustrates the feasibility of powering an EV solely using solar energy. Solar photovoltaic (PV) arrays are widely recognized as the most accessible forms of renewable energy to deploy, and their affordability continues to improve, making them increasingly appealing. Consequently, many EV owners now prefer PV array-based vehicle charging [192,197].

This chapter introduces a novel solar-integrated, interleaved direct current (DC) charging method for EVs, utilizing Maximum Power Point Tracking (MPPT) technology. The system leverages specialized coil designs within power-enhancing devices to enhance performance and durability, contributing to reduced energy waste and environmental sustainability. A central theme of this work is the seamless integration of photovoltaic (PV) battery storage with EV battery systems, optimizing the charging process through an advanced MPPT algorithm. This ensures solar panels consistently operate at their peak power output, even under fluctuating environmental conditions. Through extensive Simulink/MATLAB simulations, the proposed charging system achieves an impressive energy efficiency of 96.8%. The results underscore the effectiveness of the interleaved boost converter in mitigating ripple effects and minimizing switching losses, leading to significant improvements in system reliability and overall efficiency. This advanced charging approach represents a meaningful advancement in sustainable energy solutions for electric vehicles, supporting the transition to cleaner and more efficient modes of transportation.

An intermediate DC/DC converter and a bidirectional converter are required to integrate the PV array with the EV battery [194,198]. The interleaving technique, or multi-phasing, utilizes a parallel configuration of multiple switches, diodes, and inductors connected across a single capacitor. In addition to reducing output current and voltage ripples, this technique effectively minimizes the size of the filter components. Interleaving techniques can potentially reduce losses using 180-degree phase shift ripple cancellation. [13, 14]. The Battery Management System (BMS) is an essential component in regulating the energy stored in the battery to ensure dependable, effective, and secure vehicle operation. The BMS minimizes the stress on the battery when charging and discharging and avoids unanticipated current surges that might result in high discharge rates. It comprises sensors, a power delivery unit, and communication protocols [15, 16]. Additionally, the BMS is responsible for cell balancing, determining the state of charge (SoC), estimating the driving range, and performing various other auxiliary functions. The Energy Management System (EMS) is essential for optimizing driving range, prolonging battery life, enhancing efficiency, and ensuring the reliable operation of electric EVs. The primary function of the SoC is to facilitate communication between the vehicle and the battery's inherent state, thereby preventing overcharging and excessive discharging of the battery [17]. Traveling costs are also necessary for EV users. Considering the travel cost for EV users is crucial to ensure that the distance between the EV and charging stations is convenient, thereby enhancing user satisfaction. A traditional interleaved boost converter (IBC) produces a high voltage gain. It also reduces input current ripples and improves power transfer. The interleaved quadratic high-gain chopper further enhances this [18].

7.2 Solar PV- Cell Model

A PV system is a technology that converts sunlight into electricity. It is becoming increasingly crucial in power electronics for several reasons. PV systems can be used with energy storage devices, such as batteries, to offer a reliable and consistent power source even without direct sunshine. This makes photovoltaic installations an invaluable tool for maintaining the grid's stability and resilience [19]. The circuit

model of a PV cell, illustrated in Fig. 7.11, is a mathematical representation that depicts the electrical characteristics of a PV cell. This model is used to design and optimize PV systems across various scenarios. The PV cell's generated current I_{ph} is expressed by the current source, the diode explains its non-linear behavior, and the internal resistance of the cell is described by the resistors R_{sh} and R_s .

A PV cell's current-voltage curve is obtained by varying the cell's voltage and measuring the corresponding current. This curve is essential for designing PV systems as it identifies the cell's MPP, the optimal combination of voltage and current for maximizing power output. The equation that describes the current-voltage characteristics of a PV source modeled as a single diode can be expressed as follows:

$$I_{pv} = I_{ph} - I_d - \left(\frac{V_{pv} + R_s I_{pv}}{R_{sh}} \right) \quad (7.1)$$

$$I_{pv} = I_{ph} - I_0 \left[\exp \left(\frac{V_{pv} + R_s I_{pv}}{V_T A_d} \right) - 1 \right] - \left(\frac{V_{pv} + R_s I_{pv}}{R_{sh}} \right) \quad (7.2)$$

where I_0 is cell reverse saturation current. V_{pv} denotes the voltage of the PV cell. I_{pv} represents the current of the PV cell. $V_T = \frac{kT}{q}$ is the thermal voltage. The electron charge q is $1.602 \times 10^{-19} C$. The Boltzmann constant k is $1.38 \times 10^{-23} J/K$. The photo-current I_{ph} can be expressed as

$$I_{ph} = [I_{ph1} + K_I(T - T_0)] \frac{R}{R_1} \quad (7.3)$$

$$I_{ph1} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc} \quad (7.4)$$

The reverse saturation current I_0 can be expressed as

$$I_0 = \frac{I_{sc} + K_I(T - T_0)}{\exp \left(\frac{V_{oc} + K_v(T - T_0)}{V_T A_d} \right) - 1} \quad (7.5)$$

7.2.1 Factors Affecting Solar Power

(i) Direction of Sun

The direction of the sun significantly impacts the performance of PV solar panels. For optimal energy production, panels should be oriented to capture the maximum

amount of sunlight throughout the day. In the northern hemisphere, this typically means facing the panels south, while in the southern hemisphere, they should face north. Additionally, adjusting the tilt angle based on the latitude and seasonal sun path can further enhance the solar panels' energy capture and overall efficiency.

(ii) Age

As solar panels age, their quality deteriorates due to corrosion, delamination, and other issues. Additionally, the material properties can change over time. Consequently, the power output of the solar panels decreases with age. Each year, solar panels experience a slight reduction in efficiency.

(iii) Temperature

Temperature significantly impacts the performance of PV solar panels. High temperatures can reduce the efficiency of solar cells by increasing their resistance, which lowers their overall output. Conversely, lower temperatures can enhance efficiency. Effective thermal management, such as using cooling systems or selecting materials with better thermal properties, is crucial to maintaining optimal performance and prolonging the lifespan of PV solar panels. Monitoring and controlling temperature variations helps in achieving consistent energy production. The effect of temperature change on I-V and P-V curves is shown in Figure.

(iii) Irradiance

Irradiance is a critical parameter in the performance of solar photovoltaic (PV) systems. It refers to the power of solar radiation received per unit area, typically measured in watts per square meter (W/m^2). Understanding irradiance is essential for predicting the energy output of PV systems and optimizing their design and

operation. As solar irradiance increases on the solar cells, the current increases significantly, whereas the change in open-circuit voltage is minimal. Consequently, the output power increases with higher irradiance levels. High-intensity sunlight yields maximum power compared to low-intensity light. The impact of varying irradiance on the I-V and P-V curves is illustrated in the figure.

(iv) Shading

Shading is a significant factor affecting the performance and efficiency of photovoltaic (PV) solar systems. It occurs when objects such as trees, buildings, clouds, or even dirt and debris partially or completely block sunlight from reaching the solar panels. Shading can lead to a substantial reduction in the energy output of a PV system due to the unique characteristics of solar panels and their electrical configurations. Partial shading of solar panels may result in many local MPPs shown in the figure [199].

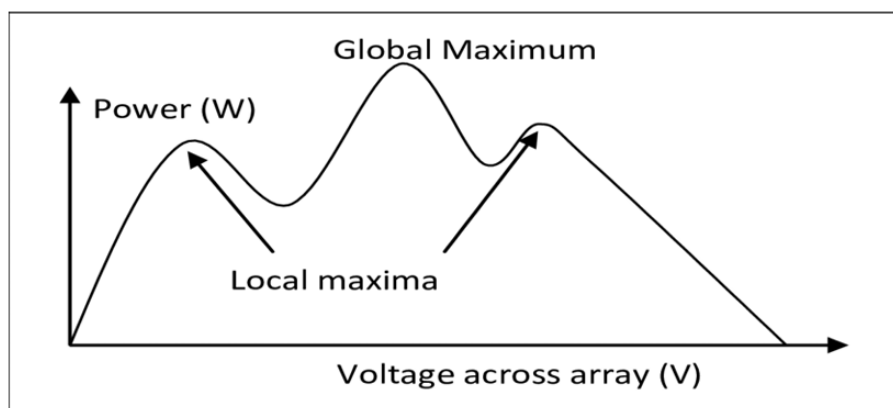


Figure 7.1: Partial Shading Effect on P-V Curve of PV Module

7.2.2 The PV System's Characteristics

PV cells have many applications, from small-scale solar panels for homes and businesses to large-scale solar farms that feed electricity into the grid. They are also used in portable chargers for electronic devices, solar-powered vehicles, and spacecraft.

Table 7.1: PV model parameters

Symbol	Parameters	Value
E_G	Energy gap	1.11
R_s	Series resistance	0.23724 Ω
R_{sh}	Parallel resistance	224.1886 Ω
V_{mp}	Voltage (at MPP)	30.7 V
I_{mp}	Current (at MPP)	35 A
N	Number of series cells	1
A_d	Diode ideality factor	1.019
I_{sc}	Short circuit (SC) current	40 A
V_{oc}	Open circuit (OC) voltage	36.3 V
T	Nominal temperature	25° C
G	Nominal solar irradiance	1000 W/m^2

The PV modeling is done using the parameters of the PV model, as illustrated in Table 7.1. To reach a maximum power output of 1000 W at solar irradiation of 1000 W/m² and temperature of 25°C, a single module in series and a single string in parallel are set up.

(i) Open Circuit Voltage

Determining the open circuit voltage V_{oc} of a Solar PV System involves measuring the voltage across its terminals without any load. Manufacturing methods influence this voltage and is also contingent on the solar cell's temperature. However, it is not equally impacted by the intensity of light and the area of the exposed surface. As the temperature rises, the open circuit voltage decreases. Typically, a solar cell's open circuit voltage falls between 0.5 and 0.6 volts.

(ii) Short Circuit Current

The short-circuit current, denoted as I_{sc} , is the current that flows through a PV system when its voltage is zero volts. This current is measured by short-circuiting

the end terminals of the system without connecting any load. I_{sc} represents the maximum current that the PV system can deliver. It is influenced by factors such as the surface area of the solar cell and the intensity and spectrum of the incident light, among others.

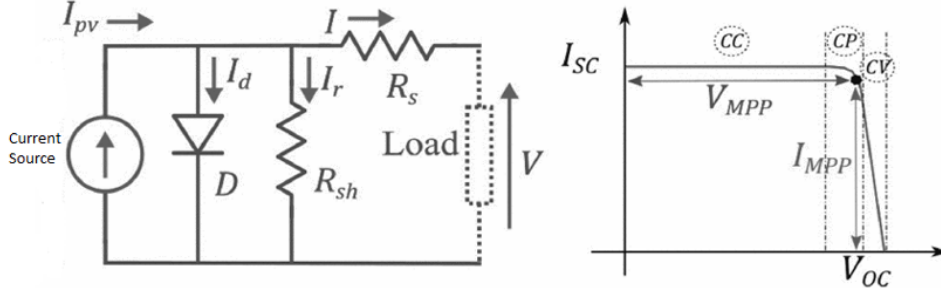


Figure 7.2: PV module circuit diagram and characteristics.

The characteristic equation of a diode is given by:

$$I_d = I_{\text{sat}} \left[\exp \left(\frac{V_d}{V_T} \right) - 1 \right]$$

where:

- I_d = diode current (A)
- V_d = diode voltage (V)
- I_{sat} = diode saturation current (A)
- V_T = thermal voltage = $\frac{kT}{q} Q_d N_{\text{cell}} N_{\text{ser}}$

Here:

- T = cell temperature (K)
- k = Boltzmann constant = 1.3806×10^{-23} J/K
- q = electron charge = 1.6022×10^{-19} C
- Q_d = diode quality factor
- N_{cell} = number of series-connected cells per module
- N_{ser} = number of series-connected modules per string

(1) I-V and P-V characteristics at different levels of illumination

Furthermore, the I-V and P-V characteristics of PV cells are illustrated below in various figures, which discuss getting MPPT-based charging of the EV battery, i.e., I-V and P-V characteristics of a module at different solar insolation levels and with variations in insolation levels. The maximum power available from solar sources varies. as depicted in Fig. 7.3. 1kW/m², 0.8kW/m², 0.6kW/m², 0.4kW/m², 0, 5, 10, 20, 30, 40 Voltage (V); 0, 10, 20, 30, 40 (A) Current; and 1kW/m², 0.8kW/m², 0.6kW/m², 0.4kW/m²; 0, 200, 400, 600, 800, 1000 Power (W); 0, 5, 10, 20, 30, 40 Voltage (V); as shown in Fig. 7.4. A decrease in sun radiation reduces the short circuit current proportionately, and the open circuit voltage decreases exponentially, resulting in a total decrease in power. MPPT techniques are designed to adapt to these variations in illumination, ensuring the PV system operates at or near the MPP. Here's how MPPT works under different illumination conditions:

- (i) The MPPT controller continuously senses the output voltage and current from the PV panel.
- (ii) The MPPT algorithm processes the sensed data to determine the optimal operating voltage.

In the I-V characteristic, I_{sc} is current when the voltage is zero (i.e., the cell is shorted). It increases linearly with illumination as more photons generate more charge carriers. Whenever V_{oc} is the voltage when the current is zero (i.e., no current flows through the cell). It increases logarithmically with illumination, though the change is less pronounced than the short-circuit current.

(2) I-V and P-V characteristics under varying temperature

Fig. 7.5 and Fig. 7.6 represent I-V and P-V characteristics of the module at different temperatures, respectively, with temperature variations, the maximum power available from the solar source varies, with 60°C, 45°C, and 25°C. As temperature changes, the maximum power output also varies. Therefore, an effective MPPT system should be able to tackle these changes and provide the necessary output current for battery charging. When the maximum power is high, it indicates that insolation levels are also high. Consequently, the charging current should be correspondingly

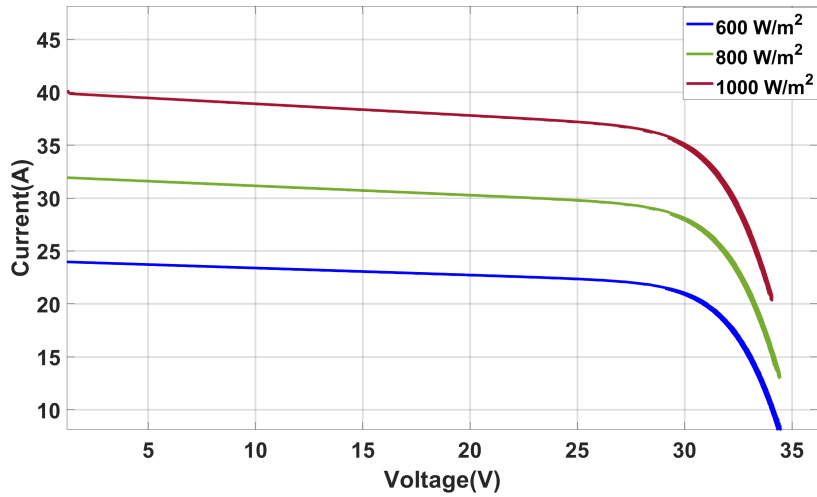


Figure 7.3: I-V characteristics under various levels of illumination

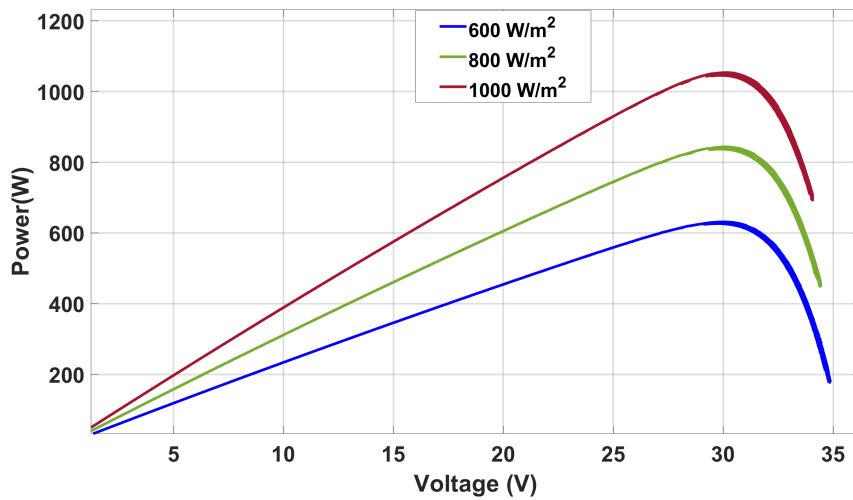


Figure 7.4: P-V characteristics under various levels of illumination.

high. As temperature decreased, the short circuit current decreased with small values, and OC voltage increased with large values, resulting in a total increase in power, as shown in Fig. 7.6. In I-V Characteristics, an increase in temperature causes the short-circuit current to increase slightly while the open-circuit voltage significantly decreases. Whenever, In P-V Characteristics, the maximum power point changes to lower voltages, higher temperatures decrease the total power output. The short-circuit current increases slightly with temperature. This is because higher temperatures result in increased generation of more charge carriers.

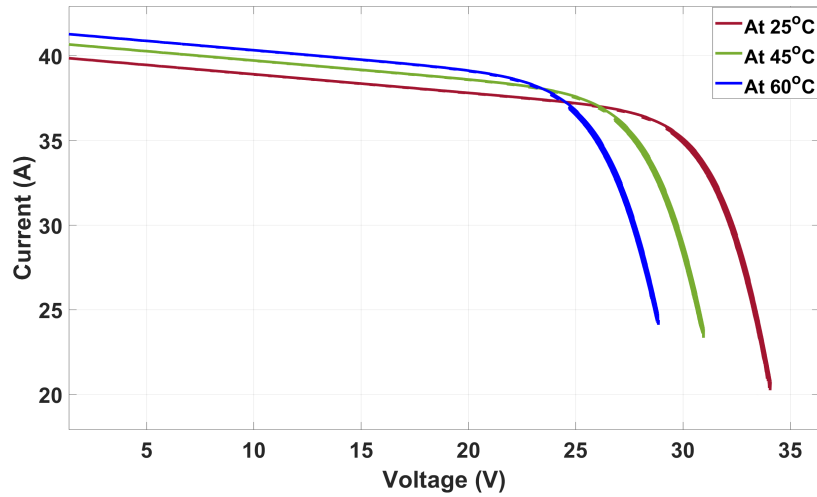


Figure 7.5: I-V characteristics under various temperature levels.

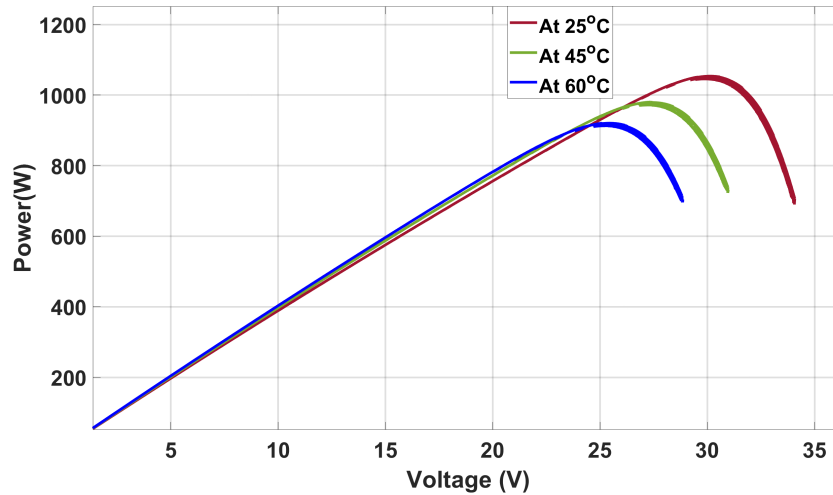


Figure 7.6: P-V characteristics under various temperature levels.

7.2.3 MPPT Controller Design

The operating point of the PV cell can be determined by finding the point of intersection between the current-voltage curve and load line as illustrated in Fig. 7.12. It is important to note that this operating point often differs from the maximum power point. MPP's location varies continuously according to irradiance and temperature, so tracking algorithms must be used to determine its location. Therefore, it becomes essential to implement MPPT techniques for the PV module. The load impedance $R = \frac{V_{dc}}{I}$. Assume, I_{α} and V_{α} is MPP current and voltage, respectively. Then, PV optimal load $R_{op} = \frac{V_{\alpha}}{I_{\alpha}}$. PV systems transfer maximum power when $R = R_{op}$.

7.2.4 DC-DC Boost Converter (BC) Model

A DC/DC converter is an electronic circuit that converts a source of direct current from one voltage level to another. In addition, there should be less electromagnetic noise, wide bandwidth, low cost, minimal ripple, and quick response to sudden changes in the converter [22]. Typically, a DC/DC converter in an MPPT system can be a buck, boost, or buck-boost converter, which adjusts the input voltage to a different output voltage level. Integrating MPPT into DC/DC converters helps maximize the efficiency and performance of renewable energy systems. The MPPT algorithm's output controls the DC/DC converter's duty cycle to adjust the PV panel's input voltage to the optimal point. In the depicted circuit Fig. 7.7, the various components are designated as follows: L signifies the inductor, $Q1$ stands for the power semiconductor switch, V_g indicates the supply voltage, C represents the capacitor, R signifies the load resistance, and D_2 represents the power semiconductor diode. Additionally, V_{dc} and I denote the output voltage and current, respectively. Consider the following dynamics:

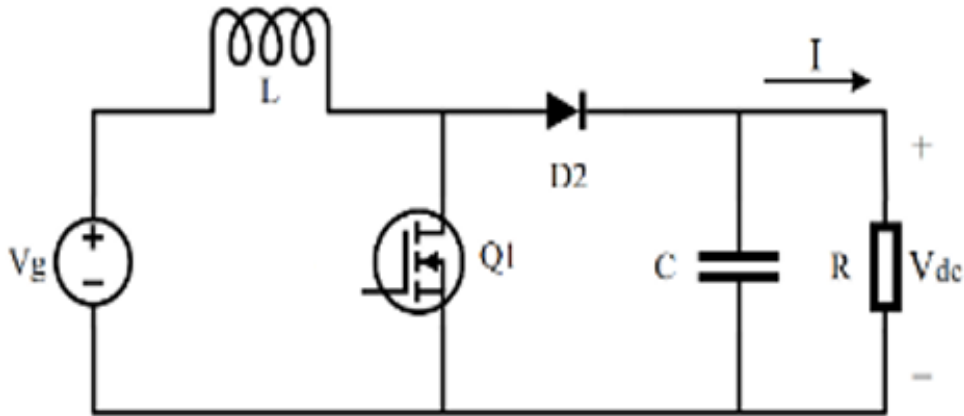


Figure 7.7: DC-DC boost converter.

when the switch is turned on

$$\begin{cases} \frac{dI_L}{dt} = \frac{V_g}{L} \\ \frac{dV_{dc}}{dt} = -\frac{V_{dc}}{RC}, \end{cases} \quad (7.6)$$

when the switch is turned off

$$\begin{cases} \frac{dI_L}{dt} &= -\frac{V_{dc}}{L} + \frac{V_g}{L} \\ \frac{dV_{dc}}{dt} &= \frac{I_L}{C} - \frac{V_{dc}}{RC}. \end{cases} \quad (7.7)$$

As $V_{pv} = V_g$ and $I_L = I_{pv}$, then (7.6) and (7.7) together, yields

$$\frac{dI_{pv}}{dt} = -(1 - \Sigma) \frac{V_{dc}}{L} + \frac{V_{pv}}{L}, \quad (7.8)$$

$$\frac{dV_{dc}}{dt} = (1 - \Sigma) \frac{I_{pv}}{C} - \frac{V_{dc}}{RC} \quad (7.9)$$

where Σ denotes the switching position of the boost converter.

7.2.5 Interleaved Boost Converter (IBC)

An interleaved boost converter is a DC-DC converter that improves performance and efficiency by operating in parallel with multiple boost converter stages. Each stage is controlled with a phase shift relative to the others, which reduces input and output current ripple, improves thermal management, and improves transient response. The IBC comprises two parallel boost converters that phase-shift 180 degrees from one another while continuing to operate at the same frequency. This design enhances efficiency, reduces size, increases reliability, and decreases Total Harmonic Distortions (THD) compared to a single boost converter. Phase-shifting of the gating - pulses for the switches in the IBC occurs by $360/n$ degrees, where n is the number of parallel boost converters. The IBC operates in two switching stages: the open and closed stages. The inductor current rises when the switch is closed, and the diode is blocked. When the switch is opened, the inductor begins discharging the load through the diode. The interleaved boost converter (IBC) consists of two parallel switches (S_{W1} and S_{W2}), inductors (L_1 and L_2), diodes (D_1 and D_2), a capacitor (C), and a load resistor (R), powered by a reliable input source (V_S). The switches are controlled by a phase-shifted switching function. The interleaved boost converter can function in four different modes, but this chapter focuses on

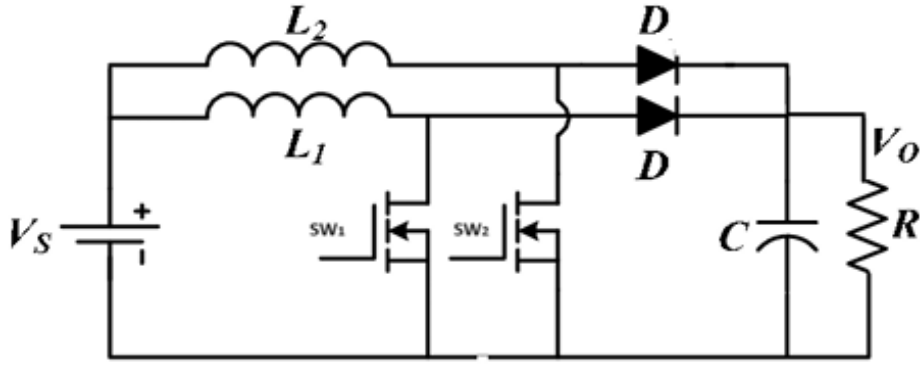


Figure 7.8: Basic circuit of IBC

the continuous current mode (CCM) to simplify the calculations. The inductors are assumed to have equal values ($L_1 = L_2 = L$), and the duty cycles are also considered equal ($D_1 = D_2 = D$), with a time delay of T .

The IBC operates in two distinct switching phases:

- **Closed switch phase:** During this stage, the inductor current rises while the diode remains non-conductive.
- **Open switch phase:** When the switch opens, the inductor discharges its energy to the load through the diode.

7.2.6 Design Parameters Considered

(i) **Duty Ratio:** The duty cycle D of the proposed charger can be expressed as follows: when the switch is turned off

$$D = 1 - \frac{V_s \times \eta}{V_o} \quad (7.10)$$

In a switching converter, V_o denotes the output voltage, V_s represents the input voltage, and η signifies the converter's efficiency.

(ii) **Boost Ratio :** The duty cycle determines the boost ratio of the converter, the

same as it does for a conventional boost converter. It is defined as

$$\frac{V_o}{V_s} = \frac{1}{1 - D} \quad (7.11)$$

Here, V_o represents output voltage, V_s denotes input voltage, and D signifies duty cycle. **(iii) Input Current:** The input current can be determined using input power and voltage.

$$I_{in} = \frac{P_{in}}{V_s} \quad (7.12)$$

Here, P_{in} denotes i/p power, and V_s represents i/p voltage.

(iv) Inductor-Current Ripple:

$$\Delta I_L = \frac{V_s \cdot D}{L \cdot f_s} \quad (7.13)$$

when f_s is the switching frequency, D represents the duty cycle, V_s is i/p voltage, and L denotes inductance.

(v) Selection of Inductor and Capacitor: In the Interleaved DC-DC Boost Converter operation, energy is transferred from the input voltage to the inductor current and subsequently from the inductor current to the o/p voltage. Both inductors must be identical under this principle to maintain a balanced current between the boost converters. Capacitor C and inductor L resonated in the suggested charger to smooth out the switch voltage during the turn-off transition. As a result, it is possible to determine the appropriate amount of energy to store in C . The values for the capacitor and inductor are determined using the following equations.

$$L = \frac{V_s \cdot D}{\Delta I_L \cdot f_s} \quad (7.14)$$

where V_s is the symbol of source voltage, ΔI_L denotes inductor current ripple, and D denotes the duty ratio. The value of the capacitor is calculated using the following formula:

$$C = \frac{V_o \cdot D}{\Delta V_o \cdot R \cdot f_s} \quad (7.15)$$

R is the resistance, and ΔV_o is a change in the o/p voltage.

(v) Resistance(R): A developed technique for overcoming the drawbacks of conventional boost converters is called interleaving or multi-phase. The filter's components can be reduced by organizing the parts in a parallel configuration with

two switches, diodes, and an inductor coupled to a single capacitor and load. The resistance or load, R , can be expressed as equation (7.16)

$$R = \frac{V_{out}}{I_{out}} \quad (7.16)$$

7.2.7 Modelling and Design

An MPPT controller's block diagram is shown in Fig. 7.9. An MPPT controller block diagram includes several parts, including a DC-DC boost converter, load or battery, controller, and PV array. MPPT is crucial for PV charging systems, especially if solar-panel-based battery charging is involved. By maximizing the solar energy conversion process efficiency, MPPT ensures that the solar panel's total output is used to charge the batteries.

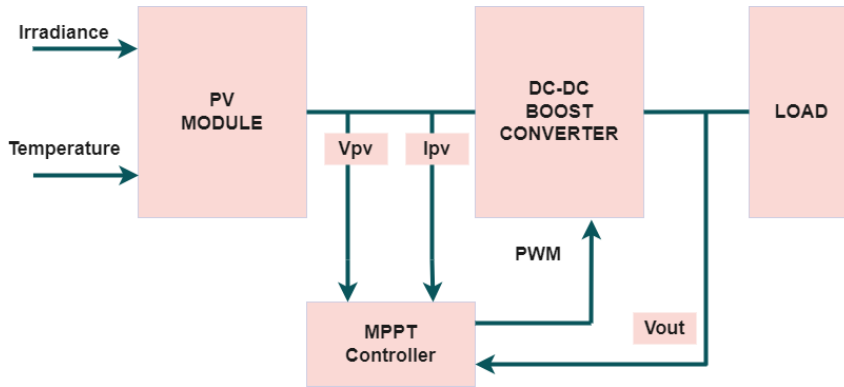


Figure 7.9: Block diagram of MPPT controller

7.3 Proposed Method: Circuit Description

This research aims to discuss using an interleaved boost converter for a PV-fed EV system, as represented in Fig. 7.10. The operation of this interleaved boost converter is managed by a PI controller, allowing for switching techniques of charging and discharging. This battery charging method is well-suited to PI controller control strategy.

Additionally, the MPPT algorithm is used to optimize power harvesting from solar PV under various irradiation conditions, ensuring that the EV's operation remains

uninterrupted. A closed-loop control approach is presented for operating the converter in boost mode using the MPPT technique. MOSFET switches are utilized for their high efficiency at low voltages and high commutation speed.

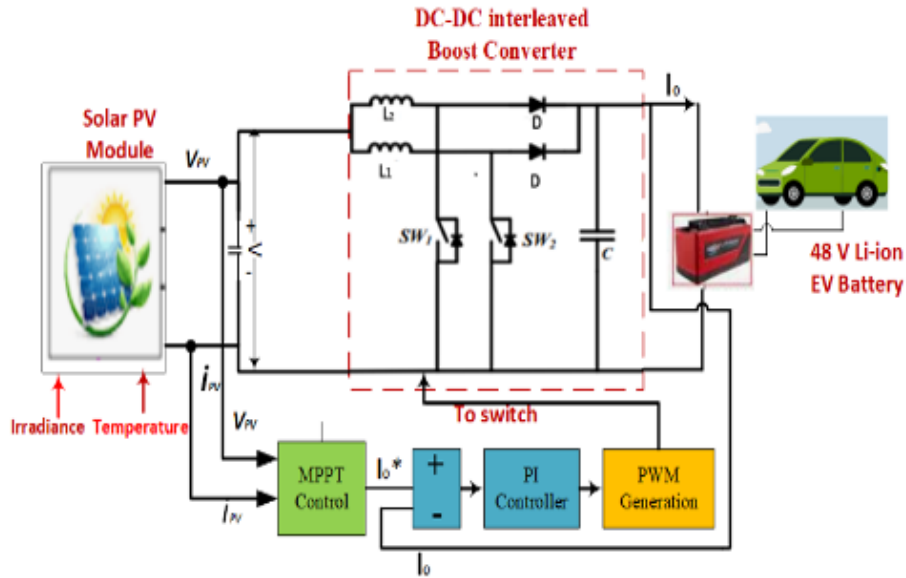


Figure 7.10: Configuration of interleaved boost converter PV-fed EV System

7.3.1 Parameters Considered

To create a design parameter specification table for a proposed converter, we must include various key parameters defining the converter's performance, capabilities, and constraints. Table 7.2 comprehensively overviews a proposed converter's specifications and design parameters.

7.3.2 MPPT Algorithms

An MPPT controller's block diagram is shown in Fig.1. An MPPT controller block diagram includes several parts, including a DC-DC boost converter, load or battery, controller, and PV array.

Maximum Power Point Tracking (MPPT) algorithms are essential for optimizing the efficiency of photovoltaic (PV) systems by ensuring that the system operates at the maximum power point (MPP) under varying environmental conditions. Two

Table 7.2: Specifications of the proposed converter

Parameters	Values
Source Voltage, V_s	30 V
Source current, I_s	35 Amp
Battery Voltage, V_o	48 V
output current, I_o	20 Amp
Output Power, P_o	1KW
Output voltage ripple, V_o , ripple (t)	5% of output voltage (V_o)
Switching frequency, f_s	20kHz
Inductance L_1, L_2	9 μ H
Capacitance C	470 μ F

widely used MPPT algorithms are the Perturb and Observe (P&O) algorithm and the Incremental Conductance (IncCond) algorithm.

The maximum power point (MPP) on a PV curve is where the power output is at its highest, referred to as the cell power at maximum P_{mpp} and the corresponding voltage as cell voltage at maximum V_{mpp} . MPPT (Maximum Power Point Tracking) is essential because the power output from a solar PV system fluctuates with varying levels of irradiation and cell temperature. The fundamental principle of MPPT is to harness the maximum energy available from the PV device by ensuring it operates at its most efficient voltage. Fig. 7.12 displays the characteristics of a typical PV cell under standard test conditions, which are primarily influenced by irradiance and cell temperature. This curve demonstrates that the V_{mpp} is less than the V_{oc} , and the I_{mpp} is less than the I_{sc} .

The primary focus of Table 7.2 is to define the electrical specifications and performance constraints of the proposed converter, such as voltage, current, power, frequency, and passive component values. Charging time, while an essential factor

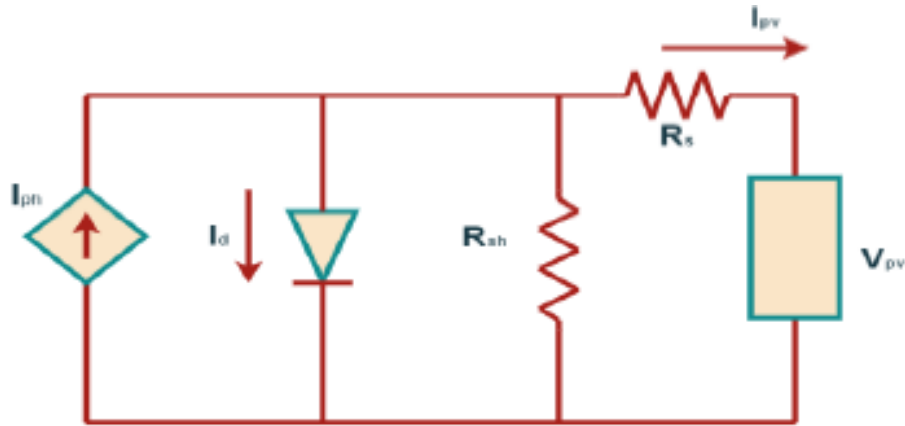


Figure 7.11: A single PV module.

in practical applications, is not explicitly listed because it depends on various external conditions, including battery characteristics, state of charge (SoC), and the control strategy used for charging. Since the converter's role is to regulate power flow rather than determine charging duration directly, charging time is considered an application-specific outcome rather than a fundamental design parameter of the converter itself.

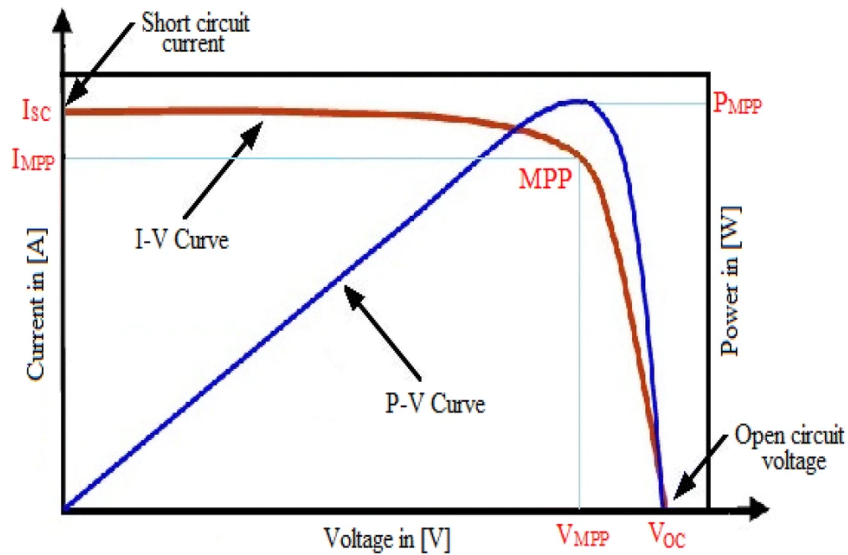


Figure 7.12: Typical characteristic of a common PV cell

Perturb and Observe (P&O) Algorithm

The Perturb and Observe (P&O) algorithm is a widely used method for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. The core idea is to

perturb (i.e., slightly adjust) the operating voltage of the PV array and observe the resulting change in power output. Based on this observation, the algorithm decides whether to increase or decrease the voltage to move toward the Maximum Power Point (MPP).

This algorithm examines the relationship between a PV module's output power and voltage. The solar panel's behavior, illustrating the Maximum Power Point (MPP) and operational principles, is presented in Fig. 7.13.

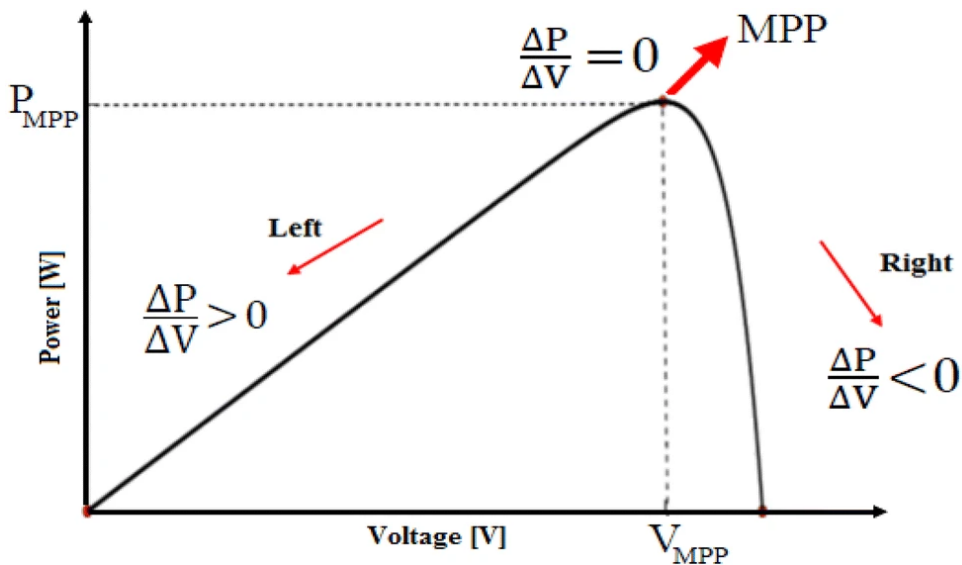


Figure 7.13: Behavior of solar panel indicating MPP and operating principle

It shows that the PV power changes as follows: When the operating point of the PV module is on the left side of the curve (where $\Delta P/\Delta V$ is positive), indicating an increase in output power, the perturbation of the PV module's voltage should be increased towards the MPP. Conversely, if the operating point is on the right side of the curve (where $\Delta P/\Delta V$ is negative), indicating a decrease in output power, the perturbation of the PV module's voltage should be decreased towards the MPP. Fig. 7.14 illustrates the flowchart for implementing the Perturb and Observe (P&O) algorithm. Initially, the actual voltage and current from the PV array are measured. The voltage and current product give the PV module the actual power. The algorithm then checks whether $\Delta P = 0$. If this condition is met, the operating point is at the MPP. If not, it checks another condition: $\Delta P > 0$. If this condition is met, it checks whether $\Delta V > 0$. If $\Delta V > 0$, it indicates that the operating point is on

the left side of the MPP. If $\Delta V > 0$ is not met, it indicates that the operating point is on the right side of the MPP. This process continues until the MPP is reached. Thus, there is always a trade-off between the increments and the sampling rate in the P&O algorithm.

7.3.3 Modeling and Design

An MPPT controller's block diagram is shown in Fig. 7.9. An MPPT controller block diagram includes several parts, including a DC-DC boost converter, load or battery, controller, and PV array. MPPT is crucial for PV charging systems, especially if solar-panel-based battery charging is involved. By maximizing the solar energy conversion process efficiency, MPPT ensures that the solar panel's total output is used to charge the batteries. In particular, when temperature and irradiance change, MPPT adjusts the battery charging current to produce faster and more efficient charging. It maximizes the efficiency of the entire system by enabling the solar panels to capture the maximum amount of energy from the sun and transfer it to the battery. MPPT controllers designed for EV charging systems often integrate seamlessly with EV chargers and energy management systems. They provide interfaces for monitoring and controlling the charging process, ensuring compatibility with various EV models and charging standards. Maximizing renewable energy sources, an MPPT controller reduces dependency on grid electricity for EV charging. Using clean energy sources effectively can lead to cost savings and environmental benefits.

7.3.4 Control Technique

In this chapter, two types of control were used. For the solar PV system, the MPPT method is the most commonly utilized algorithm. Despite the potential impact of shadowing on specific modules, the MPPT algorithm is crucial for continuously extracting optimal power from the solar PV panel. Even if specific modules are obscured, the remaining battery pack will be energized to ensure the EV functions appropriately. The MPPT algorithm adjusts the solar PV power output according to the load or battery charger requirements. A closed-loop control circuit diagram, consisting of a PI controller and a PWM generator, is used to detect and control

the error signal relative to a reference signal, as illustrated in Fig. CONT. The control circuit Fig. 7.15 consists of an inner current loop and an outer voltage loop. The battery voltage V_b is measured and compared to the outer voltage loop's reference voltage V_{ref} . The difference between these two values is fed into the PI controller. The PI controller helps reduce or eliminate the steady-state error between the measured and reference battery current. The transfer function of PI controllers is determined by its gains (proportional and integral), denoted as K_P and K_I .

$$G(s) = K_P + \frac{K_I}{s} \quad (7.17)$$

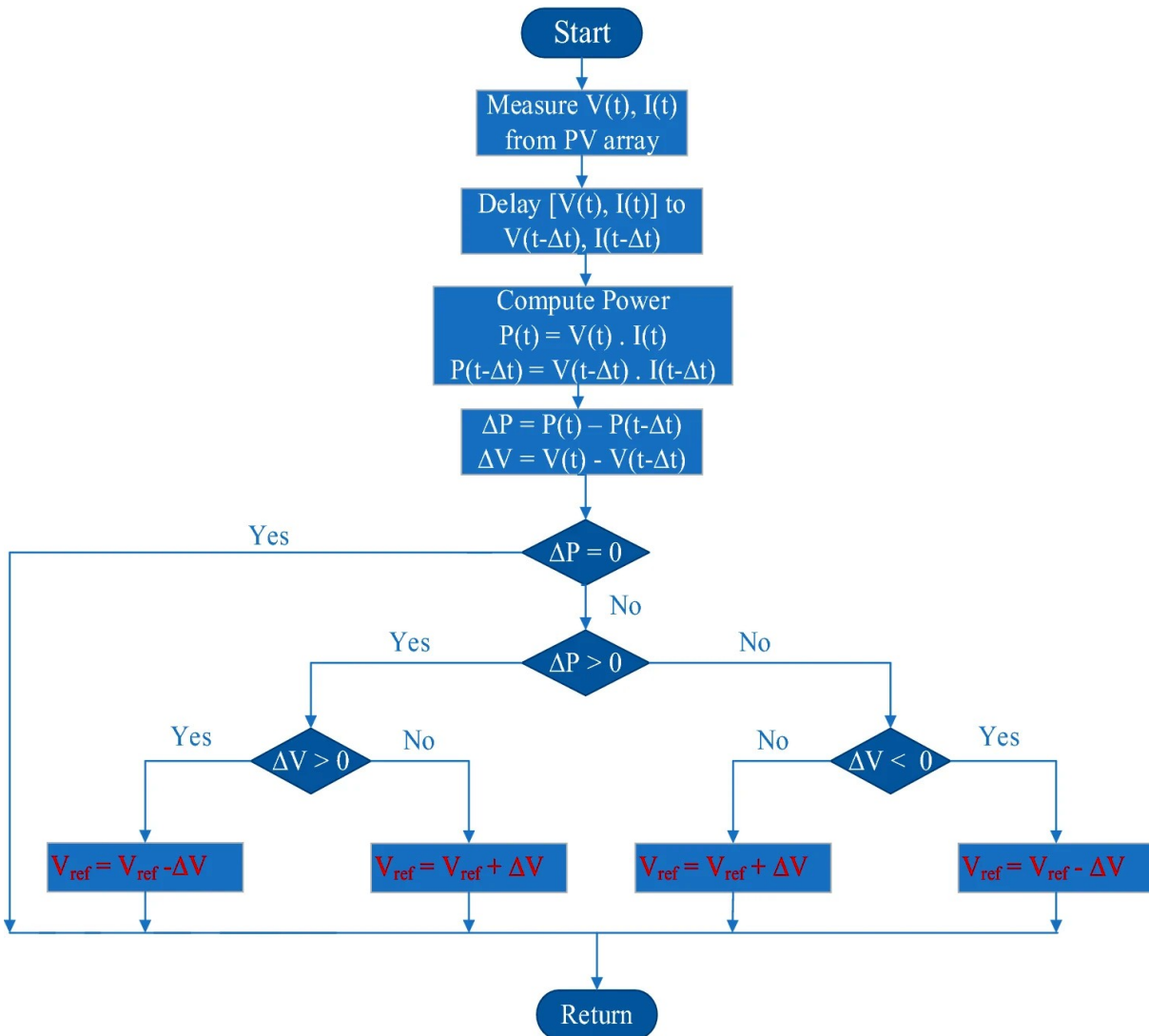


Figure 7.14: Flowchart of the P&O algorithm

This is then fed back to the current loop iteration. Finally, the difference, when

compared to the battery current I_b , is sent to the PWM modulator via another PI controller. This controller helps achieve a stable PV voltage and EV battery current. When switch SW_1 is activated, the current in inductor L_1 begins to increase linearly, storing energy in the inductor during this phase. When SW_1 is deactivated, diode D_1 conducts, and stored energy in L_1 gradually decreases, influenced by the difference between input and output voltages. After that, the inductor starts discharging, transferring current through the diode to load. After half of the switching cycle of SW_1 , SW_2 is activated, repeating the same sequence of operations. Combining both power channels at the output capacitor results in a ripple frequency that is twice that of a single-phase boost converter. The amplitude input current ripple is minimized. Here, V_o represents the output voltage, V_{in} denotes the input voltage, and D signifies the duty cycle.

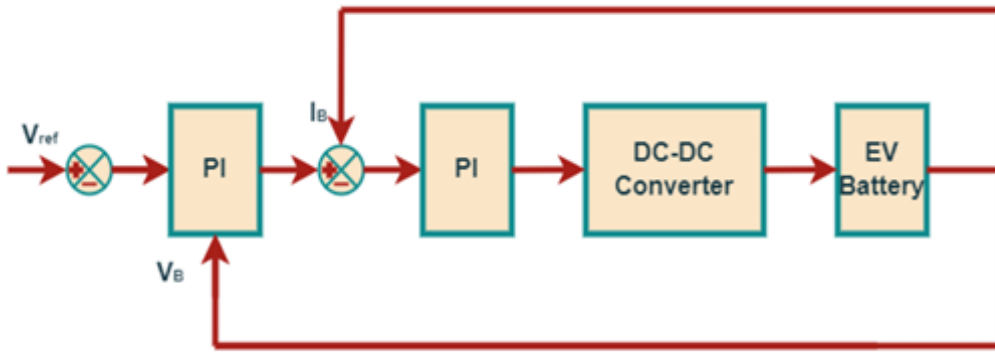


Figure 7.15: DC-DC converter closed-loop control circuit.

The performance of the conventional boost converter and IBC with two, three, and four phases has been analyzed in [21, 25], and the comparative results are presented in Table 7.3.

The approach used for comparing the power quality produced by the two converters focuses on reducing O/P current and voltage ripple effects through interleaving techniques. This, in turn, decreases switching losses and enhances efficiency. In practice, the traditional boost converter's fixed gain is limited because achieving a high output voltage requires a high duty ratio, meaning the switch remains ON for extended periods. A high current in the diode can cause the reverse recovery phe-

Table 7.3: Comparative Analysis of Boost Converter (BC) and Interleaved Boost Converter (IBC)

Parameters	BC	BC	Proposed
	[21]	[25]	converter (IBC)
O/P Voltage V_o	29.25 V	-	48 V
O/P Voltage ripple (%)	0.46	3 % peak to peak	0.2
O/P current ripple (%)	0.19	5 % peak to peak	0.01
I/P Current ripple (%)	0.15	-	0.05
Efficiency (%)	95.4	90-92%	96.8
Voltage stress	-	High	high
Current stress	high	low	low

nomenon. Mathematical analysis and simulation results comparing the traditional boost converter and the IBC demonstrate that the IBC reduces current and voltage ripple and decreases voltage stress across the switch, as shown in Fig. 7.16. As a result, the IBC shows improved efficiency compared to the traditional boost converter as shown in Table 7.3. Finally, the analysis and simulation results are encouraging, indicating that practical implementation of the IBC would be advantageous in future work.

7.4 Simulation Results and discussion

This section evaluated the interleaved DC-DC boost converter model's performance using MATLAB Simulink software. In the first step, varying irradiances are used to examine MPPT's effectiveness, and later, varying temperatures are used to examine MPPT's effectiveness. The figures below represent different parameters, such as the battery's SoC at varying PV side irradiation levels, the PV module, solar voltage, current and associated power, inductor current, battery current, and voltage stress on switches. The findings demonstrate that, in comparison to low radiation and high temperature settings, photovoltaic cells perform more effectively in high radiation and low temperature environments. Therefore, in order to maximize the

amount of incoming solar radiation, or W/m^2 , PV cells should be maintained clean and fitted with a solar tracking system for best performance [27]. To evaluate the effectiveness of the proposed topology, the following converter parameter values are considered during the final testing process. The main parameters of the interleaved boost converter are $L = 9\mu H$, $C = 470\mu F$, and $f_s = 20kHz$. Battery capacity = 10Ah, initial SoC = 60%, Battery nominal voltage = 48V. Fig. 7.16 represents the maximum power 1050W at irradiation level of $1000 W/m^2$.

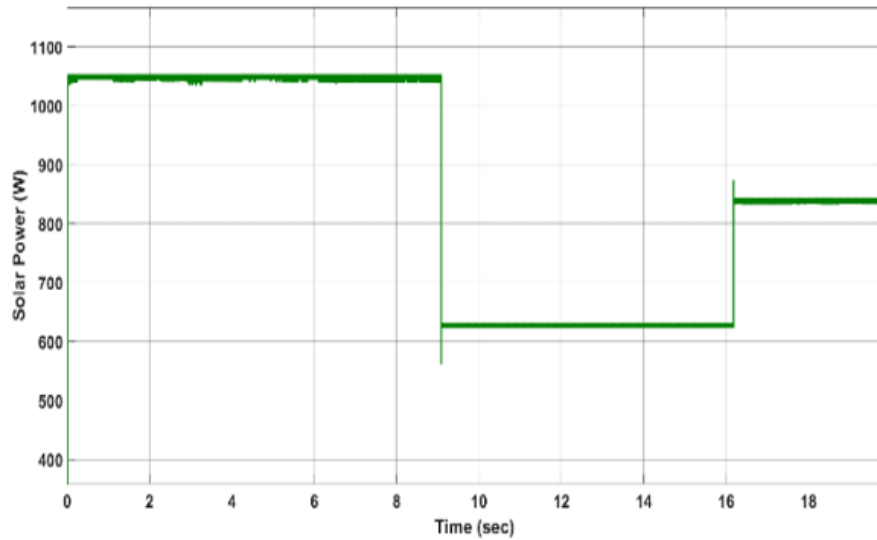


Figure 7.16: Solar power.

Fig. 7.17 illustrates the solar voltage (in red) and current (in blue) at power levels of a PV module under irradiation of $1000 W/m^2$ and a cell temperature of $25^\circ C$, depicting how they vary as the irradiation to the PV module increases or decreases.

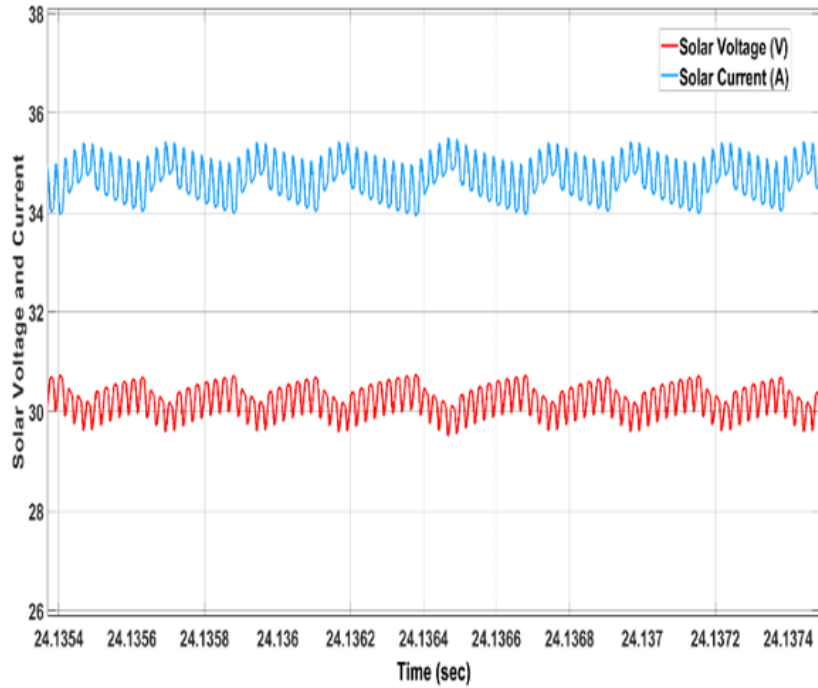


Figure 7.17: Solar voltage current.

Fig. 7.18 illustrates the charging process with a corresponding negative battery current.

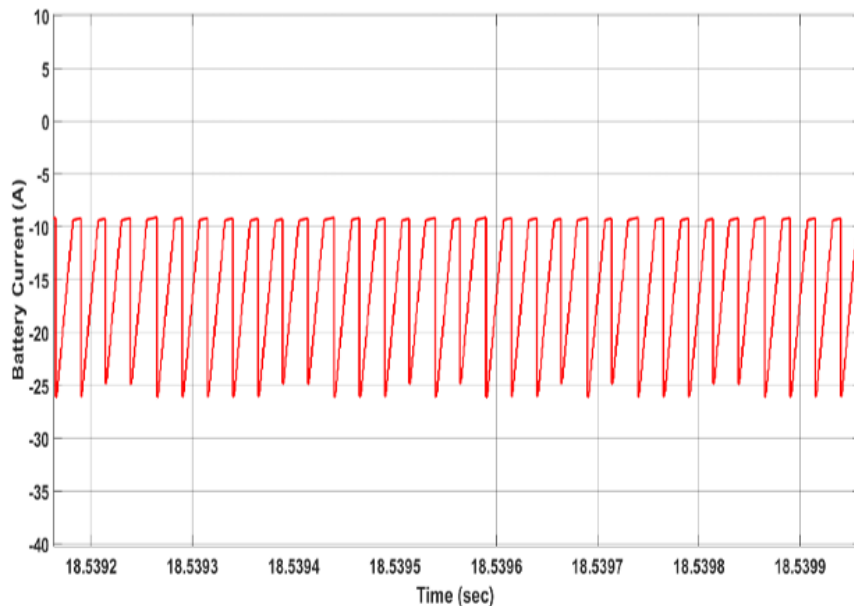


Figure 7.18: Battery currents.

In Fig. 7.19, the voltage stress in discontinuous conduction mode (DCM) is indicated in red for switch S_1 and blue for switch S_2 .

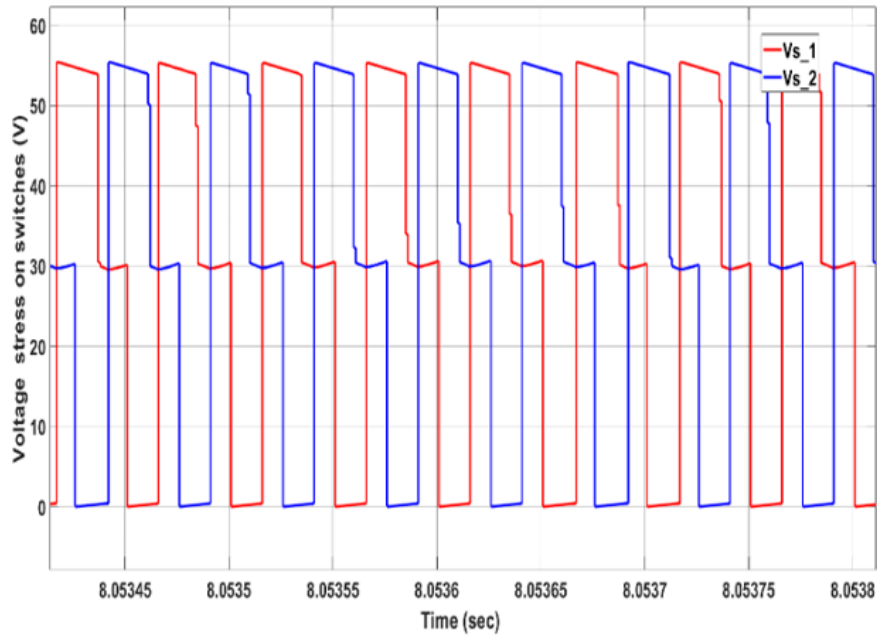


Figure 7.19: Voltage stress on switches.

Fig. 7.20 depicts the inductor current, with the current flowing through inductor L_1 in green and the current through inductor L_2 in blue.

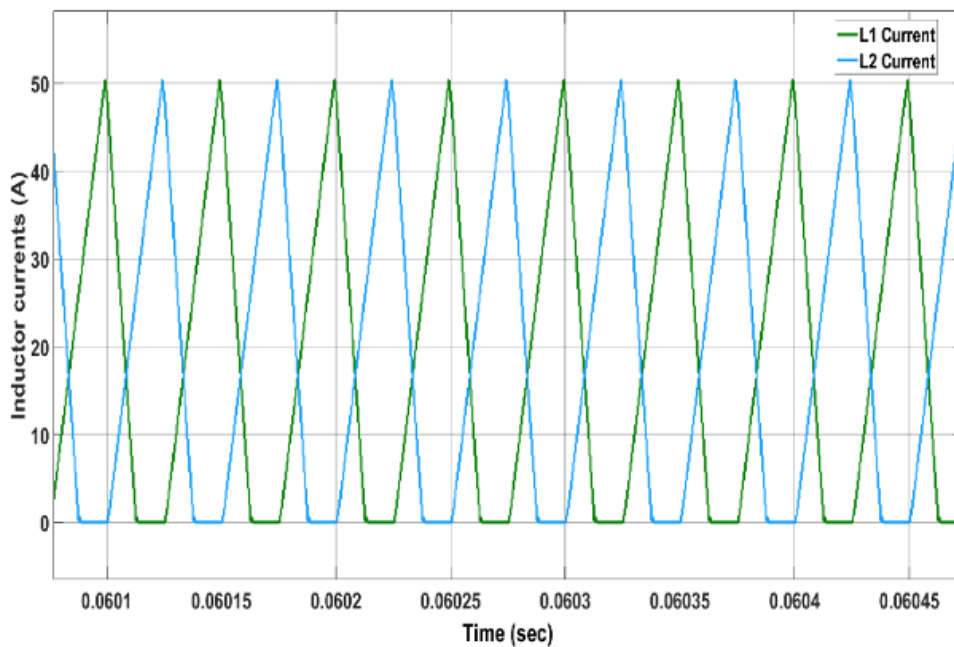


Figure 7.20: Inductor currents.

In Fig. 7.21, the voltage increases gradually, indicating that the EV battery is in charging mode. After transferring the output voltage of the PV module, optimized

by the MPPT technique, to the battery side using an interleaved boost converter, Fig. 7.21 illustrates the corresponding battery charging voltage and the battery's state of charge. Fig. 7.21 also depicts a voltage rising trend, indicating that the EV battery is in charge.

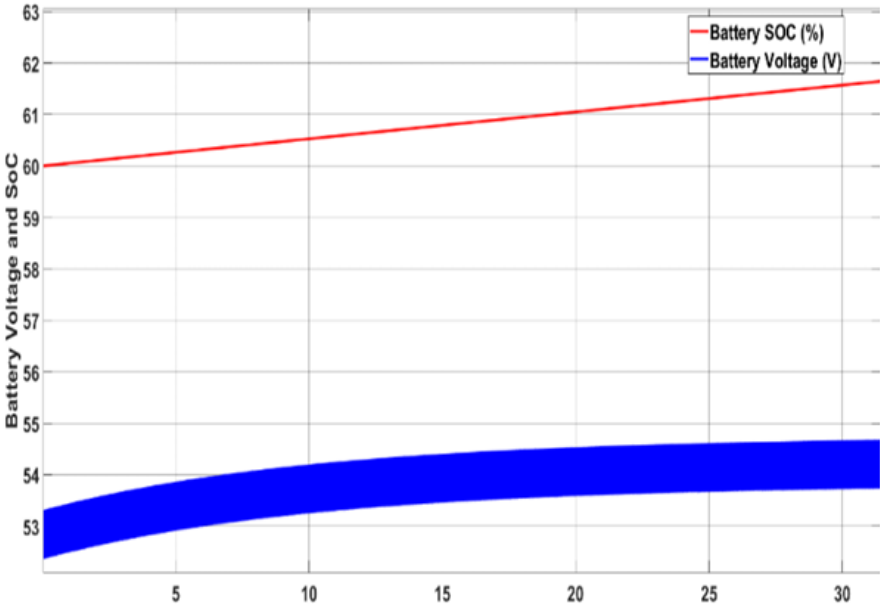


Figure 7.21: SoC of battery and 48 Volt battery voltage.

To assess the performance of the proposed topology, the final testing will involve applying various load conditions, such as a 72-volt battery, and using different parameter values.

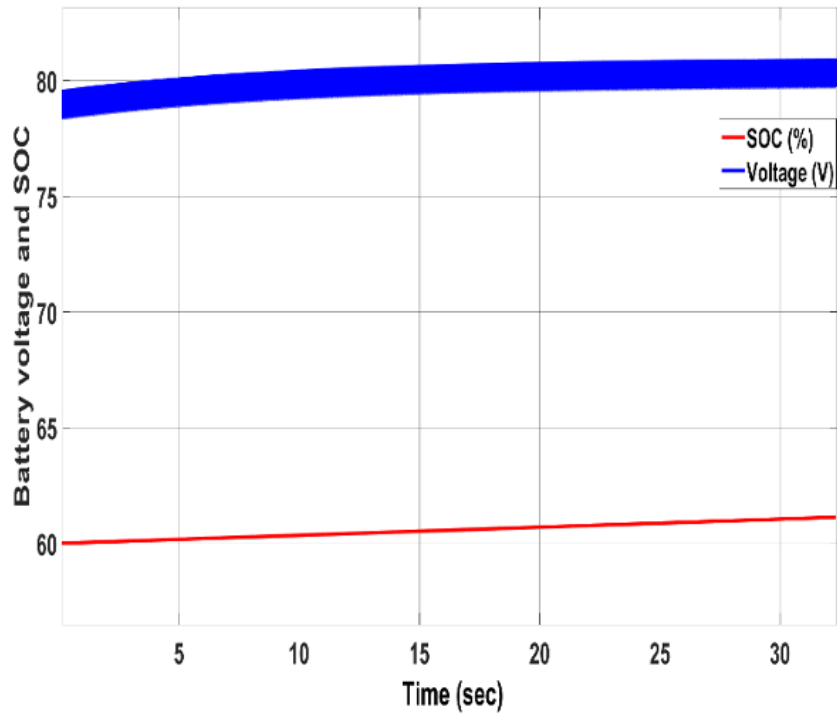


Figure 7.22: SoC of battery and 72 Volt battery voltage.

After incorporating a 72-volt battery on the load side during the simulation, the observed gradual increase in voltage indicates that the EV battery is actively charging. Fig. 7.22 shows the corresponding battery charging voltage and the battery’s State of Charge. This confirms that the proposed methodology is effective under different conditions.

7.5 Summary

This chapter presented a comprehensive study on the implementation of an Interleaved Boost Converter (IBC) for Electric Solar Cars with hybrid technology, focusing on enhancing charging efficiency and system reliability. By integrating solar PV panels and employing Maximum Power Point Tracking (MPPT) techniques, the system effectively optimized energy extraction under varying solar conditions. The use of an IBC demonstrated clear advantages over conventional boost converters, notably in reducing current and voltage ripple, as well as improving overall conversion efficiency.

The proposed design, regulated by a PI controller, allowed seamless switching between charging and discharging modes, ensuring robust performance in various operational states. Through MATLAB/Simulink simulations, the system exhibited a notable energy efficiency of 96.8%, validating the effectiveness of the IBC in minimizing ripple effects and switching losses. Additionally, the reduction in the number and size of inductors and capacitors in the converter design contributed to cost-effectiveness and lower power losses, enhancing the overall performance of the Electric Solar Car's power management system.