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Maximum Power Point Tracking in Energy Harvesting for Solar PV System

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ABSTRACT

Nowadays, the photovoltaic (PV) cell is widely recognized as a crucial component in the field of electricity. It plays a significant role in converting solar irradiance from sunlight directly into electrical energy. However, the shorter battery life of mobile devices poses a significant challenge. A Maximum Power Point Tracking (MPPT) circuit is needed to maximize the energy extracted from the PV energy harvester by enabling the operating point of the PV cells to track the maximum power point and recharge the battery. This project proposed an implementation of maximum power point tracking in energy harvesting for solar PV systems. The output current requires a 0.5 A to 2.4 A current range which is suitable for charging mobile devices, with a voltage range between 4.5 V to 5 V. The tracking efficiency of the designed Incremental Conductance Maximum Power Point Tracking (INC MPPT) algorithm is in the range of 80 % to 95 %. In the MPPT algorithm, the duty cycle is adjusted to optimize the power transfer between a solar panel and a load. The contribution of this developed MPPT algorithm is low cost, acceptable reliability, and easy implementation.

Keywords:
Photovoltaic system; maximum power point tracking; INC maximum power point algorithm; energy harvesting; mobile device

1. Introduction

Nowadays, the indispensability of mobile devices such as smartphones, laptops, and tablets in our daily lives is undeniable [1]. These devices serve various purposes, including communication, scheduling, alarm clocks, business tasks, and accessing a wide range of services. As technology advances, people anticipate increased functionality and performance in their mobile devices. However, this enhanced performance leads to faster processors and more complex computations, resulting in higher heat generation and power requirements. With each new generation of mobile devices, the demand for processing power and energy efficiency increases [2]. Current battery technology falls short of providing users with sufficient battery life to support uninterrupted usage throughout the day. As a result, users often need to charge their mobile devices multiple times a day, causing inconvenience and limiting the user experience. Consequently, battery technology needs to advance to keep pace with the escalating power demands and processing speeds [3]. To address the

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challenge of improving battery life in portable devices such as mobile phones, energy harvesting systems offer potential solutions [3-4]. The energy harvesting systems aim to harness alternative sources of energy to supplement or replace traditional batteries. By utilizing energy from the environment, such as solar, vibration, radio frequency, or thermal energy, these systems offer the potential to extend battery life and reduce reliance on conventional power sources [4-5]. Among the various energy harvesting methods, solar energy stands out as a clean and sustainable solution. Solar panels can convert sunlight directly into electricity, making them an ideal choice for mobile device charging [3, 5].

Solar energy offers a clean and sustainable solution by harnessing light and converting it into electricity. Electrical energy generation is the function of the solar cell or as it is known the Photovoltaic (PV) [6, 7]. This includes Photovoltaic Thermal (PV/T) which combines the PV and Solar Thermal collector [8]. To maximize the power output from solar panels, the implementation of Maximum Power Point Tracking (MPPT) methods and algorithms is crucial [9, 10]. This necessitates the use of a digital controller to monitor and control the MPPT system.

In photovoltaic systems, the maximum power point refers to the location where the output power reaches its peak. This point continually changes depending on the irradiance level and temperature. Therefore, to optimize power extraction from the PV generator, continuous tracking of the Maximum Power Point (MPP) is essential, which is achieved through the implementation of MPPT algorithms [9, 11]. Figure 1 illustrates the block diagram of an MPPT system for a photovoltaic system. The system comprises five main components, with the Incremental Conductance MPPT Tracking System being the focus of this project. Initially, the voltage and current from the solar panel are sensed. Subsequently, the varying voltage and current signals are directed through an Analog and Digital Converter. The digital signal obtained from the Analog-to-digital converter (ADC) is then fed into the MPPT tracking system, initiating the process of the Incremental Conductance algorithm. The MPPT algorithm's output, in the form of Pulse Width Modulation, controls the operation of the DC-DC Boost Converter circuit, facilitating the tracking of solar power.

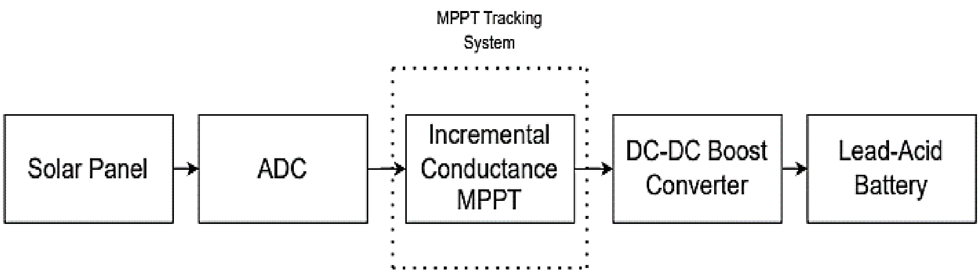

Fig. 1. Block diagram of MPPT for photovoltaic system

1.1 Photovoltaic System

The solar photovoltaic system is a technology that converts sunlight into electricity using solar panels. It is an environmentally friendly and safe way of generating clean energy without causing pollution. The discovery of the first photovoltaic cell in 1954 by Gerald Pearson, Daryl Chaplin, and Calvin Souther Fuller marked a significant milestone in the development of this technology [10]. Since then, solar PV systems have emerged as a viable alternative to fossil fuels and have become an essential source of energy for charging various devices.

Solar and photovoltaic energy sources are particularly suitable for powering portable applications due to their ability to deliver sufficient power levels. As a result, this study focuses on energy harvesting using these sources. Solar energy is a renewable energy source that complements traditional power sources. PV sources can convert solar energy into usable electric energy to power a wide range of applications, from small devices like computers and tablets to larger structures such as houses. However, the energy output of PV sources is influenced by various environmental factors, including temperature and irradiance level [9-10]. Therefore, each PV source is characterized by an I-V curve as shown in Figure 2, which illustrates the relationship between the current supplied by the source and the applied voltage [12]. The I-V curve shows that the supplied current remains constant within a wide range of applied voltage and eventually drops to zero at higher voltages. The maximum supplied current by any PV source is referred to as the short-circuit current (ISC), while the voltage at which the current becomes zero is known as the open-circuit voltage (VOC).

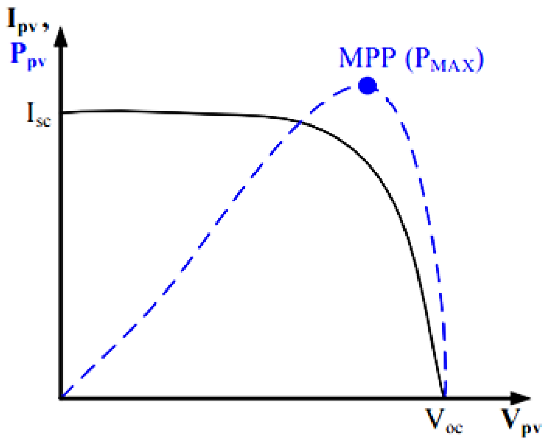

Fig. 2. I-V and P-V curves for PV sources [12]

Additionally, PV sources are characterized by the power versus voltage (P-V) curve, which represents the relationship between the supplied power from a solar cell and the applied voltage. The P-V curve demonstrates that the supplied power from a PV source varies but reaches a Maximum Power Point (P_{max}). Therefore, PV systems are controlled to operate at this point to maximize the amount of energy harvested from the PV source.

1.2 Maximum Power Point Tracking

In the market, there is a wide variety of solar panels available, and certain large-scale panels are equipped with sun-tracking capabilities to optimize their energy output. However, small solar panels lack this ability and require a special circuit to enhance their power efficiency. It is crucial to continuously track the maximum power point of a solar panel's output power. The MPP depends on factors such as the solar panel's irradiance, temperature, and the connected load, even though the panel may operate at a nominal voltage [13]. The actual voltage may not reach the nominal value if the environmental conditions are unfavorable. Additionally, the battery's state of charge also plays a role. Most batteries require higher voltages for full charging, necessitating the solar panel to provide maximum voltage. Therefore, maximum power point tracking is a vital component in solar energy harvesting systems. An efficient MPPT technique ensures that the PV system operates at the maximum power point under all environmental conditions [14]. This is necessary due to the lack of intelligence in both the solar cell and the battery. Without an MPPT circuit to optimize the match between the solar panel and the battery, a significant amount of power can be lost.

Currently, there are six known MPPT methods: Constant voltage [15], open circuit voltage [16], short circuit current [17], perturb and observe [18], incremental conductance [19], and temperature [20]. All these algorithms are designed to dynamically extract the maximum power from PV panels.

Among these techniques, the Perturb and Observe (P&O) and Incremental Conductance algorithms are the most popular due to their simplicity and extensive research on them. Consequently, this project will specifically focus on describing the Incremental Conductance method.

2. Methodology

This section will discuss the details of methods that have been used to develop this project. This chapter is mainly focused on the project framework and the circuit simulation of the maximum power point tracking circuit.

2.1 Incremental Conductance MPPT Algorithm

For this project, the chosen MPPT algorithm to be implemented is the Incremental Conductance (INC) algorithm. Several factors influenced the decision to use the INC algorithm instead of the Perturb and Observe algorithm [19]. One notable advantage of the INC MPPT algorithm is its superior tracking efficiency. It excels in precisely adjusting the operating point of the solar panel to accurately track the maximum power point. This is particularly beneficial when dealing with rapidly changing solar conditions.

Another key factor in selecting the INC MPPT algorithm is its ability to quickly respond to variations in solar irradiance and temperature [20]. Figure 3 illustrates the working principle of the INC algorithm [21]. By making incremental adjustments to the operating point, it can adapt to dynamic environmental conditions and ensure efficient energy conversion. This responsiveness is crucial in situations where solar conditions fluctuate frequently, allowing the system to consistently maintain optimal power output.

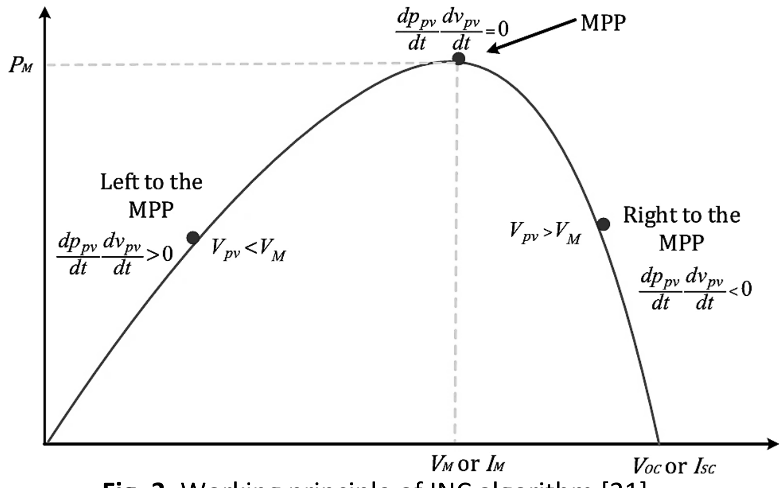

Fig. 3. Working principle of INC algorithm [21]

Furthermore, the INC MPPT algorithm helps reduce power output oscillations. Its fine-grained control and accurate tracking enable it to mitigate the effects of sudden changes or fluctuations, resulting in a smoother and more stable power output. The INC MPPT algorithm brings distinct advantages in terms of tracking efficiency, rapid response to changing conditions, and reduction of oscillations.

2.2 Flowchart of INC MPPT Algorithm

The flowchart of the Incremental Conductance MPPT algorithm is illustrated in Figure 4. When analyzing the Maximum Power Point of the solar panel, it can be observed that the rate of change of power for voltage, represented as *dP/dV*, becomes zero, as depicted in Figure 3. This indicates that on the left side of the MPP, the slope is positive, while on the right side, it becomes negative. Eq. (1) to Eq. (3) can be rewritten accordingly to mathematically represent this behavior.

$$\frac{dI}{dV} = \frac{-I}{V} \quad (1)$$

$$\frac{dI}{dV} > \frac{-I}{V} \quad (2)$$

$$\frac{dI}{dV} < \frac{-I}{V} \quad (3)$$

Eq. (1) corresponds to the MPP, capturing the conditions at the point of maximum power output. Eq. (2) describes the behavior on the left side of the MPP, reflecting the positive slope. On the other hand, Eq. (3) characterizes the right side of the MPP, representing the negative slope. The incremental conductance (dI/dV) represents the rate of change of current with respect to voltage, while the instantaneous conductance (I/V) signifies the current-voltage relationship at a specific moment [22].

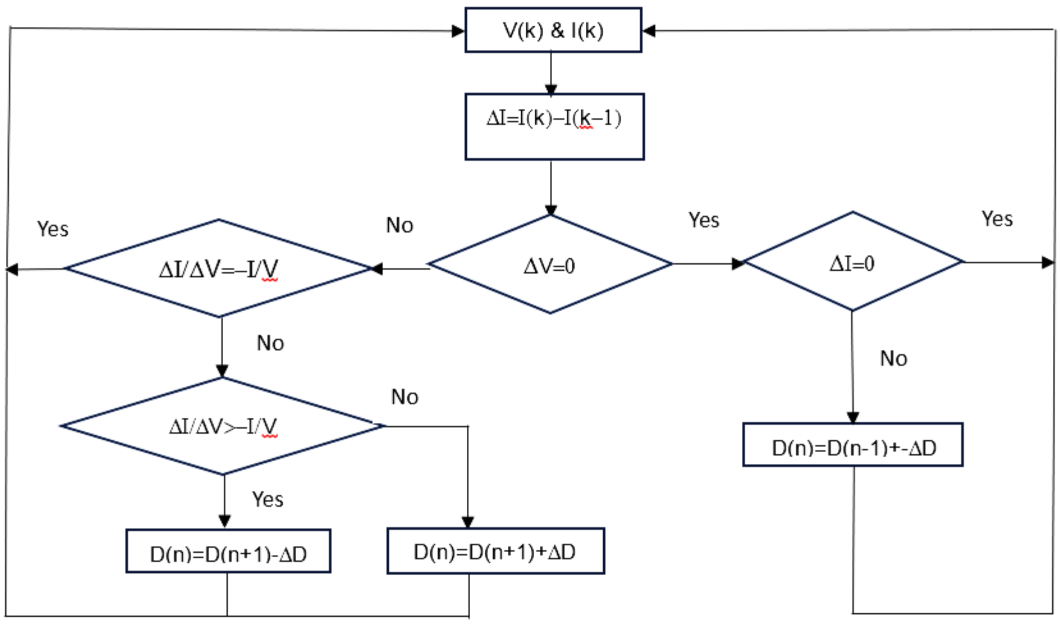

Fig. 4. Flowchart of INC MPPT algorithm

2.3 Proposed Circuit Design

Altera Quartus II software is used in this project for designing and simulating the INC MPPT algorithm by using VHDL code. Figure 5 illustrates the complete connection between the Block Diagram Files (BDF) blocks. This block includes the signal delay block (SL), delta calculation block (SU), division calculation block (divide), Incremental Conductance MPPT block (INC MPPT), and generation block.

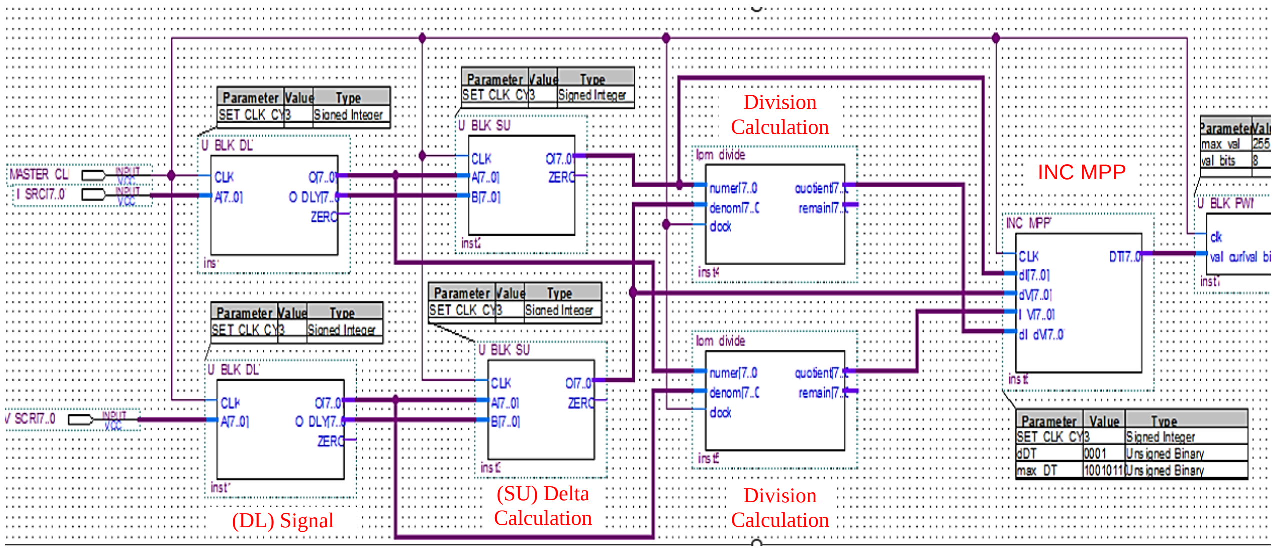

Fig. 5. Complete connection between BDF blocks

3. Results

In this section, the results of the simulation of the system will be discussed. After the process of designing and constructing of MPPT algorithm using the procedures mentioned in the previous section, the next step that should be done is the simulation of the circuit to check and make sure that the circuit design is working as expected. The simulation results of the vector complete connection between BDF blocks based on different test conditions are discussed in this section.

3.1 Simulation Result of INC MPPT Algorithm

The simulation results of the vector complete connection between BDF blocks based on different testing conditions will be discussed in this section. There are five testing conditions which are increasing current and increasing voltage, decreasing current and increasing voltage, variable current and constant voltage, constant current and variable voltage, and variable current and variable voltage. Figure 6 shows the simulation result of MPPT increasing current and voltage. In this testing, the increasing current (I_SRC) is continuously increasing from 1A to 3A. The increasing voltage, V_SCR is set from 9 V to 18 V.

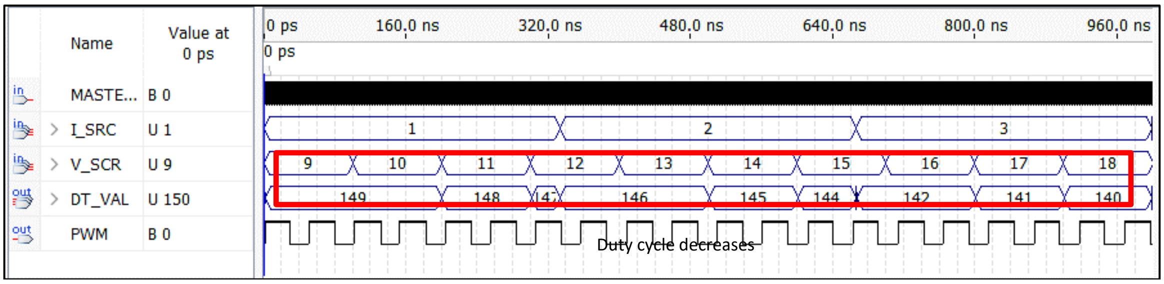

Fig. 6. Simulation result of MPPT with increasing current and voltage

The simulation result of the increasing current and increasing voltage MPPT is presented in Figure 6. Based on the result the PWM output signal (DT_VAL) reaches its maximum value and remains steady at the set value of 150_{10}or 10010110_2. This indicates the algorithm's ability to maintain stability and adhere to the predefined maximum value. The duty cycle decreases when the current and voltage increase to reach its maximum power point value based on the working principle of the INC MPPT algorithm The simulation result of the decreasing current and increasing voltage MPPT is displayed in Figure 7. The current, I_SRC is continuously decreasing from 3 A to 1 A. The voltage, V_SCR remains the same from 9 V to 18 V.

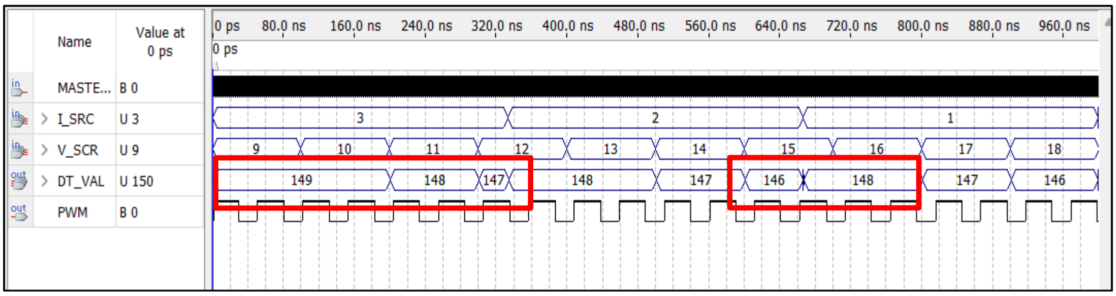

Fig. 7. Simulation result of decreasing current and increasing voltage

Based on the result, the duty cycle decreases when the voltage increases, and the current is at a constant value. It means the present point is at the left-hand side of the MPP, by reducing the PWM duty ratio, the algorithm effectively prevents the solar panel from deviating towards the right side of the maximum power point curve (as observed in Figure 3). Furthermore, when the current decreases and the voltage increases, the duty cycle increases to reach its MPP.

The simulation result of the variable current and constant voltage MPPT is illustrated in Figure 8. The voltage is kept constant while the power value fluctuates with changes in current. The duty cycle decreases with increasing current, ensuring efficient power extraction. Conversely, as the current decreases, the duty cycle ratio increases, optimizing the system's performance.

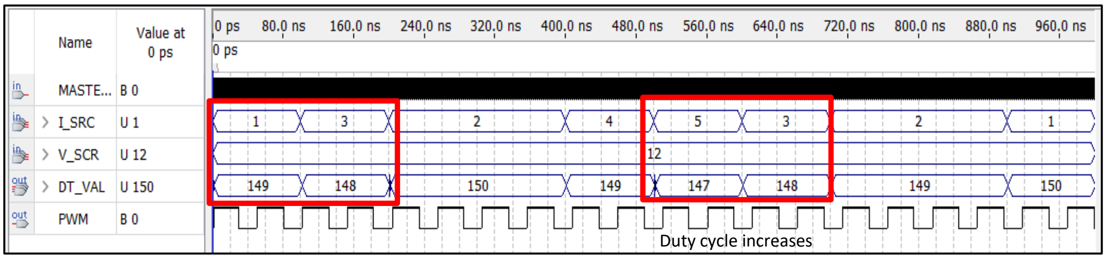

Fig. 8. Simulation result of MPPT variable current and constant voltage

The simulation result of the constant current and variable voltage MPPT is presented in Figure 9. In this simulation, the current is set to 3 A while varies for example 12, 7, 19, etc. The result proves that as the current remains constant value, and the voltage either increases or decreases; the duty cycle decreases accordingly to reach its MPP.

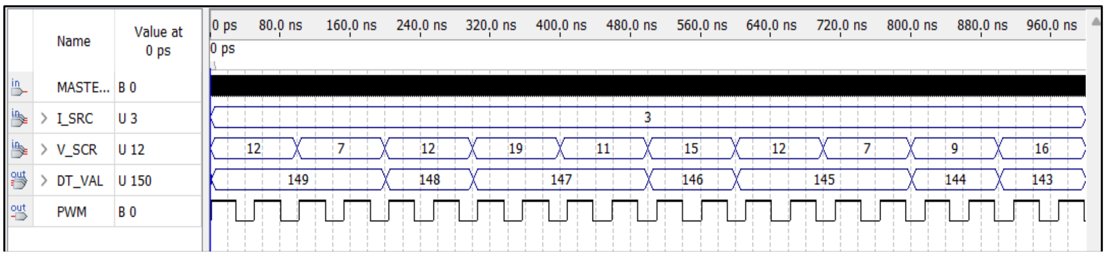

Fig. 9. Simulation result of MPPT constant current and variable voltage

The simulation result of the variable current and variable voltage MPPT is presented in Figure 10. According to the flowchart of the INC MPPT algorithm, if $\Delta I/\Delta V > -I/V$, then the duty ratio decreases. If $\Delta I/\Delta V < -I/V$, then the duty ratio increases. These adjustments maintain the system's operation at or near the MPP. For example, consider when the present I_SRC is 5 and the present V_SRC is 12, the previous I_SRC is 3 and the previous V_SRC is 12. The duty cycle, DT_VAL is reduced from 149 to 148 to ensure that it is at its maximum power point.

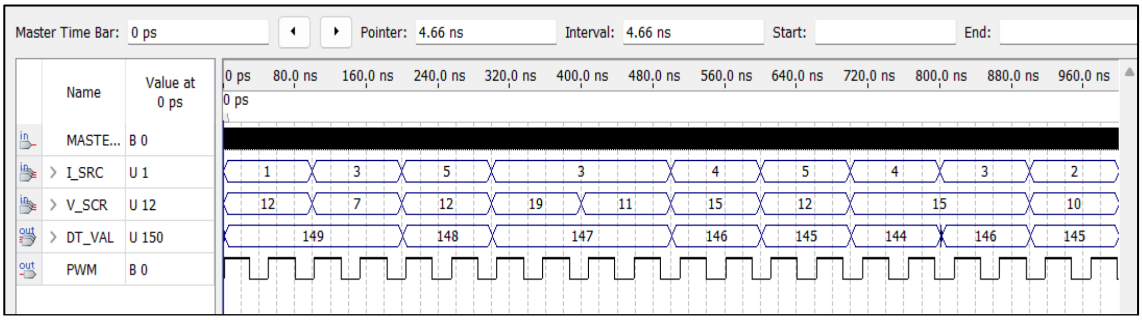

Fig. 10. Simulation result of MPPT variable current and variable voltage

Table 1 shows the summary of the INC MPPT working principle. It can be concluded that if $\Delta P/\Delta V > 0$, it will be located at the left-hand side of the MPP value as illustrated by Figure 3.

Table 1
Summary of the working principle for INC MPPT

Technique used	Incremental conductance MPPT (Based on the working principle of INC MPPT (Figure 3))	
	Position	Duty Cycle
$\Delta P/\Delta V > 0$	Left Hand Side	Decrease
$\Delta P/\Delta V = 0$	Maximum Power Point	-
$\Delta P/\Delta V < 0$	Right Hand Side	Increase

Decreasing the duty cycle is the way to reach its MPP value. Next, if $\Delta P/\Delta V = 0$, it is located at its MPP value. Meanwhile, if $\Delta P/\Delta V < 0$, it will be located at the right-hand side of the maximum power point value, increasing the duty cycle is the way to reach its MPP value. The simulation results are obtained based on the working principle of the INC MPPT algorithm.

4. Conclusions

This project focused on the implementation of a Maximum Power Point Tracking system for energy harvesting from photovoltaic cells, specifically targeting the efficient charging of mobile devices. The proposed MPPT algorithm is constructed successfully using VDHL code and the simulation results from the Altera Quartus II software also achieved the desired value. The simulation results prove that the MPPT algorithm was able to track and generate the output PWM control signal with respect to the current and voltage source. Several values of current and voltage are set during the testing process, and the designed MPPT algorithm can operate at its maximum power point by increasing or decreasing the duty cycle. In terms of achievement of the MPPT algorithm, it can ensure that the PV panel operates at its maximum power point based on different testing conditions in this project.

In conclusion, this project demonstrated the feasibility and effectiveness of an MPPT system using VHDL code. It provides valuable insights into enhancing energy harvesting efficiency and maximizing power extraction from PV cells. The MPPT algorithm is closely associated with energy harvesting for charging mobile devices. By tracking the maximum power point of the energy source, it optimizes power extraction, enhances charging efficiency, and improves the overall performance of energy harvesting systems. The MPPT algorithm ensures that mobile devices can efficiently utilize renewable energy sources, leading to sustainable and effective charging solutions.

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