Integrating DC/DC Conversion with Possible Reconfiguration within Submodule Solar Photovoltaic Systems

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by

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Dedicated to Sufang, Hsinjung, and Abigail
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<td>AM</td>
<td>Air Mass</td>
</tr>
<tr>
<td>BIPV</td>
<td>Building Integrated Photovoltaic</td>
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<tr>
<td>CCM</td>
<td>Continuous Conduction Mode</td>
</tr>
<tr>
<td>DCM</td>
<td>Discontinuous Conduction Mode</td>
</tr>
<tr>
<td>ESR</td>
<td>Equivalent Series Resistance</td>
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<tr>
<td>HF</td>
<td>High Frequency</td>
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<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
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<tr>
<td>SC</td>
<td>Solar Cell</td>
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<tr>
<td>STC</td>
<td>Standard Test Condition</td>
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<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>ZCS</td>
<td>Zero Current Switching</td>
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<tr>
<td>ZVS</td>
<td>Zero Voltage Switching</td>
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Abstract of the Dissertation

Integrating DC/DC Conversion with Possible Reconfiguration within Submodule Solar Photovoltaic Systems

by

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This research first proposes a method to merge photovoltaic (PV) cells or PV panels within the internal components DC-DC converters. The purpose of this merged structure is to reconfigure the PV modules between series and parallel connections using high switching frequencies (hundreds of kHz). This leads to multi-levels of voltages and currents that become applied to the output filter of the converter. Further, this research introduces a concept of a switching cell that utilizes the reconfiguration of series and parallel connections in DC-DC converters. The switching occurs at high switching frequency and the switches can be integrated to be within the solar panels or in between the solar cells. The concept is generalized and applied to basic buck and boost topologies. As examples of the new types of converters: reconfigurable PV-buck and PV-boost converter topologies are presented. It is also possible to create other reconfigurable power converters: non-isolated and isolated topologies. Analysis, simulation and experimental verification for the reconfigurable PV-buck and PV-boost converters are presented extensively to illustrate proof of concept. Benefits and drawbacks of the new approach are discussed.

The second part of this research proposes to utilize the internal solar cell capacitance and internal solar module wire parasitic inductances to replace the input capacitor and filter inductor in boost derived DC-DC converters for energy harvesting applications. High switching frequency (MHz) hard switched and resonant boost converters are proposed. Their analysis, simulation and experimental prototypes are presented. A specific proof-of-concept application is especially tested for foldable PV panels, which are known for their high internal wire inductance. The experimental converters successfully boost solar module voltage without adding any external input capacitance or
filter inductor. Benefits and drawbacks of new proposed PV submodule integrated boost converters are discussed.
Chapter 1

Introduction

By generating electricity directly from sunlight, solar photovoltaic (PV) technology shows tremendous potential as a means of powering the future, since solar energy is clean, renewable, environmentally friendly, and abundantly available. The maintenance required to keep PV facilities in operation is relatively minimal and low cost. With mass production, as recent trends indicate, the cost of PV modules decrease significantly, allowing PV system prices to fall within competitive rates of other energy technologies and even matching retail rates. As a result, PV power generation is becoming a mainstream of electricity supply. Globally, PV installations have grown rapidly from \( \sim 712 \text{ MW} \) in 2000 to \( \sim 227.1 \text{ GW} \) at the end of 2015, as shown in Fig. 1.1 [1].

With the continued development and research in PV technologies, solar cells and their materials have continued to improve their conversion efficiency. There are two prevalent solar cell technologies, i.e. crystalline silicon and thin-film silicon, and the first usually has higher conversion efficiency. Fig. 1.2 illustrates two examples of solar cells made by different materials and manufacturing technologies. Since high efficiency solar cells can capture more energy in the same wafer area, there has been a recent spur on the development of more solar powered devices, such as solar battery chargers for low power consumer electronic products, light-emitting diode (LED) lights, etc.

Typically, there are two different types of PV system installations, grid-tied and stand-alone. For low power and stand-alone applications, PV panels or cells provide an ideal current and voltage source which can be either connected to or integrated within the power converters to power up the electronic devices. Here are the examples of various low power PV applications:

- Portable and Consumer Electronic Devices
Figure 1.1: Global PV installations growth [1].

![Evolution of PV Installations Graph](image)

(a) Crystalline silicon  
(b) Thin-film silicon

Figure 1.2: Two different solar cell technologies [2,3].

The advancement of semiconductor manufacturing technologies has greatly reduced the power consumption of integrated circuits (ICs), allowing consumer electronic products to consume less power and operate at low voltages with a built-in battery. With this shift in consumer
electronic technology, manufacturers sought to build an efficient power converter system with a small profile. Solar powered devices, such as solar battery chargers, perfectly fulfill both the necessary energy and space efficiency, and are therefore increasingly being used to power portable electronic devices such as mobile phones/smartphones, e.g. iPhones and Android phones, laptops, tablets, global positioning system (GPS) devices, battery banks, etc. Fig. 1.3 shows the portable solar chargers for smartphone and laptop, respectively [4, 5].

Foldable, lightweight, and durable, thin-film PV panels are optimal for portable applications, such as use by the military or backpackers. These panels can easily be mounted on backpacks and helmets and carried around by soldiers, hikers, and campers to charge batteries in the battlefield or mountainous areas where an electrical grid is not accessible, as shown in Fig. 1.4 [6]. During the daytime, solar chargers are connected to the PV panels to charge the batteries, which can later be used to charge electronic equipment.

- **Stand-alone Systems**

PV cells, panels or arrays can be used for low power stand-alone equipment, such as solar powered LED lights, parking meters, speedometers, warning lights, etc., as shown in Fig. 1.5 [7, 8]. Those systems usually have a small power range, for example, from a few milliwatts to a few hundred watts. The operating voltages for these devices are in the range of a few volts to tens of volts. Typically, these pieces of equipment have battery storage, so they can operate independently during a rainy day or at night.

- **Building Integrated PV (BIPV) Systems**
PV panels or arrays can be integrated directly into buildings. Many builders today are choosing to include PV panels or arrays in building facades, skylights, and roofs in order to generate electricity, as shown in Fig. 1.6 [9,10]. However, the output power of these integrated PVs can be easily affected by shadows from other buildings or the surrounding environment, such as trees and utility poles. The reconfigurable PV method might be able to mitigate the partial shading effect by changing the PV connections [11].
1.1 Motivation

In general, PV panels or cells are connected in series to increase the output voltage and connected in parallel to generate high output current. There are drawbacks with these two basic connections: In the pure series connection, the overall performance is constrained by the least efficient panel or cell, since the minimal current from one of the cells or panels limits the entire string current. If all the cells are connected in parallel, the output voltage is usually low $\sim 0.5 \text{ V}$. This is why it is necessary to use combinations of the series connections in strings to build up the voltage to a useful value in each of the solar panels. The panels are also connected in series strings to build up arrays on roofs, often with voltages ranging from 300 V to 900 V. Then the series strings of PV panels are connected in parallel with a combiner box. A poorly producing string of PVs may not overly influence the panels in the other strings since they are parallel connected. However, the bus voltage is sufficiently high that there is not huge resistive power loss in the lines. In the series-parallel connections, of course, once the connections of PV panels or cells are fixed, they are not changed after the installation.

In the large PV systems, the PV array or strings are used to achieve sufficiently high input voltage for grid-tied inverter, and a large electrolyte capacitor is normally required at the input of the inverter [12–16]. Fig. 1.7 shows two common PV system configurations, i.e. centralized inverter and string inverters. In those PV system architectures, the partial shading and mismatches between the panels caused by aging, dirt accumulation, or manufacturing variability, can easily reduce the overall system output power. Traditionally, a bypass diode is connected within a solar panel to help mitigate
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these issues by passing the full amount of current through the panel, and therefore, the whole string current is not constrained by the underperforming portion of a single PV panel. The bypass diodes may cause multiple maximum power points (MPPs) that complicate maximum power point tracking (MPPT) algorithms for finding the absolute MPP. They also lower the string voltage when current passes through them, which can cause the other paralleled strings’ voltage to reduce to suboptimal power.

The modular architectures such as module integrated inverters, also known as microinverters, and cascaded DC-DC converters have become popular because a local MPPT is applied to each PV panel through distributed control [17–20]. Fig. 1.8 shows two modular PV system architectures, i.e. microinverters and cascaded DC-DC converters with a centralized inverter. With the module integrated inverter or converter, the mismatch between the panels is removed. The shaded panel only affects its individual output power and will not limit the performance of other panels in the string. As a result, the overall energy yield is increased. The cascaded converters may have lower conversion ratio, compared to the microinverters, which results in higher conversion efficiency.

Recently, the concepts of PV submodule and cell integrated power converters have emerged and drawn more research attention [21–23]. A small DC-DC converter is connected to a group of PV cells or a single cell, and it performs MPPT for each submodule or cell. Therefore, the mismatch between the PV submodules or cells no longer exists. Because each submodule or cell operates at its MPP, the overall energy extraction might be increased. Figs. 1.9 and 1.10, respectively, show the submodule and cell integrated DC-DC converters. The outputs of the DC-DC converters can be connected in series or in parallel for different loads. For example, for portable applications, a typical load might be a battery or a simple resistive load. Further, it is possible to integrate the switches or power converters with PV submodule or cell in the same fabrication process [24–26].

1.2 Background

1.2.1 Reconfigurable PV Panels or Submodules

There are generally two approaches to utilizing switches in-between solar panels for reconfiguration. Firstly, it is possible to slowly switch between the series and parallel configurations in response to slow changing environmental impacts, such as clouds or shadows over a panel [11] [27][28]. Since the cloud is moving slowly, the switching can occur in ~ each second if necessary, and the speed is able to adequately compensate for the changing environment. Sometimes, for example
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Figure 1.7: Two common PV system configurations.
Figure 1.8: Two recently developed PV system configurations.
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(a) Cascaded configuration
(b) Parallel-connected configuration

Figure 1.9: Submodule integrated DC-DC converters.

(a) Cascaded configuration
(b) Parallel-connected configuration

Figure 1.10: Cell integrated DC-DC converters.
CHAPTER 1. INTRODUCTION

in slow moving shadows, the reconfiguration between the panels may be programmed to alter in the 10’s or 100’s of seconds. The idea is that it is possible to connect certain panels in parallel when they are underperforming so that they do not limit the power production of the entire string of panels they are connected with. Then the low power producing PV panels are bypassed. In [27], the proposed method is able to adaptively reconfigure the solar PV array connection in real time with the controllable matrix of switches. When the fixed solar PV array is partially shaded, the solar cells from the smaller adaptive bank will be connected to the fixed solar PV array. Consequently, this reconfiguration strategy releases the array current limitation under partial shading and increases the power output of the solar PV array.

1.2.2 Submodule or Cell Integrated Power Converters

Alternatively, it is also possible to integrate switches within the PV cells to form integrated DC-DC converters between the solar cells [23] [25] [26]. The small power converters can be used to either 1) individually extract maximum power from the PV cells/submodules [21] [22] or 2) divert portions of current produced by solar cells around shadowed (or underperforming) other series connected solar PV cells [23]. For either approach, the maximum available power can be individually extracted from the submodule level. The energy yield would increase on the solar PV system, since the PV system is no longer limited by the solar PV cell or module with lowest output current. Further, it has been proposed that, for any reconfiguration scheme, the switches or power converters may be manufactured in the same fabrication process as the solar PV array itself [24] [26].

1.2.3 Internal and Parasitic Energy Storage and Filter Elements

Most power electronic converters rely on external energy storage and filter elements, i.e. capacitors and inductors. But, magnetic elements often dominate the size and weight of a power converter and occupy the most area of printed circuit board (PCB). Those discrete passive components are the impediments to the miniaturization of power converter system. To minimize the component count and achieve a high density power converter, one method is to utilize the parasitic passive components [29] and another method is to create new circuit topologies with a unique operation. In this research, we will utilize both approaches. Our vision will be to use the combination of reconfiguration of internal PV connections with the utilization of internal parasitics of solar PVs and their interconnections to create new approaches of solar cell/panel operation. By increasing the switching frequency, the required energy storage element of a power converter, such as inductors, can
CHAPTER 1. INTRODUCTION

be substantially reduced. For example, the converter switching at 10’s—100’s of MHz can reduce the required inductance down to 10’s—100’s of nH [30]. The second part of this research will investigate the internal solar cell capacitance and parasitic wire inductance and explore the possibility to utilize them to replace external input capacitor and inductive in the proposed power converter topologies.

1.3 Problem Statement

This thesis research will investigate the following topics and propose new methods along with new PV converter circuit topologies. Specifically, the goals of this research are:

- To merge the concepts from reconfigurable PV systems with integrated power converters and then develop a new classification of reconfigurable PV derived power converters. The new proposed converter topologies will also incorporate concepts from multi-input and multi-level converters to effectively reduce filter component size and voltage stress of the switches. With the new topologies, PV modules or submodules can be reconfigured in either slow or fast switching fashion.

- To design new PV submodule integrated hard-switched and resonant boost DC-DC converters that can operate with no external input capacitor and/or filter inductor by utilizing the internal solar cell capacitance and solar module wire parasitic inductance. A high frequency operation will be considered to reduce the required inductance in the proposed converter topologies. Component variations should be analyzed and examined under different sunlight conditions and wire lengths, making sure that the proposed converters have ability to function properly for environmental changes.

1.4 Dissertation Organization

This dissertation consists of two parts, and their research results solve the problems and achieve the research goals listed above. The first part of the research proposes a new method to merge the concept of reconfigurable PV systems with the concept of integrated power converters, and then, we present a new classification of reconfigurable PV power converters. The second part of the research proposes new methods to eliminate the external passive energy storage or filtering elements, and therefore, new types of PV submodule integrated step-up DC-DC converters are presented for energy harvesting applications. Specifically, the dissertation is organized as follows.
CHAPTER 1. INTRODUCTION

Chapter 2 introduces a new concept of a switching cell that utilizes the reconfiguration of series and parallel connections in DC-DC converters and then proposes new types of buck and boost derived DC-DC converters. Chapter 3 presents a new approach to eliminate the external passive energy storage and filtering components and then proposes a new type of hard-switched boost DC-DC converter that requires no-input capacitor nor filter inductor. Further, a new type of soft-switched boost DC-DC converter is proposed in Chapter 4. The non-ideal operation for the proposed boost DC-DC converters is analyzed and discussed. In Chapter 5, a summary of the thesis research results is presented, and the future research work is addressed.

A brief summary of each chapter is listed below.

**Chapter 2**: Fast Switching Reconfigurable PV Modules Integrated DC-DC Converters. In this chapter, the benefits and drawbacks of reconfigurable PV modules and integrated power converters versus the traditional PV systems are studied and compared. Then a PV switching cell is proposed and applied to basic buck and boost topologies. Therefore, reconfigurable PV-buck and PV-boost DC-DC converter topologies are proposed, and their analysis, simulation and experimental verification are presented.

**Chapter 3**: Submodule Integrated Boost DC-DC Converters with No Input Capacitor or Input Inductor. In this chapter, the internal solar cell diode capacitance and wire parasitic inductance within the PV module are first modeled. Then a new type of hard-switched boost DC-DC converter with no external input capacitor or input inductor is proposed. Its analysis, simulation and experimental prototype are presented.

**Chapter 4**: Submodule Integrated Soft-Switched Boost DC-DC Converter and Non-Ideal Operation. After the no-input capacitor, no-input inductor hard-switched boost converter is designed and validated, another new type of soft-switched boost converter topology is then proposed to mitigate the power losses due to the high frequency operation. Its analysis and simulation are presented, and finally, a proof-of-concept prototype is designed, built and tested. Besides, the non-ideal operation of the proposed boost converters is analyzed, simulated, and experimentally validated.

**Chapter 5**: Conclusions and Future Work. In this chapter, the conclusions of the thesis are presented and future research is discussed.

This dissertation demonstrates several major research contributions and technical advancements over the previous solutions.
CHAPTER 1. INTRODUCTION

**Contribution 1:** A new classification of reconfigurable PV power converter topologies is introduced, which merges concepts from reconfigurable PV systems with multi-input and multi-level converters. Periodic fast switching to reconnect PV panels or cells from series to parallel is utilized to alter the voltage and current applied to the converter’s output filter, which can sometimes reduce the voltage stresses on the switches and the size of output filter element or output ripples. Finally, new types of PV-buck and PV-boost derived DC-DC converter topologies are proposed.

**Contribution 2:** The concept of a no-input capacitor, no-input inductor high frequency boost converters is introduced. A new type of hard-switched boost DC-DC converter utilizes the internal solar cell diode capacitance and internal solar module wire parasitic inductance to reduce the size and cost of the converter and also improve the reliability of the converter. Specifically, it is suitable for low power and low voltage energy harvesting applications.

**Contribution 3:** A new type of soft-switched boost DC-DC converter is proposed. It is integrated within a solar PV submodule and utilizes the solar cell internal capacitance as input capacitor and solar cell interconnect wire parasitic inductance as input inductor. The proof-of-concept prototype is successfully designed, built and experimentally tested. Moreover, the proposed boost converters can operate in both low and high irradiance with different wire inductance at high frequencies, making it suitable for energy harvesting applications.
Chapter 2

Fast Reconfigurable Photovoltaic Modules Integrated within DC-DC Converters

2.1 Overview

The purpose of this research is to explore a possibility to merge the reconfiguration concepts of [11] [27, 28] with the integrated power converter concepts of [21–23] [25, 26]. Specifically, a new classification of power converters in which the photovoltaic (PV) cells/arrays are viewed as sources within a fast switching power converter, similar to a capacitor in a switched capacitance converter. Then, it is possible to use high switching frequency to reconnect the panels in series and parallel within each cycle. The idea also borrows concepts from traditional multi-level converters [31–33], particularly three-level DC-DC converters where the voltages applied to the output filter have unique waveforms that lead to smaller output filters [33]. Specifically, this research includes the following contributions:

- A new classification of reconfigurable PV power converter topologies is introduced [34]. The topologies merge concepts from reconfigurable solar PV systems [11] [27, 28] with multi-input [35–43] and multi-level converters [31, 33, 44]. Periodic fast switching to reconnect PV panels or cells from series to parallel is utilized to alter the voltage and current applied to the converter’s output filter.
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

- As examples of the new types of converters, PV-buck and PV-boost derived topologies are designed, simulated and experimentally tested. In the proposed topologies, two PV panels are switched between series and parallel configurations at high frequency (for example, > 50 kHz).

- The new proposed PV-buck converter has interesting benefits and drawbacks that are explained. Benefits include 1) the voltage stresses on the switches will be reduced to half of the input voltage, 2) the size of output filter element will be reduced, and 3) the output ripples will be reduced. Drawbacks may be: 1) increased complexity, 2) possible ripple currents in the PV panels, and 3) additional parts count, such as switches, compared to the traditional buck converter.

2.2 Benefits of Reconfigurable PV Modules and Integrated Power Converters

Recently, the idea of reconfigurable solar panels has been introduced [11] [27, 28], where switches are placed between solar PV cells, strings, or arrays. The connections between the PV modules can be changed from series to parallel in order to maximize energy extraction from the entire PV system. This allows for adjustment of connections in response to shadows, aging, or other environmental conditions that may affect portions of an entire panel or array. By adding reconfiguration to the PV system, it becomes possible to bypass low power producing PV modules so that they do not overly reduce the entire PV system power. In comparison, traditional PV systems are normally composed of fixed interconnected solar panels (or cells) either in series or parallel. When strings are created by connecting several PV panels in series, as is done with grid-tied centralized inverter configurations, a shadow on a single panel limits the output power of the entire string.

Expanding the idea to reconfigure PV panels or PV cells by switches [11] [27, 28], the work of [21–23, 45] proposes to integrate DC-DC converters within a panel so that groups of solar cells may have a DC-DC converter (or inverter) connecting to them. The small power converters can be used to either 1) individually extract maximum power from the PV cells/submodules [21, 22] or 2) divert portions of current produced by solar cells around shadowed (or underperforming) other series connected solar PV cells [23]. For either approach, the energy yield would increase on the solar PV system, since the PV system is no longer limited by the solar PV cell or module with lowest output.
current. Further, it has been proposed that, for any reconfiguration scheme, the switches or power converters may be manufactured in the same fabrication process as the solar PV array itself \[24\–26\].

### 2.3 A Proposed PV Switching Cell

The unique concept is to view the solar panels as power sources that can reconfigure between series and parallel at high switching frequencies. The converter is built with two solar panels, although it is simple to scale the method, i.e. each solar panel could be viewed as groups of series connected solar cells or series connected solar panels. Fig. 2.1 shows the circuit diagram of the proposed PV switching cell \[46\]. It consists of two solar panels \(PV_1\) and \(PV_2\), a MOSFET as switch \(S_1\), and two diodes \(D_1\) and \(D_2\). Note that the switch \(S_1\) is connected between two solar panels and switches at high frequency (for example, \(> 50\) kHz). For simplicity, assume that two solar panels are identical, and they have same \(V_{PV}\) and \(I_{PV}\), i.e. \(V_{PV} = V_{PV_1} = V_{PV_2}\) and \(I_{PV} = I_{PV_1} = I_{PV_2}\).

![Figure 2.1: The proposed PV switching cell.](image)

The switch \(S_1\) in the PV switching cell is used to change the connections of two PV modules. When \(S_1\) is ON, then \(V_{34}\) represents the voltage of the panels in series and \(V_{34} = 2 * V_{PV}\). The diodes are OFF and the same current travels through both panels. When \(S_1\) turns OFF, then the diodes turn ON, and the PV panels are in parallel and \(V_{34} = V_{PV}\). The panel currents add to
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

each other because of the parallel connection. Fig. 2.2 shows the block diagram of the proposed PV switching cell connected to any type of DC-DC converter.

Figure 2.2: The block diagram of PV switching cell with DC-DC converter. (Switches in the DC-DC converter are sometimes redundant and can be removed.)

2.4 Reconfigurable PV-Buck Derived Converter

Fig. 2.3 shows the circuit diagram of the proposed reconfigurable PV-buck derived converter [34]. The concept can easily be described when terminals 3 and 4 are connected to an LC output filter to form the reconfigurable buck converter.

Figure 2.3: The reconfigurable PV-buck derived converter.
2.4.1 Principle of Operation

2.4.1.1 Ideal Operation

There are two intervals of circuit operation of PV-buck derived converter.

- **Interval 1** \((0 < t < d_1 T)\): As shown in Fig. 2.4, in this interval, the switch \(S_1\) is turned ON, so \(V_{32} > 0\) and \(V_{14} > 0\), and the \(D_1\) and \(D_2\) are turned OFF. The \(PV_1\) and \(PV_2\) are connected in series. (The solar panels could also be solar cells or a series combination, thereof.) The current goes through \(PV_2\), switch \(S_1\), \(PV_1\), output filter \(L_o\) and \(C_o\), and load resistor \(R_L\). Theoretically, the filter voltage (at nodes 3 and 4) and inductor current are respectively shown in (2.1) and (2.2),

\[
V_{filt} = V_{PV1} + V_{PV2} = 2V_{PV} \tag{2.1}
\]

\[
I_L = I_1 = I_2 \tag{2.2}
\]

![Figure 2.4: Two PV panels are in series connection when \(S_1\) is ON.]

- **Interval 2** \((d_1 T < t < T)\): When the switch \(S_1\) is turned OFF, the \(D_1\) and \(D_2\) are turned ON. The \(PV_1\) and \(PV_2\) are connected in parallel, as shown in Fig. 2.5. The current goes through
two parallel $PV_1$ and $PV_2$, two diodes $D_1$ and $D_2$, output filter $L_o$ and $C_o$, and load resistor $R_L$. Theoretically, the filter voltage (at nodes 3 and 4) and inductor current are respectively shown in (2.3) and (2.4),

\[ V_{filt} = V_{PV1} = V_{PV2} = V_{PV} \]  \hspace{1cm} (2.3)

\[ I_L = I_1 + I_2; \quad I_1 = I_2 \]  \hspace{1cm} (2.4)

Figure 2.5: Two PV panels are in parallel connection when $S_1$ is OFF.

The circuit voltage waveforms in different intervals are shown in Fig. 2.6(a) and it can be seen that output voltage $V_{out}$ can be modulated between $2V_{PV}$ and $V_{PV}$. The voltage stresses of the switches ($S_1$, $D_1$ and $D_2$) equal to half of the input voltage, which is $V_{SW} = V_{PV}$, compared to $V_{SW} = 2V_{PV}$ of conventional buck converter, shown in Fig. 2.14. The filter voltage can be written as,

\[ V_{filt}(t) = q_1(t) \cdot (2V_{PV}) + (1 - q_1(t)) \cdot (V_{PV}) \]  \hspace{1cm} (2.5)
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

where

\[ q_1(t) = \begin{cases} 
1, & 0 < t < d_1 T \\
0, & d_1 T < t < T 
\end{cases} \]

and \( d_1 \) is the duty ratio of switch \( S_1 \).

Similarly,

\[ I_1(t) = I_2(t) = q_1(t) \cdot I_L + (1 - q_1(t)) \cdot \frac{I_L}{2} \]  \hspace{1cm} (2.6)

where \( I_1(t) = I_2(t) \) are discontinuous currents that jump between \( I_L \) and \( I_L/2 \). (See Fig. 2.6(b)).

In the steady state, the average voltage of output inductor equals zero, i.e. \( \langle V_L \rangle = 0 \). The output voltage can be found in the following equation:

\[ \langle V_L \rangle = 0 = \frac{(2 V_{PV} - V_{out}) \cdot (d_1 T) + (V_{PV} - V_{out}) \cdot (1 - d_1) T}{T} \]  \hspace{1cm} (2.7)

which leads to the input output transfer ratio:

\[ V_{out} = (1 + d_1) \cdot V_{PV} \]  \hspace{1cm} (2.8)

The inductor current is shown in Fig. 2.6(b). Assuming the inductor current is constant, the averaging \( \langle g \rangle \) leads to,

\[ \langle I_1 \rangle = \langle I_2 \rangle = d_1 \cdot I_L + (1 - d_1) \cdot \frac{I_L}{2} = \frac{(1 + d_1)}{2} \cdot I_L \]  \hspace{1cm} (2.9)

where \( \langle g \rangle \) represents the average value of \( g \). Fig. 2.6(b) illustrates the current waveforms of the proposed circuit. It shows that \( \langle I_1 \rangle = \langle I_2 \rangle = \langle I_L \rangle \) when two PV panels are connected in series and \( \langle I_1 \rangle = \langle I_2 \rangle = \langle I_L \rangle/2 \) when two PV panels are connected in parallel. It is possible to calculate the average current through each panel since \( I_{PV1} = I_1(t) + i_{C1} \) and \( I_{PV2} = I_2(t) + i_{C2} \). Ideally, since \( \langle i_{C1} \rangle = \langle i_{C2} \rangle = 0 \), this leads to the fact that

\[ I_{PV1} = I_{PV2} = \frac{(1 + d_1)}{2} \cdot I_L \]  \hspace{1cm} (2.10)
Figure 2.6: Ideal waveforms of (a) voltages and (b) currents of PV-buck converter.
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

It is seen that, for the ideal case with no switching losses and identical panels, the inductor current is equally split among the two panels.

The circuit can either operate as a maximum power point tracker (MPPT) with no output voltage regulation or as a typical buck regulator with output voltage control. To operate at MPP, the optimum duty ratio can be selected for one of the solar panels to work at its own maximum power point voltage \( V_{MPP} \). Otherwise, the duty ratio would be adjusted to regulate output voltage.

### 2.4.1.2 Non-Ideal Operation

In the non-ideal case, the two PV panels are not identical. They have different \( V_{PV} \) and \( I_{PV} \), i.e. \( V_{PV1} \neq V_{PV2} \) and \( I_{PV1} \neq I_{PV2} \). Also, there will be voltage drop across the diodes, i.e. \( V_{d1} \approx V_{d2} \) and \( V_{DS(ON)} \approx 0 \). Then, when two PV panels are connected in series during \( 0 < t < d_1 T \), the filter voltage is,

\[
V_{filt} = V_{PV1} + V_{PV2} - V_{DS(ON)} \approx V_{PV1} + V_{PV2} \tag{2.11}
\]

When two PV panels connected in parallel during \( d_1 T < t < T \), the filter voltage clamps to the lower PV voltage, i.e.

\[
V_{filt} = \min\{(V_{PV1} - V_{d1}), (V_{PV2} - V_{d2})\} \tag{2.12}
\]

Assume that \( V_{d1} \approx V_{d1} = V_d \), then (2.12) becomes,

\[
V_{filt} = \min\{(V_{PV1}), (V_{PV2})\} - V_d \tag{2.13}
\]

Therefore,

\[
V_{filt} = q_1(t) \cdot (V_{PV1} + V_{PV2}) + (1 - q_1(t)) \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d) \tag{2.14}
\]

with
\[ V_{out} = \langle V_{filt} \rangle = d_1 \cdot (V_{PV1} + V_{PV2}) + (1 - d_1) \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d) \] 

(2.15)

2.4.2 Simulation Results

MATLAB/Simulink models are built according to the single-diode model of PV module (amorphous silicon) shown in Fig. 2.7 to used to describe \( PV_1 \) and \( PV_2 \) and the reconfigurable PV-buck converter topology shown in Fig. 2.3 to verify the circuit operation. The I-V and P-V characteristics of two PV modules are shown in Fig. 2.8 and in Table 2.1 respectively. From the measured I-V characteristic results, these two PV panels are not identical and are degraded due to the aging. In the circuit simulation, the parameters of switching devices, i.e. \( S_1, D_1 \) and \( D_2 \), are from the model parameters of MOSFET and diodes used in the experiment (see Table 2.2). The PV-buck converter works in the same condition of the experiment in Section 2.4.3: the duty ratio \( d = 0.5 \) and the load resistance \( R_L = 50 \, \Omega \). With the same illumination and temperature conditions, two PV modules are simulated to operate at \( V_{PV1} = 9.3701 \, V \), \( I_{PV1} = 0.2238 \, A \), \( V_{PV2} = 9.3699 \, V \) and \( I_{PV2} = 0.2206 \, A \). Fig. 2.9(a) shows that the filter voltage \( V_{filt} \) is the sum of two PV modules’ voltages as they switch to series connection and approximately equals a PV module’s voltage as they switch to parallel connection. With this new proposed topology, the stress voltage on the switch and two diodes are also shown respectively in Fig. 2.9(b) and it equals a half of the input voltage of the series connected PV panels. Fig. 2.10(a) shows that the inductor current \( I_L \) equals \( I_1 \) (and \( I_2 \)) as PV panels switch to series connection and is the sum of \( I_1 \) and \( I_2 \) as they switch to parallel connection. Moreover, it can be seen that PV currents \( I_{PV1} \) (and \( I_{PV2} \)) have small ripple in Fig. 2.10(b).

![Figure 2.7](image.png)

Figure 2.7: The equivalent circuit of single-diode model for PV module.
Figure 2.8: (a) I-V and (b) P-V characteristics of two PV modules used in the simulation.
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

(a) The relation of the filter voltage ($V_{filt}$) and two PV panels' voltages ($V_{PV1}$ and $V_{PV2}$) in series and parallel configurations.

(b) The stress voltages ($V_{SW}$, $V_{d1}$, and $V_{d2}$) applied on the MOSFET ($S_1$) and two diodes ($D_1$ and $D_2$).

Figure 2.9: Simulated voltage waveforms of reconfigurable PV-buck converter.
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

(a) The inductor current during series and parallel configuration.

(b) PV modules and capacitor current.

Figure 2.10: Simulated current waveforms of reconfigurable PV-buck converter.
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

2.4.3 Experimental Verification

A prototype of the proposed reconfigurable PV-buck converter is built for verification, as shown in Fig. 2.11(a). Two amorphous silicon solar panels are used as input power sources and the halogen lamps are used to provide uniform illumination (light intensity) in the experiment, as shown in Fig. 2.11(b). Tables 2.1 and 2.2 respectively show the parameters of two PV panels and specifications of PV-buck converter prototype.

Table 2.1: Measured and Simulated PV panels’ electrical parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>PV panel #1</th>
<th>PV panel #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage (Volt)</td>
<td>$V_{oc}$</td>
<td>24.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Short circuit current (Amp)</td>
<td>$I_{sc}$</td>
<td>0.289</td>
<td>0.2889</td>
</tr>
<tr>
<td>Maximum power point voltage (Volt)</td>
<td>$V_{MPP}$</td>
<td>16.51</td>
<td>15.73</td>
</tr>
<tr>
<td>Maximum power point current (Amp)</td>
<td>$I_{MPP}$</td>
<td>0.16</td>
<td>0.1691</td>
</tr>
<tr>
<td>Maximum power (Watt)</td>
<td>$P_{MPP}$</td>
<td>2.642</td>
<td>2.6594</td>
</tr>
</tbody>
</table>

Table 2.2: Circuit parameters of PV-buck converter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Manufacturer/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>$S_1$</td>
<td>International Rectifier, IRFU3607</td>
</tr>
<tr>
<td>Diodes</td>
<td>$D_1,D_2$</td>
<td>Vishay, VF30100S</td>
</tr>
<tr>
<td>Filter inductor</td>
<td>$L_o$</td>
<td>75$\mu$H</td>
</tr>
<tr>
<td>Input capacitor</td>
<td>$C_1,C_2$</td>
<td>100$\mu$F</td>
</tr>
<tr>
<td>Load resistor</td>
<td>$R_L$</td>
<td>50$\Omega$</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_{SW}$</td>
<td>50kHz</td>
</tr>
</tbody>
</table>

Fig. 2.12(a) shows the experimentally measured voltage waveforms of PV-buck converter. As seen in the figure, the filter voltage $V_{filt}$ varies when the switch $S_1$ is turned ON and OFF. The filter voltages $V_{filt}$ can be found separately by (2.11) and (2.13) when two PV panels are connected in series and in parallel. Table 2.3 shows the experimental results of PV-buck converter with two PV panels. Therefore, using (2.11) gives

$$V_{filt} = V_{PV1} + V_{PV2} - V_{DS(ON)} = 14.99V$$

And using (2.13) gives
Figure 2.11: Photographs of (a) prototypes and (b) bench setup for experimental verification under a repeatable and controllable environment.


\[ V_{filt} = \min\{(V_{PV1}, V_{PV2})\} - V_d = 7.24V \]

With the duty ratio \( d_1 = 0.5 \), the output voltage of PV-buck converter can be found by (2.15).

\[
V_{out} = d_1 \cdot (V_{PV1} + V_{PV2}) + (1 - d_1) \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d) = 11.12V
\]

which can approximately match with the experimental result. The difference can be attributed to the nonidealities, such as wire losses, switch losses, nonlinear behavior of the solar panel, and measurement errors, etc.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panel #1’s voltage (Volt)</td>
<td>( V_{PV1} )</td>
<td>7.58</td>
</tr>
<tr>
<td>PV panel #2’s voltage (Volt)</td>
<td>( V_{PV2} )</td>
<td>7.41</td>
</tr>
<tr>
<td>PV panel #1’s current (Amp)</td>
<td>( I_{PV1} )</td>
<td>0.172</td>
</tr>
<tr>
<td>PV panel #2’s current (Amp)</td>
<td>( I_{PV2} )</td>
<td>0.142</td>
</tr>
<tr>
<td>Drain-source voltage of the Switch (Volt)</td>
<td>( V_{DS(ON)} )</td>
<td>( \sim 0 )</td>
</tr>
<tr>
<td>Drop voltage of the diode (Volt)</td>
<td>( V_{d1}, V_{d2} )</td>
<td>0.166</td>
</tr>
<tr>
<td>Filter voltage (Volt)</td>
<td>( V_{filt(s\text{eries})} )</td>
<td>15</td>
</tr>
<tr>
<td>Inductor current (Amp)</td>
<td>( I_L )</td>
<td>0.21</td>
</tr>
<tr>
<td>Converter’s output voltage (Volt)</td>
<td>( V_{out} )</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Fig. 2.12(b) shows that the stress voltages of the switch \( S_1 \) and diode \( D_1 \) approximately equal \( V_{PV} \), which is half of the input maximum voltage. Fig. 2.13 shows the PV current \( I_{PV1} \) and inductor current \( I_L \) in the switching period. From (2.9), \( \langle I_1 \rangle = \langle I_2 \rangle = (1 + d_1)/2 \cdot I_L \) and ideally \( \langle I_1 \rangle = I_{PV1} \) and \( \langle I_2 \rangle = I_{PV2} \). Therefore, it is found that \( \langle I_1 \rangle = \langle I_2 \rangle \approx 0.157 \) A. This is not the same as \( I_{PV1} \) and \( I_{PV2} \) measured from the experiment, but the calculation reflects the average value of the two PV panels currents \( \approx (I_{PV1} + I_{PV2})/2 \).
Figure 2.12: Experimental voltage waveforms of PV-buck converter during the switching period.
Figure 2.13: Experimental current waveforms of PV-buck converter during the switching period.
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2.4.4 Comparison to Conventional Buck Converter

The most common topologies used as MPPT’s are boost, buck or other up-down converters. All these topologies can be derived from the basic canonical switching cell. In the traditional buck converter in Fig. 2.14, the two solar PV sub-arrays \( PV_1 \) and \( PV_2 \) are connected in series. Therefore, the voltage \( V_{filt} \) applied to the \( LC \) output filter will vary from \( V_{filt} = V_{PV1} + V_{PV2} \) \((0 < t < d_1 T)\) when \( S_1 \) is ON to \( V_{filt} = 0 \) \((d_1 T < t < T)\) when \( S_1 \) is OFF, where \( T \) is switching period of the circuit. This leads to the switch and diode to have rating of full input voltage \((V_{PV1} + V_{PV2})\). The inductor and capacitor sizes must be sufficiently large to filter a voltage that varies from \((V_{PV1} + V_{PV2})\) to 0.

Ideally, in the proposed topology, the voltage at the \( LC \) output filter varies from \( 2V_{PV} \) to \( V_{PV} \). Thus, the switch stress is approximately half that from the traditional buck converter. Also, for the same inductor current ripple specification, it can be shown that the inductance value can normally be reduced by a factor of \( \sim 1/3 \) [33]. Alternatively, if the same inductance value is utilized as in the traditional buck converter, the output filter capacitance reduces by that factor. The reduced inductance value is due to the fact that \( V_{filt} \) has voltage \((V_{PV} - V_{out})\) in this topology when \( S_1 \) is OFF instead of switching to zero voltage when \( S_1 \) is OFF as in the traditional buck converter. On the other hand, a drawback is that the proposed buck converter must have ideal output voltage in the range from \( V_{PV} \) to \( 2V_{PV} \). The traditional buck converter has wider range of output voltage from zero voltage to \( 2V_{PV} \). Table 2.4 shows the comparisons of conventional buck converter and reconfigurable PV-buck converter.

![Figure 2.14: The circuit diagram of conventional buck converter with two PV panels in series connection.](image-url)
Table 2.4: Comparisons of conventional buck and reconfigurable PV-buck converters

<table>
<thead>
<tr>
<th></th>
<th>Conventional buck converter</th>
<th>Reconfigurable PV-buck converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch stress voltage</td>
<td>(2V_{PV})</td>
<td>(V_{PV})</td>
</tr>
<tr>
<td>Filter inductance</td>
<td>(L)</td>
<td>(L/3)</td>
</tr>
<tr>
<td>Output capacitance</td>
<td>(C)</td>
<td>(C/3)</td>
</tr>
<tr>
<td>Output voltage</td>
<td>0 to (2V_{PV})</td>
<td>(V_{PV}) to (2V_{PV})</td>
</tr>
</tbody>
</table>

2.5 **Reconfigurable PV-Boost Derived Converter and Other Extended Non-Isolated and Isolated Converter Topologies**

Fig. 2.15 shows the circuit diagram of the proposed reconfigurable PV-boost derived converter [46]. With the reconfigurable PV switching cell, the two level voltages at terminals 3 and 4 can be created, as illustrated in Section 2.3 and then fed into the boost converter.

![Figure 2.15: The reconfigurable PV-boost derived converter.](image)

2.5.1 **Principle of Operation**

2.5.1.1 **Ideal Operation**

The circuit operation can be further divided into four different modes by changing the duty ratios \(d_1\) and \(d_2\) of two switches \(S_1\) and \(S_2\). As a result, different circuit configurations can be created. And, all the circuits can operate at high frequency which can be hundreds of kHz, for example, 100 kHz.
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

• **Mode 1: Series Configuration**
  When \( S_1 \) is always ON, two solar panels are always connected in series and therefore, the filter voltage is, \( V_{filt} = V_{PV1} + V_{PV2} = 2V_{PV} \), and the inductor current is, \( I_L = I_1 = I_2 \). In this mode, the circuit works as a conventional boost converter with two solar panels connected in series, which leads to the input output transfer ratio:

\[
V_{out} = \frac{1}{1 - d_2} \cdot (2V_{PV}) \tag{2.16}
\]

• **Mode 2: Parallel Configuration**
  When \( S_1 \) is always OFF, two solar panels are always connected in parallel and therefore, the filter voltage is, \( V_{filt} = V_{PV1} = V_{PV2} = V_{PV} \), and the inductor current is, \( I_L = I_1 + I_2 \). In this mode, the circuit works as a conventional boost converter with two solar panels connected in parallel, which leads to the input output transfer ratio:

\[
V_{out} = \frac{1}{1 - d_2} \cdot (V_{PV}) \tag{2.17}
\]

• **Mode 3: Synchronous Turn-on of \( S_1 \) and \( S_2 \)**
  Two switches \( S_1 \) and \( S_2 \) are turned ON at the same time in each switching period and they can have same or different duty ratios, i.e. \( d_1 = d_2 \) or \( d_1 \neq d_2 \). Fig. 2.16(a) shows an example of circuit voltage and current waveforms in the case of \( d_1 = d_2 \). In this special case when \( d_1 = d_2 \), the average voltage of inductor equals zero, i.e. \( \langle V_L \rangle = 0 \), and therefore, the input output transfer ratio can be found as

\[
V_{out} = \frac{1 + d_2}{1 - d_2} \cdot (V_{PV}) \tag{2.18}
\]

For two switches have different duty ratios, i.e. \( d_1 \neq d_2 \), for example, \( d_1 < d_2 \), Fig. 2.16(b) shows an example of circuit voltage and current waveforms. Therefore, the input output transfer ratio can be found as

\[
V_{out} = \frac{1 + d_1}{1 - d_2} \cdot (V_{PV}) \tag{2.19}
\]

The input output transfer ratio (2.19) is also true for \( d_1 > d_2 \). As a result, either \( d_1 \) or \( d_1 \) (or both) can be chosen for the desired voltage gains.
Figure 2.16: Ideal voltage and current waveforms of Mode 3.
Mode 4: Complimentary Switching

The switch $S_1$ is turned ON while $S_2$ is turned OFF, and vice versa, at the same time in each switching period, i.e. $d_1 = 1 - d_2$. Fig. 2.17 shows the circuit voltage and current waveforms. When $S_1$ is ON and $S_2$ is OFF, the inductor is discharged. When $S_1$ is OFF and $S_2$ is ON, the inductor is charged. In the steady state, the average voltage of inductor equals zero, i.e. $\langle V_L \rangle = 0$, and therefore, the input output transfer ratio can be found as

$$V_{out} = \frac{1 + d_1}{d_1} \cdot (V_{PV}) = \frac{2 - d_2}{1 - d_2} \cdot (V_{PV})$$  \hspace{1cm} (2.20)

![Figure 2.17: Ideal voltage and current waveforms of Mode 4: $d_1 = 1 - d_2$.](image)

2.5.1.2 Non-Ideal Operation

In the non-ideal case, the two PV panels are not identical. They have different $V_{PV}$ and $I_{PV}$, i.e. $V_{PV1} \neq V_{PV2}$ and $I_{PV1} \neq I_{PV2}$. Also, there will be voltage drop across the diodes, i.e. $V_{d1} \approx V_{d2} = V_d$ and $V_{DS(ON)} \approx 0$. Therefore, in Mode 1, the output voltage in (2.16) becomes,

$$V_{out} = \frac{1}{1 - d_2} \cdot (V_{PV1} + V_{PV2})$$  \hspace{1cm} (2.21)
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

In Mode 2, the output voltage in (2.17) becomes,

\[ V_{\text{out}} = \frac{1}{1 - d_2} \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d) \] (2.22)

In Mode 3, the output voltage for \( d_1 = d_2 \) in (2.18) becomes,

\[ V_{\text{out}} = \frac{1}{1 - d_2} \cdot \{d_2 \cdot (V_{PV1} + V_{PV2}) + (1 - d_2) \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d)\} \] (2.23)

And, the output voltage for \( d_1 \neq d_2 \) in (2.19) becomes,

\[ V_{\text{out}} = \frac{1}{1 - d_2} \cdot \{d_1 \cdot (V_{PV1} + V_{PV2}) + (1 - d_1) \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d)\} \] (2.24)

In Mode 4, the output voltage in (2.20) becomes,

\[ V_{\text{out}} = \frac{1}{d_1} \cdot \{d_1 \cdot (V_{PV1} + V_{PV2}) + (1 - d_1) \cdot (\min\{V_{PV1}, V_{PV2}\} - V_d)\} \] (2.25)

2.5.2 Different Operation Modes of PV-Boost Converter

Four different operation modes are created in the reconfigurable PV-boost converter by using two switches, \( S_1 \) and \( S_2 \). The PV output voltage changes with different modes and duty ratios. The output voltage gain can be determined by two duty ratios, \( d_1 \) and \( d_2 \), in (2.19). In the conditions of \( d_2 = d \) for Mode 1 and Mode 2 and \( d_1 = d_2 = d \) for Mode 3 and Mode 4, Fig. 2.18 shows that the voltage gain changes with varying duty ratios in four modes. As seen from the graph that, in the ideal operation, Mode 1 and Mode 2 respectively have the maximum \( 20 \cdot V_{PV} \) and \( 10 \cdot V_{PV} \) output voltages at duty ratio \( d = 0.9 \). Mode 3 has the maximum \( 19 \cdot V_{PV} \) output voltage at the same duty ratio \( d = 0.9 \). And, Mode 4 has the maximum \( 11 \cdot V_{PV} \) output voltage at duty ratio \( d = 0.1 \). Moreover, it can be found from the graph that when the duty ratio is about 0.41 (\( d = 0.41 \)), Mode 1 and Mode 4 both have \( 3.4 \cdot V_{PV} \) output voltage, yet Mode 2 has only \( 1.7 \cdot V_{PV} \) output voltage and
Mode 3 has $2.4 \times V_{PV}$ output voltage. When the duty ratio $d < 0.41$, Mode 4 has higher voltage gains than the other three modes. On the other side, Mode 1 gives highest voltage gain when $d > 0.41$.

![PV-boost Converter Voltage Gain vs. Duty Ratio](image)

Figure 2.18: Ideal voltage gains with various duty ratios in different modes of PV-boost converter.

### 2.5.3 Experimental Verification

A prototype of the reconfigurable PV-boost converter is built for verification and the concept of four different modes are tested. Table 2.5 gives the specifications of PV-boost converter prototype, and Table 2.6 shows an example of experimental voltage and current results of four modes in the reconfigurable PV-boost converter. As can be seen, the $V_{filt} = 2 \times V_{PV}$ when two solar panels are connected in series and the $V_{filt} = V_{PV}$ when two solar panels are connected in parallel. The experimental output voltages of PV-boost converter can match the theoretical predictions. Figs. 2.19 and 2.20 respectively show two experimental waveforms for Mode 3 and Mode 4. Fig. 2.19 gives the case when $d_1 \neq d_2$ and the inductor current rises with two slopes as the two solar panels are changed from series connection to parallel connection and the switch $S_2$ is still ON in each switching period. Fig. 2.20 shows Mode 4, as the inductor current is charged when two solar panels are connected in parallel and is discharged when two solar panels are connected in series, for the complimentary switching of $S_1$ and $S_2$. 

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The inductor current ripple measured from the experiments can often match the theoretical calculations. For example, in Mode 1 at switching frequency $f_{SW} = 100\text{kHz}$ with duty ratio $d_2 = 0.5$, the inductor current ripple can be found in the following:

$$\Delta I_L = \frac{(2V_{PV}) \cdot (d_2 T)}{L} \approx 0.298A$$

The inductor current ripple is measured to be 0.294 A from the experiment, shown in Table 2.6. In Mode 2, the measured inductor current ripple is closely matched with the theoretical prediction which is 0.25 A. In Mode 3 and Mode 4, the measured inductor current ripples are slightly different than the theoretical calculations, which may be attributed to the nonlinear behavior of the solar panels and measurement errors, etc.

Table 2.5: Circuit parameters of PV-boost converter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Manufacturer/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>$S_1$</td>
<td>International Rectifier, IRFU3607</td>
</tr>
<tr>
<td></td>
<td>$S_2$</td>
<td>International Rectifier, IRFU4615</td>
</tr>
<tr>
<td>Diodes</td>
<td>$D_1, D_2$</td>
<td>Vishay, VF30100S</td>
</tr>
<tr>
<td></td>
<td>$D_3$</td>
<td>Fairchild, FFH60UP40S3</td>
</tr>
<tr>
<td>Filter inductor</td>
<td>$L$</td>
<td>$75\mu\text{H}$</td>
</tr>
<tr>
<td>Input capacitor</td>
<td>$C_1, C_2$</td>
<td>$100\mu\text{F}$</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>$C_o$</td>
<td>$47\mu\text{F}$</td>
</tr>
<tr>
<td>Load resistor</td>
<td>$R_L$</td>
<td>$500\Omega$</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_{SW}$</td>
<td>$100\text{kHz}$</td>
</tr>
</tbody>
</table>

2.5.4 Extension to Other Non-Isolated and Isolated Converter Topologies

It is also possible to create other reconfigurable power converters. The idea is similar: arrange the PV arrays to alternate at high switching frequencies to apply series and parallel connections to (at least portions of) the output filter of the topology using the multi-level approach similar to [32]. Three forward derived converter structures with PV switching cell are presented, including push-pull converter in Fig. 2.21(a) full-bridge converter in Fig. 2.21(b), and dual-forward converter in Fig. 2.21(c). Those converters can have transformer operating at 50% duty cycle with no deadtime operation. With the unique voltage waveforms created by switches, the size of output
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Figure 2.19: Measured voltages and current of PV-boost converter in Mode 3 at $d_1 = 0.25$ and $d_2 = 0.5$.

Figure 2.20: Measured voltages and current of PV-boost converter in Mode 4 at $d_1 = 0.25$ and $d_2 = 0.75$. 
CHAPTER 2. FAST RECONFIGURABLE PHOTOVOLTAIC DC-DC CONVERTERS

Table 2.6: Measured voltage and current results of PV-boost converter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty ratios</td>
<td>$d_1$</td>
<td>1</td>
<td>0</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>$d_2$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>PV panel #1’s voltage (Volt)</td>
<td>$V_{PV1}$</td>
<td>8.7</td>
<td>14.6</td>
<td>11.2</td>
<td>12.4</td>
</tr>
<tr>
<td>PV panel #2’s voltage (Volt)</td>
<td>$V_{PV2}$</td>
<td>8.7</td>
<td>14.6</td>
<td>11.2</td>
<td>12.4</td>
</tr>
<tr>
<td>Filter voltage (Volt)</td>
<td>$V_{filt(\text{series})}$</td>
<td>17.4</td>
<td>14.6</td>
<td>22.4</td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td>$V_{filt(\text{parallel})}$</td>
<td></td>
<td></td>
<td>11.2</td>
<td>12.4</td>
</tr>
<tr>
<td>Inductor current (Amp)</td>
<td>$I_L$</td>
<td>0.172</td>
<td>0.134</td>
<td>0.146</td>
<td>0.145</td>
</tr>
<tr>
<td>Inductor current ripple (Amp)</td>
<td>$\Delta I_L$</td>
<td>0.294</td>
<td>0.252</td>
<td>0.340</td>
<td>0.306</td>
</tr>
<tr>
<td>Converter’s output voltage (Volt)</td>
<td>$V_{out}$</td>
<td>34.8</td>
<td>29.2</td>
<td>33.6</td>
<td>31</td>
</tr>
<tr>
<td>Converter’s output current (Amp)</td>
<td>$I_{out}$</td>
<td>0.0674</td>
<td>0.0577</td>
<td>0.0616</td>
<td>0.054</td>
</tr>
</tbody>
</table>

filter can be reduced. This will subsequently lead to lower filter demands on the circuit. Further, the interleaving techniques in DC-DC converters have been reported to show that the ripple current can be significantly reduced, thus the smaller output filter size is needed. Lastly, a two-phase interleaved boost converter structure with PV switching cell is presented in Fig. 2.21(d).

2.6 Conclusions

A new classification of reconfigurable PV power converters is proposed. It is an attempt to operate PV modules in reconfiguration by a high frequency switch. The approach combines the benefits of multi-input converters and three-level converters so as to sometimes effectively reduce switch stresses, the filter element sizing and output ripples. With those benefits, the cost of building integrated PV modules or cells might be fully integrated into fabrication process.

The target applications for the topologies in this research may be in the low power range < 5 W and tend to imply energy harvesting applications. However, future research may include higher power and grid-tied reconfigurable PV systems. Since the output resistor can be replaced by another DC-DC and/or DC-AC converter, the approach could be used for an MPPT system.
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Figure 2.21: (a) PV switching cell push-pull converter, (b) PV switching cell full-bridge converter, (c) PV switching cell dual-forward converter, (d) PV switching cell interleaved boost converter.

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Chapter 3

Submodule Integrated Boost DC-DC Converters for Low Power Photovoltaic Applications

The chapter first characterizes the solar cell internal capacitance, solar module wire parasitic inductance, and their variations under different operating conditions. A hard-switched boost converter integrated with PV submodule is presented for low power and low voltage energy harvesting applications [47]. The main research contributions presented in this chapter are:

- A new concept of a no-input capacitor or no-input inductor high frequency boost converter is introduced. The topology requires no external passive elements for energy storage or filtering. It utilizes the solar cell diffusion capacitance as input capacitance and the parasitic wire inductance as filtering inductance within the PV module.

- A new type of hard-switched boost DC-DC converter topology is introduced. The proposed converter is designed, simulated, and experimentally tested. The converter prototype operates with no external input capacitor nor input inductor at a switching frequency in the range of $5 - 10$ MHz.

- Benefits and drawbacks of the new proposed PV submodule integrated boost converter are explained. Benefits include: 1) the size and cost of boost converters will be minimized, 2) the reliability of boost converters will be improved, and 3) it is suitable for low power and low
voltage energy harvesting applications. Drawbacks may be: 1) lower power efficiency, and 2) possible current ripples in solar cells.

3.1 Introduction

Typically, solar cells have low $\sim 0.5 \text{ V}$ operating voltages, yet output loads for battery chargers or other devices are at higher voltages (2.4 V, 3.6 V, 5 V, etc.). As a result, the solar cells are stringed together and normally connected to a DC-DC converter in energy harvester operations. Recent research in PV energy harvesting has attempted to integrate passive and switch components with solar cells or groups of series connected solar cells in order to create higher voltage output solar cells within small package size $[23, 26, 48, 49]$. The topologies may use traditional DC-DC converters, such as boost converters, that have input filter capacitor and inductor, or they may even utilize the internal solar cell capacitance within a switched capacitor converter $[50]$. In this latter case, neither external inductors nor capacitors are needed, but just the additional switches between the solar cells to create the switched capacitor converter. Because the switches can be built in the same silicon manufacturing process, there is potential to create small, fully integrated solar PV modules that can boost voltages to required load levels in energy harvesting applications.

This dissertation research proposes a new approach to minimizing component count in solar PV energy harvesting DC-DC converters: it is possible to combine the use of parasitic wire inductances $[29]$ with the internal solar cell diffusion capacitance to create new types of solar boost converters with fewer external passives. For proof of concept purposes, the principle is validated on applications similar to the portable, foldable solar panel commercial market, which have multiple solar cells connected by longer wires so that the panels can be folded. The extra-length wire connections between the cells have high parasitic inductance. However, the eventual fundamental (future) grand research vision is to eventually create single solar cell energy harvesters with wires connected directly to the load (e.g. 5 V USB) and with minimal need to add input capacitor or external filtering inductor. That is, the topologies proposed will connect directly to the (0.5 V) solar cell and boost to proper higher voltage by only adding switches and output capacitor. (This should require higher switching frequencies than in this research.)
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3.2 Solar Cell Diode Capacitance

The commonly used solar cell model ignores the diode capacitance and may not be sufficient for dynamic operation [51]. However, there is a diode capacitance associated with the solar cell, and it is the sum of the diffusion capacitance and depletion layer capacitance. When the operating solar cell voltage is near or greater than the $V_{MPP}$, the diffusion capacitance dominates and the depletion layer capacitance can be neglected [52]. Fig. 3.1 shows a solar cell equivalent circuit model incorporating the shunt diode capacitance. The diffusion capacitance $C_d$ has an exponential dependence on the solar cell diode voltage, or has a linear dependence on the solar cell diode current [52, 53]. $C_d$ can be expressed as [50]

$$C_d = \frac{\tau_F}{V_t} \cdot I_o \cdot \exp \left( \frac{V_d}{aV_t} \right) = \frac{\tau_F}{V_t} \cdot (I_o + I_d) = C_o + \frac{\tau_F}{V_t} \cdot I_d \quad (3.1)$$

where $I_d$ is the solar cell diode current, $V_d$ is the solar cell diode voltage, $V_t$ is the thermal voltage, and $a$ is the diode ideality factor. In addition, $I_o$ is the dark saturation current of the solar cell due to diffusion of the minority carriers in the junction, and $C_o$ is the dark diffusion capacitance. The time constant can be defined as

$$\tau_F^{-1} = \tau^{-1} + \tau_B^{-1} \quad (3.2)$$

where $\tau$ is the minority carrier lifetime, and $\tau_B$ is the transit time of the carrier across the diode. If the solar cell base thickness is greater than the minority carrier diffusion length, $\tau_B$ is negligible and $\tau_F$ can be approximated as $\tau$.

Figure 3.1: Single-diode solar cell model incorporating the diode capacitance.
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The solar cells can exhibit diffusion capacitance in the range of microfarads to hundreds of microfarads when the voltage is near or greater than $V_{MPP}$ \cite{52,53}. However, the solar cell diode capacitance differs non-linearly with sunlight conditions, temperatures, solar cell voltages, wafer sizes and materials, which can be modeled by (3.1). In this research, the 3 W monocristalline solar cell (P-Maxx-6000mA) is chosen as an example. The solar cell measures $15.6\text{ cm} \times 15.6\text{ cm}$ and is rated as having an open-circuit voltage ($V_{oc}$) of 0.55 V and a short-circuit current ($I_{sc}$) of 6 A in standard test condition (STC), which means the irradiance of 1000 W/m$^2$, the solar spectrum at air mass (AM) of 1.5 and the cell temperature at 25$^\circ$C. Fig. 3.2 shows the simulation results of diffusion capacitance of six series-connected (ideal) solar cells in different solar irradiation levels and operating voltages. As seen in the graph, the diffusion capacitance can be large near the $V_{oc}$, or even around the $V_{MPP}$ where the PV operation is usually intended to be performed. For example, the diffusion capacitance is from hundreds of microfarads to few millifarads near the $V_{oc}$ and is from few microfarads to tens of microfarads around the MPP. The simulation results in Figs. 3.3 and 3.5 illustrate that the capacitance at MPP operation, $C_d$, can increase more the 10-fold as irradiance changes from low illumination at 100 W/m$^2$ to high illumination at 1000 W/m$^2$. For example, at MPP operation, $C_d$ is $\sim 5.9\mu F$ at 100 W/m$^2$ and can be as high as $\sim 69.9\mu F$ at 1000 W/m$^2$. The proposed boost converter needs to be able to work with the variations of irradiance and diode capacitance. As a result, the range of solar cell diode capacitance can be expressed as

$$C_d - \Delta C \leq C_d (V_{PV}) \leq C_d + \Delta C$$  \hspace{1cm} (3.3)

where $\Delta C > 0$ represents a deviation from nominal diffusion capacitance due to the different solar cell illumination conditions.

Since the proposed new DC-DC converter topologies must operate under wide range of illumination, this implies that any topology must operate successfully for a wide range of $C_d$. This is demonstrated in Section 3.5. Fig. 3.4 illustrates the deviation of $C_d$ at MPPs in different irradiance levels (also refer to Fig. 3.3). It is found that $C_d$ increases as $V_{MPP}$ goes up in the irradiance level above $\sim 600$ W/m$^2$, and $C_d$ increases as $V_{MPP}$ goes down in the irradiance level below $\sim 600$ W/m$^2$.

Fig. 3.5 illustrates that $C_d$ at MPP operation increases in the linear fashion with light illumination levels from low to high, and Fig. 3.6 shows that the solar cells’ maximum power increases with higher $C_d$ from low to high illumination.
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Figure 3.2: Solar cell diffusion capacitance versus solar cell voltage in different irradiation conditions.

Figure 3.3: Solar cell diffusion capacitance around $V_{MPP}$ in different irradiation conditions.
Figure 3.4: Deviation of $C_d$ at MPPs in different irradiance levels ($G_1 > G_2 > G_3$): (a) When the irradiance is below $\sim 600 \text{ W/m}^2$, (b) When the irradiance is above $\sim 600 \text{ W/m}^2$. 
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Figure 3.5: Solar cell diffusion capacitance at MPPs in different irradiance levels.

Figure 3.6: Solar cell output power with different diffusion capacitance at MPPs.
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3.3 Wire Parasitic Inductance

Recreationists and soldiers often use foldable PV panels in outdoors to charge their electronic devices, most of them are charged by 5 V USB because they are portable. More demands for building a smaller and lighter solar PV module combined with battery chargers are presented recently. It is possible to reduce the package size by reducing the passive energy components in the converters and utilizing the parasitic inductances and capacitances in the circuit. It is known that foldable PV panels inherently have electric wires within the panel that are used to connect with solar cells, as shown in Fig. 3.7. Those wires exhibit some amount of inductance, especially in high frequency operation, and therefore, this research proposes that they can replace input inductor of DC-DC converters, such as boost converter, for low power solar energy harvesting applications.

Fig. 3.8 shows the configuration of solar cells and wires connection used in the experiment. There are six solar cells connected in series to form a return circuit of parallel wires with equal length. The self-inductance $L$ and mutual inductance $M$ can be estimated as

$$L = 0.002 \cdot l \cdot \left[ \ln \left( \frac{2l}{r} \right) - \frac{3}{4} \right] \mu H \quad (3.4)$$

$$M = 0.002 \cdot l \cdot \left[ \ln \left( \frac{2l}{d} \right) - 1 + \frac{d}{l} \right] \mu H \quad (3.5)$$

where the wire length $l = \sum_{i=1}^{3} l_i = \sum_{j=5}^{7} l_j$, $r$ is the radius of wire, and $d$ is the distance between two parallel wires.

The total loop wire inductance $L_w$ can be expressed as

$$L_w = 2 \cdot (L - M) + L_{l4} \quad (3.6)$$

Fig. 3.9 shows the experimental benchmark. The size of electric wire used to connect with solar cells in the experiment is 24 AWG, which gives the wire radius $r = 0.2553 \text{ mm}$. The wire segments are respectively chosen and measured at $l_1 = l_7 = 10.3 \text{ cm}$, $l_2 = l_6 = 7.8 \text{ cm}$, and $l_3 = l_5 = 6.8 \text{ cm}$. So, the wire length is found to be $l = 24.9 \text{ cm}$. And, the distance between two parallel wires is measured at $d = 11.5 \text{ cm}$. With those wire parameters and using (3.4) and (3.5), the self-inductance and mutual inductance of the wire can be calculated as $L = 0.3399 \mu H$, $L_{l4} = 0.1392 \mu H$, and $M = 0.1392 \mu H$, respectively. Finally, the total wire inductance is estimated as
Figure 3.7: A foldable PV panel in (a) and exposed wires to connect with solar cells in (b).
CHAPTER 3. SUBMODULE INTEGRATED BOOST DC-DC CONVERTERS

Figure 3.8: The schematic diagram of solar cells and wire connections.

Figure 3.9: The photo of experimental benchmark.
CHAPTER 3. SUBMODULE INTEGRATED BOOST DC-DC CONVERTERS

$L_w = 0.7266 \mu H (\approx 726.6 \text{nH})$ by (3.6). The wire inductance is also dependent on the switching frequency $f_{sw}$ of DC-DC converter. As a result, the range of wire inductance can be expressed as

$$L_w - \Delta L \leq L_w (f_{sw}) \leq L_w + \Delta L$$

(3.7)

where $\Delta L > 0$ represents a deviation from nominal wire inductance, often due to the different switching frequencies of DC-DC converter. Since the proposed new DC-DC converter topologies utilize the wire inductance as filter inductor, this implies that any topology must be robust to its value. The detailed analysis of wire inductance and its variation will be presented in Chapter 4.

3.4 Submodule Integrated Hard-Switched Boost DC-DC Converter

This research proposes a new solar PV submodule integrated high frequency (HF) boost converter shown in Fig. 3.10. There are two building blocks in Fig. 3.10 (1) Solar PV submodule and (2) HF boost converter cell. The converter output can be connected to a resistive load or a battery load. Fig. 3.11 illustrates a proposed hard-switched boost converter that is being connecting with solar cells [47]. It is estimated that six solar cells can be lumped into a single solar cell model of Fig. 3.1 and the wire inductance $L_w$ can be calculated using the series sum of the wire connections shown in Fig. 3.8. The solar PV submodule has solar cells connected by wires and no additional capacitor or inductor is included, yet the solar PV submodule provides all necessary filtering input capacitance and inductance. Only the input voltage $V_{in}$ and inductor current $I_L$ can be measured. The hard-switched boost converter cell has one MOSFET switch $S_1$ and one diode $D_1$. There is an additional capacitor $C_o$ in the output. In Fig. 3.11 the single solar cell equivalent circuit model includes the shunt resistance $R_{sh}$ and series resistance $R_s$. The wire’s equivalent series resistance (ESR) $R_w$ is also included.

3.4.1 Principle of Operation

Note that the solar cell voltage $V_{PV}$ is not equal to $V_{Cd}$, but is roughly equal to the difference between $V_{Cd}$ and the voltage across the series resistance $R_s$ of solar cell. In a first approximation, it can be assumed that the current through the shunt resistance $R_{sh}$ of solar cell is negligible.
Figure 3.10: A simplified schematic diagram of proposed solar PV submodule integrated boost converter. Solar PV submodule is a simplification of Fig. 3.8.

Figure 3.11: The circuit diagram of proposed solar PV submodule integrated hard-switched boost converter.

- **Interval 1** \((0 < t < dT)\): In Fig. 3.11, when the switch \(S_1\) turns ON, the \(V_{in}\) is approximately equal to the drain-to-source voltage of MOSFET. Therefore, the voltage across the inductor and the inductor current can be respectively expressed as

\[
V_{Lw} = V_{PV} - I_L \cdot (R_w + R_{DS(on)})
\]

\(= V_{Cd} - (I_{PV} \cdot R_s) - I_{PV} \cdot (R_w + R_{DS(on)})\)  \(\text{(3.8)}\)

\[
I_L = I_{PV}\n\text{ (3.9)}
\]

- **Interval 2** \((dT < t < T)\): In Fig. 3.11, when the \(S_1\) turns OFF, the \(V_{in}\) is approximately equal to the sum of the converter’s output voltage and the diode voltage \(V_f\). The voltage across the
CHAPTER 3. SUBMODULE INTEGRATED BOOST DC-DC CONVERTERS

Inductor and the inductor current can be respectively expressed as

\[ V_{Lw} = V_{PV} - [(I_L \cdot R_w) + V_f + V_{out}] \]
\[ = V_{Cd} - (I_{PV} \cdot R_s) - [(I_{PV} \cdot R_w) + V_f + V_{out}] \]  \hspace{1cm} (3.10)

\[ I_L = I_{PV} \]  \hspace{1cm} (3.11)

In the steady state, it is assumed that \( V_{Cd} = \langle V_{Cd} \rangle \) and \( I_{PV} = \langle I_{PV} \rangle \). The average inductor voltage equals zero, i.e. \( \langle V_L \rangle = 0 \), where \( \langle g \rangle \) represents the average value of \( g \) over a period time \( T \). Therefore, the input and output transfer ratio can be found as

\[ V_{out} = \frac{1}{1 - d} \cdot [V_{Cd} - I_{PV} \cdot (R_s + R_w + R_{DS(on)} \cdot d)] - V_f \]  \hspace{1cm} (3.12)

3.5 Simulation Results

MATLAB/Simulink models are built according to the single-diode equivalent circuit model of solar cell in Fig. 3.1 and the proposed hard-switched boost converter in Fig. 3.11. The I-V and P-V characteristics of six series-connected solar cells (silicon monocrystalline) used in the experiment are shown in Fig. 3.12 and in Table 3.1 respectively. The solar cells are modeled in low illumination condition, i.e. the solar irradiation level is set at 100 W/m\(^2\) which is approximately same as the measurement. The model’s temperature is set at 56°C which is the average temperature of the illuminated solar cells in the experiment. The series and shunt resistances, \( R_s \) and \( R_{sh} \), respectively, are estimated as \( \sim 1.234 \, \Omega \) and \( \sim 1.513 \, \Omega \) for simulation. In the circuit simulation, the parameters of the switching devices, i.e. \( S_1 \) and \( D_1 \), are obtained from the model parameters of MOSFET and diode used in the experiment in Section 3.6. The wire inductance is set at \( \sim 1 \, \mu \text{H} \) for the simulation. (The value of \( \sim 1 \, \mu \text{H} \) was used in the simulation because it is closer to the measured inductance in the experimental prototypes - see Section 3.6) The boost converter works in the same condition of the experiment in Section 3.6, the converter is operated at switching frequency \( f_{sw} = 5 \, \text{MHz} \) with duty ratio \( d = 0.5 \), and the output voltage is regulated at 4.93 V. Fig. 3.13 shows the simulation results of the proposed solar PV submodule integrated hard-switched boost converter. As seen in Fig. 3.13(a) the PV current \( I_{PV} \) performs as an inductor current which charges and discharges in each cycle and the simulated current ripple \( \Delta i_{PV} \) is about 59% of \( I_{PV} \). It can also be found that
Figure 3.12: (a) I-V and (b) P-V characteristics of solar cells used in the simulation.
the PV voltage $V_{PV}$ and solar cells capacitance voltage $V_{Cd}$ stay constant with small ripples, shown in Fig. 3.13(b). The detailed simulated voltage and current results are shown in Table 3.2. Overall, the circuit simulation matches the theoretical prediction, as well as the experimental result. The difference between the simulated and experimental values might be attributed to the nonidealities of the components, such as switches, nonlinear behavior of the solar cells, etc.

Table 3.1: Measured and simulated electrical characteristics of solar cells

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage</td>
<td>$V_{oc}$</td>
<td>3.305 V</td>
<td>3.305 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>$I_{sc}$</td>
<td>1.757 A</td>
<td>1.757 A</td>
</tr>
<tr>
<td>Maximum power point voltage</td>
<td>$V_{MPP}$</td>
<td>1.837 V</td>
<td>1.8178 V</td>
</tr>
<tr>
<td>Maximum power point current</td>
<td>$I_{MPP}$</td>
<td>0.996 A</td>
<td>1.0186 A</td>
</tr>
<tr>
<td>Maximum power</td>
<td>$P_{MPP}$</td>
<td>1.8297 W</td>
<td>1.8515 W</td>
</tr>
</tbody>
</table>

Table 3.2: Simulated voltages and currents of the solar PV submodule integrated hard-switched boost converter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>$V_{DS}$</td>
<td>2.686 V</td>
</tr>
<tr>
<td>Input current</td>
<td>$I_{PV}$</td>
<td>0.455 A</td>
</tr>
<tr>
<td>Input current ripple</td>
<td>$\Delta i_{PV}$</td>
<td>268.6 mA</td>
</tr>
<tr>
<td>Diode capacitance voltage</td>
<td>$V_{Cd}$</td>
<td>3.247 V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>$V_{out}$</td>
<td>4.934 V</td>
</tr>
<tr>
<td>Output current</td>
<td>$I_{out}$</td>
<td>0.223 A</td>
</tr>
<tr>
<td>Converter’s input power</td>
<td>$P_{in}$</td>
<td>1.2221 W</td>
</tr>
<tr>
<td>Converter’s output power</td>
<td>$P_{out}$</td>
<td>1.1003 W</td>
</tr>
</tbody>
</table>

Fig. 3.14 shows the simulation results of solar cell diode capacitance voltage $V_{Cd}$ and its voltage ripple $\Delta V_{Cd}$ at around MPP operation in low and high illumination conditions. As can be seen in the waveforms, the $\Delta V_{Cd}$ is $\sim$1.15 mV on the $V_{Cd}$ of $\sim$2.6361 V ($\approx$ 0.04 % of $V_{Cd}$) in the irradiance of 100 W/m² and is $\sim$0.08 mV on the $V_{Cd}$ of $\sim$2.9333 V ($\approx$ 0.003 % of $V_{Cd}$) in the irradiance of 1000 W/m². Since the $\Delta V_{Cd}$ is small in low illumination operation, this implies that the new proposed boost converter topologies can also work in illumination greater than 100 W/m². Furthermore, it is necessary to verify if the proposed boost converter can work in the irradiance less than 100 W/m². The detailed analysis and experimentally test result will be presented in Chapter 4.
Figure 3.13: Simulated waveforms of voltages and current of the solar PV submodule integrated hard-switched boost converter.
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3.6 Experimental Verification

The hardware prototype of the proposed hard-switched boost converter is successfully built and tested with six solar cells (P-Maxx-6000mA) illuminated by halogen lamps in the lab, as shown in Fig. 3.9. The detailed information of solar cell used for the experiment can be found in Sections 3.2 and 3.5. Table 3.1 shows the parameters of six series-connected solar cells which are tested in the specific light illumination and temperature conditions. Table 3.3 shows the specifications of the hard-switched boost converter prototype.

Table 3.3: Components used for the submodule integrated hard-switched boost converter prototype

<table>
<thead>
<tr>
<th>Device</th>
<th>Symbol</th>
<th>Model</th>
<th>Manufacturer/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>$S_1$</td>
<td>FDD5612</td>
<td>Fairchild</td>
</tr>
<tr>
<td>Diode</td>
<td>$D_1$</td>
<td>MBRS260T3G</td>
<td>ON Semiconductor</td>
</tr>
<tr>
<td>Gate Driver</td>
<td></td>
<td>MAX5048C</td>
<td>Maxim Integrated</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>$C_o$</td>
<td>Ceramic, Radial</td>
<td>TDK, $2 \times 10 \mu F$</td>
</tr>
</tbody>
</table>
The converter is operated in open-loop with a fixed duty ratio of 0.5 at a switching frequency of 5 MHz and the output is regulated at 5 V by DC electronic load (Kikusui PLZ303W). The pulse width modulation (PWM) signal is generated from the signal generator (Agilent 33220A) to feed the gate driver. Fig. 3.13 shows the measurement results. The magnitude of the measured output voltage is 4.93 V. It is known that the MOSFET’s $R_{DS(on)}$ is $\sim 36 \, \text{m}\Omega$ and the diode forward voltage $V_f$ is around $\sim 0.42 \, \text{V}$ in the circuit. The wire’s ESR $R_w$ is negligible. From the measurement, the average PV current $I_{PV}$ is 0.588 A and current ripple $\Delta i_{PV} (= \Delta i_L)$ is 0.268 A, which is about 45.6 % of $I_{PV}$. With the estimated parameters in Section 3.5, the solar cell diode capacitance voltage $V_{Cd}$ can be calculated and found to be $\sim 3.411 \, \text{V}$ by (3.12). And, the measured turn-on time of MOSFET is $\sim 106 \, \text{ns}$. With those parameters, the wire inductance can be estimated by the following equation:

$$L_w = \frac{V_{Lw} \cdot \Delta t}{\Delta i_L} = \left[ \frac{V_{Cd} - I_{PV} \cdot \left( R_s + R_w + R_{DS(on)} \right) }{\Delta i_L} \right] \cdot (DT) \approx 1.0538 \, \mu\text{H}$$

Differences between the experimentally measured inductance (1.0538 $\mu$H) and theoretically predicted inductance (726.6 nH) might be attributed to the high frequency operation, nonidealities of the components, such as switches and gate driver, nonlinear behavior of the solar cells, measurement errors as well as wire inductance formula inaccuracies.

### 3.6.1 Converter’s Efficiency

Referring to the experimental waveforms in Fig. 3.13, the average input voltage $V_{DS}$ and input current $I_{PV}$ are respectively measured at 2.48 V and 0.588 A, and the input power of the hard-switched boost converter can be found as

$$P_{\text{in}} = \frac{1}{T} \int_{0}^{T} V_{\text{in}}(t) \cdot I_{\text{in}}(t) \, dt \approx \langle V_{\text{in}} \rangle \cdot \langle I_{\text{in}} \rangle = \langle V_{DS} \rangle \cdot \langle I_{PV} \rangle \approx 1.4582 \, \text{W}$$

And, the output power of the converter can be found to be $\sim 1.0998 \, \text{W}$, so the efficiency of the converter is approximately 75.42 %. The discrepancy of the simulated and experimental results may be resulted from the larger power loss of the nonideal components, e.g. switches and wires, and lower efficiency of the high frequency hard-switched boost converter. The breakdown of the power loss is shown in Table 3.4. The most power loss is consumed by the diode $D_1$, which is approximately 246.96 mW ($\approx 68.91 \%$ of total power loss). Besides, the MOSFET is rated as having
Figure 3.15: Experimental waveforms of voltages and current of the solar PV submodule integrated hard-switched boost converter.
total gate charge $Q_{\text{gate}}$ to be typically $7.5 \text{ nC}$ and the supply voltage $V_{GS}$ is $6 \text{ V}$ in the experiment. Therefore, at the switching frequency of $5 \text{ MHz}$, the estimated gate drive power can be calculated to be about $225 \text{ mW}$. The circuits presented in here have not been optimized yet for efficiency: they are proof-of-concept, only, to demonstrate the feasibility of removing external input capacitor and filtering inductor in the boost derived PV converter.

<table>
<thead>
<tr>
<th>Device</th>
<th>Symbol</th>
<th>Value</th>
<th>Estimated loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>$R_{DS(on)}$</td>
<td>$36 \text{ m}\Omega$</td>
<td>$12.45 \text{ mW}$</td>
</tr>
<tr>
<td>Diode</td>
<td>$V_f$</td>
<td>$0.42 \text{ V}$</td>
<td>$246.96 \text{ mW}$</td>
</tr>
</tbody>
</table>

### 3.7 Conclusions and Future Work

In this chapter, a new concept of utilizing the solar cell diode capacitance and wire parasitic inductance within a PV panel to replace the input capacitor and input inductor of DC-DC converters is introduced for the first time. Therefore, no external discrete input capacitor or filter inductor was added to the new types of boost converters. The hardware prototype of a hard-switched boost converter is built and tested. The simulation analysis and experimental measurement are performed to validate the concept. Therefore, it is possible to eliminate the external input capacitor and input inductor of boost converter by operating at high frequencies. The target applications could be in the low power and low voltage solar energy harvesting devices in which size constraints are limiting design factors. Further, because this new type of hard-switched boost converter only requires two switches, i.e. one MOSFET and one diode, it is easy to fully integrate the small boost converters into the PV panel by the same fabrication, and the cost of manufacturing will be reduced. The main concerns for this hard-switched boost converter are that the power efficiency is low due to the high frequency operation, and the current ripple might be large so that the converter will possibly enter the discontinuous conduction mode (DCM) in some conditions. This type of application may be less suitable for higher power applications because of the ripple currents and higher switching frequencies required. In the future work, this newly proposed boost converter might be directly connected to a single solar cell to boost $\sim0.5 \text{ V}$ solar cell voltage to $5 \text{ V}$ USB output load. Other non-isolated or isolated step-up DC-DC converter topologies [55] combined with a single or a few solar cells as multiple input sources will be developed for low power energy harvesting applications.
CHAPTER 3. SUBMODULE INTEGRATED BOOST DC-DC CONVERTERS

The techniques to mitigating current ripples as a result of no-input capacitor or no-input inductor will be developed. The power loss related to hard-switching or high frequency operation could be further improved in future research.
Chapter 4

Soft-Switched Boost DC-DC Converter and Non-Ideal Operation

In order to reduce power losses of high frequency DC-DC converters, a number of methods on creating zero-current switching (ZCS) and zero-voltage switching (ZVS) have been presented in the previous literature [56–59]. In this chapter, a zero-voltage resonant boost converter topology is extended to integrate with solar cells [59]. The proposed boost DC-DC converters rely on the solar diode capacitance and wire inductance, so the possible impact due to environmental factors and solar module variations, i.e. wire length and solar cell size, need to be carefully considered. Specifically, the research in this chapter includes the following contributions:

• A new type of resonant boost DC-DC converter topology is proposed. The converter is integrated with a solar PV submodule and utilizes solar cell internal capacitance and solar cell interconnect wire parasitic inductance, and therefore it requires no external discrete input capacitor nor input inductor.

• A proof-of-concept prototype of the solar PV submodule integrated resonant boost converter is designed, built, and experimentally tested. The prototype converter operates with no external input capacitor nor input inductor at switching frequencies in the range of 5 – 10 MHz.

• The research demonstrates that the solar PV submodule integrated boost converters can operate in both low and high illumination conditions, ranging from the 10’s W/m² to few 100’s W/m², making it suitable for energy harvesting applications. Further, the converter can operate with wire inductances ranging from 100’s nH to few µH at high switching frequencies.
CHAPTER 4. SOFT-SWITCHED BOOST CONVERTER AND NON-IDEAL OPERATION

4.1 Benefits and Drawbacks of High Frequency Operation and Soft-Switched DC-DC Converters

The demand for miniaturization of power electronics has been encouraging the development of new technologies from different fields to achieve small, lightweight, energy-efficient, and cost-effective power converters. The passive components, for example, inductors and capacitors, dominate the converter size and weight. By increasing the switching frequency of power converters, it is possible to reduce the size of the inductor or capacitor. But, the switching losses increase with high frequency operation, and therefore, the converter efficiency is low. Soft-switched DC-DC converters are able to reduce the switching losses and improve converter performance and efficiency. However, high switching stresses are associated with soft-switching circuit operation. This research proposes a zero-voltage resonant switch to construct the solar PV submodule integrated boost DC-DC converter.

4.2 Submodule Integrated Resonant Boost DC-DC Converter

A new resonant boost converter circuit topology is proposed to connect with the solar PV submodule, as shown in Fig. 4.1 [47]. In the solar PV submodule, the solar cell diode capacitance $C_d$ and wire parasitic inductance $L_w$ are respectively utilized to replace the input capacitor and input inductor of boost converter. In the resonant boost converter cell, the resonant switch consists of one MOSFET switch $S_1$ and two resonant components, inductor $L_r$ and capacitor $C_r$, which are added as external passives. The total capacitance of $C_r$ includes the paralleled internal output junction capacitance $C_{oss}$ of the MOSFET which is usually small. The resonant components determine the circuit operation and resonance parameters, which are resonant angular frequency, resonant frequency, and characteristic impedance.

Figure 4.1: The circuit diagram of proposed solar PV submodule integrated resonant boost converter.
• Resonant angular frequency:
\[ \omega_r = \frac{1}{\sqrt{L_r C_r}} \] (4.1)

• Resonant frequency:
\[ f_r = \frac{\omega_r}{2\pi} = \frac{1}{2\pi \sqrt{L_r C_r}} \] (4.2)

• Characteristic impedance:
\[ Z_c = \sqrt{\frac{L_r}{C_r}} \] (4.3)

4.2.1 Principal of Operation

The equivalent circuit operation of the solar PV submodule integrated resonant boost converter is proposed in Fig. 4.2. As seen in the figure, the voltage source \( V_{Cd} \) represents the voltage across the solar cell diode capacitance. The current \( I_L \) represents the inductor current, which is the same as the PV current \( I_{PV} \) of solar PV submodule. In the steady state, the converter operation can be divided into four stages, and the corresponding waveforms are shown in Fig. 4.3.

• Stage 1 \([t_0, t_1]\): It begins from the configuration \((S_1, D_1) = (0, 0)\) with the switch \( S_1 \) OFF and diode \( D_1 \) OFF, as shown in Fig. 4.2(a). The current \( I_{PV} \) flows to the capacitor \( C_r \), so the capacitor voltage \( V_{Cr} \) rises linearly and reaches the output voltage \( V_{out} \), as shown in Fig. 4.3. The state equation can be expressed as [59]

\[ I_{Cr} = I_{PV} = C_r \frac{dV_{Cr}}{dt} \] (4.4)

With the initial condition: \( V_{Cr} (t = t_0) = 0 \). The duration of \([t_0, t_1]\) can be found as [59]

\[ \Delta t_{01} = t_1 - t_0 = \frac{C_r V_{out}}{I_{PV}} \] (4.5)

• Stage 2 \([t_1, t_2]\): In the configuration \((S_1, D_1) = (0, 1)\), as shown in Fig. 4.2(b), the diode \( D_1 \) turns ON when \( V_{Cr} \) is greater than the output voltage \( V_{out} \). A part of the current starts to flow through the inductor to the output, as shown in Fig. 4.3. The converter enters resonant stage. The state equations can be expressed as [59]

\[ I_L - I_{Lr} = C_r \frac{dV_{Cr}}{dt} \] (4.6)
Figure 4.2: Sequence of configurations in solar PV submodule integrated resonant boost converter includes (a) Stage 1, (b) Stage 2, (c) Stage 3, and (d) Stage 4.
Figure 4.3: Ideal waveforms of solar PV submodule integrated resonant boost converter.
\[ V_{Cr} - V_{out} = L_r \frac{dI_{Lr}}{dt} \] (4.7)

With the initial conditions: \( V_{Cr} (t = t_1) = V_{out} \) and \( I_{Lr} (t = t_1) = 0 \). The solution of \( V_{Cr} (t) \) and \( I_{Lr} (t) \) can be found as [59]

\[ V_{Cr} (t) = V_{out} + Z_c I_{PV} \sin (\omega_r t) \] (4.8)

\[ I_{Lr} (t) = I_{PV} (1 - \cos (\omega_r t)) \] (4.9)

Let \( \theta = \omega_r t \). From (4.8), it can be derived that [59]

\[ \theta = \omega_r t = \arcsin \left( \frac{V_{Cr} (t) - V_{out}}{Z_c I_{PV}} \right) \] (4.10)

The amplitude of \( V_{Cr} \) is determined by the product of characteristic impedance \( Z_c \) and PV current \( I_{PV} \). The peak voltage occurs at \( \theta = \omega_r t = \pi/2 \). At \( \theta = \pi \), \( V_{Cr} \) swings down to the output voltage while the current \( I_{Lr} \) continues to increase to its peak value, as can been seen in Fig. 4.3. Finally, \( V_{Cr} \) resonates down to zero voltage at \( t_2 \). The maximum voltage of \( V_{Cr} \) and maximum current of \( I_{Lr} \) can be found respectively as [59]

\[ V_{Cr(max)} = V_{out} + Z_c I_{PV} \] (4.11)

\[ I_{Lr(max)} = 2 I_{PV} \] (4.12)

- Stage 3 \( [t_2, t_3] \): In the configuration \((S_1, D_1) = (1, 1)\), as shown in Fig. 4.2(c), the switch \( S_1 \) turns ON while \( D_1 \) is ON. The inductor \( L_r \) is discharging linearly and the current \( I_{Lr} \) finally drops to zero at \( t_3 \), as shown in Fig. 4.3. The duration of \( [t_2, t_3] \) can be found as [59]

\[ V_{Lr} = 0 - V_{out} = L_r \frac{dI_{Lr}}{dt} \] (4.13)

With the initial condition: \( I_{Lr} (t = t_2) = I_{PV} (1 - \cos (\omega_r t_2)) \). Therefore,
\[ \Delta t_{23} = t_3 - t_2 = \frac{L_r I_{PV} (1 - \cos (\omega_r t_2))}{V_{out}} \] (4.14)

- **Stage 4 \([t_3, t_4]\)**: In the configuration \((S_1, D_1) = (1, 0)\), as shown in Fig. 4.2(d), the diode \(D_1\) turns OFF and the switch \(S_1\) remains ON. The current \(I_{PV}\) flows through the switch \(S_1\), which equals \(I_Q\), until it turns OFF for next cycle, as shown in Fig. 4.3. The duration of \([t_3, t_4]\) can be expressed as [59]

\[ \Delta t_{23} = T_s - \Delta t_{01} - \Delta t_{12} - \Delta t_{23} \] (4.15)

In the steady state, the input and output transfer ratio can be found as [59]

\[ \frac{V_{out}}{V_{Cd}} = x = \frac{1}{\frac{f_s}{2\pi f_r} \left[ \frac{\alpha}{2x} + \frac{x}{r} (1 - \cos \alpha) \right]} \] (4.16)

where \(x\) and \(r\) are defined as \(x \equiv \frac{V_{out}}{V_{Cd}} ; r = \frac{R_L}{Z_c}\), and \(\alpha = \arcsin \left( \frac{r}{x} \right)\).

The input-to-output transfer ratio has dependence on the ratio of switching frequency and resonant frequency. The resonance parameters are known to be determined by the added passive components in the converter circuit. In the target application, the converter output is regulated at a fixed voltage, i.e. 5 V, and is operated with a fixed duty ratio to maintain the ZVS condition. Therefore, there are only two remaining variables in (4.16), which are switching frequency and solar cell diode capacitance voltage. However, the solar cell diode capacitance voltage is known to be affected by irradiance levels and other solar cell environmental conditions. Their influence is further studied in this chapter.

### 4.3 Simulation Results

MATLAB/Simulink models are built according to the single-diode equivalent circuit model of a solar cell, shown in Fig. 3.1 of Chapter 3 and the proposed resonant boost converter, shown in Fig. 4.1. The solar cells are modeled and simulated in the same solar irradiation and temperature conditions that the experimental prototype operates in. In the circuit simulation, the parameters of the switching devices, i.e. the MOSFET \(S_1\) and diode \(D_1\), are the same as the components used in the
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The wire inductance is set at 1.0538 µH (≈ 1053.8 nH) for the simulation, which is obtained from the experiment in Section 3.6 of Chapter 3. The boost converter works in the same condition of the experiment in Section 4.4: the converter is operated at a switching frequency of 5 MHz with the duty ratio of 0.6, and the output voltage is 4.96 V. The characteristic impedance and resonant frequency are, respectively, chosen to be 31 Ω and 10 MHz, which approximately gives the parameters of resonant components, i.e. \( C_r = 510 \text{ pF} \) and \( L_r = 491 \text{ nH} \). Fig. 4.4 shows that when the solar PV submodule integrated resonant boost converter operates at 4.963 V output in the irradiance condition of around 100 W/m² and temperature of 56 °C, the PV voltage \( V_{PV} \) and current \( I_{PV} \) are respectively 2.807 V and 0.368 A, and the diode capacitance voltage \( V_{Cd} \) of solar cell remains constant at ~3.2608 V with no large ripples. Besides, Fig. 4.5 illustrates that the simulated results match with the theoretical predictions and the zero-voltage switching occurs after the resonant voltage \( V_{Cr} \) reduces down to zero volts and before the drain-to-source current \( I_{ds} \) starts to increase into the MOSFET, as shown in Figs. 4.5(a) and 4.5(b) respectively. As a result, there is no voltage and current overlapped during the switching period and the switching loss is eliminated.

4.4 Experimental Verification

The hardware prototype of the proposed resonant boost converter is built and tested with six solar cells (P-Maxx-6000mA) to verify the ZVS operation. The solar cells connection keeps the same as shown in Fig. 3.9 in Chapter 3. And, the electrical characteristics of solar cell are shown in Table 3.1. Table 4.1 shows the specifications of the proposed resonant boost converter prototype. The converter is operated in open-loop with a fixed duty ratio of 0.6 at a switching frequency of 5 MHz. The PWM signal is generated from the signal generator (Agilent 33220A) to feed the gate driver. The output of the converter is connected to a DC electronic load (Kikusui PLZ303W) and output voltage is regulated at 5 V. Since the MOSFET’s output capacitance \( C_{oss} \) is only around 180 pF, the external capacitor, i.e. 330 pF, is added to connect in parallel with the MOSFET to increase the resonant capacitance. And, the external inductor, i.e. 491 nH, is added to connect in series with the diode \( D_1 \). With the parameters of resonant components, the resonant frequency and characteristic impedance of the converter are estimated to be around 10.05 MHz and 31.02 Ω, respectively. The magnitude of output voltage is measured at 4.96 V. As shown in Fig. 4.6, the maximum \( I_{Lr} \) is around 0.66 A and the \( I_{PV} \) can be estimated to be around 0.33 A by (4.12). Therefore, the maximum \( V_{Cr} \) is estimated to be around 15.19 V by (4.11). From the experimental verification, the ZVS operation is realized. It matches the theoretical prediction, and it occurs when the MOSFET turns on after the
Figure 4.4: Simulated solar cell voltage and current waveforms when the output voltage of resonant boost converter is around 4.96 V.
Figure 4.5: Simulated voltage and current waveforms of the solar PV submodule integrated resonant boost converter.
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$V_{C_r}$ drops to zero volts and before the diode current $I_{Lr}$ drops to zero. Any differences between the experimental and simulation results, e.g. current and voltage shapes and values, might be attributed to the non-idealities of MOSFET and passive components and measurement errors, etc.

Table 4.1: Components used for the submodule integrated resonant boost converter prototype

<table>
<thead>
<tr>
<th>Device</th>
<th>Model</th>
<th>Value</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET, $S_1$</td>
<td>FDD5612</td>
<td></td>
<td>Fairchild</td>
</tr>
<tr>
<td>Diode, $D_1$</td>
<td>MBRS260T3G</td>
<td></td>
<td>ON Semiconductor</td>
</tr>
<tr>
<td>Output Capacitance, $C_{oss}$</td>
<td>FDD5612</td>
<td>180 pF</td>
<td>Fairchild</td>
</tr>
<tr>
<td>Resonant Capacitor, $C_r$</td>
<td>Ceramic, Radial</td>
<td>3 x 100 pF</td>
<td>Murata</td>
</tr>
<tr>
<td>Resonant Inductor, $L_r$</td>
<td>AIAC-4125C-R491J-T</td>
<td>491 nH</td>
<td>Abracon</td>
</tr>
<tr>
<td>Output Capacitor, $C_o$</td>
<td>Ceramic, Radial</td>
<td>2 x 10 µF</td>
<td>TDK</td>
</tr>
<tr>
<td>Gate Driver</td>
<td>MAX5048C</td>
<td></td>
<td>Maxim Integrated</td>
</tr>
</tbody>
</table>

4.5 Non-Ideal Operation and Analysis

In this research, the solar cell internal diode capacitance is utilized to replace the input capacitor of the proposed high frequency boost converter cell, shown in Fig. 4.7. Therefore, the input voltage of the two types of boost converters, i.e. hard-switched and resonant, shown in Figs. 3.11 and 4.1 as $V_{in}$ changes between the near zero volts to some other voltage as the switch turns on and off. Therefore, the voltage, $V_{in}$ of the boost converter cell is no longer a constant voltage. However, the solar cell diode capacitance voltage is approximately constant for the switching cycle, except for its small voltage ripple, as shown in Fig. 3.14. Normally, there is a variation with the solar cell diode capacitance in its different environmental and operating conditions, since its value is affected by factors, such as solar irradiation, temperature, operating voltage, wafer size and material, etc. In order to verify that the proposed boost converters are able to work properly with the solar cells in different solar irradiation conditions, both indoor and outdoor experiments are performed to examine the converter operation with low and medium to high irradiance, respectively.

Similarly, the internal solar module wire parasitic inductance is utilized to replace the input filter inductor of the high frequency boost converter cell, shown in Fig. 4.7. And, there is a variation existed within the wire inductance because of the different wire lengths within the solar module and
Figure 4.6: Experimental waveforms of voltages and current of the solar PV submodule integrated resonant boost converter.
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the switching frequencies of DC-DC converter. To find out the required minimum wire inductance, the experimental hard-switched boost converter is tested with six series-connected solar cells, shown in Figs. 3.8 and 3.9 with both different switching frequencies and the wire inductance variation.

![Circuit Diagram](image)

Figure 4.7: A circuit diagram of high frequency boost converter cell with series-connected solar cells and electric wires.

4.5.1 Different Lighting Illumination

Solar cells rely on the sunlight condition, i.e. solar irradiation, to generate current and voltage. Since the submodule integrated boost converter utilizes the solar cell diode capacitance to replace the input capacitor, the performance of the converters will be also affected by sunlight condition. And, the solar cell diode capacitance has dependence on diode voltage and current, as shown in (3.1), which depend on irradiance, temperature, parasitic resistances, etc. As a result, the proposed submodule integrated boost converters must be tested in different sunlight conditions to better understand how the solar irradiation affects the converter’s operation and performance.

In the circuit simulation, the proposed hard-switched boost converter is tested with various irradiance conditions and input voltages to verify if the converter can be operated to have 5 V output for ranges of solar cell diode capacitance. The boost converter is operated at the switching frequency of 5 MHz with duty ratios between 0.3 and 0.8. From the simulation results shown in Fig. 4.8 the proposed boost converter can have output voltage of 5 V when the input voltage ranges from 1.116 V to 3.216 V for the low irradiance and from 1.137 V to 3.356 V for the high irradiance, along with the varying duty ratios. The proposed boost converter enters DCM when the duty ratio is 0.3, so the input current and power are very small. To extract the most power, the proposed boost converter must be designed to operate in CCM with the duty ratio of at least 0.4 or above in this condition. Further, the I-V and P-V characteristics of the submodule integrated hard-switched boost converter
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Figure 4.8: Simulation results of the input and output voltages of the solar PV submodule integrated hard-switched boost converter operating in low and high irradiance condition.

Figure 4.9: Simulation results for I-V and P-V relationship of the solar PV submodule integrated hard-switched boost converter operating in low and high irradiance condition.
are simulated and plotted for both low and high irradiance conditions, shown in Fig. 4.9. As seen in the graphs, there exists MPPs at 1.818 W and 2.322 W, respectively, when the input voltages are 1.651 V and 1.665 V in the low and high irradiance conditions.

To validate the feasibility of the submodule integrated boost converters operating in different lighting illumination, the proposed hard-switched boost converter prototype is tested with six series-connected solar cells in low and medium to high irradiance conditions. For the low irradiance experiment, the proposed submodule integrated boost converter is tested with the halogen lamps in the lab and two different measured irradiance are respectively about 19 W/m² and 88 W/m². The converter’s output voltage is regulated at 5 V by a DC electronic load and the converter is operated at the switching frequency of 5 MHz with various duty ratios ranging from 0.3 to 0.8 for 19 W/m² and from 0.2 to 0.8 for 88 W/m², respectively. It is found that the proposed boost converter can be operated with the wide range of input voltage from 0.801 V to 3.01 V for 19 W/m² and from 0.863 V to 2.95 V for 88 W/m², respectively, and have the output voltage of 5 V in both irradiance conditions, shown in Fig. 4.10. In addition, the duty ratio of the proposed hard-switched boost converter must be chosen at least 0.4 or above to keep the converter operating in CCM, which matches with the previously simulated results, for the design considerations. Also, there exists MPPs at 1.043 W and 1.785 W when the input voltages are 1.92 V and 2.04 V, respectively, shown in Fig. 4.11. For the medium to high irradiance experiment, the proposed submodule integrated hard-switched boost converter is tested in outdoors and its experimental setup is shown in Fig. 4.12. The proposed converter can successfully boosts various input voltages to the output voltage of between 4.82 V and 4.99 V in the irradiance between 400 W/m² and 700 W/m², shown in Fig. 4.13. Finally, the I-V and P-V characteristics of the submodule integrated hard-switched boost converter are found and shown in Fig. 4.14. The test results match with the theoretical predictions and simulation and therefore illustrate that the proposed boost converter can be operated with ranges of solar cell diode capacitance.

4.5.2 Different Switching Frequencies

The solar PV submodule integrated boost converter utilizes the internal wires, which exhibit some amount of parasitic inductance, to replace externally added filter inductor of conventional boost converters. In this research, the submodule integrated boost converters are operated in high frequency, i.e. a few megahertz to ten’s of megahertz, and therefore, the wire inductance changes with different switching frequencies. To better understand the variant of wire parasitic inductance
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The proposed boost converter operates at low irradiance.

Figure 4.10: Experimental measurement of the input and output voltages of the solar PV submodule integrated hard-switched boost converter operating in low irradiation condition.

Figure 4.11: Experimental measurement results for (a) I-V and (b) P-V relationships of the solar PV submodule integrated hard-switched boost converter operating in low irradiance condition.
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Figure 4.12: A photograph of outdoor experiment setup.

Figure 4.13: Measured input and output voltages of the solar PV submodule integrated hard-switched boost converter operating in medium to high irradiance condition.
Figure 4.14: Experimental measurement results for (a) I-V and (b) P-V relationships of the solar PV submodule integrated hard-switched boost converter in medium to high irradiance condition.
and its dependence on switching frequency, the proposed hard-switched boost converter is tested with different switching frequencies ranging from 2 MHz to 6 MHz to estimate the wire inductance.

In the circuit simulation, the proposed hard-switched boost converter with six series-connected solar cells is tested with different switching frequencies ranging from 2 MHz to 6 MHz in the medium to high irradiance condition. Therefore, it is possible to verify the relationship between the wire parasitic inductance and switching frequency. And, the wire parasitic inductance can be estimated by measuring the amplitude of current ripples. As expected, the inductor current ripples vary with different switching frequencies with the same wire length, shown in Figs. 4.15, 4.16, 4.17, 4.18, and 4.19. It can be seen from the graphs that the current ripples become smaller with the increased switching frequencies, and vice versa.

To verify that the submodule integrated boost converters can work with different switching frequencies, the proposed hard-switched boost converter prototype is tested with six series-connected solar cells and different switching frequencies in the medium to high irradiance condition to examine the wire parasitic inductance. The wire length used to connecting with the solar cells is fixed and its detailed information is provided in Section 3.3 of Chapter 3 for the experiment. The measured input current ripples of the boost converter are respectively shown in Figs. 4.20, 4.21, 4.22, 4.23, and 4.24. The experimental results match with the theoretical predictions and simulation in the similar irradiance and temperature conditions. The measured current ripples decrease with the increased switching frequency, which are respectively 134.5% of the input current at the switching frequency of 2 MHz, 79.5% of the input current at the switching frequency of 3 MHz, 53.2% of the input current at the switching frequency of 4 MHz, 37.9% of the input current at the switching frequency of 5 MHz, and 25.9% of the input current at the switching frequency of 6 MHz. Therefore, the wire parasitic inductance can be found and estimated, which approximately ranges from 895.5 nH to 1.048 µH. In addition, the measured wire inductance shows a linear relationship to the switching frequency, shown in Fig. 4.25. As can be seen in the graphs of Fig. 4.20, the measured wire has the smallest inductance which is 895.5 nH at the switching frequency of 2 MHz that is just sufficient for the proposed hard-switched boost converter to operate in the CCM when the duty ratio is 0.5. From the experimental results, however, it is not found that the input power of the proposed boost converter is affected by the current ripples due to the different switching frequencies.
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The proposed boost converter operates at $F_{sw} = 2\, \text{MHz}$.

Figure 4.15: Simulated inductor current ripple at the switching frequency of 2 MHz.

The proposed boost converter operates at $F_{sw} = 3\, \text{MHz}$.

Figure 4.16: Simulated inductor current ripple at the switching frequency of 3 MHz.
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The proposed boost converter operates at $F_{sw} = 4$ MHz.

Figure 4.17: Simulated inductor current ripple at the switching frequency of 4 MHz.

The proposed boost converter operates at $F_{sw} = 5$ MHz.

Figure 4.18: Simulated inductor current ripple at the switching frequency of 5 MHz.
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The proposed boost converter operates at $F_{sw} = 6\text{MHz}$.

![Graph showing voltage and current waveforms for $F_{sw} = 6\text{MHz}$]

Figure 4.19: Simulated inductor current ripple at the switching frequency of $6\text{MHz}$.

The proposed boost converter prototype at $F_{sw} = 2\text{MHz}$.

![Graph showing voltage and current waveforms for $F_{sw} = 2\text{MHz}$]

Figure 4.20: Measured inductor current and ripple current at switching frequency of $2\text{MHz}$.
Figure 4.21: Measured inductor current and ripple current at switching frequency of 3 MHz.

Figure 4.22: Measured inductor current and ripple current at switching frequency of 4 MHz.
Figure 4.23: Measured inductor current and ripple current at switching frequency of 5 MHz.

Figure 4.24: Measured inductor current and ripple current at switching frequency of 6 MHz.
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Figure 4.25: Measurement results of wire inductance for the solar PV submodule integrated boost converter under different switching frequencies operation.

4.5.3 Different Wire Parasitic Inductance

Conventional boost DC-DC converter uses the external inductor to filter out the current ripples and to work as an energy storage element. Normally, the filter inductor has a large inductance so the current ripples can be reduced and the converter is able to operate in the CCM even when the input current is low. However, the proposed boost converter eliminates the external inductor and utilizes the wire parasitic inductance to be a filtering element. With the limited wire length within the solar PV module, the wire parasitic inductance is usually small so it becomes more difficult to filter out the large current ripple and to keep the converter in the CCM operation. To better understand the effects of the current ripples, the proposed submodule integrated boost converter is verified with different wire parasitic inductance in simulation.

The six solar cells with the same configuration, as shown in Fig. 3.8 of Chapter 3, are modeled and simulated in two different irradiance and temperature conditions, i.e. 100 W/m² with 56°C and 694 W/m² with 34°C, which are like the real situations of indoor and outdoor environment. The simulation results, as shown in Fig. 4.26, demonstrate the ideal solar power with not any voltage or current ripple disturbance in the steady state condition. Table 4.2 shows the
Figure 4.26: Simulation results for (a) P-V and (b) P-I characteristics of solar cell in two different irradiance and temperature conditions.
Table 4.2: Simulated electrical characteristics of solar cells at 694 W/m² and 34 °C

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage</td>
<td>$V_{oc}$</td>
<td>3.142 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>$I_{sc}$</td>
<td>4.178 A</td>
</tr>
<tr>
<td>Maximum power point voltage</td>
<td>$V_{MPP}$</td>
<td>2.508 V</td>
</tr>
<tr>
<td>Maximum power point current</td>
<td>$I_{MPP}$</td>
<td>3.957 A</td>
</tr>
<tr>
<td>Maximum power (&quot;True MPP&quot;)</td>
<td>$P_{MPP}$</td>
<td>9.925 W</td>
</tr>
</tbody>
</table>

electrical characteristics of solar cells in high irradiance condition, i.e. 694 W/m² with 34 °C. To verify the effects of input current ripples, the submodule integrated hard-switched boost converter is modeled and simulated with a fixed duty ratio of 0.5 at the switching frequency of 5 MHz but with different wire parasitic inductance. Four different wire inductance are chosen to be respectively 1000.21 nH (~1 µH) which is the original wire inductance at the switching frequency of 5 MHz, 501.05 nH (~0.5 µH) which is the half of the original inductance, 250.52 nH (~0.25 µH) which is the one-fourth of the original inductance, and 125.26 nH (~0.125 µH) which is the one-eighth of the original inductance. With the different wire inductance, the solar cell power fed into the hard-switched boost converter varies along the curve at the switching frequency and between the maximum and minimum power, i.e. $P_{Max}$ and $P_{Min}$, yet the average input power $P_{AVG}$ is not changed and affected by the input current ripples, shown in Figs. 4.27, 4.28, 4.29, and 4.30. Table 4.3 shows the maximum and minimum power and their corresponding current for four different wire inductance. As seen in the graphs, the boost converter is not operated at solar cell’s MPP with the duty ratio of 0.5 in simulation. Fig. 4.31 shows that the input current and power ripples change together at the switching frequency with the different wire inductance. In addition, both current and power ripples show an inverse relationship to the wire inductance, shown in Fig. 4.32. The simulated largest current and power ripples are respectively 65.92 % and 60.83 % when the wire inductance is the one-eighth of the original inductance and the smallest current and power ripples are respectively 8.27 % and 7.61 % with the original inductance.

Moreover, it is the first time we found that the instantaneous maximum power of the solar cell could be larger than the steady-state MPP when the current ripples become very large, shown in Fig. 4.30 and Table 4.3. As seen in the graph, with the wire inductance of 0.125 µH, the maximum power $P_{Max}$ of solar cell is around 11.303 W which is more than its steady-state average $P_{MPP}$ at 9.925 W and the instantaneous maximum power current $I_{Max}$ is also more than the short circuit current $I_{sc}$. This phenomena might be caused by the extra energy stored in the solar cell.
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Figure 4.27: Simulation results for current and power ripples with the wire inductance of 1000.21 nH.

Figure 4.28: Simulation results for current and power ripples with the wire inductance of 501.05 nH.
Figure 4.29: Simulation results for current and power ripples with the wire inductance of 250.52 nH.

Table 4.3: Simulated power and current of the solar PV submodule from Table 4.2 with integrated boost converter with four different wire inductance at 694 W/m² and 34 °C.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Wire Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 µH</td>
</tr>
<tr>
<td>Maximum power</td>
<td>( P_{\text{Max}} )</td>
<td>9.065 W</td>
</tr>
<tr>
<td>Minimum power</td>
<td>( P_{\text{Min}} )</td>
<td>8.399 W</td>
</tr>
<tr>
<td>Average power</td>
<td>( P_{\text{AVG}} )</td>
<td>8.733 W</td>
</tr>
<tr>
<td>Maximum power current</td>
<td>( I_{\text{Max}} )</td>
<td>3.309 A</td>
</tr>
<tr>
<td>Minimum power current</td>
<td>( I_{\text{Min}} )</td>
<td>3.046 A</td>
</tr>
<tr>
<td>Average power current</td>
<td>( I_{\text{AVG}} )</td>
<td>3.177 A</td>
</tr>
</tbody>
</table>

diode capacitance being released in high frequency operation. The capacitor extra energy is quickly discharged. Fig. 4.33 shows that the diode capacitance voltage \( V_{Cd} \) of solar cell is operated at a near constant value, and the diode current \( I_{Cd} \) charges and discharges while the wire inductance current varies at the switching frequency. As Fig. 4.30 shows, even though instantaneous maximum power may be higher than the true MPP, it should be noted that the average power when switching between \( P_{\text{Min}} \) and \( P_{\text{Max}} \) remains lower than the true MPP.
Figure 4.30: Simulation results for current and power ripples with the wire inductance of 125.26 nH.
Figure 4.31: Simulated waveforms of current and power ripples with different wire inductance.

Figure 4.32: The relationship of current and power ripples with different wire inductance.
In conclusion, the proposed submodule integrated boost converter without external input capacitor and input inductor is verified to be able to operate with different irradiance and temperature conditions, i.e. both indoor and outdoor environment, and with different switching frequencies and wire inductance. The electrical characteristics of the submodule integrated boost converter is validated through the simulation and experiment for both low and high irradiance conditions. The proposed boost converter is able to boost the various input voltage to 5 V load in both low and high irradiance conditions as well. The proposed submodule integrated boost converter is also validated to operate with different switching frequencies under the same solar cells connection with the fixed wire length. Both simulation and experimental results show that the boost converter can work properly with the switching frequencies ranging from 2 MHz to 6 MHz, and therefore, the wire inductance and its variation can also be estimated. The boost converter should be operated in the CCM by selecting the adequate switching frequency and duty ratio to ensure that the most solar energy could be harvested. Lastly, since the proposed submodule integrated boost converter requires no external input inductor, it must be able to sustain operation with different levels of current ripples. As a result, the proposed boost converter is verified with the different wire inductance or wire length to investigate the effects of current ripples through the wires. From the simulation results, the average input power and current from the solar cell is not affected by the large current ripples, but large
ripples might make the converter enter the DCM operation.

4.6 Conclusions and Future Work

A new type of high frequency resonant boost converter is introduced to integrate with the solar PV submodule. The proposed boost converter utilizes the solar cell diode capacitance and wire parasitic inductance to replace the input capacitor and input filter inductor, respectively. Therefore, no external energy storage passive component is required. The circuit operation of the submodule integrated ZVS resonant boost converter is analyzed and simulated. Finally, a hardware prototype is successfully built and tested to validate the concept. Besides, the non-ideal operation of the proposed submodule integrated boost converter due to the changes of environmental conditions, i.e. solar irradiation and temperature, and wire length as well as switching frequency are fully discussed and verified by the simulation and experiment.

The future research work may create or develop: 1) single solar cell harvesters directly connected to the load, e.g. 5 V USB, with not adding input capacitor or input inductor, 2) new high step-up DC-DC converter topologies which are suitable for high frequency, low power and low voltage applications, and 3) new MPPT method for non-ideal operation of the proposed submodule integrated boost DC-DC converters.
Chapter 5

Conclusions and Future Work

The research presented in this dissertation proposes new types of DC-DC converters integrated within solar PV module or submodule for low power solar energy harvesting applications. The proposed new method is able to reconfigure the PV panels between series and parallel connections. This leads to sometimes reduce the switch stresses, the filter element sizing and output ripples. A new approach is presented to utilize the solar cell internal capacitance and solar module wire parasitic inductance to replace the input capacitor and filter inductor of the boost converters. The main contributions of the research are summarized below and recommendations for future work are presented.

5.1 Conclusions

The achieved results and major research contributions of this dissertation are summarized as below:

- In Chapter 2, a new possibility to merge the reconfiguration concept with the integrated power converter concept is explored and presented. Specifically, a new classification of reconfigurable PV power converters is proposed.

  - The benefits and drawbacks of reconfigurable PV panels/systems and integrated power converters versus the traditional solutions are explored and discussed. A new PV switching cell is proposed. It views the solar panels as power sources that can reconfigure between series and parallel at high frequencies.
CHAPTER 5. CONCLUSIONS AND FUTURE WORK

– With the PV switching cell, new types of PV-buck and PV-boost derived topologies are proposed. The new approach combines the benefits of multi-input converters and three-level converters so as to sometimes effectively reduce the switch stresses, the filter element sizing and output ripples.

– With those benefits, the cost of building integrated PV modules or cells might be fully integrated into fabrication process. The target applications for the proposed topologies in this dissertation may be in the low power range and tend to imply energy harvesting applications.

• In Chapter 3 a new concept of utilizing the solar cell diode capacitance and wire parasitic inductance within a PV panel to replace the input capacitor and input inductor of DC-DC converters is introduced for the first time.

– The characteristics of solar cell internal diode capacitance and solar module wire parasitic inductance are introduced. The advantages and limitations of utilizing the solar cell parasitic capacitance and wire parasitic inductance within a PV panel are discussed.

– A new type of high frequency hard-switched boost DC-DC converter is proposed. The topology requires no external passive components for energy storage or filtering. The converter prototype is designed, built and tested to validate the concept.

– The benefits and drawbacks of the new proposed PV submodule integrated boost converter are explained. The target applications could be in the low power and low voltage solar energy harvesting devices in which size constraints are limiting design factors.

• In Chapter 4 a new type of soft-switched boost converter is proposed. The non-ideal operation of the new types of boost converters is explained and discussed.

– A new type of high frequency resonant boost converter is proposed that utilizes the solar cell diode capacitance and solar cell interconnect wire parasitic inductance. Therefore, it requires no external passive components for energy storage or filtering.

– The proposed resonant boost DC-DC converter achieves the ZVS operation that can effectively reduce the power losses and increase the power efficiency. The proof-of-concept prototype is designed, built and experimentally tested.

– The proposed submodule integrated boost converters can operate in both low and high irradiance conditions, ranging from the 10’s $\text{W/m}^2$ to few 100’s $\text{W/m}^2$. Further, the
CHAPTER 5. CONCLUSIONS AND FUTURE WORK

A converter can also operate with wire inductances ranging from 100’s nH to few μH at high switching frequencies.

The research of this thesis shows a promising result that not only validates the feasibility of merging the fast switching reconfigurable PV modules with the integrated power converters but also provides new research potentials based on the proposed methods or approaches. The possible drawbacks resulted from the high frequency operation such as ripples in the PV modules or cells and lower power efficiency may need to be further studied.

5.2 Future Work

In this dissertation, the new types of DC-DC power converters in both PV module and submodule levels are developed to realize the no-input capacitor, no input inductor submodule integrated power converters. The proposed reconfiguration scheme can switch the PV panels between series and parallel at high frequencies. With those new approaches, some interesting and potential research topics may be explored in the future.

To continue this research, possible future work may include:

- **Multiple Cascaded or Parallel Connected Reconfigurable PV Power Converter Systems.**

  - Since the reconfigurable PV DC-DC converters utilize two similar PV panels or arrays of solar cells to be power sources, they can be scaled down to submodule or cell level DC-DC converter and integrated within the submodules or cells. Fig. 5.1 shows that by stacking multiple reconfigurable PV DC-DC converters, the multi-level output voltages can be created and utilized to achieve the modified sine wave inverter, for example. By alternating the submodule or cell connections between series and parallel, the poorly performed submodule or cell could be bypassed so the overall output power of the PV panel will not be overly affected. Further, the added power management may be useful to control or arrange the energy flow between each reconfigurable PV power converter. A new MPPT method may be required for both slow and fast switching reconfiguration.

  - The proposed extended non-isolated and isolated DC-DC converter topologies in this dissertation can be further studied to achieve high voltage transfer ratio. A transformer could be added to easily boost or lower the voltage to the desired value. The reconfigurable PV power converters may be more suitable for low power and low voltage energy...
Figure 5.1: (a) Cascaded and (b) parallel connected reconfigurable PV power converters.
harvesting applications, as they can be fully integrated and easily fabricated together with PV modules. The next stage followed by the reconfigurable PV power converter can be connected to another DC-DC or DC-AC converter, so the approach could be used for an MPPT system.

• **Very High Frequency Submodule or Cell Integrated Step-Up DC-DC Converters.**

  - In this dissertation, the benefits and drawbacks of the proposed high frequency boost DC-DC converters are explored. With the higher switching frequencies, the energy storage and filtering requirements of power converters can be reduced so a smaller and lightweight power converter is achievable. However, the high frequency power conversion also brings the unwanted parasitic effects that cause the non-linear operation when the converter is operated in the very high frequency (VHF) range of 30 MHz–300 MHz. And, those frequency-dependent devices, such as transistors, diodes, passive components and wires can cause additional power losses with high frequencies [60–62]. Therefore, the optimization of circuit topology and component selection for PV submodule or cell integrated VHF DC-DC converters will need to be further studied.

  - Since the performance of the submodule integrated boost DC-DC converters relies on the environmental conditions, such as solar irradiance, an automatic MPPT with a closed loop control may be required to ensure that the converter can operate with the sufficient solar cell diode capacitance. Moreover, the extended new step-up non-isolated or isolated DC-DC converter topologies may be developed to be used in low power solar energy harvesting devices and applications.

In conclusion, this dissertation research explores the new methods and approaches to build small power converters that can be fully integrated within the PV panels or submodules and achieve no-input capacitor or no-input inductor. The target applications of this research may be in the low power energy harvesting applications.
Appendix A

Matlab/Simulink Models for Reconfigurable PV-Buck DC-DC Converter

This appendix provides the Matlab/Simulink models for PV modules and reconfigurable PV-buck converter, respectively.

Figure A.1: Numerical model for PV modules in Matlab/Simulink.
APPENDIX A. SIMULINK MODELS FOR RECONFIGURABLE PV-BUCK CONVERTER

Figure A.2: The subsystem of numerical model for PV modules in Matlab/Simulink.
Figure A.3: The reconfigurable PV-buck converter schematic diagram.
Appendix B

Matlab/Simulink Models for Submodule Integrated Boost DC-DC Converters

This appendix provides the Matlab/Simulink models for solar cells and submodule integrated hard-switched and resonant boost converters, respectively.

Figure B.1: Numerical model for solar cells in Matlab/Simulink.
Figure B.2: The subsystem of numerical model for solar cells in Matlab/Simulink.
Figure B.3: The submodule integrated hard-switched boost converter schematic diagram.
Figure B.4: The submodule integrated resonant boost converter schematic diagram.
Bibliography


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