A Phase Shedding Technique for PV system based on Interleaved Boost Converter

By Hyungmin Lim

© Hyungmin Lim

March 2016
As the size of solar photovoltaic (PV) power plants has been gradually increasing in the last few decades, interests in multiphase converters for PV applications have been escalating. Due to current sharing by the adding phase, the multiphase converters are suitable for PV systems to reduce conduction losses and increase system efficiency. However, the adding phase can be disadvantageous for the converters at low load conditions. Especially for PV applications that rely on changeable irradiation or temperature conditions, low efficiency at light load conditions is a critical problem on the PV system. This thesis demonstrates the improvement and advantages of interleaved boost converters compared with conventional boost converters. Moreover, a new phase shedding control method of an Interleaved boost converter as PV pre-regulator is proposed as a way to improve the efficiency of the converter at light load conditions. The efficiency improvement of the interleaved boost converter and the minimization of current overshoot are obtained using a hysteresis control with proposed incremental duty control (IDC) method. The output voltage of the converter is 400V and two-phase boost converters operated at continuous conduction mode (CCM) are used to build the IBC. Experimental results from a 1kW prototype are presented an improvement of the system efficiency in a wide power range.
ORIGINALITY STATEMENT

‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.’

Signed……………………………………………………………

Date …………………………………………………………………
COPYRIGHT STATEMENT

‘I hereby grant the University of New South Wales or its agents the right to archive and to make available my thesis or dissertation in whole or part in the University libraries in all forms of media, now or hereafter known, subject to the provisions of the Copyright Act 1968. I retain all proprietary rights, such as patent rights. I also retain the right to use in future works (such as articles or books) all or part of this thesis or dissertation. I also authorise University Microfilms to use the 350 word abstract of my thesis in Dissertation Abstract International (this is applicable to doctoral theses only). I have either used no substantial portions of copyright material in my thesis or I have obtained permission to use copyright material; where permission has not been granted I have applied/will apply for a partial restriction of the digital copy of my thesis or dissertation.’

Signed……………………………………………..............

Date ……………………………………………................

AUTHENTICITY STATEMENTS

‘I certify that the Library deposit digital copy is a direct equivalent of the final officially approved version of my thesis. No emendation of content has occurred and if there are any minor variations in formatting, they are the result of the conversion to digital format.’

Signed……………………………………………..............

Date ……………………………………………................
Do not be like them, for your Father knows what you need before you ask him

- Matthew 6:8 -
Abstract

As the size of as photovoltaic (PV) power plants have been gradually increasing in the last few decades, interests in multiphase converters for PV application has been escalated. Due to current sharing by the adding phase, the multiphase converters are suitable for PV system to reduce conduction losses and increase system efficiency. However, the adding phase can be disadvantage for the converters at light load condition. Especially for PV applications which rely on changeable irradiation or temperature condition, low efficiency at light load condition is a critical problem on the PV system. This thesis demonstrates the improvement and advantages of interleaved boost converter compared with conventional boost converter. Moreover, a new phase shedding control method of an interleaved boost converter as PV pre-regulator is proposed as a way to improve the efficiency of the converter at light load condition. The efficiency improvement of the interleaved boost converter and the minimization of current overshoot are obtained using a hysteresis control with proposed incremental duty control (IDC) method. The output voltage of the converter is 400V and two-phase boost converters operated at continuous conduction mode (CCM) are used to build the IBC. Experiment results from a 1kW prototype are presented an improvement of the system efficiency in a wide power range.
Acknowledgement

I would like to express the deepest appreciation to Professor Vassilios G. Agelidis, most particularly my thesis advisor, for the vision, foresight and guidance which inspired me to conceive this research work.

I am extremely thankful to my co-supervisor Dr. Minsoo Jang for his valuable guidance, keen interest, support and encouragement extended to me. Without his thoughtful encouragement and careful supervision, this thesis would never have taken shape.

I am hugely indebted to my colleagues Mr. Taekyun Kim and Hyuntae Choi from The Australian Energy Institute for their help, guidance and assistance.

My thanks go out to my family in Korea and friends for their unconditional love and support during the last two years. I would not have been able to complete this thesis without their continuous love and encouragement.

Finally, I thank Lord that you have been with me so far. I glorify your name.
# Table of contents

ABSTRACT.................................................................................................................. ii
Acknowledgement........................................................................................................ iii
Table of contents........................................................................................................... iv
List of figures................................................................................................................ vii
List of tables................................................................................................................ xi
List of acronyms........................................................................................................... xii
List of units.................................................................................................................. xiii
List of variables.......................................................................................................... xiv

Chapter 1. Introduction............................................................................................... 1

1.1 Background........................................................................................................... 1
   1.1.1 Photovoltaic fundamentals............................................................................ 1
   1.1.2 Modelling of a solar cell.............................................................................. 2
   1.1.3 Maximum power point tracking (MPPT).................................................... 4
1.2 Motivation............................................................................................................ 8
1.3 Objective............................................................................................................. 10
   1.3.1 Problem formulation................................................................................. 10
   1.3.2 Objectives................................................................................................ 10
1.4 List of publication............................................................................................... 11
1.5 Thesis outline..................................................................................................... 11

Chapter 2. An overview of DC-DC converters on PV system............................... 13

2.1 The configuration of PV system.......................................................................... 13
   2.1.1 PV array.................................................................................................... 14
   2.1.2 Power conditioning system......................................................................... 14
      2.1.2.1 Low frequency transformer type....................................................... 15
      2.1.2.2 High frequency link type................................................................. 15
      2.1.2.3 Non-isolated type.............................................................................. 16
2.2 Non-isolating converters on PV system............................................................. 19
   2.2.1 A DC-DC Buck converter........................................................................... 19
   2.2.2 A DC-DC Boost converter......................................................................... 21
   2.2.3 A DC-DC Buck-Boost converter............................................................... 22
   2.2.4 A DC-DC Čuk converter............................................................................ 24
2.3 The use of MPPT with non-isolated converters............................................... 26
2.3.1 Buck converter ................................................................. 26
2.3.2 Boost converter ................................................................. 28
2.3.3 Buck-Boost converter ......................................................... 29
2.3.4 Ćuk converter ................................................................. 31
2.4 A suitability of converters for PV system .................................. 31

Chapter 3. A PV interleaved Boost Converter .................................. 35

3.1 Introduction ........................................................................... 35
3.2 Interleaved boost converter operation in CCM and DCM ............... 36
  3.2.1 Output voltage ripple (ΔVo) in IBC ....................................... 48
3.3 Simulation results .................................................................. 50
  3.3.1 PV cell modelling ............................................................. 50
  3.3.2 PV cell curve characteristics ............................................. 51
  3.3.3 MPPT modelling ............................................................ 52
  3.3.4 PV interleaved boost converter .......................................... 53
  3.3.5 Comparison waveforms of IBC and CBC ............................ 56
  3.3.6 The improvement of PV interleaved boost converter ............ 58

Chapter 4. A Phase shedding for PV interleaved boost converter ......... 60

4.1 Conventional phase shedding techniques .................................. 60
4.2 A phase shedding technique with incremental duty control for PV system .................................................. 62
  4.2.1 Hysteresis control by Schmitt trigger ............................... 62
  4.2.2 Incremental duty control ................................................ 66
4.3 Simulation results .................................................................. 67
  4.3.1 Rapid changing solar irradiation ....................................... 67
  4.3.2 Comparison conventional hysteresis control with proposed phase shedding .................................................. 68
    4.3.2.1 Duty change by IDC and non-IDC .......................... 68
    4.3.2.2 Inductor currents change by IDC and non-IDC .......... 69
    4.3.2.3 Input current change by IDC and non-IDC ............. 72
    4.3.2.4 Comparison inductor currents at phase shedding moment .................................................. 74

Chapter 5. Experiment results .......................................................... 77

5.1 Experimental test setup .......................................................... 77
5.2 Analysis and comparison of experimental results ....................... 79
  5.2.1 Rapid changing solar irradiation ....................................... 79
  5.2.2 Comparison between PV CBC and IBC ......................... 82
    5.2.2.1 PWM outputs ....................................................... 82
    5.2.2.2 Comparison input and inductor currents ................. 82
5.3 Comparison phase shedding operations .................................... 87
  5.3.1 Phase shedding operation with only hysteresis control ......... 87
  5.3.2 Phase shedding operation with hysteresis and IDC ........... 90
5.4 Conclusion

Chapter 6. Conclusion and future work

6.1 Summary

6.2 Future work

List of references
List of figures

Figure 1-1 Electrical equivalent model – Solar Cell……………………………………… 1
Figure 1-2 VI and PV curves of PV array at varying irradiation………………………….. 4
Figure 1-3 Perturb & Observation MPPT algorithm ………………………………………… 6
Figure 1-4 Incremental conductance MPPT algorithm …………………………………… 7
Figure 1-5 Global PV installation trend from 2000 to 2014…………………………….. 9
Figure 2-1 PV power conditioning system……………………………………………… 14
Figure 2-2 Low frequency transformer type PV system………………………………… 15
Figure 2-3 High frequency transformer type PV system………………………………… 16
Figure 2-4 Non-isolated type PV system………………………………………………… 16
Figure 2-5 A circuit diagram of DC-DC Buck converter………………………………… 19
Figure 2-6 Main waveforms of A DC-DC Buck converter…………………………….. 20
Figure 2-7 A circuit diagram of A DC-DC Boost converter…………………………….. 21
Figure 2-8 Main waveforms of A DC-DC Boost converter…………………………….. 22
Figure 2-9 A circuit diagram of A DC-DC Buck-boost converter……………………… 22
Figure 2-10 Main waveforms of A DC-DC buck-boost converter…………………… 23
Figure 2-11 A circuit diagram of A DC-DC Cuk converter…………………………….. 24
Figure 2-12 Main waveforms of A DC-DC Cu’k converter…………………………….. 25
Figure 2-13 Input resistance versus duty cycle in buck converter …………………….. 27
Figure 2-14 Operation region and non-operation region in PV buck converter……….. 27
Figure 2-15 Input resistance versus duty cycle in boost converter…………………… 28
Figure 2-16 Operation region and non-operation region in PV boost converter…….. 29
Figure 2-17 Input resistance versus duty cycle in buck-boost converter……………… 30
Figure 2-18 Operation region and non-operation region in PV buck-boost converter. 30
Figure 2-19 Efficiency curves of Buck, Boost, Buck-Boost and Ćuk converters connected with PV module ......................................................... 34
Figure 3-1 Circuit diagram of IBC.......................................................... 36
Figure 3-2 Equivalent circuits in continuous current mode......................... 37
Figure 3-3 Current and voltage waveforms of IBC in continuous current mode...... 38
Figure 3-4 Diode and capacitor current in four different modes ......................... 39
Figure 3-5 Equivalent circuits in discontinuous conduction mode (Mode 1-3)........ 43
Figure 3-6 Equivalent circuits in discontinuous conduction mode (Mode 4-6)......... 44
Figure 3-7 Current and voltage waveforms of IBC in discontinuous conduction mode 45
Figure 3-8 Diode ($I_{D1}$, $I_{D2}$) and capacitor ($I_{C}$) current in six different modes........ 46
Figure 3-9 Waveforms of the diode ($D_1$, $D_2$) current ($I_{D1}$, $I_{D2}$)...................... 48
Figure 3-10 VI and PV curve characteristics of PV array.................................. 51
Figure 3-11 MPPT control diagram based on incremental conductance method...... 52
Figure 3-12 Simulation circuit of 1kW IBC............................................. 53
Figure 3-13 Input ripple by duty ratio in IBC............................................ 55
Figure 3-14 Input and output currents of IBC............................................ 56
Figure 3-15 Comparison input current of CBC and IBC.................................. 56
Figure 3-16 Comparison output current of CBC and IBC................................. 57
Figure 3-17 Comparison output voltage of CBC and IBC................................. 57
Figure 3-18 Efficiency graph of CBC, single phase IBC and two phases IBC........ 58
Figure 4-1 A principle of noise elimination by hysteresis control....................... 64
Figure 4-2 Schmitt trigger control diagram.............................................. 65
Figure 4-3 Inductor currents at phase shedding moment by only Schmitt trigger control................................................................. 65
Figure 4-4 Input currents at phase shedding moment by only Schmitt trigger control.. 65
Figure 4-5 IDC block diagram............................................................... 67
Figure 4-6 Varying solar irradiation condition............................................. 68
Figure 4-7 Duty change by IDC and non-IDC at phase-off moment.................... 69
Figure 4-8 Duty change by IDC and non-IDC at phase-on moment
Figure 4-9 Duty and inductor currents change by non-IDC
Figure 4-10 Duty and inductor currents change by IDC
Figure 4-11 Zoomed in inductor currents at phase-off moment by non-IDC
Figure 4-12 Zoomed in inductor currents at phase-off moment by IDC
Figure 4-13 Zoomed in inductor currents at phase-on moment by non-IDC
Figure 4-14 Zoomed in inductor currents at phase-on moment by IDC
Figure 4-15 Input current change by IDC and non-IDC at phase-off moment
Figure 4-16 Input current change by IDC and non-IDC at phase-on moment
Figure 4-17 Duty change by four different control methods
Figure 4-18 Input current by different duty control methods
Figure 4-19 Zoomed in input current by different duty control methods
Figure 5-1 Experimental test bed
Figure 5-2 Block diagram of Configuration of the experimental setup
Figure 5-3 Trapezoidal solar irradiation
Figure 5-4 Output voltage of the PV array
Figure 5-5 Output current of the PV array
Figure 5-6 Maximum output power of the PV array
Figure 5-7 PWM signals of PV IBC
Figure 5-8 Input current and inductor current of PV CBC
Figure 5-9 Input current and inductor currents of PV IBC
Figure 5-10 Efficiency graph of 1ch-IBC(CBC), 2ch-IBC and IBC with phase shedding technique
Figure 5-11 Daily average irradiation data of February in 2013 in Queensland University in Australia
Figure 5-12 Average daily efficiency improvement of 2ch-IBC comparison to 1ch-IBC(CBC)
Figure 5-13 Input current and inductor currents at phase shedding operation by only hysteresis control……………………………………………………………………………… 88

Figure 5-14 Zoomed input current and inductor currents at turning-on operation with only hysteresis control……………………………………………………………………………… 89

Figure 5-15 Zoomed input current and inductor currents at turning-off operation with only hysteresis control……………………………………………………………………………… 89

Figure 5-16 Input current and inductor currents at phase shedding operation by hysteresis control and IDC……………………………………………………………………………… 91

Figure 5-17 Input current and inductor currents at turning-on operation with hysteresis control and IDC……………………………………………………………………………… 91

Figure 5-18 Zoomed input current and inductor currents at turning-on operation with hysteresis control and IDC……………………………………………………………………………… 92

Figure 5-19 Input current and inductor currents at turning-off operation with hysteresis control and IDC……………………………………………………………………………… 92

Figure 5-20 Zoomed input current and inductor currents at turning-off operation with hysteresis control and IDC……………………………………………………………………………… 93
List of tables

Table 2-1 Comparison the types of power conditioning system....................... 18
Table 2-2 Resistance conversion ratios of non-isolated converters..................... 26
Table 2-3 A stability of converters on PV application........................................ 34
Table 3-1 Parameters of PV module and PV array........................................... 50
Table 3-2 Parameters of CBC and IBC.......................................................... 53
Table 3-3 Voltage and current ripple rates of CBC and IBC.............................. 58
Table 4-1 Comparison overshoot or dip in input currents by IDC and non-IDC during phase shedding moment by simulation test................................................. 74
Table 4-2 Comparison input currents overshoot or dip by for different duty control method in IDC................................................................. 76
Table 5-1 Parameters of power switches and diodes........................................ 79
Table 5-2 Efficiencies of 1ch-CBC and 2ch-IBC............................................. 84
Table 5-3 Overshoot or dip in input currents for two types of controls during phase shedding moment................................................................. 93
# List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternative Current</td>
</tr>
<tr>
<td>CBC</td>
<td>Conventional Boost Converter</td>
</tr>
<tr>
<td>CCM</td>
<td>Continuous Conduction Mode</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DCM</td>
<td>Discontinuous Conduction Mode</td>
</tr>
<tr>
<td>IBC</td>
<td>Interleaved Boost Converter</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>P&amp;O</td>
<td>Perturb and Observe</td>
</tr>
<tr>
<td>PFC</td>
<td>Power Factor Correction</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse-Width Modulation</td>
</tr>
</tbody>
</table>
## List of units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Ampere (amp)</td>
</tr>
<tr>
<td>AM</td>
<td>Air-mass</td>
</tr>
<tr>
<td>° C</td>
<td>Celsius</td>
</tr>
<tr>
<td>J</td>
<td>Joule</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>kW</td>
<td>Kilo-Watt</td>
</tr>
<tr>
<td>ms</td>
<td>Milli-second</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
</tr>
<tr>
<td>s</td>
<td>Second</td>
</tr>
<tr>
<td>μH</td>
<td>Micro-henry</td>
</tr>
<tr>
<td>μF</td>
<td>Micro-farad</td>
</tr>
<tr>
<td>V</td>
<td>Voltage</td>
</tr>
<tr>
<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>W/m²</td>
<td>Watt per square metre</td>
</tr>
</tbody>
</table>
# List of variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Ideality factor</td>
</tr>
<tr>
<td>$AC$</td>
<td>Alternative current</td>
</tr>
<tr>
<td>$C_1$ and $C_2$</td>
<td>Capacitor</td>
</tr>
<tr>
<td>$C_o$</td>
<td>Output capacitor of the DC/DC converter</td>
</tr>
<tr>
<td>$f$</td>
<td>Fundamental frequency</td>
</tr>
<tr>
<td>$f_{sw}$</td>
<td>Switching frequency</td>
</tr>
<tr>
<td>$I_{C1}$ and $I_{C2}$</td>
<td>Capacitor current</td>
</tr>
<tr>
<td>$I_D$</td>
<td>Diode current of the DC/DC converter</td>
</tr>
<tr>
<td>$I_L$</td>
<td>Light generated current</td>
</tr>
<tr>
<td>$I_{mpp}$</td>
<td>Maximum power point current of the PV array</td>
</tr>
<tr>
<td>$I_o$</td>
<td>Dark saturation current</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>Output current of the DC/DC converter</td>
</tr>
<tr>
<td>$I_{oc}$</td>
<td>Open-circuit current</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>Photo current</td>
</tr>
<tr>
<td>$I_{L1}$ and $I_{L2}$</td>
<td>Inductor current</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann's constant</td>
</tr>
<tr>
<td>$q$</td>
<td>Absolute value of electron</td>
</tr>
<tr>
<td>$R_{in}$</td>
<td>Input resistance</td>
</tr>
<tr>
<td>$R_L$, $R_o$</td>
<td>Load resistance</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Series resistance</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>Shunt resistance</td>
</tr>
<tr>
<td>$T$</td>
<td>Absolute temperature (K)</td>
</tr>
<tr>
<td>$V_D$</td>
<td>Diode voltage</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>Input DC voltage of the DC/DC converter</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>Output DC voltage of the DC/DC converter</td>
</tr>
<tr>
<td>$V_{L1}$ and $V_{L2}$</td>
<td>Inductor voltage</td>
</tr>
<tr>
<td>$V_{DS}$</td>
<td>Drain-Source voltage</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>Open-circuit voltage of the PV array</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>Output DC voltage of the DC/DC converter</td>
</tr>
<tr>
<td>$V_{py}$</td>
<td>PV array voltage</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

This chapter presents the motivation and objectives of this thesis and the background information about photovoltaic fundamentals. The background information about photovoltaic and maximum power point tracking (MPPT) is dealt with in Section 1.1. In Section 1.2 and Section 1.3 give the motivation and the objectives of this thesis. Lastly, the thesis outline is presented in Section 1.4.

1.1 Background

1.1.1 Photovoltaic fundamentals

Fig 1.1 : Electrical equivalent model – Solar Cell[1]
A solar cell which is the basic unit of PV module transforms the sun ray into electric power. A solar cell has the ideal diode and constant current source which determines $I_{ph}$ value. However, since it is not possible to design the ideal diode in reality, series resistance $R_s$ and parallel resistance $R_{sh}$ which indicate contact resistance and sheet resistance of a surface layer should be considered. Some of the light is reflected by the surface of solar cells. Absorbed light becomes a source of photovoltaic effect and the number of photon is exponentially reduced. Figure 1.1 shows the equivalent circuit of a solar cell. In this circuit, $I_{ph}$ is a photoelectric current generated by the absorbed light. Parallel $R_{sh}$ and $R_s$ indicate shunt resistance and series resistance. Because the relation of voltage and current from the solar cells has nonlinear characteristics, the modelling of solar cell should be considered to perform and show more accurate solar cell characteristics [1-3].

1.1.2 Modelling of a solar cell

To design and analyse solar cells, they are expressed mathematically as equations as follows:

The equation of open-circuit voltage of a solar cell is given by (1.1).

$$V = \frac{AKT}{q} \ln \left[ \frac{I_L}{I_o} + 1 \right]$$

(1.1)

where:

- $A =$ Ideality factor
- $k =$ Boltzmann's constant
- $q =$ Absolute value of electron
- \( I_L = \) Light generated current
- \( I_o = \) Dark saturation current
- \( T = \) Absolute temperature (K).

In order to obtain high voltage or current from PV modules, numerous solar cells are connected in series and/or parallel. PV arrays are designed by PV modules in the same way as designing PV modules.

The equations to acquire P-V characteristics of the solar cell are given by [4-5].

\[
I = I_{ph} - I_D - I_{sh} = I_{ph} - I_D \frac{V_D}{R_{sh}} \quad (1.2)
\]

\[
V_D = V + IR_s \quad (1.3)
\]

\[
I = I_{ph} - \left( e^{\frac{q(V+IR_s)}{AkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (1.4)
\]

- \( I_{ph} = \) The photo current
- \( R_s = \) Series resistance
- \( R_{sh} = \) Shunt resistance

Figure 1.2 shows V-I curve and P-V curve of PV arrays under different irradiation conditions. According to the graphs, the output characteristics of PV arrays are non-linear and each curve based on different irradiations has each different maximum power point. Due to the fact that the characteristics of PV arrays under different irradiation conditions are nonlinearly changed, in order to utilize the PV arrays efficiently,
maximum power point tracking to get maximum power from the PV arrays must be considered to operate [6].

![Graph of VI and PV curves of PV array at varying irradiation](image)

**Fig 1.2: VI and PV curves of PV array at varying irradiation**

**(a) VI curve (b) PV curve**

### 1.1.3 Maximum power point tracking (MPPT)

Due to ever changing irradiation conditions and temperature, a maximum voltage of PV array also changes. In addition, since the condition of the PV system load affects the power generation from the PV array, it is not easy to extract the maximum power from the PV array. Therefore, in order to utilize the PV array effectively, the control method to operate PV array at the maximum power point is required [7-9].
Maximum power point tracking (MPPT) technique is used to get the maximum power from PV arrays by controlling the change of current-voltage characteristics. In Figure 1.2, if the output voltage of PV array increases, the current of PV array gradually decreases. Current-voltage curve is changed by an irradiation condition. To get maximum power from PV array, operating voltage or current should be carefully controlled. However, the operating of maximum power point of PV array is not always located in the same point under rapid changing irradiation and temperature condition so that MPPT is needed to have characteristics as follows [8-9]:

- Under environmental condition change, PV system should be operated with maximum power point and supply high conversion efficiency.

- Wide range of characteristics change of PV array under environmental condition should be considered.

Among MPPT techniques, the P&O technique is the most widely used because this method has a simple feedback structure and a small number of parameters to measure. As the P&O method periodically increases or decreases the PV voltage, the maximum power point is continuously tracked by comparing previous power from the PV array and current power from PV array. Figure 1.3 shows the flowchart of P&O method [7-9]. During the next period, if the power increases, perturbation moves to the same direction. Otherwise, the direction of perturbation is on the opposite side. This means the voltage of PV array is perturbed in a whole period. Therefore, at maximum power point, P&O algorithm cannot hold the operating point at the maximum power point and shows self-oscillation, which allows the power loss from the PV array. The decrease of the perturbation step can be the way to minimize the power loss. However, under a low
irradiation condition, the characteristics of the PV array are changed and the maximum power point tracking speed could be slow due to rapid changes in the environment.

\[
\Delta V(k+1) = V(k) - \text{Step} \\
\Delta V(k+1) = V(k) + \text{Step} \\
\text{Update } V(k-1) = V(k), I(k-1) = I(k) \\
\text{Return}
\]

\[
P(k) = V(k) \cdot I(k)
\]

**Fig 1.3: Perturb & Observation MPPT algorithm**

In order to make up for the weakness of the P&O method, an incremental conductance technique is proposed. This method is based on the fact that when differential voltage and current value are zero at maximum power point. According to the graph, a differential value is bigger than zero on the left side of maximum power point. On the other hand, the differential value is smaller than zero on the right side of maximum power point. So the equations can be addressed as follows.

\[
P_{\text{max}} = V \cdot I \quad (1.5)
\]

\[
dP/dV = I + V \cdot dI/dV = 0 \quad (1.6)
\]
The flow chart of the incremental conductance method [10-15] is shown in figure 1.4. In this figure, $V(k)$ is the current detection voltage and $I(k)$ is the current detection current, $V(k-1)$ and $I(k-1)$ are the old value of the memory. The method compares the old value to the new one. In this method, the maximum power point is traced by determining the voltage and current differential. If the voltage differential is zero, the maximum power point is traced by determining the current differential to zero or bigger than zero or smaller than zero. If the voltage differential is not zero, the maximum power point is traced by the equation (1.9) [11-13]. If the voltage and current differential are the same, since it means that the operating point reaches on the maximum power point. There are no changes to the voltage and the current differential and the operating point stays at the same as before.

\[ \frac{dI}{dV} > -\frac{I}{V} \]  

(1.7)

**Fig 1.4:** Incremental conductance MPPT algorithm
1.2 Motivation

Recently due to global warming, the energy exhaustion problem and rising energy demand, the research for renewable energies such as fuel cells, wind energy and photovoltaic energy have been progressed. Among these renewable energies, especially photovoltaic energy gets the limelight for a couple of advantages as it is clean, rich, pollution-free and has a low limit for location in recent year. PV market has significantly grown up in a few decades. After hydro and wind power, PV is the third most important renewable energy source in terms of it being a globally installed capacity. In the past, the PV industry only focused on the small size of the system. However, due to increasing demand, advanced technology and interests on green industries, PV industry has been developed in various ways. Figure 1.5 shows global PV industry data. According to this, 38.4GW PV system was widely installed in the world in 2013. After having reached close to 37 GW in 2013, solar PV markets reached the 40 GW mark for the first time in 2014. Almost 11GW of 40GW grid PV systems were installed in Europe. Germany has the title of the top market in Europe with 3.3 GW. China formally installed 10.6 GW of PV systems in 2014, including 2 GW of distributed installation. This was also the similar case in Japan: 9.7 GW of PV systems were installed in 2014 [16]. Since the PV markets show moderate and huge growth, the methods to improve the efficiency of PV system get limelight and have been researched.
Fig 1.5. Global PV installation trend from 2000 to 2014 [16]
1.3 Objective

1.3.1 Problem formulation

As described above, the amount of PV installations have been increased in the world. As the increasing PV power density, an increasing the number of phases in converters is considered as one of the methods to improve the efficiency. However, the efficiency improvement is limited at only high power condition. Since multiphase converters at light load condition show low efficiency than conventional one, the converters need additional control to reduce the efficiency loss at a light load condition. Furthermore, the method to prevent a current overshoot by rapid phase shedding moment should be considered.

1.3.2 Objectives

The main objective of this thesis is to design PV interleaved boost converter and demonstrate its efficiency improvement compared with PV conventional boost converter (CBC). Furthermore, a new phase shedding scheme for PV Interleaved boost converter (IBC) to prevent the efficiency loss and current overshoot is proposed and demonstrated by the experimental tests. Detailed objectives are given as follows:

- To validate the efficiency improvement of PV IBC over CBC at a high power condition, the converters are designed, analysed and compared by simulation results.

- As a solution of the efficiency loss of PV IBC at a light condition, a phase shedding technique for PV IBC is proposed and simulated.
The solution against overshoot current by rapid phase shedding operation is proposed by incremental duty control and the improvement is verified by simulation and experimental tests.

1.4 List of publication

The research work which is reported in this thesis shows a result in an international conference paper as follow:


1.5 Thesis outline

Chapter 1 introduces a background of photovoltaic (PV) and maximum power point tracking (MPPT) briefly, and also gives the main objectives of the thesis.

Chapter 2 presents PV system types, configuration and non-isolated converters for the PV system. Furthermore, non-isolated converters in PV system are compared and analysed based on the cost, design purpose and efficiency.

Chapter 3 shows a design and analysis of interleaved boost converter and comparison in terms of efficiency, ripple and transient response between conventional boost converter and interleaved boost converter by the simulation and experiment.

Chapter 4 shows a conventional phase shedding technique and a new phase shedding technique to overcome the current fluctuation problem from rapid phase shedding operation. Also, an additional control technique is proposed for PV interleaved boost converter.
Chapter 5 shows the analysis of obtained results. By analysing the main waveforms of PV interleaved boost converter with the proposed phase shedding method and applying daily irradiation data on measurement results, improvements of PV interleaved boost converter are demonstrated.

Chapter 6 summarises the thesis and presents the conclusion of this study.
Chapter 2

An overview of DC-DC converters on a PV system

This chapter presents an overview of DC-DC converters on PV system. In Section 2.1, the configuration of a PV system and types of power conditioning system (PCS) are presented. A review of non-isolated PV converters is given in Section 2.2. The MPPT operational region by non-isolated converters is dealt with in Section 2.3. In Section 2.4, an overall comparison of non-isolated converters on PV system is given.

2.1 The configuration of PV system

A PV system is designed specifically for its different purpose, surrounding and type of system load. Figure 2.1 shows a typical PV system which consists of a PV array, DC-DC converter and DC-AC inverter [17-19].
2.1.1 PV array

A PV array consists of PV modules connected in series and in parallel. The PV modules which are the energy source in the PV system are connected in series and/or in parallel. The generated power by the photovoltaic effect from the PV array is transferred to power conditioning stage.

2.1.2 Power conditioning system

Since the voltage and current of PV array are not stable for changeable irradiation, temperature and in various environmental conditions, DC-DC converter is operated by MPPT which maintains the maximum power from PV array. By controlling the input voltage of the converter, the maximum power from PV array can be stably transferred to the DC-AC inverter. Increased or decreased DC voltage from the converter is transformed to AC voltage with a specific frequency by DC-AC inverter [17-20].

The type of PCS is determined by topologies of DC-DC converter and DC-AC inverter and its purposes on PV system. There are three typical PCSs: a high frequency link, high frequency transformer and non-isolated.
2.1.2.1  **Low frequency transformer type**

Figure 2.2 shows a low frequency transformer type of a PV system. The system consists of a PV array, DC-AC inverter and low frequency transformer. The DC voltage from PV array in the system is transformed to the AC voltage by the inverter.

![Diagram of Low Frequency Transformer Type PV System](image)

**Fig 2.2: Low frequency transformer type PV system**

The simple structure of a low frequency transformer type is advantageous and the DC harmonics are diminished, which makes it useful to the PV system. However, the low efficiency by the low frequency transformer at the output stage is not a negligible disadvantage of the system. Furthermore, because of the size and weight of the low frequency transformer, PV system results in bulky and high cost [21].

2.1.2.2  **High frequency link type**

Figure 2.3 shows a high frequency link type PV system. Full-bridge converter topology is usually selected for the high frequency link system. The PV DC output is converted to a high frequency AC at a primary winding and rectified by bridge formed diodes at secondary winding. The transformed voltage and current by the full-bridge converter are controlled by the inverter and transferred to the grid. This system has advantages, which includes high stability, size and weight reduction by using high frequency transformer
[16]. However, the increase of the number of semiconductors and complex structure are disadvantages of this system.

Fig 2.3: High frequency transformer type PV system

2.1.2.3 Non-isolated type

Non-isolated type which is also known as the transformerless type is a grid-connected PV system with no transformer. This system has PV array, DC-DC non-isolation converter, DC-AC inverter and a filter. Since this type has no transformer, it is high efficient and the reduction of the system volume can be obtained. Moreover, compared with the high frequency transformer type, there are less number of switches needed than that in a non-isolated converter type which makes it more cost efficient for designing the system.

Fig 2.4: Non-isolated type PV system
Table 2.1 shows pros and cons of three typical PCS for PV system [20-22]. As shown in the table, a low frequency transformer type is simpler to design. Furthermore, the ease of a system control and stability are additional merits of the low frequency transformer type. However, the large volume, weight and the low efficiency using the transformer are disadvantages of the system. On the other hand, since high frequency link type is based on the high frequency transformer, the system is admirable in aspects of a weight and efficiency. But this system requires a large number of semiconductors, complex circuit and control algorithm. Non-isolated type has an advantage in terms of the size, weight and efficiency of the system but with no use of transformer in the system, it has a risk of an injected dc current and huge ground leakage current due to a lack of isolation [18].
Table 2.1: Comparison the types of PCS [23-25]

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Non-isolated type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency transformer type</td>
<td>* High efficiency, miniaturization and weight lightning of the system by no use of transformer.</td>
</tr>
<tr>
<td>High frequency link type</td>
<td>* Simple structure of circuit and control.</td>
</tr>
<tr>
<td></td>
<td>* Secure the stability by the isolation of transformer.</td>
</tr>
<tr>
<td></td>
<td>* Low cost for the system.</td>
</tr>
<tr>
<td></td>
<td>* Secure the stability by the isolation of transformer.</td>
</tr>
<tr>
<td></td>
<td>* Low cost for the system by a reduction of a transformer volume and weight.</td>
</tr>
<tr>
<td></td>
<td>* High efficiency, miniaturization and weight lightning of the system by no use of transformer.</td>
</tr>
<tr>
<td></td>
<td>* Simple circuit structure by small number of semiconductors.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantage</th>
<th>Non-isolated type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight / Size</td>
<td>X</td>
</tr>
<tr>
<td>Cost</td>
<td>O</td>
</tr>
<tr>
<td>Efficiency</td>
<td>X</td>
</tr>
<tr>
<td>Stability</td>
<td>O</td>
</tr>
<tr>
<td>Complexity of a circuit</td>
<td>O</td>
</tr>
<tr>
<td>Ease of control</td>
<td>O</td>
</tr>
</tbody>
</table>

O : Good, Δ : Middle, X : Bad
2.2 Non-isolating converters on PV system

The Non-isolating converters do not have galvanic isolation between the input and output. There are typical non-isolated converters which are commonly used for PV system such as buck, boost, buck-boost converter and Cuk converter. The buck converter is utilized to step down the input voltage and the boost converter is utilized to step up. The buck-boost converter and Cuk converter have a function of both stepping up and down voltage level conversion. The detail of non-isolated converters is described in the following section.

2.2.1 A DC-DC Buck converter

Figure 2.5 and 2.6 show a circuit diagram and main waveforms of the buck converter introduced in [26-27]. The buck converter consists of inductor, power switch, capacitor, and flywheel diode. It is called the buck converter since the output voltage through the inductor opposes or bucks supply voltage. The output voltage of the buck converter should be the same or lower than the input voltage. The switching operation relies on the output voltage by varying a duty cycle with fixed operating frequency. When the switch of the buck converter turns on, the current from input source flows through the switch and the inductor, then capacitor and to the load. When the switch turns off,
energy stored in the inductor transfers current to capacitor and the load through diode. Since the voltage across the load is controlled and limited by the duty, the output voltage level should be the same or less than input voltage. The duty cycle is determined by

\[ D = \frac{V_{out}}{V_{in}} = \frac{T_{ON}}{T} \]  \hspace{1cm} (2.1)

where \( T_{ON} \) is the time for the switch and \( T \) is the switching period.

The output voltage of the buck converter is the same as the input voltage or stepped down by duty ratio.

**Fig 2.6:** Main waveforms of a DC-DC Buck converter
2.2.2 A DC-DC Boost converter

Figure 2.7 and 2.8 show a circuit diagram and main waveforms of boost converter introduced in [19, 28]. The structure of boost converter is similar as the buck converter. However the converter has components arranged in a different way. It is called the boost converter since the output voltage through the inductor boost the input voltage. The output voltage of the boost converter is always higher than input voltage therefore the circuit is suitable for the system requires higher output voltage than input voltage.

![Circuit Diagram of DC-DC Boost Converter](image)

**Fig 2.7: A circuit diagram of a DC-DC Boost converter**

When the switch of the boost converter is turned on, the current does not flow through the diode and the load current however, the charged energy from the capacitor C is transferred to the load with $V_{in} + V_L$. When the switch is turned off, due to the back-emf in the inductor, the inductor current suddenly dropped. On the other hand, the inductor voltage is increased in an instant. This results stepped-up voltage ($V_{in} + V_L$). The input current flows through the inductor, the diode, and the load R and charging the capacitor again. Since the increased voltage by the back-EMF in the inductor is transferred to the output, the output voltage can be higher than input.

The voltage boosting ratio is expressed by
The boost converter requires higher capacitance than the buck converter since the entire load current is transferred from the capacitor when the switch is turned on.

\[
\frac{V_{out}}{V_{in}} = \frac{1}{1-D}
\]  \hspace{1cm} (2.2)

Figure 2.8 Main waveforms of a DC-DC Boost converter

2.2.3 A DC-DC Buck-boost converter

Figure 2.9 and 2.10 show a circuit diagram and main waveforms of buck-boost converter introduced in [29-30]. The components in buck-boost converter are the same as the buck and boost converter. However, the components of the buck-boost converter
are arranged in different method to have a step-up and step-down function with polarity inversion. When the switch of the buck-boost converter turns on, two current paths between the inductor and input source and between the capacitor and the load are created. Due to the revered biased diode, no current is transferred through the diode to the load. At this moment, the load current is supplied from the capacitor. When the switch turns off, the stored energy in the inductor flows into the capacitor and load. The capacitor is recharged during this period. The voltage ratio between input and output is determined by

\[
\frac{V_{out}}{V_{in}} = -D = \frac{T_{ON}}{T_{OFF}}
\]  

(2.3)

**Fig 2.10: Main waveforms of a DC-DC buck-boost converter**

The buck-boost converter has duty ratio between 0 and 1. From 0 to 0.5 duty ratio, the buck-boost converter performs like the buck converter. From 0.5 to 1 duty ratio, the converter acts like the boost converter with negative polarity. Thus the output voltage
can be varied between lower and higher than the input voltage. When the duty ratio is 0.5, the output voltage is the same as the input with opposite polarity.

### 2.2.4 A DC-DC Cu´k converter

Figure 2.11 and 2.12 show a circuit diagram and main waveforms of Cu´k converter introduced in [29,31]. The inductor in buck, boost and buck-boost converters is a pivotal role to transfer the energy to output. However, the energy is transferred through the capacitor in the Cu´k converter. Therefore the analysis should be based on the current through the capacitor. The output polarity is inverted like in the buck-boost converter.

![Fig 2.11: A circuit diagram of a DC-DC Cu’k converter](image)

The Cu´k converter is derived from the cascading of the buck and boost converter. The buck, boost and buck-boost converter transfers energy between input and output by utilizing the inductor and analysis based on a voltage balance of the inductor. However, the Cu´k converter uses energy transfer using the capacitor and analysis is found on a current balance of the capacitor. When the switch turns off, as the inductor $L_1$ is connected to the capacitor $C_1$, the capacitor is being charged by the input source energy through the inductor. During this period, the current of $C_1$ is $I_{in}$. When the switch is on, the charged energy in the capacitor flows to the load through the inductor $L_2$. During
this period, the current of $C_1$ is $I_{out}$. The voltage ratio between input and output is expressed by

$$\frac{V_{out}}{V_{in}} = \frac{-D}{1-D} = \frac{-T_{ON}}{T_{OFF}}$$  \hspace{1cm} (2.4)

---

**Fig 2.12**: Main waveforms of a DC-DC $Cu¨k$ converter
2.3 The use of MPPT with non-isolated converters

The maximum power from PV arrays relies on the solar irradiation and the operating point of the converters in PV system. MPPT maximizes the system efficiency and minimizes the return of PV installation investment. However, every non-isolated converter cannot utilize entire range of VI curve of PV modules. Moreover, they have different VI characteristics by the different resistance conversion ratios. The simplest way to measure the characteristic curve of PV module is to use of a variable resistor. Through a lot of resistor measure methods, the resistance can be measured from full load condition (short circuit) to open circuit. The voltage-current (VI) curve is obtained by taking measure of the voltage and current by steps.

Table 2.2: Resistance conversion ratios of non-isolated converters [32-34].

<table>
<thead>
<tr>
<th>Converter</th>
<th>Resistance conversion ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck converter</td>
<td>$\frac{R_{in}}{R_{load}} = \frac{1}{D^2}$</td>
</tr>
<tr>
<td>Boost converter</td>
<td>$\frac{R_{in}}{R_{load}} = (1 - D)^2$</td>
</tr>
<tr>
<td>Buck-boost converter</td>
<td>$\frac{R_{in}}{R_{load}} = \frac{(1 - D)^2}{D^2}$</td>
</tr>
<tr>
<td>Cu’k converter</td>
<td></td>
</tr>
</tbody>
</table>

2.3.1 Buck converter

Figure 2.13 and 2.14 illustrate a resistance conversion ratio of the buck converter versus the duty cycle and VI curve of the PV modules based on the buck converter introduced in [32-37]. In the buck converter, the input voltage is higher than the output voltage, so the converter is suitable for the system connected high voltages of PV modules with low voltage loads. When assuming that PV resistance $R_{in}$ is same as the input resistance of
this converter, $R_{in}$ value is determined by the duty cycle. According to resistance conversion ratios in table 2.1, since the duty cycle varies from 0 to 1, the input resistance of the buck converter $R_{in}$ cannot be smaller than the load resistance $R_{load}$, which means that the buck converter cannot obtain values nearby the short circuit current $I_{sc}$ of the PV modules.

**Fig 2.13:** A resistance conversion ratio versus duty cycle in buck converter

**Fig 2.14:** Operation region and non-operation region in PV buck converter
2.3.2 **Boost converter**

Figure 2.15 and 2.16 illustrate the conversion ratio of the resistance of boost converter and operation region and non-operation region in PV boost converter introduced in [32-37]. In boost converter (otherwise known as step-up converter), the output voltage value is higher than the input voltage value, thus this converter is suitable for the system connected low voltages of PV module with high load or battery voltages. As described of the resistance conversion ratio of the buck converter before, since the duty cycle is varies from 0 to 1, the input resistance of the boost converter $R_{in}$ cannot be smaller than the load resistance $R_{load}$, which means that the boost converter cannot obtain values nearby the open-circuit voltage $V_{oc}$ of the PV modules. As a result, MPP in PV boost converter is varied only in restricted operation region.

![Fig 2.15: A resistance conversion ratio versus duty cycle in boost converter](image)

2.3.3 Buck-boost converter

Figure 2.17 and 2.18 illustrate the conversion ratio of the resistance of buck-boost converter and operation region and non-operation region in PV buck-boost converter introduced in [32-37]. In buck–boost, since the magnitude of output voltage can be lower or higher than the input voltage, the buck-boost converter is suitable to cover wide range of operating voltage. When the duty increases, the input resistance $R_{in}$ falls down. Therefore, the operating voltage point of PV module is driven to the left region of the I–V curve. Moreover, since if decreasing the duty cycle, $R_{in}$ is increased, the operating voltage point of PV module is driven to the right region of the I–V curve. As a result, buck-boost converter has no non-operational region, so that buck-boost converter is able to achieve entire operating value in the range between short-circuit current $I_{sc}$ and open-circuit voltage $V_{oc}$. Thus, it can be said that buck–boost converter is able to show the strength in MPPT in variable irradiance, load and temperature conditions. However, since the input current of buck-boost converter is discontinuous, the current transition from zero to inductor current presents at every switching cycle.
The discontinuous conduction contains a lot of harmonic components, which could produce high ripple and critical noise drawbacks to input power stage.

Fig 2.17: A resistance conversion ratio versus duty cycle in buck-boost converter

Fig 2.18: Operation region and non-operation region in PV buck-boost converter
2.3.4 Cu´k converter

Cu´k converter has the same functions as that of a buck–boost converter. Even though Cu´k converter is able to step up or down, it has reverse polarity compared to the input voltage. PV Cu´k converter has the same resistance conversion ratio and the operation region as buck–boost converter. Therefore, the Cu´k converter is able to achieve the value between short-circuit current $I_{sc}$ and open-circuit voltage $V_{oc}$. The major difference of Cu´k converter compared with buck-boost converter is that it has an additional inductor and capacitor. Inductor $L_1$ plays a role as a filter which prevents DC input harmonics and capacitor $C_1$ plays a role of the energy transfer (the role of inductor in buck-boost converter). Unlike buck-boost converter, the input and output current of Cu´k converter is operated in continuous mode. Thus tracking operating point in Cu´k converter based on I–V characteristic of PV module is more reliable. Moreover, the converter has less noise problem than buck-boost converter [38]. However, the Cu´k converter needs a lot of passive components (additional inductor and capacitor). Also, it has high electrical stress problem on the switches, capacitor $C_1$ and diodes.

2.4A suitability of non-isolated converters for PV system

To sum up, based on analysis described four non-isolated converters, as the converters can be categorized and compared by MPPT use, efficiency and cost, the best converter for a PV system can be chosen.

Buck and boost converter have different operational objects and unique characteristics. When comparing these two topologies in terms of components characteristics, cost and dynamic response, the boost converter has more advantages and suitable for PV system than buck converter due to the followed reasons [39]:
• Buck converter requires pricey capacitor than boost converter to prevent that the input current of PV module is operated in discontinuous conduction mode.

• Boost converter requires lower the current rating for MOSFETs and driver than the buck converter. Furthermore, a high-side driver of MOSFET is required in buck converter. As a result, boost converter which has a low-side driver of MOSFET is less complicated and costly than the buck converter.

• One of the techniques to extract maximum power from PV cells is to connect the PV cells in parallel. Since the lowest efficient panel connected in parallel, does not affect the current of the entire system, the method could have an advantage over the series connection. As a result, since the parallel connection of PV cell is more efficient than the series connection and the output power stage of PV system requires higher voltage than general voltage of PV cells, the boost converter is more suitable than the buck converter for PV application with low voltage. [40-42].

From a point of view of the MPPT use, buck-boost and Cu´k have the best converter configuration to utilize entire range of operating point in P-V curve compared with other topologies (buck and boost converter). The buck-boost and Cu´k converter topology can allow MPP tracking between short-circuit current $I_{sc}$ and open-circuit voltage $V_{oc}$ regardless of the load, temperature and irradiation condition. The Cu´k converter shows more reliable MPPT and less noise problems than buck-boost converter because the input and output current of Cu´k converter is operated in continuous conduction mode (CCM).

While the boost and Cu´k converter has no need any input capacitor for continuous input current, the buck and buck-boost converter require a huge input capacitor to
control the discontinuous input current from PV array and reduce the current ripple [44].

Figure 2.19 indicates efficiencies of four different DC–DC converters: buck, boost, buck–boost, and Cu´k converter [45]. Even though buck-boost and Cu´k converters stand out for more reliable MPPT than others, the efficiency of these two converters are remarkably lower than buck and boost converter at high power condition.

To summarize it all up, firstly, buck-boost and Cu´k converter have the best configuration to utilize the wide range of MPPT. Secondly efficiencies of those converters are remarkably lower than buck and boost converter. Thirdly, Buck and buck-boost converter need additional huge capacitor to reduce the ripple from discontinuous input current and Cu´k converter needs more passive components than other converters. Lastly, the configuration of buck converter is not suitable to extract power from PV module with low voltage.

Table 2.2 illustrates the stability of the converters on PV application based on MPPT operation range, efficiency, cost and stability. According to the analysis and comparison with the converters, it can be noticed that the best converter for PV application among the four converters is the boost converter.
Fig 2.19: Efficiency curves of Buck, Boost, Buck-Boost and Cuk converters connected with PV module [45]

Table 2.3: A stability of converters on PV application

<table>
<thead>
<tr>
<th></th>
<th>Buck</th>
<th>Boost</th>
<th>Buck-Boost</th>
<th>Cuk</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPPT Operation Range</td>
<td>Δ</td>
<td>Δ</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Efficiency</td>
<td>O</td>
<td>O</td>
<td>X</td>
<td>Δ</td>
</tr>
<tr>
<td>Cost</td>
<td>Δ</td>
<td>O</td>
<td>Δ</td>
<td>X</td>
</tr>
<tr>
<td>Suitability</td>
<td>Δ</td>
<td>O</td>
<td>Δ</td>
<td>Δ</td>
</tr>
</tbody>
</table>

O : Good, Δ : Middle, X : Bad
Chapter 3

A PV interleaved boost converter

This chapter introduces the IBC consisting of two phases. Operational characteristics of the IBC are discussed in Section 3.1. In Section 3.2, the operations of IBC in different two modes (CCM and DCM) are analyzed. Simulation results through comparison performances of CBC and IBC are presented in Section 3.3 to demonstrate advantages of IBC for PV system.

3.1. Introduction

An IBC is mainly utilized in systems that have renewable energy sources as input sources. By controlling two phases from two inductors in the IBC, higher efficiency can be obtained compared to CBC. When turning $SW_1$ on, $SW_2$ is turned off and the input current flows to only the inductor $I_{L1}$. After this period, $SW_2$ is turned on, $SW_1$ is turned off and the input current flows to the inductor $I_{L2}$. Two switches operate turning on and off based on the duty cycle. In the IBC, the PWM (Pulse-Width Modulation) signals for
the two switches are shifted by 180 degrees. In figure 3.1, it can be noticed that the input current of the IBC is the sum of each inductor current.

Fig. 3.1: Circuit diagram of IBC

3.2. Interleaved boost converter operation in CCM and DCM

The IBC can be operated in two different modes: CCM or DCM. In the DCM, by turning on the switch after the inductor current is diminished to zero, a diode reverse recovery losses and switching power losses can be removed, which results IBC is able to reduce a size inductor. However, the input current of the IBC is not linearly changed and complicated to analyse. Furthermore, as the power rating of the system is escalated, the number phase of the IBC can be increased, which results that it could be more complex to analyse the converter [46-49].
Fig. 3.2: Equivalent circuits in continuous current mode
Fig. 3.3: Current and voltage waveforms of IBC in continuous current mode
1) Mode 1 (SW1:OFF, SW2:ON, IC>0)

In Mode 1, inductor voltage $V_{L2}$ is determined by

$$V_{L2} = L_2 \frac{di_{L2}}{dt}. \quad (3.1)$$

Since inductor voltage $V_{L2}$ is the same as input voltage $V_{in}$, inductor current $i_{L2}$ can be expressed by

$$\frac{di_{L2}}{dt} = \frac{V_{L2}}{L_2} = \frac{V_{in}}{L_2}. \quad (3.2)$$

On the contrast, the current $i_{L1}$ across the inductor $L_1$ flows to the load through diode $D_1$. Inductor voltage $V_{L1}$ can be expressed by

$$V_{L1} = V_{in} - V_{out}. \quad (3.3)$$
And inductor current $i_{L1}$ can be expressed by

$$\frac{di_{L1}}{dt} = \frac{V_{L1}}{L_1} = \frac{V_{in} - V_{out}}{L_1}. \quad (3.4)$$

2) Mode 2 ($SW_1$:OFF, $SW_2$:ON, $I_C$<0)

In Mode 2, inductor currents ($i_{L1}$, $i_{L2}$) have the same interaction equation as one in Mode 1 but the current ($I_C$) which flows to output capacitor has negative value. At this time, charged current in capacitor in Mode 1 is discharged and flows to the load which results average output current ($I_{out}$) can be steadily maintained as positive value.

$$i_C = i_{D1} - I_{out} \quad (3.5)$$

In Mode 1 and 2, during the $SW_2$ is ON, inductor current ($i_{L2}$) reaches minimum value ($I_{min}$) at t=0 and reaches maximum value ($I_{max}$) at t=DT.

$$i_{L2}(t) = \frac{1}{L_2} \int_0^t V_{in} dt + I_{min} \quad (3.6)$$

The maximum current ($I_{max}$) at t=DT can be expressed by

$$i_{L2}(t = DT) = I_{max} = \frac{1}{L_2} \int_0^{DT} V_{in} dt + I_{min}. \quad (3.7)$$

As a result, during $DT$, average inductor current ($i_{L2}$) can be represented by

$$i_{L2} = I_{max} - I_{min} = \frac{V_{in}}{L_2} \cdot DT. \quad (3.8)$$

During the $SW_1$ is ON, inductor current ($i_{L1}$) reaches minimum value ($I_{min}$) at t=0 and reaches maximum value ($I_{max}$) at t=DT.
\[
i_{L1}(t) = \frac{1}{L_2} \int_0^t (V_{in} - V_{out}) dt + I_{\text{max}} \quad (3.9)
\]

The minimum current \((I_{\text{min}})\) at \(t=DT\) and average current \((\Delta i_{L1})\) can be expressed by

\[
i_{L1}(t = DT) = I_{\text{min}} = \frac{1}{L_2} \int_0^{DT} (V_{in} - V_{out}) dt + I_{\text{max}} \quad (3.10)
\]

\[
\Delta i_{L1} = I_{\text{min}} - I_{\text{max}} = \frac{V_{in} - V_{out}}{L_2} \cdot DT. \quad (3.11)
\]

3) Mode 3 (SW1:ON, SW2:OFF, \(I_C>0\))

In Mode 3, since switch 1 and 2 operations are completely changed, \(V_{L1}\) can be expressed by

\[
V_{L1} = L_1 \frac{di_{L1}}{dt}. \quad (3.12)
\]

Since inductor voltage \(V_{L1}\) is the same as input voltage \(V_{in}\), inductor current \(i_{L1}\) can be determined by

\[
\frac{di_{L1}}{dt} = \frac{V_{L1}}{L_1} = \frac{V_{in}}{L_1}. \quad (3.13)
\]

On the contrast, the current \(i_{L2}\) across the inductor \(L_2\) flows to the load through diode \(D_2\). Inductor voltage \(V_{L2}\) can be represented by

\[
V_{L2} = V_{ni} - V_{out} \quad (3.14)
\]

And inductor current \(i_{L2}\) can be expressed by

\[
\frac{di_{L2}}{dt} = \frac{V_{L2}}{L_2} = \frac{V_{in} - V_{out}}{L_2} \quad (3.15)
\]
Mode 4 (SW1:ON, SW2:OFF, \textit{I}_C<0)

In Mode 4, the output capacitor current is negative and the diode current \(i_{D2}\) which flows to the diode \(D_2\) is smaller than output current \(I_{out}\). At this moment, charged current in capacitor in Mode 3 is discharged and flows to the load. In Mode 3 and 4, inductor current \((i_{L1})\) reaches minimum value \((I_{\min})\) at \(t=(1-D)T\) and reaches maximum value \((I_{\max})\) at \(t=T\).

\[
i_{L1}(t) = \frac{1}{L_2} \int_{(1-D)T}^{T} (V_{in} - V_{out}) dt + I_{\max} \quad (3.16)
\]

The maximum current \((I_{\max})\) at \(t=DT\) and average current \((\Delta i_{L1})\) can be expressed by

\[
i_{L1}(t = DT) = I_{\max} = \frac{1}{L_1} \int_{0}^{(1-D)T} V_{in} dt + I_{\min} \quad (3.17)
\]

\[
\Delta i_{L1} = I_{\max} - I_{\min} = \frac{V_{in}}{L_1} \cdot (1-D)T. \quad (3.18)
\]

During the \textit{SW1} is ON \((DT~T)\), inductor current \((i_{L2})\) reaches minimum value \((I_{\min})\) at \(t=0\) and reaches maximum value \((I_{\max})\) at \(t=DT\).

\[
i_{L2}(t) = \frac{1}{L_2} \int_{0}^{T} (V_{in} - V_{out}) dt + I_{\max} \quad (3.19)
\]

The minimum current \((I_{\min})\) at \(t=DT\) and average current \((\Delta i_{L2})\) can be expressed by

\[
i_{L2}(t = T) = I_{\min} = \frac{1}{L_2} \int_{(1-D)T}^{T} (V_{in} - V_{out}) dt + I_{\max} \quad (3.20)
\]

\[
\Delta i_{L2} = I_{\min} - I_{\max} = \frac{V_{in} - V_{out}}{L_2} \cdot (1-D)T. \quad (3.21)
\]
(B) Discontinuous conduction mode

Mode 1

Mode 2

Mode 3

Fig. 3.5: Equivalent circuits in discontinuous conduction mode (Mode 1-3)
Fig. 3.6: Equivalent circuits in discontinuous conduction mode (Mode 4-6)
Fig. 3.7: Current and voltage waveforms of IBC in discontinuous conduction mode
Fig. 3.8: Diode ($I_{D1}, I_{D2}$) and capacitor ($I_C$) current in six different modes

1) Mode 1: ($SW_1$:OFF, $SW_2$:ON, $I_C$>0)

In Mode 1, the current ($i_{L2}$) across the inductor ($L_2$) shows the same current flow which steadily increases and can be expressed the same as equation (3.1). Furthermore, $V_{L1}$ and $i_{L1}$ can be represented by equation (3.4).

2) Mode 2: ($SW_1$:OFF, $SW_2$:ON, $I_C$<0)

In continuous current mode, charged current in capacitor $I_C$ in Mode 1 is discharged and flows to the load which results average output current ($I_{out}$) can be steadily maintained as positive value.

3) Mode 3: ($SW_1$:OFF, $SW_2$:ON, $I_C$:Constant)

In Mode 3, the current $i_{L1}$ across the inductor $L_1$ reaches zero and the converter is operated in discontinuous conduction mode. At this moment, the capacitor current $I_C$
constantly flows to the load.

4) Mode 4: \((SW_1:\text{ON}, SW_2:\text{OFF}, I_C>0)\)

In Mode 4, unlike Mode 1, since \(SW_1\) is ON-state and \(SW_2\) is OFF-state, the current \(i_{L2}\) across the inductor \(L_2\) can be determined by equation (3.13). Moreover, \(V_{L2}\) and \(i_{L2}\) can be represented by equation (3.15).

5) Mode 5: \((SW_1:\text{ON}, SW_2:\text{OFF}, I_C<0)\)

In Mode 5, since the current \(i_{D2}\) across the diode \(D_2\) is lower than average output current \(I_{out}\), in order to maintain the load current, the output capacitor current flows to the load and shows negative value.

6) Mode 6: \((SW_1:\text{ON}, SW_2:\text{OFF}, I_C<0)\)

In Mode 6, the current \(i_{L2}\) across the inductor \(L_2\) reaches zero and the converter is operated in discontinuous conduction mode. At this moment, the capacitor current \(I_C\) constantly flows to the load.
3.2.1. **Output voltage ripple ($\Delta V_{out}$) in IBC**

- $I_{O1}$ = Average current of the diode $D_1$.
- $I_{O2}$ = average current of the diode $D_2$.

**Fig. 3.9: Waveforms of the diode current ($I_{D1}, I_{D2}$)**

Figure 3.9 shows waveforms of the diode currents ($I_{D1}, I_{D2}$) through the diodes ($D_1, D_2$) and the quantity of electric charge ($\Delta Q_1, \Delta Q_2$) in output capacitor [50].

Since each the current through the diodes ($D_1, D_2$) flows to the load and average currents ($I_{out1}, I_{out2}$) are constantly maintained, the changed voltage values ($\Delta V_{out1}, \Delta V_{out2}$) can be represented by

$$
\Delta V_{out} = \frac{\Delta Q_1}{C} = \frac{I_{out1} \cdot DT}{C} = \frac{V_{out1} \cdot DT}{R \cdot C} \quad (3.22)
$$

$$
\Delta V_{out2} = \frac{\Delta Q_2}{C} = \frac{I_{out2} \cdot (1-D)T}{C} = \frac{V_{out2} \cdot (1-D)T}{R \cdot C} \quad (3.23)
$$

$$
\therefore \Delta V_{out} + V_{out2} = \frac{V_{out1} \cdot DT}{R \cdot C} + \frac{V_{out2} \cdot (1-D)T}{R \cdot C}. \quad (3.24)
$$
Since the average diode currents \( I_{out1}, \ I_{out2} \) are the same, \( V_{out1} \) and \( V_{out2} \) can be expressed by

\[
I_{out1} = I_{out2}, \quad V_{out1} = V_{out2}
\]  

(3.25)

As a result, when equation (3.23) substitutes in equation (3.22),

\[
\Delta V_{out} = \frac{V_{out1} \cdot DT + V_{out1} (1 - D) T}{RC} = \frac{V_{out1} \cdot T}{RC}
\]  

(3.26)

Since \( V_{out1} = \frac{1}{2} \cdot V_{out1} \),

\[
\therefore \Delta V_{out} = \frac{V_{out} \cdot T}{2RC}
\]  

(3.27)
3.3. Simulation results

3.3.1. PV cell modelling

PV cell has non-linear voltage and current characteristics. Thus, in this thesis, in order to demonstrate the performance in more accurate condition, practical PV array parameter from a commercialized PV array is considered and designed by MATLAB/Simulink [51]

Table 3.1: Parameters of PV module and PV array

<table>
<thead>
<tr>
<th></th>
<th>PV module</th>
<th>PV array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power ($P_m$)</td>
<td>300[W]</td>
<td>1000[W]</td>
</tr>
<tr>
<td>Open circuit Voltage($V_{oc}$)</td>
<td>64.2[V]</td>
<td>245[V]</td>
</tr>
<tr>
<td>Short circuit Current($I_{sc}$)</td>
<td>5.96[A]</td>
<td>5.4[A]</td>
</tr>
<tr>
<td>Voltage ($V_{mp}$) at maximum power</td>
<td>54.7[V]</td>
<td>200[V]</td>
</tr>
<tr>
<td>Current ($I_{mp}$) at maximum power</td>
<td>5.58[A]</td>
<td>5[A]</td>
</tr>
</tbody>
</table>

Measured condition: AM 1.5, 1000W/m$^2$ (Irradiation), 25°C (cell temperature)

Table 3.1 shows the parameters of PV module and PV array which are used for the simulation. PV cell modelling is based on PV module parameters from SunPower
company(SPR-305-WHT) [52] and in order to design 1kW power, 4 PV modules are connected in parallel.

3.3.2. **PV cell curve characteristics**

![Characteristics of PV array. (a) VI curve (b) PV curve](chart.png)

**Fig. 3.10:** Characteristics of PV array. (a) VI curve (b) PV curve

Figure 3.10 shows voltage-current and power-voltage characteristics of 1kW PV array based on the parameter in table 3.1. Figure 3.10 validates that PV array power is heavily relies on irradiation and temperature conditions. Due to this reason, accumulated PV power generation is higher during summer compared to winter.
3.3.3. **MPPT modelling**

![Fig 3.11: MPPT control diagram based on incremental conductance method](image)

By changing irradiation or temperature conditions, PV array characteristics and power are also change. In order to extract the maximum power from PV array, MPPT control circuit based on incremental conductance method [10-15] is designed in Simulink as illustrated in figure 3.11. In this circuit, the rapid changing voltage and current values of PV array are being the initial values of the MPPT control. The differential voltage and current are calculated by the equation of incremental conductance method to track the maximum power point. As combined signals transfer to the PI control and comparator, two PWM signals for PV IBC are made.
### 3.3.4. **PV Interleaved boost converter**

In order to demonstrate the overall performance and improvement of IBC compared with CBC, 1kW IBC has been modelled using MATLAB/Simulink. Parameters of CBC and IBC are given in Table 3.2.

#### Table 3.2: Parameters of CBC and IBC

<table>
<thead>
<tr>
<th></th>
<th>CBC</th>
<th>IBC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Power</strong></td>
<td>1kW</td>
<td></td>
</tr>
<tr>
<td><strong>Switching frequency</strong></td>
<td>160kHz</td>
<td></td>
</tr>
<tr>
<td><strong>Input Voltage</strong></td>
<td>200V</td>
<td></td>
</tr>
<tr>
<td><strong>Output Voltage</strong></td>
<td>400V</td>
<td></td>
</tr>
<tr>
<td><strong>L, L₁, L₂</strong></td>
<td>675uH</td>
<td></td>
</tr>
<tr>
<td><strong>C₀</strong></td>
<td>2uF</td>
<td></td>
</tr>
</tbody>
</table>
The duty ratio of interleaved and CBC can be expressed as below:

\[ D = 1 - \frac{V_{in}}{V_{out}} \]  

(3.28)

where \( V_{in} \) is input voltage, \( V_{out} \) is desired output voltage and \( D \) is duty cycle.

The equation to obtain the value of the inductors \((L_1, L_2)\) in the IBC is not quite different from CBC.

The values of inductors \((L_1, L_2)\) can be calculated by

\[ L_1, L_2 = \frac{V_{in} \times D}{f \times \Delta I_L}. \]  

(3.29)

Where \( f \) is the switching frequency and \( \Delta I_L \) is inductor ripple current. Generally, inductor current ripple \( \Delta I_L \) is about 40\% in CBC [53]. However, inductor ripple in IBC can be remarkably reduced by using two phases illustrated in figure 3.13 [54], thus the size of inductors in IBC can be highly reduced. Even though the size of IBC can be reduced by ripple cancellation at light load condition, it is better to operate the IBC as a single phase boost converter. In this case, the IBC with reduced size of inductors can be easily operated in DCM, which results EMI or ringing problems. Designed 1kW IBC is considered in this point so that the size of inductors in CBC and IBC are the same.
The value of capacitor can be obtained by

\[ C = \frac{I_{\text{out}} \times D}{f \times \Delta V_c} \]  

(3.29)

where: \( \Delta V_c \) is the output capacitor voltage ripple.
3.3.5. **Comparison waveforms of IBC and CBC**

**Fig 3.14: Input and output currents of IBC**

Figure 3.14 shows waveforms of input, output and each current in inductors of IBC. There is an 180° degree phase difference in each current of $L_1$ and $L_2$ which leads to a ripple cancelling effect on the input and output currents. This results to reduce the EMI problem, conduction losses and the size of output capacitor.

The improvement of IBC compared with CBC is certainly indicated when compared input currents.

**Fig 3.15: Comparison input current of CBC and IBC**
Figure 3.15 shows input currents of CBC and IBC. Compared to CBC which shows a large current ripple, IBC indicates almost zero ripple current caused by two inductors and controlling two phases.

![Graph showing input currents of CBC and IBC](image1.png)

**Fig 3.16: Comparison output current of CBC and IBC**

The comparison of the output voltages and the currents based on CBC and IBC are illustrated in figure 3.16 and 3.17. Due to the ripple cancelling by two inductors, conduction losses in MOSFETs, diode and output capacitor can be decreased.

![Graph showing output voltages of CBC and IBC](image2.png)

**Fig. 3.17: Comparison output voltage of CBC and IBC**

The balanced power by the IBC at input stage is able to reduce the output capacitor size. Since the size of output capacitor in the IBC highly relies on the output voltage ripple,
decreased output voltage ripple helps to select a lower capacitor than CBC, which show that it is more suitable in the aspects of cost, size and weight.

Consequently, as evident in the table, it is clear that the IBC shows better performance and low ripples in the input and output stage than a CBC.

**Table 3.3: Voltage and current ripple rates of CBC and IBC**

<table>
<thead>
<tr>
<th></th>
<th>CBC</th>
<th>IBC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Current Ripple</strong></td>
<td>33.4%</td>
<td>0.057%</td>
</tr>
<tr>
<td><strong>Output Ripple Voltage</strong></td>
<td>1%</td>
<td>0.074%</td>
</tr>
</tbody>
</table>

**3.3.6. The improvement of PV IBC**

![Efficiency graph of CBC, single phase IBC and two phases IBC](image_url)

**Fig. 3.18: Efficiency graph of CBC, single phase IBC and two phases IBC**
Since the main power losses in the boost converter are the switching power losses, the size of current ripple is able to affect the efficiency of the converter. Figure 3.18 shows efficiencies of CBC and IBC. Through previous waveform comparisons, the overall performance of IBC shows clear merits of the converter compared with CBC. Another improvement of the converter is efficiency at heavy load condition. Originally IBC is designed and considered for high power applications and this results show that two phase IBC has better efficiency than CBC. However, at light power condition, the IBC shows lower efficiency than the CBC. In some applications or conditions such as PV system operated in changeable input power condition, this can be fatal problem to reduce system efficiency. Thus, the technique to reduce the efficiency loss at light load condition is needed to IBC.
Chapter 4

A Phase shedding for PV interleaved boost converter

This chapter presents deals with the matter of a phase shedding for a PV interleaved boost converter. In Section 4.1, the necessity of a phase shedding for a PV interleaved boost converter is discussed. The conventional phase shedding method is described in Section 4.2. The proposed phase shedding by Schmitt trigger and incremental duty control for PV IBC is presented in Section 4.3. Through the simulation results and analysis of the control method in Section 4.4, an improvement of proposed phase shedding method is verified.

4.1 Conventional phase shedding techniques

Due to the remarkable increase of PV system power, interleaved converters or multiphase converters are preferred in current PV markets. It is true that by increasing phase in PV converters, efficiencies of the converters can be also increased. However, there is a critical problem on multiphase converters for the PV system. Although the multiphase converters show better performance and efficiency than conventional converters, this advantage is limited only at a high power condition. In the case of a PV application, the power from PV array is relied on minute by minute changing irradiation or temperature. Switching losses in converters are prominent when contrasted with other conduction losses. Due to ripple cancelling by sharing currents, the multiphase converters are able to have low switching losses at a high power condition. However, on a PV system which is easily exposed to low power conditions, operating multiphase
at a light load condition can lead the converter to show lower efficiency than conventional converters.

In order to reduce switching losses of the multiphase converters at a light load condition, decreasing the number of switches or phases of the converters at has been proposed and this is called phase shedding. By decreasing or increasing the number of phases at a specific point, the multiphase converters are able to show better efficiency at an entire load condition. As discussed in the previous chapter, the efficiency graph in figure 3.18 reveals the necessity of the phase shedding method for multiphase converters and by phase shedding, the converter can obtain higher efficiency than a conventional converter at a whole range. However, whereas conventional phase shedding techniques are implemented by output current or voltage, due to the unique control method (MPPT), one may consider implementing a phase shedding for PV application by input current or voltage. Another major challenge of phase shedding for PV application is to solve the problems from a rapid transient response of phase shedding operation such as current overshoot and MPPT control malfunction.

Numerous technical papers proposed that efficiency was increased especially at light load conditions based on interleaved converters. Specifically, phase shedding techniques for multiphase converters have been presented in many technical papers [55-61]. In [55], a current balancing framework for phase shedding control in a multiphase converter proposed to regulate output voltage and control the inductor currents during the disabling/enabling transitions. In [56], a phase shedding technique based on an adaptive voltage positioning (AVP) was used to improve transient response. A time-optimal control method based on a minimum time algorithm for minimizing output voltage deviation and transient time is proposed in [57]. The proposed method achieves
a fast transient response and output voltage deviation during phase shedding control through feedforward action. In [59], the proposed scheme deals with the drawback of switching operation during phase shedding transient in interleaved boost power factor correction (PFC) rectifier. This scheme is designed to overcome the malfunction of phase shedding operation due to the extended range of a feedback signal caused by component temperature, tolerance and aging effect. A power loss profile has been used for deciding the number of active phases of a multiphase buck converter in [60]. In [61], the proposed phase shedding technique determines the phase shedding point based on a phase configuration selector and a lookup table defined by junction temperature and on-resistance of MOSFET. However, no research papers have reported phase shedding control methods for PV systems based on an IBC. A seamless transient of the phase shedding control method for the PV system is an important step forward that has not yet been reported in technical literature.

4.2 A phase shedding technique with incremental duty control for PV system

4.2.1 Hysteresis control by Schmitt trigger

Average current control and hysteresis control are the most frequently used as a phase shedding technique for converters with advantages such as a simple structure, fast response and low incidence rate of error. However, in the case of average current control, it is not suitable for PV application which should consider input current and voltage for the control. Hysteresis control is one of the control methods which are the most basic and widely used for converter control. Since most control methods are based and operated in single reference point, the control can be very sensitive and has the
possibility to make control error. In order to compensate the stability of the control, two levels are selected to establish a band and by measuring a difference between desired value and two levels, the control can reduce the error [62-63]. This method is called hysteresis control.

Schmitt trigger is one of the hysteresis control techniques to reduce the noise or control error. Figure 4.1 shows a principle of noise elimination by hysteresis control. The reference with quite some noise is input signal. If $I_{center}$ is utilized for determining if the switches turn-on or off, four periods can be detected and used for turning on the switches. Sometimes, high sensitivity of controls can be a strong point but it could be a reason to give a lot of stress on components and show switching losses. However, it is possible to reduce this undesired detected signal by single point ($I_{center}$) by two trigger levels (Upper threshold and lower threshold) with hysteresis.
Fig 4.1: A principle of noise elimination by hysteresis control

In PV application, since the power is heavily relies on minute by minute irradiation, temperature and changeable weather condition, Schmitt trigger can be an effective control method to reduce the noise and a phase shedding control error. Figure 4.2 illustrates Schmitt trigger control diagram. Input current is transferred to comparator and compared with the previous threshold value. The value from comparator transfers upper or lower threshold value to another comparator. Finally, this transferred value changes to zero or 1 as a trigger signal by being compared to lower threshold. However, only Schmitt trigger control on PV converters has a drawback to resolve.
Fig 4.2: *Control diagram using Schmitt trigger*

Fig 4.3: *Inductor currents during phase shedding based on the Schmitt trigger*

Fig 4.4: *Input currents during phase shedding based on the Schmitt trigger*
Figure 4.3 and 4.4 show inductor currents and input current during phase shedding by using only Schmitt trigger control. Due to Schmitt trigger control, the noise and a phase shedding control error can be resolved. However, as seen in the waveform, at the moment of phase shedding, since the duty and one of the inductor current (I_L2) vertically falls to zero and the stored current (I_L2) is transferred to the inductor current (I_L1) in an instant, the dip and overshoot current can occur. Phase-on moment shows the same phenomenon. In PV application or PV system circumstance, especially in the morning, due to low and unstable irradiation condition, a phase shedding operation can be implemented with several times. If there is no additional control for phase shedding by Schmitt trigger, this problem might not only give a MPPT error or EMI problem by the stress on components from the overshoot current but also results in the decrease of efficiency.

### 4.2.2 Incremental duty control

As seen in the previous phase shedding problem based on the Schmitt trigger control, the Schmitt trigger for PV system needs an additional controller for stable control. In order to minimize the current overshoot phenomenon due to a rapid transient response of phase shedding operation, incremental duty control (IDC) method is proposed.

Figure 4.5 indicates a control diagram of IDC. IDC consists of an integrator for a control of duty increase or decrease and three switches which the output is determined by the first input and third input based on value of the second input. The signal from Schmitt trigger determines whether to shed or add a phase. When shedding an operation, the previous duty from MPPT is subtracted until it is zero. When adding a phase operation, the duty increases moderately from zero until it is the same as the duty from the MPPT. During shedding operation, the speed of subtracting duty can be controlled
by the integrator and the speed gives a crucial effect on reducing the size of current overshoot.

**Fig 4.5: Control block diagram of the IDC**

### 4.3 Simulation results

In order to demonstrate the performance and improvement of the proposed phase shedding technique, the controller in PV IBC has been modelled by MATLAB/Simulink.

#### 4.3.1 Rapid changing solar irradiation

In order to show the dynamic response of PV IBC and proposed phase shedding operation, the variation of solar irradiation has been considered in this case study. Figure 4.6 shows the irradiation variation used for the simulation test. The change of irradiation begins from zero to 1000 W/m² with a positive slope for 0.1 second. After a 0.05 second steady-state period, the irradiation changes from 1000 W/m² to 300 W/m² for about 0.2 seconds. Finally the irradiation returns to a positive slope and increases to 900 W/m² for about 0.2 seconds. Through this irradiation condition, the response of the designed PV IBC at different power conditions and the operation of proposed phase shedding can be determined.
4.3.2 **Comparison conventional hysteresis control and proposed phase shedding control**

**4.3.2.1 Duty control by IDC and non-IDC**

Duty change at phase shedding moment by IDC and non-IDC is shown in figure 4.7 and 4.8. In figure 4.7 and 4.8 phase shedding operations are implemented at 0.317 and 0.467 seconds. At the phase-off operation moment, Duty by the Schmitt trigger alone rapidly falls to zero. However, Duty by IDC shows gradual decrease and it reaches at zero at 0.326 seconds. At phase-on operation moment, while duty by only Schmitt trigger vertically increases, duty by IDC gradually increases for about 0.01 seconds.
Fig 4.7: Duty control by IDC and non-IDC at phase-off

Fig 4.8: Duty control by IDC and non-IDC at phase-on

4.3.2.2 Inductor currents control by IDC and non-IDC

The control of the duty and inductor currents by IDC and non-IDC at phase shedding operation are illustrated in 4.9, 4.10, 4.11, 4.12, 4.13 and 4.14 respectively. Due to rapid changing irradiation, the PV converter implements a phase-on and off operation at 0.32 and 0.457 seconds. At a phase-off moment, as seen in figure 4.11, one of the phases is deactivated and the current which flows in $I_{L2}$ is rapidly driven to the opposite side current $I_{L1}$. Since the Schmitt trigger control only focusses on fast transient response and shedding or adding a phase operation, drastic current flow to the opposite side results
massive current overshoot. At a phase-on operation, since only the Schmitt trigger control forcibly divides the inductor current ($I_{L1}$) and transfers half the current to the opposite side of the current ($I_{L2}$) in an instant, the current fluctuation is shown in each inductor current. However, due to the gradual increase of duty by IDC, the overshoot and fluctuation can be prevented. Figures 4.10, 4.12 and 4.14 illustrate duty and inductor current change at phase shedding moment by IDC. At a phase-off moment, due to the IDC, unlike the Schmitt trigger control alone which decreases duty to zero in an instant, duty gradually decreases for about 0.01 seconds and the inductor current ($I_{L2}$) also shows gradual decrease, followed by the controlled duty, which results the prevention of drastic current flow at phase shedding moment. Furthermore, at a phase-on operation, since the controlled inductor current ($I_{L2}$) smoothly increases until the controlled inductor current value is the same as the inductor current ($I_{L1}$), the fluctuation by the Schmitt trigger alone is likely to be prevented by IDC.

![Fig 4.9: Duty and inductor currents change by non-IDC](image-url)
**Fig 4.10:** Duty and inductor currents change by IDC

**Fig 4.11:** Zoomed in inductor currents at phase-off moment by non-IDC

**Fig 4.12:** Zoomed in inductor currents at phase-off moment by IDC
4.3.2.3 Input current by using IDC and non-IDC

As explained in the previous chapter, because the Schmitt trigger control alone is not able to control rapid current change, inductor current overshoot and fluctuation occur at a phase shedding moment. This problem affects input current as well. Figure 4.15 and 4.16 show input current by using IDC and non-IDC at a phase shedding moment. The table 4.1 indicates the calculation result of the size of current overshoot and dip at phase shedding moment. It shows that 16.7% current overshoot by the Schmitt trigger control alone is reduced to 2% at a phase-off moment and 4% current overshoot by the Schmitt...
trigger alone is decreased to zero. The calculation result indicates that IDC is remarkably effective to reduce the size of current overshoot, dip and fluctuation.

**Fig 4.15:** Input current by using IDC and non-IDC at phase-off

**Fig 4.16:** Input current by using IDC and non-IDC at phase-on
Table 4.1: Comparison overshoot or dip in input currents by IDC and non-IDC during phase shedding moment by simulation test

<table>
<thead>
<tr>
<th>Type of control</th>
<th>Phase shedding moment</th>
<th>Percentage input current overshoot or dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysteresis control</td>
<td>Phase on</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Phase off</td>
<td>16.7%</td>
</tr>
<tr>
<td>Hysteresis with IBC</td>
<td>Phase on</td>
<td>Zero</td>
</tr>
<tr>
<td></td>
<td>Phase off</td>
<td>2%</td>
</tr>
</tbody>
</table>

4.3.2.4 Comparison inductor currents at phase shedding

The purpose of IDC is to minimize the current overshoot and phase shedding operation time. However, the results can vary considerably depending on the control speed of duty increase or decrease. Figure 4.17 illustrates four different duty changes by IDC at a phase shedding moment. The first condition is to increase the duty as ramp function and reach the steady-state value in 5ms. The second condition is the same as the previous condition but the time taken to reach the steady-state value is doubled when compared to the previous one. The third condition is to increase the duty by square. The last condition is to increase the duty by cubic. The results by these four different duty controls are shown in figure 4.18 and 4.19. The first condition has the merit to reduce phase shedding operation time but it still has remarkable input current overshoot. Although the phase shedding operation time is doubled in the second condition as compared to the previous condition, thus the duty can be more smoothly increased than previous condition, it only shows a slight improvement in input current overshoot. However, from third condition which the duty increases by square, the overshoot size is remarkably reduced. At the fourth condition, a more 'curvy' shape is noted to the duty
increase but there is no improvement on the overshoot. Table 4.2 shows the percentage input current overshoot or dip by four different duty controls. As a result, it is determined that the duty increase by square is the best control method to reduce the overshoot or dip.

**Fig 4.17:** Duty control using four different duty control methods

**Fig 4.18:** Input current control using four different duty control methods
Fig 4.19: Zoomed in input current by different duty control methods

<table>
<thead>
<tr>
<th>Type of control</th>
<th>Operation time</th>
<th>Percentage of the input current overshoot or dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp_1</td>
<td>5 ms</td>
<td>8.3%</td>
</tr>
<tr>
<td>Ramp_2</td>
<td>10 ms</td>
<td>7.9%</td>
</tr>
<tr>
<td>Square</td>
<td>10 ms</td>
<td>2.1%</td>
</tr>
<tr>
<td>Cubic</td>
<td>10 ms</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

Table 4.2: Comparison input currents overshoot or dip by for different duty control method in IDC
Chapter 5

Experiment results

This chapter gives experimental results to verify the validity and improvement of the proposed phase shedding technique for PV IBC. Section 5.1 gives and summarizes the experimental setup. In Section 5.2, the improvement and advantages of PV IBC over CBC are verified by analysis and comparison of experimental results of PV CBC and IBC. The validity of proposed phase shedding and its ripple reduce effect are dealt with in Section 5.3. Finally conclusions are presented in Section 5.4.

5.1 Experimental test setup

In order to verify the validation of the improvements of proposed PV IBC, experimental tests are implemented. The experimental test bed is shown in figure 5.1. For experimental verification, a PV simulator (Regatron 600V, 16 kW) is used as a PV input and a dc-grid simulator (Regatron 600V, ±20kW) is connected at the output of the IBC. High flux core 58907A2 is chosen for the inductors ($L_1$, $L_2$). A 100-$u$F 400-V rated film capacitor is used for $C_{pv}$ and 5-$u$F, 1000-V film capacitor is chosen for $C_o$. CREE C4D20120A schottky diode is utilized for diodes ($D_1$, $D_2$) and IXFK24N100Q3 MOSFETs are chosen for two switches ($SW_1$, $SW_2$).
Overall configuration of the experimental setup is illustrated in figure 5.2. Input voltage and current are detected and transferred to an A/D converter and MPPT algorithm.
controller. The experimental parameter of PV IBC prototype is the same as the parameter used in the previous simulation test in chapter 3. In order to implement the phase shedding method, the duty from the MPPT algorithm is divided in two parts and one of them is controlled by hysteresis and IDC. Finally controlled two duties are converted to a PWM signal by PWM pulse generator and gate driver and transferred to two switches.

Table 5.1: Parameters of power switches and diodes

<table>
<thead>
<tr>
<th>Switch Model</th>
<th>(I_D(25^\circ C))</th>
<th>(I_D(100^\circ C))</th>
<th>(V_{DS})</th>
<th>(R_{DS(ON)}(MAX))</th>
</tr>
</thead>
<tbody>
<tr>
<td>IXFK24N100 Power MOSFET</td>
<td>24A</td>
<td>96A</td>
<td>1000V</td>
<td>390(\mu \Omega)</td>
</tr>
<tr>
<td>Diode Model</td>
<td>(I_F(25^\circ C))</td>
<td>(V_F(MAX))</td>
<td>(V_{RRM}(MAX))</td>
<td>(I_R)</td>
</tr>
<tr>
<td>Input Voltage (Silicon Carbide Schottky Diode)</td>
<td>56.5A</td>
<td>1.5V</td>
<td>1200V</td>
<td>35(\mu \text{A})</td>
</tr>
</tbody>
</table>

5.2 Analysis and comparison of experimental results

5.2.1 Rapid changing solar irradiation

Figure 5.3 shows a trapezoidal solar irradiation which is used for this experimental test. To demonstrate the stability of designed PV IBC, MPPT and phase shedding operation, the trapezoidal solar irradiation is utilized as the worst circumstance. The solar irradiation begins to change at 0.8 second with a positive slope from zero to 1000W/m\(^2\) for approximately 2 seconds. For about 1.4 seconds, the irradiation maintains a steady-state condition and goes back to zero for 1.8 seconds.
Fig 5.3: Trapezoidal solar irradiation

Fig 5.4: Output voltage of the PV array
The output current, voltage and maximum output power of the PV array based on a trapezoidal solar irradiation are shown in figure 5.4, 5.5 and 5.6 respectively. The current of the PV array shows the exactly same change as solar irradiation change in figure 5.3 while the voltage does not. From this result, it is observed that the current of PV array is directly affected by the solar irradiation. Furthermore, by stable tracking of the maximum current, voltage and power of PV array, the stability of the designed PV IBC and MPPT under a rapid change solar irradiation is validated.
5.2.2 Comparison between PV CBC and IBC

5.2.2.1 PWM outputs

The figure 5.7 shows PWM signals of PV IBC. According to the parameters of PV IBC, the duty should be maintained with 0.5. As a result, each signal is generated with 180 degree phase difference. One of PWM signals is used for PV CBC.

![PWM signals of the IBC](image)

**Fig 5.7: PWM signals of the IBC**

5.2.2.2 Comparison of input and inductor currents

As determined in the simulation test, input current of IBC is able to have lower current ripple than CBC by ripple cancellation effect from two phase control, which is verified in the experimental test by showing input currents of CBC and IBC in figure 5.8 and 5.9. Due to the fact that CBC has a single phase and uses just one inductor, the input current and inductor current is the same ripple magnitude. Even though ripple size of each
inductor in IBC is the same as the one in CBC, current input current in IBC shows almost zero current by crossing two inductor currents.

Fig 5.8: Input current and inductor current of PV CBC

Fig 5.9: Input current and inductor currents of the PV IBC
Table 5.3: Efficiencies of 1ch-CBC and 2ch-IBC

<table>
<thead>
<tr>
<th>Irradiation (W/m²)</th>
<th>Efficiency of 2ch-IBC (%)</th>
<th>Efficiency of IBC with phase shedding (%)</th>
<th>Efficiency of CBC (1ch-IBC) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>97.3</td>
<td>97.3</td>
<td>96</td>
</tr>
<tr>
<td>950</td>
<td>97.4</td>
<td>97.4</td>
<td>96.2</td>
</tr>
<tr>
<td>900</td>
<td>97.43</td>
<td>97.43</td>
<td>96.35</td>
</tr>
<tr>
<td>850</td>
<td>97.46</td>
<td>97.46</td>
<td>96.5</td>
</tr>
<tr>
<td>800</td>
<td>97.49</td>
<td>97.49</td>
<td>96.7</td>
</tr>
<tr>
<td>750</td>
<td>97.5</td>
<td>97.5</td>
<td>96.8</td>
</tr>
<tr>
<td>700</td>
<td>97.5</td>
<td>97.5</td>
<td>96.88</td>
</tr>
<tr>
<td>650</td>
<td>97.47</td>
<td>97.47</td>
<td>96.99</td>
</tr>
<tr>
<td>600</td>
<td>97.4</td>
<td>97.4</td>
<td>97.08</td>
</tr>
<tr>
<td>550</td>
<td>97.3</td>
<td>97.3</td>
<td>97.14</td>
</tr>
<tr>
<td>500</td>
<td>97.2</td>
<td>97.2</td>
<td>97.2</td>
</tr>
<tr>
<td>450</td>
<td>97</td>
<td>97.21</td>
<td>97.21</td>
</tr>
<tr>
<td>400</td>
<td>96.7</td>
<td>97.12</td>
<td>97.12</td>
</tr>
<tr>
<td>350</td>
<td>96.25</td>
<td>96.97</td>
<td>96.97</td>
</tr>
<tr>
<td>300</td>
<td>95.5</td>
<td>96.66</td>
<td>96.66</td>
</tr>
<tr>
<td>250</td>
<td>94.5</td>
<td>96.24</td>
<td>96.24</td>
</tr>
<tr>
<td>200</td>
<td>93.2</td>
<td>95.57</td>
<td>95.57</td>
</tr>
<tr>
<td>150</td>
<td>91</td>
<td>94.37</td>
<td>94.37</td>
</tr>
<tr>
<td>100</td>
<td>88</td>
<td>92.04</td>
<td>92.04</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
<td>84.42</td>
<td>84.42</td>
</tr>
</tbody>
</table>

Table 5.3 and figure 5.10 show efficiencies of CBC (1ch-IBC), 2ch-IBC and IBC with phase shedding technique. As verified in the previous simulation results, CBC (1ch-IBC) shows higher efficiency than IBC at a light load condition. However, at a heavy load condition, CBC has lower efficiency than IBC. In order to minimise the efficiency loss at a light load condition, it is important to find efficiency crossing points between CBC and IBC. According to the efficiency table of designed CBC and IBC, efficiencies of CBC and IBC are the same at 500W/m². From this crossing point as a starting point, efficiencies of converters show a gap at entire irradiation condition.
After finding the crossing point, by adding phase shedding technique on PV IBC, IBC is not only able to have better efficiency than CBC, but also reduce efficiency loss at a light load condition.

![Efficiency graph of 1ch-IBC(CBC), 2ch-IBC and IBC with phase shedding technique](image)

**Fig 5.10: Efficiency graph of 1ch-IBC(CBC), 2ch-IBC and IBC with phase shedding technique**

In figure 5.11, to demonstrate practical efficiency improvement of IBC with phase shedding technique compared to CBC, daily average irradiation data of February in 2013 in Queensland University in Australia is used. According to the average irradiation data, for about 6 or 7 hours of a day, irradiation is lower than 500W/m² and PV converter is operated under this irradiation level. It is noticed that PV interleaved or multiphase converters need phase shedding method to prevent efficiency loss. As a result, by applying efficiency data of CBC and IBC on daily average irradiation data, hourly efficiency improvement of IBC compared to CBC in a day can be achieved and the is indicated in figure 5.12. According to the comparison data, PV IBC with phase
sheding method has a 1.3% efficiency improvement than CBC and 0.8% efficiency improvement than IBC without phase shedding method.

**Fig 5.11:** Daily average irradiation data of February in 2013 in Queensland University in Australia [64].
Fig 5.12: Average daily PV system efficiency of the 2ch-IBC and the 1ch-IBC (CBC)

5.3 Comparison of phase shedding operations

5.3.1 Phase shedding operation with only hysteresis control

To demonstrate the performance of the proposed phase shedding technique, trapezoidal solar irradiation is used in this case study as well. Figure 5.13 illustrates input current ($I_{in}$) and inductor currents ($I_{L1}$, $I_{L2}$) of PV IBC ($I_{L2}$) is considered as controlled inductor current). Phase shedding operations are implemented in two stages. When the solar irradiation is going up and input current is higher than the upper threshold of hysteresis control, the phase shedding operation is performed to turn on one phase of PV IBC. In contrast, if input current is lower than lower threshold, one of the phases is deactivated. However, as shown in the figure 5.13, although hysteresis control is able to implement a turning-on or off operation, it cannot prevent current overshoot from rapid phase shedding operation. Figure 5.14 and 5.15 show zoomed input current and inductor...
currents at a phase shedding operation. At turning-on the phase operation, about 0.6 amp of input current overshoot is captured and about 0.7 amp of input current dip is detected at a turning-off operation.

**Fig 5.13**: Input current and inductor currents at phase shedding operation by only hysteresis control
Fig 5.14: Zoomed input current and inductor currents at turning-on operation with only hysteresis control

Fig 5.15: Zoomed input current and inductor currents at turning-off operation with only hysteresis control
5.3.2 Phase shedding operation with hysteresis and IDC

As verified in the simulation test, controlling duty increase or decrease slope at phase shedding operation is able to prevent current overshoot and dip phenomenon. Figure 5.16, 5.171, 5.18, 5.19 and 5.20 respectively show inductor currents changes at a phase shedding operation based on hysteresis control and IDC. The biggest difference between input current controlled by only hysteresis control and hysteresis with IDC is the size of overshoot and dip at the phase shedding operation. Due to the additional control by IDC, each inductor current is able to have moderate increase or decrease at a phase shedding moment. In figure 5.17, at a phase-on operation with IDC, controlled current \(I_{L2}\) and duty gradually increases until they are the same as opposite current and duty for about 0.7 seconds. At this time, due to the moderate increase, input current can have a low overshoot current with about 0.15 amp. At a phase-off operation, controlled current gradually decreases until it reaches zero. At this moment, any current dip or overshoot cannot be found. Table 5.4 summarizes the percentage input current overshoot or dip by only the Schmitt trigger and Schmitt trigger with IDC. As a result, due to the additional duty control by IDC, 15% overshoot reduction at phase-on operation and 28% overshoot reduction at phase-off operation can be obtained.
Fig 5.16: Input current and inductor currents at phase shedding operation by hysteresis control and IDC

Fig 5.17: Input current and inductor currents at turning-on operation with hysteresis control and IDC
Fig 5.18: Zoomed input current and inductor currents at turning-on operation with hysteresis control and IDC

Fig 5.19: Input current and inductor currents at turning-off operation with hysteresis control and IDC
Fig 5.20: Zoomed input current and inductor currents at turning-off operation with hysteresis control and IDC

Table 5.4: Overshoot or dip in input currents for two types of controls during phase shedding

<table>
<thead>
<tr>
<th>Type of control</th>
<th>Phase shedding mode</th>
<th>Percentage of the input current overshoot or dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysteresis control</td>
<td>Phase on</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Phase off</td>
<td>28%</td>
</tr>
<tr>
<td>Hysteresis with IBC</td>
<td>Phase on</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Phase off</td>
<td>Zero</td>
</tr>
</tbody>
</table>
5.4 Conclusion

Since the power rating for PV application has been increased, interleaved or multiphase converters for PV system preferred. However, low efficiency at a light load condition is a problem for PV converters. Many phase shedding techniques have been presented but none of them have applied on PV converters. Thus, a phase shedding technique with IDC for PV IBC has been introduced in this chapter to resolve the problem. Efficiency improvement at a light load condition for PV IBC has been obtained by phase shedding. Furthermore, the current overshoot or fluctuation by a rapid phase shedding operation can be prevented by proposed IDC based on the Schmitt trigger. In summary, interleaved or multiphase PV interleaved or multiphase converters are able to minimize efficiency loss at a light load condition and achieve better efficiency at a heavy load condition compared with conventional converters.
Chapter 6

Conclusion

This chapter provides a summary of the thesis. The thesis is concluded by proposing future research work.

6.1. Summary

The performance and improvement of the PV IBC with the proposed phase shedding control algorithm are presented in the thesis. By simulation and experimental test, the efficiency improvement of IBC for PV system with IDC is verified.

The main contents of each chapter are given below:

Chapter 1 gave detail background of this research work. It contains photovoltaic fundamentals, modelling of a solar cell and maximum power point tracking (MPPT) to understand PV system and motivation and objective of the thesis are continuously given. Lastly the thesis outline is given.
Overviews of PV PCS and PV non-isolating converters are dealt with in Chapter 2. In overview of PV PCS part, three different systems are given and compared by capability, flexibility and suitability. An overall comparison of these indicates that the non-isolated system type is the most suitable for PV system. Typical four isolated dc-dc converters ( buck, boost, buck-boost and Cuk converter) in PV non-isolating converters part. Basic structures, operation principles are given. In order to select the most suitable converters for the PV system, each converter is analysed and compared by the utilization of MPPT and efficiencies. As a result, Buck and Boost converter are judged to be the most suitable converter for PV application due to the following reasons: High efficiency, less component and low input current ripple.

Chapter 3 offered detailed principle and analysis of the PV interleaved boost converter. The interleaved boost converter is analysed by the use of two operation modes (CCM and DCM). In the simulation report, overall PV interleaved boost converter is designed and performed. The results of the 1kW PV interleaved boost converter are analysed and compared to PV conventional boost converter to verify two phase boost converter’s improvements and suitability for the PV system. As a result, the chapter shows the efficiency improvement of the interleaved boost converter and the challenge which is the efficiency problem at a light load of the converter.

Chapter 4 gave an overall introduction of conventional phase shedding techniques and proposed phase shedding method for PV IBC. The chapter also proposed IDC to prevent the current overshoot by rapid phase shedding operation. The simulation results reported were obtained to validity designed PV IBC. Furthermore, efficiency improvement of PV IBC by proposed phase shedding and current overshoot reduction at phase shedding operation by IDC is verified by the simulation results. Phase shedding is
implemented on the basis of PV IBC with MPPT. In contrast with the previous phase shedding method, proposed phase shedding is based on duty from MPPT. Moreover, due to IDC, not only the current overshoot is prevented, but an additional MPPT error from the current overshoot can be avoided.

In Chapter 5, experimental results and analysis of PV IBC with proposed phase shedding technique were given. Through the results analysis and extensive application of PV IBC with phase shedding technique on practical average irradiation data, the efficiency improvement of PV IBC by proposed phase shedding technique and current overshoot reduction by IDC can be verified.
6.2. *Future work*

**PV IBC using coupled inductors**: Coupled inductor is the simple way to improve transient response and input current ripple of converters [65-66]. By modelling and experimental test of a PV IBC with coupled inductors and IDC, the performance improvement of the PV IBC with coupled inductors compared with conventional one will be verified.

**PV IBC with soft-switching technique**: Soft-switching is the technique to achieve two improvements. Firstly, through soft-switching method, the efficiency of converters can be maximized. Secondly, the EMI can be minimized. With these advantages, the soft-switching technique will be applied on proposed PV IBC with IDC and the improvement will be verified by modelling and experimental test.
List of references


[17] D. Casadei, G. Grandi, and C. Rossi, "Power quality and reliability supply improvement using a power conditioning system with energy storage capability,"


