HU, HUAN. Control and Design of Photovoltaic Generation System based on Cascaded Multilevel Converter. (Under the direction of Dr. Alex Q. Huang).

The solar energy has become one of the most promising and attractive energy resources, since it is free, abundant, produces no greenhouse gases during power generation, and distributed throughout the Earth. However due to the fluctuating and weather-dependent characters of the solar power, certain power electronic interface and control method should be embedded into the photovoltaic (PV) generation system to deliver the power to a compatible grid.

This thesis focuses on the control and design of a PV system based on the cascaded multilevel converter. The merits of such a system are high efficiency due to single stage power conversion, individual maximum power point tracking (MPPT) capability, and potential modular design. However, the control challenges still exist. Questions such as how to achieve fast and accurate MPPT and grid current regulation, and is there any way to realize decentralized or even distributed control are not fully answered yet and therefore need further investigation.

The first work that has been done in this thesis is to propose a centralized control method for such a system. In order to delivery maximum power to the grid, an improved MPPT with fast and accurate tracking performance is proposed. The proposed MPPT method achieves fast dynamic tracking as well as small steady state oscillation. Therefore, the power loss caused by inaccuracy of MPPT is reduced. Furthermore, a control system in single phase d-q coordinate is derived, which achieves zero steady-state error grid current tracking. The
proposed controller is experimentally demonstrated in the PV system based on cascaded seven-level inverter.

Motivated by the increasing demand for modular power electronic system, the decentralized or even distributed controller is highly needed. The second work that has been done in this thesis is to propose a decentralized control method for the presented system. It greatly reduces the signals that need to be transmitted among the modules and also the communication requirement, therefore laying down the path for the modularization of such a technology. Simulation and experimental results have been done to verify the proposed decentralized control method.
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Control and Design of Photovoltaic Generation System based on Cascaded Multilevel
Converter

by
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DEDICATION

To my parents, my parents in law, and Xu She
BIOGRAPHY

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# TABLE OF CONTENTS

LIST OF TABLES ................................................................................................................... vi
LIST OF FIGURES ................................................................................................................ vii

Chapter 1. Introduction .......................................................................................................... 1
  1.1 Background .................................................................................................................... 1
  1.2 Demands for Grid-tied PV inverters ............................................................................ 4
  1.3 Review of power conversion structures of PV system ................................................ 8
  1.4 Thesis outline .............................................................................................................. 16

Chapter 2. Control and design of PV system based on cascaded multilevel converter .... 18
  2.1 Topology and operating principle .............................................................................. 18
  2.2 Characteristics of Photovoltaic Panel ........................................................................ 21
  2.3 Maximum Power Point Tracking (MPPT) method ..................................................... 24
      2.3.1 CV Method ............................................................................................................ 26
      2.3.2 Perturbation and Observation (P&O) Technique ................................................ 27
      2.3.3 Incremental Conductance (Inc-Cond) Technique ................................................ 30
  2.4 Centralized control of PV system .............................................................................. 33
  2.5 Parameters design of the cascaded multilevel inverter based PV system .................. 47
      2.5.1 Design of the input capacitors ............................................................................. 50
      2.5.2 Design of the output inductor ............................................................................. 53
  2.6 Simulation results ....................................................................................................... 58
  2.7 Experimental results ................................................................................................... 67
  2.8 Conclusion ................................................................................................................... 79

Chapter 3. Decentralized Control of PV system based on cascaded multilevel converter .... 81
  3.1 Research motivation ..................................................................................................... 81
  3.2 state of art of decentralized controller ........................................................................ 84
  3.3 Decentralized control of PV system ........................................................................... 86
  3.4 Simulation results ........................................................................................................ 90
  3.5 Experimental results .................................................................................................. 93
  3.6 Conclusion .................................................................................................................. 103

Chapter 4. Conclusion and Future Work ........................................................................... 104
  4.1 Conclusion of present work ....................................................................................... 104
  4.2 Future work ................................................................................................................ 104

REFERENCES ..................................................................................................................... 106
LIST OF TABLES

Table 1-1 Summary of the standards of grid tied PV systems................................. 6
Table 1-2 systems response to abnormal voltages...................................................... 7
Table 1-3 system response to abnormal frequency..................................................... 7
Table 2-1 Parameters of the system........................................................................... 49
Table 2-2 System parameters for experiments........................................................... 72
Table 3-1 System parameters for decentralized-control experiments....................... 95
LIST OF FIGURES

Figure 1-1 World market energy consumption................................................................. 1
Figure 1-2 Global PV installations .................................................................................. 3
Figure 1-3 PV power installations: on-grid (red bars) and off-grid (yellow bars)......... 4
Figure 1-4 Historical overview of PV system structures: (a) centralized structure; (b) string structure; (c) multi-string structure; (d) micro-inverter (AC module) structure ................................................................. 8
Figure 1-5 Modular PV system: (a) DC parallel (b) DC series (c) AC parallel (d) AC series ................................................................................................................................... 12
Figure 1-6 Cascaded multilevel inverter topology.......................................................... 15
Figure 1-7 Topology of cascaded multilevel inverter..................................................... 18
Figure 1-8 Electrical circuit of an H-bridge unit............................................................ 19
Figure 1-9 Synthesis of multilevel waveforms by using PSPWM................................. 20
Figure 1-10 Ideal model of PV cell................................................................................ 21
Figure 1-11 Output characteristic of PV panel ............................................................... 23
Figure 1-12 Simulated I-V and P-V curve of the PV panel............................................... 24
Figure 1-13 Operating principle of P&O method .......................................................... 28
Figure 1-14 Flow chart of P&O method........................................................................ 28
Figure 1-15 Flow chart of Inc-Cond technique .............................................................. 31
Figure 1-16 Topology of grid connected PV system based on cascaded multilevel converter ................................................................................................................................... 35
Figure 1-17 Equivalent circuit for controller derivation.................................................. 36
Figure 1-18 Synthesis of imaginary phase...................................................................... 37
Figure 1-19 Small signal model of the system ............................................................... 42
Figure 1-20 Control architecture of the PV system ....................................................... 44
Figure 1-21 Phasor diagram of first method .................................................................. 46
Figure 1-22 Phasor diagram of equal reactive power distribution................................. 47
Figure 1-23 PV system based on cascaded seven-level converter .................................. 48
Figure 1-24 I-V curve of the PV panels from datasheet: ............................................... 49
Figure 1-25 Topology of a single H-bridge module....................................................... 50
Figure 1-26 Output power of the inverter ..................................................................... 51
Figure 1-27 Output power pulsation of the inverter for capacitor sizing ......................... 52
Figure 1-28 Equivalent circuit of the inverter and PWM method................................... 54
Figure 1-29 Inductor current during one switching period............................................. 56
Figure 1-30 I-V curve of the PV panel: (a) datasheet curve; (b) simulation model curve ................................................................................................................................... 59
Figure 1-31 Grid voltage and current of the PV system ................................................. 60
Figure 1-32 MPPT of the PV panel voltage ................................................................. 61
Figure 1-33 Currents of the PV panels ........................................................................ 62
Figure 1-34 Grid voltage, current, and PWM voltage of the system............................. 63
Figure 1-35 THD of the grid connected current: (a) without phase shift; (b) with phase shift .... 63
Figure 2-30 DC voltage and MPPT of PV panel 2 with 0.5V step................................. 64
Figure 2-31 DC voltage and MPPT of PV panel 2 with 0.25V step............................... 65
Figure 2-32 DC voltage and MPPT of PV panel 2 with 1V step .................................... 66
Figure 2-33 Performance of the proposed MPPT method.............................................. 67
Figure 2-34 Prototype of the designed system............................................................. 68
Figure 2-35 Signal paths for the designed prototype: (a) centralized structure; (b) modularized structure.............................................................................................. 69
Figure 2-36 System configuration for experiments......................................................... 70
Figure 2-37 PV panels for the experiments ................................................................ 70
Figure 2-38 measured P-V and I-V curve of the PV panel for experiments................. 71
Figure 2-39 Start-up of the system: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ ................................................................. 73
Figure 2-40 MPPT at the start-up process: Voltage of panel 3 $V_{pv3}$, current of panel 3 $I_{pv3}$, power of panel 3 $P_{pv3}$ .................................................................................. 74
Figure 2-41 Grid voltage $v_g$, 7-level PWM voltage $v_{ll}$, grid connected current $i_s$, DC voltage of PV panel $V_{pv1}$ .................................................................................................. 74
Figure 2-42 Harmonics spectrum: (a) grid current $i_s$; (b) grid voltage $v_g$. ............. 75
Figure 2-43 Partial shading operation: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ ................................................................. 76
Figure 2-44 Partial shading operation: voltage of PV panel 3 $V_{pv3}$, current of PV panel 3 $I_{pv3}$, Grid voltage $v_g$, grid current $i_s$ ................................................................. 76
Figure 2-45 Partial shading operation: voltage of panel 3 $V_{pv3}$, current of panel 3 $I_{pv3}$, power of panel 3 $P_{pv3}$ .................................................................................. 77
Figure 2-46 DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ at different perturbation step size .................... 78
Figure 2-47 DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ at different perturbation step size .................... 78
Figure 3-1 System architecture of centralized controller.............................................. 82
Figure 3-2 System architecture based on master/slave controller ................................ 83
Figure 3-3 Decentralized control architecture for a cascaded multilevel converter in[78] ................................................................................................................................. 85
Figure 3-4 System architecture of decentralized controller ........................................... 88
Figure 3-5 Proposed decentralized controller for PV system based on cascaded multilevel converter ............................................................................................... 89
Figure 3-6 Grid connected voltage and current ............................................................ 91
Figure 3-7 MPPT tracking of the PV panel voltage ....................................................... 92
Figure 3-8 Signal paths for the decentralized-control prototype .................................... 93
Figure 3-9 measured P-V and I-V curves of PV panels for decentralized-control experiments .................................................................................................................. 94
Figure 3-10 Start-up of the system: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ .................................................. 96
Figure 3-11 MPPT at the start-up process: Voltage of panel 1 $V_{pv1}$, .................................. 96
Figure 3-12 MPPT at the start-up process: Voltage of panel 2 $V_{pv2}$, .................................. 97
Figure 3-13 DC voltage of PV panel 1 $V_{pv1}$, 7-level PWM voltage $v_H$ .................................. 97
Figure 3-14 Harmonics spectrum: (a) grid current $i_s$; (b) grid voltage $v_g$. ..................... 98
Figure 3-15 Partial shading operation: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ ......................... 99
Figure 3-16 Partial shading operation: voltage of PV panel 2 $V_{pv2}$, current of PV panel 2 $I_{pv2}$, Grid voltage $v_g$, grid current $i_s$ ............................................................ 100
Figure 3-17 Partial shading operation: voltage of PV panel 1 $V_{pv1}$, current of PV panel 1 $I_{pv1}$, Grid voltage $v_g$, grid current $i_s$ ............................................................ 100
Figure 3-18 Partial shading operation: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ ......................... 101
Figure 3-19 Partial shading operation: voltage of PV panel 1 $V_{pv1}$, current of PV panel 1 $I_{pv1}$, Grid voltage $v_g$, grid current $i_s$ ............................................................ 102
Figure 3-20 Partial shading operation: voltage of PV panel 2 $V_{pv2}$, current of PV panel 2 $I_{pv2}$, Grid voltage $v_g$, grid current $i_s$ ............................................................ 102
Chapter 1. Introduction

1.1 Background

In recent years, the demand for energy is increasing day by day due to the increase in population, urbanization and industrialization. Shown in Figure 1-1, the world energy consumption increased from 355 quadrillion Btu in 1990 to 495 quadrillion Btu in 2007, and is projected to grow by 36% from 2015 to 2035 [1].

![Figure 1-1 World market energy consumption](image)

The primary sources of energy in today’s world are the hydrocarbon based fossil fuels. Combustion of these fuels produces energy which is converted into electrical energy. As the by-product of combustion, they give rise to pollutants such as carbon dioxide, which leads to...
global warming issue [2]. Moreover, there is only a limited amount of fossil fuels available in the world. Fossil fuels are in the verge of vanishing and their reserves are also limited. Coal, petroleum and natural gas will thus be depleted in a few hundred years. The rate of energy consumption is increasing, but supply is decreasing because of energy shortage. This is called energy crisis. Hence, alternative or renewable sources of energy have to be developed to meet future continuously increasing energy requirement.

Over the past few decades, the demand for renewable energy has increased significantly. Among various types of renewable energy sources, solar energy from photovoltaic (PV) panels has become one of the most promising and attractive candidates, since it is free, abundant, produces no greenhouse gases during power generation, and distributed throughout the Earth [3]. According to expertise the energy obtained from PV panels will become the most important alternative renewable energy source until 2040 [4].

Figure 1-2 gives the PV installation data for the recent few years and also predicts the installed capacity for each year until 2015 [5]. It is observed that the global PV installations are increasing consistently year by year. In 2009, PV capacity grew to 7.5GW, up 29% from the prior year. And extra PV installations grew by a massive 166% to reach 20GW in 2010. In 2011, it is 26.9 GW and it is predicted by IMS Research to reach 45.5GW in 2015, more than 5 times the size of the 2009 market.
Nowadays, due to increasing efficiency of solar cells and the manufacturing technology improvement, the costs and prices are declining rapidly and the PV system is becoming more popular. Meanwhile, more and more PV modules have been and will be connected to utility grid in many countries. Figure 1-3 shows the PV installations growth by applications [6]. Apparently, most of the market is occupied by on-grid PV systems, and the growth rate is also much faster than that of the off-grid PV systems.

Although every year the prices of solar cells are decreasing and the grid tied PV systems are increasing, the total system costs is still higher when compared to other conventional fuels. Two important factors, which limits the implementation of PV systems, are high cost and low efficiency in energy conversion. It was mentioned that the conversion efficiency of
the solar PV panels is quite low at only 10-17% [7]. In PV systems, the PV panels represent about 57% of the total cost of the systems. Due to the low conversion efficiency and high cost of solar panels, it is very desirable to extract as much power from them as possible and to operate the panels at the maximum power point. However, the output characteristics of PV panels are nonlinear and critically influenced by solar irradiance and weather conditions. Therefore, maximum power point tracking (MPPT) technique is very important and should be implemented in the converter to achieve maximum efficiency of PV panels [8].

![Figure 1-3 PV power installations: on-grid (red bars) and off-grid (yellow bars)](image)

**Figure 1-3 PV power installations: on-grid (red bars) and off-grid (yellow bars)**

### 1.2 Demands for Grid-tied PV inverters

As the capacity of PV grid-tied system growing significantly, the impact of PV system on the grid cannot be ignored. Utility companies become increasingly concerned that the
problems they may cause, such as increase of harmonics, and aggravated stability of the power system. The PV inverter systems will impact the power quality or affect the operation of other equipment and cause it to malfunction or otherwise disrupt the stable operation of the power distribution system [9]. To maintain the power quality, the standards given by the utility companies must be obeyed.

In particular, the future international standard IEC61727 [10], the present standards EN61000-3-2 [11], IEEE1547 [12], and the U.S. National Electrical Code (NEC) 690 [13] are worth considering. These standards deal with issues as power quality, detection of islanding operation, grounding etc. The requirements are listed in Table 1-1[14].

As seen in Table 1-1, the present EN standard (applied in Europe) is easier to cope with, regarding current harmonics, than the corresponding IEEE and IEC standards. This is relevant to the development of power electronic technology. To date, the (IGBT)/MOSFET-equipped inverters at a high switching frequency domain the inverter market, compared to large thyristor-equipped inverter with a much lower switching frequency [14].

Besides the requirements of the current harmonics and THD value, the standards also set limitations on the maximum allowable amount of injected dc current into the grid. The purpose of limiting the injection is to avoid saturation of the distribution transformers.
Additionally, the allowable voltage and frequency range of the normal grid is also defined in the IEC and IEEE standard for potential protection and islanding operation. For example, according to IEEE 1547 standard [12], the PV grid tied system should possess the protection functions to detect the effective (rms) or fundamental frequency value of the grid voltage and respond appropriately to the abnormal grid conditions. When any voltage or the frequency is in a range given in Table 1-2 and Table 1-3, the system should cease to energize the grid within the clearing time as indicated.
The systems must also be able to detect an islanding condition and take proper measures in order to protect persons and equipment. Islanding is the continued operation of the inverter when the grid has been removed on purpose, by accident or by damage. In other words, the inverter is disconnected from the grid when in fault, and only supplies local loads. Till now, several approaches have been developed to deal with the islanding situation [15][16].

Table 1-2 systems response to abnormal voltages

<table>
<thead>
<tr>
<th>Voltage range (% of base voltage)</th>
<th>Clearing time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V &lt; 50$</td>
<td>0.16</td>
</tr>
<tr>
<td>$50 \leq V &lt; 88$</td>
<td>2</td>
</tr>
<tr>
<td>$110 &lt; V &lt; 120$</td>
<td>1</td>
</tr>
<tr>
<td>$V &gt; 120$</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 1-3 system response to abnormal frequency

<table>
<thead>
<tr>
<th>Size</th>
<th>Frequency range(Hz)</th>
<th>Clearing time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 30kW$</td>
<td>$&gt; 60.5$</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>$&lt; 59.3$</td>
<td>0.16</td>
</tr>
<tr>
<td>$&gt; 30kW$</td>
<td>$&gt; 60.5$</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>$&lt; {59.8 - 57.0}$</td>
<td>Adjustable 0.16 to 300</td>
</tr>
<tr>
<td></td>
<td>(adjustable set point)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$&lt; 57.0$</td>
<td>0.16</td>
</tr>
</tbody>
</table>
1.3 Review of power conversion structures of PV system

The power generated by the PV panel is a DC one, and the value is affected by the working conditions. In order to obtain the high quality power, suitable power conversions needed to be done before delivery for the customer use. Numerous architectures for PV system have been proposed, and they can be classified based on their structural arrangement as shown in Figure 1-4.

Basically, it can be divided into four categories: (a) centralized structure; (b) string structure; (c) multi-string structure; (d) micro-inverter (AC module) structure [14][17][18]. In order to identify the most suitable structures, this section reviews and compares the aforementioned power conversion structures.

Figure 1-4 Historical overview of PV system structures: (a) centralized structure; (b) string structure; (c) multi-string structure; (d) micro-inverter (AC module) structure
1) Centralized inverters

This is the most used and conventional structure, as illustrated in Figure 1-4(a). It is based on centralized inverters that interfaces a large number of PV panels to the grid [19]. At first, the panels are connected in series to form a string arrangement; each has a capability of generating sufficiently high voltage to avoid amplification separately. And then the strings are connected in parallel, through string diodes, in order to reach high power levels.

It seems to be less complex in installation and have the lowest cost solution for the megawatt PV system. However, there are several major drawbacks to this topology such as mismatch losses between the PV panels to central maximum power point tracking, higher power losses caused by string diodes, and a nonflexible design where the benefits of mass production could not be reached, low upgradeability, and very low continuity of service at low irradiation.

In general, the highest energy output is achievable only when all of the PV panels are exactly the same and operate under the same atmosphere conditions. In practice, it is nearly impossible to meet those stringent conditions due to variations of PV panel parameters caused by temperature, aging and dust on the surface of panels. Additionally, shade due to the surrounding trees or buildings, clouds, and flying birds will bring about the sun irradiance variation of PV panels [20].

One can easily interpret from the structure figure that the PV panels in the same sting share the same string current because of series connection and all the panel strings share the same string voltage because of parallel connection [21]. If there is irradiance difference between panels within the same string, the MPP current of these mismatched panels will be different.
So, it is not possible for all the panels in that string operating at their own MPP. Similarly, the series connection between the strings also has the mismatch issue. In other words, system level MPPT performance will be compromised in direct series and parallel connections.

2) **String inverters**

In more recent installations, string inverters have been preferred for commercial and residential level PV applications as shown in Figure 1-4 (b). The string inverter is a reduced version of the centralized inverter, where a single string of PV panels is connected to the inverter [22]. The input voltage may be high enough to avoid voltage amplification. And string inverters prevent mismatch losses between strings and let each string operate at its maximum power point. Furthermore, string diodes are removed which reduces energy losses. In terms of continuity of service, it is very unlikely that all string inverters are down simultaneously, which ensures at least a minimal power production to the grid.

However, since PV string is still comprised of multiple panels in series, MPPT performance for each string will still be not good due to direct series connection. In addition, the extra inverters not only add power conversion losses but also add the cost of the PV system.

3) **Multi-string inverters**

The multi-string inverter depicted in Figure 1-4 (c) is the further development of the string inverter, where several strings are interfaced with their own dc/dc converter to a common dc/ac inverter [23]. This is beneficial, compared with the centralized system, since every string can be controlled individually. The dc/dc converter is also used to elevate PV string
voltage to a high voltage dc bus. The introduction of a dc bus reduces inverter functionalities since the MPPT function is realized by dc/dc converter instead of the inverter.

This topology also makes the PV system more flexible. Indeed, the PV panels used from one string to another can be different in size, age, technology or even nominal power values. Further enlargements are easily achieved to a certain extent since a new string with dc/dc converter can be plugged into the existing system.

4) Micro inverters

It is also called AC module inverter because the PV panel and inverter are integrated into one device, depicted in Figure 1-4 (d) [24]. It removes the mismatch losses between PV panels since only one PV panel is controlled, and MPPT can be done through individual PV panels, so there is a possibility of higher efficiency. It is good for mass production due to the modular structure, which leads to low production and retail cost. Another advantage is that a single failing PV panel or inverter cannot take the entire system offline. The opportunity to become a ‘plug-and-play’ device, which can be used by persons without any knowledge of electrical installations, is also an inherent feature.

On the other hand, a single PV panel’s voltage may not be high enough to connect to the grid directly by a traditional inverter. More complex circuit topologies should be used in this structure, and then the necessary high voltage-amplification may reduce the overall efficiency and increase the price per watt. This offsets the advantage in terms of simplification of individual modules.

Considering the low conversion efficiency and high cost of PV panels, it is very desirable to extract as much power from them as possible and to operate each panel at its maximum
power point. On condition that the individual MPPT of each PV panel can be accomplished, from point of view of the conversion and the connection, the modular PV inverters can be further categorized to four groups as follows.

Figure 1-5 Modular PV system: (a) DC parallel (b) DC series (c) AC parallel (d) AC series
The DC parallel configuration consists of integrated DC/DC converters with each PV panel. And then all the DC/DC converters are connected in parallel to a centralized DC/AC inverter [25], shown in Figure 1-5 (a). This structure is similar to the multi-string inverter where exists the difference that single PV panel instead of the string is controlled by the DC/DC converter to realize the individual MPPT of each PV panels. On the other hand, the design of the DC/DC converter in this configuration is challenging since they are required to perform high voltage step up ratio in order to convert the low PV voltage to a high enough DC bus voltage. Besides, the efficiency and the cost of the system suffer due to the two stage architecture as well as the requirement for each DC/DC converters to deliver a high output voltage.

The DC series configuration consists of several series PV panels, in which each includes a DC/DC converter and a centralized DC/AC inverter, as shown in Figure 1-5 (b). Particularly, the DC/DC converters in series connection structure are usually called solar power optimizers [26], where the MPP operation of each PV panels is optimized. This series connection can obtain a DC voltage high enough for interfacing with the DC bus of the centralized inverter. Therefore, the DC/DC converters are not required to have the voltage amplification feature and then low voltage switching devices can be used, which presents advantages in cost and efficiency. Because of the series connection, the output current of the DC/DC converters remains the same, and their output voltages vary based on the amount of energy they deliver. Thus, careful design is needed in this series connection structure and it is also a two-stage architecture that damages the system efficiency.
The AC parallel configuration shown in Figure 1-5 (c) is the same as the micro-inverter (AC module) structure aforementioned. It is a single-stage inverter, which is beneficial to the system efficiency. Whereas the inverter must handle all tasks itself, i.e., MPPT, grid current control and voltage amplification. Therefore, the common inverter cannot be used here and more complex circuit topologies must be adopted, which may reduce the efficiency and add the cost.

The AC series configuration, shown in Figure 1-5 (d), consists of several series PV panels with their own DC/AC inverters. The series DC/AC inverters are then connected to form the AC grid. The individual MPP operation of each PV panel can be guaranteed with this configuration and modular design is achievable. Since the series connection itself is responsible for the voltage amplification function, the tasks of the DC/AC inverters reduce to the MPPT of each PV panels and the grid current control, compared to those in the AC parallel structure. And it can eliminate one stage of power conversion hence potentially increase the efficiency. The disadvantage is that the control may be more complex because of the series connection.

In order to combine advantages of the individual MPPT and single stage conversion, AC series technology is the most promising technique that developed recently. Among the available power inverter topologies that can be adopted in this structure, cascaded multilevel inverter topology as shown in Figure 1-6 is particularly attractive for grid tied PV applications [27][28].
The cascaded multilevel inverter contains only single stage for DC to AC conversion, and the output voltage level required for grid power injection can be achieved without the use of a transformer as the voltage is boosted by the cascade connection of H-bridge outputs. Transformer-less concepts are advantageous regarding the high efficiency. Avoiding the transformer has the additional benefits of reducing cost, size, weight and complexity of the inverter. Additionally, with the same power level, compared to the centralized two-level inverter, this topology features switching devices with a lower rating, allowing cost savings. Since the dc link voltages can be independently controlled, the maximum power extraction of each PV panel can be accomplished with the help of MPPT algorithms. This improves both PV system reliability and energy production when the PV panels operate under mismatching conditions such as in the case of partial shading.
Moreover, the topology allows the synthesis of staircase ac output waveforms with lower total harmonic distortion (THD) compared to those generated by two-level-based inverters, thus releasing output filters requirements for the compliance of grid harmonic standards [29].

However, the control of the cascaded multilevel inverter with PV panels is still complicated and challenging [30][31]. On one hand, accurate and fast MPPT algorithm and robust dc link voltage regulation should be achieved to guarantee the individual and high efficiency MPPT of each PV panel. On the other hand, the zero steady state AC current regulation is highly desirable for low total harmonic distortion (THD) and maximum available power transfer efficiency. Furthermore, the decentralized control method for this PV system is also highly desirable from the modularization point of view.

1.4 Thesis outline

This thesis focuses on the design and control issues of the PV system based on cascaded multilevel inverter.

The thesis consists of four chapters, which are organized as flows:

Chapter 1 introduces the research background. Some standards required for the inverters designed for grid tied applications are summarized. The characteristics of PV panels have been described. And the conventional and up-to-date PV system structures are reviewed. The advantages and disadvantages of different system structures are addressed and compared.

In chapter 2, several kinds of MPPT algorithms are introduced and compared. An improved MPPT method is proposed to achieve fast and accurate tracking performance. In addition, the detailed analysis of cascaded multilevel inverter is presented. The control of
cascaded H-bridge multilevel inverter on d-q coordinate is proposed and analyzed. The controller can regulate the multiple dc link voltages and the grid connected current at the same time. The individual MPPT of each PV panels and the high quality of the grid current can be achieved. Average small signal model of the system is derived. The power stage design of cascaded 7-level inverter is also given in this chapter. Finally, the feasibility of the control strategy and power converter is validated by the simulation and experimental results.

Chapter 3 proposed a decentralized controller for the PV system based on cascaded multilevel converter. Compared to the centralized control strategy proposed in Chapter 2, the decentralized controller can reduce the number of wire connections among the modules and lower the requirements of the communication network, which makes the whole system less complex. In addition, the decentralized control strategy can further modularize the hardware since the local controller, input capacitor, and inductor can be integrated with H-bridge to form the AC module, which makes the possibility of mass production. Finally, simulation work is done to verify this control strategy.

Chapter 4 summarized the conclusion of the thesis and proposes future work based on current work and research demands.
Chapter 2. Control and design of PV system based on cascaded multilevel converter

2.1 Topology and operating principle

The cascaded multilevel inverter was firstly proposed in 1975 [32]. Typically, a cascaded multilevel inverter consists of a number of identical H-Bridges, whose outputs are connected in series for generating a higher AC voltage, as shown in Figure 2-1. For the reactive power compensation application, only capacitor is needed at the DC side. For the applications involving active power transfer, each H-Bridge can be supplied by separate DC power supplies, renewable energy resources, such as PV, and energy storage devices, such as battery [33-35].

Figure 2-1 Topology of cascaded multilevel inverter
The basic H-bridge converter structure and its operating principle are depicted in Figure 2-2. Unipolar sinusoidal pulse width modulation (SPWM) method that is commonly used in inverters can be adopted in cascaded multilevel inverter for improving the harmonic performance and reducing the filter requirement. Figure 2-2 (b) and (c) illustrates the equivalent pulse generation logic circuit and the waveforms of H-Bridge by using the unipolar SPWM.

Figure 2-2 Operation principle of H-bridge unit
As is known to all, H-Bridge generates three voltage levels: \( +V_{DC} \), 0, and \( -V_{DC} \), where \( V_{DC} \) is the input DC voltage. For the cascaded multilevel converter structure, if the input DC voltages are identical, the following equation can be given, where \( E \) is the DC voltage of the single H-bridge.

\[
V_{DC1} = V_{DC2} = \cdots = V_{DCn} = E
\]  

(2.1)

The resulting AC output voltage \( V_{HT} \) swings from \(-nE \) to \( nE \) with \( 2n+1 \) levels by the phase-shift SPWM (PSPWM) technique [36]. This technique can heighten the equivalent carrier frequency and simplify the designing and implementing of filter. A typical seven-level synthesized waveform is illustrated in Figure 2-3.

Figure 2-3 Synthesis of multilevel waveforms by using PSPWM
2.2 Characteristics of Photovoltaic Panel

The commercial PV panel is built up with series and/or parallel connected combinations of PV cells. An ideal PV cell can be modeled by a light-dependent current source in parallel with a diode. In practice a shunt resistance and a series resistance are added to the model as shown in Figure 2-4 [37][38].

Where, $I_{ph}$ is the photon current, $I_{cell}$ and $V_{cell}$ are the PV cell output current and voltage, $R_{sh}$ is the shunt resistance of the cell, and $R_s$ is the series resistance; $I_d$ is the diode current. The shunt resistance $R_{sh}$ is very large and the series resistance $R_s$ is very small, so that most of the available current can be delivered to the load.

![Figure 2-4 Ideal model of PV cell](image)

Assuming that one PV panel consists of $p$ parallel strings and $s$ series cells per string , the current-voltage (I-V) characteristic equation of PV panel can be described by (2.2) to (2.5) as shown below [38].
\[ I_{\text{cell}} = I_{\text{ph}} - I_s \left[ \exp\left(\frac{qV_d}{AK_BT}\right) - 1 \right] - \frac{V_d}{R_{\text{sh}}} \]  \hspace{1cm} (2.2)

\[ V_d = V_{\text{cell}} + I_{\text{cell}}R_s \]  \hspace{1cm} (2.3)

\[ G = \frac{q}{AK_BT} \]  \hspace{1cm} (2.4)

\[ I_{\text{pv}} = n_pI_{\text{ph}} - n_pI_s \left[ \exp\left(\frac{V_{\text{pv}} + I_{\text{pv}}R_{\text{spv}}}{n_s} - 1 \right) \right] - \frac{V_{\text{pv}} + I_{\text{pv}}R_{\text{spv}}}{R_{\text{shpv}}} \]  \hspace{1cm} (2.5)

Where, \( I_s \) is the saturation current of the diode, \( q \) is the electron charge \((1.6 \times 10^{-19} \text{C})\), \( A \) is diode ideality factor, \( K_B \) is Boltzmann Constant \((1.38 \times 10^{-23} \text{J}/\text{K})\), \( T \) is the cell working temperature, \( V_d \) is the diode voltage in volts. \( I_{\text{pv}} = n_pI_{\text{cell}} \) is PV panel output current, \( V_{\text{pv}} = n_sV_{\text{cell}} \) is PV panel output voltage, \( n_s \) is the number of cells connected in series per string, \( n_p \) is the number of strings connected in parallel per panel. \( R_{\text{spv}} = R_s n_s \) is the PV panel series resistance, \( R_{\text{shpv}} = R_{\text{sh}} n_s \) is the PV panel shunt resistance.

In practice, the output characteristics of PV panel are nonlinear, as shown in Figure 2-5. On the I-V curve or the P-V curve, there is a well-defined point (at the knee of the curve), at which the module delivers maximum power or operates at its maximum efficiency [37]. This is the so called maximum power point (MPP) of the PV panel. At the left side of MPP, the PV panel is in the current source region, while at the right side, it behaves like a voltage source. \( I_{\text{sc}} \) is the current of short circuit, \( V_{\text{oc}} \) is the voltage of open circuit, \( P_{\text{MPP}} \) is the
maximum power that PV panel can deliver in that condition, $I_{MPP}$ and $V_{MPP}$ are the output current and voltage at the MPP, respectively.

Besides, the characteristic of PV panel is critically affected by solar irradiance and temperature. The curves can be simulated by the actual parameters fitted in above equations. Figure 2-6 (a) and (b) show the simulated I-V and P-V characteristic for various irradiance ($W/m^2$) at fixed temperature (25 °C), where they clearly show that output current decreases with less irradiance but panel output voltage does not change too much with varying sunlight. The irradiance mainly affects the panel output current but has very little effect on panel output voltage. The I-V and P-V characteristics for different temperatures (°C) at fixed irradiance of 1000 W/m² are illustrated in Figure 2-6 (c) and (d), respectively. On the contrary, the temperature has much more effect on panel output voltage than current, and output voltage increases with lower temperature.
2.3 Maximum Power Point Tracking (MPPT) method

Due to the low conversion efficiency and high cost of PV panel, it is significantly vital to extract as much power from the PV panel as possible and to operate the PV panel at the MPP. However as shown in Figure 2-6, the MPP varies with the level of the temperature and solar irradiance and these two environmental variables change constantly throughout the day, which makes the extraction of maximum power a complex task. Therefore, it is necessary to implement a maximum power point tracking (MPPT) algorithm.

The MPPT is the automatic control algorithm to adjust the operation of power converters to achieve the maximum power harvest, during various atmospheric conditions. It has
become an essential component to evaluate the design performance of photovoltaic power systems.

Since MPPT is a key step in maximizing the utilization efficiency of PV panel and increasing energy efficiency in PV systems, many MPPT methods have been proposed over decades [39-41]. Those methods can be divided into three types: indirect control, direct control, and intelligent or probabilistic control.

Indirect control methods are based on the use of a database that includes parameters and data such as characteristics curves of the PV panel for different irradiances and temperatures or on using some mathematical empirical formula to estimate MPP. Methods like Curve-Fitting Technique, Fractional Short-Circuit Current (FSCI) Technique [42], Fractional Open-Circuit Voltage (FOCV) Technique [43], and Look-up Table Technique [44][45]are included in indirect method.

Direct control methods can seek MPP directly by taking into account the variations of the PV panel operating points without any advanced knowledge of the PV panel characteristics. The MPPT algorithms that include in this type are Perturbation and Observation (P&O) Technique/Hill-climbing Technique [46][47], Incremental Conductance (Inc-Cond) Technique [48][49], Feedback Voltage or Current Technique [50], Forced Oscillation Technique [51], and Ripple Correlation Control (RCC) Technique [52].

Intelligent control methods include Fuzzy logic (FL)-Based MPPT Technique [53], Artificial Neural Network (ANN)-Based MPPT Technique [54], and other MPPT algorithms.
Among these methods, the constant Voltage (FOCV Technique), the P&O and the Inc-Cond are most popular methods for several reasons, which will be discussed and compared in detail in the following sections.

2.3.1 CV Method

The Constant Voltage (CV) Method results from the fact that, output voltage at the MPP $V_{MPP}$ is approximately linearly related to the open circuit voltage $V_{oc}$ under varying atmospheric conditions, which is shown in [43], described by Eq.(2.6).

$$V_{MPP} \approx K_v V_{oc}$$  \hspace{1cm} (2.6)

It is found that the value of $K_v$ varies from 0.78 to 0.92. The basic concept of this method is to set the coefficient $K_v$ to a constant value arbitrarily and to get the value of $V_{MPP}$. In practice, the basic parameters of the PV panel are given and the coefficient $K_v$ can be defined. This method can give nearly accurate $V_{MPP}$ value, since $V_{MPP}$ and $V_{oc}$ are varying little with different irradiances. However, the temperature effect that neglected in this method will make the operating point deviate from the MPP, since $V_{MPP}$ and $V_{oc}$ are highly affected by temperature changes.

The main advantage of the CV method is that it is very easy and cheap to implement. Only one voltage sensor is used and DSP or microcontroller control is not necessarily required. The drawback is the low accuracy since this method is not a true MPPT technique, but this can sometimes be adequate depending on the applications of PV systems.
In _FOCV_ Method, expect for the use of the same equation, different data are computed beforehand by empirically determining $V_{MPP}$ and $V_{oc}$ for the specific PV panel at different irradiance and temperature levels to guarantee the reliability and accuracy of the MPPT algorithm. This obviously adds to the implementation complexity and incurs more power loss.

### 2.3.2 Perturbation and Observation (P&O) Technique

The _P&O_ Technique is one of the most straightforward and popular methods due to its simplicity and easy implementation. It can be applied to both analog and digital designs and it is also compatible with any kind of PV panels.

In this technique, first the PV voltage $V(t-\Delta t)$ and current $I(t-\Delta t)$ are measured and hence the corresponding power $P(t-\Delta t)$ is calculated, corresponding to point A of the PV curve in Figure 2-7. Considering a small perturbation of voltage ($\Delta V$) in one direction, for example the direction in the Fig from point A to B, the PV voltage $V(t)$ and current $I(t)$ are measured and the corresponding power $P(t)$ is calculated. $P(t)$ is then compared to $P(t-\Delta t)$, If $P(t)$ is greater than $P(t-\Delta t)$, then the perturbation is in the correct direction and the next step is to continue to perturb the voltage in that direction, from point B to C in Fig.; otherwise the direction should be reversed, such as the trace from B to A then back to point B. The flowchart of this algorithm is presented in Figure 2-8.
Figure 2-7 Operating principle of P&O method

Figure 2-8 Flow chart of P&O method
This process is periodically repeated until the operating point moves backward and forward (\(L \rightarrow M \rightarrow L\)) around the maximum power point marked as O in the Figure 2-7. The continuous perturbation and observation guarantees that the controller can always find the new maximum power point regarding the variation of temperature and solar irradiance.

It is obvious from the \(P&O\) technique that it is almost impossible to achieve the exact MPP, which will lead to oscillation problem around the MPP in steady state. The oscillation around the MPP is an intrinsic problem of this method and means the power loss of the available delivered power. Larger perturbation will induce larger power loss and lower MPPT efficiency. For example, compared to the trace \(L \rightarrow M \rightarrow L\), the trace \(L \rightarrow N \rightarrow L\) due to the larger perturbation step size \(\Delta V_2\) will lead to larger power deviation from the MPP. The oscillation can be minimized by reducing the perturbation step size \(\Delta V\). However, the smaller perturbation size will slow down the MPPT process. As shown in Figure 2-7 in the process of MPP tracking, it need almost twice of sample time by the use of \(\Delta V_1\) from A to C, while the larger perturbation size \(\Delta V_2\) shortens the time to single sample period. Therefore, suitable perturbation size is very important in providing good performance in both dynamic and steady-state response.

Modified \(P&O\) technique is then obtained when the perturbation step is changed according to the distance of the MPP [55]. An automatic tuning controller varies the perturbation step size to a large value when the power changes in a wide range, to satisfy the fast response requirement during the transient stage. On the other hand, when the power change is less than
the lowest setting limit, the controller assumes that the system enters the steady state and the perturbation step size becomes small.

Different methods have been proposed in many literatures to get the desired perturbation step [56]. In [57], the voltage perturbation value is set to be 10% of the open-circuit voltage. Each successive perturb is 50% of the previous one until the perturbation value is 0.5% of the open-circuit voltage. [58] uses a hysteresis band and auto-tuning perturbation step. The perturbation step size of [59] is proportional to the power change.

2.3.3 Incremental Conductance (Inc-Cond) Technique

For a PV system, the derivative of PV panel output power with respect to its voltage is expressed as Eq. (2.7).

\[
\frac{dP}{dV} = \frac{d(I \times V)}{dV} = I + V \frac{dI}{dV} = I + V \frac{\Delta I}{\Delta V}
\]

(2.7)

Referring to the PV curve of the PV panel, Eq. (2.7) is zero at the MPP, negative on the right of MPP, and positive on the left side. Then, it can be rewritten as in Eq. (2.8):

\[
\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad \text{at MPP}
\]

\[
\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad \text{at left of MPP}
\]

\[
\frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad \text{at right of MPP}
\]

(2.8)

The Inc-Cond technique is based on the intrinsic characteristic of the P-V curve. The MPP is tracked by comparing the instantaneous conductance \( \frac{I}{V} \) to the incremental conductance
\( \frac{\Delta I}{\Delta V} \) of the PV panel. If \( \frac{\Delta I}{\Delta V} > \frac{I}{V} \), it indicates the operating point is on the left side, then the following step is to increase the output voltage reference \( V_{\text{ref}} \). Otherwise, when \( \frac{\Delta I}{\Delta V} < \frac{I}{V} \), the PV panel is operating on the right side and the reference \( V_{\text{ref}} \) should be decreased. The flowchart is then obtained in shown in Figure 2-9.

---

**Figure 2-9 Flow chart of Inc-Cond technique**
The method is the same efficient as P&O Technique. The difference lies on the approaches to make the correct decision: Inc-Cond uses Eq. (2.8) to verdict the operating point (left or right of MPP or at MPP); while P&O compares the current power with the previous value to generate the reference value.

It seems that the Inc-Cond technique can overcome the oscillation issue of P&O technique. It is theoretically possible to know when the MPP has been reached and therefore when the perturbation can be stopped, whereas in the P&O technique the operating point oscillates around the MPP. However as discussed in [60], in practice, considering the noise, measurement, and quantization on errors, the condition \[ \frac{\Delta I}{\Delta V} = -\frac{1}{V} \] is impossible to satisfy. As a consequence, the operating voltage cannot be exactly coincident with the MPP and will oscillate around it. Therefore, the same perturbation size problem as the P&O exists. In [61], authors recommend that the Inc-Cond technique is not treated as a separate MPPT method but as a specific implementation of P&O technique.

Furthermore, the division operation and more calculations are required in the Inc-Cond technique and therefore set higher demand on the controller, which requires complex and costly control circuits.

From the discussion above, the P&O method is the preferred choice. Specifically, an improved method is presented in this work that brings the operating point of the PV panel close to the MPP in a first stage and then uses modified P&O technique to exactly track the MPP in a second stage [62]. Conceptually, it is the combination of the CV method and P&O technique. When starting up the PV converter, setting the reference voltage value to an
empirical $V_{\text{MPP}}$ value can reduce the tracking period at the beginning. After operating in the vicinity of the MPP, a variable perturbation step size helps reach the exact MPP. This method combines the advantages of both CV Method and P&O Technique, which will be applied on the prototype.

2.4 Centralized control of PV system

For grid-tied PV system, it is required to meet the standards listed in Chapter 1. The power factor and the current THD are two important parameters to evaluate the system’s performance. Therefore the grid-connected current should be controlled to guarantee both the power factor and low harmonics. In addition, another basic function is to ensure that the PV panels operate at their maximum power points, which means each DC-link voltage should be controlled to follow the MPP reference, respectively. Therefore, in order to properly operate the cascaded multilevel converter with PV panels, the independent control of the DC-link voltages and the control of the grid current are necessary and should be accomplished simultaneously.

Several methods have been proposed to the control of this system. In [63-65], the reference signals for the modulation units of each H-bridge are multiplied by a factor that depends on the voltage in each DC-link or the power that the corresponding PV panel is delivering. Other approaches regard the DC-link voltages to be approximately equal and use the traditional cascaded multilevel converter’s control method [66], which is not adequate for the tracking of the MPP in each PV panel in the partial shading condition. In [67] and [68], control methods based on passivity controllers have been presented. However, the equations for the
controller are not explicitly described, and high-performance control platform are required for real-time implementation of the proposed control schemes.

In [69], a simple scheme is applied for the control of the PV cascaded converter system. The control scheme is enhanced with MPPT algorithms that independently adjust the reference of the DC-link voltages in order to maximize the generated energy. In addition, the inner current close loop with PI controller is provided to guarantee the quality of the grid current. However, this control method is conducted in static coordinate. It is known that the simple proportional plus integration (PI) controller cannot track the AC signal with zero steady state error, thus the system efficiency may be compromised. Therefore a single phase d-q coordinate control strategy is proposed here for the PV system enabled by the cascaded multilevel towards an independent regulation of DC-link voltage as well as high performance tracking of grid-connected current. Another benefit of the d-q coordinate control strategy is that the reactive power can be extracted from the control loop and is identically divided into the H-bridges. Whereas, the reactive power of [69] is provided only by the modulation signals of the first H-bridge, which increases the possibility of over-modulation.

Figure 2-10 shows the configuration for a single-phase cascaded multilevel interfaced PV system. $v_s$ is the voltage at point of common coupling (PCC), $i_s$ is the injected current to the PCC. $L_s$ is the smoothing inductor, and $R_s$ represents the equivalent resistor of the inductor, wire and losses. $C_i$ $(i = 1…n)$ is the DC capacitor in each DC-link. The output of $N$ H-bridges $v_{h1}, v_{h2}…v_{hn}$ are series connected to synthesize a $2N+1$ level waveform,
which is $v_{Pi} \cdot v_{pvi}$ and $i_{pvi} \ (i = 1...n)$ denote the output voltage and current of the $i_{th}$ PV panel. $T_{ij} \ (i=1...n; j=1...4)$ denotes the switch of the converter.

![Figure 2-10 Topology of grid connected PV system based on cascaded multilevel converter](image)

D-q coordinate controller is deemed to own the benefit of zero-error tracking for fundamental frequency AC signal [70]. In contrast to three phase system, there is only one phase variable available in single phase system, while d-q transformation needs at least two orthogonal variables. In order to construct additional orthogonal phase information from the original single phase system, the imaginary orthogonal circuit concept is introduced here.
The imaginary circuit has exactly the same circuit components and parameters, e.g. power switches, inductors and resistors. Ideally the state variables and control references maintain 90° phase shift with respect to their counterparts in original circuit. Imaginary H-bridges lagging 90° from the original H-bridges, must be hypothesized [72], as shown in Figure 2-11 by the dash line.

Figure 2-11 Equivalent circuit for controller derivation
The inductor current in the hypothesized cascaded H-bridges is represented as \( i_m \) and the PCC voltage for the hypothesized converter is \( v_m \). \( T_{mij} \) \((i=1, \ldots, n; j=1, \ldots, 4)\) is the switch of the hypothesized converter. The relationship between \( v_g \) in the original system and \( v_m \) in the hypothesized system is shown in Figure 2-12. \( v_m \), which is represented by dash line, lags 90\(^\circ\) with \( v_g \) shown in solid line.

\[
\text{Figure 2-12 Synthesis of imaginary phase}
\]

Define the switching functions of both original and imaginary phases in the cascaded converter as, where \( i=1, \ldots, n \).

\[
S_i = \begin{cases} 
1 & T_{i1}, T_{i4} \text{ on} \\
0 & T_{i1}, T_{i3} \text{ on or } T_{i3}, T_{i4} \text{ on} \\
-1 & T_{i2}, T_{i3} \text{ on}
\end{cases} \quad (2.9)
\]

\[
S_{mi} = \begin{cases} 
1 & T_{mi1}, T_{mi4} \text{ on} \\
0 & T_{mi1}, T_{mi3} \text{ on or } T_{mi3}, T_{mi4} \text{ on} \\
-1 & T_{mi2}, T_{mi3} \text{ on}
\end{cases} \quad (2.10)
\]
Take $S_i$ as an example for illustration. If the switches $T_{i1}$ and $T_{i4}$ are turned on, the switching function $S_i$ equals to 1 and then the output voltage of H-bridge $v_{Hi}$ equals to $v_{pvi}$. If the switches $T_{i2}$ and $T_{i3}$ are conducted, the switching function $S_i$ equals to -1 and then $v_{Hi}$ equals to $-v_{pvi}$. Otherwise, if the switches $T_{i1}$ and $T_{i3}$ are conducted or switches $T_{i2}$ and $T_{i4}$ are conducted, the switching function $S_i$ equals to 0 and then $v_{Hi}$ is 0. $S_{mi}$ has the same definition as $S_i$. Actually, $S_{mi}$ is only introduced for the single phase am-dq transformation, and it is not applied to real control since the hypothesized phase does not physically exist.

Applying Kirchhoff’s law (KVL and KCL) to Figure 2-12, the dynamic behavior of the system can be described by the following equations:

$$L_s \frac{di_s}{dt} + R_s i_s + v_g = v_H = \sum_{i=1}^{n} S_i v_{pvi} \tag{2.11}$$

$$L_s \frac{di_m}{dt} + R_s i_m + v_m = v_{mH} = \sum_{i=1}^{n} S_{mi} v_{pvi} \tag{2.12}$$

$$C_i \frac{dv_{pvi}}{dt} + S i_s + S_{mi} i_m = i_{pvi} \quad (i = 1, \ldots, n) \tag{2.13}$$

Those equations can be combined in the form of matrix as follows:

$$\begin{bmatrix}
\frac{di_s}{dt} \\
\frac{di_m}{dt}
\end{bmatrix} = \begin{bmatrix}
\frac{-R_s}{L_s} & 0 \\
0 & \frac{-R_s}{L_s}
\end{bmatrix} \begin{bmatrix}
i_s \\
i_m
\end{bmatrix} + \begin{bmatrix}
\frac{1}{L_s} v_g \\
\frac{1}{L_s} v_m
\end{bmatrix} + \begin{bmatrix}
\frac{v_{pvi}}{L_s} S_1 \\
\frac{v_{pvi}}{L_s} S_{mi}
\end{bmatrix} + \begin{bmatrix}
\frac{v_{pvi}}{L_s} S_2 \\
\frac{v_{pvi}}{L_s} S_{mi}
\end{bmatrix} + \cdots + \begin{bmatrix}
\frac{v_{pvi}}{L_s} S_{n} \\
\frac{v_{pvi}}{L_s} S_{nn}
\end{bmatrix} \tag{2.14}
$$

Define the average duty cycle in a switching period as shown in Eq.(2.15):
\[ d_i = S_i, \quad d_{mi} = \overline{S_{mi}} \quad (i = 1, \ldots, n) \]  

And average the voltage and current in a switching period, which are denoted as \( \overline{v_g}, \overline{v_m}, \overline{i_s}, \overline{i_m}, \overline{v_{pvi}}, \) and \( \overline{i_{pvi}} \). The averaged state-space equations of the system are shown as:

\[
\begin{bmatrix}
\frac{d}{dt} \overline{i_s} \\
\frac{d}{dt} \overline{i_m}
\end{bmatrix} = \begin{bmatrix}
\frac{-R_s}{L_s} & 0 \\
0 & \frac{-R_s}{L_s}
\end{bmatrix} \begin{bmatrix}
\overline{i_s} \\
\overline{i_m}
\end{bmatrix} - \frac{1}{L_s} \begin{bmatrix}
\overline{v_g} \\
\overline{v_m}
\end{bmatrix} + \frac{\overline{v_{pvi}}}{L_s} \begin{bmatrix} d_1 \\
\overline{d_{m1}}
\end{bmatrix} + \frac{\overline{v_{pvi2}}}{L_s} \begin{bmatrix} d_2 \\
\overline{d_{m2}}
\end{bmatrix} + \cdots + \frac{\overline{v_{pvi}}}{L_s} \begin{bmatrix} d_n \\
\overline{d_{mn}}
\end{bmatrix}
\]  

(2.16)

\[
d_i \overline{i_s} + d_{mi} \overline{i_m} = \begin{bmatrix} d_1 \\
\overline{d_{m1}}
\end{bmatrix} \overline{d_i} - \frac{C_i}{L_s} \frac{d}{dt} \overline{v_{pvi}} \quad (i = 1, \ldots, n)
\]  

(2.17)

The am-dq transformation matrix is defined in Eq. (2.18) [73], where \( \omega \) is the angle frequency of \( v_g \).

\[
T = \begin{bmatrix}
\sin(\omega t) & -\cos(\omega t) \\
\cos(\omega t) & \sin(\omega t)
\end{bmatrix}
\]  

(2.18)

The variables in the d-q rotating frame become that shown in Eq. (2.19), where the variables \( X_d \) and \( X_q \) may represent either voltages or currents in the rotating frame, \( X \) and \( X_m \) represent the stationary real and imaginary circuit variables, respectively.

\[
\begin{bmatrix} X_d \\
X_q
\end{bmatrix} = T \begin{bmatrix} X \\
X_m
\end{bmatrix}
\]  

(2.19)

The inverse transformation matrix from the d-q rotating frame to the stationary real and imaginary circuit variables can be easily expressed as:

\[
T^{-1} = \begin{bmatrix}
\sin(\omega t) & \cos(\omega t) \\
-\cos(\omega t) & \sin(\omega t)
\end{bmatrix}
\]  

(2.20)

Substitute (2.20) into (2.16) and (2.17):
\[
\frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -R_s & 0 \\ 0 & -R_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} -v_{gd} \\ -v_{gq} \end{bmatrix} \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix} \begin{bmatrix} v_{gd} \\ v_{gq} \end{bmatrix} 
\]
\[
\quad + \left( \frac{v_{pvi}}{L_s} T^{-1} \begin{bmatrix} d_{d1} \\ d_{d2} \end{bmatrix} + \frac{v_{pqi}}{L_s} T^{-1} \begin{bmatrix} d_{q1} \\ d_{q2} \end{bmatrix} + \cdots + \frac{v_{pnn}}{L_s} T^{-1} \begin{bmatrix} d_{dn} \end{bmatrix} \right) 
\]
\[
\begin{bmatrix} d_{di} \\ d_{mi} \end{bmatrix}^T T^{-1} \begin{bmatrix} \hat{i}_s \\ \hat{i}_m \end{bmatrix} = T \begin{bmatrix} d_{di} \\ d_{mi} \end{bmatrix}^T T^{-1} \begin{bmatrix} \hat{i}_s \\ \hat{i}_m \end{bmatrix} = \bar{i}_{pvi} - C_i \frac{d}{dt} v_{pvi} \quad (i = 1, \ldots, n) 
\]

Recall that the following equation is satisfied:

\[
T \frac{d}{dt} (T^{-1}) = \begin{pmatrix} 0 & -\omega \\ \omega & 0 \end{pmatrix} 
\]

Where, \( \omega \) is the angular frequency of the grid voltage.

The state-space equations of the system in the d-q coordinate can be simplified as:

\[
\begin{align*}
\frac{d}{dt} \begin{bmatrix} \bar{i}_{sd} \\ \bar{i}_{sq} \end{bmatrix} &= \begin{bmatrix} -R_s & \omega \\ -\omega & -R_s \end{bmatrix} \begin{bmatrix} \bar{i}_{sd} \\ \bar{i}_{sq} \end{bmatrix} - \frac{1}{L_s} \begin{bmatrix} v_{gd} \\ v_{gq} \end{bmatrix} + \frac{v_{pvi}}{L_s} \begin{bmatrix} d_{d1} \\ d_{q1} \end{bmatrix} + \frac{v_{pqi}}{L_s} \begin{bmatrix} d_{d2} \\ d_{q2} \end{bmatrix} + \cdots + \frac{v_{pnn}}{L_s} \begin{bmatrix} d_{dn} \end{bmatrix} \\
\frac{d}{dt} \bar{i}_{sd} + \frac{d}{dt} \bar{i}_{sq} &= \bar{i}_{pvi} - C_i \frac{d}{dt} v_{pvi} \quad (i = 1, \ldots, n)
\end{align*}
\]

In order to construct the small-signal ac equations, the next step is to perturb and linearize the state-space equations. Assuming that the system variables \( \bar{v}_{gd}, \bar{v}_{gq}, \bar{i}_{sd}, \bar{i}_{sq}, \bar{d}_{di}, \bar{d}_{qj}, \bar{v}_{pvi} \) and \( \bar{i}_{pvi} \) can be expressed as quiescent values plus small ac variations as follows:

\[
\bar{v}_{gd} = V_{gd} + \hat{v}_{gd}, \quad \bar{v}_{gq} = V_{gq} + \hat{v}_{gq}
\]

\[
40
\]
With these substitutions, we can get the large-signal averaged equations, which contain three types of terms. The dc terms contain no time-varying quantities. The first-order ac terms are linear functions of the ac variations. And the second-order ac terms are functions of the products of the ac variations. The second-order terms are much smaller in magnitude than the first-order terms, so we can neglect the second-order terms in the following analysis. The small signal ac equations can be summarized below:

\[ L_s \frac{d}{dt} \hat{i}_{\text{sd}} = -R_s \hat{i}_{\text{sd}} + \omega L_s \hat{i}_{\text{sq}} - \hat{v}_{gd} \]
\[ + \left( \left( V_{pvi1} \hat{d}_{d1} + D_{d1} \hat{v}_{pvi1} \right) + \left( V_{pvi2} \hat{d}_{d2} + D_{d2} \hat{v}_{pvi2} \right) + \ldots + \left( V_{pvn} \hat{d}_{dn} + D_{dn} \hat{v}_{pvn} \right) \right) \]  

\[ L_s \frac{d}{dt} \hat{i}_{\text{sq}} = -\omega L_s \hat{i}_{\text{sd}} - R_s \hat{i}_{\text{sq}} - \hat{v}_{gq} \]
\[ + \left( \left( V_{pvi1} \hat{d}_{q1} + D_{q1} \hat{v}_{pvi1} \right) + \left( V_{pvi2} \hat{d}_{q2} + D_{q2} \hat{v}_{pvi2} \right) + \ldots + \left( V_{pvn} \hat{d}_{qn} + D_{qn} \hat{v}_{pvn} \right) \right) \]  

\[ \left( D_{di} \hat{i}_{\text{sd}} + L_s \hat{d}_{di} \right) + \left( D_{qi} \hat{i}_{\text{sq}} + L_s \hat{d}_{qi} \right) = \hat{i}_{\text{pvi}} - C_i \frac{d}{dt} \hat{v}_{pvi} \quad (i = 1, \ldots, n) \]

These small-signal equations lead to the equivalent circuits in Figure 2-13.
The control strategy is based on the classical scheme for the control of a single H-bridge grid connected inverter. This idea is then extended to the case of N H-bridges connected in series for the cascaded multilevel converter. According to the analysis ahead, each DC-link voltage should be controlled to follow the corresponding voltage reference for realizing independent MPPT of each PV panel. In addition, the grid current should be controlled to achieve high quality (low THD and unity power factor) as well as to guarantee the power balance of the system.

In ideal conditions, completely independent H-bridges would be expected to manage distinct power transfers and different DC voltage levels on each module. Because of the series connection of the H-bridges, all the modules have the same circulating current $i_s$. 

Figure 2-13 Small signal model of the system
hence it is not possible to implement an independent dual control loop to control each DC-link voltage like the traditional single H-bridge inverter.

From the power balance point of view, the total available output power is the sum of the power of each PV panel without considering the converter efficiency. Due to the fact that the power is transferred to a constant voltage grid, the grid current can represent the information of power. Therefore, the power control is done in an indirect way by means of the grid current control. So in order to realize the power balance of the system, the grid current reference should be decided by concentrating all the DC-link information. In turn, the total dc voltages have to be regulated through the same grid current.

The scheme in Figure 2-14 contains \( n+1 \) control loops: \( n \) of them are used to adjust the PV voltage of each DC-link, and the other one is indispensable for the generation of a sinusoidal grid current with unity power factor. As shown in Figure 2-14, the summation of the DC-link voltages is controlled through the PI controller in the outer loop. The output of the PI controller determines the amplitude of the grid current reference, which is also the d-coordinate component of the grid current reference \( i_{sd}^* \).
On the other hand, the inner PI current controller gives the d-coordinate value of the summation of the continuous switching functions $d_d$. Since the DC-links are controlled as a whole in this dual loop, there is no certainty on how to distribute the switching function of each H-bridge. So the control of the voltages $v_{p2}$ to $v_{pn}$ is made through other n-1
controllers that generate the d-coordinate components of the corresponding switching functions \(d_{a_2}\) to \(d_{a_m}\) directly. Then the switching functions \(d_{d_1}\) can be got in an indirect way.

Considering the given grid voltage \(v_g\), it is used for the synchronous signal. The a-axis of the real stationary frame is in phase with \(v_g\), and the m-axis lags the a-axis by 90°. The d-axis of the d-q rotating frame is aligned with \(v_g\) and the q-axis lags the d-axis by 90°. Therefore, d-coordinate component of the grid current \(i_{sd}\) determines the active power \(P\), and q-coordinate component of the grid current \(i_{sq}\) decides the reactive power \(Q\). The process of derivation is shown as follows:

\[
v_g = V_p \sin(\omega t) \quad (2.33)
\]

\[
i_s = I_p \sin(\omega t + \varphi) \quad (2.34)
\]

\[
v_{gd} = V_p, \quad v_{gq} = 0 \quad (2.35)
\]

\[
i_{sd} = I_p \cos \varphi, \quad i_{sq} = I_p \sin \varphi \quad (2.36)
\]

\[
P = \frac{1}{2} (v_{gd} i_{sd} + v_{gq} i_{sq}) = \frac{1}{2} V_p I_p \cos \varphi \quad (2.37)
\]

\[
Q = \frac{1}{2} (v_{gq} i_{sd} - v_{gd} i_{sq}) = -\frac{1}{2} V_p I_p \sin \varphi \quad (2.38)
\]

Where \(V_p\) and \(I_p\) are the amplitude of the grid voltage and current, respectively. \(\varphi\) is the phase angle between \(v_g\) and \(i_s\). With unity power factor, the value of \(\varphi\) is zero.

To get unity power factor, we can simply set the reference value of the q-coordinate component of grid current \(i_{sq}^*\) to zero. The output of the PI controller for q-coordinate is \(d_{a_q}\),
which represents the required reactive power by each module. The reactive power can counteract the reactive power appeared on the inductor $L_s$ and make the system deliver pure active power to the grid.

There is a degree of freedom to the distribution of reactive power among the modules. In the control strategy, the proportional relationship between the q-coordinate component of each module’s switching signal $d_{qi}$ and that of the total duty cycle $d_q$ defines what has been called proportion factors of reactive power $k_{qi}$ ($i=1,\cdots,n$).

$$k_{qi} = \frac{d_{qi}}{d_q}, \quad \sum_{i=1}^{n} k_{qi} = 1 \quad (2.39)$$

We can set $k_{q1}=1, k_{q2}=\cdots=k_{qn}=0$, which means that only the first module takes the responsibility of providing the required reactive power of the whole system. This setting will generate the largest modulation index of the first module compared to other possible settings under the same atmosphere conditions, which will increase the possibility of over-modulation of the first module. Conceptually, it has the same effect as the control strategy in [69]. The phasor diagram for this condition is shown in Figure 2-15.

![Figure 2-15 Phasor diagram of first method](image-url)
Another straightforward yet preferred setting is that each module can bear the same reactive power. In order to keep the equal reactive power distribution, we set the proportion factors $k_{q1}=k_{q2}=\cdots=k_{qn}=\frac{1}{n}$. The phasor diagram of this method is illustrated in Figure 2-16.

![Figure 2-16 Phasor diagram of equal reactive power distribution](image)

2.5 Parameters design of the cascaded multilevel inverter based PV system

In the following work, the cascaded 7-level converter will be considered for simplicity and to easily appreciate the working principle, as shown in Figure 2-17. The H-bridge together with the PV panel and the input capacitor in the block can be regarded as an identical module.
Three PV panels KD225GX-LPB from KYOCERA are chosen for the PV system. Figure 2-18 (a) and (b) show the I-V characteristics at various cell temperatures and various irradiance levels, respectively. It is observed that the MPP voltage under the room temperature is about 30V. Additionally, this MPP voltage decreases with the increasing of the temperature.
Figure 2-18 I-V curve of the PV panels from datasheet:
(a) Under different temperature; (b) Under different irradiance

Considering the range of the MPP voltage under different temperature and irradiance, the ac ‘grid’ voltage RMS value is set to 40V(60Hz) for the designed system. The switching frequency is set to 10.8kHz. Table 2-1 lists the PV panel parameters and the system variables for design.

Table 2-1 Parameters of the system

<table>
<thead>
<tr>
<th>Circuit variables</th>
<th>PV panel parameters (25°C, 1000W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage $v_g$</td>
<td>40 V (60Hz)</td>
</tr>
<tr>
<td>switching frequency $f_{sw}$</td>
<td>10.8 KHz</td>
</tr>
<tr>
<td>PV open circuit voltage $V_{oc}$</td>
<td>36.9 V</td>
</tr>
<tr>
<td>PV short circuit current $I_{sc}$</td>
<td>8.18 A</td>
</tr>
<tr>
<td>PV MPP voltage $V_{MPP}$</td>
<td>29.8 V</td>
</tr>
<tr>
<td>PV MPP current $I_{MPP}$</td>
<td>7.55 A</td>
</tr>
</tbody>
</table>
2.5.1 Design of the input capacitors

Since the three modules are identical, the capacitor of one module is analyzed here. The circuit with one module is shown in Figure 2-19.

The dc input capacitance is sized to keep input voltage fluctuations small in order to extract accurate maximum output power from the PV panel.

Assuming that the controller can guarantee the unity power factor, the grid current has the same angle as the grid voltage. The grid voltage $v_g$, grid connected current $i_s$, the instantaneous output power $p_{out}$, and the average output power $P_{avg}$ can be expressed as follows:

\[ v_g(t) = V_{gm} \sin \omega t, \quad i_s(t) = I_{sm} \sin \omega t \quad (2.40) \]

\[ p_{out} = v_g(t) \times i_s(t) = \frac{V_{gm} I_{sm}}{2} - \frac{V_{gm} I_{sm}}{2} \cos 2\omega t \quad (2.41) \]
\[ P_{\text{avg}} = \frac{V_{gm}I_{sm}}{2} \]  \hspace{1cm} (2.42)

Where, \( \omega \) is the phase angle frequency of the grid voltage. Figure 2-20 illustrates the power flowing in the system.

![Figure 2-20 Output power of the inverter](image)

According to the energy balance of the whole system, during one period \( T_s \), we have:

\[ P_{\text{in}} = V_{pv} \times I_{pv} = P_{\text{avg}} \]  \hspace{1cm} (2.43)

Where \( V_{pv} \) and \( I_{pv} \) are the average values of PV panel voltage and current within the period \( T_s \).
As shown in Figure 2-21, during the interval $\Delta t$, the instantaneous output power $p_{out}(t)$ is larger than input solar power $P_{in}$, the shadow under the power curve indicates the required extra energy.

![Diagram showing output power pulsation for capacitor sizing](image)

Figure 2-21 Output power pulsation of the inverter for capacitor sizing

$$E_{g*} = \int_{0.125T_s}^{0.375T_s} P_{avg} \left(1 - \cos 2\omega t\right)dt - P_{avg} \times 0.25T_s = \frac{P_{avg}}{\omega} \tag{2.44}$$

The required extra energy is provided by the input capacitors. And during this interval, the inductor does not absorb or release any energy as described by Eq.(2.45). So we can get Eq.(2.46):
\[ E_{i+} = \int_{0.375T_s}^{0.125T_s} L \frac{di_s}{dt} \, dt = 0 \]  
\[ E_C = E_{g+} \]  
(2.45)  
(2.46)

During the interval \( \Delta t \), the input capacitors is discharged and the maximum energy is given by Eq.(2.47):

\[ E_{C_{\text{max}}} = \frac{1}{2} C (V_c + \frac{1}{2} \Delta V)^2 - \frac{1}{2} C (V_c - \frac{1}{2} \Delta V)^2 = CV_c \Delta V \]  
(2.47)

Assuming that the desired input voltage ripple is within 2V (less than 10\% of \( V_{pv} \)), the input capacitor value can be expressed as shown in Eq.(2.48) by combining Eq.(2.44) and Eq.(2.47):

\[ C \geq \frac{P_{\text{avg}}}{\omega V_c \Delta V} = \frac{I_{pv}}{\omega \Delta V} = \frac{7.55}{2 \times \pi \times 60 \times 2} = 10mF \]  
(2.48)

Considering the effect of other minor factors (efficiency, duty cycle angle information, esr, etc), the input capacitor value is chosen to 13.2 mF (4 \times 3300 \mu F (50V)).

### 2.5.2 Design of the output inductor

The equivalent circuit of the AC side is illustrated in Figure 2-22. \( v_{ii} \) is the output voltage of the whole H bridge. To simplify the analysis, the equivalent resistor \( R_s \) is neglected here. The unipolar SPWM aforementioned will be adopted in the system. According to the principle of unipolar SPWM, in the positive half circle, the voltage \( v_{ii} \) switches between positive DC input voltage \( V_{dc} \) and 0; in the negative half circle, \( v_{ii} \) switches between 0 and
negative DC voltage $-V_{dc}$. $v_g$ should lag behind the fundamental voltage of $v_h$ to deliver the power to the grid.

The steady state waveforms of each variable are shown in Figure 2-22(b).

![Equivalent circuit of the inverter and PWM method](image)

Figure 2-22 Equivalent circuit of the inverter and PWM method

To meet the limitation of the injected harmonic current to the grid as well as the requirement of the fast speed tracking response, proper design of the inductor should be guaranteed.

Firstly the transient response of the current tracking process is considered. From the process of the transient tracking response, we can know that the maximum current slope happens at the zero-crossing point of the current. At this instant, the inductor value should be sufficiently small to ensure the rapidity of the current response.

The current response process in a switching period which includes the zero-crossing point is analyzed as follows. During this switching period, the grid voltage approximately equals to zero.
Then in steady state condition, during the subinterval $0 < t < T_1$, the slope of the inductor current waveform is:

$$\frac{di_1(t)}{dt} = \frac{\Delta i_1}{T_1} = \frac{v_H - v_g}{L_s} \approx \frac{V_{DC}}{L_s}$$  \hspace{1cm} (2.49)

During the period $T_1 \leq t \leq T_{sw}$,

$$\frac{di_2(t)}{dt} = \frac{\Delta i_2}{T_2} = \frac{v_H - v_g}{L_s} \approx 0$$  \hspace{1cm} (2.50)

In order to meet the requirement of fast following response, the equation (2.51) should be met:

$$\left| \frac{\Delta i_1}{T_{sw}} - \frac{\Delta i_2}{T_{sw}} \right| \geq \frac{I_m \sin \omega T_{sw}}{T_{sw}} \approx I_m \omega$$  \hspace{1cm} (2.51)

Where, $I_m$ is the peak value of the grid connected current; $\Delta i_1$ and $\Delta i_2$ are the current variations with respect to time $T_1$ and $T_2$.

Substitution of Eq. (2.49) and Eq. (2.50) into Eq. (2.51) and solution for the inductor value yields:

$$L_s \leq \frac{V_{DC} T_1}{I_m \omega T_{sw}}$$  \hspace{1cm} (2.52)

When the PWM duty cycle ($T_1 / T_{sw}$) reaches to the maximum value, which means $T_1 = T_{sw}$, the system should track the fastest current response. Therefore, the inductor value should be sufficiently small and can be expressed by:

$$L_s \leq \frac{V_{DC}}{I_m \omega}$$  \hspace{1cm} (2.53)
On the other hand, the inductor value should be large enough to guarantee the small
harmonic component of the current. The worst case happens near the peak value of the
current. Then the switching period near the peak current is analyzed. The waveforms of
inductor voltage and current can be obtained in Figure 2-23.

During this switching period, the grid voltage can be approximately equal to \( V_{gm} \), which
represents the peak value of the grid voltage.

Then in steady state condition, during the subinterval \( 0 \leq t \leq T_1 \), the slope of the inductor
current waveform is:

\[
\frac{di_s(t)}{dt} = \frac{\Delta i_1}{T_1} = \frac{v_H - v_g}{L_s} \approx \frac{V_{DC} - V_{gm}}{L_s}
\]  

(2.54)

During the period \( T_1 \leq t \leq T_{sw} \),
\[
\frac{di_s(t)}{dt} = \frac{\Delta i_2}{T_2} = \frac{v_{H} - v_{g}}{L_s} \approx \frac{-V_{gm}}{L_s}
\]

(2.55)

Since the analysis is based on the steady state condition, the current variations within the switching period nearby the peak point should satisfy the following formula:

\[|\Delta i_1| = |\Delta i_2|\]

(2.56)

Substitution of Eq.(2.54) and Eq.(2.55) into Eq.(2.56) and relationship of PWM duty on time \(T_1\) and off time \(T_2\) yields:

\[(V_{DC} - V_{gm})T_1 = (V_{gm})T_2\]

(2.57)

In addition, considering relationship shown in Eq. (2.58):

\[T_1 + T_2 = T_{sw}\]

(2.58)

Replace \(T_2\) with \(T_{sw} - T_1\), we have:

\[T_1 = \frac{V_{gm}T_{sw}}{V_{DC}} = \frac{V_{gm}}{V_{DC}f_{sw}}\]

(2.59)

Assuming that the maximum ripple current that the system allows is \(\Delta i_{max}\), the inductor value should be large enough and meet Eq.(2.60) to ensure the ripple magnitude is always less than \(\Delta i_{max}\).

\[L_s \geq \frac{(V_{DC} - V_{gm})V_{gm}}{\Delta i_{max}V_{DC}f_{sw}}\]

(2.60)

So combining Eq.(2.53) and Eq.(2.60), we can get the Eq.(2.61), which is a useful guideline for design of the inductor.
(2.61) \[
\frac{(V_{DC} - V_{gm}) V_{gm}}{\Delta i_{max} V_{DC} f_{sw}} \leq L_s \leq \frac{V_{DC}}{I_m \omega}
\]

Assuming that the peak to peak ripple current is set within 10% of the peak value of the output current, which can be calculated:

\[
I_m = \sqrt{2} I_{rms} = \frac{\sqrt{2}P_{in_{max}}}{V_{grms}} = \frac{\sqrt{2} \times 3 \times 225}{40} = 23.86(A)
\]

(2.62)

Considering the unipolar SPWM together with the phase shift scheme applied in the PV system, the equivalent switching frequency in the inductor will be triple. The desired inductor value can be calculated as:

\[
L_s_{max} = \frac{V_{DC}}{I_m \omega} = \frac{90}{23.86 \times 2 \times \pi \times 60} = 10(mH)
\]

(2.63)

\[
L_s_{min} = \frac{(V_{DC} - V_{gm}) V_{gm}}{\Delta i_{max} V_{DC} f_{sw}} = \frac{(90 - 40\sqrt{2}) \times 40\sqrt{2}}{23.86 \times 10\% \times 90 \times 10.8 \times 1000 \times 3} = 0.27(mH)
\]

(2.64)

Based on the design consideration, the inductor is chosen to be 0.4 mH in the design.

2.6 Simulation results

System simulation with MATLAB/Simulink software has been conducted to verify the control strategy and the design of the power stage parameters.

In practice, given a particular location, the change of temperature is relatively small within a predictable range, while the sun irradiance can change very dramatically and thus has larger effect on panel characteristic variation. Therefore only the change of the irradiance is
simulated to see the transient response of the system and to validate the MPPT algorithm. Figure 2-24 (b) gives the I-V characteristic curves of the modeled PV panel under different irradiance: 1000W/m², 800W/m², 600W/m², 400W/m², 200W/m². Compared with Figure 2-24 (a), which is the I-V curves from the datasheet, the PV model of the simulation is correct and accurate.

In the simulation, the P&O technology combined with CV method is adopted to track the accurate MPP of each PV panel and reduce the tracking time at the beginning. The start point of the reference voltage is set to 31.25V, which is around 0.85$V_{oc}$. The voltage perturbation step size is set to 0.5V, which is within 2% of $V_{oc}$. The MPPT refresh period is set to 0.1s in
order to shorten the simulation time. In reality, the MPPT refresh frequency can be very low since the climate conditions won’t change so quickly and the system does not need to response to the sharp change due to the birds or other flying creature.

The irradiance for the three PV panels are set to 1000W/m² at first. At t=3s, the irradiance for the second module is changed to 800W/m². Then at t=4s, the irradiance for the third module is changed to 600W/m².

Figure 2-25 shows the grid voltage and current of the PV system, which indicates the power change of the system.

Figure 2-26 shows the waveforms of the PV panel voltages and corresponding reference voltages generated by the MPPT algorithm. It can be seen that the controller can realize the individual MPPT for each PV panel. When the irradiance changes the DC-link voltages follow the references after a short transient time.

![Figure 2-25 Grid voltage and current of the PV system](image)
Figure 2-26 MPPT of the PV panel voltage
Figure 2-27 depicts the currents of the three PV panels. The waveforms show that with the different irradiances, the MPP voltages change little, while the MPP currents change a lot, which is in accordance with the aforementioned conclusion that the irradiance has larger impact on the current.

![Figure 2-27 Currents of the PV panels](image)

The grid voltage and the grid connected current are shown in Figure 2-28, which indicates a unity power factor operation. When the phase shifted modulation is used in the PWM modulator, the 7-level voltage can be got and is shown in Figure 2-28. Compared with 3.7% THD of the grid current without phase shift between the H-bridges, the THD is 0.91% with the phase shifted modulation as shown in Figure 2-29, which helps improve the current quality.
Figure 2-28 Grid voltage, current, and PWM voltage of the system

Figure 2-29 THD of the grid connected current: (a) without phase shift; (b) with phase shift

The effect of the MPPT algorithm can also be evaluated in the simulation. The main factor is the voltage perturbation step size. In the previous simulation file, $\Delta V$ is set to $0.5V$. The tracking time from the beginning to the steady state is about 0.8s, and the voltage will
oscillate from $29.25V$ to $29.75V$ and to $30.25V$, then back to $29.25V$. The corresponding power is from $224W$ to $224.4W$ then back to $224W$, the power loss because of the oscillation is around $0.8W$. The steady state voltage of the PV panel 2 and the corresponding reference waveform are shown in Figure 2-30.

![Figure 2-30 DC voltage and MPPT of PV panel 2 with 0.5V step](image)

When $\Delta V$ is set to $0.25V$, the tracking time from the beginning to the steady state is 1.2s, and the voltage will oscillate from $29.5V$ to $29.75V$ and to $30V$, then back to back to $29.5V$. The corresponding power is from $224.3W$ to $224.4W$ then back to $224.3W$, the power loss because of the oscillation is around $0.65W$. The steady state voltage of the PV panel 2 and the corresponding reference waveform is shown in Figure 2-31.
Similarly, if $\Delta V$ is set to $1V$, the tracking time is only 0.7s, but the voltage will oscillate from $28.25V$ to $29.25V$, and to $30.25V$, then back to $28.25V$. The corresponding power is from 221.5W to 224W then back to 221.5W, the power loss because of the oscillation is around 2.25W, which is almost 1% of the maximum available power. The steady state voltage of the PV panel 2 and the corresponding reference waveform is shown in Figure 2-32.

This indicates that both the tracking speed and the MPPT efficiency are influenced by the perturbation step size. Larger $\Delta V$ leads to faster tracking speed but more power loss.
Moreover, the modified P&O technology combined with CV method can be adopted in the PV system. Choose the perturbation size $\Delta V(k) = 0.1 \frac{(P(k) - P(k-1))}{\Delta V(k-1)}$ and define the maximum value $2V$ and minimum value $0.1V$.

The tracking process of module 2 is shown in Figure 2-33. The tracking time is about 0.6s and the power loss is about 0.6w, which verifies the merits of the modified P&O technology combined with CV method.
2.7 Experimental results

The theoretical analysis and the simulation results can also been validated with an experimental setup system. Figure 2-34 shows a picture of the cascaded 7-level converter prototype, which includes the three modules, the inductor, sensors, TMS320F28335 DSP board, PWM and ADC interface board, and auxiliary power supply.
Depending on the controller implementation requirement, the prototype can be modified to achieve either the centralized control or distributed control algorithm. Shown in Figure 2-35 (a) and (b), the signal paths for both conditions are depicted. In the centralized control structure, one interface board and one DSP board is used for sample and calculation. Otherwise, two additional DSPs can be added and the onboard interfacing circuit in each module will be enabled. Therefore, a highly flexible hardware platform has been built for verifying various control methods.
In order to obtain an adjustable grid with protection function to help debug the hardware, the power resistor paralleled with programmable AC source is used to emulate the real grid. Figure 2-36 depicted the test bed for the whole system, where the dash-line box indicates the ‘Grid’. The system information is sent to the centralized digital signal processor (DSP), in which the switching logic is generated for all the H-bridges.

Three PV panels MSX77S from SOLAREX are used in the experiments, which are shown in Figure 2-37. Since some cells of the PV panel have been fragmented, the practical
characteristics curves of the three PV panels, which are documented by the use of the DC electronic load equipment, are more valuable than the original data from the manufacture.

Figure 2-36 System configuration for experiments

Figure 2-37 PV panels for the experiments
Figure 2-38 show the measured P-V curve and I-V curve of the three PV panels, which are got under roughly same atmosphere conditions (1060W/m², 27°C). It is observed that the open circuit voltages are around 19V; the short circuit currents are about 5A; and the MPP voltages are about 12V. Furthermore, the MPP voltages of these three PV panels are somewhat different and the corresponding maximum power values are 49.7W, 39.2W, and 45.4W, respectively, which are marked by red triangles.
Since the PV voltages and currents are smaller than the previous design, the grid voltage is set to 18V rms. The 2.5mH inductor is used to help restrain the low ripple of the grid current. The system parameters for experiments are listed in Table 2-2.

### Table 2-2 System parameters for experiments

<table>
<thead>
<tr>
<th>Circuit variables</th>
<th>PV panel parameters (roughly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage $v_g$</td>
<td>18V (60 Hz)</td>
</tr>
<tr>
<td>PV open circuit voltage $V_{oc}$</td>
<td>19V</td>
</tr>
<tr>
<td>Input capacitor</td>
<td>$4 \times 3300 \mu F/50V$</td>
</tr>
<tr>
<td>PV short circuit current $I_{sc}$</td>
<td>5A</td>
</tr>
<tr>
<td>Inductor</td>
<td>2.5 mH</td>
</tr>
<tr>
<td>PV MPP voltage $V_{MPP}$</td>
<td>12V</td>
</tr>
<tr>
<td>PV MPP current $I_{MPP}$</td>
<td>4A</td>
</tr>
<tr>
<td>Switching frequency $f_{sw}$</td>
<td>10.8 KHz</td>
</tr>
<tr>
<td>Total power $P$</td>
<td>130W</td>
</tr>
</tbody>
</table>

Similarly, the $P&O$ technology combined with $CV$ method is adopted. The start point of the reference voltage is set to $17V$, which is around $0.87V_{oc}$. The voltage perturbation step size is set to $0.5V$, which is within 3% of $V_{oc}$. The MPPT refresh period is set to 1s. In addition, the phase shifted PWM modulation is applied to the system.

1) **Tracking process and steady state operation under normal condition:**

Figure 2-39 shows three PV panels’ voltages $V_{PV1}$, $V_{PV2}$, $V_{PV3}$ and the grid connected current $i_s$ at the tracking process when the system is connected to the grid. At the beginning, the DC voltage is set to 17V as aforementioned and the grid current is zero. After the start-up
of the MPPT and grid connection, the PV panel voltage decreases to the MPP value and the grid current increases to the steady state. Figure 2-40 demonstrates the voltage, current and power of PV panel 3, which indicates the trend of the generated power and therefore demonstrates the MPPT tracking capability of the system.

Figure 2-41 shows the zoomed in waveforms of grid voltage $v_g$, PWM voltage $v_H$, grid current $i_s$ and DC voltage of PV panel 1 $V_{pv1}$ when the system is in steady state operation. Figure 2-42 depicts the harmonics spectrums of grid current and voltage. The calculated THD of the grid current is 4.129%, while the grid voltage is not a pure sinusoidal AC source, and the THD is 1.548%. The power factor is almost unity.

Figure 2-39 Start-up of the system: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$. 
Figure 2-40 MPPT at the start-up process: Voltage of panel 3 $V_{pv3}$, current of panel 3 $I_{pv3}$, power of panel 3 $P_{pv3}$.

Figure 2-41 Grid voltage $v_g$, 7-level PWM voltage $v_H$, grid connected current $i_s$, DC voltage of PV panel1 $V_{pv1}$. 
2) Tracking process with partial shading to one PV panel:

At \( t = t_c \), use a light barrier to shade PV panel 3 to emulate the irradiance change situation, the irradiance after shading is about 300W/m\(^2\). The tracking process is shown in Figure 2-43 and Figure 2-44. Figure 2-43 shows DC voltage of PV panel 1 \( V_{pv1} \), DC voltage of PV panel 2 \( V_{pv2} \), DC voltage of PV panel 3 \( V_{pv3} \), grid current \( i_s \). Due to the partial shading of the PV panel 3, the grid current decreases, while the PV panel voltages keep almost the same. Figure 2-44 shows the current and voltage of PV panel 3 for both start-up and partial shedding conditions. In addition, Figure 2-45 shows the voltage, current and the corresponding calculated power of the shaded PV panel 3. It is shown that the PV panel 3 can always track the MPP in various operating conditions. The results validates that the proposed control strategy can achieve the panel level MPPT even when the environmental conditions of PV panels are different.
Figure 2-43 Partial shading operation: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$

Figure 2-44 Partial shading operation: voltage of PV panel 3 $V_{pv3}$, current of PV panel 3 $I_{pv3}$, Grid voltage $v_g$, grid current $i_s$
3) *The MPPT performance:*

As discussed before, the perturbation step size will greatly influence the MPPT performance. The following results perfectly demonstrate the phenomenon. Figure 2-46 (a), (b), and (c) show the tracking process at $\Delta V = 0.25V$, $\Delta V = 0.5V$, $\Delta V = 1V$, respectively. It can be observed that the time from the beginning to the steady state is around 19s, 10s, and 5s respectively. The perturbation size $\Delta V = 1V$ can give the fastest tracking speed, while the oscillation is worst.
In the experiment, the modified P&O technology combined with CV method is then adopted. The equation that decides the step size is as follows.

\[ \Delta V_k = 0.3 \frac{P_k - P_{k-1}}{\Delta V_{k-1}} \]  

(2.65)
The tracking waveforms by using modified P&O technology combined with CV method is shown in Figure 2-47, where the tracking time is about 5s, almost equal to that of fixed step size $\Delta V = 1V$, but the oscillation around steady state operation is very tiny. Therefore, the modified P&O technology combined with CV method is viable.

![Figure 2-47 DC voltage of PV panel](image)

Figure 2-47 DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$ with modified perturbation step size

### 2.8 Conclusion

This chapter presents the analysis and design of PV generation system based on cascaded multilevel converter. In order to guarantee the maximum power delivery to the grid, two important issues, namely MPPT and grid current regulation, are investigated. Firstly, an improved MPPT method is proposed with fast dynamic tracking performance as well as small steady state oscillation. Furthermore, a high performance is proposed in d-q coordinate
to achieve zero steady-state error regulation of the grid connected current. Additionally, the parameter design principle of the system is given and verified by the simulation together with the control method proposed. Lastly, a prototype based on cascaded seven-level converter is built to verify the design.
Chapter 3. Decentralized Control of PV system based on cascaded multilevel converter

3.1 Research motivation

As discussed in chapter 2, the attractive reason for the use of cascaded multilevel inverter topology in PV system is that it is a single stage conversion system which promises high conversion efficiency and can achieve the panel level individual MPPT of each PV panel which makes the most use of the high cost panels. In addition, the phase shift control based multilevel modulation method may allow the use of device with much lower switching frequency. Furthermore, due to the cascaded multilevel configuration, only low voltage devices are required in the whole system. Therefore, both the switching loss and conduction loss from the power semiconductor devices may be minimized and the system cost may be reduced.

Besides, the system has the modular hardware structure since there are n identical H-bridges with n PV panels in the system. In order to further modularize the hardware, the inductor as well as the input capacitor can be integrated with the H-bridge to form an AC module and then the AC modules can be installed at the back of the PV panels to reduce the DC cables and to simplify the whole system.

Despite its inherent modular hardware structure, the control system of the cascaded H-bridge inverter is highly centralized, which is one of the main drawbacks that limit the commercialization of this system [74] [75]. This is because in order to achieve the best possible minimum harmonic modulation implementation and optimum closed loop current
regulation, the switching operations of all semiconductor devices should be globally coordinated. More particularly, the voltage and current signals of each PV panel need to be sent to the central controller and the PWM signals are required to send back to each H-bridge from the central controller. When the number of the connected PV panels is large, the wire connections and the signal transmission will be very complicated. This puts an increasing load onto the central controller. Thus the central controller must be powerful enough to deal with all the data from the PV panels and to perform more and more complex calculations to generate the modulation reference waveforms. For example, as shown in Figure 3-1, there are \( n \) PV panels and \( n \) H-bridges in the system. Then \( 2n+2 \) signals (marked by blue lines) should be sent to the central controller, and then the \( 4n \) PWM signals (marked by green lines) from the central controller will be sent back to the H-bridges, respectively.

![Figure 3-1 System architecture of centralized controller](image)

82
To reduce the burden of the central controller, a common approach is to have a central/master controller and n local slave controllers that are integrated into each module, while the master controller execute the control and modulation calculations and send the resultant switching commands across communication links to slave controllers [76][77]. The extra benefit of this approach is that it can make the system more modularized and concise, as shown in Figure 3-2, which is suitable to be mass produced and will lead to low manufacturing cost and low retail prices.

Figure 3-2 System architecture based on master/slave controller
However, the burdens of the central controller is decreased at the expense of the high cost of communication system since the bandwidth must be increased to reliably transmit the information to all slave controllers at every modulation cycle. In addition, if the voltage and current sensors of PV panels are integrated into the AC modules to reduce their voltage isolation stress, the communication system burden is further increased since the measured values must be sent back to the central controller from the slave controller of each module at every control calculation cycle.

Hence, in order for the use of low bandwidth communication system or even no communication in the PV system, developing an advanced decentralized or distributed controller is becoming meaningful and extremely urgent.

### 3.2 State of art of decentralized controller

In [78], a decentralized control strategy for cascaded multilevel converter is presented and the control architecture is shown in Figure 3-3, in which each slave controller of the corresponding module determines its own switching actions based on local sensors, a local closed loop current regulator and a local modulator. Communication among the modules is done via an optical fiber ring network, which sends the commanded current references from the master controller, and also circulates the voltages commanded by each local module current regulator. The decentralized controller implementation achieves an equivalent performance to a centralized control strategy, with a low bandwidth requirement for the intra-converter communication system.
The principle of this strategy is that each module measures the ac current and controls it by the current loop of each local controller. Since the controllers in those separate loops have the same commanded current reference, measure the same physical current, and perform the same calculations, they will generate the same commanded PWM voltage and so there will be no adverse interaction between them.

However, this decentralized control strategy cannot be used in the PV applications. The reason is that the commanded current value is unknown in advance and the local controllers will not generate the same PWM signal since the power from each PV panel will be different. Therefore, the purpose of this chapter is to develop advanced decentralized control scheme for the PV system based on the cascaded multilevel converter.
3.3 Decentralized control of PV system

In order to develop an advanced decentralized control system which is suitable for the PV applications, we can begin from decreasing the number of transmitted signals among modules.

A decentralized system structure is proposed in Figure 3-4. Each AC module has its own sensors, local controller and local PWM modulator. Here only the grid voltage signal needs to be transmitted to each AC module by wires, which largely simplifies the complex wire connections in centralized control system. The isolation requirements are also reduced because of the local sensors and controller in each module.

Moreover, the exact synchronization among the local controllers can be maintained without requiring a complex high speed communication network. The task of the supervision center is to send some simple executive commands such as start-up, protection signals of the whole system to each module as well as to monitor the status of each module.

As for the variables in Figure 3-4, the \( i \) th H-Bridge can be modeled as follows if no losses are considered:

\[
\begin{align*}
    v_{Hi} &= d_i v_{pvi} \\
    i_{Hi} &= d_i i_s
\end{align*}
\]  

(3.1)

Where \( d_i \) stands for the control signal of each H-bridge. Then the lossless operation of each H-bridge can be derived in terms of instantaneous power from Eq. (3.2).

\[
v_{pvi} i_{Hi} = v_{Hi} i_s
\]

(3.2)
\[ i_{pvi} = i_{Hi} + C_i \frac{d}{dt} v_{pvi} \]  \hspace{1cm} (3.3)

Then the transfer condition of average power over a grid period can be formulated as:

\[
\frac{1}{T_g} \int_{(m-1)T_g}^{mT_g} i_{pvi} v_{pvi} d\tau = \frac{C_i}{2} \left[ v_{pvi}^2 - v_{pvi(m-1)}^2 \right] + \frac{1}{T_g} \int_{(m-1)T_g}^{mT_g} i_s v_{pvi} d\tau \]  \hspace{1cm} (3.4)

Where \( v_{pvi} \) and \( v_{pvi(m-1)} \) are the \( i \) th PV panel voltage at the time of \( mT_g \) and \( (m-1)T_g \), respectively. If \( P_{pvi} \) stands for the dc energy produced by the \( i \) th PV panel during the \( m \) grid period and \( E_{Cim} \) is the energy stored in the input capacitor, namely:

\[ P_{pvi} = \frac{1}{T_g} \int_{(m-1)T_g}^{mT_g} i_{pvi} v_{pvi} d\tau \]  \hspace{1cm} (3.5)

\[ E_{Cim} = \frac{1}{2} C_i v_{pvi}^2 \]  \hspace{1cm} (3.6)

Then Eq. (3.6) can be rewritten as:

\[ P_{pvi} = \frac{E_{Cim} - E_{C(i-1)}}{T_g} + d_i v_{pvi} i_s \]  \hspace{1cm} (3.7)

It indicates that when the available power from the PV panel is changed during the tracking process of the MPPT or due to the variations of the atmosphere conditions, the PWM signal \( d_i \) or the grid connected current \( i_s \) should be adjusted to guarantee the power balance of the system.
Figure 3-4 System architecture of decentralized controller

The decentralized control strategy is based on the different arrangement of the control variables, as depicted in Figure 3-5. In this control strategy, the local controller in the first module is a little different from other local controllers. The grid connected current $i_s$ is the control variable in it. There is a dual control loop in module 1, which is responsible for the grid current regulation as well as voltage regulation for DC link 1. The output of the voltage
loop can reflect the power change of module and can be regarded as the reference value of $i_s$.

For the local controllers of other $n-1$ modules, they have the same voltage loops among them and the DC bus voltage is the only control variable.

Figure 3-5 Proposed decentralized controller for PV system based on cascaded multilevel converter
Strictly speaking, the grid current should be controlled by all the modules according to the power balance. Hence, this control strategy is a kind of approximate treatment. However, the topology can help compensating for the approximation. Specifically, when the input of any PV panel among those n-1 panel changes, only the PWM signal will react and give the correction. In fact, the grid current $i_i$ also plays its role indirectly since the change of the output H-bridge of that module will influence $i_i$. Similarly, when the power of the first PV panel changes, the local controller will adjust the grid current reference and then generate the corresponding PWM signal, and meanwhile, other PWM signals will be adjusted to a certain extent, then the system will reach the steady state with the help of all the PWM signals and the current adjustments. Therefore the response process to the power change of the PV panels is the same as that in centralized control system.

### 3.4 Simulation results

The simulation work has been done to validate the proposed decentralized control strategy. The circuit parameters are the same as those in chapter 2, listed in Table 2-1. Here three 0.133mH individual inductors are used in the circuit instead of a single 0.4mH inductor. Likewise, the P&O technology combined with CV method is used. The start point of the reference voltage is set to 31.25V, the voltage perturbation step size is set to 0.5V and the MPPT refresh period is set to 0.1s.
The irradiance for the three PV panels are set to 1000W/m² at first. At t=3s, the irradiance for the first PV panel is changed to 800W/m². Then at t=4s, the irradiance for the second panel is changed to 600W/m². Figure 3-6 depicts the grid voltage and current by using the proposed decentralized control method. Figure 3-6 (a) shows the change of the grid current corresponding to the change of irradiance, indicating that the proposed control system can track the power with satisfied performance. The zoomed-in grid voltage and the grid connected current are shown in Figure 3-6 (b), which indicates a unity power factor operation. The THD is 0.78% with the phase shifted SPWM.

Figure 3-6 Grid connected voltage and current

Figure 3-7 shows the waveforms of the PV panel voltages and corresponding reference voltages. It can be observed that the PV voltages can follow the references and reach the steady state after a short transient as the irradiance changes. The individual MPPT for each PV panel can be achieved by the proposed decentralized control strategy.
Figure 3-7 MPPT tracking of the PV panel voltage
3.5 Experimental results

The experimental setup system shown in Figure 2-34 is also used for validating the proposed control method. The difference is that three independent close loops exist in the control system and will be implemented in a DSP board, shown in Figure 3-8.

![Figure 3-8 Signal paths for the decentralized-control prototype](image)

The same PV panels MSX77S from SOLAREX are used in the experiments. Figure 3-9 shows the measured P-V curve and I-V curve of the three PV panels, which are got under roughly the same atmosphere conditions (1060W/m², 27°C). It is observed that the open circuit voltages are around 19V; the short circuit currents are about 5A; and the MPP voltages are about 12V. Furthermore, the MPP voltages of these three PV panels are somewhat different and the corresponding maximum power values are 39.2W, 49.7W, and 45.4W, respectively, which are marked by red triangles.
Figure 3-9 measured P-V and I-V curves of PV panels for decentralized-control experiments

The grid voltage is set to 16V rms. The 1.02mH inductor is used to help restrain the low ripple of the grid current. The system parameters for experiments are listed in Table 3-1.

Similarly, the P&O technology combined with CV method is adopted. The start point of the reference voltage is set to 15V, which is around 0.75V_{ac}. The voltage perturbation step size
is set to $0.5V$, which is within 3% of $V_{oc}$. The MPPT refresh period is set to 1s. In addition, the phase shifted PWM modulation is applied to the system.

### Table 3-1 System parameters for decentralized-control experiments

<table>
<thead>
<tr>
<th>Circuit variables</th>
<th>PV panel parameters (roughly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage $v_g$</td>
<td>16V (60Hz)</td>
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<tr>
<td>PV open circuit voltage $V_{oc}$</td>
<td>19V</td>
</tr>
<tr>
<td>Input capacitor</td>
<td>$4 \times 3300 \mu F / 50V$</td>
</tr>
<tr>
<td>Inductor</td>
<td>1.02mH</td>
</tr>
<tr>
<td>Switching frequency $f_{sw}$</td>
<td>10.8 KHz</td>
</tr>
<tr>
<td>MPPT frequency</td>
<td>1sec</td>
</tr>
</tbody>
</table>

1) **Tracking process and steady state operation under normal condition:**

Figure 3-10 shows three PV panels’ voltages $V_{pv1}$, $V_{pv2}$, $V_{pv3}$ and the grid connected current $i_g$ at the tracking process when the system is connected to the grid. At the beginning, the DC voltage is set to 15V as aforementioned and the grid current is zero. After the start-up of the MPPT and grid connection, the PV panel voltage decreases to the MPP value and the grid current increases to the steady state value. Figure 3-11 and Figure 3-12 demonstrate the panel voltage, panel current, grid voltage, and grid current for PV panel 1 and 2, respectively, which indicate the trend of the generated power and therefore demonstrate the MPPT tracking capability of the system.
Figure 3-10 Start-up of the system: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$.

Figure 3-11 MPPT at the start-up process: Voltage of panel 1 $V_{pv1}$, current of panel 1 $I_{pv1}$, grid voltage $v_g$, grid current $i_s$. 
Figure 3-12 MPPT at the start-up process: Voltage of panel 2 $V_{pv2}$, current of panel 2 $I_{pv2}$, grid voltage $v_g$, grid current $i_s$.

Figure 3-13 shows the zoomed in waveforms of DC voltage of PV panel 1 $V_{pv1}$, PWM voltage $v_H$, grid voltage $v_g$, and grid current $i_s$ when the system is in steady state operation.

Figure 3-13 DC voltage of PV panel 1 $V_{pv1}$, 7-level PWM voltage $v_H$, Grid voltage $v_g$, grid connected current $i_s$. 
Figure 3-14 depicts the harmonics spectrums of grid current and voltage. The calculated THD is 5% for grid current and 0.86% for grid voltage. The power factor is almost unity.

![Harmonics spectrum](image)

(a) (b)

Figure 3-14 Harmonics spectrum: (a) grid current $i_g$; (b) grid voltage $v_g$.

2) Tracking process with partial shading to PV panels:

At $t=t_c$, use a light barrier to shade PV panel 2 to emulate the irradiance change situation, the irradiance after shading is about 300W/m$^2$. The tracking process is shown in Figure 3-15, Figure 3-16, and Figure 3-17. Figure 3-15 shows DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_g$. Due to the partial shading of the PV panel 2, the grid current decreases, while the PV panel voltages keep almost the same.
In addition, Figure 3-16 shows the voltage, current of the shaded PV panel 2 and the grid voltage, grid current. It is shown that the PV panel 2 can always track the MPP in various operating conditions. Figure 3-17 shows the voltage, current of PV panel 1 and the grid voltage, grid current. It is observed that the PV panel 1 can stay on its MPP when other PV panels’ condition changes. The results validate that the proposed control strategy can achieve the panel level MPPT even when the environmental conditions of PV panels are different.

Figure 3-15 Partial shading operation: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$
Figure 3-16 Partial shading operation: voltage of PV panel 2 $V_{pv2}$, current of PV panel 2 $I_{pv2}$, Grid voltage $v_g$, grid current $i_s$

Figure 3-17 Partial shading operation: voltage of PV panel 1 $V_{pv1}$, current of PV panel 1 $I_{pv1}$, Grid voltage $v_g$, grid current $i_s$

Since the control loop for PV panel 1 is different from that of PV panel 2 and 3, it is necessary to shade PV panel 1 to emulate the irradiance change situation and further validate
the proposed decentralized control strategy. The tracking process is shown in Figure 3-18, Figure 3-19, and Figure 3-20. Figure 3-18 shows DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$. Due to the partial shading of the PV panel 1, the grid current decreases, while the PV panel voltages keep almost the same.

In addition, Figure 3-19 shows the voltage, current of the shaded PV panel 1 and the grid voltage, grid current. Figure 3-20 shows the voltage, current of PV panel 2 and the grid voltage, grid current. It is observed that the PV panel 1 can track to its new MPP and other PV panels can stay on their MPP when the condition changes. The results also validate the proposed decentralized control strategy.

![Figure 3-18 Partial shading operation: DC voltage of PV panel 1 $V_{pv1}$, DC voltage of PV panel 2 $V_{pv2}$, DC voltage of PV panel 3 $V_{pv3}$, grid current $i_s$.](image-url)
Figure 3-19 Partial shading operation: voltage of PV panel 1 $V_{pv1}$, current of PV panel 1 $I_{pv1}$, Grid voltage $V_g$, grid current $i_s$

Figure 3-20 Partial shading operation: voltage of PV panel 2 $V_{pv2}$, current of PV panel 2 $I_{pv2}$, Grid voltage $V_g$, grid current $i_s$


3.6 Conclusion

The demand for modular power electronics system has posed a challenging requirement for the advanced control system. This chapter proposes a decentralized control strategy for the cascaded multilevel converter based PV system. The proposed method can greatly simplify the wire connection and the requirement of the communication, therefore a modular power stage can be assembled for mass production and cost reduction. Simulation and experimental results have been provided to verify the proposed decentralized strategy.
Chapter 4. Conclusion and Future Work

4.1 Conclusion of present work

The thesis focuses on the control and design of PV system based on cascaded multilevel converter.

The background for the research work is introduced in the first Chapter.

In Chapter 2, the principle of the topology and the characteristics of PV panels are described. Three popular MPPT algorithms are compared, and an improved MPPT method is proposed to achieve fast and accurate tracking performance. Then, the design consideration of the converter is given, and the small signal model is derived. Based on the model, the centralized control on d-q coordinate is proposed and analyzed. Finally, a prototype with three PV panels is built and the simulation work and experimental results validated that the proposed control strategy can achieve the individual MPPT of each PV panel and generate high quality grid current.

In order to address the issue of the centralized controller, a decentralized controller for the PV system based on cascaded multilevel converter is proposed in Chapter 3. It can make the whole system simple by reduce the number of wire connections among the modules. The simulation and experimental results are also given to verify this control strategy.

4.2 Future work

Future research work may concentrate on the following:
1) The Optimization of the hardware design.

One of the advantages of the cascaded multilevel topology used in PV system is the potential high efficiency. So the efficiency needs to be tested and the optimization of the system needs to be done in the future.

2) A possible distributed controller.

The wire connections still exist in the decentralized control system. To completely decentralize the system, the distributed controller can be a direction for us to further develop better controller.
REFERENCES


