Resistance Control MPPT for Smart Converter

PV System

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Abstract

DC nano-grid system shows promising prospect and enjoys some advantages over AC micro-grid system. It enables easier integration of multiple renewable energy sources with multiple loads. Photovoltaic (PV) is essentially a typical renewable source that serves as main power source in DC nano-grid system. Traditional PV system includes centralized PV system, string PV system and micro-converter PV system. More recently, smart converter PV system has been introduced and shown great improvement in aspects of power generation achieved by distributed Maximum Power Point Tracking (MPPT). It is also advantageous over micro-converter PV system due to lower cost and flexibility.

Detailed case study demonstrates that power generation efficiency can be easily compromised because of mismatch between different panels in centralized and string PV systems. In smart converter PV system, this problem can be solved due to distributed MPPT for each individual panel. The smart converter system has a very wide voltage range within which all panels can generate maximum power. The location and the width of this range are subject to change under different mismatch conditions. A second stage converter is needed to locate the array MPPT range. However, there is instability problem when doing second stage MPPT with traditional methods.

Modified methods based on conductance control and resistance control are analyzed and compared. Both methods can solve the MPPT instability problem. However, in terms of steady state performance, resistance control MPPT is more promising in terms of higher utilization ratio and faster tracking speed. It is because both methods are of
inherited variable operating point step size with constant conductance or resistance perturbation step size. However, the operating point change decreases with resistance perturbation but increases with conductance perturbation otherwise. Therefore, resistance control MPPT is chosen as a good candidate. Both simulation and experimental results verifies the concept.
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Table of Contents

Chapter 1. Introduction ........................................................................................................... 1
  1.1 Background .................................................................................................................. 1
  1.2 Output Characteristics of Photovoltaic Panel .............................................................. 4
  1.3 PV System Structures for DC Nano-grid ................................................................. 5
  1.4 Review of Maximum Power Point Tracking (MPPT) Methods ............................... 14
  1.5 Smart Converter PV System and MPPT Requirement ........................................... 24
  1.6 Thesis Outline ......................................................................................................... 25

Chapter 2. Analysis of Traditional and Smart Converter PV Systems .............................. 27
  2.1 Introduction .............................................................................................................. 27
  2.2 Case Study ............................................................................................................. 27
  2.3 The Issue of Second Stage Converter MPPT ......................................................... 44
  2.4 Summary ............................................................................................................... 49

Chapter 3. Modified MPPT Methods for Smart Converter PV system .......................... 50
  3.1 Conductance Control MPPT ..................................................................................... 50
  3.2 The Concept of Conductance Control MPPT ......................................................... 50
  3.3 Process of Conductance Control MPPT ................................................................. 53
  3.4 Steady State Performance of Conductance Control MPPT .................................... 55
  3.5 The Drawback of Conductance MPPT ................................................................. 58
  3.6 Resistance Control MPPT ....................................................................................... 60
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>Steady State Performance of Resistance Control MPPT</td>
<td>62</td>
</tr>
<tr>
<td>3.8</td>
<td>The Advantage of Resistance Control MPPT</td>
<td>65</td>
</tr>
<tr>
<td>3.9</td>
<td>Implementation of Resistance Control MPPT</td>
<td>66</td>
</tr>
<tr>
<td>3.10</td>
<td>Simulation Verification of Resistance MPPT</td>
<td>67</td>
</tr>
<tr>
<td>3.11</td>
<td>Experimental Verification of Resistance Control MPPT</td>
<td>70</td>
</tr>
<tr>
<td>3.12</td>
<td>Summary</td>
<td>76</td>
</tr>
</tbody>
</table>

Chapter 4.  Summary ................................................................. 77
References ................................................................................. 78
List of Figures

Figure. 1.1: (a) DC nano-grid structure in future home; (b) Operation principle ....................... 2

Figure. 1.2: PV panel output characteristics under different irradiance with constant temperature 25° C ......................................................................................................................... 4

Figure. 1.3: PV panel output characteristics under different temperature with constant irradiance 1kW/m² ......................................................................................................................... 5

Figure. 1.4: Centralized PV system .......................................................................................... 6

Figure. 1.5: Centralized PV system: (a) Perfectly matched case; (b) Mismatched Case ........... 8

Figure. 1.6: String PV system .................................................................................................. 9

Figure. 1.7: Micro-converter PV system .................................................................................. 11

Figure. 1.8: Smart converter PV system .................................................................................. 12

Figure. 1.9: Concept of maximum power point tracking ........................................................ 14

Figure. 1.10: MPPT by controlling array voltage ................................................................. 15

Figure. 1.11: MPPT by controlling array current ................................................................. 17

Figure. 1.12: MPPT by duty cycle control ............................................................................... 18

Figure. 1.13: Fractional open-circuit voltage concept ............................................................. 20

Figure. 1.14: Perturb and observe (PO) MPPT method .......................................................... 21

Figure. 1.15: Perturb and observe (PO) in changing irradiance condition ............................... 22

Figure. 1.16: Incremental conductance (IncCond) MPPT method .......................................... 23

Figure. 1.17: Perturb and observe (PO) MPPT method .......................................................... 24

Figure. 2.1: Home in Portola Valley, California: (a) Real picture; (b) Top view of the house ......................................................................................................................................................... 28

Figure. 2.2: Mismatch case in centralized PV system ............................................................. 29
Figure 2.3: Output characteristics of string A in centralized PV system: (a) Output I-V of each panel; (b) String output I-V.

Figure 2.4: Output characteristics of centralized system: (a) Output P-V of string A; (b) array output P-V.

Figure 2.5: Mismatch case in smart converter PV system: (a) System structure; (b) input and output characteristics of single smart converter.

Figure 2.6: Determination of string A output characteristics: (a) Output of different irradiance levels; (b) Composite output of string A.

Figure 2.7: Output characteristics of smart converter system: (a) Output P-V of string A; (b) Output P-V of A,B,C and array output P-V.

Figure 2.8: Determining the system MPPT region upper and lower boundary voltages.

Figure 2.9: Analysis of string C MPPT region.

Figure 2.10: The effect of increasing voltage limit.

Figure 2.11: Analysis of string C MPPT region.

Figure 2.12: MPPT of second stage converter for smart panel array.

Figure 2.13: Voltage control MPPT for smart panel array.

Figure 2.14: Duty cycle control MPPT for smart panel array.

Figure 2.15: Current control MPPT for smart panel array in static condition.

Figure 2.16: Current control MPPT for smart panel array in increasing irradiance condition.

Figure 3.1: Incremental conductance (IncCond) MPPT method.

Figure 3.2: Choosing conductance as control variable.

Figure 3.3: Representation of conductance control MPPT with constant step size (a) G-MPPT on I-V curve; (b) G-MPPT on P-V curve; (c) G-MPPT on P-G curve.
Figure 3.4: Steady state operation of conductance control MPPT..............................56
Figure 3.5: The operating point variation with constant step size decreasing conductance59
Figure 3.6: Representation of resistance control MPPT with constant step size (a) R-MPPT
on I-V curve; (b) R-MPPT on P-V curve; (c) R-MPPT on P-R curve .................................61
Figure 3.7: Steady state operation of conductance control MPPT..............................63
Figure 3.8: The operating point variation with constant step size increasing resistance....65
Figure 3.9: The operating point variation with constant step size increasing resistance.....66
Figure 3.10: Simulation result .....................................................................................68
Figure 3.11: Simulation result .....................................................................................70
Figure 3.12: Experiment test-bed ................................................................................71
Figure 3.13: Measured output characteristics of smart converter string: (a) I-V curves; (b) P-V curves ........................................................................................................73
Figure 3.14: Experiment result of case 1 .................................................................75
Figure 3.15: Experiment result of case 2 .....................................................................75
List of Tables

TABLE 1-1 Performance of string PV system .............................................................. 10
TABLE 2-1 PV panel parameters of STP170S-24/Ab-1 .................................................... 29
TABLE 3-1 Parameters of simulation for voltage control MPPT ........................................... 67
TABLE 3-2 Parameters of simulation for resistance control MPPT .................................... 69
Chapter 1. Introduction

1.1 Background

Vastly growing concerns on energy sustainability and security have introduced significant research efforts on the penetration of Renewable Energy Sources (RES) into present electric power system. It has given rise to the development of Electronic Power Distribution Systems (EPDS), such as micro-grid, utilizing multiple RES as supplementary energy source to utility grid [1]. DC nano-grid is one kind of micro-grid EPDS at low power level (10-100kw). One typical system structure for future home is shown in Fig.1. Basically, all RES are integrated to DC bus via power electronics DC-DC converters with the energy control center (ECC) taking charge of interfacing DC bus with utility AC grid. In [2], it is addressed that a DC nano-grid is a promising EPDS since it features more efficient way to deliver energy, fast control and protection capability comparing to AC nano-grid system.

The RESs that can be integrated into DC nano-grid include photovoltaic (PV) array, wind turbine and varieties of battery storage facilities. All these RESs provide energy continuously to the loads when they have the capability. Unlike traditional energy source such as constant voltage source and constant current source, the characteristics of RES systems are strongly related to their nonlinear nature, even though the power electronics converter connected to each individual RES converts the output characteristics into a different shape. For instance, Photovoltaic (PV) system output power is limited due to the fact that PV array has only one Maximum Power Point (MPP) in perfectly matched condition, where all the PV panels are of the same model and the environment condition
for all of them are identical. Thus, the output of PV converter is regarded as a constant power source when Maximum Power Point Tracking (MPPT) is performed to maximize the energy harvesting efficiency. Similar traits can be found in Wind Turbine (WT) system. Combining of different RESs together, Fig. 1.1 (b) shows the operation principle
of Renewable Energy Nano-grid proposed by CPES. Within the nominal DC bus operating range 370V to 390V, PV and WT systems both operate in MPPT mode and behave as constant power sources. ECC operates in droop mode taking the responsibility to regulate the bus voltage. Battery and hybrid-vehicle systems can either work in droop mode or current limit mode. The actual DC bus operating voltage is determined by the power balance of sources and loads, e.g. the total load current $I_L$ matches the total source output current at 372V as shown in Fig. 1.1 (b). When load current diminishing and DC bus voltage being elevated exceeding the nominal range, PV and WT will be obliged to reduce power production accordingly by entering droop modes. Otherwise, when DC bus voltage drops below nominal range due to further increasing of load, PV and WT will either limit their output current or just shut down. From the standpoint of division of labor, MPPT is the main task for PV and WT under normal conditions. Consequently, MPPT capability and performance of PV and WT system should be looked into meticulously.

PV is no doubt a perfect RES for this system because of intrinsic DC output characteristics. The MPPT performance for PV system depends mainly on the following two aspects: (1) PV system structure; (2) MPPT algorithm. PV system MPPT performance capability is directly restricted by system configuration, which means the maximum ratio of power a PV system can produce is directly determined by its physical configuration regardless of what kind of MPPT algorithm is used or assuming a perfectly suitable algorithm is applied. For a given system structure, different MPPT algorithm renders different power generation performance. A wrong choice of algorithm will easily lead to very bad performance even for a well chosen system structure for particular
application. Therefore, different PV system structures and MPPT methods should be analyzed.

1.2 Output Characteristics of Photovoltaic Panel

First of all, the basic characteristics of photovoltaic panel should be introduced before jumping into analysis of different PV system structure and MPPT methods. As we mentioned previously, photovoltaic panel output is of strong nonlinearity. Taking the commercial PV panel product Suntech ST170-24 as an example, the panel output characteristics under different irradiances at 25°C are presented in Fig. 1.2 where it clearly shows output current decreases with less sunlight but panel output voltage doesn’t change much with varying sunlight. Maximum power points can be found on each curve.

![Figure 1.2: PV panel output characteristics under different irradiance with constant temperature 25°C](image-url)
as the solid dots in Fig.1.2. The sunlight mainly has influence on the panel output current but has very little effect on panel output voltage. Fig.1.3 shows panel output with different temperature with constant 1 kW/m² sunlight. On the contrary to the previous case, the temperature has much more effect on panel output voltage than current. That is the panel tends to output higher voltage with lower temperature.

From the above demonstration, we can see that both irradiance and temperature will influence the PV panel output characteristics. However, given a particular location, the temperature change will be relatively small within a predictable range. The sun irradiance could change very dramatically and thus has larger effect on panel characteristic variation.

1.3 PV System Structures for DC Nano-grid
As for PV system, the structure chosen is related to array power level. DC nano-grid is usually rated at 10-100kW, thus the appropriate power level of PV array can be around 5kw to 20kw accordingly. Generally, PV systems of this power level in DC nano-grid can be categorized into centralized system, string system, micro-converter [4][5] and smart converter PV system. Here we only give a brief introduction. Detailed analysis will follow in the next chapter.

(1) Centralized PV system

Fig.1.4 shows the configuration of centralized PV system. In centralized system, multiple PV panels are connected in series as PV string to reach certain voltage level. Parallel-connected strings are then wired into a centralized PV converter interfacing PV array with DC bus.

![Figure. 1.4: Centralized PV system](image)

One can easily interpret from the system structure drawn in Fig.1.4 that the PV panels in the same string share the same string current because of series connection and all the panel strings share the same string voltage because of parallel connection. Essentially, these traits actually result to low MPPT performance. One should recall what we
discussed before that irradiance differences will easily lead to differences in panel output current. Thus, when there’s irradiance difference between panels within the same string, the maximum power points current, also known as optimal currents of PV panel, of these mismatched panels will be different. In this case, it is not possible for all the panels in that string operating at MPP. A better choice is to let the one with the highest maximum power operate at MPP while others just follow its optimal current. However, even so, a large amount of available power is not delivered. In another word, system level MPPT performance will be compromised in direct series connection. Then consider the case when multiple strings are connected in parallel. In practical case, the panels of the same string are usually mounted on the same tilt of the roof, of which the irradiances are supposed to be of minor difference, although this is not true actually due to the fact that small area shading can yield much worse mismatch as we expect. Because of this, string irradiances may not be identical. Even for the case panel mismatch within one string doesn’t exist, string level irradiance difference will also lead to different string maximum power point voltage. Parallel connection forces the operation voltage of all the strings to be the same. Therefore, there’s no chance that all the strings could operate at MPP of their own. To better illustrate this drawback, we can actually use the output power versus voltage curve to draw a clearer conclusion. Considering a PV array consists of 30 panels with three ten-panel strings, the array configuration and output characteristics under matched and mismatched conditions are shown in Fig.1.5. Fig.1.5 (a) shows the output characteristics of PV array under matched irradiance and temperature conditions. In this case, the composite power versus voltage (P-V) curve for each string is simply the extension of that of a single panel. Adding three P-V curves together renders the
composite P-V curve of the whole system where there is a unique MPP. However, when mismatch of irradiance takes place as in Fig.1.5 (b), string output characteristics are not the identical which gives rise to a different system composite output P-V curve compared to the matched case. The drawback of centralized system is then explicitly represented as there are more than one MPPs residing on both the string and total P-V curves. One should note that the total available maximum power of the system (adding all the panel
maximum power together) is 4672W. Even if the system operates at the highest MPP P1, the system can only output 4085W where a large amount of available power (12.56%) is not delivered due to the fact that the operating points of string A and B both deviate from the MPP respectively.

Based on the above reasons, the centralized PV system has relatively low MPPT performance. The advantages are also very clear. Because of centralized connection, wiring cost is minimized. And only one central PV converter is needed, thus lower cost on power electronics device is achieved.

(2) String PV system

A typical string PV system is shown in Fig. 1.6. The difference with centralized PV system is it splits the second stage converter into individual converters for each PV panel string. Each individual string converter does MPPT for each string leaving no interaction
between different strings. However, because 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.

<table>
<thead>
<tr>
<th>String A maximum power</th>
<th>String B maximum power</th>
<th>String C maximum power</th>
<th>Percentage of power not delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1323W</td>
<td>1700W</td>
<td>1311W</td>
<td>7.2%</td>
</tr>
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</table>

As Table 1-1 demonstrates, even if MPPT is distributed to string level, a considerable amount of power as high as 7.2 percent is not delivered which results to low power generation efficiency.

The advantages of string PV system include the following aspects. The first one is that it is advantageous over centralized system on improved power generation efficiency although it is still bad. From standpoint of power electronics, each string converter can be modularized adding flexibility to system architecture.

(3) *Micro-converter PV system*

Micro-converter PV achieves much better power generation efficiency comparing to the centralized and string PV systems. It is derived from micro-inverter structure by eliminating the DC/AC part of micro-inverter. It distributes power electronics further into each individual panel as micro-converter. Micro-converter interfaces PV panel directly with high voltage DC bus and performing MPPT for each panel separately. The outputs of micro-converters are in parallel connection of which the voltage are fixed within a particularly small range in dependence with the DC bus voltage level. During operation, the DC bus voltage almost kept the same all the time. The benefit of this system is that
there is absolutely no interaction between panels under mismatch condition essentially because MPPT is decoupled thanks to the panel level converters and their parallel connection. Diminishing of output current of a single one will not affect others. Theoretically speaking, the power generation efficiency will be unity as every panel can operate at MPP.

![Figure 1.7: Micro-converter PV system](image)

The drawbacks are mainly about cost and efficiency. Due to the fact that these micro-converters should be high step-up ratio converters, in which topologies utilizing transformer should be applied, it generally indicates a more complex converter structure that includes more devices. Thus, cost will not be minimized. Moreover, high step-up ratio DC-DC converter suffers from lower efficiency comparing to converter that has voltage conversion ratio around unity. Therefore, practically speaking, the power generation efficiency could be limited by the efficiency of the micro-converter.

**(4) Smart converter PV system**
A typical smart converter PV system [5][6][7][8] is shown in Fig. 1.8. Essentially, per panel DC-DC converter is utilized. The main job of these converters is to do MPPT continuously for each single panel. Fig. 1.8 (b) characterizes the input and output I-V curves of the smart converter. Normally, the converter performs MPPT which continuously forces the operating point of PV panel at MPP. The output then behaves as a constant power source which is hyperbolic curve. Essentially, the MPPT region is extended from single panel MPP into a much wider range via smart converter. The width of this MPPT region is determined by the converter output current limit and voltage limit. Therefore, the
advantage is obvious comparing to conventional centralized and string PV system. If the MPPT regions of smart converters connected in one string share certain current overlapping, it is then guaranteed that all the panels in this string can generate maximum power. Due to this fact, each string is also capable of achieving MPPT within certain range. Likewise, if there is overlapping of voltage among different strings, when connecting these strings together, system MPPT can be achieved. The structure of smart panel PV system is very much like centralized system in that it contains both series and parallel connection. The significant difference is that distributed power electronics is used and the PV module MPPT region is extended from one particular MPP to a wide range.

Comparing to micro-converter system, the major difference is as follows. All the DC-DC converters in micro-converter system interfaces PV panels (20V~50V for crystalline panel, 30V~100V for thin-film panel) directly with high voltage DC bus, e.g. 250V~350V DC bus, of which the outputs are all connected in parallel. However, the DC-DC converters used in smart converter system are nearly of unity voltage gain and allow both series and parallel connection, thus enabling more flexible system configuration. Comparing to micro-converter in which case the high step-up DC-DC converter is used, smart converter is nearly with unity voltage gain. Non-isolated buck, boost or buck/boost type converter can be used with less power electronics and magnetic components and therefore more cost-effective and with higher efficiency. Among the three basic topologies, the buck/boost type has wider MPPT range because it can benefit from both buck and boost operation. A lot of commercial smart converter products, also known as power optimizers, such as Solarmagic and Solaredge, adopt buck/boost topology [3]. Detailed analysis of smart converter PV system will be presented later.
1.4 Review of Maximum Power Point Tracking (MPPT) Methods

The essential function of the aforementioned PV converters, including central and string PV converter, micro-converter and smart converters, is Maximum Power Point Tracking (MPPT).

A. MPPT classification based on the control variable

Taking the MPPT for centralized PV system as an example, the basic concept of MPPT can be illustrated as in Fig.1.9. In order to find the PV array optimal operating point, PV converter continuously monitors the output power of the PV array by measuring voltage and current. If the operating point is not the optimal, it is then regulated to be moved in the direction where more power would be delivered. This operation point movement is achieved by controlling the three variables: array voltage, array current or the duty cycle of PV converter.

(1) Controlling array voltage

The most commonly used control variable is the PV array voltage. As shown Fig.1.10 (a), the operating point moves along the P-V curve with different array voltage. Thus, the tracking for MPP can be realized by simply controlling the array voltage. A simple representation of the control structure is shown in Fig.1.10 (b). Given a time instance,

![Figure. 1.9: Concept of maximum power point tracking](image)

**Figure. 1.9: Concept of maximum power point tracking**
MPPT block outputs the array voltage reference while the array voltage is fed back and a voltage loop is applied to make it follow the reference. In this way, the array operating point is determined as expected for a particular time period. Additional information regarding array output current is also fed into MPPT block where array output power of present operating point is calculated and monitored. Once the all the information of

![P-V Curve](image)

Figure. 1.10: MPPT by controlling array voltage
current operating point is acquired, MPPT then adaptively change the voltage reference value in certain direction in order to move the operating point to a predictable new one. After that, the power of the new operating point is obtained and compared to previous case. If the power is increasing, the voltage reference will be changed in the same direction and in the opposite direction otherwise. The typical MPPT process described above utilizes control over the array voltage. The advantage of using voltage as a control variable is related closely to the PV array output characteristics mentioned previously under different irradiance conditions. Because the MPP voltage will not change much when the sunlight is changing rapidly, voltage control is more likely to maintain high MPPT performance in changing irradiance case once the MPP is tracked.

(2) Controlling array current

The MPPT based on current control is similarly understandable once we are familiar with the voltage control MPPT. The only difference is that current is chosen as control variable instead of voltage. Therefore, the MPPT block generates array output current reference and current loop is applied to make array current follow the reference.

Fig.1.11 shows the power versus current curve and a simple representation of current control MPPT. One should note that the power curve has relatively sharp drop at right side of MPP which means small change of current will introduce large change of power. Moreover, due to the fact that MPP current of PV array will change significantly with rapidly changing sunlight, current control has bad performance in such condition. Based on the above reasons, current control is not very preferable.

(3) Duty cycle
A simpler way to achieve MPPT is to control or adjust the duty cycle of the PV converter directly. Fig.1.12 presents the relationship between duty cycle and array output power assuming PV converter is of boost topology and the DC bus voltage is also assumed to be ideally constant. Suppose the converter is running in CCM, the input and output voltage of the converter should have the following relationship.
The P-D curve can then be derived from previous P-V curve as shown in Fig. 1.12 (a). Adjusting duty cycle of the PV converter gives rise to movement of array operating point along the curve. MPP can then be reached step by step through similar process described previously.

\[
V_{BUS} = \frac{1}{1 - D} V_{PV}
\]  

\hspace{2cm} (1.1)

Figure 1.12: MPPT by duty cycle control
The advantage of direct adjusting of duty cycle is that it is really simple method. No close loop control needs to be used to achieve strict voltage or current control to realize MPPT. However, the disadvantage is rather obvious. Because we get the P-D curve in Fig.1.12 based on the assumption that the output of the converter is clamped to DC bus with constant voltage, there will be issue when the voltage of DC bus is varying. Under different DC bus voltage, the actual P-D curve will change accordingly. More important to mention is that the optimal duty cycle at which the MPP is reached will be changing with varying DC bus voltage. Thus, even if the sunlight and temperature keep unchanged and MPP is reached at certain duty cycle value, DC bus voltage variation will easily lead to operating point deviation away from MPP if the duty cycle update rate is not fast enough. In another word, the MPPT performance is not only affected by environment but also influenced by load condition. Such problem does not emerge in the voltage control or current control case.

**B. MPPT classification based on tracking algorithm**

Besides the selection of control variable, the algorithm of MPPT also plays important role. Varieties of MPPT methods are presented in a wide collection of literatures. However, among all the methods, the most widely used and practical MPPT methods are presented as follows.

(1) Fractional Open-circuit voltage MPPT [27]

This method is based on the practical measurement that the MPP voltages is fractional of open-circuit voltage of PV array that can be described as following equation, where $k$ resides between 0.71 to 0.78.

$$V_m = k \times V_{OC}$$  \hspace{1cm} (1.2)
Under different irradiance, this coefficient will not change much, as shown in Fig 1.13, the MPP voltage decreases slightly when sunlight is reducing. As the open-circuit voltage also decreases accordingly, the ratio between MPP voltage and open-circuit voltage on each curve is kept at k. The Voc can be measured by open-circuit the PV array. Therefore, the MPP voltage can be derived by multiplying the open-circuit voltage by the coefficient k. Because this method does not need continuous tracking process, it is relatively simple concept. However, it is required that the PV array output need to be opened in order to measure the Voc periodically whenever the MPP voltage needs to be updated. During the open-circuit time interval, the array is not generating any power which means the total power generation performance is affected by this measuring state. Moreover, the MPP voltage described by Eq.1.2 may encounter certain level of error. In other words, the MPP voltage in this case is based on approximation lacking accuracy. Therefore, this method suffers from relatively low power generation efficiency.

(2) Perturb and Observe (PO) MPPT [9]-[16]
Perturb and Observe is the mostly widely used MPPT method. It is essentially based on Hill Climbing concept. Considering the case that the array voltage is the control variable, the following equations can be used to describe the principle of PO method that if the operating point of PV array is moving in the direction where the power is increasing, it is then decided that the operating point needs to be moved in the same direction further.

\[
\Delta P(k) = P(k) - P(k-1)
\]

\[
\Delta V(k) = \text{sign}(\Delta P(k)) \cdot \text{sign}(\Delta V(k-1)) \Delta V
\]

\[
V_{\text{ref}}(k) = V_{\text{ref}}(k-1) + \Delta V(k)
\]

(1.2)

Taking voltage control MPPT as an example, voltage perturbation is applied to array voltage reference. Assuming the current operating point is at A as shown in Fig.1.14 and the voltage is perturbed from A to B, an increasing of power is detected as P(B) is higher than P(A). According to the algorithm, as long as power is increasing, the perturbation is then applied in the same direction for next step. Consequently, the operating point will move toward and reach MPP after a few steps. Another voltage perturbation will result to
a power decrease as from MPP to C, the algorithm then makes the decision to reverse the perturbation direction which moves the operating point back to MPP.

The advantage of PO method is relatively simple algorithm structure and thus easy to be implemented. The disadvantage is that this algorithm can be confused under rapidly changing irradiance condition. As shown in Fig.1.15, assuming initially the irradiance is S1 and MPPT is achieved in which case the operating point reaches A (MPP1), the algorithm will inject perturbation further to the left. At this time, the irradiance starts to increase continuously from S1 to S2. Then the operating point will move from B to C. The power change is positive detected by the algorithm, so algorithm perturbs voltage further to the left. As the irradiance continuously increases, the operating point moves to E. Since this process makes the operating point deviate away from MPP3, MPPT performance of PO is not good.

![Figure. 1.15: Perturb and observe (PO) in changing irradiance condition](image)

(3) Incremental Conductance (IncCond) MPPT [17]-[22]

The Incremental Conductance identifies the MPP via the comparison between the absolute value of conductance (G) and incremental conductance (g). Assuming static
In the irradiance case, G is equal to –g at MPP. Therefore, if this condition is detected, the MPP is regarded to be found. Moreover, if G is larger than –g, the operating point is supposed to be at left side of MPP. Otherwise, if G is smaller than –g, it is at right side of MPP. This concept can be represented by Fig.1.16.

![Figure. 1.16: Incremental conductance (IncCond) MPPT method](image)

The equations describing the process differ from the PO in the aspect of judging mechanism where the conductance is monitored and compared as in Eq.1.3.

\[
G(k) = I(k)/V(k) \\
g(k) = (I(k) - I(k-1))/(V(k) - V(k-1)) \\
\Delta V(k) = \text{sign}(G(k) + g(k)) \Delta V \\
V_{ref}(k) = V_{ref}(k-1) + \Delta V(k)
\] (1.3)

The advantage of IncCond is that it can easily distinguish the location of the operating point in respective to MPP under static irradiance condition. However, when the sunlight is varying, the algorithm can also encounter the same problem that stated previously with PO method. The operating point would run away from MPP when irradiance is rapidly varying.
changing. Other than that, more complex judging mechanism means longer computation time for micro-controller.

In addition to the MPPT methods introduced above, other MPPT methods can be found in wide range of literatures, e.g. extremum seeking control [26], ripple correlation control [27], and fuzzy logic MPPT [25].

1.5 Smart Converter PV System and MPPT Requirement

The smart converter PV system is regarded to be of great advantageous in residential PV applications where the problem of panel mismatches impacts system performance. It is more flexible than micro-converter PV system and more cost effective.

![Figure 1.17: Perturb and observe (PO) MPPT method](image)

Considering the effect of the resistance of the wire that connects smart converter array with the second stage converter, the actual output characteristic seen by the second stage PV converter should be more like what is shown in Fig.1.17 where the cases with and without mismatch are both drawn. For the case with no mismatch, the MPPT region is
supposed to be a flat plateau. However, for the actual case, the higher the voltage is, the smaller the current which indicates less conduction loss. Therefore, the MPPT region has a tiny slope that makes the knee point at highest voltage the actual MPP. Similarly, when mismatch happens, the characteristic will change into the lower curve. The MPP2 is then the actual MPP. As a result, the second stage PV converter is inevitable and required to track the true MPP of smart converter PV system.

There’s not a very long history that power management issues of smart converter system has been studied. Starting from [5], when the concept of PV system utilizing cascaded per-panel DC-DC converter has been brought up, the research work concerning power management issues in smart converter PV system has been conducted only in recent years [6][7]. Paper [8] has proposed a central supervising system that gathers data from all smart converters and sends commands back to prevent them from output over voltage condition. However, most commercial smart converter products actually have output voltage limit function included. Thus, over voltage limiting itself is not a real critical issue. Nevertheless, detailed analysis illustrate that voltage limiting and current limiting for each smart converter gives rise to global output voltage limiting for the whole smart converter array as shown in Fig.1.17 for the case without mismatch. In [3], it is pointed out that this simple fact may cause incompatibility when connecting smart converter array to regular second stage central PV converters that perform traditional voltage control based MPPT. This problem happens intermittently and will largely affect the system performance.

1.6 Thesis Outline
The content of this thesis contains the following aspects.

In Chapter 1, the conventional and up-to-date PV system structure and practical MPPT methods are introduced and reviewed. The pros and cons of different system structure and MPPT methods are addressed and compared. The power management issue associated with smart converter PV system is briefly pointed out.

In Chapter 2, the detailed analysis of smart converter PV system is presented. Model of traditional PV system and smart converter system are both constructed. The comparison of centralized system, string system and smart converter PV system is then conducted based on the model. The advantage of smart converter system is clearly illustrated. Further analysis of smart converter system renders the demonstration of its MPPT requirements and the power management issue is clearly shown. The selection of suitable MPPT methods for smart converter is then presented.

In Chapter 3, conductance control and resistance control MPPT are proposed and analyzed. Comparison of these two methods reveals that, although they are both doable, the resistance control MPPT is more desirable than conductance control from the standpoint of steady state performance. Then the resistance control is chosen as a solution to solve the MPPT problem addressed in Chapter 2. The concept and control structure is discussed in detail. Simulation and experiment results are presented for verification.

In Chapter 4, alternative solution to the MPPT problem in smart converter system is introduced. As addition to the resistance control MPPT, the advantage and disadvantage of these alternatives are pointed out. Actually, the alternative solution may be explored in the future. It is then followed by the summary and future work.
Chapter 2. Analysis of Traditional and Smart Converter PV Systems

2.1 Introduction

Panel mismatches in traditional centralized and string PV systems lead to the issue that large amount of available power cannot be delivered. This problem is eliminated in smart converter PV system due to the distributed panel level maximum power point tracking. As introduced in the previous chapter, a typical structure is shown in Fig. 1.8 when smart converter array is applied to DC nano-grid system. The smart converter (SC) are equipped to each panel and the whole smart converter PV array are followed by a second-stage PV converter interfacing PV array to high voltage DC bus.

Actually, there are a few basic questions need to be answered. Firstly, how the smart converter system works to enhance the MPPT performance? Second, what is the function of the second-stage PV converter since the smart converters are doing MPPT already? What is the power management issue of smart converter PV system?

Without loss of generality, the following part starts with a case study in order to clearly address the issue.

2.2 Case Study

A. Case study of centralized PV system

A simple but typical case is studied in this section. Fig. 2.1 shows residential house in Portola Valley, California. The PV power system contains three ten-panel strings, thirty 170W monocrystalline PV panels total, forming a typical 5kW system. Centralized
structure is used as we can see from the top view of the house. A, B, C stands for different strings, which are connected in parallel. In fact, this arrangement of PV panel is usually regarded as a good one because of the same model and facing the sun in the same angle and direction. Therefore, the irradiances of these panels are supposed to be the same. Other factors such as aging and temperatures can have much less effect. However, one should notice the chimney and venting pipes will cause shading effect on adjacent panels. Fig. 2.1 (b) gives such an example where Panels C1, C2, C5, A8, A9, A10 are shaded at different level.
In order to quantify the analysis, approximation is made that panel peak power reduction rate is proportional to shading area, equivalent irradiance for these shaded panels can then be estimated as follows: (1) normal panels: 1000W/m²; (2) shaded panels: A8: 588.2W/m²; A9: 767.7W/m²; A10: 823.5W/m²; C1: 470.6W/m²; C2: 117.6W/m²; C5: 882.35W/m². The panel temperatures are all assumed to be 25°C. The resulting simplified PV array structure can be described by Fig. 2.2.

![Figure 2.2: Mismatch case in centralized PV system](image)

The parameters of the PV panel are given by the manufacturer is given in the following table:

<table>
<thead>
<tr>
<th>TABLE 2-1 PV panel parameters of STP170S-24/Ab-1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV panel model</strong></td>
</tr>
<tr>
<td>Open-circuit voltage (Voc)</td>
</tr>
<tr>
<td>Optimum operating voltage (Vm)</td>
</tr>
<tr>
<td>Short-circuit current (Isc)</td>
</tr>
<tr>
<td>Optimum operating current (Im)</td>
</tr>
</tbody>
</table>

29
Maximum power at STC (Pm) 170W
Operating temperature range -40° C to +85° C

The PV panel output can then be determined by using the following simplified model.

\[ I_{PV} = I_{SC} \left[ 1 - C_1 \left( e^{\frac{V+DV}{C_2 V_{OC}}} - 1 \right) \right] + DI \]  

(2.1)

Where

\[ C_1 = \left( 1 - \frac{I_m}{I_{SC}} \right) e^{\frac{V_m}{C_2 V_{OC}}} \]
\[ C_2 = \frac{\left( \frac{V_m}{V_{OC}} - 1 \right)}{\ln(1 - \frac{I_m}{I_{SC}})} \]

\[ DI = \alpha \cdot \frac{R}{R_{ref}} \cdot DT + \left( \frac{R}{R_{ref}} - 1 \right) \cdot I_{SC} \]

\[ DV = -\beta \cdot DT - R_s \cdot DI \]

\[ DT = T_c - T_{ref} \]

The additional parameters in the above equations are defined as follows.

\[ R_{ref} \]: Reference irradiance;
\[ T_{ref} \]: Reference temperature;
\[ \alpha \]: Open-circuit voltage temperature coefficient;
\[ \beta \]: Short-circuit current temperature coefficient;

\[ R \]: actual irradiance
\[ T_c \]: actual temperature

Using the above PV panel model and the assumption of different panel irradiance, all panel output characteristics can be derived and plotted. Once we get the output I-V curve
of each individual panel, the system output under this particular mismatch condition can be easily analyzed.

Taking string A as an example, firstly the output I-V curves of all the panels in string A can be plotted in Fig.2.3 (a). Actually, there are four different irradiance levels in string A. The output of panels of string A has four different kinds of curves as plotted in Fig.2.3 (a). Since all panel share the same string current, the string output can be derived by
directly stacking all panel curves along horizontal axis which renders the composite I-V curve as shown in Fig.2.3 (b). It then clearly shows that the total output of the string is no longer like the extension of one single panel essentially due to the fact that the MPP currents of panels of different irradiance levels are different. Therefore, multiple turning points can be found near different irradiance MPPs.

Figure. 2.4: Output characteristics of centralized system: (a) Output P-V of string A; (b) array output P-V
Once the string output I-V is plotted, the power versus voltage curve can be plotted as in Fig.2.4 (a). Multiple MPPs clear show on the curve. This essentially indicates the string A output is no longer with an unique MPP but multiple local MPPs instead. Similarly, through the same process, we can get the output P-V curves of string B and C as shown as the B and C curves in Fig.2.4 (b) where string B has unique MPP due to perfect matched irradiance while string C also has the similar traits as string A because of mismatch.

Three strings are in parallel connection, thus the system output P-V curve can be derived by adding string P-V curves together along power axis. Fig.2.4 (b) clearly demonstrates multiple maximum power points on system total output curve due to panel mismatch. Among the three peaks (P1, P2, P3), even if the MPPT successfully tracks the highest peak point P1, the system can deliver 4085W power. System total available power is the sum of all the panel maximum power which is 4672W. Only 87.5% of the power available is successfully utilized. It indicates significant equivalent power loss and thus not desirable.

**B. Case study of smart converter PV system**

Considering the same mismatch condition, if the smart converter system is used to improve power generation performance, PV array in previous case can be reconfigured as in Fig. 2.5 (a). The smart converter topology is assuming to be buck/boost converter, which has wider MPPT range and enjoys major popularity among commercial power optimizer products. The main job of smart converter is to continuously track the maximum power point of the connected PV panel. Thus, the converter behaves as a
constant power source when MPPT is performing. Besides, the maximum converter output voltage and current should be limited by power device rating. Therefore, output voltage and current limit are also employed. In another words, the smart converter works basically in three modes: MPPT mode, output voltage limit mode and output current limit mode. Fig. 2.5 (b) shows the three-mode I-V curve with typical voltage and current limit value 40V and 10A.
Under the same mismatch condition, the output for single smart converter in string A can be represented by one of the four curves shown in Fig. 2.6 (a) according to individual irradiance. Because of series connection, the output current should be the same for all the ten smart converters in string A. Directly stacking the ten output I-V curves along horizontal axis renders the total output I-V curve of string A, shown in Fig. 2.6 (b).
Comparing to Fig.2.3 (b), there’s a wide range (k1 to k2) within which all the panels can generate maximum power.

![Figure 2.7: Output characteristics of smart converter system: (a) Output P-V of string A; (b) Output P-V of A,B,C and array output P-V](image)

Then the resultant P-V curve can be plotted in Fig. 2.7 (a). Through the same process, output P-V curves of the other two strings and the whole system can then be drawn in Fig.
2.7 (b). The benefit of smart converter is quite obvious once we go through this process. The essence is that each smart converter extends panel maximum power region from one particular point to a wide area. Overlapping of these areas is easy to find even under mismatch conditions. On the power versus voltage curve in Fig.2.7 (b), a flat area indicates the maximum power points of all panels are tracked by smart converter and thus deliver maximum power.

\textbf{C. The inevitability of second-stage PV converter}

The most significant advantage of smart converter PV system is that the system MPPT region is largely extended. The extension may give rise to a MPPT upper voltage boundary, which is high enough, and a MPPT lower voltage boundary, which is low enough, in which case this region will encompass the operation voltage range of DC bus. If this is true, the second stage converter can be possibly eliminated. If it is not the case, as shown in Fig.2.7 (b), the 380V DC bus voltage is not encompassed by system MPPT region, a second stage converter is needed. Therefore, it is necessary to do analysis about under which conditions this would happen to determine the necessity of second stage converter.

The width and location of MPPT region is determined by the overlapping of those of all strings. In this particular case, the derivation of the MPPT upper and lower voltage is presented in Fig.2.8, from which we can explicitly see that the upper voltage limit \( V_{mph} \) is determined by that of string C and the lower limit voltage is determined by that of string B. One can easily reach the conclusion that the upper limit is related to the string with worst mismatch and the lower limit is related to the string with the highest maximum power.
The following firstly shows how to derive the MPPT region boundary voltages of each string. Fig. 2.9 (a) shows the P-V curve of string C, where the MPPT region is located between the lower voltage $V_{mpl}$ and the upper voltage $V_{mph}$. These two voltage values can be determined as follows.

Then intersection points of horizontal line representing particular string current with the different smart converter output I-V curves in Fig. 2.9 (b) give us their output voltage values. The string current range that assures string MPPT is from smart converter current limit $I_{lmt}$ to $I_{slm_c}$, as in Fig. 2.9(b). Then the sum of intersection points voltages between $I_{lmt}$ and the group of constant power curves, as shown in Fig. 2.9 (c), is equal to $V_{mpl_c}$. And the sum of intersection point voltages of constant power lines with $I_{slm_c}$ line is equal to $V_{mph_c}$. Therefore yield Eq. 2.2:

Figure. 2.8: Determining the system MPPT region upper and lower boundary voltages
Figure 2.9: Analysis of string C MPPT region
Where $n$ stands for the number of panels in a single string; $i$ stands for the $i^{th}$ panel counting from top; $P_{mi,c}$ stands for the maximum power of the $i^{th}$ panel of string C. In the case shown in Fig.2.9, $n$ is equal to 10. The maximum power of the panels under maximum irradiance in string C is $P_{m,c}$. Then we can define string C mismatch factor to be:

$$k_{msm,c} = \frac{n}{n} \frac{P_{mi,c}}{n P_{m,c}}$$

By this definition, one can notice that the mismatch factor will be unity without shading and less than one if otherwise there is. Combining Eq.2.3 and Eq.2.2 yields:

$$\begin{align*}
V_{mpl,c} &= \frac{P_{m,c}}{I_{lim}} n k_{msm,c} \\
V_{mph,c} &= V_{lim} n k_{msm,c}
\end{align*}$$

Eq.2.4 can be used to provide an analytical sensation to the change of MPPT voltage region in respective to the mismatch condition. Actually, as long as $P_{m,c}$ is kept constant, the $k_{msm,c}$ term will be smaller with more panels are shaded or severer shading for particular amount of panels. These parameters of other strings can be defined similarly by
changing the subscript. As Eq. 2.4 indicates, the boundary voltage value of the MPPT region is subject to the mismatch level represented by the term $k_{\text{msm},c}$. The severer the mismatch condition is, $V_{\text{mph}}$ and $V_{\text{mpl}}$ both become smaller. The MPPT region moves to lower voltage range accordingly. This can also be understood by looking into Fig.2.7 where the string B is perfectly matched which renders $k_{\text{msm},B} = 1$. Therefore, the highest MPPT voltage is the voltage limit. Due to the fact that the mismatch of string C is worse that string A, the string C MPPT region is with lower voltage than string A.

For the whole system, the MPPT region can then be determined as follows:

$$
\begin{align*}
V_{mpl} &= V_{mpl,B} = \frac{P_{m,B}}{I_{lim}} n k_{\text{msm},B} \\
V_{mph} &= V_{mph,C} = V_{lim} n k_{\text{msm},C}
\end{align*}
$$

(2.5)

Figure 2.10: The effect of increasing voltage limit
One should notice from Eq.2.5 that the voltage limit and current limit also play important role in determining system MPPT range, assuming the mismatch condition is determined and kept unchanged in the first place. The lower boundary voltage tends to become lower with increased current limit. And the upper boundary voltage will be higher if a higher voltage limit is applied. Based on this nature, the MPPT region can be extended by either increasing voltage limit or current limit. Since altering voltage limit does most effect on the upper voltage boundary, which is very beneficial, an example is presented in Fig.2.10. Assuming the DC bus voltage is kept at nominal 380V, the case in the previous analysis will not guarantee 380V is within the MPPT region. As we increase the voltage limit from 40V to 45V, the MPPT region then encompasses 380V. In which case, the second stage converter can be potentially eliminated. Further increasing of voltage limit, e.g. to 50V, provides even more margin.

The above analysis indicates that, properly designing the voltage limit gives us possibility to get rid of the second stage converter once the mismatch condition is known. However, the most volatile factor is the irradiance mismatch. One can certainly predict the possible range of mismatch in particular site. But for the actual case, these conditions cannot be fully predicted. This means the selected voltage limit in certain case can fail in severer mismatch conditions. Still, an example is shown in Fig.2.11. In this case, the mismatch is much worse than the previous one. Even increasing the voltage limit to 50V, the MPPT upper boundary voltage is still much less than 380V. One can imagine that an extreme large voltage limit value should be chosen in order to extend MPPT region to 380V in this case which is not really preferable.
This clearly shows that the MPPT region can be greatly influenced by severe mismatch condition, which is difficult to be improved by increasing voltage limit. It is then required that a second stage PV converter tracks this varying range under different conditions.

Figure 2.11: Analysis of string C MPPT region
irradiance conditions. In other words, the job of the second stage converter is to make the operating point of the smart converter array within the MPPT region whatever the irradiance and mismatch condition is.

2.3 The Issue of Second Stage Converter MPPT

The above analysis illustrates that the smart converter PV system has much better performance comparing to conventional centralized PV system in terms of maximizing the output power. Second stage PV converter is still required to do MPPT to find the flat plateau of the first stage. However, because the smart converter array has totally different output characteristics from conventional PV array, the MPPT of the second stage converter may also be different from conventional methods. Detailed analysis reveals that there is issue of second stage MPPT in normally perfectly matched condition.

(1) Only current control MPPT is suitable in static irradiance condition

Similar with the review presented in Chapter 1, there are three control variables that can be used to realize second stage MPPT: voltage, current and duty cycle. The following analysis will clearly show that both voltage and duty cycle control are not suitable in this case. Only current control is doable.
Firstly, considering choosing voltage as control variable, the problem can be represented in Fig. 2.13. Actually, the operating point is moved by updating the smart converter array voltage reference. Because of MPPT region has a tiny slope due to system wiring copper loss, MPPT will push the operating point rightward to higher and higher voltage range (A to B). Once it reaches the MPP, another perturbation of voltage then drives operating point drop down the cliff. This step introduces significant power drop $\Delta P$ which happens intermittently. This lowers down the equivalent power

Figure. 2.13: Voltage control MPPT for smart panel array

Figure. 2.12: MPPT of second stage converter for smart panel array
generation efficiency. The magnitude of the power drop depends on the time constant of the power converter and MPPT sampling period. In the worst case where the MPPT sampling period is much longer than the time constant of the power converter, the output power could drop down to almost zero during this process. Therefore, we can conclude that voltage control is not suitable.

Controlling duty cycle is not suitable either. As Fig. 2.14 shows, if we consider the power converter in CCM operation, the resulting operating point movement is from A to B for a particular MPPT sampling period on the power versus duty cycle curve. Eventually, large power drop still occurs when perturbing around MPP essentially because the duty cycle is almost kept constant within the system voltage limit region.

For current control MPPT, the same process can be used. One should notice that there is no abrupt power change around the MPP on power versus current curve. Therefore, if

Figure. 2.14: Duty cycle control MPPT for smart panel array
the MPPT step size is properly chosen, the significant power drop issue in previous two cases will not show up if we use current control.

\(2\) Current control MPPT is not suitable in changing irradiance condition

Although current control MPPT seems doable in static irradiance condition, it may cause the similar problem when the irradiance is continuously increasing. This phenomenon can be illustrated in Fig. 2.16. Still assuming the condition without mismatch, the initial operating irradiance is at \(S1\) and kept constant where the MPPT is achieved by using current control. The resulting operating point will move from the initial point to the MPP which is \(A\) in this case. After \(A\) is reached, the irradiance starts to increase continuously which means the irradiance is not a single step change but continuously to increase within certain amount of time. Consequently, the flat plateau will rise up continuously to \(S2\) after a certain period of time. During this course, the MPPT will find an increase of power when moving the operating point rightward. Thus, it will
continuously move toward to the right as long as the irradiance is increasing. On the S2 curve, the actual operating point will be at B which is deviated from the actual operating point. If the irradiance keeps increasing, the operating point will eventually reach the very edge of the system MPPT region as point C shown. One more step, the same problem of abrupt power drop occurs. Therefore, the current control MPPT is not suitable in changing irradiance condition.

![Figure. 2.16: Current control MPPT for smart panel array in increasing irradiance condition](image_url)

(3) From MPPT algorithm point of view

The above analysis is actually based on perturb and observe and Incremental Conductance MPPT algorithm. As introduced in Chapter 1, these two widely used MPPT algorithms are both based on the hill climbing method to determine the movement of operating point. Another MPPT method as presented in Chapter 1 is the fractional open-circuit voltage, which is based on the nearly constant ratio between maximum power point voltage and open-circuit voltage for a conventional PV array. For smart converter PV system, since there’s no such relationship, this principle cannot be applied. However,
one may think the similar method can be used to obtain the system voltage limit value by open the array terminals. However, only knowing the voltage limit value cannot directly give us information about the true MPP which should be the at the highest voltage point of the flat MPPT region. From Eq.2.4, Vmph depends additional information about the mismatch condition represented by $k_{msmi,c}$, which is relatively hard to acquire and subject to change. Therefore, the concept still cannot be applied.

2.4 Summary

This chapter begins with a simple, but typical case of centralized PV system, which suffers from low power generation efficiency when mismatch happens. The power generation efficiency can actually be greatly improved by applying smart converter to each individual panel doing distributed MPPT. In this way, when mismatch occurs, almost unity power generation efficiency can be achieved theoretically. Despite the great improvement, a second stage converter is needed to do MPPT for the whole smart converter array. However, there is issue when doing second stage MPPT. The conventional voltage control, duty cycle control MPPT are not suitable. Current control MPPT is doable in static irradiance condition but has the same problem under varying irradiance condition. Some modifications need to be done to second stage MPPT.
Chapter 3.  Modified MPPT Methods for Smart Converter

PV system

3.1 Conductance Control MPPT

As from the analysis presented in Chapter 2, the power generation efficiency can be greatly improved by applying smart converter to each individual panel doing distributed MPPT under mismatch conditions. Some modifications need to be done to second stage MPPT since conventional voltage control, duty cycle control and current control MPPT are not suitable.

One should remember from the review of MPPT methods presented in Chapter 1, the Incremental Conductance (IncCond) method identify current operating point location by calculating and comparing the absolute and incremental conductance of smart converter array. This actually gives us thoughts of utilizing other control variables other than current, voltage or duty cycle. The conductance seems to be one of the candidates.

3.2 The Concept of Conductance Control MPPT

By definition, the absolute conductance is the ratio between current and voltage as can be shown below:

\[ G = \frac{I}{V} \]  

(3.1)

The incremental conductance can be calculated by:

\[ g = \frac{\Delta I}{\Delta V} \]  

(3.2)
For conventional centralized PV array, one the most widely used MPPT methods, Incremental Conductance (IncCond) identifies the current operating point location in respective to MPP by examining the absolute and incremental conductance which can be represented by Fig.3.1. When G is larger than –g, the operating point is at left side of MPP, otherwise it is at right side of MPP. Only when G and –g are almost with the same value can we conclude that MPP is reached. Although the conductance is utilized, the movement of operating point is still driven by modifying the voltage reference of voltage control loop. According to the analysis of chapter 2, the MPPT instability issue exists in this case.

![Figure 3.1: Incremental conductance (IncCond) MPPT method](image)

The basic problem is to avoid direct controlling over voltage, current or duty cycle. The IncCond method cannot be used directly, it actually inspires us the possibility to achieve MPPT via conductance control. It means the conductance is chosen as a control variable other than voltage, current or duty cycle. During each MPPT period, it’s the conductance that is updated.
Fig. 3.2 shows the representation of the conductance control method. The blue solid line shows smart converter array output I-V curve. Instead of keeping the operating voltage $V_s$ strictly following the reference given by MPPT algorithm, the absolute conductance of smart converter array can be controlled to follow the given desired value. For example, if we make the ratio between $I_S$ and $V_s$ equal to $G_{s1}$ by conductance control, the actual operating point is then supposed to be the intersection point $(V_{s1}, I_{s1})$ of the smart converter output I-V and the dotted blue line which is constant conductance ($G_{s1}$) line. In this way, the array voltage and current are both determined as unique values. Then we consider choosing a conductance value ($G_{s2}$) of which the straight line intersects with voltage limit region. The operating point is then $(V_{s2}, I_{s2})$ which is stable. Similarly, if we choose the conductance to be $G_{s3}$, the intersection of red dotted line and
the current limit region is still a stable operating point. Changing the slope of the straight line leads to the change of operating point which can be utilized in the process of MPPT.

### 3.3 Process of Conductance Control MPPT

![Diagram](image)

(a) 

![Diagram](image)

(b)
The process of G MPPT can be represented by Fig.3.3. The group of straight lines is drawn in Fig.3.3 (a) is from $G_s = 0.015S$ to $G_s = 0.235S$ with evenly spaced step size equal to $\Delta G = 0.02S$. The true MPP is point C which needs to be tracked. Assuming the initial point is at F with $G_s = 0.235S$ and PO algorithm is used, MPPT firstly perturbs the operating point by decreasing the $G_s$ which result to operating point movement towards B because the power is increasing. $G_s$ will be further decreased step by step after entering MPPT region. Once it reaches C, another reduction of $G_s$ leads operating point to E which is a stable operating point in voltage limit region. As the power is decreasing, MPPT then decide to move back to C. The groups of constant conductance lines can be redrawn in P-V and P-G plots. In P-V plot, the constant conductance line is transformed.

Figure 3.3: Representation of conductance control MPPT with constant step size (a) G-MPPT on I-V curve; (b) G-MPPT on P-V curve; (c) G-MPPT on P-G curve
into parabola. And in P-G plot, it is represented by vertical straight line which shows more clearly the power change according to conductance perturbation with constant $\Delta G$.

The process of conductance control MPPT can be described by the following equation:

\[
G(k) = I(k)/V(k) \\
\Delta P_S(k) = I_S(k)V_S(k) - I_S(k-1)V_S(k-1) \\
\Delta G_{S_{\text{ref}}} (k) = \text{sign}(\Delta P_S(k)) \cdot \text{sign}(\Delta G_{S_{\text{ref}}} (k-1)) \cdot \Delta G_{S_{\text{ref}}} \\
G_{S_{\text{ref}}} (k) = G_{S_{\text{ref}}} (k-1) + \Delta G_{S_{\text{ref}}} (k)
\]

Eq.3.3 represents the typical PO algorithm where the conductance is chosen as the MPPT control variable.

One should notice from Fig.3.3 (c) that the power change when perturbing from C to E is still very large, although E is a stable operating point. The performance of this MPPT method could be questioned. We then need to find a way for evaluation.

### 3.4 Steady State Performance of Conductance Control MPPT

During the steady state, the operating point will move back and forth around the actual MPP. Considering an ideal case, this steady state movement will contain three points in for a MPPT used in centralized PV array. This conclusion is also applicable to smart converter array where the operating point is moving around three points (E,C,G) close to MPP as point C in Fig.3.4. From power generation point of view, the magnitude of the power deviation from C can be regarded as a criterion to evaluate the steady state performance of MPPT. For example, as in Fig.3.4, during the time interval that system operates at E, the output power will be less than MPP power. Thus, the larger the power difference is between C and E, the lower equivalent power will be generated in respective
to the idea MPP power. Since there’s only very tiny power change from C to G, the power drop from C to E dominates the MPPT performance degrading.

![Figure. 3.4: Steady state operation of conductance control MPPT](image)

In conventional PV array in inverter application, where the PV array performance is affected by the 120Hz current ripple reflected to DC side, the utilization ratio serves as an analytical factor to evaluate MPPT performance. It is defined as [28]:

$$K_u = \frac{P_{ave}}{P_m}$$  \hfill (3.4)

The $P_{ave}$ is the actual average power considering the power deviation from $P_m$ due to current ripple, which makes operating point move around MPP. The $P_m$ is the ideal MPP power.
In DC nano-grid system, there is no 120Hz ripple. However, the operating point movement caused by perturbation given by MPPT can be another factor that cause $P_{ave} < P_m$. The utilization ratio can still be used.

Assuming the MPPT sampling period is $T_{mppt}$ and the step size is $\Delta G$ which is constant. The worst case for the power drop $\Delta P$ occurs when the middle operating point C is exactly at MPP. The output power values when operating at C and G are both approximately $P_m$. However, when operating at E, the output power is $P_m - \Delta P$. The average power is then can be calculated as:

$$P_{ave} = \frac{2P_m \cdot T_{mppt} + (P_m - \Delta P) \cdot T_{mppt}}{3T_{mppt}} = P_m - \frac{\Delta P}{3}$$ \hspace{1cm} (3.5)

The utilization ratio can be then calculated:

$$K_u = \frac{P_{ave}}{P_m} = 1 - \frac{\Delta P}{3P_m}$$ \hspace{1cm} (3.6)

Eq.3.6 clearly shows that the power drop from C to E is the main reason that lowers the MPPT performance. As in the case shown in Fig.3.4, system MPP power is 4.6kW and the power drop from C to E is 2.6kW, then the utilization ratio can be calculated as:

$$K_u = \frac{P_{ave}}{P_m} = 1 - \frac{\Delta P}{3P_m} = 1 - \frac{2.6}{3 \times 4.6} = 0.8115$$

The above calculation indicates the actual output power is equivalent to 81.15% of the maximum power at C which shows relatively low utilization ratio. To improve the utilization ratio, one way is to reduce the step size of perturbation. However, that will reduce the tracking speed, e.g. the amount of time from a start point F to C.
To optimize the parameter such as the step size of conductance MPPT, a reasonable way is to firstly give the targeted utilization ratio and calculate the maximum step size accordingly. The typical acceptable utilization ratio that is acceptable is 98% [28]. Then the maximum power drop can be calculated by solving the following equation:

\[
K_u = \frac{P_{\text{ave}}}{P_m} = 1 - \frac{\Delta P}{3P_m} = 1 - \frac{\Delta P}{3 \times 4.6} = 0.98
\]

\[
\Delta P = 0.276kW = 276W
\]

Because both C and E are located within voltage limit region, the following equation stands.

\[
\Delta P = V_{\text{lmt}}^2 G_{SC} - V_{\text{lmt}}^2 G_{SE} = V_{\text{lmt}}^2 \Delta G_S
\]

Thus, it yields:

\[
\Delta G_S = \frac{\Delta P}{V_{\text{lmt}}^2} = \frac{276}{360^2} = 0.00212S
\]

The above calculation result gives us the maximum conductance step size. The conductance values at point F and C are 0.235S and 0.035S respectively. The tracking time from F to C in terms of \( T_{\text{mppt}} \) can then be estimated as:

\[
t_{tr} = \frac{G_{SE} - G_{SC}}{\Delta G_S} \cdot T_{\text{mppt}} = \frac{0.235 - 0.035}{0.00212} \cdot T_{\text{mppt}} \approx 94T_{\text{mppt}}
\]

It essentially means in order to maintain 98% utilization ratio at steady state, the selected step size gives rise to a 94 MPPT sampling periods of tracking time to move from initial point F to point C.

**3.5 The Drawback of Conductance MPPT**
The drawback of conductance MPPT in smart converter PV system case can be seen from the above calculation. Basically, in order to maintain acceptable steady state performance, the step size must be selected to be relatively small, which unfortunately jeopardizes the tracking speed.

A more insightful way to look into this matter is to examine the Fig.3.3 (a) in detail. It is redrawn in Fig.3.5 that the angle increment $\Delta \theta(k)$ becomes larger and larger as the conductance value is decreasing. Even the angle increment is small around B, it will become significantly large if the conductance perturbation step size is not small enough.

Based on the above analysis, the conductance MPPT has the advantage that it can solve the MPPT instability problem of smart converter PV system. However, it has trade-offs between steady state performance and tracking speed. To maintain an acceptable utilization ratio, very small step size should be used which slows down the tracking speed.
3.6 **Resistance Control MPPT**

In order to overcome the drawbacks of conductance control MPPT, there’s another way very similar to solve the MPPT instability problem. The reciprocal of conductance is resistance. A similar approach has been proposed in [24]. By definition, the absolute resistance is the ratio between voltage and current as can be shown below:

\[ R = \frac{V}{I} \]  

(3.7)

The absolute resistance can be used as a control variable which is also straight lines in I-V curve. The I-V, P-V and P-R plots when applying to smart converter system are then shown below.
Figure 3.6: Representation of resistance control MPPT with constant step size (a) R-MPPT on I-V curve; (b) R-MPPT on P-V curve; (c) R-MPPT on P-R curve
In Fig. 3.6, the group of straight lines is drawn in Fig. 3.3 (a) is from \( R_s = 4 \ \Omega \) to \( R_s = 34 \ \Omega \) with evenly spaced step size equal to \( \Delta R_s = 2 \ \Omega \). As long as these straight lines intersect with voltage limit, current limit region, stable operating point can be found. Thus, similar to the conductance MPPT approach, there’s no MPPT instability problem. As shown in Fig. 3.6 (c), the slope at either side of MPPT region is finite value, thus there is no abrupt power drop when perturbing around C and B.

The process of resistance control MPPT is also very similar to that of conductance control MPPT which can be described by the following equation. The only difference is it updates the equivalent resistance value \( R_{sref} \) with constant step size \( \Delta R_{sref} \).

### 3.7 Steady State Performance of Resistance Control MPPT

For resistance control MPPT, the previous analysis process is still applicable because it is also a three-point operation in steady state as shown in Fig. 3.7. Assuming the MPPT sampling period is \( T_{mppt} \) and the step size is \( \Delta R_s \) which is constant. The worst case for the power drop \( \Delta P \) occurs when the middle operating point C is exactly at MPP. The output power values when operating at C and G’ are both approximately \( P_m \). However, when operating at E’, the output power is \( P_m - \Delta P \). The average power is then can be calculated as:

\[
P_{ave} = \frac{2P_m \cdot T_{mppt} + (P_m - \Delta P) \cdot T_{mppt}}{3T_{mppt}} = P_m - \frac{\Delta P}{3}
\]

The utilization ratio can be then calculated:
Eq.3.8 and Eq.3.9 are essentially the same as conductance control case. As in the case shown in Fig.3.4 in which the step size $\Delta R_s$ is arbitrarily chosen just to get a clear picture for demonstration. However, the maximum step size can be selected through the same course by giving the minimum utilization ratio requirement. In order to make reasonable comparison between resistance control and conductance control MPPT, the acceptable utilization ratio is also set to be 98%. Then the maximum power drop can be calculated by solving the following equation:

$$K_u = \frac{\bar{P}_{\text{ave}}}{P_m} = 1 - \frac{\Delta P}{3P_m} = 1 - \frac{\Delta P}{3 \times 4.6} = 0.98$$

Figure 3.7: Steady state operation of conductance control MPPT
\[ \Delta P = 0.276\text{kW} = 276\text{W} \]

Because both C and E are located within voltage limit region, the following equation stands.

\[ \Delta P = V_{\text{lim}}^2 \frac{1}{R_{SE'}} - V_{\text{lim}}^2 \frac{1}{R_{SG'}} = V_{\text{lim}}^2 \left( \frac{1}{R_{SE'}} - \frac{1}{R_{SE''}} \right) = V_{\text{lim}}^2 \frac{\Delta R_s}{R_{SC}R_{SE'}} \quad (3.10) \]

In Eq.3.10, the \( R_{SE'} \) and \( R_{SC} \) can be further described as:

\[ R_{SE'} = R_{SC} + \Delta R_s \quad (3.11) \]

\[ R_{SC} = \frac{V_{\text{lim}}^2}{P_m} = \frac{V_{\text{lim}}^2}{P_m} \quad (3.12) \]

Combining (3.10), (3.11) and (3.12) yields:

\[ \Delta P = V_{\text{lim}}^2 \frac{\Delta R_s}{R_{SC}R_{SE'}} = P_m \frac{\Delta R_s}{V_{\text{lim}}^2} + \Delta R_s \quad (3.13) \]

Solving Eq.3.13 renders,

\[ \Delta R_s = \frac{\Delta P \cdot V_{\text{lim}}^2}{P_m^2 - P_m \Delta P} \quad (3.14) \]

In this particular case, the system voltage limit is 360V and maximum power is 4590W. To limit the power drop to be less than 276W, the maximum step size can be calculated:

\[ \Delta R_s = \frac{276 \times 360^2}{4590^2 - 4590 \times 276} \approx 1.81\Omega \]
The above calculation result gives us the maximum resistance step size. The resistance values at point F' and C are 4Ω and 28Ω respectively. The tracking time from F' to C in terms of $T_{mppt}$ can then be estimated as:

$$t_{tr} = \frac{R_{SC} - R_{SF'}}{\Delta R_S} \cdot T_{mppt} = \frac{28 - 4}{1.81} \cdot T_{mppt} \approx 13T_{mppt}$$

It essentially means in order to maintain 98% utilization ratio at steady state, the selected step size gives rise to only 13 MPPT sampling periods of tracking time to move from initial point F to point C which is much faster than the conductance control MPPT.

### 3.8 The Advantage of Resistance Control MPPT

![Figure 3.8: The operating point variation with constant step size increasing resistance](image)

Figure 3.8: The operating point variation with constant step size increasing resistance
Fig.3.8 is a detailed version of Fig.3.6 (a). Resistance control MPPT is advantageous over conductance control MPPT in aspect of tracking speed with the same utilization ratio is mainly because the angle increment is decreasing with constant resistance step size as system operates closer and closer to MPP. Therefore, relatively large step size can be chosen to acquire a high tracking speed without jeopardizing steady state performance.

3.9 Implementation of Resistance Control MPPT

During each MPPT sampling period, the desired resistance Rsref is generated by MPPT algorithm and resistance control is aiming at making the ratio between smart converter array output voltage and current following Rsref. Therefore, the control structure is shown in Fig.3.9.

The output voltage and current are sensed as Vs(k) and Is(k). They are fed into MPPT algorithm block in which the following algorithm is used to determine the desired resistance value Rsref(k):

![Figure. 3.9: The operating point variation with constant step size increasing resistance](image)
The actual operating point resistance Rs(k) can be derived by dividing Vs(k) with Is(k).

A feedback loop is applied to make Rs(k) follow Rsref(k).

3.10 Simulation Verification of Resistance MPPT

The scope of this simulation is to demonstrate the comparison between voltage control MPPT and resistance control MPPT.

(1) Traditional voltage control MPPT in smart converter PV system

### TABLE 3-1 Parameters of simulation for voltage control MPPT

<table>
<thead>
<tr>
<th>Smart converter</th>
<th>Single converter voltage limit</th>
<th>40V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single converter current limit</td>
<td>10A</td>
</tr>
<tr>
<td>Array configuration</td>
<td>Smart converter number per string</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Number of strings</td>
<td>3</td>
</tr>
<tr>
<td>Second-stage boost converter parameters</td>
<td>Inductor</td>
<td>50 $\mu$H</td>
</tr>
<tr>
<td></td>
<td>Input capacitor</td>
<td>110 $\mu$F</td>
</tr>
<tr>
<td></td>
<td>Output capacitor</td>
<td>270 $\mu$F</td>
</tr>
<tr>
<td></td>
<td>Switching frequency</td>
<td>20kHz</td>
</tr>
<tr>
<td>MPPT parameters</td>
<td>Sampling period</td>
<td>0.05s</td>
</tr>
<tr>
<td></td>
<td>voltage step size</td>
<td>4V</td>
</tr>
</tbody>
</table>

The system structure simulated is shown in Fig. 2.9 using Perturb and Observe (PO) method. The parameters of this simulation is listed in Table III-I.
The simulation waveforms of array voltage $V_s$, current $I_s$, and power $P_s$ are shown in Fig. 3.10. During the time interval when the array voltage reference exceeds the voltage limit, output power drops dramatically. Consequently, the system is delivering only partial power or even zero power if the current drops to zero. It also shows that this problem happens repeatedly because the voltage perturbations are employed back and forth around the knee point, which can be regarded as MPPT instability problem.

(2) Resistance control MPPT in smart converter PV system

Figure 3.10: Simulation result
To verify the resistance control concept, simulation model of 5kW smart converter PV system (3x10) is constructed in Matlab/Simulink. Table III-II indicates the simulation parameters. The simulation waveforms show in Fig. 3.11.

<table>
<thead>
<tr>
<th>TABLE 3-2 Parameters of simulation for resistance control MPPT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Smart converter</strong></td>
</tr>
<tr>
<td>Single converter voltage limit</td>
</tr>
<tr>
<td>Single converter current limit</td>
</tr>
<tr>
<td><strong>Array configuration</strong></td>
</tr>
<tr>
<td>Smart converter number per string</td>
</tr>
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</tr>
<tr>
<td><strong>Second-stage boost converter parameters</strong></td>
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<tr>
<td>Output capacitor</td>
</tr>
<tr>
<td>Switching frequency</td>
</tr>
<tr>
<td><strong>MPPT parameters</strong></td>
</tr>
<tr>
<td>Sampling period</td>
</tr>
<tr>
<td>Resistance perturbation step size</td>
</tr>
</tbody>
</table>
Simulation result indicates that when system enters voltage limit region (constant voltage region) from MPPT region (constant power region), it can be stable at a operating point very close to MPP. Output power slightly decreases instead of dropping to zero if perturbing voltage. These have verified the feasibility of the resistance control MPPT that can solve the MPPT instability issue in smart converter based PV system.

3.11 Experimental Verification of Resistance Control MPPT
The experiment test-bed is shown in the following Fig.3.12 (a) and the structure is shown in Fig.3.12 (b). Boost converter is constructed for testing purpose. For the sources, two E4361 Agilent Solar Simulators are used to simulate two PV panels. Each simulator module output is equipped with Solarmagic SM1230 power optimizer connected in series.
representing a two-panel smart converter string. Since SM1230 power optimizer has 40V voltage limit and 10A current limit, the string voltage will be limited at 80V. This low power experiment is for concept verification before applying to large scale smart converter array.

The experiments are conducted in two cases. In Case 1, the simulated panel is set to full power output, e.g. 170W peak power. Case 2 is when the panel output power is reduced to 140W, where the two panels are still matched. Fig.3.13 presents the measured output characteristics of the two-panel smart converter string. One can see directly from the measurements that the actual output characteristics of smart converter string are the same as what have been predicted and plotted in previous chapters for both voltage limit and MPPT regions. Although the current in current limit region is not well regulated for this particular product, no problem would stand in the way in the experiment since the current limit region cannot be reached.

(a)
Fig. 3.14 gives experiment waveforms of output voltage (Vs) and current (Is) of smart converter string of Case 1. Before the dotted vertical line, system is operating in smart converter string MPPT region, second-stage converter perturbs Rs with constant step size $\Delta R=0.5\Omega$ for every 1s. After the operation from point E1 to E6 in MPPT region, system is pushed into smart converter string voltage limit region with only minor power diminution at point E7. The perturbation is then conducted around MPPT and voltage limit boundary point C.
Figure 3.14: Experiment result of case 1

Figure 3.15: Experiment result of case 2
Similarly, the same experiment is conducted in case 2, the waveforms are shown in Fig.3.15.

### 3.12 Summary

This chapter presents two solutions to solve the MPPT instability problem when conventional voltage control MPPT is applied to smart converter array. These solutions are conductance control MPPT and resistance control MPPT. In terms of steady state performance, resistance control is advantageous over the conductance control MPPT due to the inherit decreasing operating point movement speed when approaching MPP. The tracking speed from an initial point away from MPP is also faster for resistance control MPPT than conductance control MPPT. The simulation and experimental results verifies that resistance control MPPT can successfully solve the MPPT instability problem.
Chapter 4. Summary

In DC nanogrid application, conventional PV system includes centralized PV system, string PV system and micro-converter PV system. A more state-of-art system is smart converter PV system in which distributed MPPT is achieved by equipping each individual panel with small DC-DC converter. The job of these converters is doing MPPT for each panel individually. Thus, for most of the cases, all panels can generate maximum power.

Detailed analysis shows that, the equivalent power generation efficiency can be easily compromised when mismatch occurred in conventional centralized and string PV systems. Considering the smart converter PV system, all panels can generate maximum power with the same mismatch condition, which is much more advantageous. However, a second stage PV converter is still needed to make sure system operate within the MPPT region. The MPPT instability problem is observed when conventional voltage control, current control and duty cycle control MPPT is used by second stage converter.

Conductance and resistance control MPPT is presented and compared in terms of steady state performance and tracking speed. Although both of them can solve the MPPT instability problem, the resistance control MPPT is more suitable and advantageous because it enjoys higher utilization ratio in steady state and faster tracking speed from initial point that is away from MPP. Both simulation and experimental results verify the concept.
References


