Analysis and Implementation of Fine-Grained Distributed Maximum Power Point Tracking in Photovoltaic Systems

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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This thesis deals with quantifying the merits of Distributed Maximum Power Point Tracking (DMPPT), as well as providing solutions to achieve DMPPT in PV systems. A general method based on 3D modeling is developed to determine the energy yield of PV installations exploiting different levels of DMPPT granularity. Sub-string-level DMPPT is shown to have up to 30% more annual energy yield than panel-level DMPPT. A Multi-Input-Single-Output (MISO) dc-dc converter is proposed to achieve DMPPT in parallel-connected applications. A digital current-mode controller is used to operate the MISO converter in pseudo-CCM mode. For series-connected applications, the virtual-parallel concept is introduced to utilize the robustness of the parallel connection. This concept is demonstrated on a three-phase boost converter. The topology offers reduced output voltage ripple under shading which increases the life-time of the output capacitor. The prototypes yield output power benefits of up to 46% and 20% for the tested shading conditions.
Acknowledgements

I am thoroughly thankful to my supervisor, Olivier Trescases, whose encouragement, vision and support from the preliminary to the concluding level of this thesis guided me through thick and thin during the course of this project. I will always be grateful for dedication, leadership, and technical excellence he has constantly provided me with since I joined his group. I am also thankful for all the opportunities I was given under his supervision; opportunities which are not just career-related, but also lasting for life. He is and will remain a great influence in my life.

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Chapter 1

Introduction

The energy demand in the world is steadily growing. As issued in the latest Canadian government report on energy trends [1], the energy intensity per GDP has decreased by 22%, while the energy intensity per capita has jumped by 4% in the 1990 to 2008 time-frame as shown in Fig. 1.1. This upward trend in energy consumption per person reflects the increasing use of electricity by commercial electronic goods, transportation sector and industrial processes, despite recent technological improvements in efficiency. New types of energy, especially renewable resources, must be further developed in order to compensate for the booming demands, since the conventional resources are becoming more and more expensive.

Figure 1.1: Energy use intensity per capita and per GDP in Canada for 1990 - 2008 [1].
One of the popular types of renewable resources is solar energy. The gradual reduction in the cost of photovoltaic (PV) panels, as depicted in Fig. 1.2(a) [2], combined with favorable feed-in tariffs in a variety of countries is leading to the rapid deployment of PV installations worldwide as shown in Fig. 1.2(b) [3].

![Average cost of PV modules by year per watts](image1)

![Cumulative number of PV installations worldwide](image2)

Figure 1.2: (a) Average cost of PV modules by year per watts [2], and (b) cumulative number of PV installations worldwide [3].

Various PV technologies have been developed, from which a few have been fully commercialized. More efficient technologies together with improvement in materials and
cheaper production process will result in a near future, where PV power will be more price competitive. It will reach grid parity with conventional power resources, such as oil, coal and natural gas. A price reduction of 50% is predicted over the next six years [4]. Various PV technologies and the efficiency of the developed modules are shown in Fig. 1.3 [5], while the most popular technologies in PV industry are listed in Table 1.1 with their efficiency and area specifications. The high efficiency of mono-crystalline silicon PV has made it one of the most popular technologies for small to medium-sized sub-10 kW residential and commercial installations [6]. These installations are the main focus of this thesis, although the methods and topologies developed in the following chapters can be adapted for any of the aforementioned PV types or common PV applications.

Figure 1.3: Common solar technologies and the module efficiencies [5].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Thin Film</th>
<th>Crystalline Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>(CdTe)</td>
<td>CI(G)S (a-Si)</td>
</tr>
<tr>
<td></td>
<td>10-11</td>
<td>7-11</td>
</tr>
<tr>
<td>Area Needed per kW (m²)</td>
<td>9 m²</td>
<td>10 m²</td>
</tr>
<tr>
<td></td>
<td>15 m²</td>
<td>7 m²</td>
</tr>
<tr>
<td></td>
<td>8 m²</td>
<td></td>
</tr>
</tbody>
</table>
1.1 Distributed Maximum Power Point Tracking

The energy yield of small-scale, sub-10 kW installations is usually reduced by mismatches in the operating conditions of the individual PV cells, which are typically connected in series/parallel arrangements. The non-uniformity in operating conditions is caused by external factors such as clouds, reflections, partial shading, dirt, temperature gradients, or intrinsic factors such as semiconductor process variations and aging. PV panels having non-uniform irradiation, which is the amount of energy per unit area available on the PV surface due to the sun radiation, and temperature cannot be operated at their respective Maximum Power Point (MPP). This is due to the fact that they are forced to operate with the same terminal voltage in parallel-connected systems or at the same string current in series-connected systems.

![Diagram of a conventional PV system](image)

**Figure 1.4:** Conventional PV system, where MPPT is performed on the series-connected string.

Performing Maximum Power Point Tracking (MPPT) on an array of series-connected photovoltaic panels, as shown in Fig. 1.4, has been extensively used to continuously optimize the total harvested power under time-varying environmental conditions, such as
temperature and irradiation fluctuations [7]. Using power electronic converters for Distributed Maximum Power Point Tracking (DMPPT) is well known to alleviate problems associated with mismatched panels [8–13]. This concept makes use of multiple power converter units distributed in the PV system, therefore off-loading the MPPT task from the central inverter to these smaller units. As the power is extracted at smaller sub-systems of the PV installation, partial shading, aging and other power-degrading phenomena cause lower effect on the performance of the system. This is especially true for installations in urban environments, where complex time-varying shading patterns appear on the array.

1.1.1 Architectures for Distributed Maximum Power Point Tracking

Various DMPPT architectures have been proposed and implemented for PV systems. These architectures fall mainly into two categories; micro-converter and micro-inverter architectures, as shown in Fig. 1.5 (a),(b) respectively. In the micro-converter architecture, several series-connected dc-dc converters extract power from the PV modules. The string’s output is connected to a central inverter which, in turn, supplies the power to the grid. In the micro-inverter architecture, in contrast, each PV module has a dedicated grid-connected micro-inverter that directly injects the module’s harvested energy to the grid.

Several start-up companies and PV manufacturers have emerged in recent years aiming at developing low-cost high-efficiency distributed MPPT architectures based on both micro-inverter [14, 15] and micro-converter architectures [16–18]. [18] offers a parallel-connected micro-converter solution, in which several dc-dc micro-converters are connected in parallel to the central inverter. While micro-inverters provide advantages such as low-voltage AC wiring, improved stability and further robustness compared to series connection due to immediate connection to the grid, they also suffer from higher current ratings, extra complexity, wiring costs and EMI issues. The micro-converter architec-
Figure 1.5: (a) Micro-converter, and (b) micro-inverter grid-tied DMPPT PV systems.

ture, in contrast, is generally simpler, yet less robust than micro-inverter architecture. However, this architecture still provides improved robustness and enhanced reliability compared to conventional series-connected MPPT architecture.

One of the potential advantages of micro-converter architecture is the possibility of reducing the capacitor size at inverter’s input, $C_{bus}$, in grid-tied applications. The bus capacitor should be sized accordingly to handle the power ripple at double line frequency [19]. This capacitor can be sized smaller for a given relative voltage ripple, $\frac{\Delta V_{bus}}{V_{bus}}$, in micro-converter architecture due to the high step-up ratio of the dc-dc stages. This capacitance cannot be easily reduced for micro-inverter architectures, especially for the single-stage ones [19]. However, it should be noted that the voltage rating of this capacitor must be higher in micro-converter architecture. The wiring cost can be significant in the micro-converter architecture due to the series connection of several dc-dc converters. The wiring must be thicker in micro-inverter systems to accommodate a higher bus current due to low-voltage operation. In addition, the dc-dc converters in the micro-converter architecture are generally required to have relatively high boost ratios to supply the grid through the central inverter, except for the cases where a sufficient
number of PV modules are connected in series. This causes further degradation in the efficiency of the power-stage units. The key differences between these two architectures are summarized in Table 1.2.

Table 1.2: Comparison of Micro-Converter and Micro-Inverter Architectures

<table>
<thead>
<tr>
<th></th>
<th>Micro-Converter</th>
<th>Micro-Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiring</td>
<td>extended, thinner DC wiring</td>
<td>limited, thicker AC wiring</td>
</tr>
<tr>
<td>Stability</td>
<td>more stability issues</td>
<td>less stability issues</td>
</tr>
<tr>
<td>EMI Issues</td>
<td>less</td>
<td>more</td>
</tr>
<tr>
<td>Architecture Complexity</td>
<td>simple</td>
<td>more complicated</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>higher</td>
<td>lower</td>
</tr>
<tr>
<td>Total Bus Capacitance</td>
<td>lower</td>
<td>higher</td>
</tr>
</tbody>
</table>

Micro-inverter and micro-converter technologies are rapidly evolving in recent years, as tremendous research endeavors in academia and R&D laboratories are focused on the topic. These recent efforts have generated a significant amount of excitement in the solar industry, but the outcome is still quite expensive due to packaging and semiconductor costs and have yet to be widely accepted. In addition to the cost considerations, long-term reliability concerns are likely to delay the large scale adoption of such schemes. Manufacturers have responded by eliminating electrolytic capacitors from their designs and increasing the level of integration. In at least two cases, an Application Specific Integrated Circuit (ASIC) has been specifically developed for optimizing the DMPPT performance [17, 20]. Dc-dc micro-converters are clearly more appropriate than micro-inverters at higher levels of granularity due to lower overhead cost.

1.1.2 Possible Levels of DMPPT Granularity

Each PV system consists of multiple PV cells, bundled together in panels and strings with series/parallel configurations. Power harvesting can be performed at different levels of granularity in the PV system. Today DMPPT is mainly targeted at the panel-level,
However one can envision four separate levels of granularity. The distributed power converter, either micro-converter or micro-inverter, can be designed to achieve DMPPT at the (1) cell, (2) sub-string, (3) panel and (4) string levels, as shown in Fig. 1.6. The finest granularity level extends all the way down to individual PV cell. The choice of granularity clearly impacts the voltage/current ratings and cost of the power electronics. As the granularity increases, the energy harvesting capability of the system improves under partial shading; however the total cost and part count of the system increases as well. This is despite the fact that high-density, low-voltage dc-dc converter technologies could potentially be used for the cell-level DMPPT.

![Diagram of different potential granularity levels for performing DMPPT in the PV system.](image)

Figure 1.6: Different potential granularity levels for performing DMPPT in the PV system.

### 1.2 DMPPT Realization

PV applications are generally categorized into either off-grid or grid-tied categories. The DMPPT architectures shown in Fig. 1.5 and the discussions in the previous sections have been mainly focused on grid-tied applications. However, fine-grained DMPPT concept can also be applied to off-grid systems. Depending on the load which is to be fed by
the PV system, there might be the need for an inverter to be installed in the PV setup. Sub-kW stand-alone battery chargers, especially for portable applications, do not require AC transformation while more high-power applications such as Electro Vehicles (EV) or installations in rural areas where the national grid is not available, usually make use of an inverter to feed the AC loads. Sometimes, it is a wise choice in these areas to avoid using an inverter and power all the DC loads directly from the PV setup. As a result, the micro-converter architecture is the preferable solution for off-grid PV systems.

1.2.1 Off-grid PV Applications

One of the main objectives of off-grid PV control systems is battery charging. Solar battery chargers are gaining more popularity in sensory and control systems for their availability in remote areas, as well as cost advantages due to the reduction of battery size and storage. These PV applications span ultra low-power systems such as biological sensors to medium-power setups such as battery chargers for EVs. In addition, grid-tied PV installations such as residential PV systems sometimes make use of a battery bank to supply the local DC loads and provide a means for electricity storage, as shown in Fig. 1.7 [21].

![Figure 1.7: Conventional PV system utilizing a battery bank and charge controller for local DC loads [21].](image)

There are several proposed converter topologies for different targeted off-grid PV
applications. In [22,23], high-efficiency hard-switching dc-dc converters and control techniques are proposed for mW-range low-power applications. In this power range, the MPPT algorithm itself is of major importance as the power consumption of all the control blocks affects the overall efficiency of the system significantly. For higher power systems, quasi-resonant, resonant and other soft-switching topologies have been proposed to be used inside the charge controllers [24–28]. Some researchers have tried to develop charge controllers for battery packs with multi-input terminals to combine different renewable energy resources through a single converter [29–31]. This can result in a highly integrated system with lower part count and associated cost benefits.

1.2.2 Grid-Tied PV Applications

Reliable grid connection is the common requirement for most of the medium to high-power PV installations in urban areas. In an off-grid system, once the batteries are fully charged or the storage element’s full capacity is reached, any excess electricity generated by the panels cannot be stored and thus has to be dumped to prevent the storage element from being overcharged. This results in wasted electricity, while in grid-tied systems with no storage element, the grid, as a giant network, takes in any amount of power generated by the PV system. Battery-less grid-tied PV installations, are generally cheaper and easier to install than off-grid PV systems as they do not require additional elements for local energy storage. Battery-less grid-tied systems are also less damaging to the environment due to elimination of the battery from the system.

The micro-inverter topologies for grid-connection can be divided into single-stage and multi-stage categories. Multi-stage topologies generally make use of a high-step-up dc-dc converter stage cascaded with a simple inverter stage to deliver power to the grid. The dc-dc converter needs to maintain high efficiencies at high conversion ratios as the input of the following inverter stage should see a high enough voltage for grid connection, typically 300-600 V for direct single-phase grid connection. This is a challenge for power-stage
design in these systems. In [32–34], soft-switching dc-dc converters have been proposed for very high step-up conversion. Hard-switching step-up dc-dc converters, such as boost and buck-boost topologies, are generally proposed when sufficient number of PV panels, usually a minimum of 10-15 panels, are connected in series lowering the conversion ratio of the converters. In the micro-converter architecture, many PV panels can potentially be connected in series to form a string as the partial shading effect is suppressed to a fair extent by implementing DMPPT in the system. As a result, the micro-converters might not need to have high conversion ratios in the system. This leverages the choice of hard switching dc-dc converters against the common soft-switching topologies, for their boosted efficiency at lower voltages in addition to lower conduction losses. In [8], non-inverting buck-boost topology is shown to be a powerful candidate for panel-level DMPPT in the grid-tied system. Single-stage inverters are designed to boost the PV voltage while providing a reliable AC connection to the grid. This usually makes the inverter’s topology and control more complicated and expensive, although there might be an efficiency benefit due to the integration of the dc-dc converter and inverters’ stages. Many single-stage inverter topologies have been proposed in the literature [35].

1.3 Thesis Motivation and Objectives

The goal of this work is primarily to develop a general methodology to evaluate the DMPPT benefits for a certain PV installation. Although some research efforts have been directed towards developing such a package in recent years, the lack of a fully automated software which is capable of combining both the characteristics of the installation site and power electronics converters has been a concern for the PV industry and fellow researchers. The developed methodology should be expandable to all PV technologies and system architectures. The optimal DMPPT level of granularity should be found for each PV installation, as each installation site has its own set of specific characteristics
including its extent of vulnerability to shading. The developed methodology should have an automated nature to be able to be applied to different PV installations.

Performing DMPPT at sub-panel level of granularity have always been of interest regarding the additional energy yield. A fair cost/power trade-off justification of such an approach can only be made when a detailed analysis tool is developed to accurately forecast the energy yield of PV installations for desired levels of granularity. PV manufacturers have already been trying to mitigate power-degrading effects in sub-panel level by employing several by-pass diodes in commercial PV panels, but the true contribution of such actions should be investigated.

Based on the results of the detailed analysis performed in this work, sub-string-level DMPPT is found to be an interesting level of DMPPT for many urban installations. Performing DMPPT at this level, requires the power converter to access the internal sub-strings of the PV panel, as multiple inputs. Two Multi-Input Single-Output topologies are proposed for sub-panel DMPPT in parallel-connected and series-connected applications. More specifically, a multi-input single-output buck converter is designed for low-cost DMPPT in parallel-connected PV applications. Parallel-connection of the energy resources, which can be either matched or mismatched, is extensively used in off-grid applications, such as battery chargers, to reduce the partial shading effect. A multi-phase boost converter for near-ideal DMPPT in sub-panel level is also developed for series-connected applications requiring high step-up conversion such as grid-tied systems. The auxiliary phases in this converter can be sized small enough depending on cost considerations. The proposed converters should be price-competitive with other proposed dc-dc topologies showing reasonable net output power benefit under shading test cases, as well as maintaining high efficiency in all conditions.

The thesis is organized as follows, Chapter 2 discusses the existing modeling and power estimation techniques and introduces the developed scheme for DMPPT benefit evaluation. Chapter 3 proposes and demonstrates the control technique to perform DMPPT in
multi-input converters for parallel-connected applications. The virtual-parallel concept is introduced and verified by simulation in Chapter 4. Furthermore, a three-phase boost converter utilizing the proposed technique is implemented for grid-tied applications in this Chapter. The conclusions and future work are discussed in Chapter 5.
References


REFERENCES


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Chapter 2

Quantifying the Benefit of DMPPT Using 3D Modeling

2.1 Introduction

While DMPPT hardware solutions are well covered in the literature and industry brochures, there is a significant need for an un-biased analysis of DMPPT benefits for the real-world PV installations. The additional cumulative energy savings from DMPPT must be carefully weighed against the increased system cost and the potential for reduced Mean-Time-Before-Failure (MTBF) to address the important questions which have been raised about the true benefits of a distributed approach.

One of the most important design considerations in a DMPPT PV system is the level of granularity for deploying the power converters. Thin-film PV systems offer different granularity trade-offs and are beyond the scope of this thesis. If the power converter losses are neglected, single-cell level granularity provides the maximum possible energy from a PV system. An accurate system model is then required to evaluate the yearly energy benefit versus the DMPPT granularity.

Several papers and commercial tools have attempted to address mismatch in PV
installations. In [1], a MATLAB-based model has been developed to determine the individual \( I-V \) and \( P-V \) characteristics of panels in a large PV array for general conditions. Although this tool is useful to study the effects of partial shading and temperature variations in the system for different configurations, it does not consider the real location and topography in which the PV array is installed and thus it provides limited insight into the true benefits of DMPPT. In [2], the total output energy for a certain residential installation is predicted by performing a site shade survey. This tedious task has limited accuracy, since the analysis is not automated and the data is limited to a finite number of days, from which the yearly shading must be estimated. In [3], a powerful method to estimate irradiance and shading from nearby obstacles on PV cells based on global irradiation data in the location of interest is introduced but the DMPPT design options and the power electronics interface are not discussed. In [4], the performance of DMPPT systems and the energy yield is investigated under extreme partial shading scenarios. In [5], the micro-converters are accurately modeled for a series-connected PV system. Generic irradiation and temperature profiles of varying standard deviations are used to show that DMPPT can have a net detrimental impact on the energy yield in systems having near-uniform irradiance due to the additional power converter losses. In the commercial domain, several software packages such as PVcad [6] and PV-DesignPro [7] exist; however they mainly focus on modeling the PV array and do not consider complex partial shading conditions on the array in addition to neglecting the losses in the power converters [1].

This chapter has three main objectives:

1. Develop a general methodology to accurately forecast the hourly, monthly and yearly energy yield of a specific PV installation for different levels of DMPPT granularity, in the presence of localized, time-varying shading patterns.

2. Investigate the energy losses of the most popular PV micro-converter topologies for panel-level DMPPT granularity in different installations having different shading
conditions.

3. Develop an automated software package based on the two aforementioned objectives to help system designers and power electronics engineers evaluate and develop PV architectures.

The chapter presents a versatile tool to investigate the effects of partial shading and non-ideal power converter efficiency on the total harvested energy. The developed tool can shed more insight into the cost/benefit trade-off of micro-converter topologies [8, 9] for the desired PV installation. Google Sketchup [10] is used as the core of this tool to model the installation site. Google Sketchup is a 3D design software that is easy-to-use and can be linked to Google Earth [11] to extract the geographical characteristics of a target location. After the model has been developed in this software, exact hourly data of site shading patterns are developed and transferred to the MATLAB environment for post-processing and evaluation. The DMPPT benefit for different levels of granularity and the power electronics converters in series-connected systems are then considered and studied in this environment with the objective of helping system and power electronics designers optimize the PV installation and lower the power harvesting costs.

The chapter is organized as follows: Section 2.2 introduces the DMPPT modeling approach. Section 2.3 covers the procedure for three different residential PV installations and includes a detailed energy yield analysis in each case. Section 2.4 discusses a practical approach to verify the designed simulation procedure and enhance its accuracy by considering other important factors in a PV installation. Finally, Section 2.5 concludes the paper.

2.2 Simulation Procedure

The improvement in harvested energy is the main incentive for choosing deeper levels of DMPPT granularity for a PV installation. One of the main reasons of degradation
Chapter 2. Quantifying the Benefit of DMPPT Using 3D Modeling

2.2.1 Installation Site 3D Modeling and Sun Synthesis

A 3D Computer Aided Design (CAD) tool is used to model the installation site, including the obstacles and structures that cause shading on the PV array throughout the year.

Figure 2.1: Output power degradation due to partial shading in the series-connected PV string (a) $I-V$ and $P-V$ characteristics of the series-connected panels. (b) Power loss due to by-pass diode conduction of the shaded panel.

in a system’s performance is the partial shading effect. This effect is illustrated on a series-connected PV panel string in Fig. 2.1. By-pass diodes are introduced to clamp the negative voltage $V_{pv}$, in order to avoid dissipating excessive power when a shaded panel is forced to operate at a high string current, $I_{string}$, as shown in Fig. 2.1(b) for Panel #3.

The extent to which a certain PV installation suffers from the partial shading effect depends on many factors that should be considered by the system designer. The software package presented consists of several parts that are discussed in the following subsections.
Existing CAD tools such as 3D Studio Max, Autodesk Maya and Google Sketchup were considered for this work. Google Sketchup [10] was adopted since it is free and readily usable by the power electronics and PV community, in contrast to other CAD tools, which are more targeted for graphics design experts and architects. As depicted in Fig. 2.2, Google Sketchup can be linked to Google Earth [11] in order to extract terrestrial and geographical characteristics of the location of interest. Sketchup is capable of modeling the exact sun beam direction and shadows in the installation area. Google Sketchup also offers a powerful scripting environment, Ruby [12].

![Location of the Modeled Solar Array Prior to Installation](image)

(a) ![Location of the Modeled Solar Array Prior to Installation](image)

(b)

Figure 2.2: Linking Google Earth and the Google Sketchup model by adjusting the longitude and latitude of the installation location (a) Google Earth view of the installation site. (b) Constructed Google Sketchup model of the installation site.

The method for modeling the PV installation site and calculating the shade data consists of the following steps:

1. Create a 3D model of the installation site using Sketchup. A basic site survey might be necessary to determine the relevant obstacles.

2. A Ruby script is developed to set the viewing camera perpendicular to the PV panels’ surface, adjust the date and time accordingly and synthesize the sun light and shadows using the sun tool. Ideally the camera is set manually to cover all the PV panels in the installation area. However, it is possible to decompose the screen into several sub-sets to capture multiple images if the installation consists
of a large number of panels, or if the panels cover a small portion with respect to the whole installation area.

3. The images are generated for each hour and saved in the desired resolution. Images are generated from 5 am to 9 pm for each day, resulting in $17 \times 365 = 6205$ files.

### 2.2.2 Module Recognition

As stated in Chapter 1, the distributed power converter, either micro-converter or micro-inverter can be designed to achieve DMPPT at the cell, sub-string, panel or string levels. The choice of granularity should be made wisely considering the additional cost versus benefit and system ratings. It is necessary to extract all the physical information about the potential DMPPT levels from the Sketchup model. The automated software package developed in this work includes a MATLAB script to locate all the individual cells, sub-strings, panels and strings in the PV installation. An edge detection algorithm first recognizes all the closed-form patterns in the high-pass filtered image [13]. The use of high-pass filter is necessary so that the shade patterns are not identified mistakenly as PV cell boundaries. Each pattern’s shape within the generated image is then identified accordingly. The PV cells can then be detected based on their specific shape and grey-scale in the constructed image, as depicted in Fig. 2.3. The image resolution is set such that $X$, the number of pixels on each side of the PV cell, is not less than 10 for accurate calculations. The module recognition unit sorts the recognized cells into sub-strings, panels and strings and identifies them as groups based on the identified alignment and proximity of the PV cells in the image. The post-processed graphical image for the installation site in Fig. 2.4(a) is shown in Fig. 2.4(b) with the recognized PV cells rendered in white.
Figure 2.3: A PV cell’s format in the constructed image of the installation site. $X$ represents the number of pixels on each side of the cell.

Figure 2.4: (a) Original Sketchup Model transferred to MATLAB for module recognition. (b) Recognized PV cells within the plane of panels.

### 2.2.3 PV Model

A single-crystalline silicon PV cell can be modeled by an equivalent circuit, as shown in Fig. 2.5(a) [14]. The output $I-V$ characteristic is given by

$$I_{pv} = I_{pv0} - I_0 \left[ \exp \left( \frac{V_{pv} + R_s I_{pv}}{V_t a} \right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_p}, \quad (2.1)$$
where $I_{pv}$ and $I_0$ are the panel output and saturation currents, respectively. $V_t = N_s kT/q$ is the thermal voltage of the array with $N_s$ cells in series and $p-n$ junction temperature $T$ (in Kelvin). $q$ is the electron charge, $k$ is the Boltzmann constant, and $a$ is the diode ideality constant. $R_s$ and $R_p$ are the equivalent series and parallel resistances of the PV cell. The light-generated current of the PV cell, $I_{pv0}$, depends on the total solar irradiation on the PV surface, $G_{tot}$, and temperature, $T$, according to [14]

$$I_{pv0} = (I_{pn} + K_1 \Delta T) \frac{G_{tot}}{G_n}, \quad (2.2)$$

where $I_{pn}$ is the light-generated current in nominal conditions which are usually $T_n = 25^\circ C$ and $G_n = 1000$ W/m$^2$. Also $\Delta T = T - T_n$ is the difference between the actual temperature, $T$, and the nominal temperature, $T_n$. $K_1$ is the temperature coefficient of the PV current. $G_{tot}$ represents the total sun irradiation on PV surface in W/m$^2$.

The parameters of the mono-crystalline PV cell considered for simulations in this chapter are listed in Table 2.1 [15]. For this PV panel, $N_s = 1$ for a single cell, $N_s = 10$ for a sub-string and $N_s = 60$ for the whole panel. $R_s$ and $R_p$ represent the equivalent series and parallel resistances of the cells, respectively. The simulated $I-V$ curves of this PV cell for various irradiation and temperature conditions are shown in Fig. 2.5(b). The $I-V$ and $P-V$ characteristics of the recognized sub-strings, panels and strings are calculated based on the connection architecture and stored in the MATLAB environment.

### 2.2.4 Shading Evaluation and Power Estimation

The area of each PV cell in the hourly-generated images is scanned to determine the percentage of shading across it as the sun moves across the sky. The percentage of shading, $S$, on a PV cell is calculated using

$$S = \frac{P_{ix,drk}}{P_{ix,tot}}, \quad (2.3)$$
where \( P_{x,\text{tot}} \) and \( P_{x,\text{drk}} \) represent the total number of pixels and the pixels with a higher gray scale code (shaded area) inside the PV cell boundary, respectively. The total irradiance on the PV panel surface, \( G_{\text{tot}} \), can be decomposed into three portions [16]

\[
G_{\text{tot}} = G_r + G_d + G_b,
\]

(2.4)

where the direct-normal irradiance, \( G_r \), determines the incident irradiation hitting the surface directly from the sun, while the indirect or diffuse sun-light coefficient, \( G_d \), specifies the irradiation intensity caused by reflections and contributions of atmospheric steam and surrounding obstacles. The ground-reflected diffuse component, \( G_b \), is the intensity of irradiance on the tilted surface due to the surrounding objects and ground albedo, \( \rho \).

The direct-normal irradiance, \( G_r \), can be calculated from the horizontal global direct...
Table 2.1: PV Cell Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Short Circuit Current, $I_{scn}$</td>
<td>8.22</td>
<td>A</td>
</tr>
<tr>
<td>Nominal Open Circuit Voltage, $V_{ocn}$</td>
<td>0.627</td>
<td>V</td>
</tr>
<tr>
<td>Nominal Current at Max. Power, $I_{mpn}$</td>
<td>7.87</td>
<td>A</td>
</tr>
<tr>
<td>Nominal Voltage at Max. Power, $V_{mpn}$</td>
<td>0.51</td>
<td>V</td>
</tr>
<tr>
<td>Max. Power, $P_{max}$</td>
<td>4</td>
<td>W</td>
</tr>
<tr>
<td># of Series Cells in a Sub-string</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td># of Series Cells in a Panel</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

irradiance, $G_{r,global}$, by the following equation [17]

$$G_r = G_{r,global} \cdot \cos i,$$  \hspace{1cm} (2.5)

where $i$ is the angle of the incident sun-beam on the PV surface, and is defined by

$$\cos i = \cos \beta \cos z + \sin \beta \sin z \cos (\phi_s - \phi_{pv}),$$  \hspace{1cm} (2.6)

where $\beta$ is the tilt angle of the panels, which is usually set according to the location’s latitude for maximal performance [18], $\phi_{pv}$ is the azimuth angle of the PV panels, which defines the deviation of the surfaces from the equator. If the PV panels are facing south, $\phi_{pv} = 180^\circ$. $\phi_s$ is the azimuth angle of the sun and $z$ is the zenith angle and has the following relationship with respect to location’s latitude, $\phi$, solar declination angle, $\delta$, and hour-angle of the sun, $\omega$

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega.$$  \hspace{1cm} (2.7)
The hour-angle of the sun, \( \omega \), is calculated at the mid-hour for each hour, \( h \), in the generated data set by

\[
\omega = 15^\circ \cdot h + 0.5 - 12. \tag{2.8}
\]

If the sky is considered isotropic, which means that the diffused irradiation component is the same on the PV surface in all directions, shading will not remove the diffuse portion of the incident irradiance. Thus \( G_d \) can be set to the diffuse irradiance hitting a horizontal planar surface. This assumption has been considered in many models [19,20]. However, the diffuse irradiance depends on many factors such as the geographic position, time and day of the year, level of clearness, humidity, altitude and climate. For this reason, other diffuse irradiance estimation methods have been developed which categorize the diffuse irradiance into circumsolar, horizon brightening and isotropic components [3,16,21]. If these models are used, shading will only keep the isotropic component of the total diffuse irradiance. The isotropic diffuse model has been used in this work, however the methodology can be easily applied to other diffuse light estimation methods.

The contribution of the ground-reflected diffuse component, \( G_b \), is usually small and is given by

\[
G_b = (1 - \cos \beta)G_{r,\text{global}} \frac{\rho}{2}, \tag{2.9}
\]

where the ground-reflected coefficient, \( \rho \), is a value between 0 and 1. In this work, a constant albedo value of \( \rho = 0.2 \) is used.

A PV cell with \( S \) percentage of shading, total sun irradiance of \( G_{\text{tot}} \) and a diffuse sun irradiance of \( G_d \) can be characterized by finding \( I_{pv} \) from

\[
I_{pv} = (1 - S) \cdot I_{pv,\text{tot}} + S \cdot I_{pv,d}, \tag{2.10}
\]
where $I_{pv,tot}$ and $I_{pv,d}$ are the panel currents at the total and diffuse radiations, respectively, which can be found by evaluating the $I-V$ curve for the corresponding voltage, $V_{pv}$, across the cell.

The $I-V$ curve of each cell is obtained after it has been analyzed at each hour throughout the year based on its corresponding Sketchup image. The $I-V$ characteristics and power points of the series connected cells in a sub-string, panel or string are then evaluated for different levels of granularity by combining the individual cells’ obtained characteristics in the appropriate configuration.

### 2.2.5 Micro-Converter Topologies for DMPPT

The non-isolated dc-dc converters in micro-converter architecture can be realized with a variety of topologies. For hard-switching converters, the buck-boost, boost-buck and boost topologies are the most popular choices [22, 23]. The buck-boost and boost-buck topologies have the distinct advantage that they can theoretically guarantee that each input PV operates at the MPP for any value of $I_{string}$, as these converters can be operated in either boost, buck or pass-through mode [22]. In pass-through mode the switches are set to connect $V_{pv}$ directly to $V_{out}$. The switching losses are therefore eliminated and $V_{out} = V_{pv}$. The boost converter has a higher efficiency, lower cost and reduced complexity compared to the four-switch topologies.

The three topologies of Fig. 2.6 were designed using commercially available components in order to explore cost and energy yield trade-offs for panel-level MPPT, which dominates the market today. The design procedure for other levels of granularity obeys the same rules and thus is not covered in this paper. In each case, suitable devices from Infineon Technologies are chosen based on the converter requirements. The specifications and total cost for the chosen components are listed in Table 2.2. The total micro-converter cost is substantially higher due to the need for control and auxiliary power ICs. The inductors for all micro-converters are chosen from the same manufac-
Figure 2.6: Three popular hard-switching micro-converter topologies in PV systems: (a) buck-boost (b) boost-buck, and (c) boost.

The most expensive parts of each converter are the ceramic output capacitors due to the high output voltage ratings as well as substantial capacitance needed for operation in boost mode. This fact can be readily observed by looking at the last row of Table 2.2 which contains the total cost of passive elements to the total cost of active elements for each converter. The efficiencies of the micro-converters are calculated at every operating point based on the switching and conduction losses in the power-stage, similar to [5]. Fig. 2.7 shows the efficiencies of the three designed converters versus $I_{\text{string}}$ for a fixed
irradiance of 400 W/m² on the panel. As long as the panel operates at the MPP, it behaves as a constant power source. The converters automatically change their operating modes depending on the relationship between the input and output current, as outlined in [22]. The highest efficiency is achieved in pass-through mode, where $I_{\text{string}} = I_{\text{pv}}$. The duty-cycle in the boost converter saturates for $I_{\text{string}} > I_{\text{pv}}$, which causes the panel to operate away from the MPP.

Table 2.2: Micro-Converter Component Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Buck-boost</th>
<th>Boost-buck</th>
<th>Boost</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>33</td>
<td>15</td>
<td>15</td>
<td>µH</td>
</tr>
<tr>
<td>$L_2$</td>
<td></td>
<td>33</td>
<td></td>
<td>µH</td>
</tr>
<tr>
<td>$C_{\text{in}}$</td>
<td>40</td>
<td>40</td>
<td>10</td>
<td>µF</td>
</tr>
<tr>
<td>$C_{\text{out}}$</td>
<td>18.4</td>
<td>18.4</td>
<td>18.4</td>
<td>µF</td>
</tr>
<tr>
<td>$R_{\text{on}}(S_{1,2})$</td>
<td>6</td>
<td>6</td>
<td>32</td>
<td>mΩ</td>
</tr>
<tr>
<td>$R_{\text{on}}(S_{3,4})$</td>
<td>32</td>
<td>32</td>
<td></td>
<td>mΩ</td>
</tr>
<tr>
<td>Normalized Power-Stage Cost</td>
<td>7.5</td>
<td>8.58</td>
<td>7.12</td>
<td>$¢/W_p$</td>
</tr>
<tr>
<td>Passive/Active Cost Ratio</td>
<td>3.4</td>
<td>4.1</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

† A switching frequency of $f_s = 250$ kHz is used for all designs. For the boost-buck topology, $C_{\text{bus}} = 18$ µF. The power-stage cost estimate is based on high-volume Digikey prices and normalized to 240 W.

In the general analysis presented in the following section, the operating point, mode and efficiency for each micro-converter is determined for each shading pattern, which are generated hourly. It is assumed that the dc bus voltage, $V_{\text{bus}}$, is regulated by the central inverter through the control of $I_{\text{string}}$ [22]. The value of $V_{\text{bus}}$ therefore has a strong impact on the micro-converter efficiency.
Figure 2.7: Buck-boost, boost-buck and boost converters’ efficiency for $G_{tot} = 400 \, \text{W/m}^2$ and $T = 25^\circ \text{C}$.

### 2.3 Case Studies and Simulation Results

Three urban PV installation sites were analyzed using the proposed forecasting software. Fig. 2.8 shows 3D Sketchup models of these installation sites in Toronto area.

![Sketchup models for the PV installations](image)

Figure 2.8: Sketchup models for the PV installations at (a) Site #1 (b) Site #2 (c) Site #3.

The simulation process described in Section 2.2 is used to determine the effectiveness
of DMPPT in these installation sites. Important characteristics of each site are listed in Table 2.3, including the relative extent of shading and obstacles. Site #3 is located at the University of Toronto and was installed in 2011.

Table 2.3: Characteristics of the PV Installation Sites

<table>
<thead>
<tr>
<th>Site #</th>
<th>Relative Shading</th>
<th>Main Obstacles</th>
<th>Building Type</th>
<th># of Panels</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Medium</td>
<td>Tall obstructions nearby</td>
<td>Residential</td>
<td>8</td>
<td>1.92</td>
</tr>
<tr>
<td>2</td>
<td>High</td>
<td>Trees and tall chimney</td>
<td>Residential</td>
<td>7</td>
<td>1.68</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>PV racks</td>
<td>Commercial (UofT)</td>
<td>26</td>
<td>6.24</td>
</tr>
</tbody>
</table>

2.3.1 Total Energy Yield for Different Levels of DMPPT Granularity

The simulation method described in Section 2.2 is used to estimate the total yearly energy yield in each site for different levels of DMPPT granularity. Irradiation and ambient temperature data from the University of Toronto’s meteorological station from November 2009 to October 2010 is used for the energy estimations [24]. This database contains the global irradiation, $G_{r,global}$, as well as the temperature recordings of the year. Using these information, the total irradiation on the PV surface, $G_{tot}$, can be determined from (2.5) and (2.9). Furthermore, the junction temperature, $T$, can be estimated by considering an equivalent thermal model for the PV. For simplicity, $T$ is considered to be always 5°C higher than the ambient temperature, $T_a$, in this work. The resulting energy yield for the three test sites is shown in Fig. 2.9. The results confirm that the presence of obstacles in Site #2 makes the energy yield highly sensitive to the level of DMPPT granularity. On the other hand, using cell-level DMPPT rather than sub-string-level DMPPT might not be justified, due to the added complexity, cost and reliability issues in addition to limited yield benefits.
Figure 2.9: Simulated annual energy yield for (a) Site #1 (b) Site #2 (c) Site #3.

For Site #1, which is relatively free of obstacles, there is a substantial benefit for panel-level DMPPT over the string-level DMPPT, while the benefits for deeper granu-
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Clarity levels are not easily justified. For Site #3, which is nearly unobstructed, utilizing conventional series-connected PV architectures with by-pass diodes and a central inverter is recommended.

The energy yield results for the three test cases are summarized in Table 2.4. The percentage improvement in the energy yield, \( B_n \), for the \( n \)-th level of granularity is defined by

\[
B_n = \left( \frac{E_n - E_1}{E_1} \right) \cdot 100\%,
\]

where \( E_1 \) is the energy yield for string-level DMPPT, which is used as a reference \( (B_1 = 0) \) and \( E_n \) is the energy yield for the \( n \)-th level of granularity, where \( n = 4 \) corresponds to cell-level DMPPT.

<table>
<thead>
<tr>
<th>Site #</th>
<th>Cell-level</th>
<th>Sub-string-level</th>
<th>Panel-level</th>
<th>String-level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( B_4 ) (%)</td>
<td>( B_3 ) (%)</td>
<td>( B_2 ) (%)</td>
<td>( B_1 ) (%)</td>
</tr>
<tr>
<td>1</td>
<td>14.6</td>
<td>14.5</td>
<td>11.8</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>94.0</td>
<td>93.0</td>
<td>62.3</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.17</td>
<td>0</td>
</tr>
</tbody>
</table>

2.3.2 The Effect of Micro-Converters for Panel-Level DMPPT

The following analysis deals exclusively with panel-level DMPPT. The shading data was combined with the micro-converter loss models to evaluate competing micro-converters for several regulated values of \( V_{bus} \). The total energy yield of Site #1 with all the panels in series and two different inverter bus voltages is shown in Fig. 2.10. The boost micro-converter yields 0.3 % more energy than boost-buck micro-converter for \( V_{bus} = 280 \) V due
to its higher efficiency, even despite the fact that the boost converter is unable to maintain MPPT under all shading conditions. The boost micro-converter loses its advantage for $V_{bus} = 230$ V since the duty-cycle saturation often forces the shaded panels to operate away from the MPP.

For the lower bus voltage of $V_{bus} = 230$ V, the total output energy in the system for buck-boost and boost-buck micro-converters is improved by roughly 0.2 % due to the increased time spent in pass-through and buck modes. For the boost micro-converter, decreasing $V_{bus}$ reduces the output harvested power significantly, mainly because the by-pass diodes are turned on more often.

![Figure 2.10: Simulated energy yield at the dc-dc converter output for the 8-panel series-connected string in Site #1 for (a) $V_{bus} = 230$ V. (b) $V_{bus} = 280$ V.](image-url)
Table 2.5 lists the percentage of time spent in boost, buck, pass-through events between 5 am and 9 pm, for the buck-boost micro-converter throughout the year and for four values of $V_{bus}$ in Site #1. The mode distribution of boost-buck micro-converter is nearly identical to the buck-boost micro-converter and is omitted from the figure. For each value of $V_{bus}$, the by-pass diodes turn on for less then 0.1 % of the time slots.

Finally, the yearly aggregate efficiency, $\eta_a$, of three micro-converters is given in Table 2.6 for Site #1. The aggregate efficiency, $\eta_a$, is given by

$$\eta_a = \frac{\sum_{year} V_{bus} I_{string}}{\sum_{year} \sum_{i=1}^{M} V_{mpi} I_{mpi}},$$

(2.12)

where $M$ is the number of panels in the installation and $V_{mpi}$ and $I_{mpi}$ are the operating voltage and current of the $i^{th}$ panel in its maximum power point. The aggregate efficiency obtained from the method presented in this work is an accurate way to predict the relative performance of competing micro-converters. The results show that if $V_{bus}$ is properly optimized, $\eta_a$ for the boost micro-converter is competitive with the other topologies, while offering lower cost, size and complexity.

It is informative to combine the results of Table 2.4 and 2.5. If we assume $\eta_a = 95 \%$, the yield benefit from adding micro-converters to achieve panel-level DMPPT instead of string-level MPPT reduces from 11.8 % to 6.2 % in Site #1. Using micro-converters with the same $\eta_a$ would decrease the benefit from 62.3 % to 54.2 % in Site #2, while a net loss of 5 % would be expected in Site #3. Assuming a cost of 2 $/W_p$ for PV panels, the micro-converters provide a net benefit as long as the incremental cost is below 0.12 $/W_p$ and 0.9 $/W_p$ for Site #1 and #2, respectively, which is in agreement with Table 2.2. Clearly the cost of other components and installation of the micro-converters must also be included. The analysis can be repeated for any level of granularity and power converter specifications.

The simulated operation of the buck-boost micro-converter system in Site #1 is shown in Fig. 2.11 for three consecutive days beginning from May 10, 2010 with $V_{bus} = 208$
V. The hourly irradiance on the PV surfaces, $G_{\text{tot}}$, and total output power for panel-level DMPPT are shown in Fig. 2.11(a) and (b), respectively. Fig. 2.11(c) shows the number of micro-converters operating in buck, boost and pass-through mode for the eight panel system. In general, as $G_{\text{tot}}$ increases, the pass-through and buck mode occurrences increase due to the increase in the operating voltages of the panels.

Table 2.5: Percentage of Time Spent in Each Mode for Site #1

<table>
<thead>
<tr>
<th>$V_{bus}$</th>
<th>Operating Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boost (%)</td>
</tr>
<tr>
<td>208 V</td>
<td>62.5</td>
</tr>
<tr>
<td>230 V</td>
<td>73.3</td>
</tr>
<tr>
<td>330 V</td>
<td>97.9</td>
</tr>
<tr>
<td>500 V</td>
<td>98.3</td>
</tr>
</tbody>
</table>

Table 2.6: Aggregate Efficiency, $\eta_a$, of Different Micro-Converters for Site #1

<table>
<thead>
<tr>
<th>$V_{bus}$</th>
<th>Micro-Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boost (%)</td>
</tr>
<tr>
<td>208 V</td>
<td>60.8</td>
</tr>
<tr>
<td>230 V</td>
<td>84.5</td>
</tr>
<tr>
<td>330 V</td>
<td>95.3</td>
</tr>
<tr>
<td>500 V</td>
<td>92.0</td>
</tr>
</tbody>
</table>
Chapter 2. Quantifying the Benefit of DMPPT Using 3D Modeling

Figure 2.11: Simulated working operation for May 10-12, 2010 (total of 72 hours) in Site #1 for $V_{bus} = 208$ V. (a) Total calculated irradiance on tilted PV surfaces, $G_{tot}$. (b) Total energy yield per hour at panel-level for the PV installation. (c) Number of PV panels in buck, boost and pass-through mode per hour.

2.4 Shade Pattern Measurements

Miniature stand-alone sensor modules (PV probes) were built to experimentally measure irradiance and temperature profiles on Site #3, in order to validate the modeling approach.
introduced in this paper. The PV probe architecture is shown in Fig. 2.12. Each PV probe is completely autonomous and includes a miniature mono-crystalline PV cell [25], a temperature sensor, power management circuits, a micro-controller and a flash memory module. The PV probe has two operating modes (1) re-charge and (2) data acquisition. During the re-charge mode, switches $S_1$ and $S_2$ are turned on while the op-amp is driven to tri-state mode and $S_3$ is turned off. In this mode, the 18 mW PV cell re-charges the single AA battery. Once every 5 seconds, the PV probe short-circuits the panel using $S_3$ and measures the ambient temperature, $T_a$, and the short circuit current, $I_{sc}$, through the precision sense resistor, $R_{sense}$. The sampled $T_a$ and $I_{sc}$ are saved in a non-volatile Flash memory before returning to re-charge mode.

![Simplified PV probe architecture.](image-url)

Thirty PV Probes were placed in a checker-board pattern on one of the PV panel locations shown in Fig. 2.13(a) in Site #3. Each individual PV cell’s irradiation and ambient temperature can be approximated by averaging its four adjacent recorded values. Fig. 2.14(a) shows the total solar irradiance on the tilted surface for a sunny day, calculated by extracting $I_{sc}$ and $T_a$ from three PV probes at the east, west and middle-side of the panel. As expected, there is a clear time shift in the irradiation at different
Figure 2.13: (a) Installation location of the PV probes with the east, west and middle-side probes indicated, and (b) the PV probe setup for installation site #3.

PV probe locations. The experimental curves have high-frequency variations due to non-systematic shading from non-stationary obstacles such as clouds. This introduces another potential application of the PV probes, since they can be used as means to quantify the non-systematic shading for a certain installation location.

Fig. 2.14(b) shows the irradiation curve for one of the PV probes on the panel. There are two major shading occurrences in Site #3, at dusk and dawn. The shade mode bit represents the shading condition on the corresponding cell, based on the Google Sketchup 3D model and is set to zero if the cell is partially shaded. The two measured shading events are properly predicted by the model. The slight time offset is systematic and can
be attributed to the probe positioning and has a negligible effect on the energy yield results.

![Graph](image)

Figure 2.14: Calculated irradiance, $G_{tot}$, on the PV surfaces based on measured $I_{sc}$ and $T_a$ for (a) three PV probes, and (b) one of the PV probes and the shading mode of the corresponding cell in Google Sketchup for different times of the day on May 9th, 2011 (Shade mode = 0 means there is shading on the cell).

2.5 Conclusion

One of the first detailed research efforts to combine an analysis of shading patterns on PV installations and distributed power electronic converters was presented in this chapter. The converters are modeled based on their loss equations and can be designed
for various granularity levels in the PV system. The results of this work should help to shed light on the true value of distributed MPPT. It was found that the yearly energy yield was highly dependent on the relative shading in the three installations considered in this study. Panel and sub-string-level DMPPT generally appear to be the appropriate levels of granularity for urban environments, depending on the shading conditions. The benefits of cell-level DMPPT is very limited, unless there is a strong variation in the PV cell parameters. It was found that the energy yield benefit for panel-level DMPPT easily outweighs the power electronics costs in two of the three installations, which is encouraging for the many companies and researchers working towards micro-converter and micro-inverter hardware solutions. The impact of the distributed power electronics on system reliability and control remains one of the major issues to be addressed. The analysis method can be used by PV installers for accurate yield prediction, as well as power electronics engineers who need to bound the cost of their design based on the net energy benefit of their DMPPT system.

The simulation process including 3D modeling and irradiation estimation is validated using PV probes for one of the test sites considered in this work. These low-cost PV probes can also be used to investigate the impact of non-systematic shading in the system.
References


Chapter 3

Dc-dc Converter for DMPPT in Parallel Applications

3.1 Introduction

This chapter focuses on off-grid PV systems with multiple parallel-connected modules, as shown in Fig. 3.2. One of the main applications of PV systems is to charge batteries and other storage elements, such as ultra-capacitors and fly-wheels. The smart battery charger demonstrated in this chapter implements DMPPT on each of the multiple panels connected at the input side and performs charge-control for the battery on the output side. The proposed converter is a low-cost candidate for granularity levels as deep as sub-string-level DMPPT. Potential applications include low-voltage battery applications, where high-voltage operation is not required, or in applications where a single converter should be used to extract power from a multi-source system, especially if different resources of energy are available.

Same-type parallel-connected PV panels, called matched PV systems hereafter, are much less sensitive to partial shading compared to series-connected PV systems. This is due to the fact that the maximum power point voltage, \( V_{mp} \), is not a strong function
Figure 3.1: Power curves for (a) matched three-panel and (b) mismatched two-panel parallel-connected system ($V_{oc1} = 2V_{oc2}$) under partial shading.

of the irradiance, unlike the maximum power point current, $I_{mp}$. This is illustrated in the measurement of Fig. 3.1(a) for a matched three-panel system operating under partial shading. Based on the experimental data, performing DMPPT on this system provides only about 5% benefit in the total output power at this irradiance condition. In some rare cases, it can be shown that the matched parallel PV system can lose as much as 50% in heavy shading conditions [1]. The conditions are even worse if the panels are not matched, which is the case if panels from different manufacturers are connected in parallel or if relatively large mismatches occur due to aging of the panels. In this case,
the motivation for DMPPT is very strong. This effect is shown in the measurement of Fig. 3.1(b) for a two-panel system, where panel 1 is constructed using two sub-panels in series. Each sub-panel consists of two sub-strings, as already defined in Chapter 2, connected in series. In this case of large mismatch in open circuit voltages, \( V_{oc} \), DMPPT provides a 46% power benefit. The power benefit is clearly dependent on the irradiance variation.

The DMPPT charger of Fig. 3.2(b) addresses the issue of having mismatched panels in the system by using a Multi-Input-Single-Output (MISO) buck converter, as shown in Fig. 3.4(a). Various multi-input topologies have been proposed for combining PV modules with other energy resources [2–5]. Single-inductor MISO topologies are very attractive in PV applications to reduce the cost through reducing the part count, as opposed to using a traditional multi-phase dc-dc converter as in Fig. 3.3 [3]. Furthermore the proposed single-inductor MISO scheme used in this work can handle all types of renewable energy resources that require MPPT. Despite control challenges due to the inherent coupling of

Figure 3.2: (a) Standard parallel-connected charger system and (b) proposed DMPPT system using low-cost MISO dc-dc converter.
the multiple inputs through the shared inductor [6], the MISO converter is well suited to DMPPT PV applications, where the dynamic requirements are relaxed compared to Point-of-Load (POL) converters.

This chapter is organized as follows, Section 3.2 discusses the single-inductor MISO architecture and the proposed control algorithm, including a basic MPPT error analysis. The experimental results for the MISO buck prototype are reported in Section 3.3. Finally, Section 3.4 concludes the chapter.

![Figure 3.3: Conventional MISO buck converter for three inputs [3].](image)

### 3.2 Pseudo-CCM MISO Controller

The MISO buck converter shown in Fig. 3.4(a) has three inputs connected to the panels of Fig. 3.2 and a single output, $V_{\text{batt}}$. The relative values of the input voltages, $V_{\text{pv1-3}}$, can vary substantially during shading, therefore bi-directional blocking capability is needed on the switches controlled by $c_{1-3}$ and $c_5$. The control signal $c_5$ is used to activate the free-wheeling phase. In this work, mixed-signal CPM which consists of an analog current loop with a digitally generated current reference [7, 8] is extended to control both the
valley and peak of the inductor current $i_L(t)$ in Pseudo-CCM (PCCM) mode [9,10]. This is in contrast to [9,10], where the peak current is not controlled.

The analog commands for the peak and valley currents, $i_p(t)$ and $I_v$ respectively, are generated using two DACs and two comparators connected to the current sensor. The ideal MISO waveforms are shown in Fig. 3.4(b), where it is assumed that the input voltages differ due to partial shading and $V_{pv1} > V_{pv2} > V_{pv3}$. The digital controller sequentially transfers energy from each input capacitor, $C_{i1-3}$, to the output, $V_{outt}$. A small freewheeling period of $t_{fw}$ is initiated when $i_L(t)$ reaches $I_v$ at the end of each phase. This ensures that $i_L(t)$ starts from the same value for each input. This Pseudo-CCM
operation effectively decouples the inputs and results in greatly simplified dynamics for the MISO converter. The converter is chosen to operate with the same valley current, $I_v$ for all inputs, while $i_p(t)$ is updated dynamically for each input. Further optimization can be achieved by varying both the valley and peak currents for each phase. A single ADC is used to sample the input and output voltages.

### 3.2.1 DMPPT Scheme

Using both peak and valley current control with Pseudo-CCM has several distinct advantages for the targeted DMPPT PV applications. Firstly, $i_L(t)$ is precisely limited on a cycle-by-cycle basis. Unlike conventional converters running in CCM, PCCM eliminates the need for slope compensation in the current loop. Most importantly, the current waveform is known within the digital controller since $i_p(t)$ and $I_v$ are set explicitly and they can readily be used to calculate the $n$-th phase average input current $I_{pvn} = <i_{pvn}>_{T_{sw}}$ without additional sensors. The calculated $I_{p1-3}$ are used to perform the DMPPT function within the digital controller. In steady state, the digital estimate of $I_{pvn}$ for $n$-th input is obtained from

$$I_{pvn} = \frac{L \cdot f_{sw} \cdot (I_{pn} + I_v) \cdot (I_{pn} - I_v)}{2m_{1,n}},$$

(3.1)

where $m_{1,n} = (V_{pvn} - V_{batt})/L$ is the rising slope of $i_L(t)$ in the $n$-th phase and $V_{pvn}$ and $I_{pn}$ are the operating voltage and peak current for the $n$-th input respectively. For a three-phase MISO buck converter, the digital controller has six variables to set, namely the peak currents $I_{p1-3}$, valley current $I_v$ and phase times $t_{1-2}$. The third phase time $t_3$ is obtained from the following equation

$$t_3 = T_{sw} - (t_1 + t_2),$$

(3.2)

since the switching frequency is kept constant. The objective of the controller is to operate each panel at its MPP, while simultaneously maximizing the conversion efficiency. The
input power at the $n$-th input is obtained by multiplying (3.1) by $V_{pvn}$. For the purpose of achieving MPPT, all fixed proportionality constants can be removed from (3.1), leaving the following function $g_n$ to be maximized independently for each input $n$:

$$
g_n = \frac{V_{pvn}}{V_{pvn} - V_{batt}} \cdot (I_{pn}^2 - I_v^2). \quad (3.3)$$

A corrective factor can be introduced to (3.3) to improve the estimation accuracy by accounting for the slight drop in $i_L(t)$ during freewheeling.

The digital DMPPT controller algorithm is summarized in Fig. 3.5 and can be explained as follows:

1. At startup, $I_v$ is set to a low default value of $i_{v0}$ and the phase times are set to $t_{1-3} = T_{sw}/3$. This operates the panels near their open circuit voltages, $V_{oc,n}$, leading to large inductor current’s rising slopes $m_{1,n} \approx (V_{oc,n} - V_{batt})/L$ and large free-wheeling times $t_{fw1-3}$.

2. The first optimization step is then used to minimize the conduction losses by reducing $t_{fw1-3}$. This is achieved by progressively adjusting $I_v$ and $t_{1-3}$ for each phase. Large free-wheeling times will result in lower valley current, $I_v$, while very low or zero free-wheeling times lead to the increase in the valley current by the controller. $t_{1-3}$ are set such that phases having a lower maximum power point are assigned smaller portions of $T_{sw}$. This is essential in cases of heavy partial shading. The new peak current for $n$-th phase in the $(j + 1)$-th step, $I_{pn}[j + 1]$, is actively adjusted based on (3.4) during this optimization step so that the average PV currents $I_{pv1-3}$ are maintained such that the desired operating points of the phases are not disturbed:

$$
I_{pn}[j + 1] = \sqrt{I_{pn}^2[j] - I_v^2[j] + I_v^2[j + 1]}.
\quad (3.4)
$$

3. In the DMPPT step, the power function is computed using (3.3) for each phase and the corresponding peak current, $I_{pn}$, is perturbed to maximize the phase’s
input power. After each perturbation, the first optimization step is repeated to minimize the converter’s losses and maintain the operating points for the other phases. Thus, DMPPT is effectively achieved on all inputs, while maximizing the efficiency in PCCM mode by minimizing the freewheeling times and optimizing the valley current.

![Figure 3.5: Simplified algorithm for the digital MISO DMPPT controller.](image)

3.2.2 MPPT Efficiency

The MPPT efficiency is considered to be a very important factor in determining a MPPT algorithm effectiveness and is usually defined as

\[
\eta_{MPPT} = \frac{P_{in}}{P_{ideal}},
\]

(3.5)

where \(P_{ideal}\) denotes the sum of the actual maximum power of the input panels for a given irradiance. The total input power of a MISO converter with \(N\) inputs can be calculated as follows

\[
P_{in} = \sum_{i=1}^{N} V_{pvi} I_{pvi}.
\]

(3.6)

The MPPT efficiency for \(n\)-th input, \(\eta_{MPPT,n}\), can be calculated by finding the total relative error, \(err_{MPPT}\), in each input’s operating power with respect to maximum deliverable...
power for that phase

\[ \eta_{MPPT,n} \approx 1 - err_{MPPT,n}, \quad (3.7) \]

where \( err_{MPPT,n} \) can be represented as

\[ err_{MPPT,n} = \frac{\Delta P_{in,n}}{P_{in,n}}. \quad (3.8) \]

For each input, \( \Delta P_{in,n} \) can be re-written as

\[ \Delta P_{in,n} = \frac{\partial P_{in,n}}{\partial V_{pvn}} \Delta V_{pvn} + \frac{\partial P_{in,n}}{\partial I_{pvn}} \Delta I_{pvn}. \quad (3.9) \]

Assuming ideal elements in the converter and based on (3.1), \( err_{MPPT,n} \) can thus be computed as

\[ err_{MPPT,n} = -\frac{V_{batt}}{V_{pvn} - V_{batt}} err_{ADC} + \frac{V_{batt}}{V_{pvn}} \left( \frac{2I_{pm}\delta I_{pm}}{I_{pvn}^2 - I_{v}^2} - \frac{2I_{v}\delta I_{v}}{I_{pm}^2 - I_{v}^2} \right), \quad (3.10) \]

where \( err_{ADC} \) is defined to be \( \frac{\Delta V_{pvn}}{V_{pvn}} \) which is the relative error of the ADC in reading the voltage \( V_{pvn} \). Also \( \delta I_{pm} \) and \( \delta I_{v} \) are the absolute errors of the perceived peak and valley currents from the real values. Most of the errors in this case are generated due to comparators’ offset and logic delays. For example, if \( err_{ADC} \) is assumed to be 0.1% and \( \delta I_{pm} \) and \( \delta I_{v} \) are considered to have a maximum of 10 mA which corresponds to 20 ns overall delay of comparators and logic elements for the converter’s specifications and panel’s characteristics given in Table 3.1 and 3.2, \( err_{MPPT} \) will have an upper limit of 0.3%. This is barely higher than the conventional case of having voltage and current ADCs which will lead to a maximum error of 0.2% for the given specifications. From (3.10) it can be seen that \( \eta_{MPPT} \) is expected to be smaller for lower input currents as \( i_p(t) \) and \( I_v \) are closer in this case. As the input current and power go up, the MPPT efficiency is expected to ramp up quickly. It is also important to notice that (3.1) is derived assuming ideal switches and zero inductor resistance. These nonidealities would also add other sources of error which further degrade the MPPT efficiency. MPPT in the MISO topology can still be done using the conventional method by adding an additional dedicated current sensor for each phase.
3.3 Experimental Results

The novel Pseudo-CCM digital DMPPT scheme is demonstrated on a three-input MISO buck prototype shown in Fig. 3.6. The Buck converter’s specifications are listed in Table 3.1 where \( f'_{sw} \) is the effective switching frequency in a fully symmetric system and is defined as follows for an \( N \)-input MISO converter

\[
    f'_{sw} = f_{sw} \cdot N. 
\]  

(3.11)

A mono-crystalline PV panel [11] was partitioned into three sub-panels to be used as separate inputs. The PV panel’s characteristics are given in Table 3.2. An artificial lighting system was constructed using eight PWM-controlled 500 W halogen lamps in order to emulate sunlight in the lab environment.

![Figure 3.6: Three-input MISO DMPPT prototype.](image)

The flexible digital MISO controller is programmed to operate with either one, two or three active phases. The converter efficiency in Single-Input Single-Output (SISO) mode, where \( c_1 = c_2 = c_3 \), with a current sink as the load is shown in Fig. 3.7. The efficiency was measured with one sub-panel as the input and DMPPT function operating in closed-loop. The input power is therefore nearly constant in this test, \( P_{pv} \approx 9.5 \) W.
Table 3.1: MISO Buck Prototype Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Frequency, $f_{sw}$</td>
<td>166</td>
<td>kHz</td>
</tr>
<tr>
<td>Effective Switching Frequency, $f'_sw$</td>
<td>500</td>
<td>kHz</td>
</tr>
<tr>
<td>Input Capacitors, $C_{i1-3}$</td>
<td>106</td>
<td>µF</td>
</tr>
<tr>
<td>Output Capacitor, $C_{out}$</td>
<td>100</td>
<td>µF</td>
</tr>
<tr>
<td>Inductor, $L$</td>
<td>10</td>
<td>µH</td>
</tr>
<tr>
<td>Battery Voltage, $V_{batt}$</td>
<td>5</td>
<td>V</td>
</tr>
</tbody>
</table>

Table 3.2: Characteristics of the Mono-Crystalline PV Panel [11]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Short Circuit Current, $I_{scn}$</td>
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<td>A</td>
</tr>
<tr>
<td>Nominal Open Circuit Voltage, $V_{ocn}$</td>
<td>43.8</td>
<td>V</td>
</tr>
<tr>
<td>Nominal Current at Max. Power, $I_{mpm}$</td>
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<td>A</td>
</tr>
<tr>
<td>Nominal Voltage at Max. Power, $V_{mpm}$</td>
<td>35.4</td>
<td>V</td>
</tr>
<tr>
<td>Max. Power, $P_{max}$</td>
<td>170</td>
<td>W</td>
</tr>
<tr>
<td># of Series Cells</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td># of Series Cells in a Sub-panel</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

3.3.1 Optimization Step

The MISO converter was tested in three-input mode with one sub-panel connected at each input. The inductor current at the end of the startup phase is shown in Fig. 3.8.
Figure 3.7: Efficiency in SISO mode for a fixed irradiation with MPPT running in closed-loop.

Figure 3.8: Inductor current, $i_L$, and gating signals after startup.

All three inputs start with $I_v = i_v0$, $I_{p1-3} = i_{p0}$ and $t_{1-3} = T_{sw}/3$. The glitches on the digital channels are an artifact of the measurement instrument. $i_L$ is shown in Fig. 3.9 prior to the completion of the optimization with the third input heavily shaded. The on-going optimization process is illustrated in this figure. If an input is heavily shaded, the inductor current falls instead of rising when the corresponding phase is activated. The controller detects this and turns on the freewheeling switch by asserting $c_5$ for the rest of that phase. This phase will be dedicated less time in the next cycles. The valley current, $I_v$, is adjusted to minimize the freewheeling times for minimal power loss, while the phase times are set such that each phase gains the preset amount of freewheeling.
3.3.2 DMPPT Process

The proposed DMPPT algorithm based on current estimation technique was tested experimentally. Fig. 3.10 shows the first sub-panel’s current and voltage waveforms when the system starts to perform DMPPT on all the phases from the initial low power state. It can be seen that the system effectively stabilizes at its maximum power points after about 60 ms.

![Figure 3.9: Intermediate state during heavy shading (i_L: 1A/div).](image)

![Figure 3.10: Input current and voltage waveforms of the first sub-panel with DMPPT process.](image)

The MPPT efficiency, $\eta_{MPPT}$, was measured for six different illumination conditions.
by measuring the input power of the MISO converter and comparing it to the sub-panels’
delivered power while they were individually operating in their maximum power points.
The results of this measurement are given in Table 3.3. It is important to notice that
there is ripple in sub-panels’ currents and voltages due to the finite input capacitance
of the converter. This ripple’s effect in degrading $\eta_{MPPT}$ has not been considered in the
analysis of Section 3.2.2. It was found that in most cases, at least 50\% of $err_{MPPT}$ is
due to the ripple and not the DMPPT algorithm itself.

Table 3.3: DMPPT Efficiency for Six Different Illumination Conditions (Sorted from Lowest
Output Power to Highest)

<table>
<thead>
<tr>
<th>Case #</th>
<th>Maximum Input Power (W)</th>
<th>MISO Output Power (W)</th>
<th>MPPT Efficiency, $\eta_{MPPT}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9</td>
<td>4.6</td>
<td>97.2</td>
</tr>
<tr>
<td>2</td>
<td>12.2</td>
<td>11.2</td>
<td>99.3</td>
</tr>
<tr>
<td>3</td>
<td>12.7</td>
<td>11.4</td>
<td>97.7</td>
</tr>
<tr>
<td>4</td>
<td>17.2</td>
<td>15.6</td>
<td>97.3</td>
</tr>
<tr>
<td>5</td>
<td>22.8</td>
<td>19.8</td>
<td>97.4</td>
</tr>
<tr>
<td>6</td>
<td>25.8</td>
<td>22.7</td>
<td>97.8</td>
</tr>
</tbody>
</table>

3.3.3 Steady State Operation

Fig. 3.11 shows the converter operation after the DMPPT optimization step under low
irradiance conditions, indicating that the free-wheeling times are properly minimized at
the three MPP points. The switching commands, $c_{1-5}$, are also shown for clarity. This
experiment was repeated for a case with higher irradiance and partial shading on the
sub-panels. The corresponding waveform is shown in Fig. 3.12.

In the next test, the system was operated in two-input mode with the same mis-
matched, parallel-connected sub-panels used in Fig. 3.1(b). Six different illumination
conditions with partial shading were considered for this test. The power and efficiency are reported in Fig. 3.13 for both the proposed MISO-DMPPT and single-input (SISO-MPPT) operation for comparison purposes. In all cases the MISO efficiency is comparable to SISO, however the harvested power is much higher due to the implementation of DMPPT ranging from 7 % at point #4 to 43 % at point #3. This result clearly depends on the relative mismatch of the panels. Interestingly, the MISO topology leads to higher efficiency in light-load conditions due to the inherent DCM operation in this case. DCM operation yields higher efficiencies at light loads due to its lower conduction losses compared to operating in CCM with large negative valley currents.
3.4 Conclusion

The novel multi-input, single-inductor dc-dc converter covered in this chapter is proposed for parallel-connected PV applications and compared to the conventional multi-input dc-dc converters. Using a single time-interleaved inductor for all the phases can potentially lead to a reduction in the volume and cost of the converter by reducing the total part count of the system. DMPPT can be performed on all phases, which boosts the output power in partial shading conditions. The proposed algorithm relies on the peak and valley inductor current information to estimate the average input currents, which eliminates the need for individual current sensors in each of the phases and can further reduce the system cost. The converter’s losses are also minimized by adjusting the phase times and valley current during operation. The MISO converter provides satisfying results in power savings, especially when the input PV panels have different electrical ratings, which can become increasingly common as older installations increase production capacity by incorporating newer, high-efficiency PV technologies. Furthermore, although the MISO converter’s power efficiency is slightly lower than the conventional SISO solution, it can still provide superior performance in low irradiance conditions, due to the inherent DCM
operation. The MISO converter is well suited to extracting maximum power under partial shading conditions.
References


Chapter 4

Virtual-Parallel Connection for Sub-String DMPPT

4.1 Introduction

Series-connected PV systems are well known to be much more prone to partial shading effects compared to parallel-connected systems [1], as demonstrated in Fig. 4.1, where $I-V$ of three identical sub-panels of a partially shaded PV panel are measured in series and in parallel. The parallel connection yields 59% more power, since the maximum power voltage, $V_{mp}$, is relatively insensitive to the irradiance.

This chapter focuses on grid-tied PV applications. The boost converter is one of the popular dc-dc topologies that is used in these applications to interface the low-voltage PV to the high-voltage bus at the input of the grid-tied inverter, since it offers low implementation cost and optimum performance. Although this converter is considered in this work, the virtual-parallel concept introduced in this chapter can be applied to other power-stage topologies as well. The virtual-parallel concept enhances the output power by equalizing the sub-panels’ voltages while keeping the input voltage of the converter at a high level for a feasible grid connection.
Performing DMPPT at the sub-string-level can result in substantial energy yield for the normal urban installations over panel-level DMPPT. This fact has been supported by the results of the analysis in Chapter 2 for two of the three test cases, where sub-string-level DMPPT provides ≈ 3% and 30% more annual energy yield over the panel-level DMPPT for test cases # 1 and 2 respectively. In practice, the benefit is expected to be significantly higher, since the shading analysis in Chapter 2 does not consider other important non-idealities aside from shading.

This chapter is organized as follows. The virtual-parallel concept is introduced in Section 4.2. Also, a three-phase boost converter to realize this concept is presented and compared to an existing virtual-parallel-based topology to perform near-ideal DMPPT for a PV panel decomposed into three sub-panels. Section 4.3 elaborates on different components of the three-phase boost converter control scheme, including DMPPT and variable phase interleaving. Analog Mixed-Signal (AMS) simulation and experimental results for the proposed converter are provided in Section 4.4, and the benefits of the proposed approach are discussed. Finally, Section 4.5 includes the conclusions for this chapter.
4.2 Virtual-Parallel Concept and Implementation

A commercial mono-crystalline PV panel usually utilizes three by-pass diodes, one for each sub-panel, as depicted in Fig. 4.2. If $V_{pv1}$, $V_{pv2}$, and $V_{pv3}$ denote the voltages across the sub-panels, in a converter with virtual-parallel connection, extra auxiliary phases are designed such that these voltages are regulated to be the same for all circumstances, while maintaining the series connection of the sub-panels. This is the principle of virtual-parallel operation. This helps the PV system retrieve a lot of power through auxiliary phases in case of shading as the sub-panel voltages are equalized by the auxiliary dc-dc converters. A high-level MPPT algorithm optimizes the total power at the output of the system. The virtual-parallel concept avoids processing the total power through a large conversion ratio of $V_{out}/V_{pv}$ which is the case with a true parallel connection as in Fig. 4.1, by keeping the advantage of having the series configuration. Ideally in a converter utilizing virtual-parallel concept in sub-panel level, no additional wiring changes are required outside of the junction box, which, as mentioned earlier, typically includes three bypass diodes for the six sub-strings, one for every two.

![Figure 4.2: A mono-crystalline PV panel decomposed into three sub-panels, utilizing three by-pass diodes in its junction box.](image)

4.2.1 Virtual-Parallel Realization

A dc-dc topology to realize virtual-parallel concept has been proposed in [2], where the auxiliary converters are cascaded in a hierarchical manner as shown in Fig. 4.3. This
topology has been presented as a patent with no published paper on experimental or simulation results. The control basis for this approach is as follows. Auxiliary phases 2,3 regulate $V_{pv1,2}$ to the same value as $V_{pv3}$ and phase 1 performs the high-level MPPT in the system.

![Figure 4.3: Topology used to achieve virtual-parallel operation in three sub-panels of a PV panel using the virtual-parallel implementation technique proposed in [2].](image)

The topology presented in this work builds on the discussed micro-converter based DMPPT architecture and capitalizes on the existing wiring of the junction boxes in today’s PV panels, as shown in Fig. 4.4(a). The internal voltages $V_1$ and $V_2$ can be readily tapped to achieve sub-panel DMPPT with three sub-panels per panel. The chosen dc-dc architecture consists of three synchronous boost converters with a common output, $V_{out}$. The main phase, which is designed to process the majority of the power, is connected to the top of the three sub-panels at $V_3$. The use of shared positive and negative rails on all of the three phases is convenient for driver design and future on-chip implementation. The two bi-directional auxiliary phases 2 and 3 are connected to $V_2$ and $V_1$, respectively. The proposed three-phase boost converter is depicted in Fig. 4.4. Under shaded conditions the sub-panels are effectively parallel-connected by the auxiliary converters 2 and 3. In the absence of shading, the auxiliary converters automatically turn off, as the sub-panel
voltages are properly distributed, $V_{pv} = V_{pv1} = V_{pv2} = V_{pv3}$. In this case, only the main phase, which has a low conversion ratio of $V_{out}/3V_{pv}$, is on and the losses are minimized.

Figure 4.4: (a) Topology used to achieve virtual-parallel operation in three sub-panels of a PV panel using the proposed technique. (b) Simplified control structure for the proposed converter ($\phi_{int2-3}$ denote the calculated optimal phase-shifts in phases 2 and 3).

### 4.2.2 Virtual-Parallel Topologies Comparison

While the use of cascaded converters in [2] reduces the voltage ratings in the auxiliary phases, it can be shown that in some cases, the converters on average operate with a higher processed power, $P_{pr}$, which is the sum of input power flow into the three converters:

$$P_{pr} = P_{in1} + |P_{in2}| + |P_{in3}|,$$

where $P_{inj}$ is the input power of the $j$-th phase. The ratio of total processed power in the proposed converter, $P_{pr,bst}$, over the processed power in the topology suggested by [2], $P_{pr,win}$, is listed in Table 4.1 for 95 % efficiency. In addition, the losses during shading
can be higher in some cases for [2], since the power flows through multiple converters. This fact is verified by considering eight extreme operating points for a string of three PVs. The output power is evaluated in each case for [2] and the proposed topology. Each PV is considered to be either in low irradiation or high irradiation mode, having 4.8 A or 0.2 A as the operating current respectively. The regulated voltage is considered to be 12 V for each sub-panel in both cases. The efficiency of dc-dc converters of phases 1 to 3, $\eta_{1-3}$, are assumed to be the same and the evaluation is repeated for three different efficiencies. The results of the analysis are shown in Table 4.1, which proves the overall extra benefit of the proposed virtual-parallel approach in some cases. Particularly when $PV_1$ is shaded, the excess power is driven into the two consecutive auxiliary phases in [2]. In addition, the strong coupling between the converters due to the cascaded nature of [2] potentially causes more stability issues in this topology than the proposed converter. A comparison between the proposed scheme and [2] is provided in Table 4.2.

### Table 4.1: Output Power Comparison of [2] and the Proposed Topology for Eight Different Operating Points

<table>
<thead>
<tr>
<th>Test Case Condition ($PV_{1-3}$)</th>
<th>97 % Power Benefit of the Proposed Technique (%)</th>
<th>96 %</th>
<th>95 %</th>
<th>$P_{pr;bst}$/$P_{pr;win}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>HLL</td>
<td>5.228</td>
<td>6.935</td>
<td>8.625</td>
<td>0.37</td>
</tr>
<tr>
<td>LHL</td>
<td>-0.263</td>
<td>-0.485</td>
<td>-0.785</td>
<td>1.02</td>
</tr>
<tr>
<td>HHL</td>
<td>2.816</td>
<td>3.755</td>
<td>4.693</td>
<td>0.52</td>
</tr>
<tr>
<td>LLH</td>
<td>-6.34</td>
<td>-9.039</td>
<td>-12.11</td>
<td>1.67</td>
</tr>
<tr>
<td>HLH</td>
<td>-3.181</td>
<td>-4.28</td>
<td>-5.78</td>
<td>1.5</td>
</tr>
<tr>
<td>LHH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>HHH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

† L and H represent the low and high irradiance conditions for the respected PV panel. Power benefit is defined as the overall output power of the proposed technique over the output power of the converter proposed in [2]. A negative power benefit in a specific condition shows a lower output power for the proposed approach in that condition.
Table 4.2: Comparison of [2] and the Proposed Topology to Achieve Virtual-Parallel Operation

<table>
<thead>
<tr>
<th></th>
<th>[2]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion Ratio of the Auxiliary Phases</td>
<td>2, 1.5</td>
<td>dependant on $V_{out} - V_{pv1}$, $V_{pv1} + V_{pv2}$</td>
</tr>
<tr>
<td>Driving</td>
<td>complicated</td>
<td>simple (shared supply for all high-side drivers)</td>
</tr>
<tr>
<td>Stability Issues</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>Ripple Management</td>
<td>-</td>
<td>variable interleaving algorithm</td>
</tr>
<tr>
<td>Voltage ratings of the auxiliary phases</td>
<td>$V_{pv1} + V_{pv2}$, $V_{pv1} + V_{pv2} + V_{pv3}$</td>
<td>$V_{out}$</td>
</tr>
</tbody>
</table>

4.3 Three-Phase Boost Converter Control

4.3.1 DMPPT Procedure

In all conditions, DMPPT in the three-phase boost converter is achieved by a digital controller that maximizes the total power extracted from the three sub-panels using

$$P_{pv} = V_1 I_{L3} + V_2 I_{L2} + V_3 I_{L1}, \quad (4.2)$$

where $I_{Lj} = \langle i_{Lj} \rangle_{T_{sw}}$ is the average input current of the $j$-th phase. The average of the auxiliary phase currents, $I_{L2}$ and $I_{L3}$, may either be positive or negative, depending on the shading condition. All six quantities in (4.2) are sampled and used by the digital controller. The current sensors on all three inductors are necessary for overcurrent protection and are conveniently re-used for MPPT. Fig. 4.4 (b) shows a low-power implementation of the proposed controller. A low-power micro-controller performs the high-level MPPT computations, while the high-frequency gating signals are generated by a non-volatile Complex Programmable Logic Device (CPLD).

4.3.2 Phase Interleaving Technique under Shading Conditions

The parallel phases used in this work can be carefully interleaved to reduce the voltage ripple on $V_{out}$, and thus increase the output capacitor’s life-time. The variable interleaving concept demonstrated by [3] for asymmetrical systems can be used to calculate the optimal phase-shifts at each operating point. If $I_{phj}$ represents the magnitude of the first harmonic of the current delivered by the $j$-th phase to the output capacitor, $C_{out}$, in the three-
phase boost converter, it can be shown that the proper phase shifts of auxiliary phases 2 and 3, \( \alpha \) and \( \beta \), to achieve optimal phase interleaving to cancel the first harmonic, can be calculated by [3]

\[
\cos \beta = \frac{|1_{I_{ph1}}|^2 + |1_{I_{ph2}}|^2 - |1_{I_{ph3}}|^2}{2|1_{I_{ph1}}|^2|1_{I_{ph2}}|^2} \tag{4.3}
\]

\[
\cos \alpha = \frac{|1_{I_{ph1}}|^2 + |1_{I_{ph3}}|^2 - |1_{I_{ph2}}|^2}{2|1_{I_{ph1}}|^2|1_{I_{ph3}}|^2} \tag{4.4}
\]

To calculate the interleaving angles of phases 2 and 3, we have

\[
\phi_{int2} = \pi + \phi_{ph1} - \phi_{ph2} - \beta \tag{4.5}
\]

\[
\phi_{int3} = \pi + \phi_{ph1} - \phi_{ph3} + \alpha, \tag{4.6}
\]

where \( \phi_{phj} \) represents the phase of the fundamental component of the delivered current of \( j^{th} \) phase to the output capacitor, \( C_{out} \). The optimal phase-shifts in auxiliary phases to cancel the fundamental component is depicted in the right figure in Fig. 4.5. The time-delays for the switching times of the phase 2 and 3 can be calculated as

\[
t_{delay2} = \frac{\phi_{int}2}{2\pi} T_{sw}, \quad t_{delay3} = \frac{\phi_{int}3}{2\pi} T_{sw}, \tag{4.7}
\]

where \( T_{sw} \) is the switching period of the converters. The calculations can be done in the micro-controller while the shifting procedure can be easily performed using a delay-line or counter in the Digital Pulse Width Modulation (DPWM) block in the CPLD [4,5]. The straight-forward interleaving procedure is clearly an advantage of the proposed technique to the approach in [2]. For most operating points, the current delivered by the auxiliary phases is relatively low and thus

\[
|1_{I_{ph3}}| \geq |1_{I_{ph1}} + 1_{I_{ph2}}|. \tag{4.8}
\]

In these cases, near-optimal interleaving can be achieved if the auxiliary phase-shifts are set to 0\(^\circ\) or 180\(^\circ\) depending on the direction of the power-flow. In fact, no triangle can be formed to completely remove the fundamental component of the output current as shown in Fig. 4.5, but its magnitude can be minimized using the described procedure.
4.4 Simulation and Experimental Results

AMS mixed signal simulations were run on a mono-crystalline PV panel [6] modeled in the Cadence environment. Fig. 4.6(a) and (b) show the sub-panel voltages, $V_{pv1-3}$, with and without auxiliary phases for two different irradiation cases on sub-panel inputs. $G_j$ represents the irradiation on $j$-th input, $PV_j$. It can be seen that the virtual-parallel concept works well resulting in an output power benefit. In case (a), where the mismatch between sub-panels are higher, 24% benefit is observed whereas in case (b) where the sub-panels’ mismatches is reduced, the output power benefit is close to 2%.

The same mono-crystalline PV panel [6] was tested with the 4 kW lighting system introduced in Chapter 3. An experimental dc-dc converter prototype was constructed to demonstrate the architecture of Fig. 4.4. The designed PCB of the proposed converter is shown in Fig. 4.7. The prototype is directly powered from the PV panel and consumes below 300 mW during switching, including all necessary auxiliary circuits, gate-drivers and controllers. The prototype specifications are shown in Table 4.3. The efficiency of the three individually operated phases with $V_{out} = 50$ V and $V_{1-3} = 10$, 20 and 30 V, which are typical under normal operation for the PV panel in the lab, is shown in Fig. 4.8, with $M$ representing the conversion ratio of each phase. Phases 2 and 3 are designed to handle $\frac{1}{4}$ and $\frac{1}{2}$ of the rated power in phase 1, which has the highest efficiency and cost. The converter sizing is based on the trade-off between current limits, cost and energy yield.
Figure 4.6: Simulation results for (a) $G_1 = 600 \text{ W/m}^2$, $G_2 = 1000 \text{ W/m}^2$ and $G_3 = 800 \text{ W/m}^2$, and (b) $G_1 = 900 \text{ W/m}^2$, $G_2 = 950 \text{ W/m}^2$ and $G_3 = 1000 \text{ W/m}^2$.

Table 4.3: Three-Phase Boost Prototype Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Frequency, $f_{sw}$</td>
<td>300</td>
<td>kHz</td>
</tr>
<tr>
<td>Input Capacitors, $C_{i1-3}$</td>
<td>20</td>
<td>$\mu$F</td>
</tr>
<tr>
<td>Output Capacitor, $C_{out}$</td>
<td>240</td>
<td>$\mu$F</td>
</tr>
<tr>
<td>Main Phase Inductor, $L_1$</td>
<td>100</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Auxiliary Phases’ Inductors, $L_{2-3}$</td>
<td>56</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Output Voltage, $V_{out}$</td>
<td>50</td>
<td>V</td>
</tr>
</tbody>
</table>
Figure 4.7: Three-phase boost prototype.

Figure 4.8: Measured efficiency of the phases for $V_{out} = 50$ V, $V_1 = 10$ V, $V_2 = 20$ V, $V_3 = 30$ V.

The system startup and subsequent MPPT is shown in Fig. 4.9(a). The 60 Hz oscillations in steady state are due to the fact that the PV panel is powered by light bulbs connected to the AC grid. The increase in the output power when the two auxiliary phases are turned on at $t = 0$ is shown in Fig. 4.9(b). Without the auxiliary phases, $PV_1$ is bypassed due to shading. As soon as the auxiliary phases turn on, $V_1$ is regulated.
to $\frac{1}{3}V_3$ and the output power increases by 8% in this case. The transition process is much slower than the MPPT startup, because of the soft start in the auxiliary phases and intended slower control on equalizing the sub-panel voltages so that the auxiliary phases operation does not jeopardize the main MPPT function.

![Image](a)

Figure 4.9: (a) Startup of the converter performing MPPT on the series-connected sub-panels. (b) Power increase when the auxiliary phases turn on ($I_{\text{string}}$: 1A/div).

The interleaved operation of the phases is shown in Fig. 4.10. It can be readily seen that the ripple on the output voltage, $V_{\text{out}}$, is reduced by more than 50% with optimal phase-shifting, as shown in Fig. 4.10 (b).

The measured input and output power of the system in various shading conditions (as quantified by the short-circuit currents, $I_{\text{sc1-3}}$) are shown in Table 4.4. $P_{\text{ideal}}$ is the sum of the three individual MPP points and thus represents the highest extractable power, while
\( P_{\text{series}} \) is the highest input power available for a series connection without the auxiliary phases. The measured efficiencies

\[
\eta_1 = \frac{P_{\phi 1}}{P_{\text{ideal}}} \cdot 100\%, \quad \eta_{vp} = \frac{P_{\phi 1,2,3}}{P_{\text{ideal}}} \cdot 100\% \tag{4.9}
\]

are used to quantify the benefit of the virtual-parallel converter. The power improvement due to the auxiliary phases, \( P_{\phi 1,2,3}/P_{\phi 3} \), reaches 30% in Case #2. An average of \( \eta_{vp} = 93.1\% \) is achieved for the six test cases, compared to \( \eta_1 = 77.6\% \), which proves the merit of the virtual-parallel design.

Figure 4.10: (a) Operation with no interleaving. (b) Variable interleaving operation.
### Table 4.4: Output Power for Shading Cases on the PV Panel

<table>
<thead>
<tr>
<th>Case #</th>
<th>Condition</th>
<th>$I_{sc1-3}$ (A)</th>
<th>$P_{ideal}$</th>
<th>$P_{series}$</th>
<th>$P_{\phi1}$</th>
<th>$P_{\phi1,2}$</th>
<th>$P_{\phi1,2,3}$</th>
<th>$\eta_{\phi1}$ (%)</th>
<th>$\eta_{vp}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full Light</td>
<td>2, 2.5, 2.2</td>
<td>54.3</td>
<td>52.5</td>
<td>50.4</td>
<td>52</td>
<td>52.5</td>
<td>92.9</td>
<td>96.7</td>
</tr>
<tr>
<td>2</td>
<td>PV2 More Lit</td>
<td>0.6, 1.4, 1</td>
<td>25.5</td>
<td>18</td>
<td>17.9</td>
<td>17.8</td>
<td>23.2</td>
<td>70.2</td>
<td>91.1</td>
</tr>
<tr>
<td>3</td>
<td>PV1 Shaded</td>
<td>0.6, 1.1, 0.8</td>
<td>23.5</td>
<td>18</td>
<td>17.4</td>
<td>21.2</td>
<td>22</td>
<td>74.2</td>
<td>93.6</td>
</tr>
<tr>
<td>4</td>
<td>PV3 Shaded</td>
<td>1.9, 1.5, 1.1</td>
<td>38.5</td>
<td>30.8</td>
<td>29.1</td>
<td>34.1</td>
<td>35.4</td>
<td>75.5</td>
<td>91.9</td>
</tr>
<tr>
<td>5</td>
<td>PV3 Strongly Lit</td>
<td>2.1, 0.4, 0.07</td>
<td>23.7</td>
<td>18.7</td>
<td>17.6</td>
<td>17.5</td>
<td>21.5</td>
<td>78.9</td>
<td>90.7</td>
</tr>
<tr>
<td>6</td>
<td>Low Light Operation</td>
<td>1.2, 1.2, 0.6</td>
<td>25.4</td>
<td>20.1</td>
<td>18.8</td>
<td>21.1</td>
<td>24.0</td>
<td>74.1</td>
<td>94.5</td>
</tr>
</tbody>
</table>

### 4.5 Conclusion

A low-cost topology and simple control scheme were developed in this chapter for sub-string-level DMPPT in PV applications. The target is for PV systems suffering from power-degrading phenomena such as partial shading effect while requiring series connection of the PV panels for high voltage operation. The control scheme makes use of the concept of virtual-parallel connection to gain advantage over normal series-connected MPPT schemes. The additional two phases in the proposed converter are used to achieve a virtual-parallel connection without affecting the wiring scheme outside the panel. These two phases can be sized arbitrarily to compensate for up to a desired amount of mismatch in the system and thus reduce the cost overhead of the system. A variable interleaving algorithm was also implemented using the flexible micro-controller and CPLD platform to cancel the fundamental component in the output current of the converter. This leads to increased life-time of the output capacitor and a more reliable system. The implemented technique is of crucial importance as the output capacitor is one of the most costly parts of the dc-dc converter in grid-tied PV systems.
References


Chapter 5

Conclusions

5.1 Thesis Summary and Contributions

The focus of this work is to investigate the DMPPT architectures for PV systems that are designed to extract power from the system at various levels of granularity. More specifically, panel, sub-string and cell-level DMPPT are targeted rather than string-level MPPT which is the common practice in traditional PV systems. This can potentially result in substantial energy yield benefits depending on the extent of partial shading effect, PV installation and technology, and the selected level of DMPPT granularity.

Chapter 2 addresses the cost/energy benefit trade-off for generic PV installations by developing a simulation-based methodology to examine the total annual energy yield at the envisioned levels of granularity in PV systems. The process of developing this tool consists of the following steps:

1. Google Sketchup, a 3D Computer Aided Design (CAD) tool, is decided to be used to model the installation site due to its advantages such as availability and ease of use. The shade patterns on the installation site are captured and transported to MATLAB environment for shading analysis and energy estimations of different levels of DMPPT granularity.
2. Popular hard-switching dc-dc topologies, namely boost, buck-boost and boost-buck converters, are modeled based on their loss equations and the total output energy yield of PV systems utilizing these converters is estimated for panel-level DMPPT.

3. The developed process was demonstrated on three installation sites in Toronto area, as well as being verified experimentally by means of small cell-level irradiation and temperature capturing units, PV probes.

Based on the results from the extensive DMPPT analysis, it can be observed that sub-string-level DMPPT can potentially lead to essential savings in the PV systems. The fact is verified by looking at two of the three considered test cases in Chapter 2, where sub-string-level DMPPT results in 3 % and 30 % more annual energy yield with respect to panel-level DMPPT for Site # 1 and 2, respectively. Manufacturers have already been noticing the importance of sub-panel power optimization by using three by-pass diodes for the three sub-panels of the standard mono-crystalline PV panels. The Multi-Input, Single-Output (MISO) converter in Chapter 3, and the three-phase boost converter in Chapter 4, are then developed to practice deep-level DMPPT granularity, mainly targeting sub-panel and sub-string levels of power harvesting.

The MISO dc-dc converter provides a low-cost implementation of DMPPT for solar applications requiring parallel-connected PV modules. The converter includes the following novelties:

1. A controller with digital peak and valley current control is used to operate the MISO converter in pseudo-CCM mode. This type of current mode control eliminates the need for slope compensation and provides inherent over-current protection in the system. The control scheme also optimizes the efficiency of the converter through minimizing free-wheeling time, \( t_{fw} \), by adjusting the valley current, \( I_v \), and phases’ peak currents, \( I_{p1-3} \) for each operating point.

2. A digital input current estimation algorithm based on the inductor current is pro-
posed to iteratively reach DMPPT for each input, eliminating the need for several current sensors in the system.

The overall power benefit for the MISO converter for sub-panel DMPPT reaches up to 43% in the considered experimental test cases. The proposed low-cost DMPPT solution and control algorithm provide very promising power savings compared to the conventional MPPT approach. Moreover, the novel solution allows PV systems to be easily expanded without being restricted to panels from a single manufacturer.

The virtual-parallel concept is then introduced to make use of the robustness of parallel-connected PV cells to irradiance mismatches, while still taking advantage of the series configuration. This is especially of high importance in grid-tied applications where a high voltage on PV side is required. To demonstrate the virtual-parallel concept functionality and advantages:

1. A three-phase, low-cost 300 kHz dc-dc converter prototype is implemented to demonstrate the virtual-parallel concept with sub-panel MPPT. The converter makes use of two small-sized auxiliary phases to enhance the output power during partial shading or mismatch conditions.

2. The control scheme for the converter is implemented using a micro-controller and CPLD. The low-power micro-controller is used for high-level calculations while the CPLD is used to generate driving signals and low-level control. As a result, the overall power consumed by control circuitry is very limited, which is essential in this power range.

3. A variable phase-shifting scheme is used to reduce the output voltage ripple during shading conditions, which increases the output capacitor life-time and improves the system reliability.

Finally, a set of modular hardware-based PV panel emulators (ePVs) is presented in Appendix A. The ePVs can be programmed to match the unique $I-V$ curves of real
panels under various conditions and can therefore be used to investigate future large-scale DMPPT systems in the lab environment.

The research work in Chapter 3 and Appendix A have been published as two conference publications [1, 2], while the contents of Chapter 2 and 4 have been submitted for future publication [3,4].

5.2 Future Work

The DMPPT analysis tool developed in this work can be extended in the following directions:

1. The central inverter can also be modeled in the micro-converter based system for a more complete analysis. The inverter itself, introduces new losses and trade-offs to the system. Furthermore, the value of dc-bus voltage, $V_{bus}$, is very important in the system’s stability as well as the overall energy yield [5]. Developing such a complete model for a micro-converter system, enables the system designers to come to a potential strategy to optimize this voltage based on the PV installation’s specifications.

2. In a more general view, the same procedure can be done for micro-inverter systems by focusing on modeling of the micro-inverters instead of individual dc-dc converters. The modeling procedure can be extended to any desired topology other than hard-switching converters considered in this work by considering their loss equations.

3. The developed tool can be combined by other methods which consider the effects of other shading phenomena, such as cloud effects. The combination can lead to a precise method to evaluate the PV installation at any point in time. For example, the new forecasting tools for cloud coverage based on camera-on-site technology [6] can be successfully merged with the presented features of this work.
The MISO scheme and control can be applied to the boost topology as well, although the prototype presented in this work is a buck converter. This opens up a new perspective for this scheme in the high-voltage applications where maximal power extraction from mismatched sources of energy is necessary. Furthermore, the optimization step can be extended in heavy shading conditions by splitting the phase time for the phase with high irradiation into multiple switching cycles. This way, the ripple on the inductor current, $i_L$, is reduced resulting in lower conduction losses. In addition, a variable frequency approach is currently being developed to eliminate the need for free-wheeling time, $t_{fw}$, to achieve lower cost and higher efficiency.

The three-phase boost converter’s performance can be enhanced by incorporating light-load efficiency techniques, such as Pulse Frequency Modulation (PFM), in the auxiliary phases. This is expected to improve the system’s output power by a considerable amount as the auxiliary phases are generally expected to process low power, unless in heavy shading conditions. In addition, the operation can be optimized by regulating the sub-panels not to the same voltage, but by slight voltage differences so that the actual maximum power point of each sub-panel is captured. The control algorithm to achieve this optimal operation is still to be investigated.
References


Appendix A

Emulated PV: Concept and Implementation

A.1 Introduction

The purpose of this appendix is to develop a hardware platform to be able to verify a large DMPPT system, such as a PV farm, in the lab environment. Applying complex and repeatable time-varying environmental conditions to each PV panel in a big array is not practical in the lab environment.

The approach proposed here is shown in Fig. A.1. The real PV panels in the test-bed are replaced by programmable hardware-based PV emulators (ePV). Each ePV contains a regulated dc-dc converter to achieve the unique $I-V$ characteristic of each PV panel under the desired irradiance and temperature conditions. The parameters of the emulated PV panel, as well as the irradiance and temperature conditions are fully programmable using a communication link. The resulting modular system is highly scalable and provides a flexible platform for DMPPT demonstration.

A.2 ePV Implementation

The implementation of the hardware PV emulator (ePV) of Fig. A.1 is shown in Fig. A.2. The system parameters are listed in Table A.1. For each ePV, an isolated off-the-shelf AC-DC power supply provides a 12 V input voltage to the dc-dc converter, which is implemented using the non-inverting buck-boost topology [1]. Digital voltage-mode control
Appendix A. Emulated PV: Concept and Implementation

is implemented in an FPGA using a digital DPID compensator. The voltage reference, $V_{ref}$, is generated by the $I-V$ lookup table (LUT) that is stored in a RAM memory module. The LUT contains the $I-V$ characteristic of the ePV for a particular combination of irradiation, $G$, and junction temperature, $T$. The ePVs are connected together using an optically-isolated serial communication bus, which is managed by a PC USB interface. The PC acts as the master and uploads the individual $I-V$ characteristics to each ePV, based on interrupts from the user input. The individual $I-V$ characteristics are calculated in the PC, based on the input from a LabVIEW Graphical User Interface (GUI). The calculation is based on the modeling approach of [2] using the parameters of the PV system which are defined by the user. The GUI allows the user to enter the PV parameters, as well as the temperature and irradiation conditions for each ePV. The current GUI is configured for a 4 ePV system, as shown in Fig. A.3. The ePV operates in one of two possible modes depending on the PV parameters selected by the user in the GUI. If the open-circuit voltage, $V_{oc}$, is below the 12 V output of the off-the-shelf AC-DC converter, the ePV operates in buck mode. If $V_{oc} > 12$ V, the ePV is programmed to operate in boost mode to cover the full range of the $I-V$ curve.
Table A.1: Dc-dc Converter Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>On Resistance of MOSFETs, $R_{on}$</td>
<td>15.4</td>
<td>mΩ</td>
</tr>
<tr>
<td>Switching Frequency, $f_{sw}$</td>
<td>234</td>
<td>kHz</td>
</tr>
<tr>
<td>Inductance, $L$</td>
<td>22</td>
<td>μH</td>
</tr>
<tr>
<td>Inductor DCR, $R_L$</td>
<td>10</td>
<td>mΩ</td>
</tr>
<tr>
<td>Output Capacitance, $C_{out}$</td>
<td>50</td>
<td>μF</td>
</tr>
</tbody>
</table>

Figure A.2: Architecture of the emulated PV prototype.

Figure A.3: LabVIEW GUI for the 4 ePV system.

A.3 Experimental Verification

The measured $I$-$V$ and $P$-$V$ characteristics of the fabricated ePVs are shown in Fig. A.4(a) and (b) respectively, for four different combinations of $T$ and $G$. The specifications are set to those of the mono-crystalline panel in Chapters 3 and 4 [3]. The solid lines correspond to the ideal values. The ePV voltage-loop compensation is optimized for high stability.
near the peak power point, where the DMPPT system is intended to operate. The ePVs are unable to regulate voltages below 300 mV due to duty-cycle saturation. The voltage mode controller is inherently more stable beyond the peak power point, where the \( \frac{\text{dv}}{\text{di}} \) in the \( I-V \) curve is low. If accurate matching of the \( I-V \) curve is required near \( I_{sc} \), an alternate control scheme such as Average Current-Mode Control (ACMC) can be used [1].

The mismatch in the experimental data is primarily due to accuracy limitations in the current and voltage sensing hardware, as well as the finite precision of the \( I-V \) curve stored in the RAM. The system provides a flexible platform for testing future DMPPT controllers.

Figure A.4: (a) Simulated and measured \( I-V \) and (b) \( P-V \) characteristics generated by the ePV under 4 different conditions.
References

