Sub-Module Differential Power Processing for Photovoltaic Applications

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Outline

1 Background
   - Problem Statement
   - Differential Power Processing

2 Proposed Approach
   - Architecture
   - Control

3 Experiment
   - Experiment Setup
   - Result and Analysis
1. Background
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PV Module Mismatch Problem

- PV modules are connected in series to increase voltage
- Series connected PV modules suffers from current mismatch
  - Partial shading
  - Manufacturing variability
  - Non-uniform ageing characteristics
Two major conventional solutions for MPPT:
- DC Optimizer
- Micro-inverter

(a) DC optimizer

Overall Efficiency: 95%

(b) Micro-inverter

Overall Efficiency: 95%
Differential Power Processing MPPT
An Alternative Solution

- The bulk power goes directly to the central converter
- Each converter processes only the power difference
- Avoid intermediate conversion of the bulk power

Overall Efficiency: 97.5%
Each PV module typically consists of three sub-modules.

PV module power output impaired by sub-module mismatch.

![Diagram of PV module with sub-modules and bypass diodes](image)
## Related Work

<table>
<thead>
<tr>
<th>Topology</th>
<th>Generation control circuit</th>
<th>Distributed converters (E to E VP)</th>
<th>SubMIC (E to B VP)</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Multi-stage chopper</td>
<td>Resonant SC</td>
<td>Flyback</td>
<td>Buck-Boost</td>
</tr>
<tr>
<td>Local current sensing</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Communication</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Switch voltage rating</td>
<td>String voltage</td>
<td>Sub-module voltage</td>
<td>String/Sub-module voltage</td>
<td>Twice Sub-module voltage</td>
</tr>
<tr>
<td>MPPT</td>
<td>True MPPT</td>
<td>Near MPPT</td>
<td>Near MPPT</td>
<td>True MPPT</td>
</tr>
<tr>
<td>Easily Scalable</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Module Integrated</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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Sub-module DPP system

- DPP Converters implemented as buck-boost
- Each converter process only power mismatch
Proposed Approach

Converter Miniaturization

- Low converter voltage and power rating
- Low voltage, high frequency transistor
- Integration into module junction box

Module

S. Qin, R. Pilawa-Podgurski (UIUC)
### DPP Converter Implementation

#### Table: Converter Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter Topology</td>
<td>Buck-Boost</td>
</tr>
<tr>
<td>Sub-module Voltage Range</td>
<td>3-13.5 V</td>
</tr>
<tr>
<td>Converter Power Rating</td>
<td>60 W</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>250 kHz</td>
</tr>
<tr>
<td>Converter Peak Efficiency</td>
<td>97%</td>
</tr>
<tr>
<td>Converter Weight</td>
<td>4.55 grams</td>
</tr>
<tr>
<td>Converter Volume</td>
<td>1.91 cm³</td>
</tr>
</tbody>
</table>
Control Problem Statement - True MPPT

\[ P_{string} = V_{string} \times I_{string} \]

- Overall MPP achieved only when MPP at each sub-module (all circuit variables fully determined)
- Central converter performs P&O to \( I_{string} \) in a ‘slow’ loop
- Maximize \( V_{string} \) to maximize output power
- DPP converters perform P&O to \( D_1, D_2, D_3 \ldots \) to maximize \( V_{string} \) in a ‘fast’ loop
System Model

- $V_{string}$ is a function of duty ratio $D_1, D_2, D_3......$ given other parameters fixed
- This function only has one maximum point for a given string current
- Perturb each duty ratio in turns and observe change in string voltage to find:
  \[
  \arg \max_{D_i \in [0,1]} V_{string}(D_i)
  \]

3-dimensional plot of string voltage ($V_{string}$) versus DPP converter duty ratios ($D_1, D_2$) for a 3-sub-module 2-converter system.
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PV module emulation enables controllable and repeatable PV experiment in an indoor environment.

(c) Hardware connection.  
(d) Equivalent circuit schematic.

Figure: Emulation of PV module.

\[ I_{ph} = 0 \]
\[ I_{ext} \]

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\(^1\)S. Qin, et al, "Laboratory Emulation of a Photovoltaic Module for Controllable Insolation and Realistic Dynamic Performance", PECI 2013
Experiment Setup

- Test system consists of three PV sub-modules
- Two converters communicate to a computer through $I^2C$
- An electronic load acts as the central inverter

Schematic drawing of laboratory test setup

Experiment Result

- Output current sweep performed by electronic load
- Substantial power output improvement
- Elimination of local maxima caused by bypass diode
Power output improvement in different partial shading conditions

- Insolation Level of the 2nd Sub-module:
  - 40%
  - 60%
  - 80%
  - 100%

- Insolation Level of the 3rd Sub-module:
  - 40%
  - 50%
  - 60%
  - 70%
  - 80%
  - 90%
  - 100%
Efficiency Considerations

Efficiency of DPP Converter

- Fixed Frequency CCM
- Burst Mode Operation
- Dual Mode Operation

Graph shows efficiency as a function of output current, with different modes of operation.

Inductor Current (A)

- \(I_{av} = 0.5A\)
- \(I_{RMS} = 1.08A\)

\(I_{av} = 0.5A\)
\(I_{RMS} = 0.89A\)
Differential power processing can significantly improve power yield, and reduce size and cost of PV system.

True MPPT can be achieved with no local current sensing and fast tracking by the architecture and control scheme presented.

The effectiveness of the proposed solution has been experimentally verified by a controllable indoor test setup.
QUESTIONS?

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Email: sqin3@illinois.edu
Power Rating of DPP Converters

5% Mismatch

- Bulk power
- Differential power

Power [W]

PV Sub-Module

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