Module-Integrated Power Electronics for Solar Photovoltaics

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Solar Photovoltaic System Challenges
Solar Photovoltaic Challenges - Residential

- Solar panel mismatch
  - Shading by external structures
  - Self shading
  - Dirt
  - Aging
  - Orientation
  - Panel manufacturing

- Lower energy capture
  - Weakest link limits overall performance
Solar Cell Characteristics

- Need to operate solar cell at maximum power point (MPP)
  - MPP varies greatly with insolation
- Each cell is very low voltage
- Some series-stacking is necessary
Standard PV System Architecture

- **Advantages**
  - Efficient power electronics
  - Low cost
  - High reliability (per unit)

- **Disadvantages**
  - Reduced energy capture
  - No diagnostics
  - Safety issues
Distributed Power Electronics

Advantages
- Each panel operates at optimum point
- Inherent voltage stacking - can use high efficiency inverter
- Diagnostics and Safety

Disadvantages
- Higher cost
- Some energy lost in power electronics
- Control challenges?
Challenges of Per Panel MPPT

- Poor Efficiency
  - High voltage (40-250 V) power electronics
  - Low switching frequency to minimize loss
  - Bulky passive components

- High cost
  - Extra components
  - Expensive enclosures

- Internal Panel Mismatch
  - Partial shading across single panel leads to reduced energy capture
Single Panel Mismatch

Panel is not producing maximum power – internal panel mismatch
Sub-Module MPPT
Panel Integrated Sub-Module MPPT

- Increased energy capture
- Fully integrated into existing junction boxes
  - Reduced cost
  - Low (<15 V) voltage power electronics
- Work with conventional inverter
  - Drop-in “smart” panel
  - All intelligence resides in the local power electronics
Experimental Hardware

- Experimental evaluation
  - Small enough to place in junction box
  - Isolated individually addressable (I2C) converters for evaluation of algorithms and performance
  - Bypass mode to collect empirical data

**Converter Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Input Voltage Range</td>
<td>5-27 V</td>
</tr>
<tr>
<td>Output Voltage Range</td>
<td>0.8-20 V</td>
</tr>
<tr>
<td>Max Output Power</td>
<td>80 W</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>250 kHz</td>
</tr>
<tr>
<td>Converter Peak Efficiency</td>
<td>98.2%</td>
</tr>
<tr>
<td>Tracking Efficiency (\eta_{MPP})</td>
<td>&gt;99%</td>
</tr>
</tbody>
</table>
Control Algorithm

- All converter in series → share the same current
  - Maximize individual power by maximizing output voltage
    - Perturb and Observe
  - Perform startup sweep to locate approximate MPP

- Global MPPT
  - No feedback
    - Utilize inverter MPPT algorithm to find best operating point
  - 1-bit feedback
    - Inverter reduces current until strongest MPPT runs at full duty cycle
      - Feedback possible through existing wiring
System Setup

Integrated Power Stage

$V_{IN}$ $C_{IN}$

$R_{PT}$ $V_P$

$R_{PB}$ $C_P$

$R_{HT}$ $V_H$

$R_{HB}$ $C_H$

$R_{LT}$ $V_L$

$R_{LB}$ $C_L$

$V_{PV}$ $V_H$ $V_L$

Microcontroller

Computer

electrical isolation
Partial Shading
Static Evaluation

25 percent shading of Section 3

Max Conventional Panel Power: 103 W
Max Distributed MPPT Power: 115 W
Improvement with Distributed MPPT: 11 %
Static Evaluation

50 percent shading of Section 3

Max Conventional Panel Power: 80 W
Max Distributed MPPT Power: 100 W
Improvement with Distributed MPPT: 24 %
Static Evaluation

75 percent shading of Section 3

Max Conventional Panel Power: 75 W
Max Distributed MPPT Power: 83 W
Improvement with Distributed MPPT: 11%

Power [W]

0 10 20 30 40 50 60 70 80 90

Current [A]

Panel Section 1
Panel Section 2
Panel Section 3
All Panel
With Distributed MPPT
Static Evaluation – No Shading

0 percent shading of Section 3

- Max Conventional Panel Power: 135 W
- Max Distributed MPPT Power: 132 W
- Improvement with Distributed MPPT: -2%


- Blue line: All Panel
- Green dots: With Distributed MPPT

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Instantaneous Power of PV Panel

- Conventional Panel
- With Distributed MPPT

Panel Output Power [W]

Time

11:00:00 EST, 12:00:00 EST, 13:00:00 EST, 14:00:00 EST, 15:00:00 EST

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Department of Electrical and Computer Engineering
Dynamic Evaluation

Accumulated Energy of PV Panel

- Conventional Panel
- With Distributed MPPT

Total Energy Conventional: 499.9 Wh
Total Energy Distributed MPPT: 601.6 Wh
Improvement with Distributed MPPT: 20.3%
Inverter Control

Instantaneous Power of PV Panel

![Graph showing the power output of a PV panel vs. panel current. The graph indicates a peak power output at a particular panel current.]
**Performance Evaluation**

Table 8.4: *DC-DC Optimizer Performance Comparison*

<table>
<thead>
<tr>
<th>Work Type</th>
<th>[71]</th>
<th>[70]</th>
<th>National</th>
<th>Azuray</th>
<th>This work</th>
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<tbody>
<tr>
<td>Topology</td>
<td>Academic</td>
<td>Academic</td>
<td>Commercial</td>
<td>Commercial</td>
<td>Academic</td>
</tr>
<tr>
<td>Topology</td>
<td>Buck-Boost</td>
<td>Boost</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Buck</td>
</tr>
<tr>
<td>Volume [cm³]</td>
<td>255 cm³</td>
<td>unknown (big)</td>
<td>680 cm³</td>
<td>740 cm³</td>
<td>12 cm³</td>
</tr>
<tr>
<td>Cost [$/W]</td>
<td>$20⁴</td>
<td>unknown (high)</td>
<td>$150</td>
<td>$90</td>
<td>$12.80</td>
</tr>
<tr>
<td>Power [W]</td>
<td>85 W</td>
<td>60 W</td>
<td>230 W</td>
<td>300 W</td>
<td>200 W</td>
</tr>
<tr>
<td>Cost/Power [$/W]</td>
<td>0.24 $/W</td>
<td>high</td>
<td>0.65 $/W</td>
<td>0.3 $/W</td>
<td>0.064 $/W</td>
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<tr>
<td>Efficiency [%]</td>
<td>95%</td>
<td>93%</td>
<td>98.5%</td>
<td>97.6%</td>
<td>98%</td>
</tr>
<tr>
<td>FOM [$/W]</td>
<td>5.22 $/W</td>
<td>7.81 $/W</td>
<td>4.07 $/W</td>
<td>0.50 $/W</td>
<td></td>
</tr>
</tbody>
</table>


- **Figure of Merit:** $ spent per additional Watt (average)
  - Assume 10% increase in energy capture by dc-dc optimizer
  - Assume additional 5% energy capture by sub-panel tracking
- **Typical cost of installed solar PV ~** $5/Watt ($8/Watt in 2009)
Current Work

- **Pursue Integration**
  - Lower cost
  - Higher efficiency (custom MOSFETs)
- **Reduce number of components**
  - One controller for many converters
- **Reduce size of components**
  - Phase-shifted operation
- **Improved Algorithms**
  - Intelligent bypass detection
- **Distributed control**
  - Work with existing inverters
    - Automatic global MPPT operation
    - No global controller
- **Diagnostics and Safety Benefits**
  - Communication without additional wires

**Lower Cost**

**Higher Efficiency**

**Added Functionality**
Conclusions

- Photovoltaic Intelligent Distributed Power Electronics
  - Low voltage connection
  - Higher efficiency
  - Smaller size
  - Lower cost

- Intelligent localized tracking
  - No local maximum problems
  - Inverter can operate at optimum point
  - Further testing to verify plug-and-play operation with conventional inverters

- Experimental results
  - Static testing shows improved energy capture
  - Dynamic testing illustrates potential gain in shaded situations
Questions?
Instantaneous Power of PV Panel

- Conventional Panel
- With Distributed MPPT
Accumulated Energy of PV Panel

- **Conventional Panel**
- **With Distributed MPPT**

<table>
<thead>
<tr>
<th>Time</th>
<th>Captured Energy [Wh]</th>
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<tr>
<td>13:05:00 EST</td>
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<tr>
<td>13:15:00 EST</td>
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<td>13:25:00 EST</td>
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<tr>
<td>15:15:00 EST</td>
<td></td>
</tr>
<tr>
<td>15:25:00 EST</td>
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</tr>
</tbody>
</table>

- Total Energy Conventional: 165.6 Wh
- Total Energy Distributed MPPT: 182.4 Wh
- Improvement with Distributed MPPT: 10.1%