Power Optimization and Monitoring in Photovoltaic Systems

Perry Tsao, Ph.D.

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Outline

• Photovoltaic (PV) System Basics
  – PV Cells and characteristics
  – Max Power Point Tracking (MPPT)
  – PV system mismatch
  – Power Electronics Architectures in PV Systems

• Power Optimizers
  – What is a power optimizer and how does it work?

• Monitoring systems
  – Why do I need a monitoring system? What could possibly go wrong?
Circuit model for a PV cell

Under normal operating conditions:

$I_L$ proportional to # of photons generating EHPs =>

$I_L$ proportional to irradiance ($W / m^2$)
PV Cell I-V Curve and P-V Curve

- I-V and P-V curves for multicrystalline PV cell under standard test conditions
- 1000 W/m², 27°C, air mass 1.5 (light spectrum)
Conventional Grid-tied PV array

- PV Cells connected in series in a panel
- PV panels connected in series strings
- Strings connected in parallel to inverter input
- Max power point tracking function implemented in inverter
Centralized Max Power Point Tracking

- Inverter adjusts input impedance to keep panels at peak power setpoints Vmp and Imp
- Sometimes it’s simple…

I-V and P-V curve for unshaded panels
Centralized Max Power Point Tracking

...sometimes it’s complicated

- Shading or other conditions can create multiple peaks in P-V curve

I-V and P-V curve for shaded and unshaded panels

Shading 15% of panel area reduces power by 33%
Shade in Residential Installations
Mismatch in a Commercial Installation

• Challenges:
  – Vent pipes
  – Orientation of modules due to roof curve

• Commercial installations often restricted in size because of shade and irregular roof shapes
Dust and Precipitate Soiling
“Flagpole” Example – Munich, Germany
Case Study – Impact of Shading

- 9 Photowatt PW1650 panels, multi-crystalline, 1.5kW
  - 72 cells per panel
  - 4 bypass diodes (1 for every 18 cells)
  - Connected to a SMA Sunny Boy SB1100 grid-tied inverter
- Tested in two configurations
  - Single string of 9 panels (1x9)
  - 3 strings of 3 panels each (3x3)

<table>
<thead>
<tr>
<th>Shade pattern</th>
<th>Shade</th>
<th>Power Loss- (1x9)</th>
<th>Power Loss- (3x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Shade pattern" /></td>
<td>0.15%</td>
<td>3.7%</td>
<td>1.7%</td>
</tr>
<tr>
<td><img src="image" alt="Shade pattern" /></td>
<td>2.6%</td>
<td>16.7%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Source: EFFECTS OF SHADOW ON A GRID CONNECTED PV SYSTEM
N. Chaintreuil, F. Barruel, X. Le Pivert, H. Buttin, J. Merten
### Case Study – Impact of Shading

<table>
<thead>
<tr>
<th>Shade pattern</th>
<th>Shade Area %</th>
<th>Power Loss- (1x9)</th>
<th>Power Loss- (3x3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Shade Pattern" /></td>
<td>13.9%</td>
<td>22.2%</td>
<td>36.8%</td>
</tr>
<tr>
<td><img src="image2" alt="Shade Pattern" /></td>
<td>11.1%</td>
<td>36.5%</td>
<td>30.5%</td>
</tr>
<tr>
<td><img src="image3" alt="Shade Pattern" /></td>
<td>12.5%</td>
<td>18.3%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Source: EFFECTS OF SHADOW ON A GRID CONNECTED PV SYSTEM
N. Chaintreuil, F. Barruel, X. Le Pivert, H. Buttin, J. Merten
How come shade affects power so much?

- Example: single string of 3 cells without bypass diodes

- Same current through each cell
- Small currents through diodes and $R_p$

$I_1 = 5A$

$I_2 = 5A$

$I_3 = 5A$

I-V curve for three cell string
How come shade affects power so much?

- **Example:** single string of 3 cells without bypass diodes

\[ I_d = I_1 - I_2 \]

- “Extra” current in unshaded cells flows through inherent diode

- **A single shaded cell reduces current and power for all cells in string**
Power Electronic Architectures for Grid-tied PV

Central inverter

String inverter

Panel inverter

MPPT

String Optimizer

Power Optimizer (Series)

Power Optimizer (Parallel)
SolarMagic™ Power Optimizers – SM1230

PV Module

PV Module

PV Module

PV Module

PV Module

MPPT

DC

AC
SolarMagic makes panel look like constant power source
SolarMagic String IV Curves

- SolarMagic makes a string of panels look like constant power source

String I-V

String P-V
SolarMagic makes a string of panels look like a constant power source... even when there is shade.

Use of SolarMagic increases power available.
SolarMagic: Single String Operation

Inverter Interaction

- SolarMagic Maintains Max Power Over Inverter Voltage Range

\[ P \]

Min

Inverter Voltage

Max

w/o SolarMagic

w/ SolarMagic

SolarMagic by National Semiconductor
Example

Before

1000W

200W

PV Panel

30V @ 6.7A

200W

PV Panel

30V @ 6.7A

200W

PV Panel

30V @ 6.7A

200W

PV Panel

30V @ 6.7A

565W

135W

PV Panel

35.5V @ 3.8A

135W

PV Panel

35.5V @ 3.8A

135W

PV Panel

35.5V @ 3.8A

25W

PV Panel

6.6V @ 3.8A

After

150V

150V

150V

0V

0V

1000W

200W

PV Panel

30V @ 6.7A

200W

PV Panel

30V @ 6.7A

200W

PV Panel

30V @ 6.7A

135W

PV Panel

35.5V @ 3.8A

135W

PV Panel

35.5V @ 3.8A

135W

PV Panel

35.5V @ 3.8A

25W

PV Panel

6.6V @ 3.8A
Example

Panel output = 30V @ 6.7A

Before

200W
PV Panel
SM
30V @ 6.7A

200W
PV Panel
SM
30V @ 6.7A

200W
PV Panel
SM
30V @ 6.7A

200W
PV Panel
SM
30V @ 6.7A

150V

Panel output = 27V @ 3.7A

After

200W
PV Panel
SM
33.3V @ 6A

200W
PV Panel
SM
33.3V @ 6A

200W
PV Panel
SM
33.3V @ 6A

200W
PV Panel
SM
33.3V @ 6A

100W
PV Panel
SM
16.7V @ 6A

0V

1000W

SolarMagic
by National Semiconductor

National Semiconductor
When to use power optimizers

- **Mismatches**
  - Shade
  - Aging
  - Dust / soiling / bird droppings
  - Different panel types
  - Clouds
  - Temperature variation across the array
  - Difference in reflected ambient light
  - Snow
  - Damaged panels
  - Difference in panel azimuth or tilt

- **Design flexibility**
  - Different string lengths
  - Different panel orientations

SolarMagic
by National Semiconductor
Different String Lengths

• When do you need it?
  – Multiple rooftops of different orientation and size

– Get more panels on your roof!
Different Orientations Within A String

**When do you need it?**

- Small rooftops where only one string is practical
  - Japan
  - San Francisco Row House
- Rooftops with obstacles
SolarMagic™ Power Optimization

- Power Optimizer
- SmartPanel
- String Optimizer

SolarMagic by National Semiconductor
PV System Monitoring

- Why do I need monitoring? What could possibly go wrong?
  - Bad connectors
  - Ground faults
  - Someone forgot to turn on the inverter
  - Weeds grow and create shade
  - Inverter failures
  - Blown fuses
  - Disconnected strings
  - Moss grows on your panels
  - Panel failure
  - Birds build a nest on your panels
  - Dirt accumulation
  - DC arc faults
  - Fires
  - Trees grow and create shade
  - Panels fall down
  - Theft
  - Wind damage
  - Rodent dig holes and throw dirt on panels
  - Rodents chew through wiring
  - Your neighbor puts up a flagpole
SolarMagic™ Monitoring

Weather Station

Internet

Solar Operations Center

Internet

String Manager

Smart Combiner

AC Meter

by National Semiconductor
SolarMagic™ Monitoring Portal

Weekly Power Overview:

- Power (kW)
- Chart showing power generation from Sat, 2010-01-09 to Fri, 2010-01-15
- Data points indicating solar power generated
SolarMagic™ Monitoring Portal

Daily Overview

<table>
<thead>
<tr>
<th>GENERATION METER</th>
<th>January 15th, 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Meter</td>
<td>#1348002</td>
</tr>
<tr>
<td>PV energy generated</td>
<td>451 kWh</td>
</tr>
<tr>
<td>PV tare losses</td>
<td>1000 Wh</td>
</tr>
<tr>
<td>Peak generation</td>
<td>89.8 kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENVIRONMENT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather Station</td>
<td>Air Temperature</td>
</tr>
<tr>
<td></td>
<td>46.9°F - 66.8°F</td>
</tr>
<tr>
<td>Weather Station</td>
<td>Cell Temperature</td>
</tr>
<tr>
<td></td>
<td>17°F - 49.3°F</td>
</tr>
<tr>
<td>Weather Station</td>
<td>Peak Irradiation</td>
</tr>
<tr>
<td></td>
<td>399 W/m²</td>
</tr>
<tr>
<td>Weather Station</td>
<td>Total Insolation</td>
</tr>
<tr>
<td></td>
<td>1.97 kWh/m²</td>
</tr>
<tr>
<td>Weather Station</td>
<td>Max Wind Speed</td>
</tr>
<tr>
<td></td>
<td>0.6 mph</td>
</tr>
</tbody>
</table>
## It Takes a Complete Solution for Maximum System Performance

<table>
<thead>
<tr>
<th>Power Optimization</th>
<th>Monitoring</th>
<th>Smart Management</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Random Performance</td>
</tr>
<tr>
<td>✓</td>
<td></td>
<td></td>
<td>Feel Good With Random Performance</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Predictable But not Optimal Performance</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>High Performance</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Maximum Assured Performance (ROI)</td>
</tr>
</tbody>
</table>

**Power Optimization** includes optimizing power use to ensure system efficiency.

**Monitoring** involves tracking system performance in real-time.

**Smart Management** ensures that the system adapts to changes and optimizes performance accordingly.

**Performance Levels**:
- **Random Performance**: Not predictable or optimal.
- **Feel Good With Random Performance**: A level of performance that meets basic needs.
- **Predictable But not Optimal Performance**: Performances that are predictable but not at their highest potential.
- **High Performance**: Performances that are consistent and reliable.
- **Maximum Assured Performance (ROI)**: The highest level of performance, ensuring maximum return on investment.
SolarMagic™ Product Portfolio

- Weather Station
- Power Optimizer
- Smart Panel
- Solar Operations Center
- Internet
- String Optimizer
- String Manager
- Smart Combiner
- AC Meter

SolarMagic by National Semiconductor
Thank you

Questions?

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For product info on Solarmagic™:
Visit solarmagic.com or
Email solarmagic.com