Smart Solar Energy for the Smart Grid

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Seminar at IEEE COMPEL; June 26, 2018
Outline

1. PV Basics and Problem Statement

2. Advances in Smart Solar PV’s:
   a) Smart Fault Detection
   b) Dynamic Reconfigurability
   c) Lego Solar Panels
   d) Modular Differential Power Processing

3. Conclusions

- Presenting research, with gratitude from many students and colleagues: D. Nguyen, Y. Zhao, P. Li, Y. Li, J. Huang, F. Khan, R. Balog,, S. Lu, S. Shu, L. Yuan, G. Spagnuolo, G. Petrone, C. Ramos Paja, Y. Zheng, B. Scandrett, Y. Zheng, C. Liu, D. Li, J.-F. De Palma, K. Kim, P. Krein, R. Pilawa-Podgurski, B. Scandrett, M. Gutierrez, and others…

- Funding from NSF, PowerFilm, Mersen, DOE (SunShot), US Army Natick, DOD, Arpa-e
What do you call a bear that uses renewable energy?

A Solar Bear
1. PV Basics and Problem Statement
Central Inverter: PV, power conversion unit, protection devices and utility grid.
Different approaches grid-connected inverters

a. Centralized technology.

b. String technology.

c. Multi-string technology.

d. AC-module

(DC optimizer technique not shown)

Newer Approach: Differential Power Processing

Voltage Bus

PV₁, PV₂, PV₃, PVₙ

DC/DC

DPP converter

Work by K. Kim, R. Pilawa-Podgurski, P. Krein, R. Balog, S. Qin, P. Shanoyand, D. Maksimovic, and others…
Do you agree?

• Many of the solar MPPT methods were designed 40 years ago and have not taken advantage of modern technological advances:
  • Computer/microprocessor revolution
  • Machine learning
  • Wireless communication
• PV installation hardwired and left alone until failure. What about expansion of the system?

How can we take advantage of the advances we have seen to create new approaches in PV systems??
2. Advances in Smart Solar Energy
Fire hazards in a 1,208kW PV array, in Mount Holly, North Carolina, in 2011.

Traditional Overcurrent Protection Devices (fuses) have “Blind Spots” in PV Systems with Centralized Inverters!!
Sometimes the MPPT makes it worse: moves operating point to lower current before the fuses melt


(See also work by F. Khan, J. Johnson, X. Wang, A. Etemadi, and others)
Fault at $t = T_1$ may be current limited in PV (low irradiance, line-line)

Oh No! MPPT reduced fault current so fast that fuses cannot clear fault!
Machine Learning in PV Strings

- Compare string currents to find faults
  - Fault detection using outlier rules at PC (Matlab GUI)
  - Real-time operation

Combiner box (Mersen): DSP fuses, Machine Learning
Statistic outlier detection rules

• Univariate variable \( \{x_i\}, i = 1,…,n, \quad x = \text{string current} \)

• \( x_i \) is an outlier if
  \[ |x_i - x_0| > \alpha \zeta \]

• Reference value \( x_0 \), a measure of variation \( \zeta \) and a threshold \( \alpha \)

• Upper bound \( x_0 + \alpha \zeta \) lower bound \( x_0 - \alpha \zeta \)


Statistic outlier detection rules

• Three sigma rule
  – Might be the best-known criterion, but poor performance in practice
  – Breaks down if CL >10%
    \[ |x_i - \mu| > 3\sigma \]

• Hampel identifier
  – Breaks down if CL >50%
    \[ |x_i - \tilde{x}| > \alpha S \]

• Boxplot rule
  – Breaks down if
    \[ x_i > x_U + 1.5Q \quad \text{or} \quad x_i < x_L - 1.5Q \]
    \[ Q = x_U - x_L \]

• Outlier rules are updated at each sampling time.

Sample mean
\[ \mu = \frac{1}{n} \sum_{i=1}^{n} x_i \]

Sample variance
\[ \hat{\sigma}^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \hat{\mu})^2 \]

where \( S = \frac{1}{0.6745} \) median \( \{ |x_i - \tilde{x}| \} \)

\( \tilde{x} \) is the sample median

\( x_L \) is lower quartile (25th percentile)
\( x_U \) is the upper quartile (75th percentile)
Photo of the experimental setup

Fault algorithm is running in a GUI at PC

- DC power supply
- DC electronic load
- Matlab GUI
- Power resistors
- GreenString in the combiner box
2. b) Dynamic Reconfiguration

Why keep all the wiring connections the same between the PV panels all the time?
**SMART PV PANEL**

- **Smart Solar Arrays**
  - Merge electronics to be inside the solar panel instead of in a separate room
  - Automatically adjusts to shadows and the environment by changing its interconnections
  - Senses, diagnoses, and alerts user of problems with the array (cracks, malfunctions, etc.)
  - Heals itself when solar cells degrade
  - Smart grid interaction
  - Optimum power output at all times

Slow Reconfigurable Panels

- Place switches between solar PV cells, strings, or arrays
- Switch between series and parallel connections in response to clouds or shadows
- **Increase the power output of the solar PV array**


- Fixed solar cells: $m \times n$
- Add $m \times 1$ reconfigurable solar cells

**When PV cells in fixed part are shaded or blocked, the PV cells in reconfigurable part will rearrange and connect to shaded rows.**

Shaded cell
2. c) Lego Solar Panels

Even Without Faults, Are There Benefits to Changing PV Connections?
“Solar Blanket”-Modularity

Y. Zheng, Y. Li, S. Sheng, B. Scandrett and B. Lehman (APEC 2016, 2017),
Introduction – modular solar panels

New challenges:
• Need to carefully design control to
  ➢ Shed power if producing too much power for load.
  ➢ Turn off MPPT if user connects to another MPPT

Submodule 1

Submodule n

Subpanel

PV Bus

DC-DC

Power management/
charger

Battery

Loads
System Operating Mode

Scenario I: Resistive load, $P_{\text{MPPT}} \leq P_{\text{load\_max}}$

Scenario II: Resistive load, $P_{\text{MPPT}} > P_{\text{load\_max}}$

Scenario III: Constant power load, $P_{\text{MPPT}} \leq P_{\text{load\_max}}$

Scenario IV: Constant power load, $P_{\text{MPPT}} > P_{\text{load\_max}}$

Y. Li, et al APEC 2016
System Operating Mode

Scenario I: Resistive load, $P_{MPPT} \leq P_{load\_max}$

- All PV subpanels are in individual MPPT mode
- The operating point would be the intersection (O) of load curve $R_{load}$ and power contour $P_{MPPT}$
- The operating point moves between $O_L$ and $O_H$ along the red straight line (solid), or between $O'_L$ and $O'_H$ along the blue curve with source/load changes
System Operating Mode

Scenario II: Resistive load, $P_{MPPT} > P_{load\_max}$

- Controller must shed power
  - Option 1: Do NOT have all modules in MPPT mode
  - Option 2: turn off power from individual PV module.
- The area shaded in the Figure represents the amount of shed power

When PPV is too high, the voltage might rise above threshold $V_H$. 

$P_{PV} = P_{load\_max}$
One Last Idea: What happens when we combine Lego (Modular) solar panels with Differential Power Processing
2. d) Modular Differential Power Processing (mDPP)

Voltage Bus

\[ V_{\text{cap}} \] is voltage difference between the string and the bus

\[ V_{\text{mpp}} = ?V \]
\[ I_{\text{mpp}} = 0A \]

C. Liu, D. Li, Y. Zheng and B. Lehman (2017, COMPEL) and (2018, APEC)
Advantage of modularity
Advantage of modularity

24V Voltage Bus

Plug out

7V  mDPP
6V  mDPP
5V  mDPP

8V

7V  mDPP
3V

5V  mDPP
2V
Advantage of modularity
Simulation results

3 PV panel in series
2 PV string in parallel
PV13 - voltage mismatch
PV 22 - current mismatch

<table>
<thead>
<tr>
<th></th>
<th>PV#11</th>
<th>PV#12</th>
<th>PV#13</th>
<th>PV#21</th>
<th>PV#22</th>
<th>PV#23</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal MPP (P)</td>
<td>13.23</td>
<td>12.3</td>
<td>10</td>
<td>12.59</td>
<td>6.13</td>
<td>12.81</td>
<td>67.06</td>
</tr>
<tr>
<td>Simulated Power with mDPP</td>
<td>13.23</td>
<td>12.3</td>
<td>10</td>
<td>12.58</td>
<td>6.13</td>
<td>12.81</td>
<td>67.05</td>
</tr>
</tbody>
</table>
Simulation results
• Comparison between Different Methods

<table>
<thead>
<tr>
<th></th>
<th>cMPPT</th>
<th>dMPPT</th>
<th>sDPP</th>
<th>sDPPcc</th>
<th>mDPP(ours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power ($P_{out}$ - Watts)</td>
<td>53.56</td>
<td>62.36</td>
<td>42.60</td>
<td>61.11</td>
<td>65.86</td>
</tr>
<tr>
<td>System Efficiency ($\eta_{sys}$ - %)</td>
<td>79.86%</td>
<td>92.99%</td>
<td>63.51%</td>
<td>91.11%</td>
<td>98.21%</td>
</tr>
</tbody>
</table>

\[ \eta_{sys} = \frac{P_{out}}{P_{ideal,max}} = \frac{P_{out}}{\sum_{i=1}^{6} P_{i,mpp}} \]

Harvest most power 98.21%

cMPPT: centralized MPPT converter- one converter for all PV panels
dMPPT: distributed MPPT converter- one converter for each PV panel [1]
sDPP: series DPP method [2]
sDPPcc: series DPP converter with centralized converter [3]

Experimental results

Up to 97.6% efficiency with 90% efficiency converter
1. Legacy approaches to operating PV arrays?

2. Hidden Faults in PV can now be discovered

3. Dynamic Reconfiguration is possible

4. Modular solar panels due to miniaturization and control in power electronics

5. Differential Power Processing might improve performance of Lego PVs