The Impact of Microinverters in Photovoltaic Systems

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Overview

Energy and PV Introduction
PV Module Characteristics

Understanding Installations

Inverter Hardware Design
Advanced Grid Controls
Enphase installations

Total Energy Generated By All Enphase Systems

47.4 GWh

>20,000 North American installations in 30 months
Energy and PV
Figure 1: Comparing finite and renewable planetary energy reserves (Terawatt-years). Total recoverable reserves are shown for the finite resources. Yearly potential is shown for the renewables (source: Perez & Perez, 2009a)
Photovoltaic Module Costs

Crystalline Si and Thin Film Module Learning Curves

- Historical Prices
- 1980: > $1 per kWh equivalent PV electricity cost
- 2007: $1.00/W @ <20 GW
- 2008: $1.00/W @ >100 GW

Note: Based on Module Purchase Price Not Manufactured Cost

Ken Zweibel/GWU

- http://solar.gwu.edu/
Photovoltaic Source

- **PV module** (not panel)
  - Translates light into electricity
  - Series connected *cells*

- Multiple types of cells
  - Crystalline Silicon (poly, mono)
  - Multi-juntion
  - CdTe, CdInGaS, GaAs

- Environmental Dependency
  - Temperature
  - Soiling
  - Age/Optical degradation

- Efficiency from 12-20%
- Changes in irradiance modify the IV characteristic
- Superposition of a string can lead to suboptimal curves, local maxima
Inverters and Installations
“Typical” Considerations

- System Cost
  - Single centralized inverter
  - Decentralized module-level inverters
  - Hybrid approach – dc-dc optimizers

- Residential – Primarily Rooftop
- Commercial – Rooftop and carpark
- Ground-mount Utility
The Other 50% of Solar Costs

Total Solar Installation Cost (%)

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Percentage</th>
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<tbody>
<tr>
<td>Balance of System</td>
<td>10%</td>
</tr>
<tr>
<td>Inverters</td>
<td>10%</td>
</tr>
<tr>
<td>Labor</td>
<td>30%</td>
</tr>
<tr>
<td>Modules</td>
<td>50%</td>
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</tbody>
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Source: Enphase Energy estimates

Microinverters are only 10% of the total system cost, yet affect BoS and labor costs more than any other component.
Central String Inverter
Central dc-dc Optimizer System
Microinverter System
Traditional Centralized/Hybrid Inverter

- DC Combiner Box
- Modules
- Centralized Inverter
- AC Disconnect
- Electrical Meter
- DC Disconnect

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Traditional Microinverter
Modules are controlled independently to maximize energy harvest
Increased Energy Harvest

Greater energy production means a better return on investment
System Availability Model

Central Architecture

Enphase Microinverter System

Enphase System Availability

>99.8%
Traditional Inverter vs. Microinverter Failure Rates

Westinghouse Solar (Residential)

<table>
<thead>
<tr>
<th></th>
<th>Traditional inverters</th>
<th>Microinverters</th>
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<tbody>
<tr>
<td>Installed</td>
<td>3,373</td>
<td>10,630</td>
</tr>
<tr>
<td>Replaced</td>
<td>318</td>
<td>22</td>
</tr>
</tbody>
</table>

*Source: Westinghouse Solar, March 2011*
**Standard Inverter Dangers**

**DC Arcs are Difficult to Suppress**

- No inherent detection of wire faults
- Disconnects may not interrupt fault path
- System cannot de-energize during daytime
NEC 2011 has changes that mandate detection of – and preventative measures for – series DC arc faults in systems where the DC voltage exceeds 80VDC.

690.11 Arc-Fault Circuit Protection (Direct Current)

Photovoltaic systems with dc source circuits, dc output circuits, or both, on or penetrating a building operating at a PV system maximum system voltage of 80 volts or greater, shall be protected by a listed (dc) arc-fault circuit interrupter, PV type, or other system components listed to provide equivalent protection.
Inverter Design Challenges
Inverter Design Challenges

- Single-phase Energy Storage
- Efficiency
- Reliability and Robustness
- Wide operating ranges
Inherent input/output power-flow mismatch
Bulk energy storage required at 120Hz
Microinverter CEC Test Data

Testing using the CEC or EN 50530 definitions
**Burst Mode**: High efficiency at low irradiance
Grid Standards / Compliance

Typical US Grid, 60Hz:
- Residential: 120V/240V
- Commercial: 120V/208V, 3 phase
- Industrial LV: 277/480V, 3 phase

Typical Euro Grid, 50Hz:
- Residential: 230V, single phase
- Commercial/Industrial LV: 230V/400V 3 phase

Safety:
- NEC
- UL 1741

Interconnection:
- IEEE 1547
- FERC 661

EMI:
- CFR 47 Part 15

Surge testing:
- ANSI C62.41
AC Grid Realities

▪ It's nasty:
  ▪ Voltage surges of >1000 V from indirect lightning strikes
  ▪ Tap changes, misplaced zero crossings, dc offset
  ▪ Distortion, double zero crossings
▪ Surviving it everyday and in all cases is very, very difficult
Design Challenges

- From a dc-dc perspective:
  - Wide input voltage range: 20-40 Vdc
  - Wide output voltage range: 0-340Vdc (+/-)
  - Wide power range: 0-200 W
  - Large energy storage requirement
  - Additional monitoring functions:

- DC Side Functions:
  - Maximum peak power tracking (speed and accuracy are important)
  - DC voltage and current reporting
  - Arc-fault detection

- AC Side Functions
  - Grid synchronization
  - Voltage and Frequency (out of range thresholds)
  - Anti Islanding (AI) checks
Some Conversion Topologies
Some Conversion Topologies

P. Krein and R. Balog
Some Conversion Topologies

B. Pierquet, D. Perreault
One Power Conversion Topology
Inside the box...
Review of Advantages

Productive
Harvests more energy

Reliable
No single point of failure, high reliability electronics

Smart
Allows for full system monitoring and analysis
No string calculation, regular AC wiring
Lowers installation time

Safe
No high voltage DC: DC faults cannot lead to fires
No lethal power source present when AC is shutdown
Challenges

Very difficult product to get right

- Efficiency
- Cost
- Reliability
- Lifetime
- Robustness
- Ease of use
- Compliance to standards
- Communication
- Packaging
- etc.
Advanced Grid Controls
(brief)
Advanced Grid Controls

- New Islanding behavior
- VAR injection
- Power slew based on frequency / voltage
- Spinning reserve emulation / Transient compensation
- All bring stability and jurisdiction issues.
- Under discussion and very controlled trials

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<td>Voltage</td>
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<td>Phase</td>
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Conclusion
Some Example
Installation Photos
Roof-mount in Hawaii
Tracker Mount (Concentrated PV), Colorado
Commercial Rooftop, Colorado
Residential “Ground mount”
Energy Production

Past Month: 151kWh, Lifetime: 1.78MWh (Since 7/15/11), Peak: 34kWh/day