Grid-interactive Solar Inverters and Their Impact on Power System Safety and Quality

Dr. Anil Tuladhar
Jan 16, 2008
Objectives

• Introduction to PV Solar Industry.
• Grid Interactive Solar Inverter Design.
• Impact on Grid Safety.
• Impact on Grid Quality.
• Site Installations.
• Challenges.
• Future Developments.
• Conclusions.
PV Solar Industry

• Why PV Solar?
  – Abundantly available.
  – Benign in Nature.
  – Favorable programs and policies (rebates/tax credits, RPSs/Renewable goals and NM/IC guidelines) are being implemented by the states as well as the federal government.
Why PV Solar?

• Abundantly Available¹

¹Source: http://www.apricus.com/html/insolation_levels_usa.htm

1kWh = 3412 Btu = 3.6MJ = 859.8kcal

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<table>
<thead>
<tr>
<th>Month</th>
<th>AK Anchorage 61° 10’ N 150’ 1” W</th>
<th>AZ Phoenix 33° 26’ N 112’ 1” W</th>
<th>MI Detroit 42° 25’ N 83’ 1” W</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>12</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
Why PV Solar?

• Abundantly Available\(^1\)
  
  – Sunlight striking the earth for 40 minutes equivalent to global energy consumption for a year.
  
  – The US has 250,000 square miles of land in southwest alone that receives 4,500 quadrillion BTU of solar radiation/year.

\(^1\)Source: Scientific American, Jan 2008 issue

1kWh = 3412 Btu = 3.6MJ = 859.8kcal
Why PV Solar?

• Abundantly Available\(^1\)
  
  – Only some 30,000 square miles of photovoltaic arrays would have to be erected to generate 3000 GW of power.
  
  – Land required to produce each GW of power from solar less than that needed for a coal-powered plant when factoring in land for coal mining.

\(^1\)Source: Scientific American, Jan 2008 issue

\(^1\)kWh = 3412 Btu = 3.6MJ = 859.8kcal
Why PV Solar?

• Benign in Nature

  – Negligible CO$_2$ footprint.
  – No moving parts. No noise.
  – No water consumption.
  – No emissions.
  – Less geographical restrictions.
Why PV Solar?

- Rebates and Incentives.

  California is offering $2.50/W for residential solar installation upfront. The residential systems also get 30% of the cost or $2000 federal tax credit which ever is smaller. The governmental installations and non-profit organizations get $3.25/W upfront. The tax credit of 30% is NOT limited to $2000 for non-residential systems. Systems bigger than 100 kW get performance based rebate.

Please visit: http://www.gosolarcalifornia.ca.gov/csi/performance_based.html for more details.
Why PV Solar?

Renewables Portfolio Standards

**State RPS**
- Minimum solar or customer-sited RE requirement
- *Increased credit for solar or customer-sited RE

**State Goal**
- PA: 8% Tier I / 10% Tier II (includes non-renewables)

**Solar water heating eligible**

- HI: 20% by 2020
- TX: 5,880 MW by 2015
- CA: 20% by 2010
- AZ: 15% by 2025
- NM: 20% by 2020 (IOUs)
- MT: 15% by 2015
- ND: 10% by 2015
- WI: requirement varies by utility; 10% by 2015 goal
- IA: 105 MW
- MN: 25% by 2025 (Xcel: 30% by 2020)
- WI: RE meets load growth by 2012
- VT: RE meets load growth by 2012
- ME: 30% by 2000
  - 10% by 2017 - new RE
- NH: 23.8% in 2025
- MA: 4% by 2009 + 1% annual increase
- RI: 16% by 2020
- CT: 23% by 2020
- NY: 24% by 2013
- NJ: 22.5% by 2021
- PA: 18% by 2020
- MD: 9.5% in 2022
- *DE: 20% by 2019
- DC: 11% by 2022
- *VA: 12% by 2022

- OR: 25% by 2025 (large utilities)
- 5% - 10% by 2025 (smaller utilities)
- *WA: 15% by 2020
- *NV: 20% by 2015
- CO: 20% by 2020 (IOUs)
- *10% by 2020 (co-ops & large munis)
- NC: 12.5% by 2021 (IOUs)
- 10% by 2018 (co-ops & munis)
- MA: 4% by 2009 + 1% annual increase
- NH: 23.8% in 2025
- WI: RE meets load growth by 2012
- VT: RE meets load growth by 2012
- ME: 30% by 2000
  - 10% by 2017 - new RE
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DSIRE: www.dsireusa.org

September 2007
# Why PV Solar?

## Figure 1.1 PV Module Efficiency Status and Forecast (% DC Efficiencies for Production Modules)

<table>
<thead>
<tr>
<th>Cell Technology</th>
<th>2006</th>
<th>2010*</th>
<th>2015*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocrystalline Silicon</td>
<td>14–19</td>
<td>16-22</td>
<td>22-25</td>
</tr>
<tr>
<td>Multicrystalline Silicon Cast Ingot</td>
<td>13–17</td>
<td>16-18</td>
<td>20+</td>
</tr>
<tr>
<td>Crystalline-Based Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a-Si/ Monocrystalline slice (HIT)</td>
<td>16–18</td>
<td>18-20</td>
<td>22-24</td>
</tr>
<tr>
<td>Ribbon/ Sheet Silicon</td>
<td>14–16</td>
<td>16-18</td>
<td>20+</td>
</tr>
<tr>
<td>Concentrators Silicon Cell / III-V Cell</td>
<td>24 / 36</td>
<td>26 / 37</td>
<td>28 / 38</td>
</tr>
<tr>
<td>Non-Crystalline Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amorphous Silicon (a-Si)</td>
<td>6-8</td>
<td>9-10</td>
<td>12</td>
</tr>
<tr>
<td>Silicon Film</td>
<td>10</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Non-Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Indium (G) Diselenide (CIS/ CIGS)</td>
<td>8–11</td>
<td>10-12</td>
<td>14</td>
</tr>
<tr>
<td>Cadmium Telluride (CdTe)</td>
<td>9–10</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

*Forecast by Paul Maycock of PV Energy Systems

Source: PV Technology, Performance, and Cost 2007 Update
Produced by Prometheus Institute for Sustainable Development and PV Energy Systems
## Why PV Solar?

### Figure 1.2: Module Manufacturing Costs and Profitable Price Forecast (2006 US$)

<table>
<thead>
<tr>
<th>Cell Technology</th>
<th>2006</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost/Price ($)</td>
<td>Cost/Price ($)</td>
<td>Cost/Price ($)</td>
</tr>
<tr>
<td>Crystalline Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocrystalline Silicon</td>
<td>2.50/3.75</td>
<td>2.00/2.50</td>
<td>1.40/2.20</td>
</tr>
<tr>
<td>Multicrystalline Silicon Cast Ingot</td>
<td>2.40/3.55</td>
<td>1.75/2.20</td>
<td>1.20/2.00</td>
</tr>
<tr>
<td>Crystalline-Based Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ribbon/Sheet Silicon</td>
<td>2.00/3.35</td>
<td>1.60/2.20</td>
<td>1.00/1.70</td>
</tr>
<tr>
<td>Concentrators Silicon Cell</td>
<td>3.00/5.00</td>
<td>1.50/2.50</td>
<td>1.00/1.70</td>
</tr>
<tr>
<td>Non-Crystalline Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amorphous Silicon (a-Si)</td>
<td>1.50/2.50</td>
<td>1.25/1.75</td>
<td>0.90/1.40</td>
</tr>
<tr>
<td>Non-Silicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Indium (G) Diselenide (CIS/ CIGS)</td>
<td>1.50/2.50</td>
<td>1.00/1.75</td>
<td>0.80/1.33</td>
</tr>
<tr>
<td>Cadmium Telluride (CdTe)</td>
<td>1.50/2.50</td>
<td>0.80/1.50</td>
<td>0.65/1.25</td>
</tr>
<tr>
<td>Factory Profitable Price</td>
<td>2.50 – 3.75</td>
<td>1.50 – 2.50</td>
<td>1.25 – 2.20</td>
</tr>
</tbody>
</table>

Source: PV Technology, Performance, and Cost 2007 Update
Produced by Prometheus Institute for Sustainable Development and PV Energy Systems
Solar Inverter Design

• Electrical Requirements
  – The design of solar inverter starts with specifying the electrical requirements.

• Thermal Requirements.
  – In order to handle the harsh outdoor operating environment, thermal system shall be designed properly.

• PV Specific Control and Protection Functions.
  – In order to meet the NEC and UL requirements, many PV related control and protection functions shall be included in the design.

• Testing
  – Elaborate Testing is required to UL list the product.
Solar Inverter Design

- PV Array and Combiner Box
- DC Disconnect
- Inverter Controller
- Inverter Core
- Cooling System
- Line Filter
- EMC Filter
- Fused AC Disconnect
- Output Contactor
- Efficient Shielded Isolation Transformer
- GRID
Solar Inverter Design

• Electrical Requirements
  – DC input voltage range (e.g. 250V to 600V)
  – AC output voltage (e.g. 120V, 208V, or 480V)
  – Number of phases (1 ph, split ph or 3 ph)
  – Frequency (50Hz or 60Hz)
  – Output Power (e.g. 100kW)
  – Output current (e.g. 95 A)
  – Voltage Total Harmonic Distortion (e.g. < 2%)
  – Current Total Demand Distortion (e.g. < 5%)
  – Overall efficiency (e.g. > 95%)
Solar Inverter Design

• Thermal Requirements
  – The inverter system and components shall not attain a temperature at any operating condition so as to result in risk of overheating, fire, or insulation damage.
  – Junction temperature of switching devices shall be maintained below maximum allowed value (e.g. 120 C).
  – Solar inverters are generally installed outdoor so shall handle extreme temperature conditions like –40 C to 50 C.
  – Solar power is not generated uniformly throughout the day so the cooling system does not have to be turned ON all the time. A power output based cooling system control shall be designed to improve the efficiency.
Solar Inverter Design

• PV Specific Performance Requirements
  – Auto-Wakeup.
  – Maximum Power Point Tracking.
  – DC Bus Over Voltage handling
  – DC Bus Over Current handling
  – Optimum Efficiency operation.
  – Outdoor condition design. Wide ambient temperature range and AC DC surge protection.
  – Design to perform well under rapid cloud movement.
  – Remote monitoring.
  – Monitoring Weather parameters (humidity, wind velocity, insolation level, and temperature) desirable.
PV Specific Controls/Protections

• Auto wake up

  – The PV inverter shall be able to wake up when the available power is more than the total loss of the inverter system.
  – Pre-mature wake up will cause negative power flow from the grid thus hampers the energy production.
  – Delayed wake up also hampers the energy production.
  – Since the available power changes with weather condition, the wake up algorithm has to be adaptive in nature.
PV Specific Controls/Protections

- Maximum Power Point Tracking
- IV / Power characteristics of a 170 W Sharp polycrystalline panel.
PV Specific Controls/Protections

• Maximum Power Point Tracking

  – The peculiar IV curve causes the available power to change as a function of the output voltage/current.
  – The tangent on the IV curve represents the power.
  – Power curve has a distinct maximum power point for a given IV curve.
  – The IV curve changes as the insolation level changes.
  – Temperature of the PV cell also changes the characteristic curves (not shown in the previous diagram).
  – The maximum available power changes as the day progresses.
  – The control algorithm in the inverter shall track the maximum power point to fully utilize the solar panel capacity.
PV Specific Controls/Protections

• Desired features of an MPPT algorithm

  – MPPT shall be fast enough to increase the energy extraction by following the insolation level closely but not too fast to cause the instability.
  – Tracking along the left slope of the power curve is not stable so should be avoided.
  – MPPT shall take the grid voltage into account while tracking lower. If DC bus voltage drops too low but grid voltage is higher, the quality of the current to the grid will suffer.
  – MPPT shall not find and lock to a local maxima. It shall sweep the whole IV curve and find the global maxima.
PV Specific Controls/Protections

• DC bus Over Voltage Protection
  – In very cold condition, failure of grid and solar enhancement can cause DC Over Voltage condition.
  – When DC bus exceeds the designed maximum voltage (e.g. 600V), the inverter shall shutdown and array shall be disconnected from the DC bus to protect the DC bus Capacitors, Disconnects and Wire Insulations.
PV Specific Controls/Protections

• DC Bus Over Current Protection

  – Can be caused by too low DC bus voltage, higher AC grid voltage transient, and enhanced solar condition.
  – Or due to some hardware failure/short circuit in DC bus circuitry or wrong DC bus connection.
  – Or due to sudden in-rush current to the DC bus capacitor (connecting the array already generating the voltage).

The inverter shall be shutdown and isolated from the grid as well as the PV array when the over current condition occurs.
PV Specific Controls/Protections

• Reverse DC Bus Protection
  – Inverter shall be able to identify the reverse polarity of the DC connection and warn the installer and remain in sleep state.
  – Reverse voltage can potentially damage the capacitors and can also cause excessive current in the DC circuit.
PV Specific Controls/Protections

• Ground Fault
  – For a grounded system, the ground fault occurs when DC terminal of PV array touches the chassis. Current flows through the ground to the negative terminal first then goes to the positive through the PV cells.
  – The current sensor on the wire between the negative and the ground terminal will pick up the fault.
  – Inverter shall shutdown and disconnect itself from the grid as well as the PV array as soon as the ground fault is detected.
  – The ground fault current shall be interrupted.
PV Specific Controls/Protections

• Ground Fault
PV Specific Controls/Protections

• Remote Monitoring

  – The PV inverters are generally installed in not-so-convenient places. It is therefore desirable to have a capability to find out the status of the unit remotely.
  – Monitoring power, power factor, energy, currents, and voltages over days, weeks, months and years help us extract useful economic information.
  – Remote monitoring also help diagnose the problem by furnishing the information around the event.
Impact on Grid Safety

– Possible Islanding Operation.
– Single Phase Open.
– AC Over voltage condition.
– AC Under voltage condition.
– Over frequency condition.
– Under frequency condition.
– AC Over current condition.
– Short circuit condition.
Impact on Grid Safety

- Anti-Islanding Control and Protection
Impact on Grid Safety

- Anti-Islanding Control and Protection
  - In Grid Link mode of operation, when the output power of the inverter matches with the total load on the grid, the failing of grid does not create any change in voltage or frequency. The inverter continues to support the load.
  - This condition is not safe. It is mandatory for power exporting inverters to detect grid failure and stop exporting power to the grid within 2 seconds (UL 1741/IEEE1547).
Impact on Grid Safety

• Anti-Islanding Control and Protection
  – There are two types of anti-islanding control techniques:
    • Passive
      – The voltage and/or the frequency change during the grid failure is measured and employs a positive feedback loop to push the voltage and/or the frequency further away from its nominal value.
      – Frequency or voltage may not change if the load matches very well with the inverter output or the load has a very high quality factor (reactive to real power ratio).
      – So there exists some Non Detection Zone (NDZ).
    • Active
      – Injects some error in frequency or voltage.
      – When grid fails the error accumulates and pushes the voltage and/or frequency beyond the acceptable range.
      – Ballard Power System has developed and patented a couple of active anti-islanding techniques to overcome the NDZ (See U.S. Patent No. 6,853,940 and 7,106,564)
Impact on Grid Safety

• Anti-Islanding Control and Protection
  – According to UL1741/IEEE1547, inverters shall stop exporting power to the grid within 2 seconds of grid failure.
  – The voltage and/or frequency drift cause over/under voltage/frequency fault and inverter shuts down.
  – UL listing of the product requires an elaborate test setup to verify the anti-islanding and abnormal voltage/frequency detection capabilities.
Impact on Grid Safety

• Grid Over/Under Voltage/Frequency Protection
  – The following table shows the trip points and trip times as per IEEE1547:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Trip Point and Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over Voltage1 fault</td>
<td>&gt; 110% for &gt; 1 second</td>
</tr>
<tr>
<td>Over Voltage2 fault</td>
<td>&gt; 120% for &gt; 160 ms</td>
</tr>
<tr>
<td>Under Voltage1 Fault</td>
<td>&lt; 88% for &gt; 2 seconds</td>
</tr>
<tr>
<td>Under Voltage2 Fault</td>
<td>&lt; 50% for &gt; 160 ms</td>
</tr>
<tr>
<td>Over Frequency fault</td>
<td>&gt; 60.5 for &gt; 160 ms</td>
</tr>
<tr>
<td>Under Frequency fault</td>
<td>&lt; 59.3 for &gt; (160 to 300000) ms</td>
</tr>
<tr>
<td>Under Frequency fault</td>
<td>&lt; 57.0 for &gt; 160 ms</td>
</tr>
</tbody>
</table>
Impact on Grid Safety

• AC Over Current Detection and Protection
  – Grid Transients or grid faults can cause over current condition.
  – Fault in transformer or line filter can also cause over current condition.
  – Faulty switching devices can cause dead short circuit.

Over current fault shall shutdown the unit and disconnect from the grid.
Impact on Grid Safety

• Single Phase Open Detection

  – Loss of any phase of the grid shall be detected and the inverter shall be shutdown to avoid possible safety hazard.
  – Loss of a phase can be detected by using current sensors on each phase.
  – If the output transformer is external to the inverter, the single phase open shall be detected on both sides of the transformer.
  – New requirement needs the single phase open to be detected at 5% of the full load or above the minimum current level.
Impact on Grid Quality

• Synchronization (IEEE1547)

<table>
<thead>
<tr>
<th>Aggregate Rating of DR Units (kVA)</th>
<th>Frequency Difference (Δf, Hz)</th>
<th>Voltage Difference (ΔV, %)</th>
<th>Phase Angle Difference (ΔΦ, °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 500</td>
<td>0.3</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>&gt; 500 - 1,500</td>
<td>0.2</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>&gt; 1,500 - 10,000</td>
<td>0.1</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

Inverter shall not close the contactor if the phase or frequency error exceeds these limits.
Impact on Grid Quality

- AC Current Harmonics (IEEE 1547 limits)

<table>
<thead>
<tr>
<th>Table 3. Maximum Harmonic Current Distortion in Percent of Current* (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual Harmonic Order h (Odd Harmonics)*</td>
</tr>
<tr>
<td>Percent (%)</td>
</tr>
</tbody>
</table>

(a) I = the greater of the Local EPS maximum load current integrated demand (15 or 30 min) without the DR unit, or the DR unit rated current capacity (transformed to the PCC when a transformer exists between the DR unit and the PCC).

(b) Even harmonics are limited to 25% of the odd harmonic limits above.

- Flicker shall not cause irritation to humans or cause equipment mis-operations.
Impact on Grid Quality

• DC injection (IEEE 1547 limits)
  – Shall not exceed 0.5% of the full rated output current at the point of Distributed Resource (DR) connection.
UL Listing

• Testing for UL Listing
  – Normal Safety Related Tests
  – Abnormal Safety Related Tests
  – Performance Related Tests
Testing for UL Listing

• Normal Safety Related Tests
  – Hardware
    • Dielectric Test.
    • Maximum Continuous Rating Test.
    • Thermal Stress Test.
    • Rain test.
    • Over Current Test.
    • DC Bus Over Voltage Test.
    • EMC Test.
Testing for UL Listing

• Normal Safety Related Tests
  – Software
    • Anti_Islanding Test
    • Over/Under Voltage/Frequency Test
    • Over Current Test
    • DC Bus Over Voltage Test
    • Ground Fault Test
Testing for UL Listing

• Abnormal Safety Related Tests
  – Output Overloading Test.
  – Short Circuit Test.
  – Single Phase Open Test.
  – DC Reverse Polarity Test.
  – Component Short and Open Test.
  – Ventilation Test.
Testing for UL Listing

• Performance Related Tests
  – Software
    • Voltage and Current Harmonics Test
    • Thermal De-rating Test
    • Power Limiting Test
    • MPPT Tracking Test
      – Accuracy
      – Response time
    • Wakeup Strategy Test
Site Commissioning

- Grounding shall be done properly.
- AC and DC disconnects shall be placed near by the inverter.
- PV capacity shall be closely matched with the inverter capacity.
Site Commissioning
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Site Commissioning
Challenges

• Thermal Management.
• Robust performance (right wake up voltage calculation, riding through grid disturbances, finding the global maximum power point on a shaded or dirty PV panels).
• Achieving the targeted inverter price of $0.25-$0.3 per W by 2020.
• Achieving an inverter life time > 15 years.
Future Developments

- AC modules (Micro-inverters).
- Innovative topologies (e.g. multiple inverters in parallel) to get more power, more reliability and more efficiency.
- Transformer-less design to improve cost, weight, and efficiency. Regulation has to change in many countries to allow the transformer-less design.
- Development of Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screening would help improve inverter quality and reliability.
- Use of new components (e.g. film capacitors instead of electrolytic capacitors) to prolong the life.
- Reducing the component count to lower the cost and enhance the reliability.
- Hybrid PV systems with energy storage options (Compressed air or pumped hydro).
- Micro grids for better grid quality and reliability.
Conclusions

- Design innovation in inverter topology is imperative to improve efficiency, cost, reliability and life.

- Innovation in manufacturing and testing side is also needed to improve the quality of the inverter.

- More research needed to develop advanced robust control techniques to improve inverter performance, to reduce the inverter downtime and to eliminate costly sensors.
Q&A

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