Sandia’s Systems Approach to Photovoltaic Reliability

PV Systems Integrator Workshop
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Presentation Outline

• Why System Reliability?
• Some of the basics
• Increase detail and complexity
• Summary
Diverse Users/Stakeholders Pose Challenges

How do you align these?
Some Considerations

• Reliability is the probability of simultaneously satisfying:
  – The performance requirement
  – In a specified environment
  – At a particular time

• Reliability takes into account service life (expected lifetime)

• Quality is defined as creating a product suitable for the intended purpose, and doing it consistently.

• Failure definition can be inconsistent--user dependent--causing difficult to attain reliability objectives
Sandia’s Systems Approach to PV System Reliability

- System: all components used to convert sunlight to electricity and deliver it to the grid in a usable form; adhering to all safety and grid quality requirements.
- Identify system reliability requirements; apply these to development of components as early as possible
- Comprehensive reliability plan requires:
  - Data
  - Methodologies
  - Tools
  - Models
Why is a Systems Approach Needed?

• Reliable components alone do not deliver reliable power
• Reliable systems can deliver reliable power in well understood applications and environments
• Supply chain is getting increasingly diverse; e.g. CEP
• Increasingly sophisticated components/systems; e.g. CPV
• Designs, materials, and technologies are getting increasingly diverse
• Increasingly numerous stake-holders making system reliability a much more complex target
  – Utilities
  – States
  – System owners
  – PPA brokers
  – Underwriters
  – Etc.
Complex PV Systems Deployed in Complex Markets

Sandia’s PV Program Takes a Comprehensive Approach

- Cross Cutting Issues
  - Metrology
    - Data Precision & Limiting Uncertainty
  - Data Format and Transmission
  - Data Pooling

- Technical Blocks
  - Minimum Monitoring Specification
    - Issues of Remote Monitoring & Web Based Systems
  - Array
  - Inverter
  - Storage
  - Additional Generator / Hybrid Systems
  - Power Quality
  - Multi-User Systems
  - Building Integration / Building Energy Balances
  - Climate
    - Advanced Climatic Inputs (GIS, satellite, etc.)

- Non-Technical Blocks
  - User Satisfaction & Performance Perception
  - Maintenance
  - Revenues & Data for Energy Markets
  - CO2 Avoidance & Green Certificates
  - Financing
  - PPA’s

Tendency of rising complexity
Sandia Program Elements

- Reliability
  - Predictive Modeling
  - Real-Time Studies
  - Accelerated Testing and Failure Modes Effects and Analysis
  - Technology Transfer and Codes & Standards
- System Modeling and Analysis
- System Grid Integration
- Test & Evaluation (System, Inverter, BOS, Modules)
- Market Transformation

Adapt Common Tools --Focus on Adoption--Minimize Cost
Presentation Outline

• Why System Reliability?
• Some of the basics
  ❖ Define system and its functional operation; define components and their functional operation
  ❖ Define failure modes
• Increase detail and complexity

Boundary Diagrams
Codes & Standards
FMEA’s
Baseline Performance
RBD’s
Real-time Data
Long-term exposure
Failure Analysis
Mitigation
Accelerated Tests
Predictive Modeling
Factors that influence how reliability is addressed

We divide factors into three categories:

– Performance is the primary factor

– Economics enters the picture as we consider the cost of reliability measures vs. cost of unreliability

– Social factors are driven primarily by bureaucratic and/or aesthetics factors
We use Boundary Diagrams to Define Types of Inter-Relationships that Affect Reliability
Physical/Mechanical Interactions

Tracker Controller and Drive

Array

Sub-Structure

Environment

Physical/Mechanical Interactions
Tracker Controller and Drive

Data Acquisition System

Met System

Inverter

Array

DC BOS

AC BOS

Distribution grid

Data, Control, and Communication Interactions
EFFECTIVE FMEA PROCESS

Planning Stage

1A. Develop & Execute FMEA Strategic Plan
1B. Develop & Execute FMEA Resource Plan

Performing FMEAs Stage

2. Develop Generic FMEAs (Optional) (Xfmea)
3. Develop Program-Specific FMEAs (Xfmea)

Program A
Program B

Review Stage

4. Management Review
5. FMEA Quality Audits
6. Supplier FMEAs

Implementation Stage

7. Execute Actions to Reduce/Eliminate Risk
8. Linkage to Other Processes

Integrated Software Support
Inverter FMEA

Cause-effect diagram shows possible failure modes

**System**

**Failure**

**Effect**

**Cause**

1.1 - Open circuit
- 1.1.1 - Loose screw
- 1.1.2 - Broken wire
- 1.1.3 - Failed solder joint
- 1.1.4 - Corrosion
- 1.2.1.1 - Loose screw
- 1.2.1.2 - Broken wire

1.2 - Intermittent contact
- 1.2.1 - Inverter stops operating
- 1.2.1.1 - Dirty AC power
- 1.2.1.2 - Broken wire

1.3 - Short circuit
- 1.3 - Allow high voltage spike through

1.4 - Arcing (maybe should be moved to lower level)
- 1.4.1 - Heating
- 1.4.2 - Damage to electrical components

1.1 - Doesn't disconnect
- 1.1.1 - Dirty AC power

1.1.1 - No output power
- 1.2.1 - Temporary power interruption
- 1.3.1 - Trip Branch Breaker
- 1.3.2 - Heating (high impedance short). Melt conductor.
- 1.4.1 - Heating
- 1.4.2 - Damage to electrical components

1.1.1 - Damaged to other components
- 1.1.2 - Blow fuse

1.1.1 - Loss of output power
- 3.32.37 - Capacitors
- 3.32.38 - Inductors

1.2 - Catastrophic failure
- 3.33.34 - Grid sensors

1.1 - Safety - direct contact with grid
- 1.1.1 - Personnel safety concern

2.1.1 - Fire, electrical failure
- 3.30 - Connection terminal block
- 3.31 - Surge suppression
- 3.32 - Filter components
- 3.33 - Control circuitry
- 3.35 - Disconnect (isolation) switch
- 3.36 - Grid isolation switch (automatic)
- 3.39 - Fuse block

3 - AC output

System Component
OxS (occurrence X severity) plots (pareto) help to focus attention on critical aspects of the system

**Project:** Crystalline Silicon Device

**Causes Ranked by Initial Occ x Sev (1 - 25)**

1: Oi x Si = 20 (4 x 5) - corrosion (Item: 14 - Frame)
2: Oi x Si = 20 (4 x 5) - improper installation (wrong metals, poor processes) (Item: 14 - Frame)
3: Oi x Si = 15 (5 x 3) - One or more cracked cells (Item: 3 - Cell Strings)
4: Oi x Si = 12 (4 x 3) - Increased series resistance due to solder joint degradation & or failure at gridline interface (Item: 3 - Cell Strings)
5: Oi x Si = 12 (4 x 3) - Fatigue due to thermal cycling (Item: 3 - Cell Strings)
6: Oi x Si = 12 (3 x 4) - improper use / installation (Item: 9 - Junction Box)
7: Oi x Si = 12 (3 x 4) - improper installation (Item: 14 - Frame)
8: Oi x Si = 10 (2 x 5) - Cracked cell (Item: 3.7 - Solar Cell)
9: Oi x Si = 10 (2 x 5) - Solder bond failure (Item: 3 - Cell Strings)
10: Oi x Si = 9 (3 x 3) - Decreased power in a single cell (Item: 3 - Cell Strings)
11: Oi x Si = 9 (3 x 3) - open circuit (Item: 9.10 - Bypass Diodes)
12: Oi x Si = 9 (3 x 3) - Delamination from glass (loss of optical coupling) (Item: 2 - EVA (Front))
13: Oi x Si = 8 (2 x 4) - moisture uptake by EVA (Item: 2 - EVA (Front))
Presentation Outline

• Why System Reliability?
• Some of the basics
  • Increase detail and complexity
    - Develop data resources
    - Develop methodologies
    - Share information/data, tools and processes
• Summary

Codes & Standards
FMEA’s
Baseline Performance
RBD’s
Real-time Data
Long-term exposure
Failure Analysis
Mitigation
Accelerated Tests
Predictive Modeling
Some Current Activities/Recommendations

1. Develop a **reliability model** of the system
2. Use reliability block diagrams (**RBD’s**) to describe relationships (series, parallel, etc)
3. Collect component and subsystem **field data**
4. Collect component and subsystem **lab based (ALT)** data
5. Adjust data to fit environmental/operational constraints and conditions (natural and man-made environment)
6. Use **stochastic and deterministic methodologies** to predict reliability
7. Verify and/or adjust prediction through field data
PV Reliability O&M Database

- Database used as a repository for field data: PVROM
- Standardized method for collecting and maintaining O&M data
- Web-based: user friendly
- Secure/Proprietary
- Data directly exported to predictive model tools
- Initially populated with legacy TEP data; others are adopting
- More partners are being sought
System Long Term Exposure Tests

Objective: Determine system degradation rates through controlled exposure tests in varied environments

- System configurations assure real life effects
- Tests being initiated in hot/dry, hot/humid, and cold climates
- Subset of modules subjected to lab level baseline tests
- Exposure tests subjected to quarterly inspections and semi-annual performance tests
- Maintain control modules indoors
- Minimize measurement errors
System Level Model/RBD

Blocks have lower level reliability models

Analysis of failure data rolls up for system reliability.

Analysis of repair and maintenance data rolls up for system availability.

Maintenance resources and associated costs can be tracked and critical inventory anticipated for planning purposes.
PV150 Inverter

Controller → Interlock → Design → Internal → Matrix → Solid State relay

Environmental

Software

Grid Effects

Other

Inverter Failure Events

Relay failure

Weeds too high

Wrong voltage limits

Lightning outage

Insects short PWB

Rodents chewing insulation

This type of field experience is impetus for conducting Inverter level FMEA’s
Photovoltaic Reliability and Availability Model (PVRAM)

- Model predicts for any component and any level of the system: 
  - degradation vs time--**reliability** vs time--**availability** vs time

<table>
<thead>
<tr>
<th>Component</th>
<th>Actual Number of Failures 5 yr Cum</th>
<th>Expected Number of Failures 5 yr Cum</th>
<th>Expected Number of Failures 10 yr Cum</th>
<th>Expected Number of Failures 20 yr Cum</th>
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<tbody>
<tr>
<td>PV 150 Inverter (26 cSi arrays)</td>
<td>125</td>
<td>132</td>
<td>231*</td>
<td>429*</td>
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<tr>
<td>PV Module</td>
<td>29</td>
<td>26</td>
<td>31</td>
<td>38</td>
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<td>AC Disconnect</td>
<td>22</td>
<td>17</td>
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<td>Lightning</td>
<td>16</td>
<td>10</td>
<td>20</td>
<td>41</td>
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<tr>
<td>Transformer</td>
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<td>3</td>
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<td>Row Box</td>
<td>34</td>
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<td>Marshalling Box</td>
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<td>4</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>480VAC/34.5KV Xformer</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

- Model prediction is accurate at 5 years
- Predictions for 10 and 20 years need additional data
- Model is being exercised by running sensitivity analyses
How would system reliability change by doubling inverter lifetime?

- **Real field data** (limited amounts, always more data needed)
- Viewing reliability of each component within a system shows “weakest links” – opportunities for improvements and R&D efforts
- Model the changes in availability or cost if improvements are made to one of the weak links – how LCOE is affected? Do changes produce ROI?
- Allows for trade-offs: Accept O&M costs for replacing less reliable inverter vs. cost of more reliable inverter and reduced O&M
How do I improve my module design?

- Design of Experiment methods drive Accelerated Lifetime Testing
- ALT allows lifetime determination; reduces uncertainty
- **R&D or process improvement** opportunities identified
- Module manufacturers benefit from *module improvement, warranty predictions*
- More data needed!
Reliability Methodologies With Industry Partner—a Success Story

- Teamed with module manufacturer to demonstrate Sandia’s reliability tools
- Created FMEA in a team environment; specific issues to manufacturer’s process identified

Accelerated tests developed to quantify failure risk

Sorensen et al., *The Effect of Metal Foil Tape Degradation on the Long Term Reliability of PV Modules*, 34th IEEE PVSC

Next steps:
- Long term exposure tests at array level
- Baseline performance; degradation
- Modules/coupons for ALT validation
- Apply diagnostics as needed
- Reliability model
- Incorporate ALT results into RBD model
Summary: Major Themes in Sandia’s Program

• Define reliability needs; some needs vary with application and customer (residential, commercial, utility), industry segment (integrators, manufacturers, financiers, etc.), technology, and stakeholder.

• Reliability database of fielded system failure modes, failure rates, degradation rates and O&M costs to be used to create predictive model(s)
  – data needs to be protected from disclosure and potential misuse

• Fielded system reliability and accelerated aging evaluation needed
  – for predictive models and correlations between lab and field tests

• Safety-related failures are high priority; risk of injury and industry liability/reputation

• Improve existing tests, increase use of best practices/methodologies for reliability and accelerated aging tests, and expanded applications of the information derived from lab and field evaluations