System Reliability for Utility PV Inverters

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Abstract

The availability of a PV plant is highly dependent upon the system reliability of the inverter. Systems engineering for PV inverters is accomplished by first performing top down design-for-reliability (DfR) principles including fault tree analysis & reliability prediction methods which result in subsystem reliability allocations. A critical aspect for the design of PV inverters is the ability to simulate both performance as well as environment thereby gaining an understanding for the subsystem and component stress state. Physical testing of the simulation results are accomplished by usage of advanced power supply equipment with the capability to provide both DC and AC performance conditions which represent large scale PV arrays and grid interactions.

Systems reliability analysis provides a basis for subsystem and component technology choices and development. One example of the linkage between simulation and test is applied to the critical inverter subsystem consisting of the IGBT switching subsystem. Simulations and testing to the required performance envelop and environment of operation results in component choices, subsystem design, derating strategies and required cooling methods.

Qualification of inverter reliability is attained by envelope performance testing at environmental extremes to provide for manufacturing burn-in profiles. Durability tests such as system level accelerated life testing (ALT) and component & subsystem highly accelerated life testing (HALT) are key tools to qualify the reliability of new designs. Environmental testing of inverter equipment is performed to ensure that the system availability is maintained over a long lifetime at temperature and humidity variations.

A key aspect for understanding inverter fault modes and the design of efficient maintenance & repair methods is the ability to data mine fielded inverter operation at the component, subsystem, and system level. For that reason, the attainment of high availability is tied to real-time site data acquisition for inverter operational conditions and subsystem states. Actual field performance is fed back into lifetime models used during qualification testing as well as prediction and simulation criteria. Reliability growth is attained by improvements found during prediction, simulation, qualification testing, and field experience.
Methodology - Reliability Assurance Milestones During Inverter Product Lifecycle

- AE uses a closed loop reliability process
- Design for Reliability
  - MTBF, DFMEA, Fault Tree
- Reliability Test
  - ALT, HALT, Thermal, Environmental
- Qualification Test
  - Power profile, efficiency, harmonics, waveform, modulation, control loop, compliance, WCSA, limits, control & communication, burn-in development
Inverter Reliability Assurance Program

• Design for Reliability (DfR) Focus Areas
  ➢ Modularity; Improves reliability, repair, test, and manufacturing
  ➢ Derating; Component and subassembly derating to reduce operating stress
  ➢ Temperature Management; Achievement of reduced operating temperatures
  ➢ Predictive Methods – MTBF, DFMEA, Fault Tree Assessments

• Reliability Test
  ➢ Verification of potential causes based upon DFMEA
    • Subassembly ALT, Thermal, Thermal Cycle
    • Environmental Testing – Temp/Humidity, Salt Fog
    • HALT
    • System Level ALT

• Experience; Reliability Growth
  ➢ Product lifecycle learning experiences into design
    • Improvements based upon assurance testing and field experience
Design-for-Reliability; Reliability Calculation

- MTBF calculation with software (Such a Windchill) using failure rate libraries (MIL-HDBK-217, Telecordia)
- Provides an understanding for the comparative reliability of different configurations
- Also useful for observing how the reliability is related to cooling efficiency and component stress
- Should not be used as a primary method to predict the actual failure rate

Reliability calculation assesses performance during constant failure rate region
Design-for-Reliability; DFMEA Example

- Team Oriented
- Structured Method, Early Evaluation of Design, Controls to Reduce Risk
- Design FMEA; Detailed, Functional, Interfaces
- RPN Scoring; Severity x Occurrence x Detection

### Design Failure Mode and Effect and Analysis

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Item Function [Item]</th>
<th>Potential Failure Mode</th>
<th>Potential Effect(s) of Failure</th>
<th>Potential Cause(s)/Mechanism(s) of Failure</th>
<th>Current Design Controls Prevention</th>
<th>Severity</th>
<th>Occurrence</th>
<th>Detection</th>
<th>RPN</th>
<th>Recommended Action(s)</th>
<th>Responsibility &amp; Target Completion Date</th>
<th>Action Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subsystem 1</td>
<td>Overheating</td>
<td>Loss of Power</td>
<td>Thermal, Current Derating</td>
<td>DFMEA, Derating, Fault Tree</td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>128</td>
<td>ALT; Fault Tree Analysis</td>
<td>Pwr Eng, Rel Eng, Test Eng</td>
<td>2 2 2 8</td>
</tr>
</tbody>
</table>

FMEA Number: INVERTER 1
System: INVERTER
Item: Design Responsibility: System Engineer
P/N: Updated Date: DFMEA Date (Orig.) 2/25/14 (Rev) 1
Core Team: System Eng, Firmware Eng, Power Eng, Mechanical Eng, Quality Eng, Reliability Eng, Manufacturing Eng, Test Eng, Project Mgr
Design-for-Reliability; Fault Tree Analysis Applied to Utility Inverters

Fault Tree

Logic Symbols

Top Event

Failure Rate of Subassemblies; Effects of Fault Tolerance

Example of Maintainability Importance with Modularity Improvement

Graph showing system unavailability over repair time with and without redundancy.
1000NX Modular Design

- DC Cabinet
- Magnetics Cabinet
- Inverter Cabinet
- Cooling Cabinet
- Control Cabinet
- AC Cabinet
Performance Testing – Solar Simulation

- AE has installed programmable supplies to perform solar simulation testing
- Example of NREL test profile demonstrated with 1000NX
- Example of actual site irradiance data programmed for test
Accelerated Life Test (ALT) – Temperature Acceleration

- Durability tests such as system level accelerated life testing (ALT) and component & subsystem highly accelerated life testing (HALT) are key tools to qualify the reliability of new designs.

- The most common temperature acceleration factor AF(T) is based upon the Arrhenius model:
  - $K_b$ is the Boltzmann's constant, $T_o$ is the initial ambient temperature in °K, $T$ is the life test temperature in °K, and $E_a$ is the activation energy in eV.

\[
\lambda \propto \frac{\text{Failures}}{\text{(Total Device Hours} \times \text{AF(T)})}
\]

\[
\text{AF(T)} = \exp\left[\frac{E_a}{K_b}(1/T_o - 1/T)\right]
\]

ALT is a gage of the inverter durability to reach end-of-life failure rate region.
Life Test Profile Example; System Level ALT

AC Power

Temperature

Time = 10 HOURS

Repeat Cycle

System Environmental Chamber

System Level Life Test

Unit Life Test

Subsystem Life Test

480VAC
Service

Active Rectifier

Inverter

440VAC
Auto Transformer

Isolation Transformer

ELEVATED TEMPERATURE FACILITY

System Power Supply

Filter

WATLOW
Thermal Qualification – Efficient Cooling Design

• Meet thermal challenges in desert solar site environments

• Thermal characterization has exhibited thermal margins for long lifetime
  ➢ Reliability Rule of Thumb: For every 10degC decrease in temperature, the equipment lifetime is doubled

• Detailed thermal mapping is completed at all operation envelopes

1000NX Installed in Desert

1000NX Tested in Thermal Chamber
Utility Inverter Qualification for a Wide Range of Environments

- Cold
- Moisture
- Indoors
- Desert
- Humidity
- Office Park
- Agricultural
System Level Burn-In for Utility Inverters

- Burn-in testing takes place at the unit level to stress the components for a designated period time to precipitate component early lifetime mortality - Temperature and Voltage Acceleration Factors

- The burn-in cycle contains voltage and power cycling which is done to ensure that power connections such as the bolted-joint assemblies are robust as well as to test low power electrical connector interfaces

Weibull statistics are accumulated to assess the burn-in cycle

Production Burn-In reduces the number of failures in the early (decreasing failure rate) lifetime region

The Bathtub Curve
Hypothetical Failure Rate versus Time

- Infant Mortality
- Decreasing Failure Rate
- Normal Life (Useful Life)
- Low "Constant" Failure Rate
- End of Life Wear-Out
- Increasing Failure Rate
Inverter Data Monitoring

Example of 1000NX data monitoring – There are 50 performance variables that are constantly monitored

• The attainment of high availability is tied to real-time site data acquisition for inverter operational conditions and subsystem states. Actual field performance is fed back into lifetime models used during qualification testing as well as prediction and simulation criteria.
Conclusion; High Inverter Availability

- Availability is the most important attribute for utility inverters

- High availability is achieved by
  - Design-for-Reliability
  - Design-for-Maintenance
  - Reliability Growth
    - Assurance testing and design improvements
    - Field experience with design improvements

\[
\text{Availability} = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}}
\]