# Accelerated Testing of Grid-Tied Photovoltaic Inverters

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# Outline

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- Worst Case Temperature Environment and Stress Equivalent Temperature
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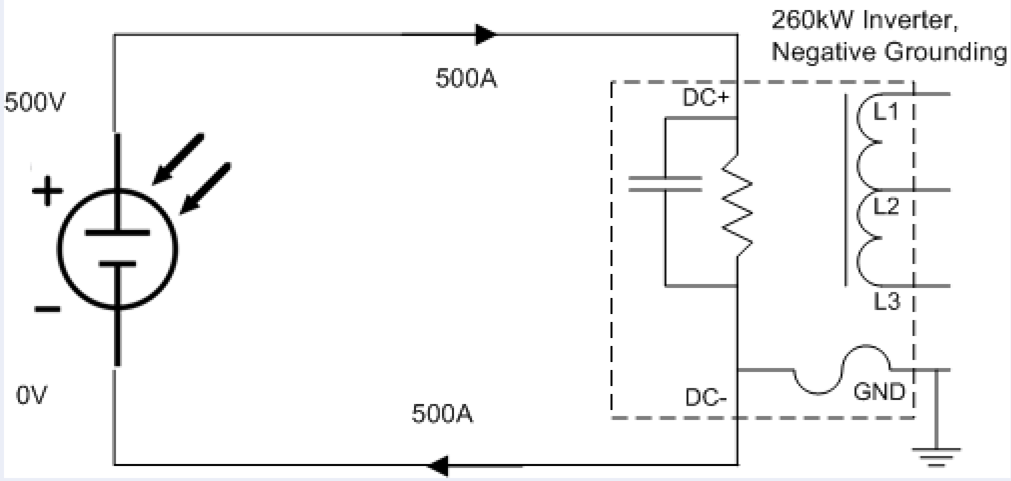
# OVERVIEW OF PV INVERTERS AND ACCELERATED TESTING CONSIDERATIONS

# PV Inverters Description

PV inverters convert DC power from PV panels to AC power.



Some inverters use active cooling, and others passive.

# PV Inverters: Typical Exposure

- PV inverters are typically exposed to the environment on a concrete pad uncovered or on the sides of homes.
- They typically cool at night to near ambient temperatures and heat during the day to a maximum temperature that is many tens of degC above ambient, so low cycle thermal fatigue must be evaluated.

# Failure Modes and Stresses

Main failure modes and causal stresses for PV inverters:

- Mechanical Wear-Out (temperature; voltage; current; number of cycles)
- Chemical Degradation, Diffusion, and Electromigration (high temperature; voltage; current)
- Low Cycle Thermal Fatigue (temperature swings)
- Corrosion (moisture; contamination; voltage; current)
- High Cycle Mechanical Fatigue (vibration mainly during shipping)

For temperature-related failure modes, rough acceleration factors can be calculated and used as a basis for accelerated life testing. For other failure modes, standard reliability tests can be used.

# Commercial PV Inverter Testing: Additional Considerations

In planning accelerated stress testing of commercial PV inverters, the following are important to consider:

1. Commercial inverters can be very large (~4000 lb for a 250kW inverter).
2. Test samples of commercial inverters can cost over $75k.
3. Commercial inverters have active cooling systems (air and/or liquid).

Testing equipment of this class typically involves small sample sizes. Approaches that are useful in this case are:

1. Subsystem-level stress testing
2. Integrated testing with test-to-failure; repair; restart; …
3. Step stress testing to failure

Standards exist (e.g. IEC 62093 and IPC-9592) but are not necessarily practical for large commercial inverters with active cooling systems that operate on a cyclic basis.

# Commercial PV Inverter Testing: Approach

1. Initial Integrated Accelerated Life Test (1.5 lifetimes)
   1. Start with a nominal accelerated test profile which is calculated with appropriate life-stress relationships to simulate 1.5 lifetimes in a worst case environment.
   2. Upon failure, repair and restart test.
   3. Implement corrective action for failures.
2. Opportunistic HALT
   1. After completion of the nominal accelerated test, increase the stress or test time as economics allow.
   2. Upon failure, repair and restart all tests.
   3. Implement corrective action for failures.

# Integrated Accelerated Tests for Commercial Inverters

| Failure Mode | Tests |
|---|---|
| Mechanical Wear-Out | Integrated Power Cycling |
| Chemical Degradation; Diffusion; Electromigration | High Temperature Operating Life Test |
| Low Cycle Thermal Fatigue | Temperature Cycling Test |
| Corrosion | Damp Heat |
| High Cycle Mechanical Fatigue | Transportation Vibration |

# WORST CASE TEMPERATURE ENVIRONMENT

# AND

# STRESS EQUIVALENT TEMPERATURE

# Worst Case Temperature Environments

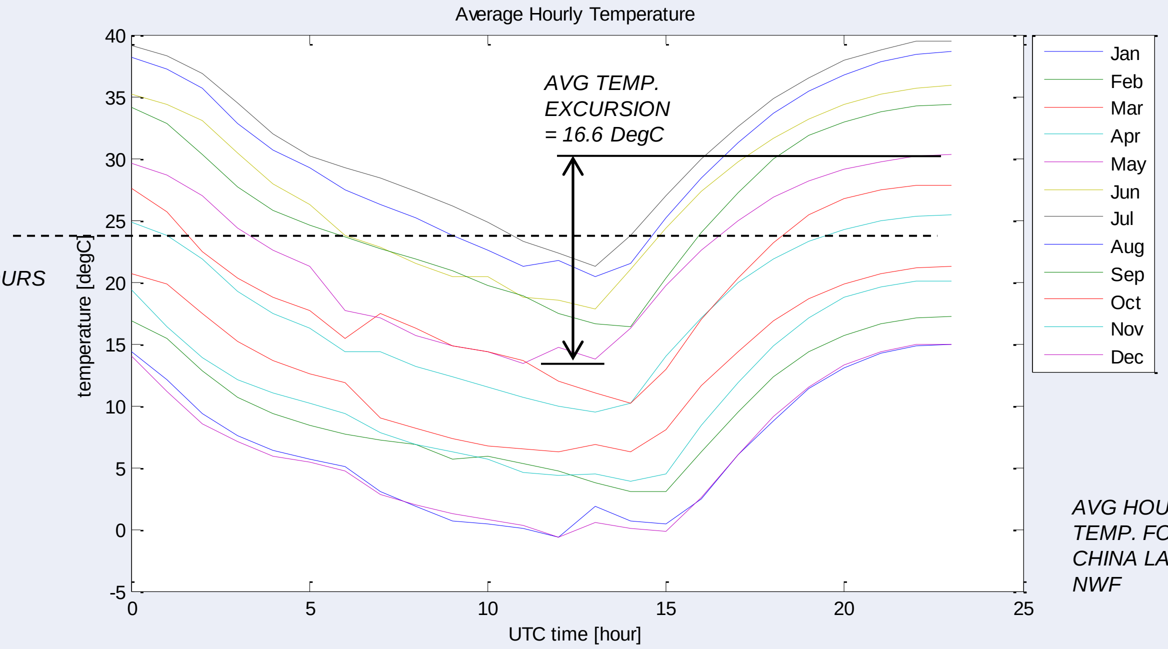
- A survey of local weather data was performed in search of temperatures that represent a worst case thermal environment
- Two stresses were considered: High Temperature and Thermal Cycling
- Site selected with worst combination of temperature stresses: CHINA LAKE NAVAL AIR WARFARE CTR.

| Location | Avg. Temp. (degC) | Avg. Temp. Excur. (DegC) | Min Avg. Low Temp. (degC) | Max. Avg. High Temp. (degC) | Max. Temp. Excur. (degC) | Stress Eq. Temp. (degC) | Stress Eq. Temp. Excur. (degC) |
|---|---|---|---|---|---|---|---|
| Bishop | 18.9 | 17.7 | -3.2 | 35.6 | 21.2 | 25.1 | 18.9 |
| China_Lake_NWF | 23.1 | 16.6 | -0.6 | 39.5 | 18.2 | 29.0 | 17.2 |
| Daggett | 24.1 | 13.7 | 3.3 | 39.2 | 15.8 | 29.4 | 14.4 |
| Needles | 27.4 | 11.8 | 7.5 | 42.7 | 13.8 | 32.7 | 12.5 |
| Phoenix | 26.7 | 11.2 | 7.6 | 40.2 | 12.9 | 31.3 | 11.8 |
| Redmond | 12.9 | 13.0 | -2.7 | 29.1 | 19.7 | 19.0 | 15.3 |
| San_Diego | 18.6 | 4.7 | 10.4 | 23.4 | 7.1 | 19.4 | 5.5 |
| San_Jose | 17.9 | 9.2 | 7.0 | 26.1 | 11.1 | 20.0 | 9.8 |
| Twentynine_Palms | 23.6 | 12.7 | 4.1 | 38.2 | 14.0 | 28.8 | 13.2 |
| Yuma | 27.1 | 11.8 | 9.0 | 41.0 | 14.0 | 31.5 | 12.6 |

# Average Temperature Exposure

Ideally, reliability should be calculated by considering the changes in temperature throughout each day of the year (time-dependent reliability modeling). But this is not very practical with most mainstream modeling tools, which typically assume constant temperature exposure over the lifetime of the part.

*Average temperature and average temperature excursion may be obtained from NOAA data. But average temperatures do not necessarily translate to average stress.*



*AVG TEMP. DURING DAYLIGHT HOURS = 23.1 DegC*

*AVG TEMP. EXCURSION = 16.6 DegC*

*AVG HOURLY TEMP. FOR CHINA LAKE NWF*

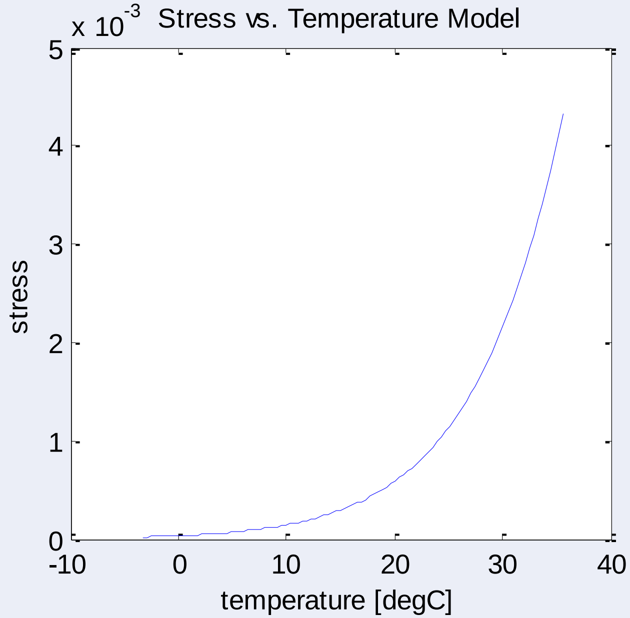
Mike Fife

# Stress-Equivalent Temperature

The stress on electronic components is known to vary nonlinearly with temperature. To take this nonlinear behavior into account, stress-equivalent temperature ($T_{seq}$) may be calculated, which is the <u>constant temperature that will produce the same cumulative stress that the time-varying temperature profile does</u>:

$$CS = S(T_{seq})Y = \int_0^Y S(T(t))\,dt$$

$$= \int_0^Y \int_{-\infty}^{\infty} G(T, T_{avg}(t), \sigma_T(t))\,S(T)\,dT\,dt$$



Where

S = stress (Ahrrenius model w/Ae = 1.0)
Y = one year of operation time
G = Gaussian probability distribution
$T_{avg}$ = hourly average temperature
$\sigma_T$ = standard deviation of hourly temperature

Depending upon the physics of failure, Ae can vary.

# Stress-Equivalent Temperature Excursion

Stress-equivalent temperature excursion can be approximated as:

$$\Delta T_{seq} = \Delta T_{avg} + 0.35(\Delta T_{max} - \Delta T_{avg})$$

Where the constant 0.35 is consistent with the preceding stress averaged temperature results.

This approximation is reasonable, especially since the difference between maximum and average temperature excursion is small (~3 degC typically).

# Application to Inverter Subsystems

One approach to defining a worst case constant temperature stress for inverter subsystems is to use the worst case stress equivalent ambient temperatures and add component temperature rise (over ambient) from thermal testing.  Component stress equivalent temperatures can be estimated from time-dependent thermal modeling of the inverter, or by thermal testing:

| **Part/Subsystem** | **Temp. Rise (degC)** | **Stress-Eq. Temp (DegC)** | **Stress-Eq. Temp. Excursion (DegC)** |
|---|---|---|---|
| Ambient | **0.0** | 29.0 | 17.2 |
| Electronics_Enclosure | 9.6 | 38.4 | 26.8 |
| Card_Cage | 9.6 | 38.4 | 26.8 |
| DSP | 17.2 | 45.7 | 34.4 |
| CPLD | 18.4 | 46.9 | 35.6 |
| DC Converters | 17.4 | 45.9 | 34.6 |
| Gate_Drive_Board | 19.8 | 48.3 | 37.0 |
| DC_Bus_Caps | 17.4 | 45.9 | 34.6 |
| DC_Power_Supply | 3.9 | 32.8 | 21.1 |
| AC_Panel | 12.3 | 41.0 | 29.5 |
| DC_Panel | 15.7 | 44.3 | 32.9 |
| Magnetics_Enclosure | 17.1 | 45.6 | 34.3 |
| Inductor | 53.8 | 81.4 | 71.0 |
| Transformer | 34.2 | 62.3 | 51.4 |

(Temperature rise measured at nominal blower speed.)

We now have the worst case baseline constant temperature condition (AF = 1) for the inverter components.

# INITIAL ACCELERATED LIFE TEST EXAMPLE
# (1.5 LIFETIMES)

# Power Cycling

|  |  |
|---|---|
| Failure Modes: | Mechanical Wear-Out of Contactors and Other Components |
| Expected (AF=1): | 10 cycles per day (worst case)<br>30 year simulated lifetime<br>109,500 cycles |
| Accelerated Test (AF=288): | 2 cycles per minute = 2880 cycles per day<br>109,500 cycles<br>Test time = 38 days |
| Test Procedure / Conditions: | 1. Start inverter and ramp to full power<br>2. Shut down inverter on fault<br>3. Repeat until failure of for 109,500 cycles |

# High Temperature Operating Life

| | |
|---|---|
| Failure Modes: | Chemical degradation; diffusion; electromigration |
| Expected (AF=1): | Lifetime = 30 yr (105,000 op. hr at 3500 op. hr. per year)<br>Stress-Equivalent Temperatures: Various (depends on component). Estimate from time-dependent thermal modeling or from thermal testing at nominal blower speed. |
| Accelerated Test (AF=132): | Lifetime Equivalent Test Time = 2000 hr (83 days)<br>$T_{\text{IGBT junction}}$ = 150±5 degC<br>$T_{\text{PCAs}}$= 97±2 degC<br>$T_{\text{transformer}}$ = 164±5 degC<br>$T_{\text{ambient}}$ = 67±5 degC |
| Test Procedure / Conditions: | 1. Full Power; Maximum DC and AC voltage<br>2. Test to failure |

# Thermal Cycling

| | |
|---|---|
| Failure Modes: | Thermal Fatigue |
| Expected (AF=1): | Lifetime = 10,950 cycles (30 yrs at 1 cycle per day)<br>Stress-Equivalent Temperature Excursion: Various (depends on component). Estimate from time-dependent thermal modeling or from thermal testing at nominal blower speed. |
| Accelerated Test (AF = 66): | Test Cycles = 1000 cycles<br>6 cycles per day -> 167 days<br>$\Delta T_{\text{IGBT case}}$ = (varies depending upon manufacturer)<br>$\Delta T_{\text{PCAs}}$= -40 to 75 degC (similar $\Delta T$ to IPC 9701A) |
| Test Procedure / Conditions: | 1. Install drive assembly in environmental chamber<br>2. Cycle on PCA temperature control<br>3. Adjust Inverter power to achieve IGBT temperature excursion |

# Damp Heat

| | |
|---|---|
| Failure Modes: | Corrosion |
| Expected (AF=1): | Lifetime = 30 yr.<br>Temperature and humidity and corrosive conditions are highly variable based on location |
| Accelerated Test (AF=263): | Test to failure/repair/retest for 1000 hours (see IEC 62093)<br>T = 85 degC<br>RH = 85% |

# Transportation Vibration

| | |
|---|---|
| Failure Modes: | High Cycle Mechanical Fatigue |
| Expected (AF=1): | Various – highly dependent upon transport mode, distance, and road conditions |
| Accelerated Test Options: | High Cost Option: test to standards<br>(e.g. ASTM D999 or IEC 62093)<br>Low Cost Option: ship multiple samples rough ride and inspect |

# SUMMARY

# Commercial Inverter Integrated Accelerated Stress Test Plan

Proposed test plan involves

1. Initial Accelerated Life Testing (1.5 Lifetimes)
2. Opportunistic HALT

Example of an Initial Accelerated Test Plan (1.5-Lifetimes):

| **Test** | **Conditions** |
|---|---|
| Mechanical Wear-Out | Full power start-up and shutdown for 109,500 cycles |
| High Temperature Operating Life | $T_{ambient}$ = 67±5 degC; other component temperature requirements for 2000 hr |
| Temperature Cycling | 1000 cycles (PCAs and drive assembly)<br>$\Delta T_{PCAs}$= -40 to 75 degC |
| Damp Heat | 1000 hr (PCAs and drive assembly)<br>85 degC, 85% RH |
| Transportation Vibration | ASTM D999 or IEC 62093 (high cost)<br>Ship multiple samples rough ride and inspect (low cost) |