Using Reliability Modeling and Accelerated Life Testing to Estimate Solar Inverter Useful Life

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SUMMARY & CONCLUSIONS

Three-phase inverters are physically large, complex and expensive elements of major solar power generation systems. The inverter converts DC power created by the photovoltaic (PV) panels to AC power suitable for adding to the power grid.

The inverters’ reliability testing is a complex task and relies on reliability block diagrams (RBD), vendor and field data, plus selecting accelerated life tests (ALT) based on critical elements of the product.

This paper illustrates a case study that developed an RBD, used field and vendor data, and includes the design and use of two ALTs. The result is a working framework or model that provides a reasonable estimate of the expected lifetime performance of the inverter. While any project similar to this, is always a work in progress, the examination of the decisions and inputs for the model proves valuable for the continued improvement of the model and resulting life predictions. This project provides an excellent real life example of reliability estimation having a multitude of constraints including: sample size, test duration, and field data, thus having to rely on all sources of available data starting from field and vendor data to theoretical component reliability calculations, ALT plan execution, failure analysis, and finally summarizing the results using RBD to estimate product expected lifetime. At the time of writing this paper, based on completion of system level ALT, an availability of 99.97% is valid over a 10 year period according to southern Ontario weather as the main installation base. This will be revisited once subsystem ALT is completed.

1 INTRODUCTION

With the rising cost of energy and strive for finding alternative energy sources, the last decade has witnessed a boom in the photovoltaic industry along with other alternative energy technologies. Market competition in this field has driven the industry towards higher product quality and longer warranty. Over the last decade warranty period for solar inverters has increased from 5 to 10 years and very recently to 20 years. During the product development cycle, it is quite challenging to estimate useful life of the product to optimize warranty costs. Additionally, planning accelerated life testing on a large three-phase Solar Inverter system can be quite complex and expensive.

This paper will discuss an approach that Schneider Electric has taken based on reliability modeling and accelerated life testing to estimate a solar inverter’s useful life in order to minimize warranty costs for large three-phase solar inverters. Since useful life is measured based on product availability, the goal is to achieve an availability of 99.5% or higher over a 10 year warranty period. This work was divided into four phases: 1) Establish the RBD for the system and calculate theoretical Availability, 2) Select an optimized list of subsystem blocks and system to perform ALT and study long term effect of environment in practice, 3) Design ALTs for subsystems and system level, 4) Based on ALT test results update RBD to estimate availability after 10 years.

This paper is a case study for estimating the reliability of large three-phase solar inverter systems using theoretical and field data combined with an optimized ALT plan execution.

2 ESTABLISH SYSTEM RELIABILITY BLOCK DIAGRAM

As part of phase 1, reliability block diagram was established to determine current reliability of the system based on existing information.

Figure 1. Solar inverter System Reliability Block Diagram

The structure of the model is essentially a series system and reflects the n-out-of-k redundancy of the DC buss capacitors. The remaining elements are all essential for the operation of the unit. There are a few elements that are not critical for the operation, yet do require replacement or repair relatively quickly for continued safe operation of the equipment. These elements are included in the series model.

Based on the gathered reliability information, we have a mix of distributions describing the data. Therefore, we used Weibull distribution for critical parts as described in Section 3.2 in order to make closer reliability estimations, and used exponential for the remaining parts. The existing reliability information include predictions based on characteristic life (η)
as well as the slope (β) to calculate reliability for each block based on the reliability formula:

\[ R(t) = e^{-\frac{t}{\eta}} \]

Also, to calculate availability, mean time-to-repair for each block was captured from field data. Then, by entering both reliability and time-to-repair for each block in ReliaSoft's BlockSim tool and assuming inverter operation of 8 hours per day, a mean availability of 99.97% was calculated over a 10 year period. The mean availability \( \bar{A}(\bar{t}) \) is the proportion of time during a mission or time period that the system is producing power.

\[ \bar{A}(\bar{t}) = \frac{1}{\bar{t}} \int_{0}^{\bar{t}} R(u) du \]  

(2)

where \( R(t) \) is calculated based on reliability, \( R(t) \) and mean time to repair, \( m(u) \):

\[ A(t) = R(t) + \int_{0}^{t} R(t - u) m(u) du \]  

(3)

The following figure provides the reliability graph as a function of time, \( R(t) \) based on using BlockSim RBD simulations.

Note that in all calculations throughout this study, conditions of 45°C, 480Vdc, and full power were used as the baseline which provide conservative theoretical calculations.

2.1 Vendor data reliability calculation example

As an example of the calculations based on vendor data, let us review the fan calculations, which are used in the RBD at this point. There are three types of fans in the inverter; here we only consider one of the three.

The most likely failure mechanism for a properly constructed and installed fan is the failure of the bearing grease which leads to eventual increase in bearing friction and the loss of fan operation. The work of Xijin [1] on cooling fan reliability modeling we can translate the provided vendor data to a Weibull life distribution. Equation 4 has an \( AF \) formula suitable for cooling fans:

\[ AF = 1.5^{\frac{\text{Ttest}-\text{Tuse}}{10}} \]  

(4)

where, \( T_{\text{test}} \) is from the data sheet and \( T_{\text{use}} \) is the expected use condition temperature. The fan data sheet also provides an L10 value of 57,323 hours, which represented the expected duration until 10% of units are expected to fail at 40°C. Using equation 4, we determine the \( AF \) to convert the L10 duration to the value corresponding to 45°C, which is 45,310 hours.

With the L10 at the appropriate temperature we then conduct some algebra to determine the \( \eta \), value for the Weibull distribution. Equation 5 shows the Reliability function of the Weibull distribution solved for \( \eta \). Inputting the known \( R(t) \) of 0.10 and including the L10 duration of \( 45 \)°C for time, \( t \), we can calculate the characteristic life of the Weibull distribution for the fan operated at 45°C.

\[ \eta = \frac{-t}{\ln(R(t))} \]  

(5)

The one missing element is the beta, \( \beta \), which Xijin recommends the use of a value of 3.0. Therefore, with beta of 3.0 we can calculate the \( \eta \) value using the adjusted vendor L10 data at the expected use temperature 95,933 hours.

The fan Weibull values for the expected use temperature of 45°C are then input for the fan within the RBD using ReliaSoft’s BlockSim software package.

3 SELECT AN OPTIMIZED LIST TO PERFORM ALT

To evaluate long term outdoor performance of solar inverters, we would really need the outdoor field performance data; however, practically we cannot wait for 10 years to determine warranty costs. Given the 85 fielded system as an average less than a year of operation time, the field data does not represent the end of life characteristics of the design. Therefore, ALT is used to predict what will happen in the field in the long run and ALT plans should be performed such that field failure modes due to degradation are replicated. Ideally, each subsystem as well as the entire system as the integration of subsystems would need a specific ALT, but due to high cost of such test plans, optimization was made in selecting ALT plans. In the following, we will first discuss a review of field data followed by parts stress analysis to design ALT plans.

3.1 Field Data Analysis

To determine failure modes due to degradation, field data was analyzed based on time to failure (TTF) of a fleet of 85 systems with close to one year age. The analysis on the data set using ReliaSoft Weibull++ tool included using both non-repairable systems and repairable systems as described below.

Non repairable systems- In this analysis, we used Weibull distribution model with the assumption that multiple failures cannot happen on the same unit, hence, consecutive failures are assumed to belong to a brand new unit. Also, each unit is considered separately as a censored data point. Based on Weibull++ analysis of “Time to Failures”, a \( \beta \) value of less than 1 indicated that all these failures are indications of early life failure i.e. no sign of degradation. Additionally, “Time to Repair” data was analyzed using Lognormal models and fit well. The plot of the time to repair data is in
3.2 Review list of critical parts and initial calculations

Since the results from field data indicated early life failures, no aging trends or degradation signs could be extracted to design ALT. Therefore, to optimize ALT plans, a list of critical parts in the system was reviewed and component stress level and aging mechanisms were studied. List of critical parts included: IGBT’s, DC Buss capacitors, Inverter bridge fans, Inductor fans, AC filter capacitors, Circulation fans. Based on, derating analysis on the list of critical parts, IGBT’s and DC Buss capacitors were selected to focus ALT plans on.

The selection was done based on reviewing design FMEA, component derating, and reliability predictions. In the case of fans, AC filter and DC Buss Capacitors, additional reliability calculation was done based on characteristic life from vendor data, electrical and thermal stress conditions, and \( \eta \) and slope \( \beta \).

4 ALT TESTING

Based on the reliability calculations, discussions with engineering and component vendors, IGBT and DC Buss capacitor aging were identified as the main drivers of product aging. Thus, the inverter bridge ALT plan was designed as a subsystem level ALT to address IGBT aging and the system level ALT plan designed to address DC Buss capacitor aging.

In both ALT plans, we chose a reliability goal of 80% and had sample size limitation of 6 for bridge and 2 for system. Southern Ontario region was used as the representative usage weather environment for this pilot study.

4.1 Inverter Bridge subsystem ALT

As IGBT’s are designed with thermal margin in our Solar Inverters, thermal cycling is the main stress factor to cause aging. The two most likely thermal cycling induced failure mechanisms are bond wire fatigue and solder attach fatigue. The high operating temperatures increase the relative motion of the assembled materials due to coefficient of thermal expansion mismatch leading to material fatigue initiation and propagation.

Bridge test plan was created primarily based on temperature cycling as the main stress factor causing IGBT aging. Bond wire fatigue is more prevalent with rapid switching applications which is not a characteristic of this application. Thus, solder attach failure is expected to be the driving factor. To determine duration of test in this study, weather data for Southern Ontario was studied and acceleration factor (AF) for ALT plan was calculated based on Coffin-Manson equation and parameters provided from the vendor.

\[
N = 10(\Delta T_c)^{-3.831}
\]

\( N \) is the number of cycles to 1% failure. Using this number combined with the assumption of \( \beta \) value of 2.3 (assuming a gradual metal fatigue wear out over time for planning purposes and based on a study [3] and using Weibull++

The plot indicates the build of the repair do not take very much time with majority of probability density function (PDF) being below 3 hours, whereas a few may take significant time to implement.

**Repairable systems** - This method uses Weibull++ general renewal process (GRP) 6, which considers multiple failures for a single Inverter and hence should provide a more realistic approach for this data analysis. Both parametric and nonparametric analyses were considered here.

In the parametric RDA analysis we chose “Type I” since it was known that repairs did not make the system any younger. Similar to analysis based on non repairable systems, a \( \beta \) value of less than 1 indicates infant mortality.

In nonparametric RDA analysis a plot of failure history as number of failures versus time for each inverter is generated. As can be observed in the Figure 4, the Mean Cumulative Function (MCF) shows the increasing time between failures over time; which indicates infant mortality.

The early life failures may represent the first year of operation of a unit well, and not represent the expected performance from 10 years and beyond at all. Therefore, field data is not directly useful for the RBD when considering reliability beyond the first year.

**Figure 3. Time to repair rate versus time**

**Figure 4. Multiple Cumulative Function versus Time**
distribution, we can estimate population time to failure distribution. To calculate Acceleration Factor (AF) using equation (4) and (6), we have:

$$AF = \frac{N_u}{N_t} = (\frac{\Delta T_u}{\Delta T_t})^{-3.831} \quad (7)$$

where $N$ is number of cycles at u (use level) and t (test level) temperature, $\Delta T$ is temperature cycling at u (use level) and t (test level) conditions. Based on 20 year weather data gathered at Southern Ontario weather stations, we calculated environmental data as summarized below. The weather stations considered here include: Toronto, London, Gatineau, Ottawa, Peterborough, Sarnia, Sudbury, Ann Arbor, Detroit, Flint.

Table 1. Calculation of AF based on Southern Ontario region weather $\Delta T$

<table>
<thead>
<tr>
<th>Environment $\Delta T$, at 480Vdc</th>
<th>AF B=3.831</th>
<th>Test cycles for 10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ontario $\Delta T$, 90th percentile, 69.6°C</td>
<td>34</td>
<td>107</td>
</tr>
<tr>
<td>Ontario $\Delta T$, 50th percentile, 63.5°C</td>
<td>48.6</td>
<td>75</td>
</tr>
</tbody>
</table>

Also, planning to run environmental chamber from -40°C (powered off) to +90°C (at full power), the IGBT case temperature will cycle from -40°C to 135°C. Therefore, we will have AF value of 34 for the 90th percentile Ontario weather data. Note that a recalculation of acceleration factor was made to take into account the effect of mini temperature cycling of IGBT’s due to cloud coverage, however, the overall effect proved to be minimal. To calculate confidence level for ALT plan, making the assumption of failure free operation during test period for the bridges, we use the extended success testing exponential distribution based sample size formula:

$$n = \frac{\ln(1-C)}{m \ln(R)} \quad (8)$$

where $n$ is sample size, $C$ is sampling confidence (type I error or alpha statistical error), $m$ is number of lifetimes the sample experience in the test, $R$ is the reliability or probability of successfully operating over the time period. Having the limit of 6 samples due to cost, we can demonstrate 80% reliability, and have 74% confidence level for our ALT plan. Thus, ALT plan is summarized as: testing 6 Bridges within a test chamber set to cycle from -40°C to 90°C for 108 cycles simulates 10 years of temperature cycling at Ontario’s 90th percentile weather conditions, which if the unit operates without failure demonstrates 80% reliability with 74% confidence.

4.2 Inverter Bridge System ALT

Many failure mechanisms are competing to cause the system to fail. The most likely set of failure mechanisms given the stress of high temperatures, humidity, current and voltage bias include the following: metal migration, corrosion, electro-migration, and time dependent dielectric breakdown among others.

As discussed earlier in the paper, system level ALT plan was designed to address the most likely aging of DC bus capacitors but Inverter bridge fans, Inductor fans, AC filter capacitors, Circulation fans would also age throughout this test. For a complex system like the inverter, there is most likely a dominant failure mechanism that limits the system operating life. This test is aimed at providing evidence of that failure mechanism if failure during planned testing or if the test duration is extending until failure occurs.

Table 2. Calculation of AF based on Ontario weather data

<table>
<thead>
<tr>
<th>Ontario Weather</th>
<th>AF</th>
<th>Test hours for 10 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>90th percentile, 30°C/90% RH</td>
<td>19</td>
<td>4,660</td>
</tr>
<tr>
<td>50th percentile, 15°C/70% RH</td>
<td>241</td>
<td>364</td>
</tr>
</tbody>
</table>

Based on Table 2 and considering the cost of test execution, test hours for ALT plan was calculated based on 50th percentile weather data. The system will not experience steady values of temperature nor humidity, and exposure to the highest rated values is limited in time with daily and seasonal variations. Testing to meet the higher values for these two stresses does provide additional margin for the translation of the test results to the use conditions.

The primary constraint is the number of samples for testing due to high cost of entire system. The systems are also large physically plus require significant resources to simulate actual operation voltage and currents. The testing was thus limited to two systems. Using a large walk-in environmental chamber which can provide controlled ambient temperature and humidity level an ALT plan was designed to run at 60°C and 85%RH. The duration of this test is calculated based on acceleration factor (AF) as follows. Assuming the dominant failure mechanism is electro-migration throughout this test, permits us to use Peck’s relationship to calculate the acceleration factor.

$$AF = \left(\frac{RH_u}{RH_t}\right)^{\frac{3}{0}} \exp\left[\frac{E_a}{k} \left(\frac{1}{T_u} - \frac{1}{T_t}\right)\right] \quad (9)$$

where $RH$ is relative humidity at u (use conditions) and t (test conditions), $E_a$ is the activation energy and is equal to 0.9 eV based on Peck’s equation [4] and his work to fit numerous past studies and results experience, $k$ is the Boltzman’s constant or 8.617385x10^-3 eV/k, $T$ is temperature in Kelvin at u (use conditions) and t (test conditions). Using equation (8) to calculate confidence level based on a sample size of only 2 and a reliability goal of 80% the confidence level is limited to 36%. Thus, ALT plan for the Inverter System is summarized as: testing 2 samples of Inverter Systems at 60°C and 85%RH for 326 hours simulates 10 years (8 hours per day) usage at Ontario’s nominal weather conditions, which if the unit operates without failure would demonstrate a 80% system reliability with 36% confidence. Given the constraint of system level sample size of 2, the confidence level is very low, thus the system level ALT plan is to explore any failure mechanism within the expected nominal life span of the unit assuming aging of critical components follow Peck’s equation.

5 RESULTS AND LIFE CALCULATIONS

At the time of writing this paper, the ALT plans are under execution. Once tests are completed, whether no failure is
observed or we have some failures, the results will be used to recalculate reliability of blocks in the system ALT. Then BlockSim tool will be used to recalculate Availability and estimate system Availability over the 10 year life period.

So far, system level testing has been completed which confirms a minimum of 80% reliability over 10 years of use. Since system ALT was designed based on accelerating failure modes of DC buss capacitors and no failure was observed throughout the test, original reliability calculations based on vendor data and life calculations can be trusted and there is no need to update RBD. In subsystem testing, out of the 4 samples tested so far, we have had 1 bridge failing within the total 108 cycles. This means that if this failure is proven to be due to aging mechanism of IGBT’s and not due to test setup, we should continue testing all samples for longer cycles to get failures and update RBD based on new reliability calculations for IGBT’s.

This project demonstrates a pilot project and provides the steps to calculate useful life based on field data and ALT plans. Although having more field data and using more samples and longer test duration provide more accurate estimations, this project provides a real life example of reliability estimation having multitude of constraints including sample size, test duration, and field data and thus having to make optimization based on multiple sources of data from field, to vendor and ALT results.

APPENDIX- WEATHER DATA

The expected storage environment is indoor sheltered conditions that may or may not have temperature control. In some situations the storage temperatures may match the outdoor ambient temperatures. The unit’s storage is expected to be in populated areas of the world. Rather than use rated limits or absolute maximum storage temperature expectations which would only apply to a very few situations and units, we will use the 50th percentile (nominal) or 90th percentile values for daily average temperature and daily average temperature range. The National Climatic Data Center [2] has available worldwide weather station daily data readings.

The weather data is from 20 randomly selected weather stations with data from July 1st, 2005 to July 1st, 2010 from the worldwide list of stations within the database. The resulting 162,000 lines of daily data readings include minimum, maximum, and average temperatures.

The maximum temperature is generally only obtained for an hour or so per day. Calculating the difference between daily minimum and maximum temperatures provides the daily temperature range. Then, using the Excel percentile function the 90th percentile and nominal data will be as shown in Table 1 and Table 2.

REFERENCES


BIographies

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