RELIABILITY AND AVAILABILITY ANALYSIS OF A FIELDED PHOTOVOLTAIC SYSTEM

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ABSTRACT

System level reliability and availability estimates are required to facilitate cost tradeoff studies associated with competing photovoltaic systems. Estimates of reliability are necessary in developing maintenance cost projections over the system lifetime. Availability estimates provide an input into annual energy generation projections.

This paper describes a comprehensive approach to developing reliability and availability estimates for a large photovoltaic system. System reliability and availability were defined based on the operator's expectations and a Reliability Block Diagram (RBD) was developed to model system behavior. The RBD developed is a hierarchical reliability model. Larger functional elements are decomposed into smaller functional elements. The granularity of the model is determined by the level that failure data are collected.

Field data, failure times and repair times, were collected and analyzed for a five year time period from a 4.6 MWdc photovoltaic system operated by Tucson Electric Power (TEP) at Springerville, Arizona. Failure and repair distributions were fitted to these field data. These results were then used to populate the RBD and produce system level estimates of reliability and availability. The results of these analyses are:

1. a summary of failures for each main component of the system,
2. a summary of failure distributions/rates and repair times for each main component,
3. system reliability and availability versus time projections, and
4. an estimate of the number of failures for each main component over the system's life.

INTRODUCTION

The reliability and availability of large photovoltaic systems have not been thoroughly investigated. Manufacturers in the photovoltaic industry are offering warranties of 20 years and better for photovoltaic modules with incomplete knowledge of their reliability in the diverse environments in which these modules are deployed. All stakeholders, including entrepreneurs, manufacturers, regulators, utility operators and consumers, need a useful predictive model for reliability and availability. This predictive model can facilitate trade-offs in requirements and life cycle cost, identify improvements in design, manufacturing and in-situ operation and provide estimates of performance over the system's lifetime.

This paper describes a standard methodology used to characterize a system's reliability and availability. The elements of a reliability/availability improvement program are illustrated in Figure 1. The three basic activities associated with a reliability/availability program are Failure Modes and Effects Analysis (FMEA), System Reliability/Availability Modeling, and Accelerated Life Tests.

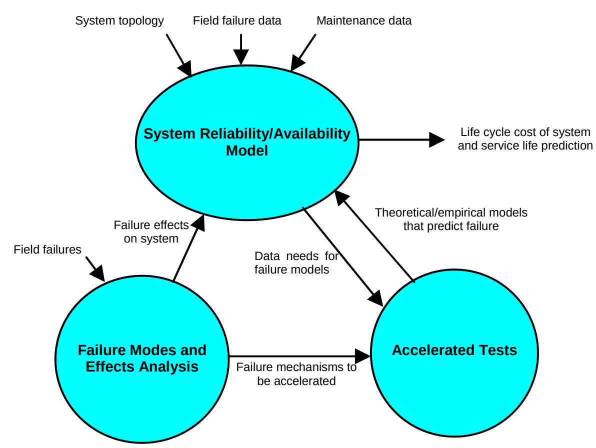

Fig. 1. Overview of Reliability Program for Photovoltaic Systems.

FMEA is a technique for systematically identifying, analyzing and documenting the possible failure modes within a design and the effects of such failure modes on system performance or safety. FMEA is an inductive bottom-to-top analysis. Failure modes are identified at a basic part level and their effects are worked upward through each level of the system to identify overall system level impact. The purpose of FMEA is to identify failure effects on the system to be included in the RBD and identify potential failure modes/mechanisms that could be accelerated to provide failure rate information.

System reliability/availability modeling allows quantification of system reliability and availability using multiple data inputs, such as field data, test data, and accelerated life test data. A system reliability model is a diagrammatic representation of all functions, in terms of subsystem or component events, that must occur for successful system operation. An RBD is constructed by identifying all necessary functions and their associated components that must occur for the system to provide an output. The blocks are then arranged in a diagram in order of operation. Hierarchical system block diagrams are high level diagrams that contain one or more subsystems or components within a block. Each block may have an associated RBD defined by lower level functions.

Accelerated life tests are tests that are run at elevated stress levels outside the stresses expected in normal operation. The objectives of these tests are:

1. identification of the life distribution parameters of time-to-failure for the applied stress,
2. identification of relationships (mathematical or physical/chemical) between time-to-failure and stress, and
3. evidence about whether failure mechanisms stimulated by the accelerated stresses are expected to occur at operational stress levels.

Accelerated life tests allow collection of time-to-failure information in situations where the time to test at normal stress levels is inordinately long or the sample sizes required are too large. In this program, accelerated life tests will be used to estimate time-to-failure for failure mechanisms that require long periods of time to manifest.

CASE STUDY OF A FIELDED PHOTOVOLTAIC SYSTEM

Reliability Model for TEP Springerville Photovoltaic System

This reliability study focused on the crystalline silicon PV portion of TEP Springerville, Arizona grid–connected PV system shown in Figure 2. Crystalline silicon PV modules comprise approximately 80% of the PV generating system's capacity. The 4.6 megawatt PV generating plant consists of 26 arrays with 450 crystalline silicon modules per array. The crystalline silicon module is an ASE Americas (Schott Solar) ASE-300-DG/50. An array string includes nine of these PV modules with two strings per row. Twenty five rows of these modules (50 array strings, 450 PV modules) are connected to a Xantrex PV150 inverter. The Xantrex PV150 inverter converts the variable voltage (380 V to 480 V) dc power to 208 V three phase ac power. Each inverter has a dc disconnect, a 150 kVA 208/480 V step-up isolation transformer, a revenue meter and an ac disconnect. Groups of four of these units are connected in parallel to a 500 kVA 480 V/34.5 kV step-up transformer. The high voltage sides of the 500kVA transformers are connected in parallel to a 34.5 kV underground distribution line that connects to the overhead 34.5 kV distribution line through fused disconnects. The overhead distribution line feeds the well field pumps of the nearby 1160 MW coal-fired Springerville Generating Station. A more detailed description of this PV generating system is provided by reference [1].

Fig. 2. TEP Springerville Photovoltaic Generating Facility.

A RBD was developed for the crystalline silicon portion of the PV system. To develop the RBD, a definition of system success was needed. A decision was made to have a simple definition for system success. Success was defined as the PV system delivering power to the grid. A hierarchical system model was developed describing the functional elements necessary to deliver power to the grid using a commercial software tool, ReliaSoft BlockSim 7™. The granularity of the model, the basic blocks in the model, was based on the major components of the system and the level of identification of field failures in the reporting process. The RBD is shown in Figures 3 through 8. To yield useful reliability and availability metrics, the RBD must be populated with both life distributions and repair distributions within each block.

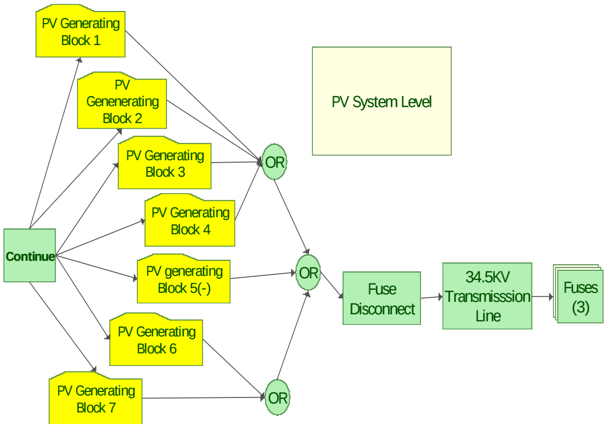

Fig. 3. Top Level RBD for TEP PV System, Level 1.

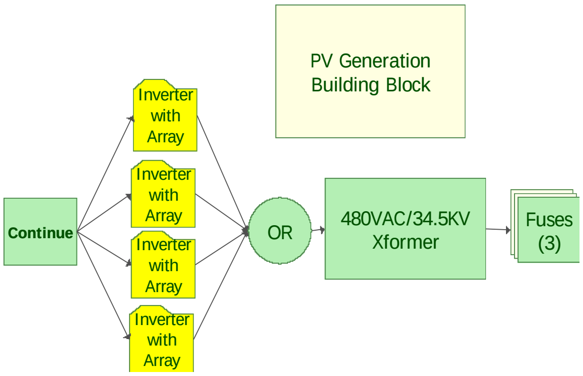

Fig. 4.   RBD of PV Generating Block, Level 2.

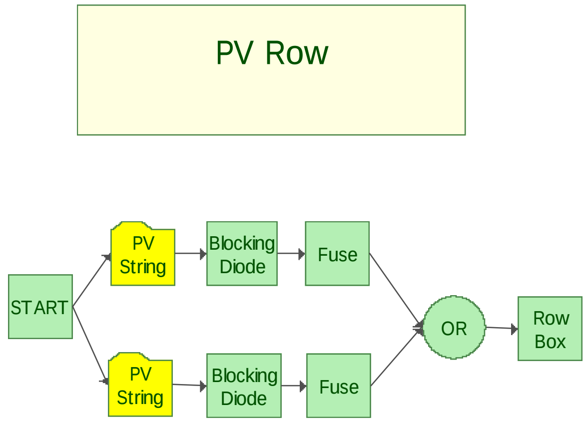

Fig. 7. RBD of PV Row, Level 5.

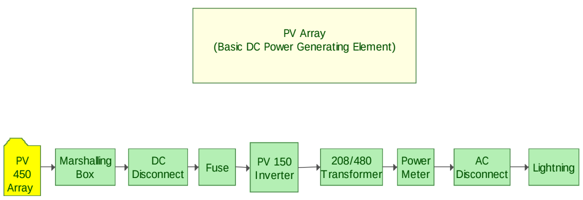

Fig. 5. RBD of PV Array, Level 3.

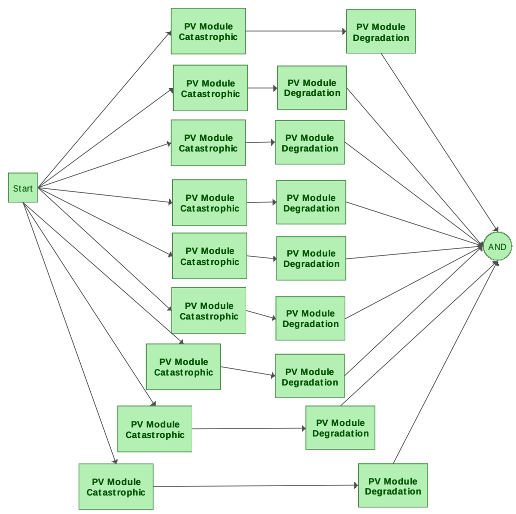

Fig. 8 RBD of PV Strings, Level 6.

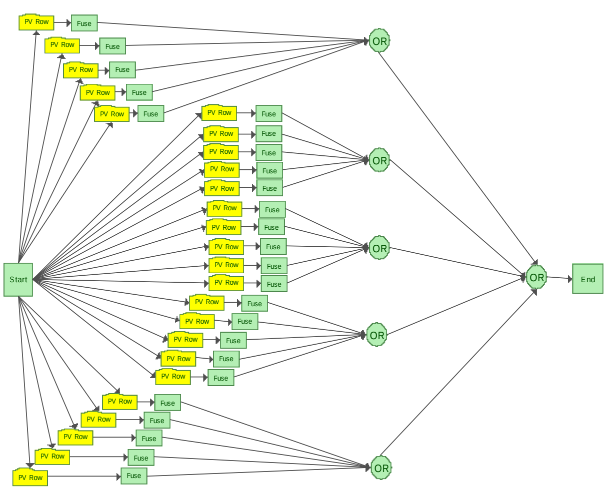

Fig. 6. RBD of PV 450 Arrays, Level 4.

Life Data to Populate the Reliability/Availability Model

TEP shared detailed production and outage reports for the years 2003 to 2007. These reports were analyzed to extract data about failures, failure causes, times to failure, and repair times for elements of the system. The times to failure data for each major element of the system were analyzed using commercial software, ReliaSoft Weibull++™, to fit life distributions and estimate parameters of the distributions. Some decisions were necessary to interpret failure events for this analysis. The following is a list of the decisions on data treatment that were made:

1. Multiple occurrences of the same failure symptom without corrective action for the root cause were treated as a single failure at the time of first

occurrence. The downtimes associated with each occurrence after the first failure were treated as unscheduled maintenance events.

2. Grid-related perturbations outside the PV system boundaries that resulted in inverters tripping and resetting without physical damage to the system were treated as unscheduled maintenance events.
3. Lightning events that damaged multiple elements of the system were treated as separate series blocks in the RBD.
4. For fitting the repair distributions, only downtimes that resulted in a loss of power were included.
5. Fuses, blocking diodes, and connections were included as part of the analyses of components in the model.

RESULTS OF ANALYSIS

Simple Reliability Metric – Failure Count

A simple reliability metric is a count of failures associated with each component. Figure 9 provides a failure count for each major component by year.

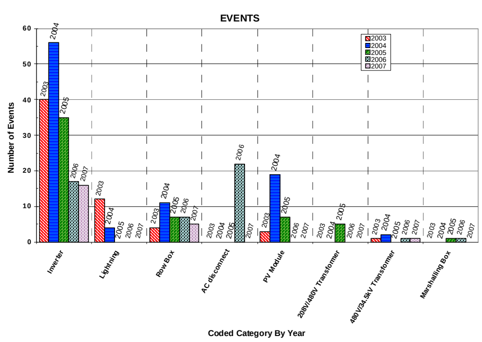

Fig. 9. Failure Count for Components with Failure.

The component with the most failures is the Xantrex PV Inverter. During the first two years, the lightning event block was second on the list of failures. This block is not a physical component of the system, but represents the multiple failures caused by lightning strikes to the PV system. Lightning damaged inverters, PV modules and the monitoring system. Severe lightning storms resulted in significant damage to the system in 2003 and 2004.

Life Distributions and Parameter Estimates for Blocks

The life data extracted from the production and outage reports for 2003 to 2007 were organized in times-to-failure or times-to-suspension for situations where no failures occurred for each component grouping. These data were then analyzed using the ReliaSoft Weibull++™ and RGA (Reliability Growth Analysis) 6 ™ software tools. Components that did not fail during the five year data period were assumed to have a reliability of 1.

Two basic approaches to data analysis are used for the components of the PV system. For the components that are replaced when they fail, life data analysis is employed. Data are fitted to common life distributions such as lognormal, exponential, two parameter exponential, two parameter Weibull, and three parameter Weibull. Once data are fitted to a distribution, the parameter(s) of that distribution are estimated using one of several available techniques. The "best" match life distribution is then selected based on weighting of three criteria;

1. goodness of fit (the p-value from the Kolmogorov-Smirnov test), the maximum absolute difference between the hypothesized and empirical cumulative distribution functions (cdfs),
2. a likelihood ratio, the value of the log likelihood of the hypothesized distribution with the estimated parameters evaluated with the given data set, and
3. plot fit, the mean absolute difference between the hypothesized and empirical cdfs.

Table 1 provides a summary of the distributions and estimated parameters used to model the components that are replaced when they fail. Scale and location parameters are in days or the applicable transformation.

PV Component / RBD Block	Distribution	Beta or Log SD (Shape)	Eta or Log Mean or Lambda (Scale)	Gamma (Location)
AC disconnect	Weibull 3-RRX	0.35	11000	3.9
Lightning	Exponential 1-RRX		0.00022	
Row Box	Weibull 2-RRX	0.51	1.2E+06	
PV Module	Weibull 3-RRX	0.28	5.2E+12	17
480/34.5 KV Transformer	Weibull 2-RRX	0.58	7100	
208/480 Transformer	Weibull 3-RRX	0.15	1.3E+10	28
Marshalling Box	Lognormal 2-RRX	2.3	10	

Table 1. Summary of Life Distributions and Parameters Estimates for Replaced Components.

For components that are repaired rather than replaced parametric recurrent data analysis is used. This approach is based on the General Renewal Process (GRP) model [2, 3, and 4]. It is used when a component accumulates more than one failure over its service life. This model is particularly useful in modeling the failure behavior of a component and understanding the effects of repair on the age of the component. In order to obtain a virtual age, the exact occurrence time of failures should be available. However, the times are unknown until the corresponding event occurs. Therefore, the software uses Monte Carlo simulation to predict values for virtual time, failure number, Mean Time Between Failures (MTBF) and failure rate. Three coefficients are estimated by the software, two power law coefficients and a repair effectiveness coefficient.

Parametric recurrent data analysis was used for the inverter only. Many inverters had multiple failures over the analysis time period 2003-2007. Life data analysis was used for all other components of the PV system.

Analysis of the field data for inverters yielded a power law model with estimates of beta equal to 0.75 and lambda of 0.019 per inverter. The repair effectiveness q was estimated to be zero. A zero value means repair did not degrade the inverter's reliability.

Maintenance Distributions and Parameter Estimates for Blocks

Repair times, time from failure to restoration, and other downtimes were identified for each component from the production and outage reports. For Inverters, these downtime events were sorted into three categories: corrective maintenance, preventive maintenance (scheduled and unscheduled), and grid effects. Downtimes caused by grid effects are a special category. These downtimes are associated with inverters tripping and resetting due to voltage or frequency excursions in the external power grid connection that result in no physical damage to the system.

A similar approach to life data analysis was taken for fitting repair distributions and estimating parameters. Data are fitted to common life distributions, such as lognormal, exponential, and Weibull. Once data are fitted to a distribution, the parameter(s) of that distribution are estimated. Scale parameters are in days or the transformation. The results are provided in Table 2 and 3.

PV Component/ RBD Block	Distribution	Beta or Log SD (Shape)	Eta or Log Mean and Lambda (Scale)
Corrective Maintenance	Lognormal 2-RRX	2.27	-4.25
Preventive Maintenance	Exponential 1-RRX		2.62
Grid Effects	Weibull 2-RRX	1.07	0.16

Table 2. Summary of Repair Distributions and Parameter Estimates for the Inverter.

PV Component / RBD Block	Distribution	Beta or Log SD (Shape)	Eta or Log Mean (Scale)
AC disconnect	Weibull 2-RRX	0.71	1.4
Lightning	Weibull 2-RRX	0.73	10.8
Row Box	Lognormal 2-RRX	2.07	-0.98
PV Module	Lognormal 2-RRX	3.11	-1.37
480/34.5 KV Transformer	Weibull 2-RRX	0.53	1.36
208/480 Transformer	Lognormal 2-RRX	1.6	-2.33
Marshalling Box	Weibull 2-RRX	0.35	3.55

Table 3. Summary of Repair Distributions and Parameter Estimates for the other Components.

Plots of Reliability and Availability versus Time

The life and repair distributions for all the components were imported into the BlockSim™ RBD for the PV System. A Monte Carlo simulation that sampled from the life distributions at discrete intervals and determined component and system state (operational, or down due to failure or maintenance) was executed. For availability, repair times are sampled for the various repair distributions associated with each block to determine component and system states. Results of these simulations at the system level were a straight line plot indicating an availability of 100%. At this level, the model predicts at least one inverter will always supply some power to the grid. Figure 10 illustrates plots of reliability and availability for the inverter with PV array segment of the system. The reliability in Figure 10 reflects the effect of no repair or replacement of components. TEP's rapid repair policy enables very high levels of availability with lower component reliability.

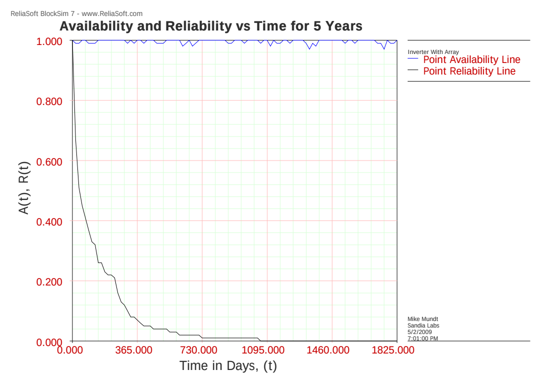

Fig. 10. Plot of Reliability and Availability versus time for Inverter with PV Array.

Expected Number of Failures in 20 Years

The expected number of failures as predicted by the model for each component for 5, 10, and 20 years are shown in Table 4. The number of failures predicted for the inverter assumes no additional reliability growth, a conservative assumption. The model does not currently incorporate the effects of degradation or wear out failure mechanisms. These data are not currently available for the TEP PV system.

Component	Actual Number of Failures 5 yr Cum	Expected Number of Failures 5 yr Cum	Expected Number of Failures 10 yr Cum	Expected Number of Failures 20 yr Cum
PV 150 Inverter (26 cSi arrays)	125	132	231	429
PV Module	29	26	31	38
AC Disconnect	22	17	23	31
Lightning	16	10	20	41
208/480 Transformer	4	3	3	3
Row Box	34	25	35	50
Marshalling Box	2	4	7	11
480VAC/34.5KV Xformer	5	4	5	9

Table 4. Predicted Number of Component Failures.

For the first five years, the inverter repair rate was 0.96 per inverter per year. For the PV modules, the replacement rate was approximately 5 in 10,000 PV modules per year.

CONCLUSIONS

The mean availability predicted by the model approaches 100% for the five year period. The effective availability reported by TEP for the system was 99.91% in 2007. Effective availability is defined as the actual power produced divided by the total power that could have been produced. The model predictions differ from the reported results for several reasons:

1. The model's definition of success is less conservative than the TEP availability definition. The system was assumed to be available if only one inverter was supplying power to the grid. The TEP metric was based on a ratio of actual power produced to a theoretical power that could be produced.
2. TEP measures actual KWh from the system. The model is not yet augmented to predict kWh output with the effects of seasonal and weather variability on solar insolation.
3. TEP calculation of total power that can be produced is based on reference cells on site. These references cells have not always been periodically recalibrated and therefore may introduce some error into the calculation. Measurement uncertainty for expected power output of the TEP PV system is unknown.
4. The model generates availability estimates using Monte Carlo simulation that involves some inherent variation.

Inverters are the most unreliable component in this system. Yet the availability of continuous power delivered to the grid is projected to be very high over the life of this system. However, an increase in inverter reliability can still lower corrective maintenance costs over the system life.

FUTURE WORK

Future research goals include:

1. Expansion of the database to include other utilities, manufacturers, and operators. With enough data from diverse locations it may be possible to analyze environmental effects on reliability.
2. Incorporate accelerated test results from sources such as the National Renewable Energy Laboratory and PV module manufacturers in the model to better predict degradation and wear out failure mechanisms.
3. Improvement of predictive model to match effective availability definition used by the power industry. Enhance the model to predict kWh output.

ACKNOWLEDGEMENTS

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Sandia acknowledges the support of the DOE Solar Energy Technologies Program in particular for funding the work presented in this paper.

The authors acknowledge Tucson Electric Power for sharing failure and maintenance data for the Springerville, AZ Photovoltaic Generating Facility. Also, we thank Tom Hansen and Kaleb Brimhall who assisted in interpretation of the data logs. This work would not have been possible without this valuable information.

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