FIELD DATA COLLECTION FOR QUANTIFICATION OF RELIABILITY AND AVAILABILITY FOR PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Predicting reliability and availability is a data driven capability of interest to the entire photovoltaic community, from material suppliers to system owners. Sandia National Laboratories is developing a predictive model and a host of methodologies needed for creating accurate predictions. Operational and maintenance (O&M) data from operating systems is only one piece of a broader data set required to make accurate predictions. Estimating reliability and availability of fielded photovoltaic systems requires times-to-failure or times-to-suspension and downtime data for each of the major components of each system. This paper addresses the collection (data set) and organization (standardized format) of data necessary for reliability and availability analyses.

Typically, for a large photovoltaic system the data are censored. The data sets are composed of a mixture of components with failure and components without failure. The data sets must be organized into times to failure, or suspension time in use without failure, for each component that is being analyzed. To accurately estimate availability the various contributors to system downtime, such as corrective or preventative maintenance and grid perturbations, must also be identified and modeled.

Preparation of the data for analysis usually consumes a significant percentage of the time required to generate a system reliability or availability estimate. A case study with data from a five year period of a fielded photovoltaic system is used to illustrate how a commercially available software tool for failure reporting and corrective action, XFRACAS™, was adapted to efficiently organize field data and transfer data into a suite of software tools. The software tool Weibull++™ was used to fit life distributions or growth models and to estimate parameters of the distributions. Another software tool, BlockSim 7™ was used for Reliability Block Diagram (RBD) development and simulation of system reliability and availability.

XFRACAS™ is a web-based application that provides the capability for point of source data entry into a centralized data base. With some slight modifications, XFRACAS™ is capable of exporting data from the database that is properly organized and formatted for analysis by the life data analysis or reliability growth analysis tools.

INTRODUCTION

Sandia National Laboratories' (SNL) Department of Energy (DOE) Photovoltaic Reliability Program is developing a suite of tools to facilitate system-level reliability and availability predictions. SNL is creating a database of failures and repairs associated with operating utility-scale photovoltaic systems. This Photovoltaic Reliability Operations and Maintenance (PVROM) database is the foundation data used to create system-level reliability and availability predictions.

Typically, each system is composed of thousands of individual components and is capable of producing megawatts of power. PVROM will be used by SNL and our industry partners to predict the availability of each system, the effect of various maintenance policies on availability, and the kilowatt hour (kWhr) energy each system will be capable of producing. The database also permits easy retrieval and comparison of field data from all these sources for various components of the system.

Thus far, the database has been populated with five years of O&M data from the Tucson Electric Power Springerville Photovoltaic Generating Plant, reference [1]. An example of a reliability and availability analysis using these data is provided in reference [2].

With such a potentially large amount of data to organize and analyze, an efficient data collection tool was needed. ReliaSoft XFRACAS™ was selected as that database software tool. The main considerations in the selection of XFRACAS™ as the data collection tool were:

- the ability to capture data at its source and automatically organize it in the desired format for analysis by standard reliability techniques, and
- the ability to control data access among multiple users.

GENERAL DATA REQUIREMENTS FOR RELIABILITY AND AVAILABILITY ANALYSES

Data collected from large utility-sized PV systems typically consist of times-to-failure of components that have failed and times-to-suspension of components without failure. These data are said to be ”right censored”. For such data the event of interest, failure time, occurs to the right, in the future, of our observation. Some data may be interval censored or “left censored”. These are components where the exact time of failure is not known. It is only known that a component failed within a specific time interval. The data collection tool must be capable of distinguishing and organizing both data types.

In addition, other contributors to system downtime, such as corrective or preventive maintenance and grid perturbations, must be categorized and recorded.

The minimum data identified necessary for subsequent reliability and availability analyses of PV systems are as follows:

1. incident occurrence date/time,
2. Bill of Material part number,
3. part serial number,
4. part commissioning date (in-service date),
5. incident description,
6. incident category (defined later),
7. service response date/time,
8. service completion date/time,
9. restoration to service duty date/time, and
10. estimated energy lost (KWh).

XFRACAS™ AS A DATA COLLECTION TOOL

The tool selected for the collection and organization of PV system field data is ReliaSoft's XFRACAS™, a Web-based, closed-loop, incident (failure) reporting, analysis, and corrective action system designed for the acquisition, management and analysis of quality and reliability data from multiple sources. XFRACAS™ is primarily intended for managing a failure reporting and corrective action process. It was not designed specifically for reliability database applications, but has some convenient features that SNL adapted for that purpose. The ability to export PV system times-to-failure and times-to-suspension for analysis by ReliaSoft Weibull++™ and RGA™ was a primary consideration in choosing XFRACAS™ as a data collection tool for PVROM.

Before field incident data can be entered into the XFRACAS™ database it is necessary to construct an appropriate PV installation Bill of Materials.

Bill of Materials

The first step in creating a Bill of Materials (BOM) for a PV installation is to obtain or create a detailed configuration of the installation. Figure 1 is an example of an electrical one-line diagram that is suitable for use in creating a system BOM. A PV installation will typically consist of power transformers, AC and DC disconnect switches, inverters, PV modules, and various AC and DC system connections (e.g., cables, fuses, diodes, etc.). PV installation components can generally be grouped into one or more power blocks, where a power block consists of the collection of components associated with an inverter.

BOMs can be created using the XFRACAS™ Parts Import Template, which is a Microsoft Office Excel file (.xls). Figure 2 illustrates the construction of a PV power block BOM using this template. The top level (Level 1) of each BOM template is the power block designation. The major components of each power block (i.e., power transformers, AC/DC disconnect switches, inverters, PV modules, etc.) are all Level 2 entries in the template. Note that the various electrical system connections (i.e., cables, fuses, etc.) are entered into the template as a single entry. The lightning event is explained in a later section.

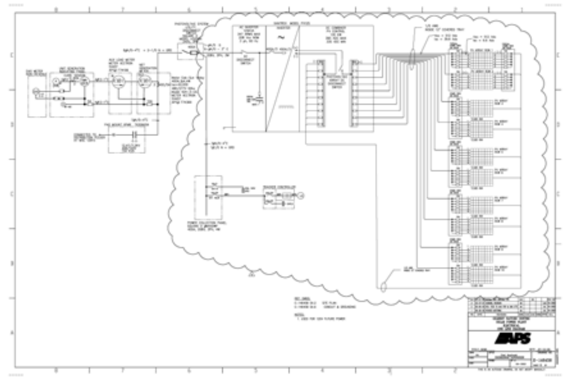

Figure 1. PV System One-Line Diagram

Level	Part Number	Part Description	Part Version	Serial Number	Quantity	Build Date
1	SGSSS	SGS Solar System Power Block		SGS-1	1	07/13/2001
2	TXL	480V/34.5kV Transformer		SCL-2	1	07/13/2001
2	TXS	208V/480V Transformer		TXS-1	1	07/13/2001
2	ADS	AC Disconnect Switch		ADS-1	1	07/13/2001
2	DDS	DC Disconnect Switch		DDS-1	1	07/13/2001
2	ECON	Array Electrical Connections		ECON-1	1	07/13/2001
2	INV	Inverter		INV-1	1	07/13/2001
2	LIGHT	Lightning Event		L-1	1	07/13/2001

Figure 2. Example PV System Bill of Materials Template

Although there is probably little reason to go to a third level (e.g., parts internal to the inverter), the complexity of the BOM template depends upon the desired detail to which system component/part reliability is to be ascertained. However, the parent-child relationship of BOM entries needs to be kept in mind (i.e., Level 3 parts are necessarily children of the associated Level 2 parts). When a BOM part is replaced, XFRACAS™ assumes that all of the children associated with that part are replaced as well. This is most certainly the case if all of the children are sub-components of the part being replaced.

Note that the BOM contains a “part” titled lightning event. A single lightning event may affect multiple components in a PV system, resulting in component damage and/or interruption of equipment operation.

This BOM entry is necessitated by the need to consolidate potentially multiple, common-event (lightning) incident records into a single incident record in addition to recording the individual BOM part incidents. Such an incident record affords the ability to account for multiple hardware failures/suspensions due to a common lightning event as a single incident occurrence in the reliability/availability analysis.

Next, a serialized BOM is created by applying serial numbers to all entries in the Parts Import Template. Each of the major system components (i.e., transformer, inverter, disconnect switches, PV modules) in a power block is initially serialized. Figure 3 illustrates a serialized version of the BOM shown in Figure 2.

Level	Part Number	Part Description	Serial Number
1	SGSSS	SGS Solar System Power Block	SGS-1
2	TXL	480V/34.5KV Transformer	SCL-2
2	TXS	208V/480V Transformer	TXS-1
2	ADS	AC Disconnect Switch	ADS-1
2	DDS	DC Disconnect Switch	DDS-1
2	ECON	Array Electrical Connections	ECON-1
2	INV	Inverter	INV-1
2	LIGHT	Lightning Event	L-1
2	MOD	PV Module	M-U1-1
2	MOD	PV Module	M-U1-2
2	MOD	PV Module	M-U1-3
2	MOD	PV Module	M-U1-4
2	MOD	PV Module	M-U1-5
2	MOD	PV Module	M-U1-6
2	MOD	PV Module	M-U1-7
2	MOD	PV Module	M-U1-8
2	MOD	PV Module	M-U1-9
2	MOD	PV Module	M-U1-10
2	MOD	PV Module	M-U1-11
2	MOD	PV Module	M-U1-12
2	MOD	PV Module	M-U1-13

Figure 3. Example PV System Serialized Bill of Materials

Each PV facility/installation will have one or more BOMs, depending on the complexity and configuration of the PV system (e.g., the number of power blocks). This facilitates the proper component associations when system incident records are created in XFRACAS™ without adding unnecessary complexity. Lower level component/part details should be provided in XFRACAS™ incident descriptions. Furthermore, this approach provides the necessary level of detail for performing system reliability/availability analyses. Once a serialized BOM is created it can then be imported into XFRACAS™ using the Administrative Utility.

INCIDENT REPORTS

Real-time Data Entries

The Incident Tracking Utility allows authorized users to create system reliability-related incident reports. An incident is any event that results in interruption of system operation (e.g., hardware failure, grid- or environment-related operational interruption, preventive maintenance, etc.). To create an incident report, **Create Incident** is selected from the **Incidents** menu on the Home Page (Figure 4). This opens the Incident Wizard (Figure 5), which guides the user through the steps of creating a new incident report. Some information required in the creation of an incident report (e.g., system status, incident status, report type, and incident category) is obtained from drop-down menus that can be customized for the specific XFRACAS™ application.

Figure 4. Home Page Incidents Menu

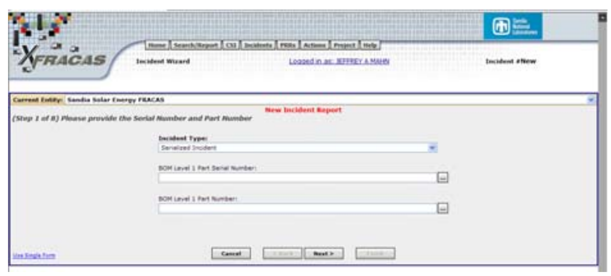

Figure 5. Incident Wizard

Upon completion of the Incident Wizard screens, the new incident report is opened in the Incident Tracking Utility (Figure 6), where additional information can be entered into the incident record (e.g., operating company, system/facility location, power block commissioning date, clock hours, etc.). Incident reports are entered into the database upon their creation and each report is assigned a unique number (Figure 6) by which it can be accessed using the Quick Search Utility on the left side of the Home Page (Figure 4). An incident record consists of 4 sections as illustrated in Figures 6-8. The first section at the top of the incident record (Figure 6) contains a summary of incident information, while the second section contains system/component information (Figure 6). Incident disposition and repair information is entered into the third and fourth sections (Figures 7 and 8, respectively) as it is available.

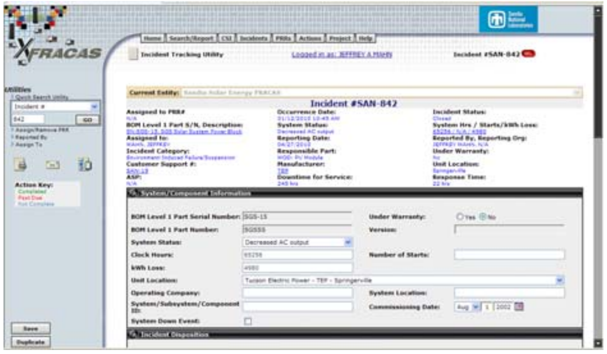

Figure 6. Incident Report – Summary and System/Component Information Sections

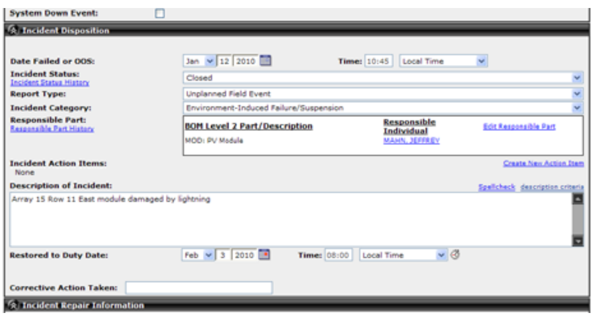

Figure 7. Incident Report – Incident Disposition Section

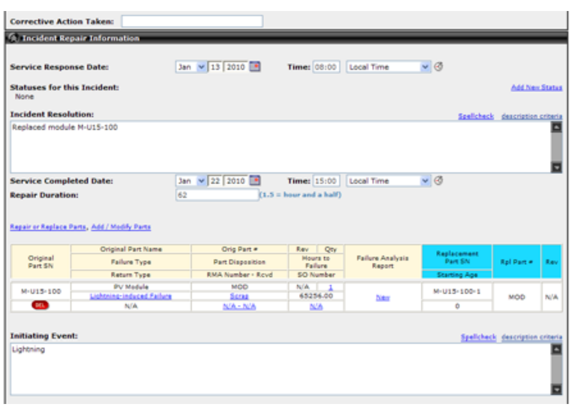

Figure 8. Incident Report – Incident Repair Section

Record information can be modified as long as the Incident Status is Open, and in fact may need to be as the response to an incident reveals additional information. When equipment associated with the incident is finally returned to service the Restored to Duty Date and Time (Figure 7) and kWh Loss (Figure 6) are entered into the record and the Incident Status (Figure 7) is changed to Closed.

As indicated in the introduction to this paper, PV system times-to-failure and times-to-suspension are the requisite data for reliability and availability analysis. This information is recorded as Clock Hours in the incident reports. Incident Clock Hours entries are based on the commissioning date (i.e., date of initial operation) of the applicable power block (see BOM discussion above) or the date on which operation of a replacement component is initiated.

Legacy Data Entry

Legacy (historical) incident data is entered into the database via an Incident Import Template (Figure 9). Data columns in the import template are mapped to specific data fields in the incident report. Since incident report data field names can be customized for the specific XFRACAS™ application, associated template data column headings must be similarly customized. When all legacy data has been entered into the template it is then imported into XFRACAS™ using the Administrative Utility.

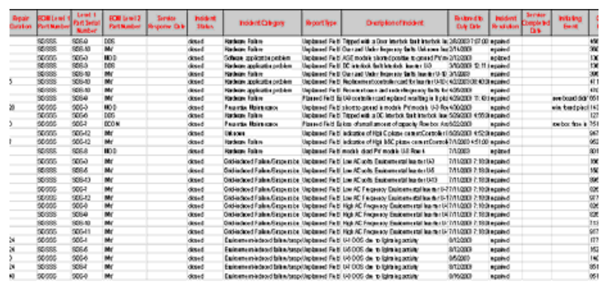

Figure 9. Incident Import Template Incident Summary Reports

A summary of all incident records (Figure 10) can be obtained by selecting **My Search Page** from the **Search/Report** menu on the Home Page (Figure 11) and selecting **Query All Unassigned Incidents** on the left side of the Search Page (Figure 12).

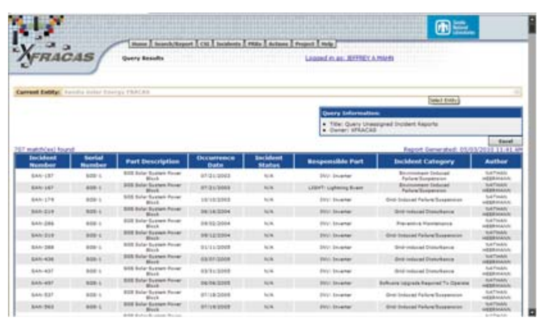

Figure 10. Incident Summary Report

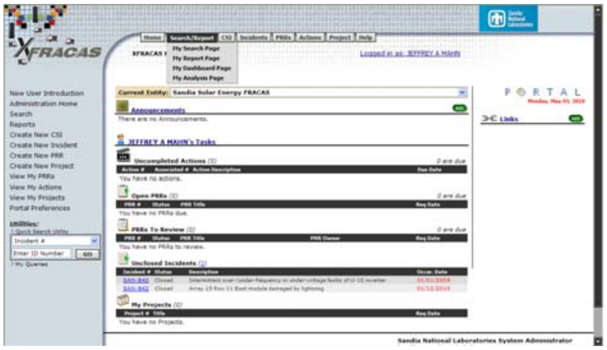

Figure 11. Home Page Search/Report Menu

Figure 12. Search Page

Export of Data to Analysis Tools

One of the primary reasons for using XFRACAS™ to record PV system incident data is that the software organizes and exports data that is readily useable by ReliaSoft's reliability analysis tools, Weibull++™ and RGA™.

Data to support failure analyses can be readily exported from XFRACAS™ into Weibull++™ and RGA™. However, analysis of downtimes and repairable systems requires some additional data handling. Downtimes can be analyzed in Weibull++™ after minor pre-processing in Excel. Preprocessing involves sorting and organizing the exported data in a format suitable for analysis. Failure times in repairable systems cannot be assumed to be independent, since the life of a repaired component is partially restored by the repair as opposed to being completely restored if it was instead replaced with a new component. Repairable systems can be analyzed in the Weibull++™ RDA folio after minor pre-processing in Excel. BOM Level 1 data for repairable systems can be directly exported from XFRACAS™ to RGA™ without pre-processing.

To perform a data export, **My Analysis Page** is selected from the **Search/Report** menu on the Home Page (Figure 11). This opens the Analysis Page shown in Figure 13. Next, a product (i.e., Weibull++™ or RGA™) must be selected for which XFRACAS™ data is to be exported.

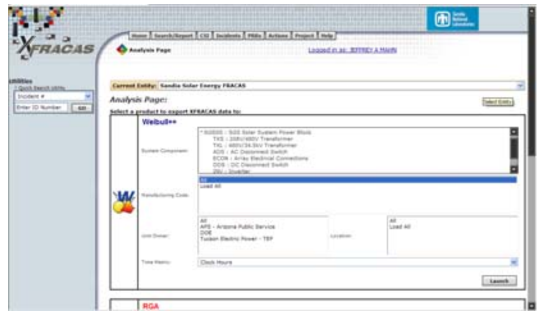

Figure 13. Analysis Page

The PV system template in the System Component box is expanded by clicking on the + sign and the component for which failure data is to be exported for Weibull++™ analysis is selected. Additional selections can be made for Unit Owner(s) and Location(s), if necessary, to further define the specific data to be exported (Figure 13). Note that "Clock Hours" is the applicable time metric for Weibull++™ reliability/availability analysis. Clicking on the **Launch** button on the lower right of the screen completes the data export. Figure 14 illustrates an example of exported failure data as it will be used by Weibull++™.

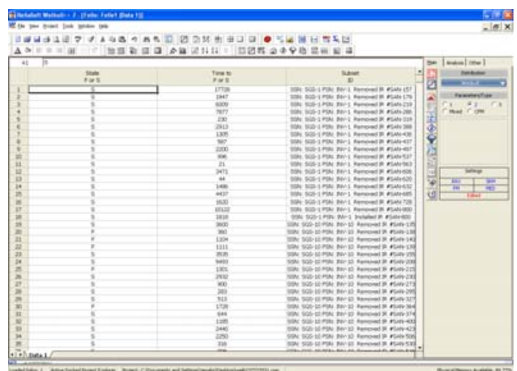

Figure 14. Weibull++™ Folio

Similarly, data from repairable systems can be directly exported to RGA™, *if* the systems are at Level 1 in the bill of material (BOM) hierarchy in XFRACAS™. Otherwise, XFRACAS™ accepts a user-customized Structured Query Language (SQL) query to export the required data from repairable subsystems and lower level components in the BOM hierarchy into Excel for minor pre-processing and transfer to RGA™ or Weibull++™ RDA. Different user-customized SQL queries were written for exporting data to Excel for pre-processing and transfer into Weibull++™ for analyzing downtimes due to repair, preventive maintenance, grid perturbations, and environmental causes like lightning.

IMPETUS FOR PVROM: AVAILABILITY PREDICTIONS

PVROM provides stakeholders in the photovoltaic industry the capability to make useful data-driven predictions for availability. For the power industry availability is interpreted in terms of kWhr production. Availability predictions require life data analysis, repairable systems analysis for reliability growth determination, and downtime analysis from all sources. Sandia adapted the XFRACAS™ software tool to collect and efficiently organize for analysis the data required for making availability predictions. Figure 15 illustrates a system availability prediction from a study in reference [2].

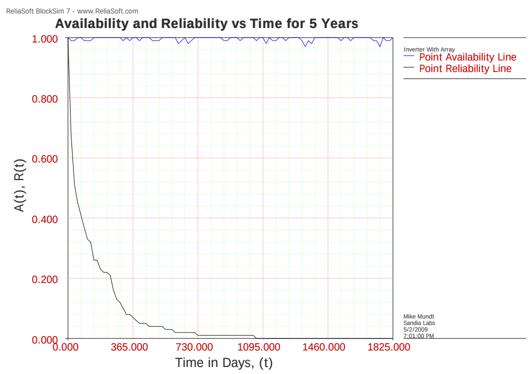

Fig. 15. Plot of Reliability and Availability versus Time for Inverter with PV Array

CONCLUSIONS

The authors have collaborated with ReliaSoft to successfully modify XFRACAS™ features to export data for reliability/availability analyses. We have successfully demonstrated the import of legacy data into XFRACAS™ and the export of that data in analysis format to Weibull++™ and RGA™ analysis tools. Also, we have successfully demonstrated entry of additional real-time data into XFRACAS™ and the export of that data to the analysis tools. The use of this software tool for automated data collection, entry, and organization for analysis should increase the efficiency of the analyses and the accuracy of results by minimizing the handling and transformation of the data.

FUTURE WORK

1. SNL's DOE Photovoltaic Reliability Program is interested in partnering with Renewable Energy manufacturers, installers and operators to develop baseline O&M and reliability data for photovoltaic components and systems. Inherent in XFRACAS™ is the cyber security features that assures data entered into PVROM is protected and only accessible to the partner that entered their data.
2. Development and adoption of a reliability database using XFRACAS™ could support a life cycle approach for managing maintenance cost from conceptual development to retirement of fielded PV systems.
3. Integration of a reliability and availability model with a model of variations in solar irradiance due to factors such as weather, seasons, and geography and a model of module performance into a higher level simulation model can be used to predict the yearly kWhr output of a photovoltaic system. SNL is currently developing this model.

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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