A TEN YEAR REVIEW OF PERFORMANCE OF PHOTOVOLTAIC SYSTEMS

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ABSTRACT

This paper presents data compiled by the Photovoltaic Design Assistance Center at Sandia National Laboratories from more than eighty field tests performed at over thirty-five photovoltaic systems in the United States during the last ten years. The recorded performance histories, failure rates, and degradation of post-Block IV modules and balance-of-system (BOS) components are described in detail.

INTRODUCTION

The Photovoltaic Design Assistance Center (DAC) at Sandia National Laboratories (SNL) has been responsible for the development and maintenance of a comprehensive database on the performance of photovoltaic systems for the U.S. Department of Energy during the past ten years. This work has addressed the critical issues of long-term module and system reliability, performance degradation and its mechanisms, and related maintenance topics. The DAC and the Southwest Technology Development Institute (TDI) have performed site visits to over thirty-five PV systems located in thirteen states, Washington DC, Bermuda, and Puerto Rico. The installation dates for the systems tested range from 1979 to 1992. Installed system ratings range from 0.1 to 1180 kW. Multiple visits were made to many of the sites, thus providing valuable measurements of changes in system performance with time.

The thirty-five PV systems evaluated for the system performance database represent a wide range of system designs, PV technologies, hardware and manufacturers. Technologies include single-crystal, amorphous, polycrystalline, and ribbon silicon modules. Arrays with fixed-orientation mounting as well as single and dual-axis tracking were tested. All of the major manufacturers of PV modules and power conditioning systems (PCSs) are represented. The sites are dispersed geographically.

EVALUATION METHODOLOGY

At least one site visit was made to each system. During each site visit, the following field activities were performed:

- Observation of the physical state of the system noting broken or damaged modules, failed structural components, shading of the array, or any hardware failure such as non-functioning tracking devices;
- Inspection of the electrical circuitry and components noting improper installation, corrosion, failures, evidence of fire, or PCS problems;
- Testing to identify and mark non-producing modules, failed bypass diodes, or improper wiring connections; and
- Electrical testing at the array, subarray, string, block, and module level (as appropriate) using portable current-voltage (I-V) curve tracing equipment.
- When possible, maintenance records and other performance data collected by site operators were integrated into the data base.

From the measurements and observations made during field tests, statistics for the following were compiled: failed or non-producing modules, shattered modules, failed balance-of-system (BOS) components, wiring failures, and accuracy of system dc ratings.

Simple repairs were made during the site visits. Recommendations for system maintenance also were provided to the operators of the systems following completion of the site visit. A detailed trip report for each site visit was prepared and is kept on file at TDI.

GENERAL RESULTS

Some early generation PV modules exhibited serious reliability problems. Test results from approximately 20,000 pre-Block V modules are included in the DAC system performance database. About one half of these were found to have been non-producing at the time of testing. Figure 1 provides a breakdown of the findings from field tests of arrays with pre-Block V modules. Of the over 10,000 non-producing modules that were found, approximately 90% had experienced some form of module failure (1). Within this paper, a PV module is defined as having failed when two criteria are met: 1) its power output has fallen to less than half of its original rating; and 2) it can not be repaired in the field.

Pre-Block V modules failed for a variety of reasons. Some of the most common reasons for failure of pre-Block V modules were: breakdown of the encapsulation material, hot spot formation from inadequate or lack of bypass diode protection, cell-interconnect ribbon failures and, the frequent use of experimental designs and materials during this early phase in the development of PV technology.

The implementation of the Block V module qualification test specifications (2) in the early and mid-eighties brought much improved module reliability to fielded systems. Figure 2 presents the distribution of failure modes of non-producing modules found in the Block V module arrays tested. In contrast to earlier generation modules, the failure rate for Block V modules was less than 1.3% of those tested. Overall, 6.5% of the modules tested were found to be non-producing, but these were generally the result of failures of components other than the modules themselves.

Failures of BOS components such as switches, fuses, blocking diodes, surge protectors, and dc contactors were responsible for 54% of the non-producing modules that were found. A single BOS failure can affect a large number of modules. An open fuse, for example, can take an entire string off-line.

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Figure 1. Non-Producing Modules Pre-Block V

Wiring problems due to failure of the metal ribbons used in laminate/bus bar construction or within the connectors of module junction boxes were responsible for 7% of the non-producing modules that were found. Each module wiring problem not only affects the single module directly involved, but often results in a condition of severe mismatch for the other modules wired in the same parallel block. When one module in a parallel block fails or becomes non-producing due to a wiring problem, the other modules in the block can become bypassed as a result. In this way, the effect of a single module or wiring failure is often multiplied by 8 or 10 in its net effect on power output. Severe mismatch was the second most common cause of non-producing Block V modules, responsible for 38% of the total.

PERFORMANCE TRENDS

The reliability of Block V modules has enabled the collection of long-term performance histories for these modules and the systems in which they are used. Earlier, module failure rates were so great that long-term performance histories were unobtainable: systems often failed or were manually disconnected after only a year or two of operation. The PV systems installed during the mid- and late-eighties have now been in continuous operation long enough for trends to emerge from the system performance database.

The dc array ratings for several Block IV and V systems have been monitored for the last seven years. Ten sets of these data are presented in Table 1. The system ratings presented in Table 1 are those determined from field test measurements for STC conditions (1000 W/m² irradiance, 25°C module temperature) and do not reflect manufacturers' nameplate values.

The data indicate that, on average, the dc performance of these systems has been declining approximately 2% per year. This decline in plant rating is seen to some extent in all PV module technologies: single crystal silicon; polycrystalline silicon; amorphous silicon. It is also seen in a variety of climates.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

In the late 1970's and early 1980's, the first generations of terrestrial PV systems were being implemented. For the most part, these systems were small, though a few government sponsored systems in the tens to hundreds of kilowatts were also installed. For these early generations of systems, PV module costs and failure rates were so high that the market was totally constrained by these two elements. During this time, the DOE sponsored SNL/TDI program of long-term performance monitoring and field evaluation began. The program documented the problems associated with these early systems. As module problems were observed, the field evaluation team would provide the module development team at JPL with samples of the failed hardware for evaluation. Through this process, prevalent problems in fielded systems were identified and their rates of occurrence quantified, causes were evaluated, and the information was then fed back to development efforts in industry.

During the mid-1980's, a new generation of PV systems was being installed. These systems benefited from the lessons learned from earlier generations of PV systems. Much of the improvement of the new systems was the result of the DOE program which developed a standard specification for modules: even today, systems are specified with the phrase "modules must meet or exceed JPL Block V Specification". Module failure rates dropped by an order of magnitude. Long term field

Figure 2. Non-Producing Modules Block V

evaluation continued but at a significantly reduced rate because of the beliefs that:

- The most significant problems for PV systems had been eliminated (module failures);
- Only necessary and sufficient information (i.e. better module life) was required for validating this belief;
- The technology was now ready for large-scale commercialization.

Current efforts continue to improve the performance and reliability of PV systems. SNL has begun to support manufacturers directly in identifying problem areas. Through these joint efforts between industry and SNL, progress is being made to correct deficiencies found in the field. These efforts span from improvements in module design to power processing evolution. The field evaluation team from TDI continues to evaluate and document the performance of new and existing systems installed in the field.

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**Table 1
Array Degradation Trends
(kiloWatts)**

System	1985	1986	1987	1988	1989	1990	1991	1992	Degradation Per Year
AUSTIN PV300			288	274	267	268			1.7%
FOND DU LAC				1.7	1.6				1.6%
GEORGETOWN	270			210					6.8%
JOHN LONG			181		171			161	2.3%
NEWMAN PS	16.9			15.8		13.8			3.9%
SMUD PV1	1050	990			947				2.1%
SMUD PV2		988	926		931				1.8%
WP&L MUNI		2.1	2.0		1.9				1.9%
WP&L RES		2.0		1.9	1.8	1.8		1.8	1.5%
WP&L SOC			1.8	1.8	1.6				4.7%

*Accuracy of the data is within $\pm 2\%$

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