Sandia National Laboratories Photovoltaic Balance of Systems Program

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Abstract

The Sandia National Laboratories photovoltaic balance-of-systems (BOS) program is sponsored by the Department of Energy to increase the reliability and lower the cost of BOS components. Efforts for FY1998 are discussed. Principal efforts include a quality program for inverter manufacturers, a grid-tied anti-islanding program, development of a hybrid inverter, hardware benchmarking program, and a battery evaluation program.

HIGHLIGHTS OF SANDIA'S BALANCE-OF-SYSTEMS PROGRAM

This paper focuses on some of the major issues addressed by Sandia's balance-of-systems (BOS) program in FY1998. The SNL BOS program concentrates on power electronics and battery health. The goals of the program are to:

- advance the reliability of photovoltaic electronic components to the levels achieved by more mature products,
- reduce life-cycle cost,
- remove barriers to implementing photovoltaics,
- assist component manufacturers and system integrators with the development of more reliable, cost-effective systems.

The program includes both contracts with industry and laboratory evaluations. The in-house laboratory supplements the capability of photovoltaic component manufacturers by providing a test-bed that includes extensive measurement capability and realistic reproduction of field conditions. These conditions include complex loads, photovoltaic arrays, engine generators, and batteries. Further testing support is obtained from laboratories at the Southeast RES and private labs. Benchmarking of products is conducted to obtain product information. Contracts with the photovoltaic industry have been focused on improving system reliability and reducing life-cycle cost. These have included the development of quality programs, HALT™ (highly accelerated lifetime testing), quality audits at the contractor's facilities, and some product development. Information about the BOS work at Sandia is available on Sandia's WEB site (www.sandia.gov/pv).

Islanding of Multiple Grid-Tied Inverters

A section of a utility distribution system that has been disconnected from the rest of the utility is called an island. Utilities currently require photovoltaic inverters to disconnect when they are in an island, because of reasons related to safety, protection of loads, and utility reclosure. During the summer of 1997, Sandia conducted a series of tests to investigate islanding of multiple inverters on a single 120-V ac circuit. It was found that for $Power_{generation}/Power_{load}$ ratios in the range of .8 to 1.2 the inverters frequently islanded for more than the 2 the seconds (times > 30 seconds were observed) required by some utilities. It was also observed that the presence of a transformer in the islanded circuit resulted in shorter islanding times (disconnect times of < .5 seconds) because the transformer required nonlinear magnetizing current that most inverters could not supply.

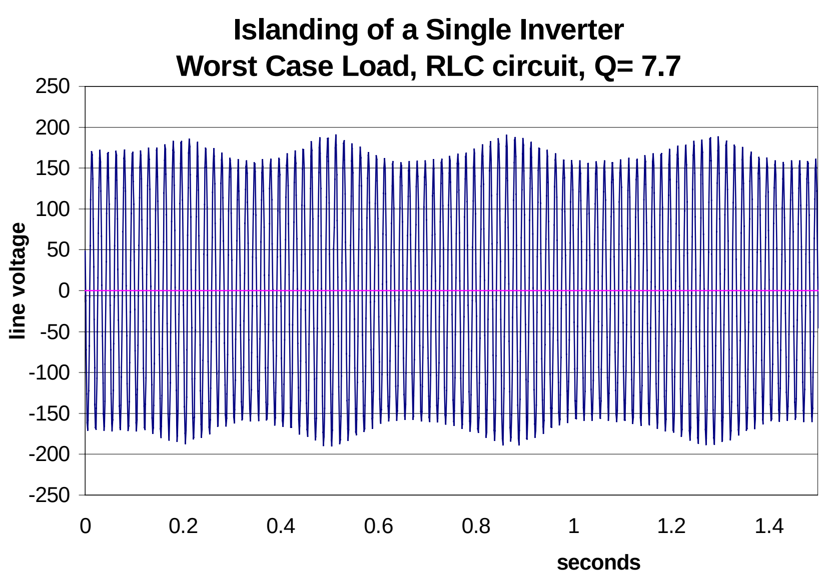
The conclusions drawn from these tests were

- multiple inverters on a single 120V ac circuit were not disconnecting quickly enough,
- the presence of a distribution transformer resulted in quicker disconnect,
- future tests should include other than purely resistive loads, so that worst-case islanding conditions could be determined,
- the use of multiple inverters utilizing different anti-islanding techniques increased islanding times.

Sandia initiated a working group composed of U.S. inverter manufacturers to address these issues, and sponsored the development of a new approach to prevent islanding through Ascension Technology, Inc. This method has been developed and tested; the results, titled "Results of Sandia National Laboratories Grid-Tied Inverter Testing," are on the Sandia WEB page and were presented at the 2nd World Conference and Exhibition on Photovoltaic Solar Conversion in Vienna. The salient points of this work are the definition of a non-islanding inverter, an acceptable design to develop a non-islanding inverter, and the identification of a resonant RLC circuit as being "worst case" for islanding. A non-islanding inverter is defined as an inverter that does not island when the inverter output frequency is within the defined operating frequency and voltage ranges, and the Q (quality factor) of an attached resonant RLC load is less than 5. Typically, in the U.S. the acceptable frequency range is from 59.5 to 60.5 Hz and the voltage range is from 110 V ac to 132 V ac. If the frequency is outside the defined frequency range, the RLC circuit can have any Q. The value of Q=5 was selected because input from utility engineers on the IEEE P929 (Recommended Practice for Utility Interface of Photovoltaic Systems) working group indicated that higher values of Q were unlikely.

A further requirement is that all inverters in parallel with the non-islanding inverter also be non-islanding and that no synchronous generators be present. A method for designing an anti-islanding inverter that includes combined passive and active techniques was included in the Vienna paper. The passive methods are over/under frequency and over/under voltage. The active methods are defined as SFS (Sandia frequency shift) and SVS (Sandia voltage shift). For the inverter developed during the course of this project, all of these methods were required to prevent islanding in a resonant RLC circuit with a Q of 5. Loads other than the RLC circuit disconnected very rapidly with the exception of an induction motor. The case with the induction motor was slightly easier to disconnect from than a resonant RLC circuit with a high Q.

When manufacturers develop new grid-tied inverters, it is inconvenient to require a multiple inverter



test to verify non-islanding inverters. Furthermore, Underwriters Laboratories desires a single inverter test. Therefore, Sandia is currently working on the development of a single inverter test that identifies an "islanding" inverter. In addition, Sandia is preparing a Sandia report that documents a procedure for evaluating multiple inverters. When IEEE P929 becomes a standard, it is likely that a single inverter UL test will be required and that Sandia's multiple inverter work will be referenced. Utilities that feel uncomfortable with the UL single-inverter test may either conduct their own multiple inverter tests or refer to Sandia's multiple inverter evaluations. Work in 1999 will include multiple inverter testing of several new inverters, each of which will be evaluated alone and with other inverters. At this time it appears that any inverter that will island in the multiple-inverter scenario will also island by itself with a high Q resonant RLC load. This is demonstrated by the waveform above, where the utility disconnects at .1 second and the inverter runs on indefinitely.

Development of a New Hybrid 30-kW Inverter

Some large hybrid systems have experienced reliability problems, which may be attributed to their unique, site-specific designs. With that in mind, a specification was developed jointly between Sandia and Trace Technologies for a replicable design of a 30-kW hybrid power processor as a first step toward standardization. The inverter was to be tested at Sandia and provided to Arizona Public Service (APS) for use in its STAR facility. At STAR, it is to be integrated with a bank of tubular gel batteries of a new type that has been developed jointly by Yuasa Exide and by Sandia's battery group specifically for hybrid applications. The objectives of the project were 1) to assist in the development of reliable photovoltaic-hybrid power-processing products with widespread applications, 2) to provide APS with a useful tool for its application-driven research, and 3) to enhance understanding of hybrid power-processing issues.

Many of the observed problems in past installations resulted from the approach to site development. That approach assumed that the inverters existed for the intended application, but then defined a specification that required a new product, and, consequently, fielded an untried prototype. The preferred approach, used in this development, includes the following steps:

1. define system requirements for a wide range of applications
2. define inverter specification for a universal design
3. build and evaluate an alpha unit
4. field the unit at a test site
5. and, finally, go to the production stage.

The key point is that development and evaluation be completed prior to field deployment. The objective is to prevent deployment of a new, under-tested, prototype in a high visibility field installation. This product (see photo) is now being deployed at other sites.

Testing: During the course of testing at Sandia, several issues were identified. All were addressed by Trace Technologies in a cooperative, cost-sharing effort. The major modifications involved primarily the control system and were made in response to suggestions by Sandia and APS personnel. These modifications have an impact on system reliability, generator compatibility, battery maintenance, and/or user satisfaction. They should make the inverter more universally applicable and less site-specific so that it can be applied in various sites with minimal field interaction required from the design engineer.

Lessons Learned: Reliability is a critical concern of APS. From the perspective of a utility, the number of conditions that could result in a loss of load should be minimized.

A second lesson is that if a protective ac current limit is in place, voltage sags are inevitable when large loads are applied. To minimize such sags, a reduced-voltage starter should be considered for motors that are a significant fraction of the inverter rating. Installation of such relatively inexpensive equipment can enhance performance significantly and should be considered a routine part of site load management when installing a photovoltaic-hybrid system. Site loads should be assessed for their sensitivity to disturbances and, if necessary, protected with an uninterruptible power supply.

Selection of an undersized or poorly regulated generator can undermine system performance. Generators for photovoltaic-hybrid systems should include modern electronic (isochrynous) governors and should be rated for the maximum "expected" site load.

Battery treatment is key to the reliability and life-cycle cost of a hybrid system. As such, the charging algorithm should provide

1. user-adjustable voltage and time set points for both normal and finish charge,
2. temperature compensation,
3. battery over-temperature protection, and
4. automatic finish charge.

Battery temperature compensation is important for ensuring the battery is properly charged. Lowering the charge voltage avoids overcharging when the battery is hot. Conversely, raising the battery charge voltage avoids undercharging when the battery is cold. However, temperature compensation has limits. The manufacturer's specifications should be consulted.

Additional Work Three issues related to battery treatment were discussed at a pre-installation kickoff meeting for the STAR project that included representatives of Sandia, APS, Arizona Sate University, and Yuasa Exide. The issues are

1. disabling temperature compensation outside a selectable range of battery voltages
2. addition of a separate set point for the taper value of finish charge current
3. addition of a "time at battery voltage" set point to avoid unnecessary generator starts due to large short-duration loads.

Trace Technologies is evaluating the impact and the level of risk associated with implementation of these refinements. System performance at APS is being monitored by a data-acquisition system developed by the Southwest Technology Development Institute and operated and maintained by Arizona State University.

Sandia's Quality/Reliability Program Results in Improved Inverter Reliability

Accelerated Lifetime Testing of Photovoltaic Electronics. Highly accelerated lifetime testing (HALT™) is an effective tool for increasing reliability. By identifying latent problems; HALT™ lowers the failure rate from that typically associated with new products to that of a mature product. This evaluation stresses products beyond design specifications, establishes destruct limits, determines the root cause for failures and corrects problems before a product is fielded. Sandia is acting as a facilitator between the photovoltaic manufacturers and highly accelerated test laboratories (such as QualMark), which provide this testing. A typical test on a small inverter or charge controller costs $11,000, takes 200 hours for a humidity test and about 30 hours for vibration, temperature, and electrical stresses. Products in the development stage are targeted for HALT™ testing.

Quality and Reliability Contracts. Sandia has initiated contracts with selected companies to install quality programs at the contractor facilities that can lead to ISO 9000 certification. These programs are leading to more robust balance-of-systems components.

Quality Audits at Contractor Facilities. In lieu of funding full-scale quality programs at the contractors' facilities, a quality audit can be provided by Sandia. The quality audit consists of a visit by a quality inspector who then provides a written list of problem areas and suggested improvements. Quality audits are provided to qualified contractors who request them.

Sandia's Testing/Benchmarking Activities

There is a continuing need for an evaluation laboratory to support PVMaT, photovoltaic manufacturers, and the photovoltaic industry. This laboratory includes instrumentation, loads, and power sources that may be beyond the means of balance-of-systems manufacturers. Evaluations are provided free of cost to most U.S. manufacturers of photovoltaic components. As well as supporting the development of new products, the laboratory facilities benchmark existing products. These evaluations include:

- Evaluations of small, grid-tied inverters for islanding, power quality, and inverter response to power disturbances, including voltage sags, surges, and EMI pulses while the inverters are connected in parallel with other inverters.
- Benchmarking evaluations of inverters that identify inverter problems or result in a report posted on the WEB. These are products that are generally not the result of a government contract and are available to the public for purchase. The tests of four such inverters in the past year resulted in redesign of the inverters and no report for the WEB. One evaluation of a product led to a WEB report.
- Evaluations of PVMat hardware. When delivered to Sandia, PVMat prototypes undergo a rigorous characterization. This is generally the first real evaluation of these prototypes, and design changes invariably result from this evaluation. Correcting problems and retest are an essential element in the development of any new product. Frequently, however, the contract is near its end and the contractor has not allotted funding for more product changes.
- Prototypes and other developmental photovoltaic balance-of-systems hardware. These evaluations typically result from a manufacturer's request.

Battery Evaluations for Hybrid Photovoltaic Systems

Using the extensive experience of Sandia and the Florida Solar Energy Center (FSEC) with small stand-alone photovoltaic battery testing, new work is now underway to address battery charging issues associated with photovoltaic hybrid power systems. Photovoltaic hybrids represent a relatively large group of renewable energy power systems with multiple power sources that vary considerably with respect to system design, size, load characteristics, and possible battery management strategies. The hybrid system variables make it difficult to use experience with stand-alone photovoltaic battery charging to predict battery performance in a photovoltaic hybrid system. Preliminary test results at Sandia indicate that both vented and valve-regulated lead-acid batteries can quickly lose capacity in a photovoltaic hybrid environment. This premature capacity loss stems primarily from an operational mode known as deficit-charge cycling. Deficit-charge cycling occurs when a discharged battery is not fully recharged after each discharge. This is a common cost-reduction practice because of the high cost of sizing the photovoltaic array to fully recharge the battery or the added engine generator runtime required to finish charge the battery. Work at Sandia is now focusing on identifying the minimum hybrid battery-charging requirements to prevent premature capacity loss resulting in a shortened battery cycle-life. The goal of this work is to minimize operation and life-cycle costs in photovoltaic hybrid systems.

A photovoltaic array and/or engine generator can charge batteries in photovoltaic hybrid systems in a variety of configurations. Multiple power sources provide more system design flexibility and improved availability, but they also increase complexity. With complexity come more uncertainties with respect to system design and management of that design. Since there can be a wide variation of power contributed by the photovoltaic array or other power sources, it is possible to design photovoltaic hybrid systems that are almost totally dependent on the engine generator for battery charging or systems that are essentially stand-alone photovoltaic systems. Battery charging requirements and the necessary controls will vary considerably as the dependence on the engine generator varies. Therefore, batteries in photovoltaic hybrids may be subjected to more harsh conditions than in stand-alone photovoltaic systems if the system design does not provide the necessary controls. An engine generator does not guarantee proper battery charging. With this in mind, laboratory testing is now under way to identify appropriate deficit-charge cycle periods, finish charge ("equalization") times, regulation voltages, and time intervals between finish ("equalization") charges for vented and valve-regulated lead-acid (VRLA) deep-cycle batteries. It should be noted that even though equalization is frequently used interchangeably with finish charge, equalization is a distinct process that begins at the end of the finish charge.

Preliminary Test Results: Test results have shown that the deficit-charge cycle time and full recovery requirements are significantly different for vented (flooded) and VRLA batteries; therefore, it is critical to understand the specific charging requirements of the battery used in the photovoltaic hybrid system. Vented batteries that spend more than a few days in a deficit-charge condition will begin to suffer from electrolyte stratification. Stratification makes recharge more difficult by prematurely raising battery voltage during recharge. This condition falsely indicates a higher battery state of charge than is actually present. In addition to stratification in vented batteries, the charge efficiency of both vented and VRLA batteries needs to be accounted for by charging more amp-hours (Ah) into the battery than were removed during each cycle. The Ah overcharge requirement for a vented battery is usually between 120 and 130%. VRLA batteries usually require between 105 and 112% overcharge. Therefore, the combination of renewable energy power sources and engine generator battery charging must meet the overcharge requirement to compensate for the stratification and battery efficiency loss.

In all cases photovoltaic hybrids need to be designed to minimize deficit-charge cycling while still minimizing engine generator run time. This can be accomplished by using appropriate regulation voltages and providing only the required finish charge intervals. If the photovoltaic and/or engine generator charge controller regulation voltage is too low, or the time at regulation voltage is too short, then the required battery overcharge cannot achieve the required value effectively with either the photovoltaic or engine generator. Proper battery management requires a photovoltaic or engine generator charge controller with an appropriate photovoltaic regulation voltage, and time at regulation voltage, using temperature compensation to recover from deficit-charge conditions. A key element in achieving this is an engine generator battery charging control that provides an automatic battery finish charge at set intervals from one to four weeks for specified finish charge times and voltages.

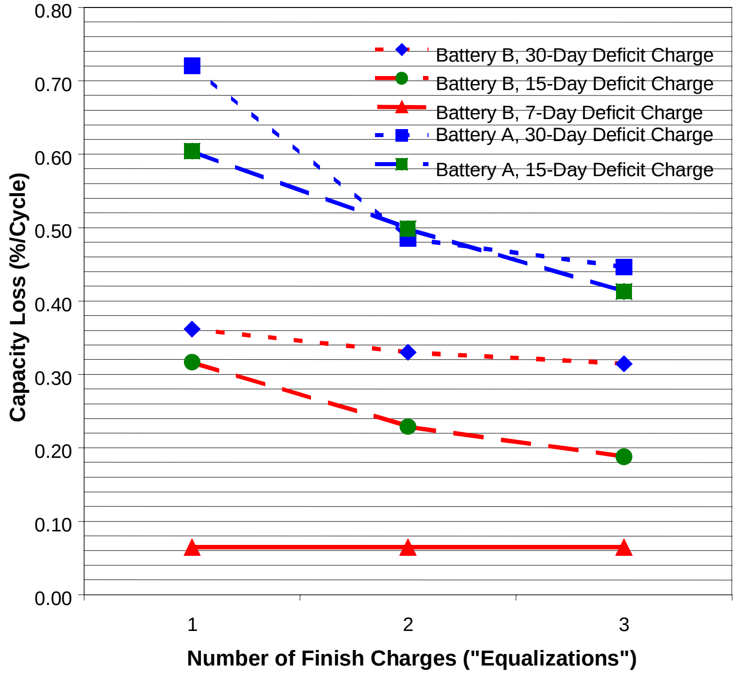
As an example of this work, the two batteries in the photograph below (Battery A and Battery B) are being tested in the laboratory to identify appropriate deficit-charge intervals and finish charge requirements. Follow-up field tests will be conducted to further validate the findings. However, since these preliminary results are important they are being released at this time.

Laboratory testing has shown that Batteries A and B lose capacity quickly after just short periods in deficit-charge cycling. Battery A lost 27% and Battery B 19 % of capacity after only three 30-day deficit-charge cycle intervals in which the battery was only bulk charged to 2.35 Vpc (14.1 volts) every 1.5-days and finish charged at 2.35 Vpc for 12-hours every 30-days.

The graph shows permanent capacity loss after each finish charge indicates that Battery A lost about 0.45 and 0.41% per cycle after the third 30- and 15-day deficit charge interval. If this capacity loss rate continued, then the battery would lose 50% of its capacity in just 100 to 122 deficit-charge cycles. Using the same deficit charge cycle and finish charge, the graph also shows capacity loss for Battery B at 0.31, 0.19, and 0.06% per cycle for the 30-, 15-, and 7.5-day deficit charge interval. Again, that’s a 50% capacity loss in 161 to 833 deficit-charge cycles if the capacity loss continues as indicated from the initial 15 to 60 cycles. The graph clearly shows that both batteries do experience less capacity loss with more frequent (7.5-to 15-day) finish charges. This is an important departure from past thinking where it was felt that either no finish charges were required or that 30-day intervals between finish charges ("equalization") were acceptable.

Hybrid Battery Summary: Battery management in photovoltaic hybrid systems needs to follow a few simple rules even though system design can vary considerably. If the photovoltaic system designer provides the photovoltaic battery with its basic charging needs on a regular basis, then the traditional photovoltaic battery problem of premature capacity loss and early cycle-life failure can be minimized. Maintaining photovoltaic batteries in a healthy condition in many cases will more than double cycle-life and thus increase reliability, thereby significantly reducing overall life-cycle costs.

Proper Battery Charging of Photovoltaic Hybrids: Any photovoltaic hybrid battery management strategy should limit the number of days the battery spends in a deficit-charge condition and provide a means for full recovery of that battery on a regular basis.



Capacity Loss Versus Length Of Deficit-Charge Interval For Batteries A and B