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OVERVIEW OF PV BALANCE-OF-SYSTEMS TECHNOLOGY: EXPERIENCE AND GUIDELINES FOR UTILITY TIES IN THE UNITED STATES OF AMERICA*

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ABSTRACT

The U.S. National Photovoltaic Program began in 1975 by supporting the development of terrestrial PV modules and hardware associated with grid-connected PV systems. Early PV-system demonstration programs were also supported and cost shared by the U.S. Department of Energy (DOE). A wide variety of PV systems were deployed, usually with utility participation. The early demonstration projects provided, and continue to provide, valuable PV system experience to utilities, designers and suppliers. As a result of experience gained, several important milestones in codes and standards pertaining to the design, installation and operation of photovoltaic (PV) systems have been completed. These code and standard activities were conducted through collaboration of participants from all sectors of the PV industry, utilities and the US DOE National Photovoltaic Program. Codes and standards that have been proposed, written, or modified include changes and additions for the 1999 National Electrical Code® (NEC®), standards for fire and personnel safety, system testing, field acceptance, component qualification, and utility interconnection. Project authorization requests with the Institute of Electrical and Electronic Engineers (IEEE) have resulted in standards for component qualification and were further adapted for standards used to list PV modules and balance-of-system components. Industry collaboration with Underwriter Laboratories, Inc. (UL), with the American Society for Testing and Materials (ASTM), and through critical input and review for international standards with the International Electrotechnical Commission (IEC) have resulted in new and revised domestic and international standards for PV applications. Activities related to work on codes and standards through the International Energy Agency (IEA) are also being supported by the PV industry and the US DOE. This paper discusses PV system experiences and knowledge gained from utility-interactive installations, new or changed codes, and standards for PV systems. The paper also shows relationships between activities in standards writing.

INTRODUCTION

The U.S. National Photovoltaic Program emphasized grid-connected PV systems once affordable terrestrial modules were developed and commercially available. The program

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sponsored and co-funded demonstration projects, resulting in a wide variety of PV systems that were normally deployed with a utility's participation. The early programs did provide valuable experience to utilities, designers and suppliers. Many of the early systems were heavily monitored. The specifications often burdened the early hardware with set point limits that were too restrictive and too numerous. The early conservatism did produce untold volumes of data, but also produced data that pointed to hardware deficiencies that were actually design errors. Whenever data from an evolving industry is analyzed, it must be recognized that the variables are constantly changing or not known, and that conclusions, especially those that point to a particular weak link such an inverter, may be unknowingly biased. Many of the early suppliers were selected because they submitted low bids. The request for proposals or system requirements were also found to have flaws after the fact.

This paper reports on selected experience gained, but the data and information are generic in content. Early PV installations were heavily instrumented and monitored, but the methods for gathering the data varied considerably. For example, averages using different time intervals were calculated in the different systems. Six-second averages produce different results than fifteen-minute or one-hour averages. Many system interruptions or failures were reported, but the fine details of the event were often missing. Some interruptions lasted for days until a manual reset was operated, resulting in long down time that would not have occurred with automatic resets. Thus, events were reported as reduced availability or inverter failures.

Developments of utility-interactive, PV-compatible inverters have been supported through the U.S. National PV Program. Early designs occasionally came from modified uninterruptible power supply (UPS) hardware or were developed from inverters intended for other uses, such as wind power. The inverter industry is much more mature today. New PV inverters have been designed specifically for PV applications, but this paper will not discount the need for still more reliable balance-of-system hardware and better system design practices. It focuses on findings and known solutions learned from controlled utility-interactive PV system experience.

Several important milestones in codes and standards have recently been completed as a consequence of PV system experience gained over the years, and to help avoid code or standards related installation problems with future PV projects. The NEC is an evolving document that is continually updated in a three-year cycle [1]. The 1999 "code cycle" began for the PV industry with the issuance of the 1996 NEC [2]. Collaborative work was completed by a PV-industry supported Task Group to write proposals for changes to bring Article 690 of the 1999 NEC up to the state-of-the-art in PV device and system technology. The task group was also supported by the DOE Photovoltaic Program, the Solar Energy Industry Association (SEIA), and most importantly by all sectors of the PV module and balance-of-system industries. Close coordination with the Institute of Electrical and Electronic Engineers (IEEE) standards committees and Underwriters Laboratories, Inc. (UL) have also been an important part of the code work.

OVERVIEW OF SYSTEM EXPERIENCES AND DESIGN RECOMMENDATIONS

System Experiences

General analysis of the early utility-interactive installations is very difficult because of variability in the data, data collection methodologies, general system designs, component replacements, and expected system performance. Individual system analysis is often excellent, but comparative system analysis often led to incorrect conclusions. Ascension Technology has been tasked through various contracts with installing and logging the performance of over 126 PV systems from July 1994 to the present [3]. These systems are installed in 62 different locations, but the data collection method has been consistent. The data represents over 2847 inverter-months (237 inverter years) of utility-interactive inverter operations. The inverters range from 2- to 6-kW power ratings. System anomaly data was classified as events in PV modules, inverters, source circuit protectors, and disconnect switches. Other events such as snow, wiring mistakes, utility outages, vandalism, dirt and other variables are not recorded in this study as specific events. Of the total 190 events recorded, approximately 75% were related to inverters. Inverters from four different manufacturers and several models from the same manufacturer were used. The array accounted for approximately 11% of the events and switches accounted for approximately another 10% of the events. It should be noted that, of the 62 sites monitored, 53 had no PV module events.

Inverter events were found to range from improper trip-point settings, faulty sensors, capacitor failures, blown fuses, transistor failures and over temperatures. The difficulty of detailing all of the field failures arises in this well-controlled study with more than 60 unknown inverter failure modes. It should be noted that 17 of the 62 sites had no inverter events. Inverter failure frequency, using the data for all systems, averaged an inverter event each 1.65 years in this study. Obviously some inverter designs were found to have fewer failures than others. Trends show a decline in the frequency of events in one model of inverter of approximately 20%, but overall inverter events show no trend. Wiring events have also decreased over the last three years, but other events remain apparently random in nature with no obvious trends.

System Design Observations and Suggestions

Pacific Gas and Electric has conducted a study to identify system-related design strengths and weaknesses using the systems installed at PVUSA [4]. The study categorized installation and design areas where success and failures were experienced. The categories include inverter design, inverter performance, wiring, control, instrumentation, structures, trackers, and general assembly practices.

An important finding about inverters is the environmental conditions to which the inverter will be subjected. Inverters should be mounted in shady areas or in temperature-controlled spaces. Inverter designs that require special air conditioning should be avoided. The inverters installed were often not as efficient as expected because the inverters' operating point is where the efficiency is lower. Inverters with efficiency profiles non-flat often do not operate at peak-efficiency. Inverters should be able to handle transient peak irradiances either by power limiting or changing the operating point so that a lower power level is available from the PV array. Dust and humidity have produced a variety of connector problems especially with pc-board edge connectors. All components should be rated for the expected temperature and humidity ranges.

Acceptance testing and scheduled field testing of installations has been extremely beneficial and has avoided potential catastrophic failures by finding wiring and operational problems. The field testing can also be used to help to train personnel. All PV-system designs should minimize maintenance. Air filters, fans, seals, and the need to reload control programs are maintenance-intensive and expensive. More complete O&M manuals will also minimize future failures because proper maintenance will be more likely.

Many of the failures recorded in PV systems are closely related to following properly written codes and standards. Loose connections, especially on the dc side of systems, are often related to temperature cycles, marginally rated connector blocks or terminals, marginally sized wiring, or improper torque applied during installation. Torque procedures must be strictly adhered to. Blown fuses may also be closely related to the temperature ratings of the fuse or the fuse holders. The use of listed and recognized components will often alleviate most of the system installation and operational problems. Using listed and recognized components, however, does not guarantee that the components are compatible with each other. Compatibility must be determined by the system designers.

OVERVIEW OF CODE WORK

A number of the changes in the NEC were needed because of recent advances in technology. Several new products and applications have been emerging from the PV industry. They include AC PV modules, modular inverters with multiple modes of operation (utility-interactive, stand-alone, and hybrid), triple-junction PV modules, building-integrated PV products such as roofing shingles, PV laminated roofing, window walls, and facades. Many changes were also written for clarifications of the current language or to modify requirements currently included in the NEC.

A Task Group wrote and submitted 59 proposals for PV system-related changes to the National Fire Protection Association (NFPA). The work concentrated on PV industry-prioritized issues related to safety and installation. Changes were proposed for fire and personnel safety, system servicing, AC PV modules, integration of PV into building electrical systems, point-of-connection for building-integrated systems, clarifications for hybrid systems, batteries, and charge controllers. All proposed changes were based first on safety. Other considerations were PV system installation impacts, good engineering practice, interconnection with the utility grid, availability of hardware, and system cost and performance. A complete set of 1999 NEC proposals and code making panel actions are published for public comment in the NFPA Report on Proposals [5].

New Part I Was Added for PV Systems Greater than 600 V

One new part was written for Article 690 to provide requirements for PV systems operating at greater than 600 Vdc. The addition of Part I, dealing with PV systems with dc voltages greater than 600 volts, and clarification that installations in single- and two-family dwellings be limited to 600 volts, gives valuable safety requirements for PV installations. The addition also clarifies the intent of system voltage calculations and requirements, and makes it perfectly clear that systems with maximum system voltages over 600 volts must use requirements in other parts of the NEC.

Definitions

Proposed changes addressed all of Article 690. A significant number of changes and additions

Definition	New or Change	Impact, Consequence or Description
AC Module (AC PV Module):	New	Allows AC module applications. Defines AC modules as a complete listed package for Section 690-6 (AC Modules).
Array:	Change	Removed the old reference to thermal controller.
Charge Controller:	New	Defined the role of charge controller in PV systems.
Electric Production and Distribution System:	New	Defined a utility grid as one that is not controlled by the PV system. Needed to better differentiate hybrid systems.
Hybrid System:	New	Defined hybrid systems and energy sources in hybrid systems.
Interactive System:	Change	Defined an interactive system as tied to the utility grid.
Inverter:	Change	Better defined charging functions associated with some inverters.
Inverter Input Circuit:	Change	Defined inverter input circuit for both stand-alone and interactive inverters.
Inverter Output Circuit:	Change	Clarified definition to be consistent with proposed Figure 1 of Article 690.
Module:	Change	Clarified definition and differentiated AC modules.
Photovoltaic Output Circuit:	Change	Changed to make language consistent.
Photovoltaic Source Circuit:	Change	Changed to make language consistent.
Stand-alone System:	Change	Clarified and removed tie to utility interactive systems.
System Voltage:	New	Added to provide consistency throughout Article 690.

Table 1. List of proposed definition changes for 1999 Article 690, NEC

were proposed in the definition section. They described new devices, tied the Sections of Article 690 to the remainder to the code, and provided consistency in language throughout Article 690. See Table 1 for the affected definitions.

New Sections for Article 690

Several new sections for Article 690 were proposed for the 1999 NEC. One completely new section (Section 690-6 - AC Modules) was added to address requirements for the new AC PV module products and their connection to the utility lines. Other new sections included 690-10: Stand-alone Inverter, 690-11: Sizing and Protection, 690-52: AC Photovoltaic Modules, 690-54: Interactive System Point-of-Connection, 690-60: Identified Interactive Equipment, and 690-72: Charge Control. Some of the new sections consisted of language modified and/or moved from other parts of Article 690. Other changes were added for clarification or to address new applications, other new language and/or definitions.

Ground Fault Protection

A revised Section 690-5 provides much-needed clarification for ground-fault protection of residential roof-mounted PV installations for fire protection. The revisions provide rules for the detection, interruption and indication of ground faults. Indication is a very important addition since ground-fault interruption of grounded PV sources may involve disconnecting (or lifting) the grounded conductor or placing a high resistance in the ground path. The 1996 NEC gave no direction. The 1996 NEC Handbook tried to address the issue, but used the term "disable the array" that was a topic of more confusion, since the only way to truly disable an array is to block the sunlight [6]. The revisions give requirements for disconnecting the faulted PV source, interrupting the fault current, and indicating the status or condition of the system.

AC PV Modules

A very significant proposal for building integrated PV was the addition of Section 690-6 to provide the hardware, circuit and labeling requirements for installation of the evolving AC module technologies. Although just emerging as a new product, these devices will very likely find their way to hardware and department stores, architects' manuals, and builders' product lines by the time the 1999 NEC is issued. There have been more than 100 AC PV modules installed in the USA already, and orders exist for almost 1000 more. This new section provides the necessary functional requirements for safe installation and connection of listed AC modules to the utility lines and provides the requirements for labeling AC PV modules.

Solar Irradiation and Conductor Deratings

Solar irradiation of 1250 W/m^2 is common in many parts of the U.S. Bringing together the PV module current factor of 125% that is currently written as a UL requirement, and the NEC required 80% derating factor for continuous current for all conductors and overcurrent devices has been needed. Many opened fuses and loose connections in early PV systems can be attributed to overheating due to undersized wiring or improper temperature ratings for terminal blocks and fuses. There has been much confusion in applying these factors because they appear in different documents, but the proposed change (690-8) for 1999 puts all requirements in the NEC and simplifies the calculation. Coordination with UL will remove the 125% requirement from the UL-1703 Standard used for listing PV modules [7].

Interconnection Requirements

Two related proposed sections address connecting inverters to service entrance panels. They were written to clarify the requirements for supplying power (690-10) to service entrance hardware at lower than service-panel-rated currents and sizing conductors (690-11). Proposals using a "maximum system voltage" terminology were also written to provide code language consistency. A proposal was also submitted to provide the necessary language in Section 690-64(b) to allow the ac connection of PV systems at the load side of the service disconnecting means or at any distribution equipment on the premises. This serves the practical side of PV systems since PV arrays may be located on the roof of buildings, and the service disconnecting means is usually at a lower level in an equipment room. These changes will better facilitate building-integrated PV installations.

The restrictions for residential service entrance panel installations [690-64(b)(2) (Exception)] are not as stringent as for commercial applications. The sum of the overcurrent devices in residential applications can be up to 120% of the rating of the load center. A residential load center rated at 100 amps may accept a 20-amp feeder from a PV system (2400 watts of PV at 120 volts or 4800 watts at 240 volts). A load center rated at 200 amps may accept a 40 amp feeder from a PV system (4800 watts of PV at 120 volts or 9600 watts at 240 volts). These power levels are consistent with the maximum expected sizes of residential PV systems.

Inverters and Multi-wire Branch Circuits

A proposal was submitted to permit a single-phase, 120V inverter to supply power to a single-phase 120/240V service entrance panel provided there are no multi-wire branch circuits. There are estimated to be more than 50,000 such inverter installations already, but no allowance is given in the existing code. The multi-wire branch circuits contain a common neutral conductor that may be overloaded when used with single 120V-inverters. The task group will provide additional input to the NFPA to ensure concerns are addressed in the 1999 NEC.

LISTING AND CERTIFICATION STANDARDS

It was proposed that PV systems connected to the utility grid be required to use listed components. Other proposed changes for the 1999 NEC will require coordination with other standards groups. Underwriters Laboratories, Inc. is currently in the process of reviewing the proposed first edition of the "Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems, UL1741." The draft UL1741 includes new language for testing and listing of AC modules, charge controllers and inverters. UL conducted an Industry Advisory Group (IAG) meeting in January 1997 to review the latest version of its Subject 1741 [8]. That meeting was held to allow IAG members to provide PV industry input during preparation of the draft standard and before public review. The IAG consisted of participants associated with PV module manufacturing, inverter manufacturing, charge controller manufacturing, ac module development, systems integration and the US DOE Photovoltaic Program. The draft was distributed for public review in August 1997. The UL goal for publishing the standard is tentatively set for December 1997. The proposed effective date for the UL1741 standard is January 2, 1999, which was established to coincide with the effective date of the 1999 NEC.

COORDINATION WITH OTHER STANDARDS

The IEEE has published important standards and guidelines related to PV system components. These publications were written by the Standards Coordinating Committee 21 (SCC21) on Photovoltaics. Published SCC21 documents include terrestrial PV system criteria and recommended practices for installation and sizing of batteries for PV systems.

Utility Interconnect and Interface Guidelines

A very critical standard for utility interfaces and interconnects, now designated PAR 929, "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems," is currently being revised and rewritten with a targeted publication date 1997 [10]. This document is being revised by a team of utility and PV industry experts in order to integrate the utility and PV system perspectives into a document that can be used by utilities, and designers and installers for utility-interactive PV systems. The focus of the PAR 929 revision includes defining a set of guidelines for inverter shutdown under abnormal utility conditions, islanding protection, reconnects after a utility disturbance, the guidelines for manual and external disconnects, power quality requirements, and direct current isolation from the grid.

PV System Safety Guideline

Fire safety and personnel safety of installed PV systems are a top priority for designers, installers, inspectors and users. The NEC describes the installation requirements for installation of all electrical systems, but its 1069 pages are often unfamiliar to those involved with PV systems. A Project Authorization Request (PAR) 1374 to write a guideline titled "IEEE Guide for Terrestrial Photovoltaic Power Systems Safety" is in progress. It is written to provide an easily read safety document targeted specifically for PV systems. It is also closely correlated with the 1996 NEC, other ANSI/IEEE recommended practices, standards, and widely used suggested practices [9].

The purpose of the IEEE PV Safety guide is to describe PV-specific topics or components related to the design and installation of PV power systems that affect safety. It suggests good engineering safety practices for PV electrical balance-of-system design, equipment selection and hardware installations. Many system types are analyzed for correct wiring practices for PV modules, balance-of-system hardware and batteries. Particular attention is given to the critical temperature considerations required for PV systems at the module and array level, voltage ratings, cable and insulation types, wiring ampacity, and sizing calculations needed for safe and reliable design. Other important topics such as overcurrent protection, disconnects, grounding, surge and transient protection, and instrumentation are also described with examples and recommendations for selection of the hardware.

SUMMARY

PV installation experience is briefly discussed, with statistics on small utility-interactive showing a majority of failures related to the inverter. The experiences have been used to help develop numerous code and standards activities. Publication of the 1999 National Electrical Code, with a strong and well-developed Article 690 on PV power systems, will represent a safety code that will enable future PV systems to be installed using well-understood requirements. IEEE and ASTM standards will guide installations of PV systems. New standards for safety, field acceptance and interconnection to the utility grid will remove some roadblocks for PV installations. Future PV installations will be easier to design and inspect, and above all, will provide better safety and performance for all concerned because of experiences gained and the evolving codes and standards.

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proposed standards and code's changes. Many of the PV experiences were reported by experts that included Brian Farmer of PG&E, Miles Russell of Ascension Technology, John Bigger of UPVG, and Dave Collier of the Sacramento Municipal Utility District. The experiences were reported at the joint SNL/NREL PV System Reliability Workshop held in Las Cruces, New Mexico and the EPRI/DOE Photovoltaic Application Experience Workshop held in Golden Colorado in August 1997.

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