Summary Report on the DOE High-tech Inverter Workshop

Sponsored by:

The U.S. Department of Energy

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Solar Energy Technologies Program

and

Office of Electricity Delivery and Energy Reliability

Energy Storage Program

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High-technology Inverter Workshop
October 13 and 14, 2004
Baltimore, Maryland
Summary Report

Abstract

This report provides a summary of the DOE High-technology Inverter Workshop that was sponsored by the United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Program and the Office of Electricity Delivery and Energy Reliability, Energy Storage Program. The workshop was the second in a series to focus on inverter issues. The first occurred 18 months earlier and focused on a Systems-Driven Approach to Inverter Research and Development. This workshop used a similar format of presentation and facilitated group discussion to explore in greater depth issues and needs for the next generation of high technology inverters for photovoltaics, energy storage technologies and other synergistic applications. The first day focused on inverter technology issues. The second focused on codes, standards and certification issues. Needs for future technology development and for improvements in codes, standard and certification activities were presented and discussed during the meeting. The group developed priorities and recommendations for technology development and for addressing codes and standards issues that will help DOE to create a "High-tech Inverter and Balance-of-systems R&D Strategies" document, as well as help industry itself set priorities for future action.

Executive Summary

This DOE High-technology Inverter Workshop was sponsored by the United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Program and the Office of Electricity Delivery and Energy Reliability, Energy Storage Program. The two-day workshop was the second in a series to focus on inverter issues. The first occurred 18 months earlier and focused on a Systems-Driven Approach (SDA) to Inverter Research and Development. This workshop used a format of presentations from leading experts on important topics followed by facilitated group discussions to explore in greater depth the issues and needs for the next generation of high-technology inverters for photovoltaic technologies, energy storage technologies and other synergistic applications.

The first day focused on component, inverter and system technology issues. The second day focused on inverter-related codes, standards and certification issues. The needs for future high-technology inverter applications and for relevant improvements in codes, standards and certification activities were all presented, discussed and prioritized during the workshop. The participants developed six sets of priorities and recommendations for technology development and for addressing relevant codes and standards issues. These priorities and recommendations will aid the DOE in creating a "High-tech Inverter and Balance-of-systems R&D Strategies" document and ultimately a R&D program. The outcome will help industry itself set priorities for future action as well.

In summary of the workshop activities, the outcomes and recommendations are split into three inverter and system technology topics (day 1), and three standards, codes and certification topics (day 2). All of the technical and some of the standards related topics that ranked in the top five from each breakout session will require R&D for high-technology and evolutionary advances.

The inverter and systems technology topic was divided into three focused categories. They were:

- ✓ Capacitors and Components;
- ✓ Surge Protection, Thermal Management and Packaging; and,
- ✓ Power Electronics, Communications and Controls.

The standards, codes and certification topic was also divided into three focused categories. They were:

- ✓ Underwriters Laboratories Standards, Related Issues and Needs;
- ✓ Utility-related Issues and Needs; and,
- ✓ Inverter Manufacturer-related Issues and Needs.

The inverter and systems technology summary shows a great deal of similarity to the outcomes of the SDA to Inverter Research and Development workshop. The graphics that follow show the top five priorities using the ratio of percent of votes received for technology-related issue to the total technology-related votes for the top five. Most breakout sessions also listed selected priorities for how to best accomplish the goals and are recorded in this report. Some of the common "how to" priorities included topics such as teaming with synergistic industry and collaboration with similar programs, but also called for innovative controls and inverter topologies.

Figure 1 shows the prioritizations of Technical Breakout Session "A", Day 1 for the topic of "Capacitors and Components" that also included magnetic cores and devices, dc bus hardware and interconnects. "Improved capacitors" stands out as the highest priority recommendation. The improvements addressed advancements in electrolytic, film and ceramic capacitors with calls for twice the lifetime at one-half the costs. Another very important aspect of the capacitor prioritizations included investigations of new inverter designs and topologies that use feed-forward controls to reduce the values and numbers of capacitors needed. All topics from this session except the "Component Database" represent opportunities for both high-technology and evolutionary advancements. The component database was retained in this chart because it was found to be a critical deficiency, and is a necessary starting point for R&D for advanced components and inverters.

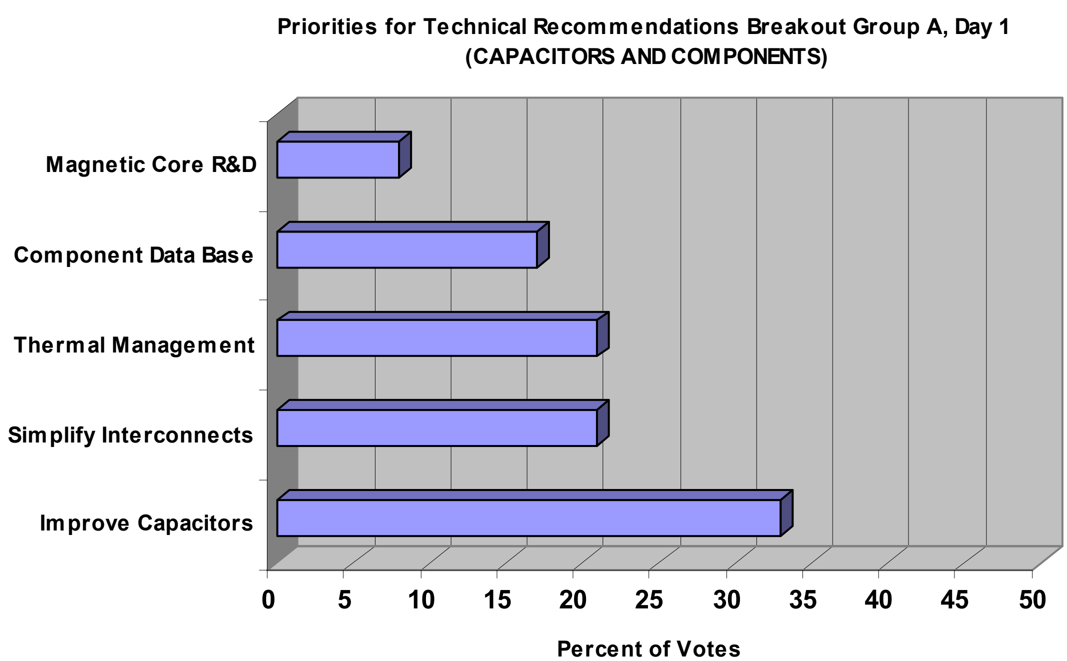


Figure 1. Capacitors and Components Breakout Prioritization.

Technical Breakout Session "B" focused on surge suppression, thermal management and packaging for inverters. This group conducted lengthy discussions about the deficiencies of today's surge suppression devices, particularly for the dc side of systems. Smarter devices with self-diagnosis was agreed upon to be particularly important, hence an influence on the communications priority. The "DC Surge Protection" topic could be categorized as a subset of "Surge Device Advances" but received enough attention and votes to warrant a distinct topic. "Thermal Management" is a topic that included the surge suppression devices as well as other electrical and electronic devices in inverters, and was voted the highest priority to be considered for high-technology R&D and evolving device R&D. Again many opportunities for technology advancement were identified and discussed. The self healing/self diagnosis topic rose to an important level of interest because the failure mechanisms of today's surge suppression devices is either

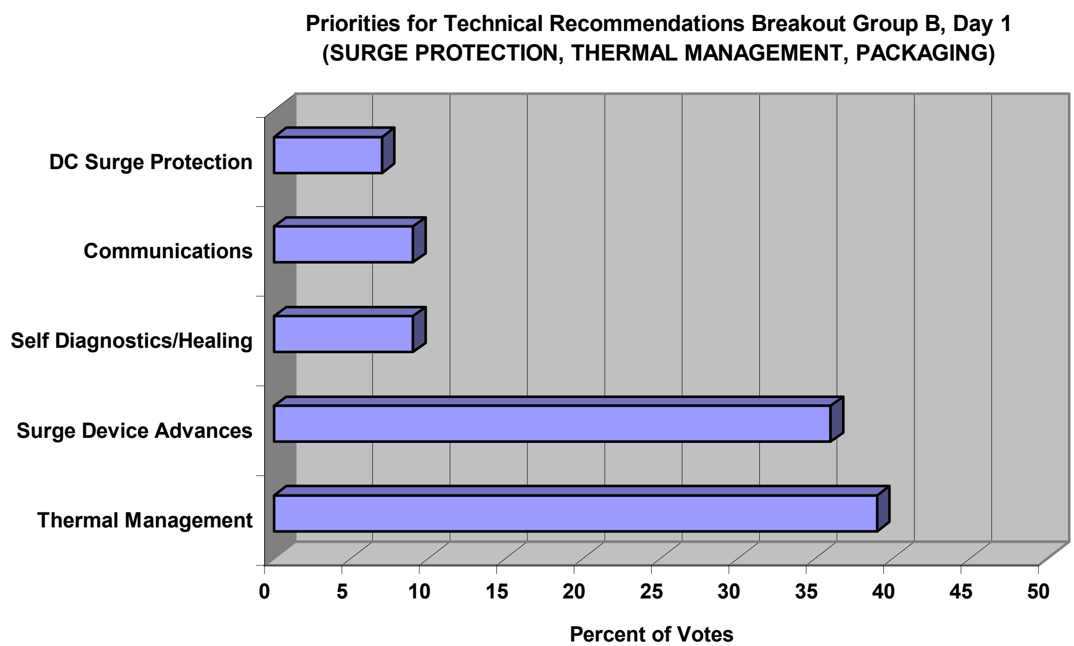


Figure 2. Surge Protection, Thermal Management and Packaging Breakout.

an explosion or a device that is inoperative, but does not announce its condition. Figure 2 shows the relative priorities for the top five technical topics for surge protection, thermal management and packaging.

The Technical Breakout Session "C" focused on power electronics, communications and controls. This group had to deal with a tremendous diversity of topics. The recommendations were heavily concentrated on communications for inverter controls. Communication was a hot topic during the workshop and was the highest priority topic in this breakout session. Transformerless inverter designs and applications followed communications with a much lower, but important priority, given the large field of topics considered. Transformerless inverters are common in Europe and Japan today, and are possible in the United States since ungrounded PV array installations are now allowed per the 2005 National Electrical Code. The result is that manufacturers are rethinking designs and circuit topologies to take advantage of the improvements in efficiency and costs. The power electronics, especially the wide band-gap technology detail, was somewhat unfamiliar to many of the participants making prioritization difficult. Non-the-less, the wide band-gap device topic received a respectable recommendation for further

R&D and application studies. The topics of standards, as they are related to interconnecting new topologies received the forth highest priority in this session. Energy storage, especially with larger systems and for future grid support was recommended as the fifth most important and an area needing more R&D. The R&D for all of the top-five applies to high-technology and evolving advancements.

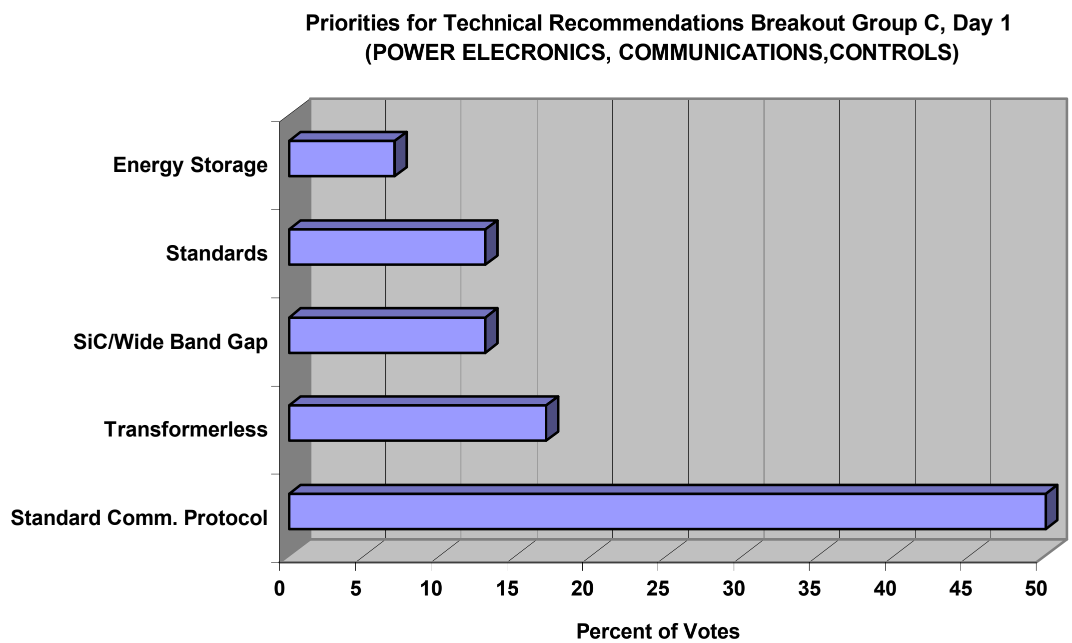


Figure 3. Power Electronics, Communications and Controls Breakout Priorities.

After excellent presentations on relevant codes, standards and certifications, the new breakout groups convened to focus on individual topics. The most focused was the Standards Breakout Session "A" that dealt strictly with Underwriters Laboratories Standards, and in particular the UL 1741 entitled "Standard for Inverters, Converters and Controllers for Use in Independent Power Production Systems." This standard tests primarily for safety but is one of very few UL standards that include performance testing. The performance test conducted before listing an inverter includes harmonic distortion, anti-islanding and set point reactions. Instead of voting for recommendations, this breakout group simply prioritized the issues related to UL listing and certification. The following list shows the five highest relative rankings in order of priority.

1. Increase industry support for development of UL 1741 and increase industry participation in UL 1741 development.
2. Require that manufacturers pretest equipment before submitting to UL and provide only the necessary bill of materials and descriptions of their tests. *Note: A barrier to this recommendation is lack of capital and lack of instructions.*

3. Determine whether manufacturers should build to UL 1741 or IEEE 1547. *Note: This needs a speedy resolution.*
4. Tied for fourth place:
    a. Make printed UL standards more affordable to increase information dissemination. *Note: There has been a ten-fold increase in UL standards costs.*
    b. Lessen the multiplicity and changing requirements. *Note: A major concern is that proposed IEEE 1547 changes will be adopted by UL 1741 with uncertain time constraints.*
5. Improve response times from UL.

Many other issues and needs were discussed and ranked. Some of the key issues included harmonization with European/Asian standards, self certification, software change impacts, support from outside UL, modular listing process, utility adoption, UL/NEC collaboration, periodic replacement of components and the value added by listings.

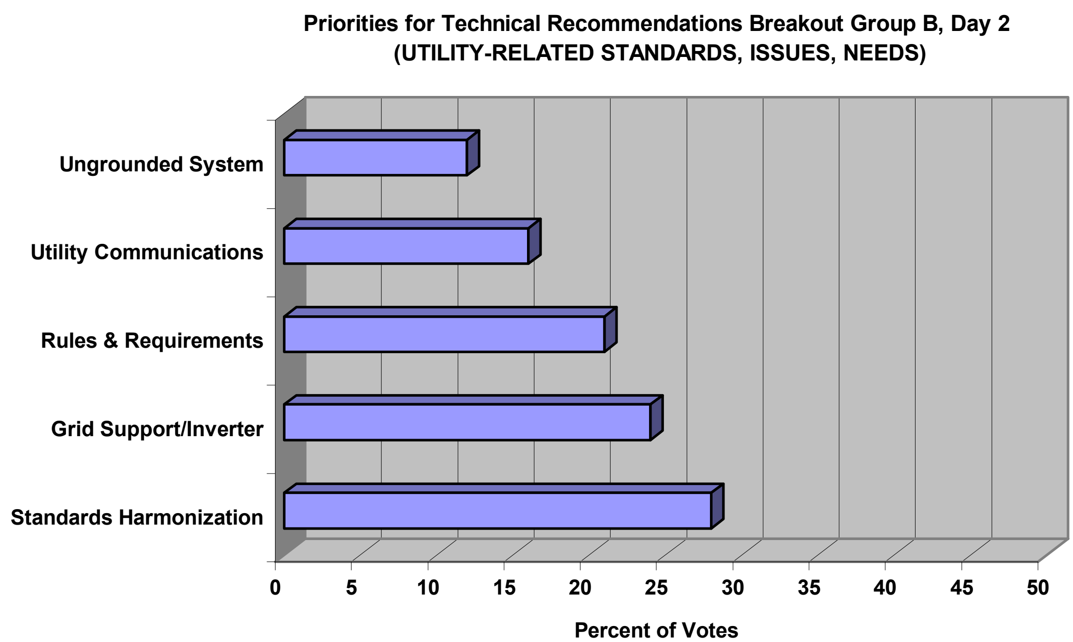


Figure 4. Utility-related Standards, Issues and Needs Breakout Priorities.

Standards Breakout Session "B" for utility-related (standards, codes and certifications) issues and needs covered an impressive list of nearly twenty inverter- and control-related topics. The long list of topics was categorized and the top five shown in Figure 4. The "Standards Harmonization" was a universal high priority topic in all of the breakout sessions and rose to the top for the utility related issues and needs as well. The grid support by the inverter was the second highest priority, and illustrated a potential reversal in the roles for inverters that are tied to the utility. Instead of being required to disconnect in the event of utility disturbances as is the case today, the new role would be to support the ailing grid by riding through voltage droops and power shortages. This new role will require new and advanced control algorithms and design changes in inverters that are opportunities for high-tech advances in communications, control and power electronics. The new role may also require new roles for energy storage working in unison with the traditional alternative energy sources. The rules and requirements priority in this session stems from a conglomeration of a wide range of state, regional and national requirements and guidelines, and indicates more need for standards harmonization. Utility communications will be a necessary element in alternative energy generation and was voted fourth priority. The ungrounded system was the fifth highest priority and ties closely to new allowances by the National Electrical Code, creating new inverter requirements and opportunities, and revisions in the UL 1741 standard.

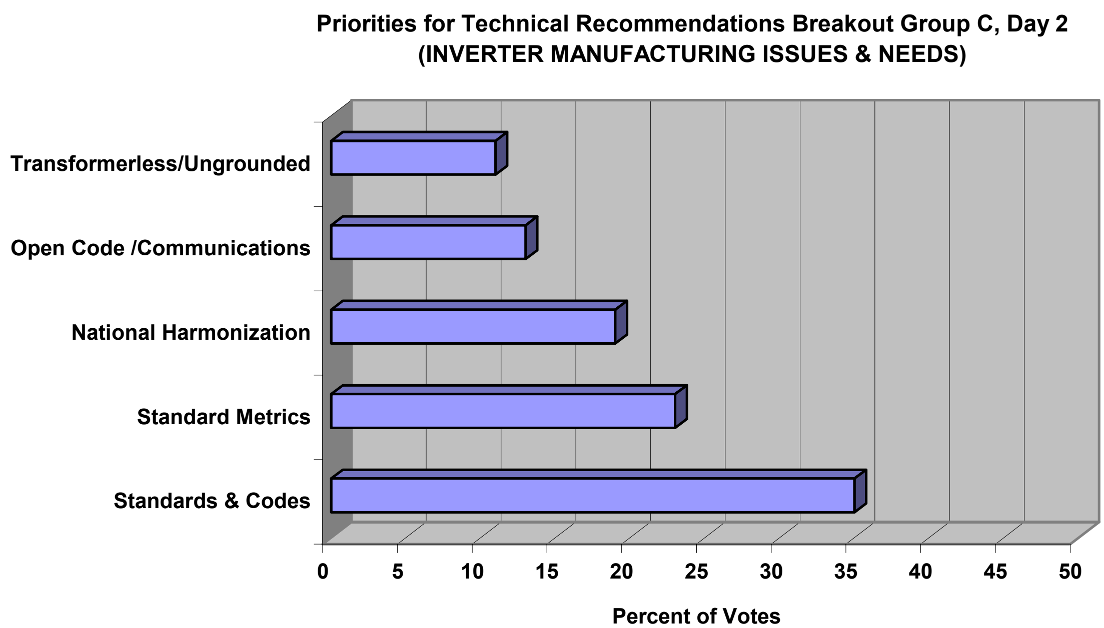


Figure 5. Manufacturer-related Standards, Issues and Needs Breakout Priorities.

Standards Breakout Session "C" was the manufacturers' equivalent to the utility standards issues and needs group. This session tackled the same standards issues from the manufacturer's perspective and the results were similar. Figure 5 shows the top five priorities from the manufacturer's perspective. Again, standards and codes dominated. This represents a summation of several lower level, but closely related topics that pointed to a need for more work on standards and codes including harmonization, industry participation, calming the proliferation and possibly alternatives. A call was being made for standard metrics for reporting the performance and characteristics of inverters. These metrics must be understandable, consistent and reliable while being consumer friendly.

Communications was ranked fourth from the manufacturers' perspective. It was spurred by the agreed on the need for open-source codes for communications to replace the inconsistent and product specific protocols being used today. Transformerless inverters were again in the top five as more interest is emerging to improve inverter performance while cutting costs.

Introduction

The United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Program and the Office of Electricity Delivery and Energy Reliability, Energy Storage Program, sponsored a two-day workshop to discuss high-technology inverter issues. The meeting was held at the Radisson, Cross Keys, in Baltimore, Maryland, on October 13 and 14, 2004. The participants – from the inverter industry, utilities, solar-power equipment manufacturers, developers of storage technologies, universities and national laboratories – spent two days sharing information on the latest developments in inverter technology and related codes and standards, and then discussing issues, needs and priorities for research and policy to overcome barriers. The focus of the discussion was on inverters for solar power technologies. Related developments for inverters for energy storage technologies and for automotive and other applications were also well-represented.

Like the first workshop on a “Systems Driven Approach to Inverter Research and Development,” conducted in April of 2003, the presentations and discussions covered similarities and differences in research and market trends between solar power, energy storage, automotive and other inverter applications. However, this meeting went into greater depth in terms of the requirements for the next generation of high-technology inverters. It also focused the entire second day of discussion on inverter-related standards, codes and certifications currently available or being drafted – including their economic and technical impact on inverter designs. Needs for improvements in standards, codes and certifications and in the processes used to develop them were discussed and prioritized. The results of this workshop will be incorporated into a “High-tech Inverter and Balance-of-systems R&D Strategies” document, which is expected to be released simultaneously with the final report for this workshop in mid January of 2005.

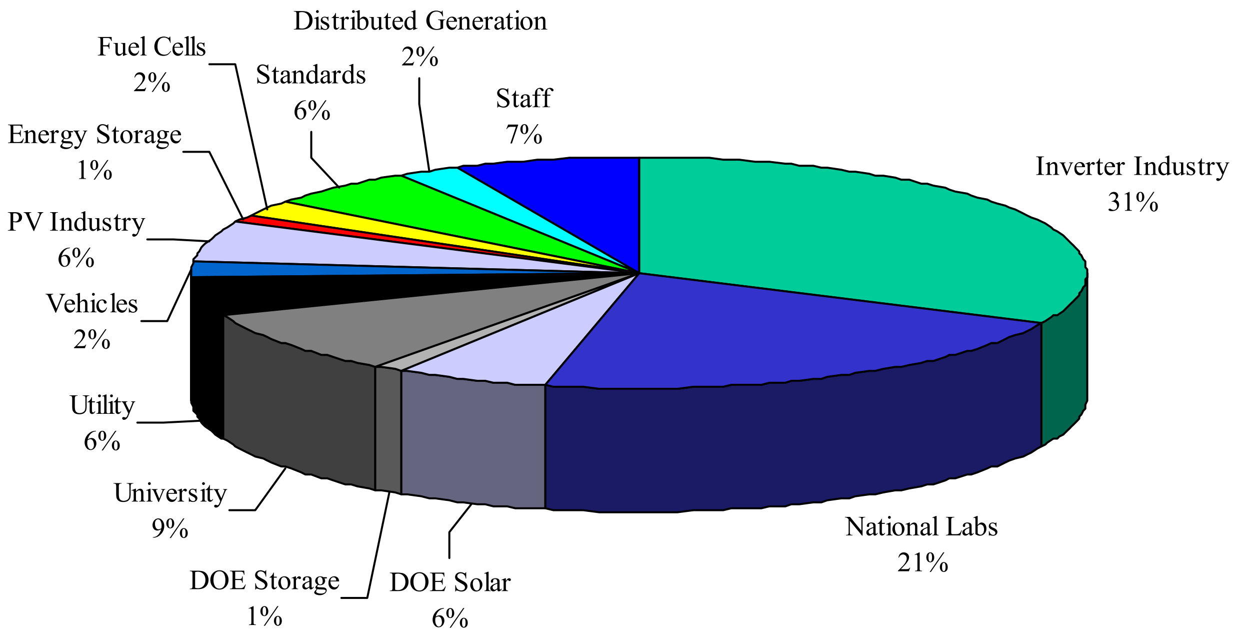
Workshop Organization

The workshop was organized to be a follow up to the first systems driven approach workshop on inverter R&D held in April 2003. The structure was very similar, with half of each day devoted to presentations from leading experts on important topics for high technology inverter development, and the rest of the day devoted to group discussions of the morning topics and development of actions and priorities. The workshop was organized by the two DOE sponsors, Ward Bower of Sandia National Laboratories and McNeil Technologies.

Workshop Goals and Objectives

This workshop was designed to explore in depth the next generation of high-technology inverters for PV, energy storage and synergistic applications. There were two main topic areas: inverter technology on the first day; and codes, standards and regulations on the second day. The participants were asked to identify key challenges in both topic areas, prioritize work that needed to be done, start developing milestones and metrics for the near- and mid-term, and finally to discuss who should take the lead in addressing priority questions.

Figure 6. Breakout of Workshop Participant Primary Affiliations.



Workshop Participants

Ninety people attended the workshop. Figure 6 shows the mixture of organizations and expertise at the meeting. Note that many of the attendees represented more than one category, particularly among inverter manufacturers. The breakdown in this graphic shows their primary affiliation. For example, many of the inverter industry and PV manufacturers also participate in certification and standards activities, as do the utilities. Some of the university staff also serves a dual role as industry representatives because they are working with startup companies developing new technology and materials. Each participant took valuable time from their regular duties to participate in this meeting and the DOE and sponsors are very appreciative. Each participant left the meeting with expanded knowledge of what is happening throughout the component and inverter fields and with a better understanding of the key issues in codes, standards and certification and many expressed gratitude and the need to continue such workshops. The complete list of participants is included in Appendix A.

Workshop Speakers

The complete list of presenters and the title of each presentation is shown in Table 1 and Table 2. The presentations are also available on the U.S. DOE website, or may be obtained on a CD-ROM. Presentation material can be requested from Kevin DeGroat at McNeil Technologies (kdegroat@mcneiltech.com) or Ward Bower at Sandia National Laboratories (wibower@sandia.gov).

Table 1. High-tech Inverter Workshop Day One Activities.

DOE High-technology Inverter Meeting Presentations	
Day One: Inverter Technology	
Dan Ton U.S. Department of Energy	Welcome to the DOE High-tech Inverter Workshop
Imre Gyuk U.S. Department of Energy	Energy Storage: Advanced Inverter Issues and Research
Chris Cameron Sandia National Laboratories	The Solar Energy Technologies Program's Systems Driven Approach to Managing the Solar R&D Portfolio
Ward Bower Sandia National Laboratories	High-tech Inverter Research and Development: A Five-Year Strategy
Ray Hudson Xantrex Technology, Inc	Development of a High Reliability Inverter
Joseph Smolenski GE Global Research Center	GE High Reliability PV Inverter Initiative
Leo Casey SatCon Technology Corporation	High Reliability Inverter Initiative: Status Update
Bruce Tuttle Sandia National Laboratories	Capacitor Technologies: A Comparison of Competing Options
Clayton Handleman Heliotronics, Inc.	Heat, …, The Last Frontier
Michael Ropp South Dakota State University	Transient Protection for PV Power Electronics
Frank R. Goodman Electric Power Research Institute	Communication and Control for Inverters
Michael S. Mazzola SemiSouth Laboratories, Inc, and Center for Advanced Vehicular Systems Mississippi State University	Power Electronics for High-tech Inverters

Table 2. High-tech Inverter Workshop Day Two Activities.

DOE High-technology Inverter Meeting Presentations	
Day Two: Inverter Codes and Standards Development	
John Wiles Southwest Technology Development Institute	The 2005 *NEC*, Standards, and the Real World: Inverters, Inverters Everywhere, but System Acceptability Needs Improvement
Tim Zgonena Underwriters Laboratory	UL 1741 Update: A Safety Standard for Distributed Generation
Tom Basso National Renewable Energy Laboratory	IEEE 1547 Overview: IEEE (SCC21) 1547 Series of Interconnection Standards
Christoph Panhuber FRONIUS International GmbH	IEC and European Inverter Standards
Chuck Whitaker Behnke, Erdman and Whitaker Engineering, and Endecon Engineering	Inverter Performance Certification: Does it Make Sense?
Chuck Whitaker Behnke, Erdman and Whitaker Engineering, and Endecon Engineering	Distributed Utility Integration Test (DUIT): Facility and Unintentional Island Results
Bill Brooks Endecon Engineering	California Rule 21 Overview

Workshop Facilitation

The staff of McNeil Technologies, Inc. of Springfield, Virginia, facilitated the meeting presentations and breakout groups. McNeil also arranged the meeting location, food, and assembled the presentations for the meeting handout. Meeting facilitators included Kevin DeGroat, Conrad Mulligan and Douglas Eisemann. Mamatha Gowda, Amy Diaw and Ribkha Hailu took notes on behalf of McNeil. Staci Dorsey of Sandia National Laboratories provided additional notes.

Workshop Agenda and Organization

The meeting was organized so that the first part of each day was used to provide background information on critical topics, and then moved forward to organized breakout sessions of approximately 30 people each to discuss critical issues and needs, responses, timelines and performers who should be responsible for addressing the issues and needs.

Day One: Inverter Technology

On the first day the meeting started with overviews of DOE research goals, inverter technology topics and then moved into detailed examinations of related research on components and their technologies. Dan Ton and Imre Gyuk of DOE discussed current inverter research and its importance to the Solar Energy Technologies Program and the

Energy Storage Program, respectively. Chris Cameron and Ward Bower provided a status report and update on research planning and execution of inverter research. All three of the high reliability inverter initiative awardees presented the objectives of their research, milestones accomplished, funding, the significance of the research and the results for improving technology and market potential. The next five presentations focused on specific inverter related issues and components: capacitors, thermal management, packaging, surge protection, communications, controls and high-tech power electronics.

The meeting then divided into three break out groups to focus on Capacitor/Component Technologies (facilitated by Douglas Eisemann); Surge Protection, Thermal Management and Packaging (facilitated by Conrad Mulligan); and Power Electronics, Communications and Controls (facilitated by Kevin DeGroat). Each group was given a matrix of technical issues related to single-phase inverters, inverters for PV applications, 3-phase inverters, and inverters for energy storage. They were then asked to chart out key influences (temperature, energy, power, packaging, interfaces, standards, etc.) in relation to an R&D timeline of near- and mid-term activities. At the end of the day the entire group was reassembled to review and discuss the recommendations from each subgroup.

Day Two: Codes and Standards Development

The presentations on day two were focused on issues concerning inverter related standards, certification, codes and their impact on real world applications. The topics covered the *National Electrical Code (NEC)* and its impact on solar system installations; UL 1741 development, the IEEE 1547 standard and its annexes, IEC standards; inverter certification issues; inverter testing; and state rules, particularly California. Each speaker explained and discussed the standard or issue and related applications, explained its importance, gave examples of impacts, and the key outstanding problems or issues.

In the afternoon the participants were again assigned to three breakout groups: UL Standards Related Issues and Needs (moderated by Douglas Eisemann), Utility Related Standards Issues and Needs (moderated by Conrad Mulligan), and Inverter Manufacturer's Issues and Needs (moderated by Kevin DeGroat). Each group was asked to make a complete listing of responses to issues and needs in their topic area, and then to vote on which items should be a top priority. All the participants were then reassembled to discuss the findings of each breakout group and refine the findings.

Day One Inverter Technology Presentations

Welcome, Outline of Workshop Goals, Guidelines for the Workshop

Dan Ton of the Solar Energy Technologies Program, one of the sponsors of the meeting, provided opening remarks outlining the goals and expectations of the workshop. He emphasized that this workshop would continue discussing inverter research in the context of the systems-driven approach – a formal, rigorous method of identifying and evaluating research needs relative to goals and objectives that are relevant to target markets. It emphasizes how research, materials, components, systems and applications must be examined in relation to each other, and how they ultimately influence the market potential of technology. At the broadest level, the PV program's goal of $.06/kWh solar electricity is what is believed to be necessary to achieve significant market penetration. There are other technical and cost metrics that contribute to that goal, including how inverters contribute to the cost of solar power systems, which in turn relates to different combinations of lifetime, initial cost, efficiency and other parameters. The systems-driven approach helps to organize and illuminate the potential technical paths to reaching market objectives – including the risks, sensitivities and tradeoffs inherent in different research paths.

For photovoltaics, inverter research is a key element of the Technology Development element of the program, which emphasizes PV balance-of-systems and complete systems development. Inverters are in a critical position on the research path to $.06/kWh solar power, and the inverter's role in PV systems is gaining increasing attention as the solar power market grows – especially when they cause problems. He described the key goals of the DOE-directed research as to overcome today's problems with inverters, and ultimately to leap-frog current inverter technologies and develop new technology with lower cost and higher reliability that doubles today's mean-time-between-failure (MTBF) rate. This research has already succeeded in developing prototypes for new inverter technologies with advanced controls, a draft "Inverter Test Protocol" and evaluated the performance, safety, and reliability of 11 new designs. Phase II contracts for the High-Reliability Inverter Initiative were awarded in December 2003, with an update on progress that was to be presented at this workshop. Prototypes of these new inverters are nearly complete, and their development should be completed by January 2006, after Phase III of the initiative.

This area of research has been recognized by DOE program peer reviewers as "…outstanding and essential to PV industry development." Peer reviewers also emphasized that there is great potential for collaboration and synergy with inverter research and other technologies like storage and fuel cells that the program should leverage. That is why this workshop was co-sponsored by the DOE Office of Electricity Delivery and Energy Reliability, Energy Storage Program. It is also why we have invited representatives from automotive and other areas that use inverters to share information on their issues, needs and progress on inverter development. Together the participants in this meeting can map areas of agreement and controversy related to inverter technology development, codes, standards and certification that will help DOE scientists develop effective strategies for inverter development.

Introduction to Energy Storage Inverter Issues and Ongoing Work

Dr. Imre Gyuk, also a sponsor of the workshop, described the research and priorities of the Energy Storage Program and its relation to inverter development – why inverter technology is important to the Storage Program and what is being done to advance the state of the art.

Dr. Gyuk, head of the Energy Storage Program of the DOE Office of Electricity Delivery and Energy Reliability presented an overview of the key issues in inverter development, from the perspective of energy storage technologies. The primary technical drivers for power converter equipment are first, the power rating involved (as small as 1 kW for solar, to 500 kW, 10 MW and beyond for storage). Second, the speed of the converter measured in thousandths of Hertz (Hz). Third, the quality of the power required. Finally, size, particularly for mobile applications but also for residential and other applications where space is at a premium. Technical drivers are tempered by market drivers – reliability and cost – with the emphasis on cost. The power conversion system represents a sizable part of the cost of an energy storage or distributed generation system – for an energy device approximately 25%, for a power device up to 65%.

Today's issues and research for energy storage inverters involve five areas:

- Devices:
  - Emitter Turn Off (ETO) Thyristor Development.
  - Wide Band Gap (WBG) Applications.
- Optical Sensors and Controls.
- Passive Elements: Advanced Capacitors.
- Thermal Management: Advanced Composites.
- Manufacturability: ETO Generation 3.

For devices, advanced switch design involves applications at less than 750,000 V where off-the-shelf insulated gate bi-polar transistors (IGBT) switches and controls are the main issues. Above 750,000 V, switches are needed that are faster than the gate-turn-off (GTO), can handle more power than IGBTs, and that are cheaper.

In device research, Virginia Tech has developed a 16-MW ETO switch. It is 15 to 20 times faster than a GTO, delivers three times the power and is less expensive than IGBT. It is being incorporated into a transmission stabilization device with the Tennessee Valley Authority. It was honored with an R&D 100 award in 2003. This research is currently being continued at North Carolina State University.

In WBG materials research – Silicon Carbide (SiC) – the focus is on reducing expense and dealing with the limited current levels the material can handle. Advantages are high frequency operation, lower switching losses, higher blocking voltages, and much higher operating temperatures. An FY 2005 SBIR solicitation is planned for design of power conversion systems (PCS) using available WBG devices. The focus will be on improving performance, manufacturability, thermal management and cost. Construction of a prototype 100- to 500-kW power conditioning system is planned for Phase II.

Controls research is investing in optically isolated inverters. Airak, Inc. is one developer, working on a system that is rated at 1.7 MW per phase, provides an optical interface for controls that are combined with optical voltage, current and temperature sensors. The objective is smaller, more reliable, and cost effective inverters. This work also received an R&D 100 award in 2003.

In passive elements, research is focused on improved capacitor lifetime. It will be the subject of an FY 2005 SBIR solicitation. Currently capacitors have the highest failure rate of any PCS component, so it is a key to improving reliability by designing converters with advanced capacitors that demonstrate increased reliability and manufacturability, as well as lower costs. Polymeric film is one avenue of research.

In thermal management, Rhinehardt Motion Systems has developed a low-cost, high-current 100- to 500-kW inverter with integral liquid cooling. It also uses a non-uniform pin topology and advanced composite materials (Al-C) for high heat conductivity at key points, paired with low-cost injection molding for less critical elements.

While generations 4 and 5 of ETOs are being designed, generation 3 is being prepared for commercialization with work on improved packaging and manufacturability.

The Systems Driven Approach to Managing the Solar R&D Portfolio

Chris Cameron of Sandia, on assignment to the Office of Solar Energy Technologies, discussed the inverter elements of the systems-driven approach (SDA), and the importance of the shift toward looking at the whole PV system and how inverters and controls impact the system. Codes and standards are also relevant to the systems-driven approach because they are essential to understanding the market realities that should drive the SDA.

The SDA is defined in the Solar Energy Technologies Program Multi-Year Technical Plan as: "All technical targets for R&D on the components and systems funded through the Solar Energy Technologies Program are derived from a common market perspective and national goals, and the resultant technologies are tested and validated in the context of established criteria for each market."

The market focus – the end goal – is important to the solar program because solar is an applied research program. The SDA provides a framework for program planning. It helps to benchmark technology to document its current state and to validate model input. It helps in developing models that can provide a common platform for sensitivity studies at the systems-level and below that can be used to evaluate the benefits of proposed and ongoing R&D, and identify new R&D opportunities through parametric studies. Finally, it provides a framework for analysis of the market impact of achieving program goals and of the feasibility of proposed research tasks.

Benchmarking begins with the standard system configurations in the multi-year technical plan for residential PV systems (with and without storage) and utility-scale PV. Commercial building PV will be added in the next round of revisions. There are also benchmarks for utility-scale troughs and towers, parabolic dish-engine and concentrating PV, solar water heating and hybrid lighting. Cost and performance are benchmarked at the system, component and subcomponent level, although subcomponent assumptions are not yet documented in the multi-year technical plan.

Modeling is focusing on creating a user-friendly platform for systems-level sensitivity studies. The graphical user interface provides access to various standard configurations of solar systems. Users are allowed to change the parameters from default values, and to explore technology details through in-depth drill-down menus. Optional or user-defined submodels can be connected to the main model to provide input to key parameters. Results are produced as exportable data and graphics.

Analysis is designed to provide context – to explore the relationship of key parameters to market penetration, for example how the size of the market is influenced by delivered energy costs, or by first cost for equipment. Analysis can help identify the key advances needed to achieve gigawatts of installed solar, and investigate whether proposed research tasks are realistic in terms of cost, schedule and performance.

This is what the systems-driven approach wants to deliver. Progress is being made in benchmarking, modeling and analysis. The initial goal is information and tools that can be used by program managers and researchers to evaluate research options. Technically, the focus is on flat-plate photovoltaics, partly because that is where most of the program's resources are invested, and partly because concentrating solar power and parabolic troughs benefited from a recent, detailed evaluation by Sargent and Lundy.

In benchmarking, the team of Sandia, Florida Solar Energy Center (FSEC), the Southwest Technology Development Institute (SWTDI) and the National Renewable Energy Laboratory (NREL) are working closely with private and public sector partners to gather information on component cost, performance, installation costs, O&M and other key parameters. Gathering such detailed data while at the same time protecting proprietary information is a challenge, but is also essential if the program is to gather the quality data it needs. For example, monitoring from more than 250 school and home systems in Florida is providing data on prices, daily performance, operation and maintenance (O&M) and availability.

In modeling a graphical user interface has been developed and tested. Computer codes for PV system performance models have been written, and writing codes for individual PV components is underway. Cost models are currently rudimentary. They need more development to support the sensitivity studies that the program managers want. The model is capable of sensitivity analysis, but the

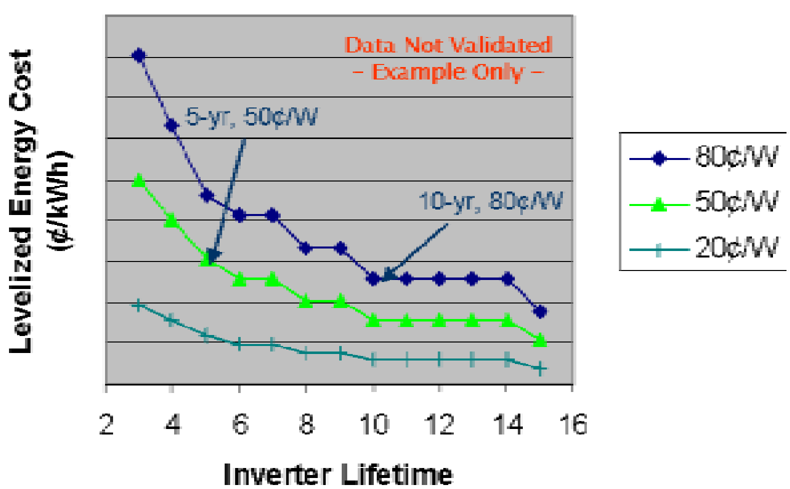


Figure 7. Example Analysis from Systems-Driven Approach Model.

results have yet to be validated. As an example, inverter costs versus lifetime were examined in residential systems, with the un-validated results shown in Figure 7. This is an example of the kinds of issues the model will be able to explore.

In analysis, NREL recently completed a Solar 2050 study that illustrates long-term projections for solar using the Energy Information Administration's National Energy Modeling System (NEMS). Key findings are that without constraints on carbon emissions coal will continue to dominate generation, but assuming a carbon value opens markets to all renewables. It also showed that attaining R&D goals quickly has a major impact on market penetration by 2050. It also showed that policies to encourage market development are needed to supplement R&D.

A PV market penetration model that will be compatible with the systems-driven approach is currently in development. A value analysis is also underway, exploring the effect of net metering on PV system value and finding initially that the value of switching to time of use (TOU) rates and net metering is highly dependent on the customer's original load profile and system size.

Finally, a review of program literature is in progress to explore PV cost, efficiency and other targets, in preparation for an upcoming analysis of real-world experience versus cost model estimates for PV manufacturing experience and for inverter cost and performance experience and projections.

The model will be demonstrated at the Solar Program Review in Denver at the end of October, with initial release of the beta version by the end of the year. In 2005 the PV subprogram will begin using it in planning and management. Benchmark, modeling and analysis will evolve in response to program need, and to added capability. An improved inverter model is planned that examines Mean Time to Failure rates as distributions, and is able to use parametric analysis to find opportunities for cost reduction. In applying the systems-driven approach to inverters we need to understand the most sensitive cost drivers in inverters, and get feedback and input from industry on components and subcomponents that could benefit from modeling, and provide access to existing models, costs and other data.

High-tech Inverter, BOS and Systems Research and Development: A Five Year Strategy

Following the update on the systems-driven approach and its relevance to inverter development, Ward Bower of Sandia discussed the High-technology Inverter Research and Development Strategies in terms of benefits for galvanizing research and the importance of this meeting for completing the strategy. Determining how the acquired information will be used was emphasized.

The presentation began with a brief review of the systems-driven approach with examples directly connected to inverter research and development. The concept is shown in Figure 8.

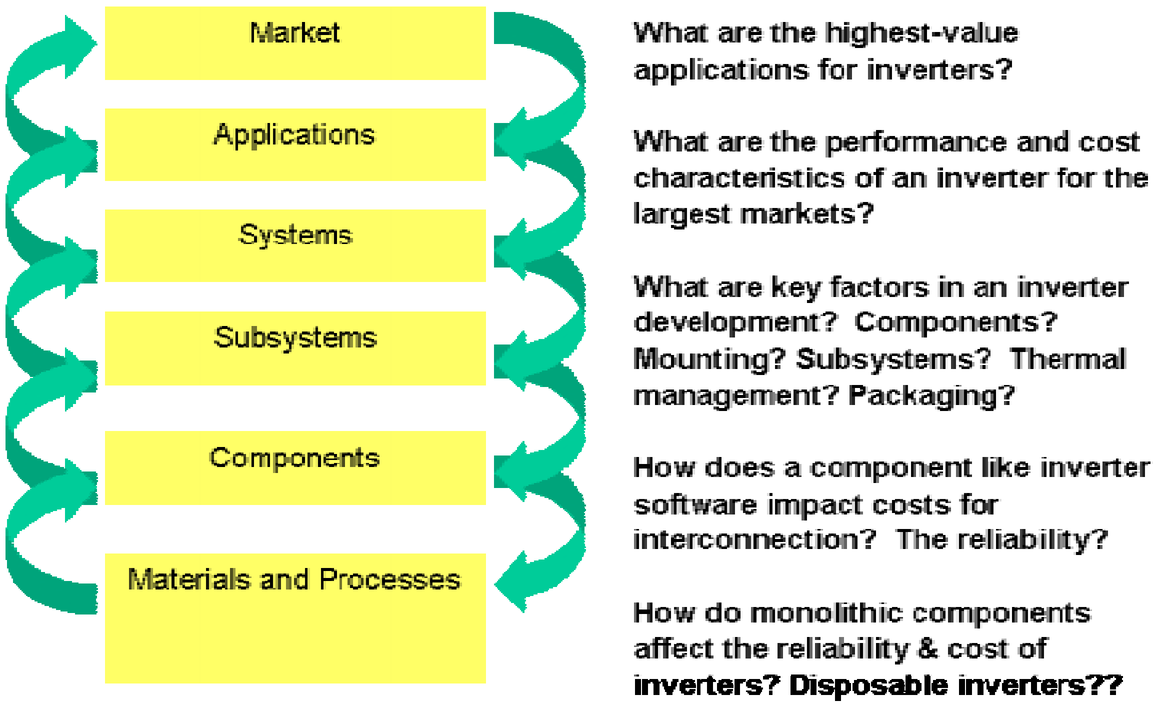


Figure 8. Inverters and the Systems-driven Approach.

The high-tech inverter R&D strategy document is being developed within the context of the systems-driven approach. It will become a platform for collaborative work that affects multiple technologies, and it will be designed to identify priorities and leverage very scarce funding resources to where they will be most productive. It will contain a set of targets and goals for the benefit of the U.S. industry, and advance communication among different technologies that use inverters, and among inverter manufacturers.

The strategy document is based in part on the first inverter workshop held in April 2003. It is already using and will continue to employ the systems-driven approach to determine priorities. This workshop will help to more clearly focus research priorities for the major elements of the strategy, which address device needs (technology advances, cost reductions, reliability, synergisms, etc…); and modeling needs. Industry, academia, end-users and funding partners have been involved in its development. And it will have an impact – eventually it will be included in the Solar Multi-Year Technical Plan which guides DOE's R&D investments and program management.

Device needs are a key element of the strategy – new and advanced semiconductor devices, advanced long-life capacitors, surge suppression and magnetic materials. In new and advanced semiconductor devices we are investigating silicon-carbide (SiC) diodes and wide band-gap switching devices, smart drivers and switching modules, and higher temperature printed wiring boards.

New and higher-temperature metal-film capacitors are important to developing advanced, long-life capacitors. Researchers are investigating high-temperature multilayer ceramic capacitors, integrated thick-film capacitors, self-healing capabilities and electrolytic capacitors with longer lives.

New surge suppression devices are needed for both ac and dc circuits. Circuit layouts need to be improved to mitigate surge potentials. And eventually we need maintenance-free devices, with built-in diagnostics, ability to manage transients and improved peak current requirements.

Lower-cost, higher-performing magnetic materials are needed for inductors and transformers, including advancements on nano-crystal materials and applications.

Technology needs for future, high-technology inverters include hybridization of sensors, controls and drivers, innovative thermal management, advanced control methodologies and work on automated manufacturing and hardware synergism. Hybrid integrated circuits could reduce the use of solder joints through thin- and thick-film hybridization utilizing advanced metal bonds in place of solder. Isolating sensors could improve reliability, and controls could be integrated directly into power modules.

In innovative thermal management there is potential to combine high-temperature electronics with management and development of high-temperature components and layouts that could eliminate fans and reduce the need for heat sinks.

Advanced control methodologies could utilize feed-forward topologies to reduce energy storage requirements, and new control algorithms could make it easier to combine technologies like solar and storage for synergistic applications.

Automated manufacturing and hardware synergism focuses on opportunities to combine packaging and layout to minimize labor intensive tasks. Standardizing inverter packaging could allow more standard inverter packages to be used in multiple applications.

High-reliability Inverter Initiative Status Updates

Xantrex Technology Inc. Research

Ray Hudson of Xantrex Technology, Inc, began his presentation on their work on the high-reliability inverter initiative with five areas where today's inverters need improvement – high reliability, high efficiency, enhanced communications, lower cost and flexibility to support specialized applications. The objective of Xantrex's project is to develop a prototype inverter and charge controller with an MTBF greater than 10 years, an efficiency of 94%, and lower cost.

Xantrex's inverter design is for a single-stage unit with very high toroid-transformer efficiency, high surge capability, simple taps for output voltage configuration and low magnetizing current for reduced tare losses. They have also developed an improved insulated metal substrate power H-Bridge that has rugged solder mounting of the MOSFET arrays. The new design minimizes thermal resistance from junction to back-plane to heat sink – and with lower temperature comes longer system life. The design dramatically reduces the need for fasteners in both thermal and electrical paths, leading to reduced assembly time, lower costs and fewer manufacturing related failure modes.

For the control design, Xantrex focused on minimizing the number of parts to improve reliability. The controller is based on a Digital Signal Processor (DSP) with a supporting microcontroller. It provides direct digital control of the H-bridge, plug-and-play network communication support and supports several modes of operation for battery charging, inverting and grid-tied applications.

At this point Xantrex has produced “A” model prototypes which have been verified and tested to full loads. The sub-assemblies have also undergone highly-accelerated lifecycle testing. So far, the prototypes are exceeding the project’s efficiency targets. After completing the “A” model testing, Xantrex designed and fabricated “B” models based on the results of the “A” prototypes. Full verification tests are underway, control loops have been optimized and MTBF calculations have been completed.

MTBF testing has isolated the MOSFET arrays in the H-bridge as the dominant source of failures. Design work is focused on further reducing thermal and electrical stress there, with a fan that is thermally controlled to extend the life of the part. Initial reliability can also be improved during manufacturing with a Highly Accelerated Stress Screen (HASS). Today, the predicted MTBF at 25° C is 33.4 years, and 18.6 years at 40° C. The reliability testing also examined infant mortality rates, and found that a system is 3.8 times more likely to fail in the first year it is installed, but after that point it settles into a range from 18.6 to 33.4 years that is the target for shipping products. Highly Accelerated Live Testing (HALT) that subjects products to vibration and thermal stress can pinpoint failure modes early in the design stages, and by cycling between destruction limits it can verify operating margins. HASS can then use the insights developed by HALT testing for production screening, leading to more reliable units in the field.

Xantrex’s research has shown HALT testing to be effective in finding design defects and marginal conditions. Xantrex has also developed approaches to reduce operating stress on key components identified by MTBF calculations. All indications are that this new inverter will be able to meet reliability, efficiency and cost targets.

GE Research

Joseph Smolenski of General Electric Global Research began his presentation by placing GE’s inverter research clearly in the context of its recent large investment in a broad array of energy generation and efficiency products, which are part of a $132 billion company. GE first focused on the issues facing PV today, which are only partly related to inverters. Among these issues are overall system cost, architectural appearance, lack of completely integrated systems, poor compatibility with building construction, the need for large-scale manufacturing and finally, inverter reliability and inverter performance.

GE has completed Phase I of its research, which involved soliciting customer inputs, developing product requirements, developing a conceptual design, and then assessing design tradeoffs and selecting the best pathway for proceeding. Phase II is currently in progress. Phase II involves updating market information and then developing a detailed design. The design is then thoroughly analyzed for reliability issues, and when it appears satisfactory prototypes are fabricated. At that point, the design can be validated. HALT testing can then be applied, and based on the results, manufacturing planning can commence. If Phase II is promising, Phase III will transition the design to manufacturing, to agency listing/certification, and then to further reliability testing in the field.

The key project goals for GE are:

- Mean Time Before Failure (MTBF) >10 Years;
- Cost<$0.90 per watt @10,000 units per year;
- 1-10 kW;
- Peak efficiency >94%;
- UL 1741 listing; and,
- Meet codes and other standards.

GE's inverter has been designed for reliability, starting with a six sigma design process that insures the product can meet requirements under the worst case conditions, and accounts for component and process variability. Key requirements were identifying operating and fault modes, testing against real-world disturbance data as well as specified I/O disturbances, and then applying failure modes and effects analysis (FMEA). Components were selected and derated for targeted voltage, current, junction temperature and power. This work highlighted the dilemma involved in how expensive it would be to go to different levels of derating and reliability – how reliable is reliable enough at different price points?

The product design factors in thermal issues to control component temperatures, reliability factors like voltage spacing, shock, vibration, connections, insulation, hot spot temperatures, and finally what can be practically manufactured in large volume.

GE's manufacturing quality requirements also adhere to a six sigma standard, and meets ISO-9000 and QS-9000 certifications. GE has a supplier quality management system that requires all suppliers to develop a manufacturing quality plan, to qualify manufacturing processes and implement a procedure for continuous feedback on items that are critical to quality. Design for manufacturing involves requiring the development team to work with the manufacturing team during the design process, to ensure that the design uses standard processes and compatible tolerances, like IPC2221 design standards for printed wiring boards. Manufacturing quality is backed up with field failure analysis and a corrective actions system to ensure that field data is used to correct any quality problems.

Some of the ideas GE has explored include advanced switching components using SiC devices that can handle high temperatures, have lower losses, essentially no reverse recovery and higher switching frequencies. In capacitor improvements, GE has investigated aluminum electrolytic wear-out mechanisms. To reduce interconnections, GE is exploring more integration of functions and an "inverter on a chip" approach. Improved thermal management techniques are being developed, including lower maximum junction temperatures. In transient protection devices, GE is working on long-term performance, reducing cost and higher energy ratings.

SatCon Technology Corporation Research

Leo Casey of SatCon Technology Corporation described its research for high reliability inverters that is focused on developing a more reliable, long-lived and rugged inverter, that can justify a 15-year warranty and reach an MTBF of 50 years or more. SatCon began by looking at the inherent weaknesses in systems and components, then at the external and internal forces that impact reliability and life. Inherent weaknesses include defects, aging and wear out caused by micro-cracks, metal migration, diffusion, filamentation and crystallization, as just a few examples. External forces include temperature, air density, humidity, ultra-violet exposure, power surges and voltage sags on the line. Variations in the solar array power, shock and vibration are critical in the inverter design and must be characterized. The design must be tolerant of the external forces. Plasticizers, conductive condensation and device stress are just three examples of where external forces are at work. Internal forces include power thru-put and dissipation, which impact temperature. Thermal shock, the differentials in temperature over time where the system is exposed, is also an internal force issue. Voltage, current, and aging mechanisms are also internal. Examples of how internal forces have an impact include fatigue due to cycling and cracks in components induced by thermal shocks.

To address these problems SatCon focused its initiative on eliminating, where ever possible, unreliable parts and parts with pronounced wear out problems. Next, SatCon worked to mitigate and minimize environmental stress, and then minimize dissipation and maximize heat transfer. SatCon worked on developing a rugged PV array and grid interface, with rugged packaging. Finally, SatCon focused on the critical transition to manufacturing, with detailed examination of parts qualification and handling, and design rules that facilitate manufacturing.

For Failure in Time (FIT) effects, temperature is critical, and is related to ambient temperature, changes in temperature in relation to power input and output, and with cycling consequences such as cracking, crack propagation, flexing, shear stress at interfaces and fatigue. SatCon's approach has been to squeeze reliability into design by reducing FITs. First we focused on reducing stresses, then reducing component counts, then on eliminating components if possible, and finally investigating alternative technologies. Figure 9 shows parts derating in response to voltage, power and maximum temperatures.

SatCon took a systems approach to increasing reliability and service life, examining the impact of weak components like ceramic capacitors and electrolytic capacitors, and relating them to the following items:

- Power Circuit Topology,
- Component Life/Reliability,

- Control,
- Hardware,
- Software,
- Packaging,
- Thermal,
- Passive (magnetics/capacitors),
- Design for manufacturing, and
- Transition to manufacturing.

SatCon is nearly finished with Phase II of this project, having completed the conceptual design and they are now verifying the design through the stage of full electrical testing. Worst case electrical testing still has to be completed as well as abnormal electrical testing, specification review and developing a preliminary datasheet. SatCon's Phase III development will involve proof of design, proof of manufacturing and manufacturing integration.

COMPONENT	APPLIED VOLTAGE	POWER	MAXIMUM TEMPERATURE
Film Resistors, Thermistors	80% rated	75% rated	125°C (150°C rated)
Metal Sense Resistors	N/A	75% rated	125°C (170°C rated)
Power Semiconductors	80% rated VGS, BVBEO	Observe temperature derating	125°C (Tj max; 150-175°C rated)
Signal Level Discretes	80% rated (if applicable)	75% Power, forward current, surge current	125°C (Tj max; 150-175°C rated)
Ceramic Capacitors	Continuous: 80% rated Peak: 100% rated	N/A	Self Heating <5°C, (125°C case temp rated)
Tantalum Capacitors	Continuous: 33% rated Peak/reverse: 50% rated	75% of rated ripple current	125°C max case; (170°C Tg)
PCB	Observe UL spacing for ISO barrier	N/A	120°C (135°C Tg); 125°C (170°C Tg)
Optocouplers	80% rated	75% rated forward current	110°C max case
Linear/Analog	80% rated	80% rated Pdiss	125°C (Tj max)
IC - Logic	80% rated	80% rated Pdiss	125°C (Tj max)
IC - ASIC/uP	80% rated	80% rated Pdiss	125°C (Tj max)
IC - CMOS	80% rated	80% rated Pdiss	125°C (Tj max)
IC - Bipolar	80% rated	80% rated Pdiss	125°C (Tj max)
Fuses	100% rated	80% rated current	75% I^2t rating

Figure 9. Parts Derating in Response to Voltage, Power and Maximum Temperatures. (Courtesy of SatCon)

Questions and Answers for High Reliability Inverter Presentations

The following is an overview of the commentary and discussions that followed the inverter technology presentations. Although not verbatim, the questions, discussions and comments are presented with no attempt to draw conclusions. Conclusions and priorities are drawn and presented as part of the breakout session summaries and the group discussion summarizing day one activities.

The first question for the inverter technology presenters concerned the voltage rating of the inverters being developed. Leo Casey remarked that SatCon's was at 400 V. GE noted there was no specified voltage requirement in the request for proposals and that all three may have different voltages. Each contractor chose voltage ratings consistent with the product they determined met market priorities.

The next question concerned the conditions used in "Highly Accelerated Life Tests" (HALT). Ward Bower explained that HALT goes beyond testing that is done in the field. It actively looks for problems that may pop up, like capacitors that wiggle back and forth and that are susceptible to vibration or shock. There is no direct correlation between MTBF and HALT. HALT testing goes far beyond normal operating ranges to find weaknesses that will produce reliability problems.

As a follow up, the group was asked if there has been any work to replicate field failures of inverters. Joe Smolenski replied that it is important to do that, but it is not part of traditional HALT procedures. Rob Wills raised two related issues concerning toxics that might be released during failure and recyclability of materials. For example, lead that may end up in landfills needs to be addressed. In reply, it was noted that fire retardants and plastics are a big issue internationally because many are proven carcinogens. It is likely many materials will be removed by pressure from other markets soon even if U.S. requirements are not imposed.

An installer who is often asked to provide guarantees that go beyond manufacturer's warranties asked whether systems were being designed to facilitate fixing inverters when they break, particularly replacement of vulnerable components. The reaction was that typical installers are not really capable of performing field repairs, and repairing equipment may raise issues with the UL listing. Simplifying field repair through hardware design would drive design toward connectors to allow parts to be removed and inserted, which introduces very familiar failure mechanisms. Inverter designers have looked at addressing one of the main sources of failure – voltage surges caused by lightning – but bringing in the extra protection and making it replaceable adds to costs.

Tom Basso noted that there is lots of talk about long life and reliability, along with the need to address single failures and independent failure modes. He wanted to know what kinds of models are used and how they are validated. Ward Bower replied that modeling is very difficult and whatever model is developed, it is almost assured to be wrong at some point. On the validation issue, Rob Wills noted that distributed technologies are unfortunately going to become a reality without communications, particularly of information that addresses system reliability. We probably see between 15% and 20% failures today and if those were monitored it would be easy to see the failure processes and characterize them over time. The whole area of communications is essential and is the best way to find problems and identify how to fix them.

The next question raised issues about SiC, and problems that exist due to defects in the device. The question was: Are they commercially viable today? The second part of the question concerned costs, and the fact that Hitachi motor drives are available on the shelf at roughly $0.09/Watt. Why are inverter costs so much higher, particularly for the high-reliability inverter research goals? Ward Bower replied that $0.90/W was put in the guidelines for the high-reliability inverter solicitation as a limit and all the contractors are doing better than that. Ward then asked what the benchmarks for efficiency, cost and reliability should be. Finley Shapiro replied that $1/W on the inverter is what is expected, and installers hope a distributor will give a discount from that. That is a ballpark figure that applies to residential systems in the 3-kW size range. For efficiency, 94.5% is the benchmark today, but it depends on a lot of factors. Efficiency must be above 94% to play today. Rob Wills noted that it would be useful to have numbers other than peak efficiency – something like the weighted efficiency that is used in Europe.

In going back to the referenced $0.09/W motor drive devices it was explained that unlike motor drives, inverters that act as power generators have to meet FCC Class D requirements plus lots of grid and source interconnection requirements, so their costs can not be comparable to motor drives. There are also several different costs being compared. We have been talking about retail at this workshop, but actual cost is more like $0.60 to $0.70/W, and $0.50/W or less for the manufacturer. Retail is much different because the price depends on how many dealers and distributors are between manufacturer and end-user and quantity discounts. Retail costs for inverters can be as low as $0.20/W for very large industrial users, to $0.40/W for resellers, and eventually up to $0.90/W costs for the end user. It was noted that the only reason the inverter manufacturers can get $1/W today is that the PV portion of the system is even more expensive and somewhat masks the inverter costs. Ward noted that one reason the five-year strategy is being developed is the fact that DOE program management could not envision inverters coming down to $0.10/W with business as usual. However, another person commented that the whole industry has unrealistic expectations for pricing and reliability, dragging some manufacturers into bankruptcy. There are some inverters that are less expensive today because they are also made in mass quantities for other applications.

Someone else said that looking back 8 to 10 years, we had goals for today –whether they were realistic or not or if inflation has taken its toll is another issue. Price depends on a range of issues. What is the driving force behind revisiting our benchmarks? Ward replied that $1 doesn't go as far as it used to, so yes, there are inflation factors to consider. But, there is also the big picture of what is influencing the final cost of the product. First we need to get inverters to be rock solid functionally, and then we can look at volume of sales to drive industry prices down. Ray Hudson noted that Xantrex does look at the parts it sells and compares it to other prices. And, it is true that you can buy a 1000W inverter for $70 (7 cents/W), at Costco? But it is a totally different product.

Capacitor Technologies: A Comparison of Competing Options

Bruce Tuttle of Sandia National Laboratories provided a review of capacitor options based on extensive discussions with experts at Penn State, General Motors, AVX/TPC, Argonne National Laboratory, Ford, DOE, Biztek Consulting, Oak Ridge National Laboratory, TPL, Inc. and Brady Corporation.

His presentation began with the statement that the optimum capacitor for an inverter depends on the application. Photovoltaic inverters are typically 1 kW to 10 kW for residential systems and 100 kW to 300 kW for commercial systems and emphasize reliability, cost, physical size and temperature in that order. In comparison, a vehicle inverter operates at 50 kW to 150 kW, and the priority is on temperature, size, cost and reliability (fail safe), in that order. Utility inverters range from 10 kW to 500 kW now, and in the future will range up to 2 MW and then to 20 MW, with first priority on reliability, then cost, temperature and size.

Reducing dc bus capacitor size has a big impact for power electronic modules (PEMs) – particularly for hybrid electric vehicles. There are three types of capacitors in hybrid vehicle PEMs. They include dc bus capacitors that operate in the 0.3 to 1 mF range. Then there are snubber capacitors in the 0.1 to 1.0 μF range, and filter capacitors in the 1 to 10 μF range. The big payoff in developing a technology for dc bus capacitors is the ability to replace aluminum electrolytics and finding a technology that can also apply to snubber and filter capacitors. Electrolytic capacitors simply cannot meet the 110^{o}C temperature requirement for dc bus capacitors for 2004 electric hybrid vehicles. The best they can do is 70^{o}C, while tantalum (Ta) electrolytics have a voltage max of 124V and experience high losses at elevated temperatures.

DC bus capacitors are a large reliability concern. Current electrolytic capacitors used in dc busses are made of Al or Ta, which have temperature limitations that lead to reliability problems. Other key options are polymer-film capacitors, multilayer ceramic capacitors, ultra capacitors or super capacitors, and solid tantalum capacitors (low voltage, good ESR, expensive). Ceramic thin-film capacitors are still in the early stages of commercialization. They are used in Motorola mobile phones, but do store up to 20 J/cm^3.

For reliability, the strongest options are multilayer ceramics (although they have temperature limits) and polymer-film multilayer capacitors, where the main concern is soft breakdown behavior. If size is a priority, electrolytics, ceramic capacitors and polymer films are attractive. In terms of cost, the best options are electrolytic, polymer-film (which are three times less expensive than ceramics) and multilayer ceramics. Figure 10 shows the capacitor specifications developed for the dc bus by DOE/EE.

DOE/EE Tech Team DC BUS CAPACITOR SPECIFICATIONS

Property	Now	2010 Tech Team Requirements
• CAPACITANCE	240 µF +/-10%	2000 µF+/-10%
• VOLTAGE RATING	525 VDC	600 VDC
• TRANSIENT VOLTAGE	600 V PEAK 50ms	700 V Peak for 50 ms
• LEAKAGE CURRENT		1 mA at rated voltage
• DISSIPATION FACTOR	<2%	<1%
• ESR, ESL	<3 milliohms	< 3 mohms, <20 nH
• RIPPLE CURRENT	90 Amps RMS	250 Amps RMS
• **TEMPERATURE**	**-40°C to +85°C**	**-40°C to 140°C**
• **SIZE; WEIGHT**	170cc **(1.4 µF/cm³)**	**400 cc (5 µF/cm³), 10.8 kg; 27 g/cm³** **Semikron 1500 µF/1687cm³ = 0.9 µF/cm³**
• **COST**		**$30**
• FAILURE MODE	Benign	Benign
• Life @80% rated Voltage		>10,000 hr, 200 A rms, +85°C

Sandia National Laboratories

Figure 10. Capacitor Specifications Developed for dc Bus by DOE EE.

Thermal Management and Packaging

Clayton Handleman, President of Heliotronics, began his presentation with an overview of inverter design goals, followed by a survey of approaches to thermal management (information on Heliotronics inverter work), a summary of lessons learned and ideas for further consideration.

In the early 1980s industry was focused on getting inverters to operate connected to the grid. The main problems were with the requirements for low harmonics and maintaining reasonable efficiency. In the late 1980s to early 1990s the focus turned toward maximizing efficiency, followed by adhering to codes and standards in the mid 1990s. That phase was followed by a focus on "getting to the bottom of the reliability bathtub," which refers to the classic chart that shows high infant mortality (1^{st} year failures) declining quickly to a much lower level of failures in the field (the bottom of the bathtub) then another sharp incline in failures at the end of their projected lives (the other end of the bathtub). The focus now is on stretching the bathtub, extending lifetime, by controlling temperatures resulting from power semiconductors (point sources) and magnetics (diffuse). For electrolytic capacitors, an increase of 10°C from normal can halve the expected lifetime. For power semiconductors, the junction should be at least 25°C below its rated maximum.

The approaches for thermal management include combinations of vented and unvented boxes with passive extruded heat sinks, active cooling with vented or unvented boxes, or a fully passive engineered heat sink/enclosure. More exotic approaches involve heat pipes or convection driven liquid cooling.

For thermal management, cast aluminum has many advantages. It can have a large distributed surface area. It can be engineered to control heat flow. There can be relatively easy thermal partitioning, and it is fully passive. It operates in sealed enclosures and can work with potted magnetics. Finally, there are solid modeling and thermal design tools for cast aluminum so that it can be easily integrated into the design process.

Heliotronics work on inverter designs, including thermal management, has been funded through three NYSERDA (New York State Energy Research and Development Authority) awards to develop inverters with high reliability and serviceability. Heliotronics focused its attention on effective passive cooling, with a cast aluminum enclosure/heat sink. Heliotronics received testing support from Sandia National Laboratories, including using their test chambers, imaging and expertise. Sandia confirmed the unit's anti-islanding performance, conducted surge testing, maximum point power tracking (MPPT), power quality, total harmonic distortion (THD) and power factors. Sandia also conducted radio frequency interference (RFI) testing. Some of the techniques we applied include potted magnetics to move heat to the exterior without vents, taking advantage of a large surface area for passive cooling, and working with 3-D geometry to make the design more flexible and work more effectively for fin design, component mounting, partitioning, and engineering heat flow.

He said the work has moved from concept to model to modification to building and testing of devices. The concept we started with involved no fins. Heat distribution was partly controlled by varying wall thickness. Potted magnetics helped deal with diffuse thermal sources. Strategic mounting of point thermal sources – semiconductors – was also an important part of the strategy. Finally, we worked with enclosure partitioning to control exposure of sensitive parts to thermal stress.

That is where we started, but the first simulations quickly showed the importance of fins for heat control, so we brought them back into the design, and moved through the remaining modeling, to final modifications and the construction of units that are now operating in the field. In the process Heliotronics learned that it is very helpful to have thermal design as part of the design process from the beginning. Cast aluminum is a very promising approach to increasing the lifetime of high-reliability inverters, based on Heliotronics results and on Outback Power's successful commercialization of a cast aluminum enclosure. Thermal modeling is a valuable addition to the designer's tool box.

Great engineering innovations still come out of small companies. We recommend that DOE diversify its project portfolio to include both high- and low-risk players, especially to capitalize innovators who have limited access to capital. Large players could then commercialize new technology by acquiring the technology or company once new concepts are proven. An example is Beacon Power's purchase of Advanced Energy's technology.

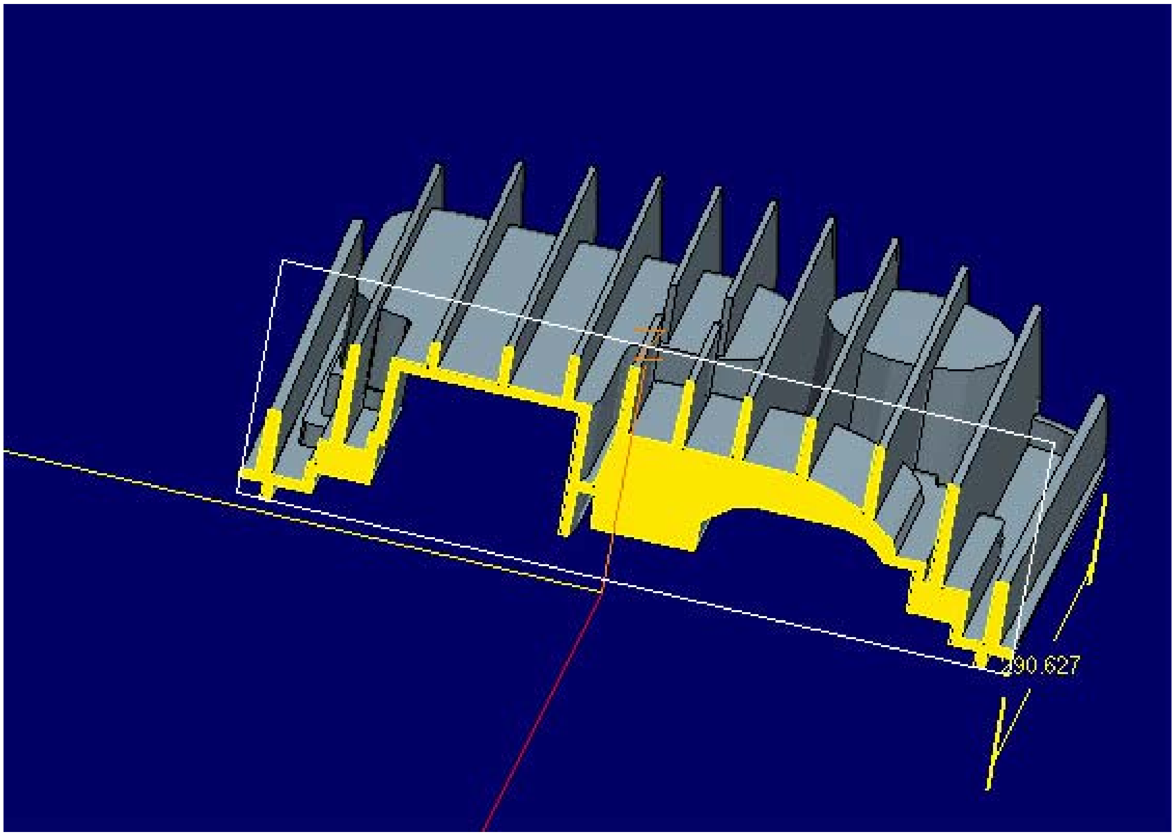


Figure 11. Engineered Heat Flow and Thermal Management.

Sandia's role in providing testing services that would generally represent high capital costs for the manufacturer is also critical. Sandia's environmental chambers, IR imaging equipment, support of HALT, surge testing and MPPT characterization are essential tools for proving new designs. Investments are needed to speed the turnaround on these services, and to upgrade essential equipment – for example, for IR imaging. In the future we would like to see high-end, 3-D modeling that is compatible with industry standard tools like Solid Works©. Figure 11 shows an example of modeling to design an engineered heat flow layout. The industry also needs help with component testing and verification for electrolytic capacitors, power semiconductors, connectors, fans and other components. Well-designed booklets discussing the options and application of these technologies would be helpful. Sandia could be a catalyst in system standardization, in inverter connectors and data communications in particular.

Surge Protection for Inverters

Dr. Michael Ropp, professor at the Electrical Engineering Department of South Dakota State University began his presentation with a chart showing the change in the level of energy needed for the destruction of electrical and electronic components from year 1850 to 2000, from 10^{-3} W to roughly 10^{-8} W. Today's equipment is sometimes five orders of magnitude more sensitive to transient voltages and current from lightning and switching. The ac side transients are fairly well-understood, but dc-side transients – from equipment like solar power arrays – are not.

Most transient suppression devices are shunts that operate by presenting a high impedance to low voltages, but low impedance to high voltages. They operate basically like zener diodes. Varistors based on MOVs (Metal Oxide Varistors) are the most common, with a smaller number based on SOVs (Silicon Oxide Varistors). Other options are silicon avalanche devices (SADs or Transorbs), ionizing tubes and spark gaps (for very high voltage and filters).

MOVs have the advantage of being the least expensive option, and one of the most readily available from many manufacturers. They consist of a matrix of metallic oxide (usually zinc oxide) or ceramic sandwiched between two electrodes. The grain boundaries in zinc oxide act as rectifying junctions, so the MOV is equivalent to an array of back-to-back diodes.

SADs are back-to-back zener diodes – one forward, one avalanching. They have excellent clamping properties and are also widely available in a range of energy/voltage ratings.

In selecting transient surge devices (TSDs), the four key factors are clamping or pass-through voltage, surge current capability, energy or power dissipation and response to common transient pulses. Table 3 summarizes the attributes of the main TSD options. Table 4 compares the response to different clamping voltages and peak currents for the TSD options.

TSD comparison

Device	Rel cost	Degradation	Effect on normal op	TS effectiveness
MOV	Low	High	High	Good
SAD	Moderate	Low/mod	Low	Excellent
Ion tube	Moderate	Low	Low	Good
Filter	Moderate	Moderate	High	Moderate

South Dakota State University
Electrical Engineering Department

Table 3. Transient Surge Device Categorization.

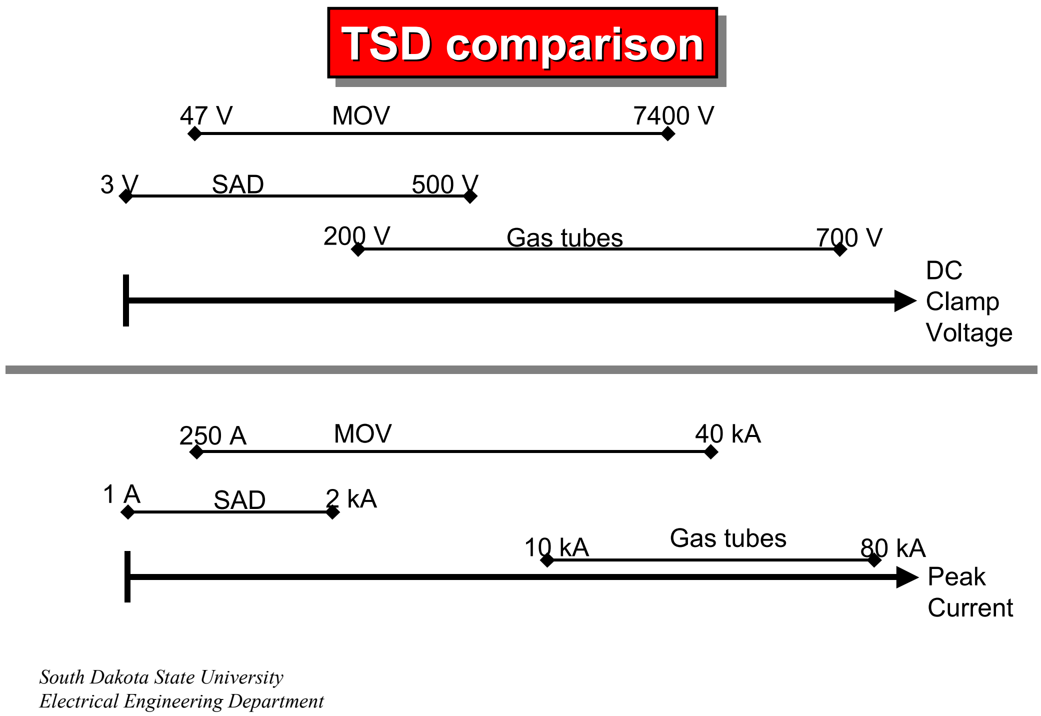


Table 4. Transient Surge Protection Voltage and Current Characteristics.

The critical issues for transient suppression include proper device selection so you are protecting against the most likely transient in the application it is being used. For PV this is a problem, because dc-side transients are not as well understood as ac-side transients. Lead length and layout is also critical. At transient frequencies, L dominates, not R. So the wires should be very short and straight, which is a common goal in all power electronic layouts. TSDs do affect circuit design, because the capacitance of TSDs can be significant for MOVs, although less so for SADs. Capacitors are not good TSDs – especially aluminum electrolytics – because they tend to perform more like inductors at very high frequencies.

UL does list TSDs, under UL-1449, with voltage ratings based on the average let-through voltage of two 6-kV, 1.2/50 msec, 0.5-kA, 8/20 msec impulses, separated by a duty cycle test of ten, 6-kW, 1.2/50 msec, 3.0 kA, 8/20 msec impulses. IEEE-C62-41.1 and IEEE-C62.41.2 standards cover transient voltage suppressors in ac circuits of 1 kV or less.

As for future trends in TSDs, it is not an intense area of research. There is some work on new – or revisited – materials like selenium (which was first used in TSDs in 1928) and nanostructured materials. There is also some work on new device structures based on thyristors and cellular structures, as well as incremental performance improvements in existing TSDs. Lead length, finding ways to minimize inductance, is a lingering issue for research. End of life issues is another problem area – explosion and release of toxics for example, the fact that SADs can fail open or short-circuited and so may need monitoring, and how to monitor MOV degradation over time. To have long-term energy absorption capability, work is needed on preventing slow burn deterioration, thermal control and new structures with better long-term properties.

Communications and Controls for Inverters

Frank Goodman, Technical Leader for Distributed Systems research with EPRI/E21, (Electric Power Research Institute/Electric Innovation Institute) discussed power electronics in the distribution system of the future – what EPRI calls Advanced Distribution Automation (ADA™). He also discussed integrating distributed energy resources (DER) into open communication architecture standards for future power systems and the E21 Consortium for Electric Infrastructure to Support a Digital Society (CEIDS) project on DER/ADA open communication architecture standards.

ADA is expected to lead to the distribution system of the future, which will include intelligent universal transformers at distribution substations and end-user sites to detect and communicate in real time the status of the local grid and its elements, via satellite uplinks. ADA is designed to include DER integration into the system, so that DER can be monitored and controlled just like other generating sources on the grid. ADA will also provide a framework for other intelligent electronic devices to interact with the grid, for example by controlling or shifting loads in response to system requirements. The future is in making all of these devices and functions interoperable:

- DER;
- Intelligent, universal transformers;
- Protection coordination;
- Knowledge-based demand-side management (DSM);
- Power system and customer equipment;
- Advanced power electricity for power quality, switchgear, other uses;
- Integrated Volt/VAR management;
- Supervisory control and data acquisition (SCADA); and,
- Fast simulation modeling.

Intelligence will be the key to enabling new electrical system configurations, such as looped secondaries and new reconfiguring options, dc ring busses and new customer service options, DER integration, intentional islanding, microgrids, two-way power flows and circuit to circuit power exchanges, to name just a few. An adaptable microgrid will be able to break apart into multiple regions in emergencies, so that sub-micro-grid elements will be able to isolate themselves when necessary.

The objectives of the CEIDS DER/ADA standards project includes developing internationally-promulgated DER communication object model standards that will enable the strategic use of DER in ADA for functions such as:

- Routine energy supply,
- Peaking capacity,
- Voltage regulation,
- Power factor control,

- Emergency power supply,
- Harmonic suppression, and
- Disaster recovery operations.

It will also establish a methodology for standardized "**object model**" development, and coordinate with other related work to identify gaps and implementing plans for filling the gaps with other new project work. The work takes advantage of synergies between a flexible electrical architecture and an open communications architecture, with DER/ADA being just one component of the open communication architecture, with secondary impacts on the flexible electrical architecture.

The DER/ADA standards project works to develop international industry standards for information exchange models for DER and ADA. The first phase of the work involves obtaining inputs to develop the standards from existing standards working groups, vendors, integrators, utilities and other stakeholders. It also involves developmental testing in laboratories and in the field, and studies of ADA operation with DER. This will then contribute to the standards development process, with a goal of creating an international standardized information exchange model for DER in ADA. These standards will then be implemented in equipment, as other groups adopt them. Figure 12 below shows the DER/ADA Standards Project Plan.

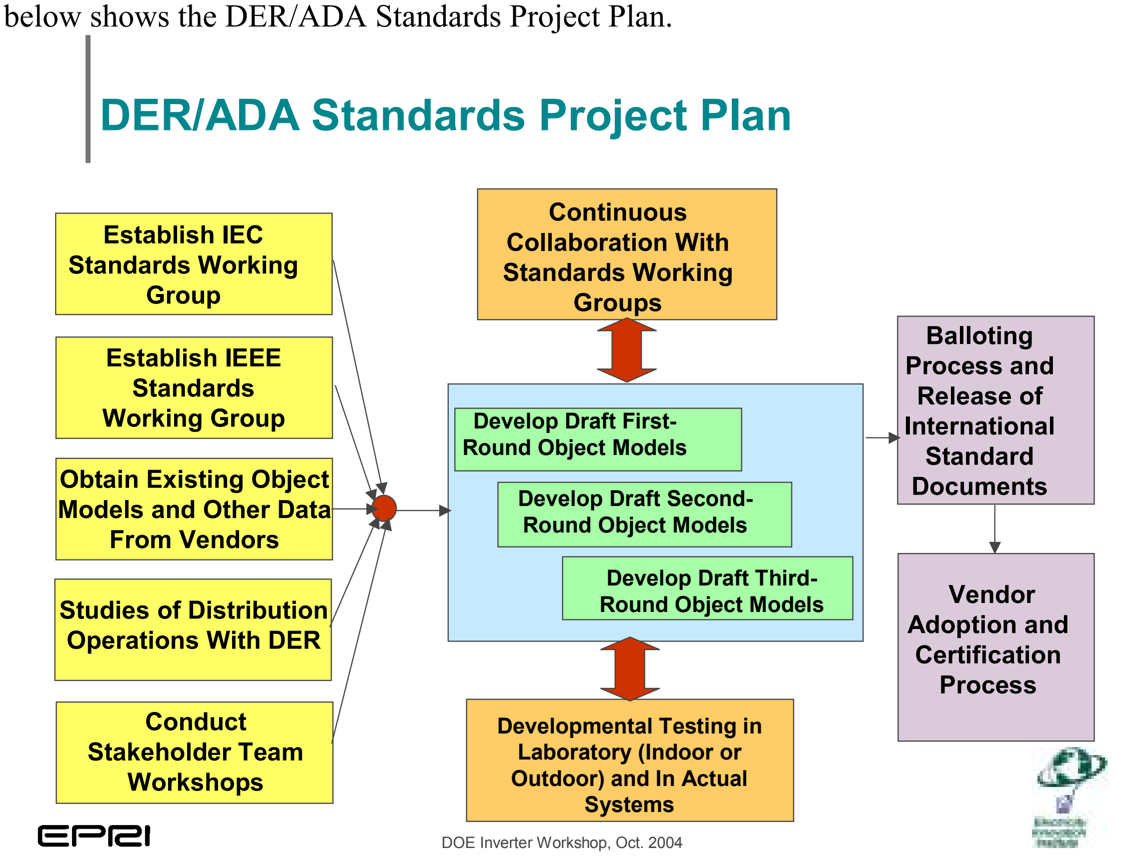


Figure 12. DER/ADA Standards Project Plan.

The standards documents will be built up incrementally, starting with relevant existing logical nodes in IEC 61850, then adding nodes from round one work, from round two work and finally round three. Some of the DER logical nodes will be reusable in future object models for other equipment used for both generation and distribution. When it is finished, our standards will be part of a larger body of international open communication architecture standards – for distributed automation, customers, generation, substations and other devices and applications.

IEC Working Group 17 is the main forum for developing "Communications Systems for DER." They intend to provide one international standard that would define the communication and control interfaces for all DER devices. This would simplify DER implementation from a technical standpoint, and should reduce installation and maintenance costs. It will also enable new system-level ADA options, such as microgrids. It will increase the functionality (capabilities) and value of DER utility distribution systems and improve reliability and economics of power system operations. Standards for power quality, wind, DER and hydropower are all scheduled for development, with DER in February 2005 starting with a committee draft, then to a committee draft for vote by October 2005, a final draft of the international standard by October 2006 and a final international standard by February 2007. Power quality is currently working on a committee draft for voting, and will be through final draft and international standard approval by April 2006. Wind is on a similar track, with completion expected in June 2006. Hydropower is on the same development schedule as DER. EPRI wants to prepare an object model for developmental testing with actual vendor data.

Power Electronics

Jeff Casady of SemiSouth Laboratories and the Center for Advanced Vehicular Systems at Mississippi State University discussed inverter components, power component R&D, and the system benefits, capabilities and trends in silicon carbide power electronics. Figure 13 shows major components as percent of weight and percent of volume in inverters, converters and motor controllers.

The typical inverter uses switches that are typically IGBTs or MOSFETs. Each switch usually has an integral anti-parallel rectifier. A key applications driver is power density – power density is expected to continue to improve in the future, driven heavily by civilian transportation and communication applications that require affordable systems. The ultimate goal is monolithically manufactured power supplies.

Increasing the power density depends on increasing the conversion frequency, increasing the voltage or improving the package to remove heat more effectively. Increasing the conversion frequency involves working with the size and weight of passive components, which typically make up 75% of the size and weight of power converters. For example, a 10-kVA transformer can be reduced from 150 pounds to just 5 pounds with a change in the frequency from 400 Hz to 100 kHz. Increasing the voltage involves working with insulation, which is always lighter than copper and working with skin depth to leverage advantages of higher frequencies.

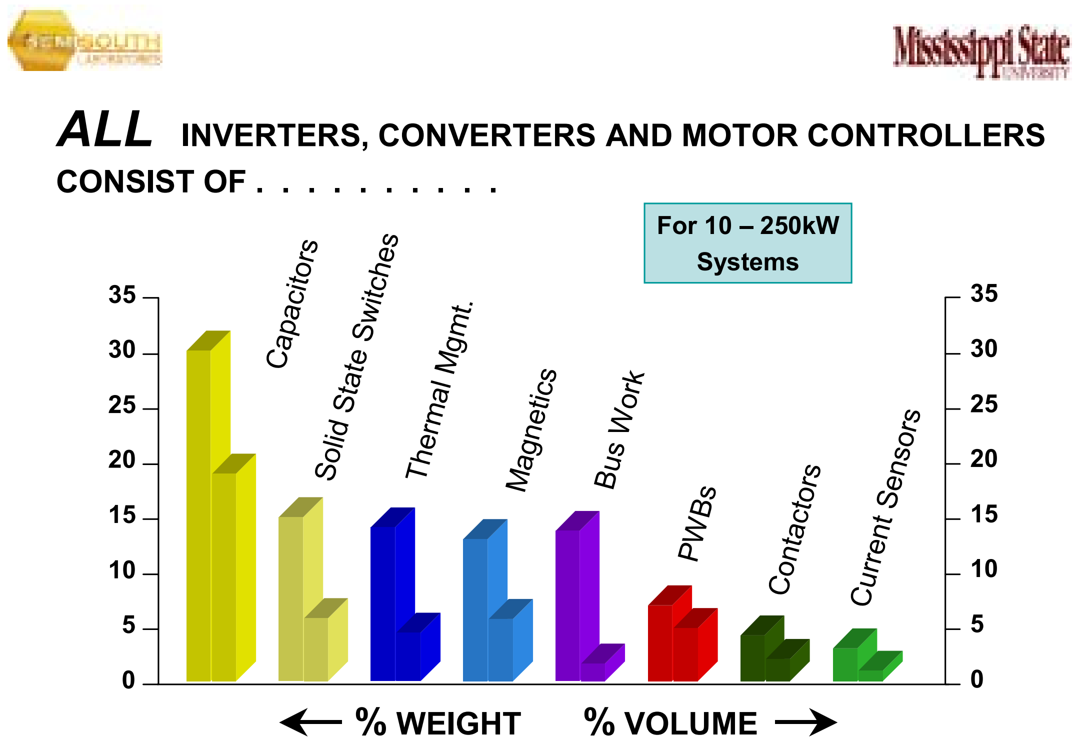


Figure 13. Major Components as a Percent of Weight and Volume in Inverters, Converters and Motor Controllers.

The anti-parallel diode is necessary for bi-directional power flow for dc-ac inverters, for supplying reactive power and conducting harmonic currents. In motor drives it provides energy recovery of energy stored in parasitic inductances. It also conducts resonant currents in soft-switched power supplies and drives. To continue increasing conversion frequency, minimizing the inductance between the switch and anti-parallel diode is essential. The lowest possible inductance is achieved in monolithic devices.

In a dc-ac inverter for on-vehicle application the limiting components are the Si MOSFETs. In this application a typical configuration might be a 28 V_{dc} to 208 V_{ac} conversion, with a 10 kW rating and 3-phase. Voltage boost comes from a parallel load resonant (PLR) converter. A high-frequency ac link means there is no link rectifier required. The inverter itself is a six-pulse system with bi-directional switches and preprogrammed digital controls. The PLR voltage pulse in the ac link inverter puts peak inverter stress on the MOSFET of > 800 V, with a MOSFET RMS current of 28 A. The PLR resonant voltages and currents end up being well in excess of inverter terminal ratings.

The next topic was component research. The Air Force investment strategy in high temperature electronics is heavily weighted toward high temperature SiC and high-temperature passive components, with 10 studies funded in each area. Light-controlled device study has 7 research projects. The remainder of Air Force research funds work in cryogenic power conditioning, pulse power capacitors, high voltage power switching, transformers/inductors, high voltage wiring and low-voltage and high-energy capacitors.

Silicon carbide has several promising attributes for research. The silicon forms a strong chemical bond to carbon and the combination is very hard; it can operate at very high temperatures. Wafers are made at over 3600°F, and the resulting device handles very high voltages (ten times higher than silicon and gallium arsenide). It is becoming attractive because single-crystal SiC wafers for electronics are commercially available, and wafer size has been growing steadily from 1 inch diameter in 1990 to 4 inch diameters expected in 2006. Early versions of SiC power devices perform better than the best silicon power devices, and SiC power products are commercially available and in commercial use. Figure 14 compares some of the key attributes of silicon-carbide versus silicon that drive research.

Motivation to Develop SiC Power Devices

Silicon vs. Silicon Carbide Power Semiconductors

PROPERTY	SILICON	SILICON CARBIDE
BANDGAP (eV@ 300K)	1.1	2.9
MAXIMUM OPERATING TEMPERATURE (K)	425	>900
BREAKDOWN VOLTAGE (10^6 V/cm)	0.3	4
THERMAL CONDUCTIVITY (W/cm - °C)	1.5	5
PROCESS MATURITY	HIGH	LOW
INTRINSICALLY RAD HARD	NO	YES

Figure 14. Comparison of Silicon and Silicon Carbide Power Semiconductors.

The benefits of SiC devices includes lower on-resistance, which increases system efficiency, higher frequency, which allows smaller power supplies, and higher operating temperatures, which helps reduce cooling requirements. Taken together, these operating attributes pay off in terms of improved system performance – size, weight, cost, reliability and efficiency. Current commercial applications are for high-end server power supplies. Potential future SiC power switch applications include motor drives and inverters, and high power-density resonant inverters with high voltage stress that can operate at high-temperature.

There are significant obstacles to increasing power density with current technologies. Simultaneous increases in voltage and frequency are limited by silicon – efficiency cannot be compromised. Specifically, MOSFET silicon switches are fast but not voltage scalable. IGBTs are voltage scalable, but not fast (~20 kHz). Reverse recovery of anti-parallel diode adds another limitation.

Parasitic inductances and capacitances, which require resonant circuits (soft switching) above 100 kHz and 1-10 kW are obstacles. Soft switching requires designing to team fast switches with ultra-fast anti-parallel diodes.

Today the vertical junction field-effect transistor (VJFET) is the best SiC available option with greater than 1 MHz operating frequencies and 600 to1800 V ratings. They have both a "normally on" and "normally off" mode available, and incorporate the best possible anti-parallel diode – a Schottky barrier diode.

SiC benefits in vehicle applications come from weight and volume reductions – an estimated minimum of 177 pounds and 3,210 cubic inches of savings that is highly valuable in a vehicle.

SiC power electronics offer new capabilities for device designers. SiC allows both MOSFET and JFET switches. Both types are uni-polar. The MOSFET is normally off, has a p-n body diode that is always present, low channel mobility and oxide reliability issues. The JFET is normally on, but also offers normally off and "quasi-on" options. The benefit of the quasi-on option includes circuit protection, improved blocking and acceptable current trade-off compared to the normally on state. There is no body diode requirement, and it is not as sensitive to oxide interface and reliability issues. SemiSouth's VJFET switches have high drain current and drain voltage performance at an on resistance $R_{on} = 6.8\ m\Omega*cm^2$. It provides a hard switch at 20 MHz, a $T_{jmax} \leq 300^oC$ and a parallel multiple die for high total current.

In summary, SemiSouth's 600V VJFETs had typical R_{on} values from 6.5 to 10 $m\Omega*cm^2$ at room temperatures. Devices had an expected decrease in drain current with increasing temperature with I_{DS} at 300°C = ~30% of I_{DS} at 25^{o}C. Early generation VJFETs had maximum switching frequencies in the MHz range, which increased with temperature. The next generation VJFET will have much reduced on resistance and switching at over 20 MHz.

Future trends in SiC power electronics indicate improved switches with lower on-resistance, simpler and less expensive fabrication processes, and lower packaging costs. In the next 3 to 5 years we expect increased requirements for high temperature electronics, with maximum junction temperatures hitting 250^{o}C to 300^{o}C, while active cooling requirements are reduced. Over the long term, 5 to 9 years, maximum junction temperatures are expected to rise from 300^{o}C to 350^{o}C.

Question and Answer Session

The first commenter asked why Power Integrated Circuits (PICs) have not been mentioned. He went on to comment that there is a lot of commonality if we tap into that industry. PV is a small industry and PV power conditioning can't influence radical technology moves.

In a second question, he asked if there are opportunities for commonality in terms of a modular approach for power integrated circuitry. In the electrical environment there are physical issues that will come in to play so there will always be a need for an engineering review.

He went on to comment that there is action in the communications area and there are not physical issues in communications. It's becoming widely embraced internationally, for all components in power systems and for countries of jurisdictions that adopt the standards.

Additionally he commented that there are also differences in voltages. Engineering is involved to make up for voltage differences.

Another person noted that there's a lot of talk about sending data over power lines. Do you envision using power lines for data transmission or fiber optics? The reply was yes, we do envision using power line carriers as they become available. It's an information structure that includes a set of protocols that will work with many media.

Day One Inverter Technology Breakout Sessions

Each group was provided with a matrix with cells for listing key needs and issues for single-phase inverters for ratings less than 10 kW, three-phase inverters for ratings greater than 10 kW, PV-specific applications and energy storage applications. For each group there were specific categories of needs listed, and the groups were also asked to add any additional issues they felt were important. They were then asked to split into smaller groups to begin filling in the matrix with specific objectives to address these needs. Each group split into three smaller subgroups: single-phase inverters less than 10 kW, PV-specific applications and 3-phase inverters larger than 10 kW with and without energy storage. The original matrixes are included in Appendix B. The groups were then asked, if any time remained, to try and order the objectives in terms of whether they were near-term, mid-term or long-term objectives.

Panel A – Capacitor/Component Technologies

Breakout group A was asked to discuss the R&D needs of capacitor/component technologies, and to address 2010 and 2015 goals and objectives for these technologies. In response to adding other capacitor/component technologies that were missing from the provided matrix, the group agreed to add internal dc bus to the existing list.

Capacitor Discussion

Group "A" identified increasing capacitor reliability and reducing costs as primary needs with more interest in higher reliability. The group acknowledged that with the PV industry being a relatively small player when it comes to using capacitors, it would not have a big influence over capacitor designs and requirements. They discussed other methods of addressing capacitor issues including reducing the requirements for capacitors with innovative circuit topologies. But they concluded that PV most likely could not influence capacitor reliability, because the PV industry does not have a large segment of the market and cannot demand improvements in reliability.

The group discussed other methods of accelerating capacitor development. While manufacturer interest in high-voltage capacitors for inverters is limited, there is some interest from manufacturers and they are making capacitors on a prototype basis. The question is whether they are going to be driven to enhance reliability? A comparison study might be an effective approach toward addressing the reliability issue where different capacitors with different costs are compared. A Xantrex representative noted that they bought different capacitors from different companies and performed tests that showed some perform substantially better than others. He suggested that a similar comprehensive public study would give more critical information to the people designing the inverters.

It was suggested that it would be good in general just to have additional testing to help at least filter down to the top 3 or 5 capacitors. The National Laboratories probably could not perform such a consumer reporter study. A member of the group asked if DOE would fund this sort of activity and the response was that sort of activity falls into the category of "is this going to specifically help the PV industry?", then the DOE solar program could provide support. If they are just capacitor studies that would not directly help the industry, then perhaps not. He said that his answer to the question was a qualified yes.

In regard to other studies that could be undertaken, the group suggested that there is a need for having better and more accurate information regarding capacitor characteristics to help create new data sheets that are clearer and that can be used correctly.

What sort of information on capacitors and other components is needed and what are we looking for? An important discussion was related to capacitor temperature specifications and related lifetimes. One inverter manufacturer stated that for our use, we don't know enough about temperature issues. In relation to reliability, a lot more research is needed in several areas besides capacitors. For example, investigating new topologies that would aid thermal management could provide an alternative solution by bypassing temperature related capacitor lifetime limitations.

On the subject of inductors and transformers, replacement in large systems is not as much an issue as it is in residential applications. The issues with transformers are size and core losses – all of the losses. How do we tackle that? Who do we team with?

Residential and commercial customer service contracts could address reliability and maintenance, perhaps provided by the utility, especially if it involves a 20-year period. A member asked the group about requirements for transformers: specifically what are the attributes or other standards required for the transformers? If getting rid of the transformer is allowed, can it be eliminated? A member of the group replied that the transformer can be eliminated but the utility will not let you hook up to the grid unless you have the transformer. But there is actually nothing in the code that says you have to have the transformer.

A member of the group said that her company didn't use transformers and interconnected microturbines with the grid. Other participants cited major problems hooking up to the grid without transformers. Capstone, a major microturbine manufacturer, would not use transformerless designs either. None-the-less, looking into transformerless systems is a good suggestion. There are cases where you have to have a transformer, but if you don't there is a cost saving and possibilities for enhanced performance. Many transformerless systems have been installed in Europe, but it was mentioned that the grid there is more stable than in the United States. Transformerless systems are also installed in a lot of places such as islands. Although transformerless inverter installations are doable, it is sometimes desirable to have a transformer because it protects the equipment and that implies higher reliability.

Inductors and Transformers Discussions

The group discussed potential teaming opportunities to improve transformers for inverters. The wind industry was discussed but there was concern that it was not big enough. The Department of Defense (DOD) has the same issues that the PV industry has but they do not talk to us. DOD collaboration is probably a great opportunity to pool funding to improve transformers and capacitors. The energy storage and automotive industries were also identified as potential allies.

DOE's Office of Science and the National Science Foundation (NSF) is another funding avenue, because many of these issues involve fairly basic research. The NSF is an ideal source for providing funds to universities.

A member of the group added that he liked the idea of letting researchers play, but research also needs a component of practical application. In regard to NSF, they do not want researchers to be too focused, but still focused enough that they will see the benefit of the work that is being done. The space industry has probably done work in this area as well. The National Labs are looking at this, and some of their research could trickle into commercial technology.

One of the advantages of specifying what the problems are is helping the National Labs target their research. For example, we have all heard about unidirectional flow and carbon fibers, which are new developments, and about prices coming down. Mainstream industries often have brought the price down after the Labs spearheaded the early development. In our case, the problem is easy to define. Components and designs must have fewer losses.

Connectors and Circuit Boards Discussions

In regard to connectors/circuit boards, the group discussed ways to improve these technologies including high temperature printing of circuit boards and layering them right into the substrate. Circuits imbedded in the chip could eliminate the interconnections altogether. One participant commented that since interconnections are always a weak point, the more integration the better.

In California, the industry cannot tolerate lower reliability because of scrutiny from the state program and the end-use customers involved, but we can replace capacitors as disposable components on a scheduled or regular basis.

In specifying research targets and objectives the PV industry tends to ignore the guy who chooses the installers that do the work. This is the invisible customer. We do not want to have to have them come back again and again for repairs, whether they are a utility or an agency.

Internal Connections Discussions

Regarding internal connections, we do not know what the opportunities are for this – maybe standardization could be beneficial to installers – the "plug" part of "plug-and-play." It would be preferable to minimize internal and external connections. Optical versus non-optical approaches need to be investigated and categorized with reliability as a goal.

DC Bus Discussions

Regarding internal connections, improvements can be made by eliminating as many as possible. For what's left, what can be done? One company said that they had gone to all optical connections. A member of the group added that he does not know why some feel negatively about optical connections. The Navy still likes it and so do a lot of other people. It has got to have an advantage. Fiber optics solutions are at the top of the list. This discussion confirmed that there is a real need for further device improvements for optical coupling.

Current State of Capacitors

A member of the group pointed out that Figure 10 of this report showed capacitor information on the current state of capacitors and goals by 2010. The bottom line on capacitors is that they are lousy and they need improvement. The positives about capacitors are that they are commercially available – the question in our case is how do you get the tail to wag the dog (i.e., have the PV industry that is a small customer for capacitors influence the industry's technology)?

Cost is an issue – capacitors are still very expensive. There is a need to reduce capacitor cost. Currently orders of at least 1,000 are needed to get some kind of break in cost.

Goals for 2010 and 2015

The automobile industry has 15 years for desired lifetime of a capacitor – that was offered as one starting point for the group to consider.

The best film capacitors today are reliable up to 105°C. For electrolytic, it goes to 70°C. Ceramic capacitors last longer at higher temperatures, but are too expensive.

It should not matter what technology is used, as long as it meets the specifications. In setting goals we should not put a limitation on which technology to use. At least 10-year lifetime for inverters seems to be a common number, and usually the capacitor is the first thing that fails so it needs to last 10 years.

The group suggested that residential and commercial applications need different goals, because of the difference in access to skilled maintenance, attitudes toward repairs and other factors. On the commercial side there are opportunities for replacement. For residential applications, replacement of capacitors is not likely a favorable option. For cost reduction, we need twice the life and half the cost for capacitors. Today's ceramic capacitors do not reduce costs by one-half or more, and that is the reduction that is needed. If costs were reduced, they would be used because they are more reliable.

There are also other ways of increasing lifetime without changing the capacitor design; suggestions included better control algorithms, innovative circuit topologies and better packaging, etc. To the extent possible inverter manufacturers should also reduce reliance on capacitors and examine ways to repackage inverters using different topologies to address some of the problems.

The goal of increasing the current rating of capacitors is related to what was just discussed. Rating is a generally a thermal issue. Reducing equivalent series resistance (ESR) may also be a goal, but like the other goals that we have discussed, it is typically reduced in better quality capacitors. A practical goal is to reduce ESR by a factor of 4. There are several ways to accomplish that.

Table 5 summarizes the discussions and recommended actions for the capacitor and component technologies breakout panel.

Table 5. Recommendations for Capacitor and Component Technologies.

Topic	Near- and Mid-term
Capacitors	Accelerate capacitor R&D through influential synergistic partnerships with larger industry and other government programs.
	Reduce the need and requirements for capacitors in inverters through innovative circuit topologies, better control algorithms and packaging designs.
	Conduct a comparison study to determine which capacitors perform as expected and what the costs are coupled with a reliability check.

Table 5. Recommendations for Capacitor and Component Technologies.	
Topic	**Near- and Mid-term**
	Perform additional testing to sort out the good capacitors.
	DOE Solar Program provide capacitor development support where appropriate.
	Create a more accurate database regarding capacitor characteristics with good temperature specifications and related expected lifetimes.
	Determine if capacitors can be disposable and replaceable components without seriously affecting the safety and listing of inverters.
	Strive for capacitors that will support a 10-year lifetime at elevated temperatures for the typical inverter.
	Double the life and half the cost of capacitors for energy storage in inverters.
	Support improved ceramic and film capacitors to reduce their costs by one-half.
	Reduce the equivalent series resistance in energy storage capacitors by a factor of four. Also improve equivalent series inductance through innovative designs.
Transformers and Inductors	Strive to reduce magnetic component losses.
	Investigate transformerless inverter designs and use where possible.
	Work with utilities to overcome barriers to transformerless or non-isolated inverter ties.
	Investigate transformerless applications in island situations.
	Improve component protection for non-isolated designs.
	Investigate teaming opportunities with larger industries and programs such as the automotive industry and the U.S. DOD to improve transformers and magnetic materials.
DC Bus	Investigate higher temperature printed wiring boards and incorporate integrated substrates.
	Reduce interconnects on the dc bus as much as possible.
	Investigate surge protection for the dc bus.
Connectors and Circuit Boards	Eliminate as many interconnects (internal and external) as possible though improved and larger-scale circuit integration.
	Investigate optical approaches for coupling signals with a push to further device improvements.

Panel B – Surge Protection, Thermal Management and Packaging

Breakout group B discussed the status, goals and needs for surge protection, thermal management and packaging. They began their discussion by adding the following issues/components to their matrix: lead free/environmentally friendly, EMI and thermal packaging. They formed three subgroups: PV specific, generic/single phase and generic three phase/energy storage.

John Berdner began a discussion to categorize various surge categories. There is generally some probability of lightning and probabilities for switching induced surges. It is clear that most surges come from the ac side of the inverter, but the dc side can also be an effective antenna for lightning. The problem then becomes where you install the surge protection. Should it be on the dc side, the ac side, or both? Siemens has one of the best arrangements today. External units in general are difficult to install. There was some support for putting surge protectors at the main service panel of the entire house, which might allow for a more brute-force approach to controlling surges. On the dc side there are no UL listed products – that is something industry may want to develop on its own. The dc-side surges would come from lightning strikes on or near to the PV array, with the array acting like an antenna. A UL listed device is needed, and in the meantime it is not reasonable to recommend an unlisted device.

If an MOV is subjected to a large surge, it will explode, a catastrophic failure that is bad for safety and destructive for or contaminates the rest of the equipment. Coordinated surge protectors are needed – why prepare an inverter to survive the worst-case surge, if it won't be in an environment where it could be subjected to that surge? Should the mode of failure be a requirement? Is it a safety issue? Is it a reliability issue? In other words, it can sacrifice itself to save the rest of the inverter. Currently all the thought on surge protectors is based on the premise that inverters cannot be crippled and they cannot misoperate or go offline after a surge. It will be a real challenge to sell a standard less than that.

At this point, the group began to come to conclusions on surge protection for generic single-phase inverters. First, the closer the surge protector is to the surge entrance, the more effective it is. It will be easier to justify the cost if we can also justify the benefit. Surge protection impacts packaging and a lot of other design issues. A dc surge arrestor has to be developed. Inverter manufacturers should only have to comply with one standard for surge protection. At this point we are talking about a number of things being taken out of the inverter package and put in separate installations. To achieve that industry must figure out how to achieve these goals. A key goal is to develop surge protectors that absorb surges and are still safe (i.e., not catch on fire, explode or release toxics)?

Advanced Devices for Thermal Management

The group suggested exploring carbon fibers for thermal management with a workable technology in 2015 as an objective. Cost effective potting compounds are another significant topic. Today, the only UL listed potting compounds cost too much. Ideally industry would want a system compound that can be used to manufacture the transformers as well as serve as the potting compound. Controlling dimensions and topology to minimize the need for potting compounds is also useful. By 2010, Sandia should deliver advanced thermal modeling and support, ideally with full 3-D capability.

General Input/Output and Packaging

All PV equipment should have the same interface and fittings as standard electrical equipment. That includes the same distance from walls, same fittings, etc. Although for some of these items there are not formal standards, there are defacto standards based on the typical junction boxes, service panels, conduit and other items that are most commonly used by electricians – inverter manufacturers should follow their leads.

The PV industry also needs properly rated non-trade cable that comes right out the inverter that does not need conduit. That means getting suppliers to offer and win approval for double-insulated class 2 wiring. Installers objected to this when Solectria used it a few years ago because they had to stuff the cable into the enclosure, but it is worth revisiting. In general, we need some type of armored cable, to make it rodent-proof that is rated for wet conditions.

By 2015, we should have plug-and-play products. Unfortunately, DOE did not realize that connectors (the plug element) were a reliability issue when it was suggested a few years ago, so little has been done to simplify or standardize them. That was over 10 years ago and connectors are still a problem. It needs to be addressed now. It takes more time to install an inverter today than it does to build it. The most common cause of failure is improper installation.

Controls

Europe is considering developing a generic anti-islanding device, although it has not been developed yet. A UL listed anti-islanding device would be useful. On the control side, it would be useful to work out a communication protocol so that utilities could broadcast a "stay on-line" message, independent of voltage and frequency, on the power lines that the inverter would be able to respond to by either disconnecting or staying connected, depending upon the utility's needs. This would help reduce unwanted trips that often disconnect distributed generation at the worst moment, when the loss of generation actually exacerbates a problem on the system. This would help move responsibility for determining utility conditions out of the inverter and back to system operators. It would have to be ultra-robust and ultra-reliable, in order to guarantee that islanding would not occur. The feasibility of such a system should be established by 2010. For utilities, this would finally make distributed resources controllable and possibly dispatchable.

Internal Connections/Terminals

By 2010, there should be spring-loaded connectors for field terminations that are immune to vibration, that are not changed by torque, and that are immune to cold flows. They should also be designed for error-proof installation (i.e., they can only be connected correctly).

Interface Connections/Terminals

Communication connections have not been developed. It is difficult to specify now given the number of possible communication pathways that might be feasible. Some communication options today include signals over power lines, high throughput WIFI, etc. Today's water proof, exterior grade communication connections are expensive, and by code anything located outside is considered a wet location.

Tables 6a, 6b and 6c summarize the recommendations for applications of generic single-phase inverters, PV-specific applications and large applications/storage that uses three-phase inverters.

Table 6a. Recommendations for Applications of Generic Single-phase Inverters.

Topic	Near- and Mid-term
Surge Protection	UL listed dc-side surge arresters (up to 600 volts).
	Emission-free, hazard-free failure mode.
	Coordinate surge protection; whole house surge protection and inverter-specific protection (move surge protection out of the inverter).
Advanced Devices	DOE supported thermal modeling for inverters.
	Carbon-fiber high temperature plastic.
	Die casting of high temperature plastics to be used for thermal packaging to more effectively remove heat from the unit (less weight, less cost).
	Potting compounds: cost-effective, UL-listed, thermally conductive, materials compatibility and dimensional control of magnetics with 250^{o}C rating.
General Input/Output	Standardized conduit, knockout sizing and spacing.
	Double-insulated, class 2 wiring without conduit.
	Plug-and-play connectors that are rodent proof (already available in Europe).
Controls	UL listed external, anti-islanding device (add-on).
	Utility broadcast, stay on-line signal to control islanding.
Internal Connections	Error-proof spring-loaded connections for field termination.
	Low-cost, exterior grade communication cables and connectors.
Thermal Management	DOE support for thermal modeling for inverters.

Table 6b. Recommendations for Applications of Generic PV-specific Inverters.

Topic	Near- and Mid-term
Surge Protection	Establish standard based on IEEE C62.41 for dc-side surge environmental standard (so that listed equipment can be designed to meet that standard).
	UL listed, field installable surge arresters.
Packaging	Address solar gain in standards (lot of inverters located in outdoor locations and have to deal with rejection of heat developed by switching losses and magnetics, but also heat of sun); there are no good standards to test for it. Have to have standardized approach.

	Model and research impacts of solar thermal gain, including in combiner box (often overlooked).
	Thermal modeling tool to help in reliability and to address thermal gain effectively.
	Model and research diurnal thermal stress to characterize night cooling, phase change, heat exchangers or other passive solutions, advanced thermo-electrics, composites.

Table 6c. Recommendations for Applications of Generic Three-phase Inverters.

Topic	**Near- and Mid-term**
Surge Protection	Self alarming/self alerting diagnostics; self healing.
Advanced Devices	1kW/cm^2 heat rejection.
	Research on SiC and how to manage the heat they tolerate.
	Improve efficiency by 98% and cut costs.
General Input/Output	Size reduction/using higher switching frequency.
	General package improvements for magnetics, heat sinks, capacitors, others.
	Comply with standards in place, standard conditions.
Controls	Reduce THD and develop feed-forward control using active filtering.
	State-of-charge control/indicator for energy storage.
	Paralleling inverters, multiple controllers. Solve problems involving line-to-line voltage differences that cause controller problems.
	Intelligent controllers able to deal with different line voltages.
	Temperature controls.
Internal Connections/Terminals	Minimize wire bonds; higher levels of integration.
	Internal temperature sensing of energy storage.
Interface Connections/Terminals	Idiot-proof, user-friendly connections.
Higher Temperature Circuit Boards	Meet other component requirements. The whole system has to withstand higher temperatures requiring thermal matching of materials and components.
Lead-Free /Environmentally Friendly	Meet legislation to have lead-free inverters.
Automation and Manufacturing	Lower cost of system design for manufacturers, approaches to eliminating hand assembly.
Value Added Versus Costs	Reliability. What is value of R&D and the return on investment?
EMI	Modeling for electromagnetic interference (EMI) by 2010.

Panel C – Power Electronics, Communications and Controls

Breakout group C discussed power electronics, communications and controls. The discussion opened with a review of the matrix and whether it included all the elements that should be discussed. They then formed three subgroups: PV specific, generic/single-phase and generic three-phase and energy storage.

The PV systems subgroup discussed the relative merits of wide band gap devices, but the majority of the group didn't have enough understanding of their potential benefits versus their costs.

The subgroup conducted an extensive discussion on ungrounded PV systems and the European experience with ungrounded PV. They noted that transformerless designs coupled with ungrounded systems may be difficult for U.S. inspectors and regulators to accept. It will take substantially more work on codes and standards to see them accepted in the U.S. market.

In discussing reliability standards for PV inverters, the group noted that comparisons to other applications may not be appropriate. Automobile companies don't have to offer a 25-year warranty. Homeowners and businesses have different expectations than a utility or an industrial customer. Residential consumers have less access to skilled maintenance, and there is greater concern for safety. What happens when the inverter fails becomes more important? Releases of toxic gases or excessive heat into homes could very quickly give PV a bad name. This led to discussion of a maintenance-free inverter as a goal. The inverter must be a device that survives neglect and when it fails would simply be replaced by a new unit. There are also unique utility views on reliability. For example, for utilities, replacing an inverter is an obligation because they would otherwise have stranded the cost of the entire PV system. They are hostage to the inverter because without it, the remainder of the investment is stranded.

Somewhat in contradiction to that concept, the group also discussed the importance of communications and diagnostics. If inverters had some way of communicating system conditions that might predict a failure (or degradation) it would be easier to forestall problems before end-users experience the failure and become irritated with the product. This would also facilitate predictive maintenance, and could also help manufacturers identify weak spots in their designs by getting feedback on a large number of real installations and how they fail. Utilities could also use information on the distributed generation on their systems to better predict its impacts and improve planning and operations.

This brought up the importance of developing a common "language" for accessing and disseminating important system information at both the hardware and software level, so that it can be compatible with the thousands of potential combinations of hardware and software that are used by utilities, manufacturers and integrators. If the structure and format of system data is consistent it can create a platform that software and equipment developers can build on to create whatever applications of the data they need. Without a common vocabulary, each manufacturer's system is potentially a unique proprietary platform. These individual platforms will require customized development of software and hardware unique to that manufacturer's equipment. That is bound to lead to fragmentation of the market, leading to fewer systems that any single software or application developer can address, and therefore higher costs and slower development of applications that can use the data. There needs to be collaboration and agreement on the vocabulary to make sure that system information is presented in a consistent format. The common vocabulary also extends to the definition of terms used to characterize the data. For example, the definition of "voltage" may require a specification of how or where the equipment is connected to measure what it is reporting as voltage. Finally, there has to be enough vocabulary and structure in communications protocols to accommodate all the information that may be necessary. Not every device may use all the possible vocabulary, but it should be available.

Another important need is performance standards for inverters that are similar to those in place for PV modules. PV module efficiency reporting is not perfect, but at least it is always measured and reported in the same way, providing some basis for comparison. Inverter efficiency and performance claims are made by manufacturers who measure and report what makes their products look best, not necessarily what is best for the consumer.

There also needs to be more attention to making PV/inverters plug-and-play – limiting the need for site-specific design, limiting the need for adjustments in the field and limiting the amount of time and effort involved in installation. That includes greater attention to size, weight, dimensions and general ease of installation of inverters.

For larger PV systems, 10-kW and up, the group felt that wide band gap materials like SiC might have benefits if they can boost efficiency and lower cost – then money should be put into research.

Large-scale integration of PV into the electrical system is a growing problem as more and more distributed systems are deployed. Today, PV inverters actually destabilize the grid because of their anti-islanding circuitry and sensitivity to disturbances on the grid. Just when the system operator could use distributed generation to make up for a sudden surge in demand or the loss of another power source, the PV inverters are likely to take all the PV systems off the system, making the situation worse. Utilities need to be able to work with installers and customers to adjust the sensitivity of the inverter controls, and if possible allow the utility to order them to stay connected to the grid despite conditions that would normally trip them off. It would be ideal if the utility could tie into inverters remotely and change their set points when necessary. Large-scale integration also includes storage and other technologies that can back up distributed PV generation. Utilities with large PV systems have seen that weather has major short-term impacts on PV availability that creates problems during peak periods. There needs to be some way to offset those interruptions. As the number of installations grows, so do the problems. There will be a big difference between today when there are zero to a few systems on the typical grid, and the future when there will be thousands. The integrated system operator (ISO) will need reporting on the status and location of these distributed generators.

Other issues/needs that were mentioned include modular power devices, eliminating connectors, harmonizing with international standards, security and research on disconnect versus isolation transformers, clarifying EMI requirements, more work on safety and grounding and predictive maintenance capability. Security is being addressed in the communications protocols that are under development. There have to be safeguards to ensure that only authorized personnel can access certain features of the systems, otherwise a terrorist or hacker could potentially disrupt the power system by misusing communication and control processes. There will have to be several different levels of access and control, so that some people are completely precluded from accessing the systems, others have permission to use data only, and others have permission to actually change system operating parameters.

Tables 7a, 7b and 7c summarize the Breakout Session C – Power Electronics, Communications and Controls recommendations.

Table 7a. Recommendations for Applications of Generic Three-phase Inverters, Storage.

Topic	**Near-/Mid-Term**
Wide Band Gap Materials	Packaging for 300^{o}C and up.
	Investigate other materials, beyond SiC.
	Boost efficiency.
	Prove reliability.
	Coordinate research with the Defense Advanced Research Projects Agency (DARPA).
Large-scale Integration	Integration with energy storage to provide grid stabilization.
	1-5 sec VAR support.
	Subcycle sag support.
	Power factor control.
	Develop "Modular Power Device/Bridge."
	Characterize degraded mode operations.
	Multiple-use inverters.
Thermal Management	Improve thermal management – magnetics.
Controls and Communications	Develop self-testing, diagnostic devices.
	Compatibility with international communication standards.
	Ability to externally modify power factor and power.
	Ability to reset faults.
	Remote connection capability – Ethernet.
	Security applications – ability to coordinate and control/communicate with PV, battery and diesel systems.
	Security procedures and rules – national security in terms of who controls system, protecting access.
	Standardized set of controllable parameters for command and control.
	Improved user interfaces, with some standardization.
	Predictive maintenance capability.
Connectors	Reduce/eliminate connectors.

Table 7a. Recommendations for Applications of Generic Three-phase Inverters, Storage.	
Topic	**Near-/Mid-Term**
Safety and Grounding	Disconnect versus isolation transformer benefits.
	Quick-connect plug to replace disconnect, ease installation
	Address ground leakage – Now a 1A to 10A industry standard versus 5 milliamp for human safety.
	Personnel training on safety and grounding.
	Clarify EMI standards.
	I/O filtering for power control unit (double-buffered).
	Approaches to eliminate ground faults entirely.
	Approaches to making system ground fault tolerant.
Internal Connections	Safety disconnect, physical lockout.
	High current and high voltage connections – increasing power density, safety, environmental protection (enclosure) and reliability.
Reliability	Small inverter unreliable, lack of warning when they have failed.
	Develop small amount of internal storage to allow system to ride through transients.
	Problem of IEEE 929 and IEEE 1547 voltage windows causing nuisance trips.

Table 7b. Recommendations for Applications of PV-specific Inverter Applications.	
Topic	**Near-/Mid-Term**
Wide Band Gap Materials	MOSFET/JFET – module integrated inverter applications.
Ungrounded PV	Europe has allowed ungrounded and transformerless, and there has not been a safety problem – transfer the experience to the United States.
	Address utility misgivings.
	Investigate lightning induced differential voltages between ground and neutral.
	Implications of transformerless design for codes and standards, especially in regard to grounding.
Communications and Diagnostics	PLC hardware/protocol development or wireless.
	Drive-by metering applications.
	Developing performance metrics similar to those used for modules.
Large-scale Integration	Multiple inverters on a feeder and islanding.
Thermal Management	Combined thermal and electrical modeling and analysis of inverters.
Reliability	Comparisons to other applications like automotive is inappropriate! They don't have 25-year warranties and have different standards that lead to different designs and results.
	Address problems with aluminum electrolytic capacitors.
	Partnering; is the auto industry already doing much of our work for us?

Table 7b. Recommendations for Applications of PV-specific Inverter Applications.	
Topic	**Near-/Mid-Term**
	Materials and components research not driven by PV. PV is too small an industry. Must focus on what we can influence.
	Design for field repair with minimal effect on listing.
	Design with size, weight and ease of installation in mind.
	Research on safety in the plug-and-play environment – standards/constraints.
	Develop maintenance free inverter.
	Define "**object models**" for inverter, PV, storage and metering. Define the nouns and verbs needed for communication.
	Fund demonstrations of advance communication.
	Lower cost of entry to manufacturers by developing open source code, protocol stacks, subsidized testing, listing and certification – protocols and media are interchangeable with gateways.

Table 7c. Recommendations for Applications of Single-phase Inverters.	
Topic	**Near-/Mid-Term**
Communications and Diagnostics	Define object models for inverter, PV, storage and metering – the nouns and verbs needed for communication.
	Fund demonstrations of advance communication.
	Lower cost of entry to manufacturers by developing open source code, protocol stacks, subsidized testing, listing and certification. Protocols and media are interchangeable with gateways.
	Define object models for inverter, PV, storage and metering. The nouns and verbs needed for communication.
	Fund demonstrations of advanced communication.
Ungrounded Systems	Vehicles have leak detectors. Are they applicable here?
	NEC and double-jacketed wire; need approval and product.
	Address utility concerns with dc injection, protection, monitoring of dc equipment and analysis of failure modes.
	Need development of equivalent protection to grounding.
	HF versus LF isolation transformers.
Gate Drives	Suited to FETS, but not IGBTs.
	High temperature.
	Inter-operability.
	Magnetic versus optical.
	Improvements to optical reliability – today's components are not adequate for all applications.
Wide Band Gap	Reduce prices.
	PV requires different power range than vehicles, may need separate research funding. Advantages likely in size, component count and efficiency.
	One-forth losses could lead to one-forth components; smaller or no heatsink.

	Higher frequency, smaller filters, less EMI.
	Need system level economic analysis versus today's available technology.
Large Scale Integration	Integrated modules are too expensive; need research if that approach is going to work.
	Analyze value of separate gate drive – lower temperature, increased reliability?

Group Discussion of Day-One Breakout Summaries

The first observation was that no one mentioned maximum power point tracking. Another missing topic was large inverter power electronics – multimode, stand alone. Another person suggested that in the next 3 to 5 years we need to complete development of standards for measuring and reporting inverter efficiency. Right now, everyone calculates and reports efficiency the way they want to report it. There needs to be standardization of inverter tests and definitions of performance terms. Is it even reasonable to use one number to report inverter efficiency?

The moderator observed that most of the suggestions added features and capabilities to inverters and asked if we are encouraging gold-plated inverters? Where are the tradeoffs among the objectives? John Berdner replied that we do keep adding things that inverters are supposed to do, so we are never going to hit a $0.09/W goal. Instead of embracing every suggestion, maybe we should "just say no." The inverter should not be required to perform all of these functions.

In the area of surge protection in a home, it was stated that there are numerous devices that are sensitive to external surges, so why shouldn't the whole house be protected from surges, instead of just the PV system? The uncertainty is whether we become too dependent on another technology succeeding if we assume development and deployment will happen elsewhere.

There has been significant change in requirements for inverters. Thermal protection is needed in all TVS devices so that if they do overheat, they won't litter the rest of the product with residue material, particularly toxic material.

Another person noted that overall economic goals should be the issue, not just the inverter portion of the system. This suggested complete system designs are needed. Another person suggested that we might want to try modular construction, separating out different functional elements of the inverter and reducing some of them to single chips. Ward Bower noted that it was an interesting concept, but it causes major listing difficulties because UL has to test multiple combinations of the modules instead of just a single piece of equipment. Ward also agreed that there is a trend to put more and more into the inverter. The challenge is to keep the things that are added as options, not mandates. James Worden noted that when an electrician installs and checks a new PV system in Massachusetts, he also has to verify that the system is grounded on either side of the water meter. This gets added to the cost of the PV system installation or check.

Finley Shapiro noted that if a decision is made that a surge protector for a whole house is needed for safety, it isn't likely that it will be retroactive – will the industry be willing to limit where we install systems, based on where houses already meet safety requirements? Larry Rinehart commented that one reason surge arrestors are distributed around the house is because equipment, particularly older equipment, generates its own transients. In that case there is no longer a single household point of failure. John Berdner noted that he doesn't think surge arrestors should be inside inverters, because when they fail it can be explosive, destroying the whole inverter as well as the surge arrestor.

Chrisoph Panhuber commented that the American approach makes things more complicated when they shouldn't be. The industry should look for ways to eliminate the dc disconnect. It needs to look at the problems from a different perspective.

Finley Shapiro noted that he saw no mention of size and weight, and that we are focused just on cutting costs. Designers might consider giving up a little efficiency to save on weight and size.

Another participant asked if there are any implications for modules and the PV elements of the system in our discussions. Someone replied that it is going to be a real challenge for thin-film modules and inverters to operate at 120°F, which is a common temperature in Arizona. Arizona will be a big market in the long run, and thin film PV may be able to get to $1/W, but operating under real conditions is an issue. He also sees very different requirements for single- and three-phase inverters.

Another participant said they have not yet heard much talk about inverters themselves. He asked "Are they an issue at all?" Do we have problems with inverters as a whole? Ward Bower offered that eventually we want full integration of inverters and systems. John Berdner offered that right now we have code issues that need clarification.

The next question concerned where modeling should begin. Someone suggested that SNL should tap into the facilities used by weapons designers to deal with the complex modeling issues. It was noted that the beta model for inverters and the SDA model only has three parameters. As more sophisticated models are developed they can be incorporated into the SDA model. We will be soliciting proposals from this workshop group. At this point it is difficult to get manual performance inputs and data, much less the inputs needed for modeling.

It was noted that the *NEC* reorganized code-making panels last cycle. For the 2005 edition, the panels started from scratch as far as knowledge about PV systems and several decisions were made due to lack of knowledge.

A comment related to the U.S. position in the PV community reflected the need for R&D at home. On a related note, one comment was "We should look at our research competitors and see where we are losing access to technology because it is not being developed here."

There is a lot of frustration among people in the field. People don't know what their systems should be doing because they have no metrics. A performance matrix that would show what parameters should be used to measure performance would be wonderful. In reply, it was suggested that this issue could be addressed by communication protocols. There are several organizations interested in improving communications, and private industry itself may do it. Another person replied that all that is really needed is kW output numbers every 15 minutes. They would not recommend putting performance calculations into the inverter itself due to all the possible sources of error and differences. We should minimize the amount of data offered or used to avoid complexity and confusion. In reply one participant noted that knowledge of waveform and voltage can be used to monitor the condition of the inverter. We should also bear in mind that some of the information available from the inverter has more value to the system operator than the owner. Utility grade kWh monitoring would add the cost of the revenue meter, and could introduce utility ownership issues.

A general observation was that a lot of things we're talking about in this workshop will involve huge amounts of data and the information may have to be processed locally. We may need a local processor built into one of the chips in the inverter, hopefully at very small additional cost.

In the future the availability of low-cost mixed radio networks will have a great impact. When that happens, inverters and energy monitoring will become just another node on a home network.

One of the participants asked "What are the inverters of the near term and the future that are being discussed here? Are we talking just evolution or next generation?"

The group commented that our industry is still very small. It was reiterated that we don't have enough volume to go to capacitor makers and tell them we need this or we need that. But it's evolving and as the markets get bigger we will have more influence.

We need to consider what can be drawn from other industry research. We're not the only industry to use inverters.

Michael Quintana asked if there are any metrics that we can really grab hold of today so we can focus development of R&D activities toward that. We need a set of benchmarks today so we can understand how we can improve them over time.

Another participant pointed out that we face a dilemma between adding on to inverters, but also wanting to increase reliability, and at the same time reduce costs. What do we want to build from this discussion? What is the real value of all these enhancements?

Day Two: Codes, Standards and Applications in the Real World Presentations

The National Electrical Code® and Other Standards in the Real World

John Wiles of the Southwest Technology Development Institute presented an overview of developments to expect in the *National Electrical Code (NEC)* in 2005, and issues with standards when they collide with real world applications. In 2002, a paper that presented the results of inspections, tests and informal surveys of practitioners was published in the Institute of Electrical and Electronic Engineers (IEEE) PV Specialist Conference proceedings. That paper described problems that arose when inverters were rushed to market with inadequate testing. It revealed facts about inverters and systems that were very unfriendly to installers and users, with poorly written inverter instruction manuals adding to the problem. The surveys also pointed out that there was a problem because of uninformed systems designers, uninformed system installers and uninformed electrical inspectors. Revisiting the situation in 2004, they found more of the same, despite some minor improvements in the *NEC* and changes in UL 1741. But the fact is that while well-done codes and standards can help, codes and standards are not the only answer.

Inverter manufacturers could make significant contributions knowing and following codes and standards when they are designing their products. They need to create effective manuals that also account for codes and standards, but are also logical and easier to use for installers. And there needs to be separate manuals for the owner. Owners should not, and probably will not, wade through the installer manual to find information they may or may not be able to use. Manufacturers also need more thorough and effective product testing, better training for their reps and installers, and follow up to identify problems and then fix them.

Why should manufacturers take these expensive steps that add to the costs of their systems? The answer is because it will ultimately reduce costs. When inverters don't perform or fail, when instructions are unclear, when the inverters are hard to install, and when the user has questions, then the inverter manufacturer will have to hire a very large, expensive customer support staff to deal with the product returns and field problems. Otherwise the manufacturer and ultimately the PV industry will see its reputation and sales go down the tubes.

How can they deal effectively with these problems? First, each manufacturer should appoint a codes/standards/systems person to represent them on the International Association of Electrical Inspectors (IAEI) (and join IAEI if they haven't already), then apply for UL 1741 representation on the Standards Technical Panel (STP), and also participate in the *NEC*/PV Industry forum. The manufacturers also need to understand and apply the requirements of the *NEC* handbook and appropriate UL standards to their products and installation instructions. They should consult with at least one and maybe more than one master electrician concerning installation. They should finalize their electrical design before specifying mechanical hardware, because the electrical design should be the first priority. And finally, they should realize that international standards are different, and they may have to adapt their products to U.S. requirements to sell them here and vice versa if they are moving from U.S. markets to Europe, Japan or other countries.

In designing a product, electrical configuration is critical. The design should clearly specify input and output currents, both steady state and maximum. Terminals should be properly designed so that they are sized for the currents, enlarged for voltage drop/rise considerations, marked for temperature limits and equipped for multiple-conductor paralleling. The design also needs to consider wire bending space, so that it accommodates sufficiently large wire to address voltage rises and drops.

Then, after the electrical configuration is ready, designers should consider the mechanical configuration. The unit and all key components should have access from the front. Conduit openings should be at electrical industry standard positions and distances so that an installer is not forced to rig up special conduit runs or mounting structures just to connect the inverter. Mechanical fittings and electrical terminals should be robust, so that they are not easily broken off or damaged, thus comprising the entire unit. There should be more than the minimal wire bending space built into the design. Finally the unit should be designed and tested to fit a practical shipping container – one that won't require special shipping, odd dimensions or weight that make it difficult to ship in or return if necessary.

If it works electrically and mechanically, then the designer should think about a user interface. A user should at least be able to easily determine if the unit is on. The user should probably also be able to see how much power is being delivered. Beyond that, additional information may or may not be helpful. KISS (keep it simple stupid) should be the rule. Avoid confusing customers and users at all costs.

Installers also need an interface with the inverter that is more robust than the user interface and accessible only to qualified professionals. It should not be easy for an inexperienced user to access the higher levels of inverter trouble shooting and controls because they will not know how to use them. There should even be different levels of access for a field installer versus a factory rep. Trouble shooting has to be allowed, but at a level appropriate to the skills of the person working on the system.

Finally, every system should have two manuals – one for the installer and one for the user. The user should not have to wade through, and shouldn't be tempted to use, the detailed information an installer needs. All most users really want or need are basic instructions on how to turn the unit on or off, how to determine if the inverter is on and working, how to find out what its power output is compared to what it should be, and warnings about safe operation. A simple explanation of the theory of operation in an appendix may be appropriate. Again, KISS should be the guiding principle.

For the installer/system designer, the manual should provide sufficient information to avoid a call to the factory. Installers do need an explanation of the theory of operation.

They also need mounting instructions for multiple surfaces, because no two installations ever seem to be alike. And they need electrical instructions. But those instructions need to be presented carefully. They should not try to interpret or advise on the *NEC* requirements, because if they leave anything out that becomes a liability issue for the manufacturer.   Reference the *NEC*. It should specify inputs in PV/*NEC*-related terms so the installer can apply the *NEC* effectively. Specifications should also include clear instructions on conductor sizes and types, external overcurrent devices, conduit types and voltage drop/rise requirements.

Products also need to be tested. In-house or overseas testing is not sufficient. I recommend the Sandia Inverter Testing Protocol currently in draft form but to be published in 2005. Lengthy alpha and beta testing is required, covering all configurations of the inverter, widely varying locations, varying levels of installer competence, exercise of all modes of operation and accelerated life cycle testing.

Once you have a product, factory training is essential. Two to three days of training should be a minimum. The training should cover basic electrical theory. It should address basic applicable codes. Installers should get a thorough review of system design implications of different types of installations, and of the features of the inverters. Installation training should also be hands-on, and it should include realistic troubleshooting.

Finally, new products need follow-up with distributors, dealers and installers as soon as the product hits the market. You should talk to them before they start contacting your very large and expensive customer support staff. Find out what does and does not work, solicit feedback on a regular basis. Respond to it and implement suggestions.

In summary "Those who cannot remember the past are condemned to repeat it" (George Santayana, 1905). Invest the time and money to do things right before shipping the first customer unit. And finally, if you do things right, may your customer support staff be very small.

Overview of UL 1741 Changes and Additions

Tim Zgonena, Principal Engineer for Distributed Energy Resources at Underwriters Laboratories, opened his presentation with a brief history of UL 1741. UL 1741 was originally published on May 7, 1999 under the title "The Standard for Static Inverters and Charge Controllers for Use in Photovoltaic Power Systems." In January 2001, it was revised to address changes in IEEE 929, "The Recommended Practice for Utility Interface of Photovoltaic (PV) Systems." In addition to substantive changes to address a broader range of technologies, it was retitled as "The Standard for Inverters, Converters and Controllers for Use in Independent Power Production Systems." Currently, a range of utility-interactive products listed under UL 1741 are being accepted by many utilities across the nation for interconnection. Some of the tests conducted for completing inverter listing is the anti-islanding test required by UL 1741, IEEE 929 and IEEE 1547. Figure 15 shows the specialized inductors used for that test and illustrates the complexity of the test.

Figure 15. UL's Inductive Load Bank for Conducting Anti-islanding Tests.

UL 1741 and IEEE standards have been developed under challenging circumstances. The traditional utility power system was designed to support only a one-way flow of energy from the point of generation through a transmission system then to distribution level loads. They were not designed or intended to accommodate the backfeed of power from distributed generators at the distribution level.

Electric utilities have needs and concerns regarding the safety and performance of distributed generators. They are concerned with reliable power grid operation, and the impacts distributed generation may have on reliability. They want protection against faults, and they want protection to ensure power quality. The impact of distributed generation on their monitoring and switching equipment is also a problem, as well as other equipment and loads. And around all of these concerns there is a fear of liability if something is adversely impacted by distributed generation.

There is a basic incompatibility between the utility test methods and equipment. They have historically been used to test protective relays and the new microprocessor-based distributed generation equipment they are concerned about. Utilities want an assurance that interconnected distributed generation will operate properly after it is manufactured and after years of service in the field, but they often lack the equipment to test it, and most of it has not been in the field long enough to prove that it will operate safely after years of use.

As a result, most utilities and utility regulators are proceeding very cautiously when it comes to distributed generation. Individual utilities or states have created their own interconnection requirements, which are used to closely evaluate distributed generation projects. Distributed generation products and installations are regularly subjected to burdensome investigations by a variable cast of inspectors and regulators. A typical example of the hurdles came from Madison, Wisconsin, where a senior engineer at Madison Gas and Electric had to ask whether there were any tests of an inverter used on a PV project connected to a 208-V system. There just hasn't been enough experience or guidance on distributed generation out there for utility staff to know what works and what does not, what should be a concern and what should not be a concern.

A lot of work has been done to evaluate the safety of distributed generation products. Electrical inspectors use the *NEC* or an augmented version of the *NEC* for their evaluations. Articles 690 (PV) and 692 (Fuel Cells) specifically call for utility-interactive equipment to be listed by a National Recognized Testing Laboratory (NRTL). Typically, any unfamiliar equipment will be required by local inspectors to be listed by a NRTL. When seeking listing for a product, it is best for manufacturers to seek evaluations early in their production design, to avoid designing in problems. Listing is not a panacea. It may not be able to address all installation-specific concerns, and local utility authorities may still require more features.

It all adds up to a difficult time for distributed generation manufacturers and installers who have to deal with utilities, regulators, inspectors and UL or another NRTL to get their products connected to the utility grid and operating. UL now has experience in testing and evaluating distributed generation equipment, and we have improved our testing procedures and equipment based on what we have learned. Surge testing, anti-island testing with inductive and capacitive load banks, and other capabilities have progressed steadily. Under our current project with DOE, we are working to combine UL's safety and utility interconnection requirements with those published in IEEE 1547. The UL 1741 directly references IEEE 1547 and IEEE 1547.1 in their present drafts, in order to maximize interpretation consistency and acceptance. The problem is that it takes a long time for IEEE standards to become final, so we have had to proceed based on drafts, with the risk that we may have to adjust our UL standard once IEEE 1547 is final. But we felt it was better to proceed with updating our UL standard based on what we know so that we can do the best testing possible now, rather than delay improvements. It will be harmonized with IEEE 1547 once it is published. When we are done, the result will be an American National Standards Institute (ANSI) standard that can be used to evaluate utility interconnected distributed generation products to address the needs of electrical authorities having jurisdiction (AHJ) and utility interconnection engineers.

Items that have already been added in reference to IEEE 1547 and IEEE 1547.1 include surge withstand, synchronization, immunity protection, flicker, field verification test capability and temperature stability. The ultimate goal of this work is to facilitate a streamlined system with identifiable, nationally common tasks and goals under which utility interconnected distributed generation products may be designed, produced, evaluated, certified, sold, installed and operated in a smooth and agreeable manner for all parties involved. It will benefit everyone by creating an ANSI Standard that everyone can use to evaluate utility-interconnected distributed generation products for both electrical safety and utility interconnection. This would be particularly helpful for the electrical AHJs and utility interconnection engineers that are the key to getting projects connected and operating. For distributed generation owners and installers, it should standardize procedures and requirements, and make them more predictable and reliable. Ultimately, standardization should lead to reduced interconnection costs.

UL 1741 is also expanding to cover all types of distributed generation: photovoltaic modules, fuel cells, microturbines, wind and hydro turbines and engine gen-sets. We are also dealing with additions and revisions to address more of the products and installation situations people are encountering. There are additions and revisions to address ungrounded PV inverters, transformerless inverters, PV combiner boxes, ac battery charging circuits, grounding electrode terminals, ground-fault detection and interruption (GFDI), increased bus bar temperature limits, standalone voltage requirements, maximum surface temperatures, more accurate output ratings and controllers for rotating generators.

Immediately following the publication of IEEE 1547.1, we plan to publish UL 1741, second edition. We expect to publish it in the spring of 2005.

Review of IEEE Standards for Inverters: IEEE *1547.1 (Test Procedures),* IEEE *1547.2 (Application Guide),* IEEE *1547.3 (Communications Protocol)*

Tom Basso of the National Renewable Energy Laboratory presented a comprehensive report on the latest developments in IEEE's series of interconnection standards. IEEE 1547 (2003) is a standard for interconnecting distributed resources with electric power systems. Beneath IEEE 1547 are IEEE 1547.1, a Draft Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems; IEEE 1547.2 Draft Application Guide for IEEE 1547 Draft Standard for Interconnecting Distributed Resources with Electric Power Systems; IEEE 1547.3, the Draft Guide for Monitoring, Information Exchange and Control of DR Interconnected with Electric Power Systems; and IEEE 1547.4, Draft Guide for Design, Operation and Integration of Distributed Resource Island Systems with Electric Power Systems. Figure 16 shows the organization of the IEEE 1547 documents.

There is also an IEEE 1547.5 project in progress to develop technical guidelines for interconnection of electric power sources greater than 10 MVA to the power transmission grid. This document will provide guidelines regarding the technical requirements, including design, construction, commissioning, acceptance testing and maintenance/performance requirements for interconnecting dispatchable electric power sources with a capacity greater than 10 MVA to a bulk power transmission grid. Its purpose is to provide technical information and guidance to all parties involved in the interconnection of dispatchable electric power sources to a transmission grid, and about the various considerations that need to be evaluated to operate within acceptable parameters. It is sponsored by standards coordinating committee 21 (SCC21), for Fuel Cells, Photovoltaics, Dispersed Generation and Energy Storage, which is chaired by Dick DeBlasio. The project was authorized in September 2004, with the ballot expected to be completed by December 2007.

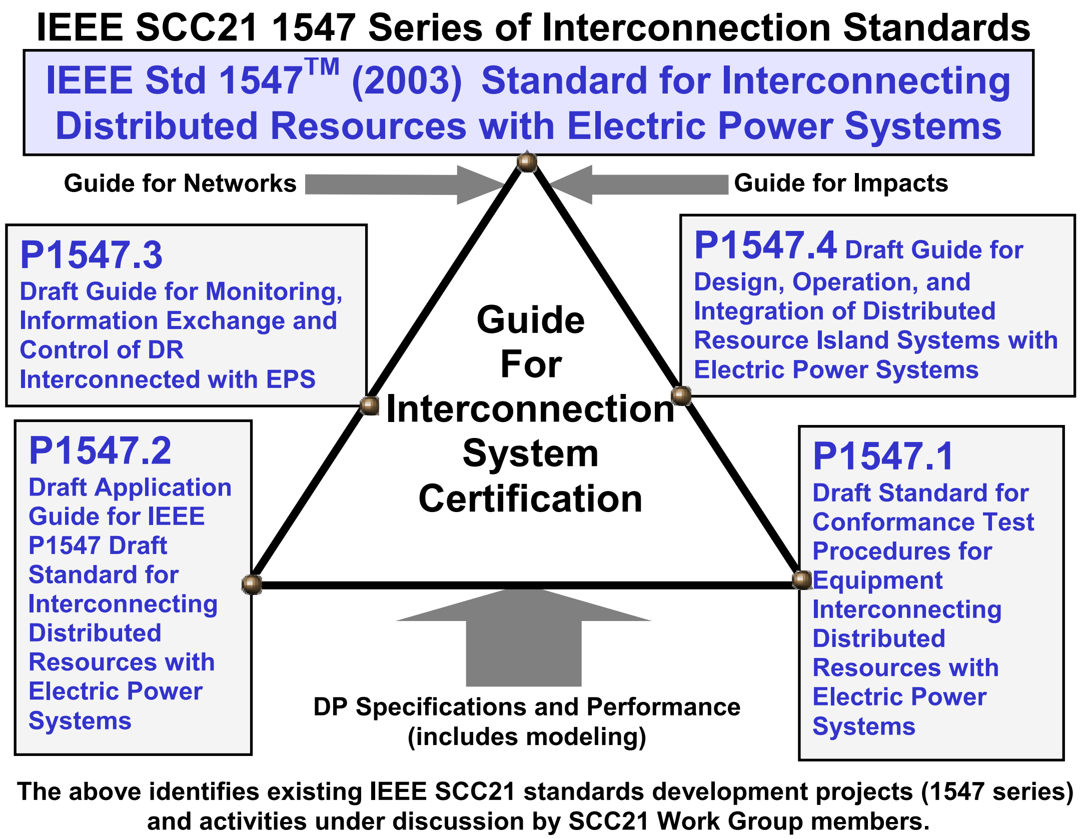


Figure 16. Organization of the IEEE 1547 Series of Standards, Recommended Practices and Guides.

Basically, the original standard for interconnection of DR with the grid embodied in IEEE 1547 is now more detailed with information on interconnection test procedures (IEEE 1547.1), a practical guide to using the IEEE 1547 standard (IEEE 1547.2), a practical guide for information exchange for interconnected DR (IEEE 1547.3), a guide to islanding issues (IEEE 1547.4) and a guide for interconnection to transmission as distinct from distribution grids (IEEE 1547.5). These standards and guides have been developed and written to deal with the insertion of new, distributed generation sources into a grid that was designed for central station generation. The traditional view of the grid has seven layers, starting with central station generation, then transmission, then sub-transmission, substations, feeders, service lines, and finally the customer. Suddenly distributed resources are jumping into the system at the customer, service, feeder, substation, and sub-transmission levels. To operate safely and effectively there had to be standards and guides to determine how these new interconnections should be done. The traditional approach was to deal with each layer and option as an independent technology issue, but that is evolving toward more generic technology platforms – a platform for DR, for interconnection and for distribution, that creates a more general, open platform for different types of technologies to connect, from PV to microturbines. Standards help create the platforms that multiple technologies can then use.

Standards have multiple benefits. At the most basic level, they ensure safe operation and maintenance. They also foster quality design and manufacture, by requiring equipment to meet or exceed set standards. They can increase competitiveness in the industry by creating an even playing field for manufacturers and consumers to compare products so that everyone knows that each product at least meets the basic standards. Standardization can also create and expand markets, by defining what a product must deliver and giving users confidence that what they buy will perform to those standards. Obviously by expanding markets, they can also facilitate trade and commerce. It is all based on the fact that when products meet quality standards, users don't have to be concerned with further testing or evaluation of the product. Good standards also accelerate engineering advances and implementation, interoperability and installation by providing a common framework. They should also simplify compliance and permitting. Effective standards should also create rules for software platforms to improve communications and facilitate interchangeability of equipment, including enhanced DR systems and grid intelligence.

Ideally standards development should be part of a process that leads to broad, common rules for interconnection and communication that apply across the United States, and hopefully internationally as well. Our current work is on a national consensus standard established via industry-driven partnerships and balanced stakeholder participation – not only from the representatives on the committee but also from the many organizations that comment and submit information for the committee to consider. Harmonization of national and international standards is being pursued with the International Electrotechnical Commission (IEC), with hopes that we can have a dual logo arrangement through IEC adoption of IEEE standards for electronics, telecom and power generation. In the IEC, the main areas are IEC TC 82 (Technical Committee 82) for Photovoltaics. The United States is the Secretariat for this IEC activity. Another important activity is IEC TC 82, System Aspects of Electrical Energy Supply, which facilitates functioning of electricity supply systems, encompassing transmission and distribution networks and interfaces with user installations. Finally, the IEC Joint Coordinating Group (JCG) is developing international standards on distributed rural electrical systems.

IEEE is one of the pre-eminent standards bodies in the world. It is an internationally recognized technical professional society with over 375,000 members from 150 countries. They are dedicated to advancing the theory and application of electro-technologies and allied sciences. IEEE produces over 30% of the world's published literature in electrical engineering, computers and controls.

It is important to understand the differences between standards, recommended practices and guides. Standards are documents with mandatory requirements. Recommended practices represent procedures and positions that practitioners should follow, but they are not mandatory. Finally, guides provide alternative approaches to good practices, but they are not clear-cut recommendations. A practitioner may or may not follow guides.

IEEE develops its standards through a consensus building process. First, it makes sure that the group that is allowed to vote on a standard is balanced, with each interest group representing less than 50% of the total vote. Voters may provide comments, and the sponsor of a standard or guide must respond to each negative comment and try to resolve it. Unresolved negative comments are recirculated to allow voters to change their vote. A minimum of 75% affirmation is needed to pass to the IEEE Standards Board for their approval.

All standards projects and standards for publication must be approved by the IEEE Standards Board. It is the board that establishes the Standards Coordinating Committees (SCCs) to develop new standards, and each SCC reports directly to the board. SCC21 is the group developing IEEE 1547, and Dick DeBlasio is its chair. SCC21's scope includes fuel cells, photovoltaics, dispersed generation and energy storage. SCC21 currently has 400 members, 230 involved in voting for IEEE – 31% general interest, 4% government, 30% manufacturer/producers and 35% utilities/users. They are building on a long series of earlier standards dating back to IEEE Std 1001, which was a guide for interfacing dispersed storage and generation with electric utility systems, followed by IEEE Std 929 which established the first recommended practices, and now IEEE 1547 and its supporting guides and practice documents for interconnecting distributed resources. IEEE Std 1547 was approved by the IEEE Standards Board on June 12, 2003, and was adopted by ANSI on October 20, 2003. Ideally IEEE standards may go on to become adopted as American National Standards by ANSI, and/or international standards if IEC agrees to adopt them and put a dual logo (IEC and IEEE) endorsement on a standard.

There are still some important IEEE 1547 development issues that are not normally addressed as IEEE universal, mandatory requirements. First, IEEE does not control Federal or state implementation of IEEE standards – Federal, state and local officials have to decide to incorporate IEEE standards into their rules. IEEE creates the standards, but products that meet them still have to be commercialized and certified, and after sale support and warranties are up to the manufacturers. Liability for problems – DG owner versus grid operator – is not addressed by IEEE. The functionality of the interconnection package has to comply with IEEE standards, but there is a lot of capability that can and will be added beyond that. Interconnection costs – the fees and other costs involved with interconnection – are not part of IEEE's scope, nor are the cost and cost allocation of refitting the electric power system to accommodate large amounts of distributed generation. Operation – who is in control – is not determined by a technical standard, nor is durability and availability over a long period. Any standard, guide, or recommended practice, particularly in an area this complex, is also subject to misunderstanding and misinterpretation that will have to be settled over time, as will disagreements over the meaning and implementation of the standards between utilities and distributed generators.

There is still plenty of further R&D to perform in areas beyond IEEE 1547 that may have implications for its future. Work is needed on improved interconnection technology. Testing in the field versus type testing is an issue. There may be a case for interconnection equipment certification. Impacts of large amounts of distributed generation on the secondary grid and spot networks need more consideration. Better monitoring and control of the grid and DG are being developed. We don't understand enough about voltage regulation and stability. We still need to address ground faults. In the near future, we may have to consider ways to aggregate DG and consider the impacts of broader market penetration on the grid. And last but not least, how to deal with islanding is still a problem. The current IEEE 1547 minimizes the use of distributed resources in the event of system disturbances, and may actually exacerbate them, by forcing them off-line through tight anti-islanding requirements. IEEE 1547 and its current series will probably need revision in the future to deal with new developments in all of these areas.

NREL currently has a contract with UL to update UL 1741 to include all DR interconnections, going beyond IEEE 1547 requirements to include product safety issues including construction, materials, wiring, component spacing, protection against injury, output characteristics and utility compatibility, rating and marking, and specific tests for different distributed generation technologies. Basically, UL is specifying the equipment qualifications needed to list inverters that are then governed by IEEE 1547 in terms of their operating characteristics and how they are tested for interconnection.

Questions and Answers for Presenters

Larry Rinehart asked if there are provisional specifications available for purchase at this time. They are currently on the website and available for review. The IEEE 1547.4 is not yet in draft form since the inaugural meeting was held in August 2004. So far there is just an outline.

The next question concerned the half of one percent limit for dc current – is there an acceptable limit, in hundred milliamps or something measurable? The reply was that it is based on a percentage of nameplate rating. John Berdner commented that it is not possible to measure dc at 0.5 percent – it is extremely difficult and not very accurate, so we will end up with 0.5% plus or minus 3%. The requirement doesn't take into account that DG output is often far lower than the transformer rating it is connecting with. There was a reply that those issues are being addressed in IEEE 1547.1. Clayton Handleman noted that it is a difficult issue, so it might make sense to have an allowance for a way to aggregate them – to group measurements from a number of tests. Arthur Rudin commented that the 0.5% looks ridiculous when compared with practical ranges in the real world, where 0.5% is vanishingly small. Tom Basso noted that IEEE 1547 is a voluntary standard and it allows negotiation. John Wiles commented that IEEE 1547 will be merged into UL 1741, which may blunt the issue – we are hoping that the UL sticker on inverters will keep the utilities happy. Tim Zgonena suggested that small inverters could be tested in bulk, or that the issue of practical measurement could be addressed in UL 1741. The fact that Europe is considering 1% and not 0.5% indicates that Europe is not following IEEE 1547 and it is an issue that may need to be revisited. Someone else noted that the IEC standard originally had zero percent; the current modification to one percent is out for vote right now. From the U.S. point of view, the 0.5% was recommended, but that was not sustained. We were trying to make a point of harmonizing with Europe.

The next topic was the assumption that inverters could be crippled by a surge or other event and still operate properly. In testing many products are destroyed, and those that are not are assumed to pass the test. But the problem is that if you test at one level and it fails, it is no assurance that at one step below that level it may not fail, but still sustain critical damage short of complete failure.

John Wiles and Ward Bower commented that we need to address these issues in the *NEC*, and industry needs to be aware of *NEC* implications. We need to participate, not just read the drafts. People should e-mail John Wiles or Ward Bower if they want to become active.

There was a lot of concern about the test for flicker. In response, Tom Basso said that there wasn't really a test for flicker. It is a site-specific issue, so there is no test you can do ahead of time. IEEE 1547.1 includes a test that is related to flicker, based on testing inrush current. It is not a flicker test per se, but it gives a reviewer an opportunity to do a flicker count. It is mainly applied to voltage-source inverters and inverters that could operate in multiple modes.

An audience member asked what is the technical specification for double-insulated wire. The reply was that there isn't one yet. Europe has specifications but we do not. We are trying to bring some of the product to the United States and have the U.S. adopt the same specifications. The code still calls for conduit or sheathed multi-jacket cable. We hope the specifications will result in thicker jackets with UV resistance, long duration, sunlight resistance, and rodent-proofing as well. Right now wiring issues are more related to modules – there doesn't seem to one wire that meets all needs. Basically you can use applicable UL listed wire for PV systems.

Ward Bower ended the Question and Answer Session by reminding people to think of the impacts of codes and standards and certifications for the breakout sessions. Are we creating standards that are over-restrictive, or under-restrictive?

Overview of IEC Inverter Standards

Christoph Panhuber of Fronius presented a very different view of standards development from the International Electrotechnical Commission (IEC). IEC's mission is to prepare and publish international standards for all electrical and electronic technologies. In theory, they want to ensure that a component or system manufactured to IEC standards and manufactured in any country that is part of IEC can be sold and used in any other IEC member country. Currently IEC has 63 members and associate members, including the United States of America, Canada, all of the European Union, China, Australia and Korea.

The IEC committees are trying to establish unified standards in key areas of PV balance-of-systems and installation, including:

Figure 17. Simplified European Inverter Installation.

- IEC 61727: Characteristics of the Utility Interface;
- IEC 62109: Safety of Static Inverters;
- IEC 62116: Testing procedure of Islanding Prevention Methods for Utility-interactive Photovoltaic Inverters; and,
- IEC 60364-7-712 (an existing standard): Electrical Installations of Buildings: Requirements for Special Installations or Locations – Solar Photovoltaic Power Supply Systems.

The scope of IEC 61727 is 10 kW or smaller PV systems connected to the low voltage grid. Its main focus is on power quality, voltage and frequency range, flicker, dc injection, harmonics and waveform distortion and power factor. It addresses behavior in cases of over- and under-voltage, and over- and under-frequency. There are no specific anti-islanding requirements in this document. A reference is made to IEC 62116.

IEC 62109 addresses safety concerns in a manner comparable to UL 1741. In fact it is based on input from UL 1741, IEC 60950, IEC 60103 and IEC 61010. It mainly deals with mechanical and electrical safety. It is currently awaiting a committee vote, which should occur within the next few weeks. It could have a major impact on existing products – reactions to it should be very interesting.

Other European standards include separate requirements for micro-combined heat and power (CHP) units, and a special case for transformerless inverters. One of the most important because of its market impact is Germany's DIN VDE 0126.

The micro-CHP standard is CENELEC TC8X, which covers stirling engines, fuel cells and other micro-CHP units up to a size of 16A per phase at 230 V. The main focus is on power quality issues (harmonics, power factor, flicker, EMC, dc injection) and safety issues. Safety addresses behavior at abnormal voltage and frequency conditions. It leaves room for countries to develop their own shutdown requirements. It also has no specific anti-islanding requirements at matched load – shut down is required if a 25% imbalance between generation and load is detected. European standards, unlike standards in the United States are based on a fit and inform approach to regulation. Type tested equipment may be installed, connected and commissioned by licensed electrical outfitters without involvement of the utility. Most EU countries have no concept of an electrical inspector. Documentation about the installation process, the equipment used and a commissioning protocol has to be sent to the utility/network operator within 30 days. The approach is to install first and inform the utility later. Figure 17 shows an example of a simplified European installation that does not use disconnects but instead uses multi-contact connectors for the disconnect device.

Europe is working much more extensively with transformerless inverters. With transformerless inverters there is the possibility of a dangerous dc fault current, so personal safety is not assured. A dc sensitive residual current monitoring unit (RCMU) is installed to address the problem. The dc fault currents are distinct from, and should not be mixed up with, dc current injection. The dc current injection is not a fault current, but a small asymmetry between the positive and negative half-wave of the current fed into the grid.

The DIN VDE 0126 German safety standard defines the requirements for an automatic ac-disconnect feature that eliminates the need for a lockable, externally accessible ac-disconnect. It defines redundancy and one-fault tolerance requirements, anti-islanding and dc current injection requirements. For transformerless inverters, it establishes requirements for the RCMU which is sensitive to both ac and dc currents. Recent changes include a type-test similar to the anti-islanding rest in UL 1741, which has been added to the impedance test and an improved test for the RCMU. As it exists now, it provides more options to achieve the required technical performance related to anti-islanding, and well-defined requirements for transformerless inverters.

It is necessary to drive down the costs of PV without sacrificing safety. Installation costs for a grid-connected system are in the range of 4.2 to 5.0 Euros/kWp installed in Germany. System prices in the United States are roughly $6.50 to $9.00/kWp installed. However, module prices are lower in the United States than they are in Europe, and inverter prices are about equal. So why is there such a difference in system costs? The answer is "installation." In contrast to the United States, Germany and Austria we have no requirements for externally accessible ac disconnects. They aren't required. Instead multi-contact plugs substitute for disconnects. Instead of the conduit required in America, simple, inexpensive plastic raceways are used for cabling. And therefore installation costs are significantly less.

In conclusion, it is evident that standards are absolutely necessary to define clear rules. It is also desirable to have globally accepted standards to reduce costs. The IEC is the forum to create these standards – both Europe and the United States are actively involved in drafting international standards. But there is a difference in implementation strategies between the United States and Europe that has serious consequences for costs.

Certification of Inverters: Does it Make Sense?

Chuck Whitaker of Endecon Engineering addressed the topic of certifications of inverters by talking about the reluctance of the PV industry to accept certification and by making the case for its benefits. First, there are different types of certification aimed at ensuring safety, at boosting consumer confidence, and at addressing reliability or performance. Formal product certification usually involves a certifying body and a certification program, which in turn will involve consensus test procedures, usually applied by an accredited laboratory independent of industry influence or bias.

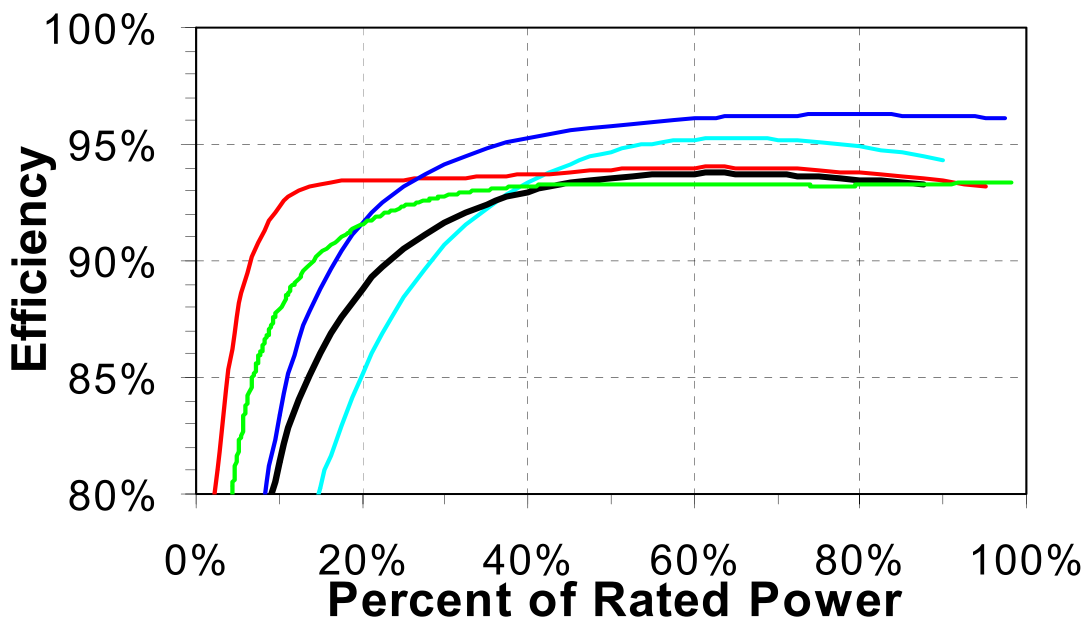


Figure 18. Plots Showing Typical Ranges of Inverter Efficiency Curves.

The inverter industry needs another certification to verify our key product characteristics. UL 1741 does that for product safety, but a UL listing (certification) says nothing about how well the product works – just that it is safe. PowerMark certifies PV modules today, but so far has not moved to certify inverters. Right now there is no way of knowing or comparing how each manufacturer measures and specifies its inverter performance, and therefore no way to trust those numbers, particularly if you are a consumer. It is difficult for installers to compare the performance of different inverters and difficult to get an accurate estimate of how it will perform in a system. Just looking at an inverter efficiency curve as a percent of rated power as shown in Figure 18, it is clear that a manufacturer can choose any of a number of points to claim as their inverter efficiency.

There are economic concerns about instituting another product certification. It is an added cost, which may disproportionately impact small manufacturers. It may slow product introduction, and if it is a complicated or time-consuming process, it is likely to deter minor product improvements, which in turn restricts innovation, flexibility and customization. All these problems are exacerbated by the fact that we deal with multiple jurisdictions with differing requirements. Many of these could be relieved, however, by a system that relies more on self-certification and less on third-party certification.

Certification is often not an option, it is a requirement. Large purchasers have and will continue to seek performance guarantees that amount to guarantees. In the past this included DOE when they were funding systems for PVUSA and Technology Experience to Accelerate Markets in Utility Photovoltaics (TEAM-UP). Currently, California is moving in a similar direction, and will be implementing efficiency and power measurement requirements for its rebate program. Revisions to California Title 24 on "Building Energy Efficiency" are being considered to create requirements for PV system performance. And, although these are the organizations that are requiring certifications of performance, the people who usually pay for it are tax payers for government funded projects, utility rate payers if they are utility systems and consumers if they are buying products and want to get rebates and incentives.

There are several options for deciding who would do certification. UL, PowerMark, PV Gap and CSA are all existing certifying bodies that might take on some aspect of inverter certification. Accredited laboratories include OSHA, American Association for Laboratory Accreditation, and the National Voluntary Laboratory Accreditation program. Additionally, there are testing laboratories and agencies.

As far as who actually performs the tests, the preferred option from a cost standpoint would be manufacturers. This may be possible with a program to witness or verify the testing. With manufacturers, testing could be part of their regular product development and quality control activities. Owner/installers might test for larger systems, but that would limit the testing to field situations, and would necessarily focus more on system tests than component tests. A third party testing laboratory or agency might be necessary when results are contentious, or when results are critical. When manufacturer data is suspect, third party laboratories are more credible, and if an owner or installer is unable or unwilling to test they may be the only option. They may also be required by contract or legislation, but they are the most expensive option, so their involvement should be minimized.

Sandia has been working with Endecon Engineering to develop an inverter performance test protocol. The protocol specifies general requirements, test equipment requirements and dc input characterization. It also focuses on maximum continuous output power, one of the indicators that is of most interest to users. In addition, it addresses inverter efficiency, maximum power point tracking accuracy, tare losses at night, power foldback and other inverter performance factors.

Sandia and Endecon Engineering are continuing to solicit industry and user feedback on the protocol, and refining needs and test procedures. It will be published as a Sandia report and submitted to the IEEE/IEC as a draft standard. Later, we would like to identify a certifying body, develop certification requirements and define laboratory accreditation requirements. We are seeking a certification program that is standardized, cost-effective, flexible and valuable to the consumer. These are achievable goals.

DUIT Multiple Inverter Testing Results

Chuck Whitaker also delivered the presentation on the (Distributed Utility Inverter Testing (DUIT) project. The DUIT is a research facility for evaluating grid impacts of commercial-grade distributed resources. It addresses the following research issues/problems:

- Islanding,
- Power Quality,
- Sectionalizing,
- Short Circuit Contribution,
- Stability,
- Voltage Regulation,
- Reclosing Coordination,
- Fuse Coordination,
- Capacitor Switching, and
- Adjacent Feeder Faults.

It is working with a wide and growing range of both inverter-based and rotating machine-based technologies, all selected based on today's and future market demand. Currently it includes three classes of equipment: Residential (single-phase, ≤≤ 5 kW), Commercial (three-phase, 30 kW to 250 kW) and Industrial (three-phase, ≤ 250 kW).

Bay 1 of the facility is outfitted to test residential DR. It currently has several DR, PV and other power supplies, and load banks to provide test loads for multi-unit testing. Bay 2 is similarly outfitted with equipment appropriate to commercial sized DR, and Bay 3 is designed for industrial DR testing. Each bay is tied into PG&E's medium-voltage distribution system via one or more pole-mounted transformers, with a 21–kV, motor-operated load-break switch that allows isolation of the total DUIT facility from the grid.

DUIT's data acquisition and control system is based on National Instruments "LabView" equipment, with 6-kHz sampled data collected for voltage and current at every relevant node in the system for each test. The anti-island test plan for the DUIT project is shown in Figure 19.

The anti-islanding test plan has seven discrete steps with growing complexity and more challenging conditions. It starts with a basic islanding test for the individual unit. It then adds multiple DRs in homogenous, and then in small groups and various progressions. Systems are challenged with non-linear load situations, dynamic loads and loads from rotating equipment. Harmonic content from anti-islanding measure are tested, and finally voltage/frequency trip settings for each situation are tested. The basic test is based on combined IEEE 1547, UL 1741 and California Rule 21 procedures that are applied to the single unit to setup a test baseline and data acquisition prior to multi-unit islanding tests. Test setup procedures are kept consistent from unit to unit, to produce consistent,

Anti-Islanding Test Plan	Test Description and Sequence
6.1	*Basic Islanding Test* Individual unit testing
6.2	*Islanding with Multiple DRs* Homogeneous Groups Small Groups Progressions
6.3	*Non-Linear Loads, Anti-islanding Tests* Individual Units
6.4	*Islanding with Dynamic Load:Generation Ratios* Individual Units
6.5	*Anti-islanding with Rotating Loads* Individual Units
6.6	*Harmonic Content due to Anti-islanding Schemes* Individual Units
6.7	*Voltage/Frequency Trip Settings* Individual Units Homogeneous Groups Small Groups Progressions

Figure 19. Anti-island Test Plan for the DUIT Facility.

comparable results. It also gives researchers an understanding of manufacturer's anti-islanding methods to select appropriate combinations for multi-unit testing. Shutdown times are measured with three generation/load ratio conditions – 25%, 50% and 100%. In each case inductive and capacitive loads are adjusted to the resonant frequency of 60 Hz with a quality factor (Q) of 2.5 for the first test. The value of L or C is then adjusted in steps of 1% between – 5% and +5% of the nominal value used in the first tests, resulting in a total of 33 tests per DR.

Results show a wide range of device responses and trip times. Trip times varied to levels in excess of 30 seconds under some conditions for some devices.

State-by-state Rules

Bill Brooks of Endecon Engineering provided a review of California's new Rule 21 for DG interconnection. Rule 21 was created by the California Public Utilities Commission (CPUC) and is published in the electricity tariff booklets of investor-owned utilities under CPUC jurisdiction. It provides technical and procedural criteria for connecting generation equipment to the utility distribution and sub-transmission systems. The rule is intended to be technology and size neutral.

When the rules for interconnection were first created they had major weaknesses, particularly for small-scale DG. First, they did not address the benefits of having a standardized rule in place, and as a result it sets its own standards and increased costs for DG manufacturers, who had to significantly customize their systems to comply. It also overlooked the need to set a time limit for review of applications or to limit the cost of review.

In developing the new rule, the CPUC wanted the new rule to satisfy several key principles. First, they wanted to have the rule, protocols and processes to be clear and transparent to all parties involved. Second, the rule should be technology neutral except when differences are fully justified. Third, a rule should provide a level playing field for all DG providers. Fourth, rules should be uniform throughout California, and finally, utilities should be fairly compensated for distribution services that support DG installations and customers.

The new rule is applicable to all projects within CPUC's jurisdiction. It creates a standardized process that involves a standard CPUC application form and set application fees: $800 for the initial review only, and $600 additional if a supplemental review is required. A cost estimate must be provided if an interconnection study is required. Utilities must complete their review and respond within 10 to 20 days if a project only involves an initial/supplemental review (10 days for the initial review, 10 for the supplemental review).

The working group that developed California Rule 21 also addressed the other principles the CPUC had established for the new rule. Rule 21 creates a standardized, technology and size-neutral set of technical requirements. It establishes a clear engineering review process along with testing and certification procedures. Interconnection fees are set beforehand. The interconnection agreement is also standardized. Applicants can submit their projects on standardized application forms on hard copy or electronically. And, the CPUC has established a process for continued feedback and refinement.

Safety is the first priority addressed in Rule 21. The technical requirements are designed to be performance-based, to minimize specification of particular equipment or technology approaches. It also clearly addresses review time and potential costs, and is intended to be technology neutral. It was also recently revised to comply with IEEE 1547-2003.

Section D on "Design and Operating Requirements" addresses protective functions, momentary paralleling, equipment requirements, visible disconnect and drawings that are required. The "Prevention of Interference" section addresses voltage regulation, operating voltage range, paralleling, flicker, integration with distribution system grounding, frequency, harmonics, dc injection and power factor. Technology specific requirements are added for three-phase synchronous generators, induction generators, inverters and single-phase generators. Supplemental generating facility requirements address fault detection, transfer trip and recluse-blocking. The rule is the basis for the California Interconnection Guidebook, which was released in November 2003. It provides basic guidance on the process of interconnection.

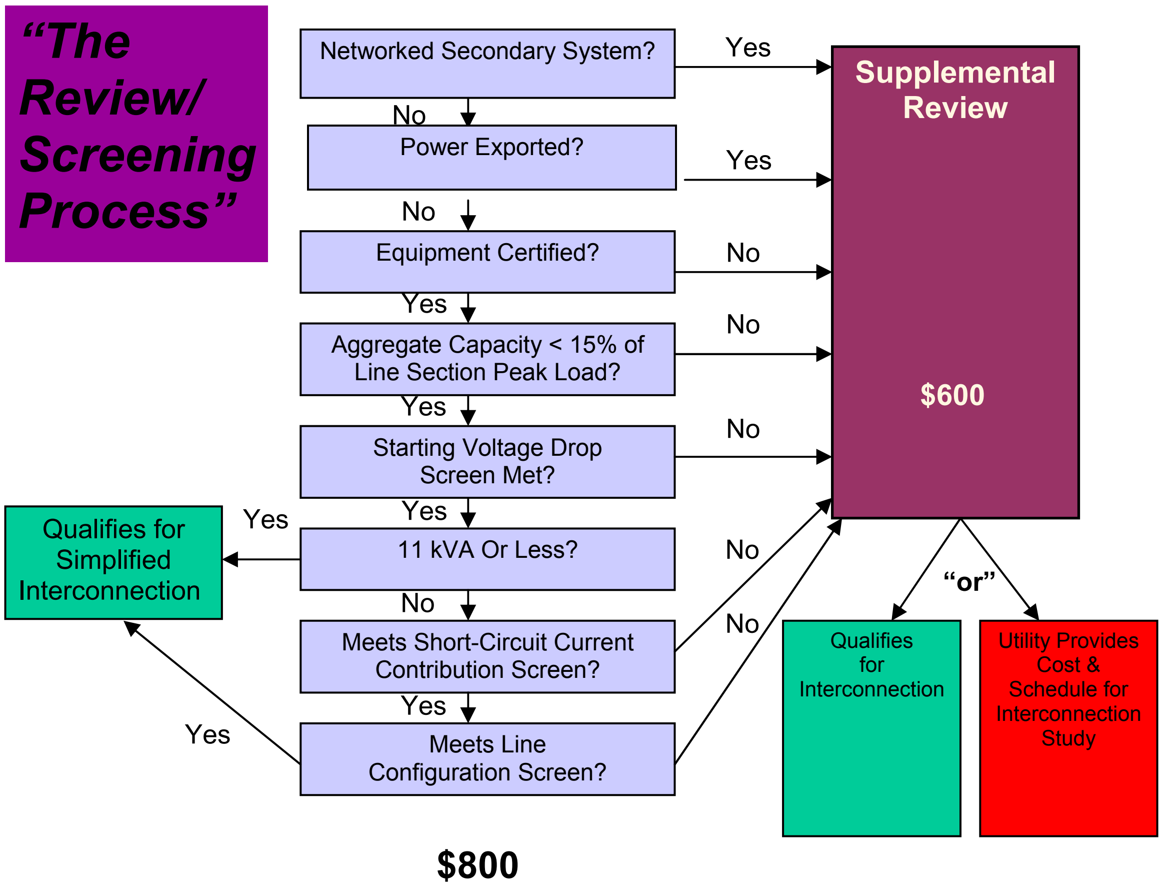


Figure 20. The California "Rule 21" Screening Process.

Section I explains the review process, including steps for simplified interconnection through an initial review, supplemental review, determination of additional requirements for interconnection, and finally whether an interconnection study may be required. A process flow chart for review is shown in figure 20.

In the case of a supplemental review, guidelines were originally developed in 2002 through the Rule 21 Working Group Process. The goal of the working group was to identify review criteria and study requirements. The result was a draft guideline issued in December 2002.

Section J of Rule 21 concerns testing and certification requirements, includes certification criteria and provisions for type testing. Type testing includes individual tests by technology, with reference to UL 1741, and is compliant with IEEE 1547-2003. Section J also addresses production and commissioning testing. For commissioning it goes into detail on general requirements, protective functions to be tested, impact of certification, verification of settings and trip testing.

Rule 21 has had an impact on developers and system owners, in helping to define the process more clearly, and in the fact that inverter-based technologies are now viewed by the utilities as safer and easier to interconnect.

Since its inception, Rule 21 has been updated to coordinate with IEEE 1547-2003. Rule 21's technical section is actually more detailed in its coverage of some issues, so that portion of the original rule was not replaced by IEEE 1547. Rule 21 also covers non-technical issues that IEEE 1547 does not. The revised rule is currently under review by the California Public Utilities Commission.

For manufacturers, changes they are making to comply with IEEE 1547 should also make their products compliant with Rule 21. UL 1741 is still the basis for testing procedures, and all the testing requirements in Rule 21 were updated to be compatible with UL 1741 and IEEE 1547.

The California incentive program has had a significant impact on the inverter market. So far, the California Energy Commission program has provided incentives for 10,000 systems totaling nearly 40 MW of PV. Most of the systems are less than 30 kW. The CPUC Self-Gen program has funded many more PV systems rated over 30 kW. Thanks to Rule 21, UL 1741 and IEEE 929, inverter interconnections in California are essentially a slam-dunk. Rule 21 could be a model for other states and utilities. It has the benefit of being comprehensive, addressing the entire interconnection process from application through review and approval. The technical requirements were designed to be standardized yet flexible, to bend with future changes in IEEE 1547. The initial review process it establishes clearly and appropriately favors acceptable projects, which is a major benefit for inverters. Taken altogether it has been a benefit to solar power development and inverter markets.

Day Two Codes, Standards and Applications Breakout Sessions

Panel A – UL Standards Related Issues and Needs

Breakout group A identified issues and needs related to UL standards. The group discussed the need for more intense industry participation in the UL process, and how to improve participation. The UL representative said that with more people now on the STP there is a need to revisit the issue of participation and look at the people who are in line to participate and potentially readjust the mix of members.

The discussion addressed increasing industry support in the process. While the process relies on volunteers, it was suggested that DOE or Sandia should make travel funds available to boost participation. Other suggestions included scheduling meetings around other functions in more convenient locations or holding meetings in conjunction with conferences or at times when everyone will be in the same location. A member of the group added that that approach was tried in the past and the combination of meetings got substantially longer, tiring and less productive.

Participation could be improved by providing travel funds, scheduling concurrent meetings, convincing people that it is in their best interest to participate, and reiterating UL's acceptance of comments from all parties, even those who are unable to attend the meetings. It was pointed out that UL currently does not widely circulate the minutes to people outside of those on the STP. UL's representative said that UL can create a process for circulating minutes more widely. He added that they treat all comments the same, and that meetings are open to everyone. Other suggestions for circulating the minutes included having Ward Bower start up a separate group, or creating a secondary STP list comprised of those who are interested in STP but are not currently members. It was noted that prompt dissemination of meeting minutes is provided to UL subscription service members.

A member of the group commented that the atmosphere at the UL meetings almost discourages participation. For instance, some felt that comments/criticisms are not welcome at the meetings unless the person making the comment/criticism provides a solution. The UL representative said that in the past the meetings were not productive and in an effort to keep the meetings more focused they had to institute a strong hand as far as chairing the meetings. A similar atmosphere was felt in the writing meetings.

The group also identified UL 1741 type testing in more locations as an important need. There was interest in having UL 1741 type testing performed on location, not just back at headquarters. It was pointed out that there are many type test events and that the testing is very specialized requiring a big investment for UL to equip all of the test sites.

A member of the group asked the UL representative if UL would have someone in Europe to perform testing and if there is a timeline for testing in Europe. The UL representative replied that UL is not performing testing right now in Europe, but UL is planning to provide testing in Europe.

The group identified and discussed the need for harmonization with the IEC and other standards setting organizations, particularly in Europe.

The group expressed much concern about the need for faster service from UL. They discussed how the competition provides prompt service, but not at the same level of quality as UL. Many who do use UL's competitors do not realize that they are getting less than satisfactory service, but they prefer to get products listed without complying with the content of the law. They are not likely to lodge complaints about poor service, maybe not until someone gets hurt. The group noted that many go to the competition specifically because they do not look at all of the areas that UL examines. The group thought that the marketplace would motivate UL to provide faster service.

On the subject of the cost of the standards, the group agreed that the standards should be more affordable. The cost of the standards has increased ten fold. It was suggest that perhaps a discount could be offered for participation on the standards technical panels or a volume discount for bulk purchasing. The UL representative agreed that while the costs are high, UL loses money every year putting together the listing (certification) documents. That is why UL is relying more on industry participation and other efforts. A member of the group suggested this as an area where DOE could potentially contribute.

Regarding the cost of purchasing the standards, a member of the group suggested offering discounts for bulk purchasing, maybe an industry discount program or perhaps providing files that can be viewed but not printed because of copyright issues. UL has a new process to disseminate standards but prices have not been reduced. It was mentioned that DOE/Sandia has a central library of standards and makes them available to those who need access.

On the subject of self-certification, the group discussed witness test data and requirements. There was discussion on how self-certification starts out as witness test data and when the manufacturer has confidence in the test data it can be submitted to UL. UL is working out the list of requirements for witness test data.

The group addressed UL 1998 software listing (certification) regarding UL 1741 inverter listings and making it easier for manufacturers to make minor software changes.

The group expressed much concern about how the standards seem to be a constantly moving target for the industry. The discussion focused on the issue of changes in the requirements without actually changing the standards and how the changes in requirements have never been published. There was consensus that inverter manufacturers feel like they are chasing a moving target. A member of the group noted that this concern could be rectified by increasing participation in the process and developing an industry plan for transitioning from UL 1741 to IEEE 1547. In many instances people have only become involved after they had experienced problems. Also with UL bringing some utilities to the table, it is understandable that it would appear that there have been changes to the requirements. A member of the group proposed extending some sort of subscription notification to field inspectors, or some sort of pre-notification in the effort to keep parties updated.

The UL representative said that the new version of the standard that references IEEE 1547 should be published by the end of first quarter next year. They are looking at 18 months before the effective date. That would mean industry would have to be compliant by autumn of 2006. In response to a question about increased costs, he added that there is considerably more testing in the new version.

In response to a question about UL backlog and response time, the UL representative replied that UL has been revising its program. He noted that what most do not see from the outside is all of the engineering time and revisions that takes place between testing, which usually results in new firmware and new software. UL is trying to break down the listing process into smaller discrete pieces in an effort to keep updates more on schedule.

The group discussed pre-testing prior to submission to UL as a potential solution to not only reducing manufacturer listing costs but also to reducing response time. In addition, companies can provide a complete bill of materials and provide UL documentation for those components. Companies could also save money by writing their own descriptions. A member of the group said that rather than turning away clients, UL should encourage potential clients to do as much testing and evaluation that conform with UL standards before sending equipment to UL. A member of the group said that UL customer service encourages manufacturers to test before submitting to UL, but it was noted that new inverter companies do not have the means to perform in-house testing.

In regard to an inquiry about conducting pre-tests and the format for testing, the UL representative replied that very often they will get an entire ream of drawings at the component level, down to the washers. This does not help when what they really need are just the critical parts list. He will check if there are guidelines written for pre-testing. It was suggested that the industry could help by preparing a guide or generic sample. It takes going through the process once to know how they are looking at the product.

The UL representative said that in his experience what is needed depends on what the testers find when testing. Someone would need to very thoroughly look at the complete product to be able to tell what they are potentially going to stumble over.

A member of the group inquired about retesting every four years. The UL representative said that retesting shows continued manufacturer compliance.

On the subject of whether to test to UL 1741 or IEEE 1547, the UL representative said that manufacturers should pick the standard that is more difficult and if there is a minor change you will not be far off. He added that testing to UL 1741 plus New York and California requirements will get you where you need to be when IEEE 1547 is implemented. Utilities want to know where manufacturers set trip limits and when an inverter actually trips. Industry should develop a plan for transition from UL 1741 to IEEE 1547.

The group discussed other standards that manufacturers need to meet, e.g. FCC compliance, and how the industry is addressing this issue. They spoke about the expense associated with compliance and marketplace enforcement.

A member of the group commented that UL's customer service does not work very well. The UL representative replied that the customer service system does not work perfectly yet and that UL is modifying the system to improve it. They're supposed to be pre-screening to evaluate the appropriate channels to send the problems to. Customer service is attempting to speed up service and let the engineers focus on the technical aspect as opposed to the non-technical aspects.

Today's inverters are meeting the criteria for the most part. Equipment spends a lot of time at DETL and often gets tweaked to become compliant. There will be no grandfather clause during the change, but manufacturers will have 18 to 24 months to become compliant.

If utilities do adopt IEEE 1547 and apply it nationwide, it at least becomes one target. Unfortunately, some utilities choose their own standards. It would help if we made the first cut easy to use and understand.

A member of the group recommended that UL make introductions between the code guys and the UL panel representatives on the *NEC* Code Making Panel 13. It would be useful to have introductions between the code-making panel and the PV industry representatives.

The group discussed the subject of cost versus value added from the code compliancy process and the need to educate consumers and installers on the importance of being code compliant. The discussion focused on standards enhancing reliability.

Each breakout group was asked to create a list of needs in their topic area, and then reorganize and rank them in terms of priority. The breakout group focused on UL standards-related issues and needs developed the following list of needs. The top five are grouped at the top and bolded. Note that similar recommendations were regrouped together throughout the list to add detail to the list of needs, including the top priority items.

1. **Increased industry support for development of UL 1741, increase industry participation in UL 1741 development.**
2. **Firms test equipment before submitting to UL, provide bill of materials descriptions of their tests. UL should encourage potential clients to test themselves. A barrier to this: the lack of capital.**
3. **Do manufacturers build to UL 1741 or IEEE 1547? This needs resolution.**
4. **Tied for fourth place:**
    a. **Printed UL standards should be more affordable to increase dissemination – there has been a ten-fold increase in costs and keeping a library of standards is expensive.**
    b. **Sensitivity to multiple/changing requirements and standards, because of multiple sources of standards, challenge in staying current with standards.**
5. **Need for timely responses from UL.**
6. UL 1741-type testing in more locations:
    a. Need 250-kW power supply.
    b. European UL 1741 grid connect testing.
7. Harmonization with European/Asian standards organizations.
8. Need for speedier service from UL.
9. Self-certification:
    a. Witness test data.
    b. Requirements are available.
10. UL 1998 software listing (certification) re: UL 1741.

11. IEEE 1547/Rule 21 testing can be combined with UL 1741 testing:
    a. IEEE 1547 new hurdles.
12. Additional administrative support from outside UL.
13. Break down the listing process into discrete segments.
14. Other standards, e.g. FCC compliance.
15. UL provide examples of upfront documentation for industry to provide pre-testing:
    a. Generic samples.
16. List of UL 1741 changes and IEEE 1547 changes.
17. Deal with engineers or customer service?
    a. Process: pre-screen, collect info.
18. Utilities adopt IEEE 1547 provides a standard.
19. UL PV Representative on Code-making panels:
    a. Introduce the code-making panel to PV industry people.
20. Value-added:
    a. Standards increase reliability.
    b. New Ideas.

Regarding the number two issue ("firms test equipment before submitting to UL"), the group recommended that UL Customer Service should emphasize pre-testing to reduce manufacturers' costs.

For priority number three ("Do manufacturers build to UL 1741 or IEEE 1547?") the proposed solution was to develop an industry plan for transition from UL 1741 to IEEE 1547.

Regarding priority issue number four, "Printed UL standards should be more affordable to increase dissemination" the group recommended a discount program, CD-ROM, or a Web site with pdf files.

For priority issue number five, the recommendation was that manufacturers (1) conduct testing; and (2) provide bill of materials descriptions.

Panel B – Utility Related Standards Issues and Needs

Breakout group B identified utility related issues and needs. The group rated the following issues/needs: harmonization of standards, grid support, inverter behavior and utility communication as key priorities. They rated the need to create a process to harmonize standards as a top priority and agreed that the harmonization of UL 1741 and IEEE 1547 was a positive development and noted that there is a minimum 3-year timeframe for its completion. Harmonization of IEC TC82 standards and IEEE 1547 is needed. Group B noted the importance of harmonizing the IEC standards with the U.S. standards and noted that this harmonization is more likely to happen in the second generation of both standards documents (dual-logo standards) by having the IEC and United States work together from the start. They agreed on the importance of harmonizing upper voltage limits (600 versus 1,000 V), grounding and dc disconnects.

Group B discussed the importance of exploring IEEE power systems and other standards societies. They discussed writing standards with dual requirements. They also noted the need to harmonize current safety listings (certifications) with proposed performance certifications and how ideally they would not have to repeat some parts for separate certifications. Group B also agreed on the need to establish a process to coordinate rulemaking and resolution for U.S. standardizing bodies versus international standardizing bodies – IEEE, NFPA, ANSI and IEC.

Group B rated grid support and inverter behavior as a second priority issue and they noted that attention to this issue is especially necessary in the U.S. southwest in the next 9 years. The group discussed how inertia is constant for grid support and that inverters are not helping to stabilize the grid, but simple software changes could help (insufficient grid inertia). What does inertia mean?: Twenty-five years ago hydropower was the main source of power in the West, and hydropower has lots of inertia to keep the power source stable, but with solar you are dealing with a lot of variability, so the power source is very inconsistent. The following list highlights some of the issues the group discussed concerning this topic:

1. Low frequency and low voltage drifts. Should time delays be introduced?
2. Having the frequency responsive inverter be a new model that is similar to a rotator machine (inertia and power-on-demand (POD) consistent).
3. Sub-synchronous frequency response (controls).
4. Frequency droop. Deal with having energy storage (drop in power that comes about during transition stages).
5. If grid-tied, inverters must follow droop characteristics.
6. Support requires about five minutes of full-load energy storage.
7. Spinning reserve (is it a role of the inverter?).
8. Not *NEC* requirement.
9. Load following.
10. Cloud passage has high impact.
11. Will have to charge customer for backup for that event if there is no load following.
12. Thinks there is going to be up to 1% solar penetration by 2013.
13. Four-quadrant voltage and frequency control.
14. Need generators that you can change the power factor on—not minute-by-minute, but hour-by-hour.
15. Anti-islanding or deliberate islanding.
16. Need to be able to send message to inverter to not trip.
17. Compatibility with large area grid stability control.
18. Out of frequency and out of voltage time delays.

The group identified several solutions in regard to grid support and inverter behavior, including launching a needs assessment involving a broad spectrum of utilities and power system manufacturers; conducting outreach to stakeholders and regulators to increase awareness of coming challenges; forming a working group, e.g. IEEE committee, to identify and address challenges; and encouraging greater involvement of power system people and those with central generating experience. The grid support issue is closely linked to IEEE 1547.4 requirements and impacts on intentional islanding. Instead of automatic response, high level dispatch control would be preferable, including research into how controls might help with economic dispatch. Energy storage R&D is also related, and needs to be integrated with inverter development over the short and long term.

The group rated utility communications as a third priority issue. On this subject, the group noted the need to adopt international standards and processes and their interest in government policies in the form of federal R&D support and tax credits to reduce the cost of implementing new standards. They discussed how new protocols and new architecture could be supported in the short term with gateway systems, especially with full implementation requiring at least 10 to 20 years. The responsibility for gateways should not necessarily rest on OEMs. The following list shows all of the needs identified by the group and the number of votes each item received.

1. Harmonization of standards: (8 votes)
    - Find/create process to harmonize.
2. Grid support and Inverter Behavior: (7 votes)
    - Inertia constant for grid support:
        - Grid stability increases with increasing DG penetration.
        - Out of frequency/voltage trips (time delay).
        - Model frequency response.
        - Compatibility with large area grid stability control.
        - Sub-synchronous frequency response controls.
    - Frequency droop:
        - Five minutes of energy storage.
    - Spinning reserve:
        - Role of the inverter.
    - Load following.
    - Four-quadrant voltage and frequency control.
3. Operational protocols: (1 votes)
    - Assess system operations and impact on standards.
        - Planned islanding.
4. Fragmentation of control requirements across utilities: (2.5 votes)
    - Homogeneity…develop policy to deal with the issue.
5. Anti-islanding: (3 votes)
    - Define methods/open-source, generic algorithm.
    - Assure compatibility in multi-inverter environment.
6. Potential for dc voltage on utility lines (safety issue). (1.5 votes)
7. DC injection with respect to transformer saturation for any inverter that has a dc transformer. (0 votes)
8. Ungrounded systems (e.g. transformerless). (3.5 votes)
9. System grounding requirements/Fault. (0 votes)
10. Utility network systems standards. (1 votes)
11. DG penetration aggregation. (2 votes)
12. Utility communications. (4.5 votes)

- Ref IEEE 1547.3.
- EPRI CEIDS program.
- IEC TC57, WG17.

13. State/regional (RTOs)/federal rules: (3 votes)
    - Have the same requirements across these lines.
14. UL 1741 listing (certification). (2 votes)
    - Tested by whom?
    - Field versus type testing.

Panel C – Inverter Manufacturers Issues and Needs

Using the matrix table as starting point, breakout group C set out to identify issues and needs from the inverter manufacturer's perspective. The group brainstormed and developed a wide range of inverter manufacturers' issues and needs. Group C began by discussing the cost of codes and standards, especially for small companies and the difficulty in recouping that cost. It was also noted that the high first cost associated with codes and standards can be a damper on innovation and the introduction of new products. The group also discussed the need to start thinking differently about ungrounded systems. There was also consensus on the need to get communications into inverters and how open-source code would benefit small manufacturers. The discussions were focused on standardization and interfacing with the code. There was also consensus that security should be a key criterion and that the programming interface should be secure and encrypted.

The group also addressed in-rush current protection on inverters and the issue of interfacing with the utility. There was a lengthy exchange on the subject of national harmonization versus global harmonization and the need for getting rid of fragmentation and moving toward letting all the standards apply equally. The group agreed that with the current patchwork of different codes and standards, inverter manufacturers cry out for national harmonization. Inverter manufacturers are sometimes held back under the proliferation of often conflicting and uncoordinated standards. National harmonization is a logical next step. It was noted that global harmonization would not be likely until there is a push on the national level.

The group discussed the issue of proving the value or the need for a standard, and what value it actually delivers compared to its cost. Night-time isolation from the grid was another issue that was discussed.

There was discussion on how inverter output should be rated. There was consensus on the need for a standardized and reliable set of metrics that consumers and installers could understand. The group pointed out the need for a rating label similar to the Environmental Protection Agency's *ENERGY STAR*® label. While the group noted that there was not sufficient consistency in the EPA's test procedures, there was agreement that the rating label is one that is easily recognized by consumers and provides information allowing consumers to compare the efficiency of products.

The group addressed the subject of standard test conditions for modules and FCC and EMI standards. It was noted that currently there are no standards in the United States for inverters. The subject of FCC regulation of electromagnetic resolution was raised and how this applies to inverters, because they have microprocessors.

Other issues and needs that the group identified included system efficiency; failures and emissions, hazardous materials and safety; recyclability and disposability; ISO9000, ISO 140001 and QS9000, and whether these standards require attention; the National Electrical Code and how it needs to be evolved; uniform input to panels; transition from IEEE to UL; European – no-inspector system; building codes; legal liability in inspections; noise regulation; UL/FCC and rationalizing the codes; the proliferation of codes and standards and how many can be tracked; training for inspectors; and alternatives to regulation.

After identifying a broad set of issues and needs pertinent to inverter manufacturers' the group was asked to rate this list in terms of priority and to think about what needs to be done and who the responsible parties should be. The group began prioritizing the list by discussing each identified issue and need. The following is a summary of the top priority items for Breakout Group C.

The group agreed that the number-one priority should be the creation of a set of standardized, reliable and understandable metrics that consumers and installers can use to compare inverters. There was consensus that a performance protocol should be the first step in the effort to stop some of the gaming and ideally the creation of a label similar to ENERGY STAR® should be a key tool. Part of the discussion focused on inverter parameters and the protocol and the interest in providing simple and recognizable efficiency information for the target audience. Members of the group talked about why the consumer would care about performance. There was also discussion about creating a label for consumers and a separate label directed at installers.

The group spoke about how the industry would prefer that manufacturers work together on metrics for standardization and determine what really matters as the main issue is to stop some of the gaming. The following questions were raised including: Is this going to cost real money or resources? How much of a barrier is this for the small manufacturer? And is there enough value in doing this? There was consensus that gaming has been enough of a problem for a solution to be developed. One of the comments made was that the selection of an inverter should become as easy as picking out a personal computer.

The group rated national harmonization as its second priority need for inverter manufacturers and discussed potential strategies and resources to make progress on this front. Some members of the group saw national harmonization as an ideal role for DOE, while others members of the group were not as convinced. As far as strategies, it was suggested that making the linkage to national security, specifically to "Homeland Security" would be a useful tactic. The group also talked about EERE's deployment initiative at DOE and the use of this initiative as an opportunity. But members of the group pointed out that DOE does not have a regulatory role except through the Federal

Energy Regulatory Commission (FERC) and that FERC should mandate national harmonization.

A member of the group said that while FERC and DOE are necessary to bringing about national harmonization, each state has its own set of rules and that state system benefit charges might be an opportunity to get the big players (states and utilities) moving in the right direction. There was discussion about the National Association of Regulatory Utility Commissioners (NARUC) and their work on standard's harmonization. The Million Solar Roofs Initiative and net metering were also suggested as other points of leverage. Other suggestions included looking to the Solar Industry Energy Association as a means of organizing the industry's input into national harmonization.

Cost was also rated a number two priority issue by the group. The group talked about cost estimates associated with codes and standards including cost estimates for Europe. The discussion included the impact on innovation and the internal costs associated with changes in code that force manufacturers to redesign and rework their products. There was concern that manufacturers could be in violation of some standard because no one can know all of them. Some of the comments included that codes and standards can be a real juggling act and often a double-edged sword. The group expressed concern about the return on investment from standards compared to the cost imposed upon the industry. The following list shows all the needs the group developed and the number of votes for each. The top 5 also show their ranking.

1. Standardized, reliable, understandable: (11 votes - #1)
    - Metrics that consumers/installers can understand and use to compare products.
2. Cost – UL 1741 $60-70K, $100K: (9 votes - #2)
    - A substantial cost just to start manufacturing.
    - Retesting, should be made less expensive by sharing manufacturer information on their test methods.
    - Internal costs add a lot to the basic fee charged by UL – lots of time preparing for UL testing.
    - Damper on innovation because anything but major innovations are too expensive to pursue, because minor innovations trigger new testing.
3. National Harmonization: (9 votes - #2)
    - Let all the standards be equal in the United States or eventually worldwide.
    - Getting rid of fragmentation.
    - Minimizing number of exceptions to the rules.
4. Open Source Code on Communication: (6 votes - #3)
    - Writing the code for DSP is a major expense.
    - Standardization of language and parameters.
    - Benefit to small manufacturers.
    - Security would have to be an important component, and to interoperate that needs to be developed jointly.

5. Transformerless/Ungrounded Adoption in the United States that is based on European experience. (5 votes - #4)
6. Proving value or need for a standard versus cost, a cost/benefit analysis of proposed regulations and standards. (5 votes - #4)
7. Proliferation – there are too many different rules and rule making bodies. (5 votes - #4)
8. Global Harmonization – standards and regulations should be common worldwide to the maximum extent possible. (4 votes)
9. From IEEE to UL, improving the process so that the two are in closer harmony and schedule: (4 votes)
    - Suggestion to law.
    - Process.
10. Failures and emissions, hazardous materials, safety – setting a safe failure mode that takes these hazards into account. (3 votes)
11. *NEC* – evolution or revolution. (3 votes)
12. Alternatives to regulation. (3 votes)
13. ISO9000, ISO14001, QS9000: (2 votes)
    - To distinguish products.
14. Building codes – roof attachments? (2 votes)
    - California?
    - Building integration.
    - Wiring walls.
15. UL/FCC, other conflicts, internal inconsistencies. (2 votes)
16. Training for inspectors: (2 votes)
    - Self-certify.
17. In-rush current protection: (1 vote)
    - Should have standards.
    - For utility interface.
18. Disconnect from the grid during night-time: (0 votes)
    - To reduce transformer losses.
    - Can be large on bigger systems.
    - Could be a performance standardization feature.
19. FCC and EMI: (0 votes)
    - Do we need it on inverters?
    - Inherent in CE standard.
20. Just efficiency: (0 votes)
    - Comparability – system and inverter.
21. Recyclability – lead-free, etc.
22. Uninformed input to codes and standards panels. (0 votes)
23. European – No-inspector system: (0 votes)
    - Code system perpetuates.
    - Inspection necessary.
24. Legal liability in inspection. (0 votes)
25. Decibel levels in large units – noise regulation. (0 votes)

General Discussion of Breakout Group Results

The general comments ranged from testing to standards. Some suggestions were simply improvements in logistics. One comment was that if some tests were more highly automated, it would speed up the entire process. The discussions also addressed the cost of UL listing (certification). "It is significant, and we all have to deal with it" was the consensus. One participant commented that "this is an expensive business, and as the industry grows it will continue to become more expensive." Further discussions disclosed that small business should not stay away, but they need to realize the expenses before jumping on board. "They need to have enough capital to prove that their products are safe, that they work and they can stand behind them."

The consensus also included statements such as having some legitimate expenses as a barrier to entry is not all bad. If they are undercapitalized, then their customers can be left out in the cold when businesses fail. The UL standards really do create a high level of competence, because you must have a team that is up for the challenge of safety standards. It is not UL's or any other certification agency's job to prove your inverter is unsafe, it is your job to prove that it is safe.

Comments on anti-islanding included, one of most costly expenses associated with UL testing is anti-islanding tests. Testing today only addresses one problem of anti-islanding. There needs to be much more work done on this industry wide. What we really need it to move beyond is blackbox methods in inverters and have methods we know will work together. There should be a DOE-sponsored effort to bring anti-islanding efforts out of the closet and we all should use a common methodology. There was general consensus but not unanimous agreement on all comments. Stop looking at how do we keep inverters from islanding and start looking at the cost benefit and just get past it.

It was suggested that Europe had a fairly simple efficiency standard that makes sense, and that might be what we want to adopt.

A longer term goal is that IEEE 1547 will need to be adapted for high penetration.

What Next?

General discussion on what the PV and DR industry can do about the apparent lack of coordination of codes, standards and certifications resulted in the following list of suggestions.

1. Go to conferences and talk with people about PV. Educate people – dispense of old wives tales. Educate the trainers in organizations such as the International Brotherhood of Electrical Workers (IBEW).
2. It may take a long time to get new coordinated standards adopted, but once they're adopted the utilities can disconnect at their own choosing if you're not compliant with the new standard. Industry can't afford to spend money redesigning for a standard that may not even be adopted. (Comment regarding compliance) There's sometimes

not a timeframe given for manufacturers to redesign to become compliant with a new standard.
   Note: While it may not be law to the jurisdictional body that inspects it, it can be held against you if there is a lawsuit. Once published, it's out there.
3. There's a big disconnect in the process in which you have standards you must adhere to, methods to certify and methods to prove you've been certified.
   a. IEEE is muddling the process – it's writing technical standards that have to be recognized by Nationally Recognized Testing Laboratories (NRTLs).

Summary of Findings

At the end of the first day the entire group was asked to pick their five top priorities for action from the recommendations made by each of the subgroups. Each participant labeled an index card for each group and then picked the top five items in that area. The participants also added comments and clarifications to their selections. There was wide variation in what people selected and emphasized, although the majority of choices gravitated to two or three general areas. The results of the polling are explained below. Votes were taken for breakout groups on the second day as well.

Day One: Inverter Technology Recommendations

Group A: Capacitor/Component Technologies

The topic that received the most attention was also familiar and similar to the results of the first inverter workshop: it was "IMPROVE CAPACITORS." The comments from this group emphasized lowering costs, increasing reliability, increasing lifetime and improving performance. A goal suggested was to cut costs by one-half and to double life expectancies. Suggestions for how to conduct research into new materials, investigating lower equivalent series resistant (ESR) capacitors, developing alternatives to electrolytic capacitors, and focusing on higher ripple current ratings and high capacitance density. Most of the how-to suggestions pointed to forms of high-tech capacitor development. There were 8 votes for this topic.

The next most frequently cited topic, with 5 votes, was in the general area of reducing and simplifying inverter components and internal connections to lower cost and improving reliability. Size and weight, again suggesting the need for high-tech magnetic materials and components, were grouped in with these comments.

There were also five participants who suggested thermal management as the next highest priority. Their suggestions focused on packaging design for thermal management, providing better information about passive cooling and fans, approaches to getting the heat out of wire-wound components, and improving air movement around components. The suggestions did not include high-tech thermal management methods, but the discussions and presentations included the methods. Thermal management was a topic that was tied to many of the issues related to components, hence there is no doubt that high-tech methodologies will be needed.

The next most frequently cited category of actions focused on better data and information on components, evidenced by four votes. Suggestions included creating a database of available components, independent testing and reporting on the performance of component classes (i.e., fans, capacitors…), better data sheets and comparable specifications. There was also a suggestion that a standardized/best practices certification/listing be developed for suppliers that would lead to greater comparability of parts and specifications.

The call for better data and information was related to suggestions for benchmarking in order to define what is an inverter, its functions today and what performance ranges exist to use as inputs for developing future goals. There was also a recommendation to use testing and measurement of inverters throughout environmental and simulated disturbances, including "inside the box" measurements, to pinpoint the weakest components. Two other modeling and measurement recommendations suggested modeling for reliability and performance, and using modeling software to assess the price sensitivity of the inverter to component cost and performance.

Three votes were recorded for better leveraging of research by other organizations and in other technology areas – specifically with DARPA. The recommendation was for more collaboration on new research and development and investigating ways to use new technologies to benefit inverter development.

Two votes were recorded on safety issues, including promoting listing and developing methods for improving safety while reducing installation costs.

Finally, two votes recommended research in magnetic cores, including better materials and advances in magnetic cores. The votes for magnetic material were closely related to the size and thermal management votes that were recorded as a higher priority.

The remainder of the responses included the following suggestions or questions:

- Power semiconductors for higher speed and lower losses and less thermal dissipation.
- Regulatory changes to allow transformerless designs (utility concerns).
- Standardize some transformers/inductors.
- Electrical connectors.
- Can capacitors be switched out?
- Standardize protocols on EMI.
- Better optical gate drives or alternatives to gate drives.
- Second-minute scale energy storage.
- Surge arrestors.

The above list of priorities and responses related to capacitors and other component technologies suggests that today's inverters still need evolutionary changes if not high-tech leap-frog advances. The list does prioritize several commonly used components such as capacitors and magnetics as needing major advances. Suggestions for leveraging scarce R&D funds should be investigated as avenues for accomplishing critical needs.

Group B: Surge Protection, Thermal Management and Packaging

Not surprisingly, 16 participants flagged advances in surge protection technology as key needs. Six specifically cited a need for dc-side surge protection that is UL listed for 600-V operation, and possibly developing new standards for dc surges. Almost half the responses in this category mentioned integrated surge suppression, which during the meeting was used as shorthand for a strategy of moving surge suppression out of the inverter package and into whole house protection. The concept was to try to reduce the trend toward putting too many functions into the inverter, especially functions that could be better handled with separate devices.

Seventeen participants cited improvements in thermal management as a priority. Two areas of emphasis were improved potting compounds for magnetics and more advanced thermal modeling and design tools that are capable of handling solar heat gain as well as internal heat sources. The modeling suggestions extended to simplifying life prediction models and using more HALT and integrated reliability testing to establish the most frequent sources of failure and then target them for remediation. Benchmarking to define failure modes, in particular thermal issues, and to explore what are potential sources of future failures. Coordination of component and system designs was advocated so that maximum thermal benefit is achieved for the whole inverter system. Some specific comments suggested more work on heat transfer approaches, heat pipes, new techniques for thermal rejection and setting a target of 1 kW/cm^2 heat dissipation.

Four participants emphasized various aspects of communications. One advocated the need for standards for EMI and communications protocols. Another suggested smarter devices that report their condition, and another suggested a powerline carrier signal to control islanding, in order to reduce the number of spurious trips. There was a single related vote for an external, UL-listed anti-islanding device external to the inverter.

The remaining suggestions garnered three or fewer votes. Three people emphasized research on inverter failure modes, and developing approaches that would guarantee a safe failure, free of emissions, excess heat or other catastrophic events that damage other inverter parts and/or property. The following were individual suggestions:

- Self-diagnostic capability.
- Self-healing surge protection.
- Double insulated cabling.
- Safety.
- Manufacturer support for torroidal magnetics, particular emphasis on dimensional repeatability.
- Packaging: compact enclosures without plastics.
- Improved packaging for performance and reliability maintainability.
- Coordinate “PV inverter” specific needs/desires to push “parts” developers in other fields (DOD, medical, information technology, etc.) to reap benefits from their advances.
- Reliability.
- Definition, test protocol and standard for MPPT.

- Systems energy output.
- Non-grounded systems.
- Multi-system operations.

A general comment offered by one participant suggested that advanced inverter development should not make presumptions about whether utilities or someone else will own the inverters. A generic approach that supports both possibilities should be pursued. Regulators are becoming more enlightened about situations in which utility ownership is preferred and have reversed earlier rulings about this issue in some states.

Group C: Power Electronics, Communications and Controls

By far the largest number of votes, 15, supported standardization of communications protocols and development of the “nouns and verbs” needed for effective communication and control. Design for compatibility with international communication standards where the IEC 61850 series was noted specifically was a strong suggestion, particularly where object models for devices, protocols and characterization of services are involved.

Looking to the future, there were recommendations to pursue greater integration with utilities, including use of power line communications to allow greater control and multi-mode operation of inverters in response to utility conditions. At the same time, several people noted that communications would have to be low-cost, especially for smaller inverter applications. Research into the best means for communication was also cited, whether wireless, power-line carrier, fiber optics or emerging options like “WiMax.” Security and encryption protocols were also prominently cited to protect unauthorized access to the grid and to equipment.

Five participants voted for advocating communications for diagnostics and prognosis to log failure modes and ultimately reduce failures.

Five participants also focused on issues with ungrounded and transformerless (non-isolated) inverters, generally citing the need to learn from European experience and to incorporate similar options into U.S. codes and utility interconnection guidelines and standards.

Three people voted to adjust today’s standards to reduce nuisance trips, either by widening the voltage window in IEEE 929 or by providing more flexibility to stray from the IEEE 929 standard. Developing technology to allow utility control of inverter trips depending on conditions was considered advantageous. UL would also have to address issues created by changing set points on the fly.

Three participants supported more research on SiC and wide band gap devices, especially in reducing costs and exploring ways to deal with higher temperatures associated with them and the potential for reducing part counts by using these devices.

Two people supported work on energy storage for grid stabilization, particularly for large-scale solar power penetration onto the grid. The rest of the responses were individual items, including:

- Revenue metering built in (at least as an option).
- Effects of large scale deployment of DER with islanding or dominant source.
- Novel power electronic circuit topologies in inverter design – performance, reliability and control.
- Benchmarking: define what these modular components are; what they do what performance ranges exist. How does this impact future goals?
- Standardized architectures/topologies for inverter "submodules"; include modeling.
- Standardized settable parameters in all inverters.
- Improve reliability of inverters for PV to match better with PV reliability; or reduce costs to expect replacement to avoid stranded costs of PV.
- Performance.
- State-of-charge (SOC) indicators for battery based systems.
- Revise *NEC* as applicable to eliminate unnecessary components – stop making things difficult for ourselves.
- Piggyback on automobile and motor drive industries.
- Interconnection technology away from soldering and more integration.
- More integration of drivers.
- Look at higher temperature aspects of new designs.
- Inverter performance standardization.
- Reduce errors by inverter manufacturers (Manufacturing defects).
- Magnetic components – design for low core loss, lower cost and low weight.

Day Two: Codes and Standards Recommendations

Group A: UL Issues

The following were the top five recommendations selected by the entire group for addressing UL-related issues:

1. Increased industry support for development of UL 1741, increase industry participation in UL 1741 development.
2. Manufacturers test equipment before submitting to UL, provide only the necessary bill of materials, and descriptions of their tests. UL should encourage potential clients to perform pretests themselves. A barrier to this is lack of capital and some lack of instructions.
3. Do manufacturers build to UL 1741 or IEEE 1547? Needs speedy resolution.
4. Tied for fourth place:
    a. Printed UL standards should be more affordable to increase dissemination – there has been a ten-fold increase in costs and keeping a library of standards is expensive.

   b. Sensitivity to multiple/changing requirements and standards, because of multiple sources of standards, challenge in staying current with standards.
5. Need for timely responses from UL.

Group B: Utility Issues

The following were the top issues from the utility breakout group's list of recommendations:

1. Harmonization of standards (8 votes)
   - Find/create process to harmonize
2. Grid support and inverter behavior (7 votes)
   - Inertia constant for grid support
     - Grid stability increases with increasing DG penetration
     - Out of frequency/voltage trips (time delay)
     - Model frequency response
     - Compatibility with large area grid stability control
     - Sub-synchronous frequency response controls
   - Frequency droop
     - 5 minutes energy storage
   - Spinning reserve
     - Role of the inverter
   - Load following
   - 4-quadrant voltage and frequency control
3. Operational protocols (1 votes)
   - Assess system operations and impact on standards
     - Planned islanding
4. Fragmentation of control requirements across utilities (2.5 votes)
   - Homogeneity…develop policy to deal with issues
5. Anti-islanding (3 votes)
   - Define methods/open-source, generic algorithm
   - Assure compatibility in multi-inverter environment

Group C: Manufacturer Issues

The following were the top priorities from the manufacturer's list of issues/recommendations.

1. **Standardized, reliable, understandable: (11 votes - #1)**
   a. Metrics that consumers/installers can understand and use to compare products
2. **Cost – UL 1741 $60-70K, $100K (9 votes - #2)**
   a. A substantial cost just to start manufacturing
   b. Retesting, should be made less expensive by sharing manufacturer information on their test methods
   c. Internal costs add a lot to the basic fee charged by UL – significant amount of time preparing for UL testing
   d. Damper on innovation since anything but major innovations are too expensive to pursue, because minor innovations trigger new testing

3. **National Harmonization** **(9 votes - #2)**
    a. Let all the standards be equal in the U.S., or eventually worldwide
    b. Getting rid of fragmentation
    c. Minimizing number of exceptions to the rules
4. **Open Source Code on Communication** (6 votes - #3)
    a. Writing the code for DSP is a major expense
    b. Define quantities and approaches
    c. Standardization of language and parameters
    d. Benefit to small manufacturers
    e. Security would have to be an very high priority, and to incorporate security it must to be developed jointly
5. **Transformerless/Ungrounded Adoption in the U.S., based on European experience** **(5 votes - #4)**
6. Proving value or need for a standard versus cost, a cost/benefit analysis of proposed regulations and standards (5 votes - #4)
7. Proliferation – there are too many different rules and rule making bodies (5 votes - #4)

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Appendix A – Participants of the DOE High-Tech Inverter Workshop

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Appendix B – Breakout Group Matrices for Day One

Technical Matrix for Capacitor and Component Technologies [Group 1A]

R&D Needs and Priorities for High-Tech Inverter

Component	Generic Single Phase (Small <10kW)	Generic Three Phase (Large >10kW)	PV Specific	Energy Storage Specific
Capacitors				
Inductors				
Transformers (Core Materials etc.)				
Inductors				
Internal Connections/ Terminals				
Interface Connections/ Terminals				
Circuit Boards				
Costs				

Technical Matrix for Surge Protection, Thermal Management, Packaging [Group 1B]

R&D Needs and Priorities for High-tech Inverter

Component	Generic Single Phase (Small <10kW)	Generic Three Phase (Large >10kW)	PV Specific	Energy Storage Specific
Surge Protection				
Advanced Devices for Thermal Management Devices				
General Input/Output and Packaging				
Controls				
Internal Connections/ Terminals				
Interface Connections/ Terminals				
Higher Temperature Circuit Boards				
Lead-free				
Automation and Manufacturing				
Value Added vs. Costs				

Technical Matrix for Power Electronics, Communications, Controls [Group 1C]
R&D Needs and Priorities for High-tech Inverter

Component	Generic Single Phase (Small <10kW)	Generic Three Phase (Large >10kW)	PV Specific	Energy Storage Specific
Wide Band-gap Devices				
Large Scale Integration				
Controls				
Internal Hi-temp Connections/ Terminals				
High Temperature Circuit Boards				
Reliability				
Communications				
Value Added vs. Costs				
Manufacturing and Automation				

Appendix C – Final Agenda for DOE High-Tech Inverter Workshop

Sponsors: DOE Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Program
DOE Office of Electricity Delivery and Energy Reliability, Energy Storage Program

Objective: This is a follow-up to the first systems driven approach workshop on inverter R&D held in April 2003. Participants will use a similar methodology to explore in greater depth the ***next generation of high-tech inverters*** for PV and Energy Storage technologies and synergistic applications. Your insight will be used to guide the "High-tech Inverter R&D 5-Year Strategies" document that is to be completed by January 2005, a key by-product of this workshop. The second day of the workshop will examine inverter-related standards, codes and certifications currently available or being drafted with discussions of the economic and technical impacts on inverter designs today. Needs for future standards, codes and certification with inputs from the standards writing groups and the inverter/systems industry will be discussed and prioritized.

Day 1: Inverter Technology Discussion

7:30 – 8:00 Sign-in, Breakfast Buffet

8:00 – 8:15 Welcome, Outline of Workshop Goals, Guidelines for the Workshop (Dan Ton; DOE)
[Discuss importance of 5-year strategy, value of the input from the meeting to managing the program and directing R&D.]

8:15 – 8:30 Introduction to Energy Storage Inverter Issues and Ongoing Work (Imre Gyuk; DOE)
[Research and priorities of the Energy Storage Program and its relation to inverter development – why inverter technology is important to our program, what we are doing to advance the state of the art.]

8:30 – 8:45 The Systems Driven Approach (SDA) (Status and Update) (Chris Cameron; Sandia)
[Focus on the inverter elements of the SDA – the importance of the shift toward looking at the whole PV system for focusing on the importance of inverter and control technology. Understanding market realities is at the heart of the SDA, which includes the practical codes issues. Codes and standards discussions on second day will shape SolarAdvisor modeling and technology forecasting.]

8:45 – 9:00 High-tech Inverter Research & Development: A Five-Year Strategy (Ward Bower; Sandia)

[Benefits of strategy for galvanizing research, current status and key elements of the strategy, what is needed from this meeting to make it complete, how it will be used, and how the results of this meeting will have an impact.]

9:00 – 9:45 High-reliability Inverter Initiative Status Update

9:00 -- 9:15 Xantrex
9:15 – 9:30 GE
9:30 – 9:45 SatCon
[For each presentation at the minimum the objective of the research; milestones accomplished; funding; significance of the research and the results for improving technology and market potential; highlights or surprising findings; opportunities for further research – what should come next.]

9:45 – 10:15 Questions, Answers, Discussion (Moderator)
[Questions open for Chris Cameron, Dan Ton, Imre Gyuk, Ward Bower and High-Reliability Inverter presentations. Staff to record questions and answers as they occur.]

10:15 – 10:30 Break

10:30 – 12:15 High-tech Inverter Issues and Needs

10:30 – 10:50 Capacitor Technologies: A Comparison of Competing Options (Bruce Tuttle; Sandia)
[What are main points of comparison -- cost, performance? Technological maturity of competing options, current applications experience, implications for other inverter elements – codes and standards implications? Include capacitor issues/technologies for large inverters (>500 kW)].

10:50 – 11:10 Thermal Management and Packaging (Techniques and Advances) (Clayton Handleman; Heliotronics)
[Nature of thermal management problems, different approaches being applied, cost/performance and other parameters for analysis, implications for other inverter components – codes and standards implications?]

11:10 – 11:30 Surge Protection for Inverters (Status and Needs) (Michael Ropp; South Dakota State University
[Operating environment and requirements, options and main tradeoffs in cost/performance/design, implications for

other inverter components and costs, codes and standards issues related to surge protection.]

11:30 – 11:50 Communications and Controls for Inverters (Frank Goodman; EPRI)
[Current status, where communications and controls may be headed based on market trends – distributed generation, advances in energy management systems. Protocol, standardization and interface challenges. Main competing technologies and approaches – upgradeability, disposability. Implications for performance and cost of inverter/system package.]

11:50 – 12:15 Power Electronics (Michael Mazzola; SemiSouth)
[Current options and major trends in development. Role of advanced power electronic devices in system performance and cost. Key parameters – what are the characteristics of power electronics that are most important and can be influenced by R&D? Comparison of technologies for large and small scale inverters. Long- and short-term cost implications.]

12:15 – 12:30 Questions and Answers (Moderator)
[Bring presenters back to front as a panel to answer questions.]

12:30 – 1:30 Lunch, Buffet Style

1:30 – 3:30 Parallel Breakout Sessions: Status, Goals and Needs for these parameters:

efficiency
reliability/durability
cost
maintenance/maintainability
manufacturability, and
cross-technology application

An important prioritization goal for all breakout sessions is a three-dimensional matrix mapping technologies (wide band-gap devices, capacitors, surge protection, large scale integrated devices, communication modules, etc.) with key influences (temperature, energy, power, packaging, interfaces, standards, certifications, etc.) with respect to a R&D time line. Each breakout session will discuss and fill out a matrix table.

Parallel Breakout Session A – Capacitor/Component Technologies

Parallel Breakout Session B – Surge Protection, Thermal Management and Packaging

Parallel Breakout Session C – Power Electronics, Communications, and Controls

[1:30 to 1:45, break people into groups and organize how groups will operate. Approximately 30 people per breakout. Blue stickers are group A, Red group B, and Yellow group C. Have staff from Laboratory and DOE assigned to appropriate groups beforehand so they can help move the discussion along. Lab and DOE should take the role of contributors, but try to avoid leading or dominating discussions. Each breakout will have a moderator and a recorder provided by McNeil. One laboratory person will also be asked to take notes in order to be sure highly technical information is captured accurately.]

[1:45 to 2:00 Discuss current goals and topics in research. For each breakout a matrix will be prepared for the group to discuss and fill in. This will be the starting point for discussion. Then the panel should consider how the matrix criteria relate to the key influences on the technology they are discussing – is efficiency really relevant to communications, controls and power electronics? Define the parameters that are most important for each breakout group, adding additional items as necessary. Keep the list of critical parameters down to as few as possible, but go deeper into components like wide bandgap devices, and into specific technical issues like temperature, energy, power, and certification. It is likely someone will ask what we are designing for – PV is the focus of this meeting but is not the only, or in some cases the primary, driving force in technology development. Adding Energy Storage brings us to systems on the order of 10's of KW-10's of MW) We should ask them to bring it back to solar as much as possible.]

[2:00 to 2:30, Ask the group to break up into smaller groups to address the parameters. Because there are tradeoffs between efficiency and cost, cost and reliability, etc., each group will be asked to address all the parameters. The group can decide if they want to break the technology issues out in more detail – for example one group on communication modules, one on surge protection circuitry. Ask the group what makes sense. Each smaller group will first describe the current status of technology. Then they should develop what the goals should be in 2010 and 2015 for each parameter. Then they should decide what is needed to accomplish the goal, and how it can be done. They are basically filling in the matrix with as much detail as possible. They should prioritize once they have captured all the information – the objective is to identify the most critical parameters and fill in the matrix.]

2:30 – 2:45 Break *[During break staff should label the flipcharts and matrix summary sheets clearly as to which session they are from and apply a numbering system to the goals/actions. For example Group A's first goal/action would be A1, the second A2, etc., Group B's would be labeled B1, B2, etc.]*

2:45 – 3:30 Resume Panel Breakout Sessions *[Reassemble the breakout groups and discuss the status, goals and needs discussion from the small groups. Identify where there is agreement/consistency. These are the core results. Identify where there are disagreements or where a group developed something unique. Discuss these and if the group agrees consolidate the information into the consensus findings. If there is time discuss whether there are inconsistencies between goals, where there are tradeoffs that should be made explicit, how realistic the goals are, etc…Make modifications where necessary in preparation for presentation to whole group, allow group to choose spokesperson.]*

3:30 – 4:15 Session Summaries (Moderated by Various)
[3:30 to 3:45, Breakout Group A summarizes the current status of Capacitor Technology, proposed goals for 2010 and 2015, and how to accomplish them. Leave 5 minutes for questions and answers]
[3:45 to 4:00, Breakout Group B summarizes the current status of Surge Protection and Thermal Management Technology, proposed goals for 2010 and 2015, and how to accomplish them. Leave 5 minutes for questions and answers.]
[4:00 to 4:15, Breakout Group C summarizes the current status of Communication, Control and Power Electronics Technology, proposed goals for 2010 and 2015, and how to accomplish them. Leave 5 minutes for questions and answers.]

4:15 – 5:15 Summary presentations and discussions -- prioritization, sequence, critical paths
[Ask everyone to reflect on the session summaries and take a few moments to rank the top five activities in order of priority on the front of their note cards – start with Session A, then do Session B, then do Session C. This will be a check and affirmation of the priorities developed in the breakouts. Ask the group to hand them in at the end of the discussion. It is okay to modify them as we speak, and it is okay to put your name on them. If they want, they can put their final rankings on the other side of the note cards and mark them as final. Both sets of votes will be recorded.]
[Discussion – are there sequence issues here? Do some of these items have to happen before others are possible? We are looking for critical paths and bottlenecks that have to be addressed. Or is this a Rubik's cube problem, where adjustments are inherently part of a whole system that reacts to changes in any one element?]

5:15 – 6:45 Reception
[No meeting business, just networking and socializing. There are plenty of attractions and restaurants at the Inner Harbor for people to enjoy afterward.]

Day 2: Codes, Standards and Applications in the Real World

7:30 – 8:15 Breakfast Buffet

8:15 – 8:30 Review of Day 1, Questions/Answers/Parking Lot (Moderator)
[Staff will record comments on previous day as they occur.]

8:30 – 8:55 National Electrical Codes and Other Standards in the Real World – Horror Stories, Successes, and Looking Forward to 2005 (John Wiles; SWTDI)
[This should remind everyone that codes and standards have real impacts – on consumers, on manufacturers, installers in the field, utilities, regulators and inspectors. Sometimes the results of small changes in wording are completely unexpected. We need to keep our eye on practical impacts as we discuss the issues today, and as we look forward to the issues coming up in 2005.]

8:55 – 9:15 Overview of UL 1741 Changes and Additions (Tim Zgonena; Underwriters Laboratories)
[Describe the changes and additions, then to the extent possible their implications for manufacturers, consumers, utilities, installers. What key problems does it solve, are there new issues it brings up, how will it be implemented and when?]

9:15 – 9:45 Review of IEEE Standards for Inverters: IEEE 1547.1 Test Procedures, IEEE 1547.2, IEEE 1547.3 Communications Protocol (Tom Basso; NREL)
[Describe the changes and additions, then to the extent possible their implications for manufacturers, consumers, utilities, installers. What key problems does it solve, are there new issues it brings up, how will it be implemented and when?]

9:45 – 10:00 Break

10:00 – 10:30 Review of IEEE Standards for Inverters, Continued

10:30 – 10:50 Overview of IEC Inverter Standards (Christoph Panhuber; Fronius)
[Describe the changes and additions, then to the extent possible their implications for manufacturers, consumers, utilities, installers. What key problems does it solve, are there new issues it brings up, how will it be implemented and when?]

10:50 – 11:10 Certification of Inverters: Does it make sense? (Chuck Whitaker; Endecon Engineering)
[Pros and cons of certification. Practical issues involved in implementation. Who would certify? Who would pay for it? How much would it cost? What are the pros and cons from the perspective of manufacturers? Consumers? Regulators? Utilities?]

11:10 – 11:30 DUIT Multiple Inverter Testing Results (Chuck Whitaker; Endecon Engineering)
[Probabilities and impacts of multiple distributed resources connected to utility distribution systems.]

11:30 – 11:50 State-by-state rules (California Rule 21- Does it take precedence over interconnect standards?) (Bill Brooks; Endecon Engineering)
[What do we know for sure about the rule and its application, and what is still unclear? Why is it important? Who does it impact? Is the precedent of a state-level rule like this good or bad – should it be standardized across states? Could this be the model for implementation across states, for good or bad?][In the last 10 minutes put up view graphs showing who is assigned to the afternoon breakout sessions – First A, then B, then C. Have copies of assignments handy for people to check.]

11:50 – 1:00 Lunch

1:00 – 3:00 Parallel Breakout Session A – UL Standards Related Issues and Needs
Parallel Breakout Session B – Utility Related Standards Issues and Needs
Parallel Breakout Session C – Inverter Manufacturers Issues and Needs
[1:00 to 2:00. For each breakout panel ask the group to identify issues/needs. Then give them note cards and ask them to go and rate them in terms of priority. Summarize the results of the voting.]
[2:00 to 2:45. Group discussion of responses to issues/needs – what can be done, who is needed to do it, and which issues/needs do the suggested actions address? Start with the top priority items and work down.]
[2:45 to 3:00. Ask group to prioritize responses in cases where there is more than one option. What needs to be done first, what has the best chance of success? Ask group to pick a spokesperson before taking break.]

3:00 – 3:15 Break *[During break moderators work to summarize results.]*

3:15 – 3:45 Session Summaries (Moderated by Various)
[3:15 to 3:30 summary of issues/needs for UL Standards, and responses.]
[3:30 to 3:45 summary of issues/needs for Utility Related Standards, and responses.]
[3:45 to 4:00 summary of issues and needs for Inverter Manufacturers, and responses]

3:45 – 4:30 Summary presentations and discussions – priorities, sequence, critical paths
[Since the breakout groups were organized around groups there has to be some discussion of where there may be conflicts in issues/needs and responses to codes and standards for consumers and insurers (UL group), utilities and manufacturers. Where are the disagreements? Where is there

consensus? Then the discussion should consider priorities among the group reports, and identify any problems with sequence/bottlenecks.]

4:30 – 5:00 Where do we go from here? Working groups, review of outputs, coordination with other stakeholders….
[Considering the outputs from today's meeting, are there volunteers for working groups to follow through on the actions? What stakeholders were missing? How do we involve them? Who wants to be involved in the 5-Year Strategy?]

WHERE TO GO FROM HERE????

Appendix D – Glossary of Terms and Acronyms

ADA	*Advanced Distribution Automation*
ASIC	*Application Specific Integrated Circuit:* A highly integrated circuit package containing hundreds of logic functions that is modified by burning-away internal paths to produce application specific circuit functions. ASICs are used to provide design flexibility and to reduce cost and parts count in the control section of an inverter.
AC PV Building Block	A complete, environmentally protected photovoltaic modular system consisting of a PV module, a complete integrated inverter enclosed with a housing eliminating exposure of any dangerous voltage and generally doubling as the module frame or mounting structure that also encloses all of the necessary ac bus work, interconnects, communication, surge protection and terminations.
AC PV Module	A complete, environmentally protected photovoltaic unit consisting of PV cells, optics, inverter and other components designed to produce ac power when exposed to sunlight.
ASTM	American Standards for Testing Materials
Bi-directional inverter	An inverter that can be operated in all four quadrants of the voltage/current regime hence may function as an inverter or as a rectifier by applying the proper drive signals. Power flow may be in either direction.
CHP or micro-CHP	Combined Heat and Power or the micro-combined heat and power
Converter	A general term used to describe a device for changing direct current power to alternating current power or vise versa or from one frequency to another.
Current-controlled Inverter	An inverter designed to convert dc power to ac power where the output current is controlled and unaffected by output voltage fluctuations. Typically used in utility-interactive applications where voltage is controlled by the utility.
DAS	Data Acquisition System
DSP	Digital Signal Processor
Electromagnetic Interference or Compatibility (EMI/EMC)	Generally refers to electromagnetic interference (radio frequencies) produced by a device and electromagnetic compatibility (EMC) of the device. Inverters must not emanate excessive EMI or be susceptible to normal EMI. EMI may be radiated as a radio wave or conducted on the ac and dc lines.
ESL	Equivalent Series Inductance, a term associated with the inductance associated with the construction and leads of capacitors.
ESR	Equivalent Series Resistance, a term associated with the power losses of a capacitor.
ETO	Emitter-Turn-off Thyristor: A new solid-state switch consisting of a thyristor device under development that is configured to facilitate device turn-off via emitter signals and generally switches faster than the commercial GTOs and can handle more power than IGBTs.
FCC	Federal Communications Commission
FET	Field-Effect Transistor: A solid-state device that uses a voltage field to control the current flow through it. Devices used in today's inverters are usually metal-oxide-silicon FET's (MOSFETs) and are generally used when the dc voltage is less than 100V. They can easily be wired in parallel with each other to increase the current/power rating of the inverter.
GTO	Gate Turn Off device
HALT	Highly accelerated life tests that are conducted in a manner to reveal component and package layout weakness that have been related to premature failure mechanisms and mean-time-to-first-failure (MTBF).
HASS	Highly Accelerated Stress Screen
Hz	Hertz or cycles per second
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronic Engineers
IGBT	Insulated Gate Bi-polar Transistor: A solid-state switch that combines the advantages of the FET and a bi-polar transistor. It requires low control power but has the advantages of low losses when in the "on" state. IGBTs are generally used when input voltages are greater than 100V. IGBTs have a wide range of capabilities and are now being integrated with built-in drivers and self-protection.
Inverter	A device designed to convert dc power to ac power. Inverters are also commonly referred to as power conditioning systems and power conditioners in photovoltaic applications. Inverters are often referred to as static power converters (SPC) in standards documents. The boundaries of the inverter were discussed extensively in this workshop, but it was not determined if the inverter included all disconnect switches, communications options, transformers or ground-fault detection/interruption.
JFET	Junction Field-effect Transistor
Line-Commutated Inverter	An inverter designed to be attached to the utility grid or other ac source that requires the switch current to pass through zero in order to turn the switching devices "off." Several versions of small, single-phase, line-commutated inverters were used early in the photovoltaic program. Line-commutated inverters are still used for some three-phase intermediate-sized and all large (>500 kW) inverters.

Maximum Power Point Tracker (MPPT)	Circuitry associated with utility-interactive inverters (and some larger stand-alone) that continuously adjust the dc operating point to obtain the maximum power available from a photovoltaic array at any given time.
Modular Inverter	An inverter design that is compatible with the paralleling or summing with one or more inverters of the same or similar design.
MOSFET	Metal Oxide Field Effect Transistor
MOV	Metal Oxide Varistor, a commonly used surge suppression device.
MTBF	Mean-time Before Failure
Multi-level Inverter	An inverter using a circuit topology that switches segments of the energy source in and out of the output circuit in order to synthesize a current sourced low frequency (typically 50 or 60 Hz) sine waveform.
NEC	National Electrical Code, a publication of the National Fire Protection Association
NFPA	The National Fire Protection Association, the organization responsible for the National Electrical Code and numerous other installation related codes.
Non-Islanding Inverter	An inverter defined in IEEE 929 as one that will cease to energize the utility line in 10 cycles or less when subjected to islanded loads that are > + 50% mismatch to inverter real power output and power factor is less than 0.95. Alternatively, a disconnection from the line is required within 2 seconds if the load to inverter match is <50%, the power factor is >0.95 and the quality factor is 2.5 or less.
PCS	Power Conditioning Subsystem or Power Conditioning System (see SPC the IEEE definition associated with inverters)
PVUSA	Photovoltaics for Utility Scale Applications
PWM	Pulse Width Modulated: A method used in self-commutated inverters to generate a synthesized waveform (e.g. a 50- or 60-Hz sinewave) through a combination of varying the duration of time that the switches in a bridge are turned "on" and "off." PWM switching frequencies may be constant or vary. PWM offers the advantages of using high-frequency transformers and much smaller filter components. PWM frequencies may range from 5kHz to 100kHz for photovoltaic inverters. Many utility-interactive inverters use PWM.
RCMU	Residual Current Monitoring Unit
SAD	Silicon Avalanche Device, a transient surge suppression device
SBIR	Small Business Innovative Research program conducted by several programs of the U.S. Government.
SCR	Silicon Controlled Rectifier: A semiconductor that is a member of the thyristor family. It cannot be switched from "on" to "off" with gate controls unless current through it passes below a holding threshold (typically through zero). These devices are typically used in line-commutated inverters.
Self-Commutated Inverter	An inverter that uses switches and controls that may be turned "on" or "off" at any time. Generally this inverter uses a PWM method to generate a synthesized waveform. Self-commutated inverters may be utility-interactive or stand-alone. They may be voltage controlled or current controlled.
SOV	Silicon Oxide Varistor, a transient surge suppression device
SPC	Static Power Converter: Terminology used in some standards for any static power converter with control, protection and filtering functions used to interface an electric energy source with an electric utility system. Sometimes referred to as power conditioning subsystem (PCS) or power conditioning units. Typically sold as inverters for photovoltaic applications.
Stand-alone Inverter (S-A)	An inverter designed to operate with the loads connected directly to its output and independent of any other ac power source. This inverter requires a battery at the input to provide dc voltage regulation and surge currents. The stand-alone inverter provides frequency and voltage regulation, overcurrent protection and surge capabilities for the loads. The S-A inverter must be a self-commutated, voltage-controlled inverter so that loads can be operated within their specified voltages.
String Inverter	An inverter designed to use a single photovoltaic string of modules for its input. The ac output of many inverters can be combined and fed to a common transformer. String inverters can be used to reduce dc wiring and protection costs and to improve redundancy of a large system.
TEAM-UP	Technology Experience to Accelerate Markets in Utility Photovoltaics
Thyristor	A term used for a family of semiconductor switching devices characterized by bi-stable switching (either "on" or "off") through internal regenerative feedback. Some thyristors can be forced to turn "off" but many will turn "off" only when current through it falls below a holding current threshold.
Transistor (Bipolar Transistor)	A semiconductor device characterized by output current that is dependent upon an input current. They exhibit low forward losses but require more drive power than FETs or IGBTs. Several early inverters used bi-polar power transistors as switching devices.
TSD	Transient Surge Device sometimes referred to as TSSD or transient surge suppression device.
Utility-interactive Inverter (U-I)	An inverter designed to be connected to the utility grid or other stable ac source. This inverter does not require dc energy storage and usually incorporates a MPPT to maximize power delivered to the grid. It may be self- or line-commutated and may be voltage-or current-controlled. Non-islanding requirements now apply to U-I inverters in the United States, some European countries and in Japan.
VJFET	Vertical-Junction Field Effect Transistor: Generally referring to the physical construction of a

	field effect (SiC) device as referred to in this report.
Voltage-controlled Inverter	An inverter designed to convert dc power to ac power where the output voltage is controlled. Typically used in stand-alone applications since the output voltage must be regulated within the inverter. Voltage controlled inverters are also used as utility-interactive where they employ a line-tie impedance to limit current flow between the inverter and the utility.