DEVELOPING A "NEXT GENERATION" PV INVERTER

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ABSTRACT

The most serious reliability issue for photovoltaics (PV) is the inverter. Mean time to first failure (MTFF) is estimated to be about five years. Recent efforts to rapidly expand the production of grid-tied inverters have not resulted in improved reliability. At this time the inverter industry is uniquely positioned to develop a 'next generation' inverter that has ten-year MTFF, better performance and lower cost. The recent advents of new technologies such as DSP (digital signal processing), the growth in sales to a few hundred thousand inverters per year and the emergence of larger companies with interest in PV inverters make this possible today. At this time the Department of Energy is considering the development of a new inverter for use in distributed energy applications [1]. This report summarizes the status of power electronics today, identifies technology issues, and identifies inverter manufacturer attributes thought to be essential for the production of a ten-year lifetime inverter.

Introduction

For inverters, low cost and high reliability are conflicting goals. There are three ways to improve reliability of a new product [2]. One can 1) over-design, 2) implement redundancy, or 3) obtain a detailed knowledge of the product working-environment, its failure modes and mode causes and then feed this information back into product redesign. Both over-design and redundancy will result in increased cost. The third option requires large numbers of fielded product so that the failure mechanisms have an opportunity to occur, and can be identified and corrected. The proper integration of field data is the only option that does not increase the cost or complexity of the inverter. It is one of the goals of this development project to identify common elements in applications so that the numbers of inverters (or inverter subsystems) manufactured can be increased. Poor inverter reliability has been identified as a problem for PV; however, these problems are not a unique PV issue. DER (distributed energy resources) sources, such as fuel cells and microturbines, also have inverters. Because these technologies are newer than PV and have not been fielded in large quantities, their pending inverter problems are not yet evident.

The PV experience has, however, identified a few key issues that are expected to limit the reliability of other technologies if the approach to providing inverters is not changed. These include:

- poor requirement definition that results in frequent product retrofits,
- immature manufacturing processes which do not incorporate a structured approach to product planning, quality control, manufacturing, or marketing, and,
- outdated designs that do not include the newest architectures, packaging methods and technologies.

Thus, a significant improvement in inverter reliability can be achieved today while still lowering cost. Furthermore, because of the similarities of all the grid-connected DER technologies, the inverters for these applications can be very nearly identical and could be designed to be interchangeable or to have interchangeable modules/subsystems. Such an approach will result in higher quantities of inverters and/or subsystems and thus provide the larger numbers of fielded units that would, in turn, provide the feedback necessary to improve inverter reliability. A modular design could further improve reliability through the development of standardized subsystems that are utilized for different products, such as PV inverters of small and large size. Such modular components would thus be manufactured in larger quantity and lead to higher reliability.

A next generation inverter will have improved performance, high reliability (ten-year MTFF), and improved profitability. *What is required is not simply an improved version of what has not worked well; it is an order-of-magnitude step forward.* Such a development will have risk. Success is not guaranteed. It has been estimated that the development of a 'next generation' inverter could require approximately 20 man-years of work over an 18- to 24-month time frame. Companies with existing design and manufacturing capability could accomplish the task with fewer resources. The investment, however, is not small for most companies interested in the task. For that reason a government-industry partnership will greatly improve the chances of success. While most companies that are developing or contemplating the development of PV inverters are not starting from zero, they must have financial resources and management commitment for a multi-year effort.

Objective of a "Next Generation" inverter.

The objective of the proposed 'Next Generation' inverter is to develop a high reliability grid-tied DER inverter while containing cost and improving performance. The approach would include:

- incorporation of new technologies,
- use of mature manufacturers,
- large product manufacturing volume, and
- failure mode feedback.

The objective is to make reliable inverters available for PV, fuel cells, energy storage, microturbines, etc. To accomplish this, the development effort will concentrate on the grid-tied inverter that has the largest expected short-term market, i.e. PV residential inverters. The intended inverter market could include foreign markets, and fuel cell or other DER sources as well as photovoltaics.

The decision to include storage has not yet been made. Inverters with storage (batteries) do offer the advantage of providing backup power. This would be an essential consideration for individuals concerned with power reliability; however, the resulting inverter system is more complicated, less reliable, and also has higher cost for the batteries and power electronics for battery charging.

Present Reliability. Because the number of fielded DER inverters is small and because designs are rapidly changing, it is difficult to benchmark the reliability of power electronics in general or DER inverters in particular. There are however a couple of data points. In 2000 Sandia commissioned Trace Engineering (presently Xantrex) to quantify the reliability of their PV inverters. The result of that study [3] indicated that the MTFF of PV inverters was about 4.7 years. Another snapshot was provided by an article that indicated that 2% of computer power supplies fail in the first year [4]. This industry is much more mature than DER and typically provides a warranty of one year. It is clear that the entire power electronics industry can benefit from improved reliability.

PATH TO HIGH RELIABILITY

The following three sections discuss the author's perception of essential elements in developing a high reliability inverter. No single approach for the inverter configuration stands out. The need to increase manufactured volume, however, suggests that some standardization should be employed. This has prompted the use of the term 'universal' inverter. The configuration could be a single box that performs all tasks, a single power section with various, interchangeable, dc-to-dc converters, or a building block concept similar to that used for personal computers. In the building block concept certain black boxes (e.g. a controller, a power converter, and so on) will be identical for various inverter configurations. Just as a computer can have varying amounts of memory, so the inverter could mix and match capabilities as required.

1. Essential Elements of the Inverter Manufacturer

It is clear that many of the past problems with PV inverters result from the absence of mature manufacturing processes in the PV inverter business. The low quantity of inverters produced has limited the market to small manufacturers. This is beginning to change with current inverter output of a few hundred thousand per year for all types of inverters. Some of the smaller companies have installed quality programs and are currently ISO (International Organization for Standardization) registered. Others have formed agreements with larger companies that do have some or all of the requisite features in place. Developing inverter manufacturers who have the desired capability **and** who can demonstrate a long-term commitment to the production of DER inverters is the key to developing a next generation inverter.

Those features, that maximize the probability of a successful 'high reliability' inverter, include an understanding of how the inverter product fits with the overall business plan. For example, it is essential that management have commitment to the development, thus the product must be important to future corporate development plans. The corporation must have performed market research and have a firm understanding of the prospective market. Key market drivers [5] such as quality of product, reliability, price, standards, flexibility, performance/features, size/packaging/weight, and system integration, must also be clearly understood. A product distribution and service network must either exist or be clearly attainable.

Essential mature manufacturing processes include ISO certification, quality programs, a systems engineering design approach, structured documentation, and access to experienced assemblers. Automation is desirable because it can enhance reliability. Experience in the design and manufacture of power electronics is essential.

2. Definition of Requirements

A systems engineering design approach focuses on defining requirements; the first step in defining requirements is an understanding of the environment. For DER sources the environment includes nearby lightning, line voltage perturbations, overloads, number of temperature cycles, ambient temperature, dust, humidity, vibration etc. Additional requirements include compliance with regulations such as IEEE 929, IEEE 1547, IEEE-519 (US), IEC-1000 (European), FCC Part 15, and familiarity with utility interconnect requirements.

Technical Issues. The prospective inverter manufacturer must also be cognizant of known failure modes in power electronics (not limited to inverters). Some of the more salient issues are identified below.

One of the principal problems in inverters is **heat** that results from losses in the semiconductor switches. Heat generation can be reduced by decreasing switching time and by selecting devices with smaller conduction losses. Advances in power electronic switches, such as the COOLMOS™ [6], are continuing to improve these parameters. Additional issues related to excessive heat are junction over temperature, inadequate heat transfer, and fans. Computer analysis of heat flow and advanced bonding materials can improve heat removal. **Fans** are a limited lifetime component and special consideration should be given to removal of heat to minimize this failure mode. Wire bond breaks in semiconductor switches result from frequent power cycling [7] and the resultant change in switch temperature. This is less a problem in DER inverters than automotive inverters since grid-connected DER inverters tend to operate at slowly changing power; they do not undergo no-load to full load transition frequently.

Optimum selection of the **switching device** is essential for high reliability. Faster control responses, frequently aided by on-device control, have significantly improved fault tolerance. Inductive turn-off of large currents must be mitigated to prevent high dv/dt stresses across device terminals that can exceed device voltage specifications.

Selection of a **switching scheme** is equally important. Soft switching offers lower heat generation and lower rfi (radio frequency interference); however, circuit parasitics that cause high frequency ringing are difficult to suppress. Hard switching has the understood problems with interrupting large currents at high voltages, generates undesirable heat, and is limited in the flexibility of control schemes.

Capacitor failure is another area where failures are well understood, but unlike semiconductors, research is proceeding slowly. US government research in capacitors has been limited [8]. Manufacturers for the largest markets (except power correction capacitors) have been dominated by foreign companies. Further, the capacitor market of $25 to $50 million generates marginal IR&D investment.

A further inverter requirement is a **reasonable cost and user-friendly design**. The cost of existing residential sized inverters (.5 to 5 kW) is approximately $1/watt with quasi-sine inverter cost of as low as $.5/watt. The target cost for the 'next generation' inverter is less than $.5/watt. The user-friendly design of a residential sized inverter should start with consideration for the installer. Minimizing installation cost would indicate that the inverter weight should be less than 70 pounds and installable by a single individual in one hour. All connections should be easy to make; all individual components should be UL approved. Communication, while not a requirement, is a highly desirable feature that will help ensure proper operation, ease installation of latest software, and provide useful reliability data.

3. Analyze Potential New Technologies, Packaging Methods, and Control Schemes

There are areas where significant improvements in inverter design can result from emerging technologies. Each of these must be evaluated to determine its suitability for an improved inverter.

The adaptation of **flexible architecture** that leads to subcomponent standardization and eases assembly is one of the desirable features of a next generation inverter. The design and implementation of such architecture for both software and hardware will reduce design time and facilitate interchangeability of modules for varying applications.

Interconnection must be easy, inexpensive, and reliable. Standardization is essential to modularization. "Pushing the standardization of key power electronic interfaces to near optimum configuration is a lesson learned from the world of small signal/logic signal processing [5]."

Modularity is extremely desirable for both hardware and software. Modularity will decrease time to market, simplify repairs, reduce need for new design, and improve reliability. In the initial stages of this inverter development it is more likely that inverter subsystems will be more likely to be manufactured in larger volume than a complete integrated inverter of a single design.

DSP (digital signal processing). Digital signal processing is now available on a chip and easily incorporated into an inverter design. In fact a new inverter design has been accomplished entirely by DSP and includes no microprocessors [9]. The reason DSP is important is that inverter control functions that have traditionally been accomplished with hardware can now be accomplished with software. Thus by accessing different software packages the power converter can accomplish different tasks with fewer hardware changes. This results in more applications for a single piece of hardware and thus more quantity of product. New chips, such as the TMS320F2810 having a speed of 150 MHz provide wider bandwidth for processing data. This results in the ability to provide better power quality with very rapid response to changing loads. Historically DSP had limited peripheral I/O capability; however, new chips come with serial peripheral interface (SPI), serial communications interfaces (SCIs), standard UART, enhanced controller area network (eCAN), and multichannel buffered serial port (McBSP) with SPI mode [10]. These features allow DSP to perform both inverter control functions and user interface functions. DSP also offers the opportunity for reducing the parts count, thus improving reliability directly.

Over the past 20 years improved semiconductors have resulted in very significant gains in inverter performance; however, further reductions in on-resistance are reaching the theoretical limit for silicon and faster switch rates may be reaching their practical limit, as designers limit dv/dt's to reduce rfi [5].

In general, "faster semiconductor switching speeds are desirable but will by definition result in higher di/dt across the semiconductor die. You can't have one without the other in hard switching topologies. High dv/dt is not the power switch killer (as long as the absolute rated voltage of the device is not exceeded). High di/dt, however, causes current crowding on the die resulting in localized hot spots. High di/dt is desirable in hard switching topologies to achieve high conversion efficiencies. Designing for high di/dt is a matter of proper device selection, low inductance dc bus design, and appropriate snubber and EMI filter design. Also, basically all power topologies are based on switches that interrupt large inductive currents [11]."

A subset of semiconductor switch design is **made-to-order** power electronics [4]. Made-to-order power electronics include the semiconductor designer in the inverter design. Thus the resulting inverter will have a semiconductor switch that is optimized for the application and includes many control and protection features on-board.

Packaging technologies include system layout, bonding, interconnection, and laminated bus bars. System layout can be optimized with computer tools including heat flow analysis. In medium voltage applications (< 500 Vdc) traditional bonding methods using thermal grease or polymer pads can be replaced with anodized films [12] placed on aluminum substrates. The anodized layer makes a uniform connection (35 to 50 microns thick) to the chassis or heat sink permitting maximum heat transfer.

Potential components should also be analyzed for the reliability of their interconnects. Wire bonding technology has been the standard interconnect method in power device and module fabrication [13]. Some advances include ThinPak technology (Silicon Power Corp), Power Overlay technique (GE), Bottom-less SO-8 package using flip chip technique (Fairchild semiconductor), PowerConnect technology (Vishay Siliconix) and Dimple-Array Interconnect (CPES).

Communications and control may be important for establishing that the product works, as expected, in the field. Furthermore field data is essential for the enhancement of reliability in future products and can be obtained from an inverter with communications.

These elements must be carefully evaluated during the development process. The need for a high reliability inverter is inherent in the goals of all DER programs in that they all require inverters with low cost and dependable power

TESTING

Given the increasingly robust design of most inverter components, manufacturing and design problems may be responsible for the largest number of field failures. An important new approach in product testing is highly accelerated lifetime testing (HALT). This test approach provides multiple stresses to an operating product, stressing the product beyond specification to identify failure modes. The rationale is that, if the product can be damaged in the laboratory, it will eventually experience the same failure in the field. After a failure mode is identified the failure mode is eliminated and the product is stressed further. Typical stresses include rapid changes in temperature and shock while the inverter is exercised with varying output power levels. Humidity is also an important parameter; however, humidity chambers that can contain an entire inverter are limited in number.

In addition to HALT, the product developer must perform design verification testing (DVT). The purpose of this testing is to ensure that the product meets all design requirements. Third party laboratories often accomplish this testing so that an impartial assessment is obtained. Sandia National Laboratories power electronics test laboratory has performed this type of testing for many of the PV inverter manufacturers.

Conclusions

Inverter failure continues to plague the PV industry and is likely to also plague emerging DER industries, such as microturbines and fuel cells. At this time there is an opportunity to double the inverter MTFF to ten years. This can result from implementation of new device technologies, increased sales, and the use of more sophisticated design and manufacturing processes. Given good design and manufacturing processes, large numbers of product manufactured may be the single most important issue related to reliability. Large quantities of fielded product make possible the feedback of failure mode data that, over time, results in a highly reliable product. For that reason, the first of the 'next generation' inverters that is developed is likely to be a small (residential sized) PV inverter with alternative applications in fuel cells.

Examination of failures of fielded inverters indicates that the following factors contribute to poor reliability:

- poor requirement definition,
- immature manufacturing processes, and
- outdated designs.

A significant improvement in inverter reliability can be achieved by correcting them.

The path to high reliability inverters is to incorporate mature manufacturing processes with solid designs that result in an inverter that can be marketed in large quantities. The design and lessons learned can then be extrapolated to other sizes and applications. Three issues are thought to be critical to achieve the 'next generation' inverter. These are

1. inclusion of an inverter manufacturer who has mature manufacturing processes in place
2. definition of adequate inverter requirements and features, and
3. incorporation of new technologies, packaging techniques, and control schemes.

Finally, an extensive testing regimen must be developed. Testing is a part of each phase of development as well as part of the validation of the final product. [14]

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[14] Sandia is a Multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under contract DE-AC04-94AL85000.