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Advanced Power Electronics Interfaces for Distributed Energy Workshop Summary

August 24, 2006
Sacramento, California

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California Energy Commission

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National Renewable Energy Laboratory

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NREL/BK-581-40480
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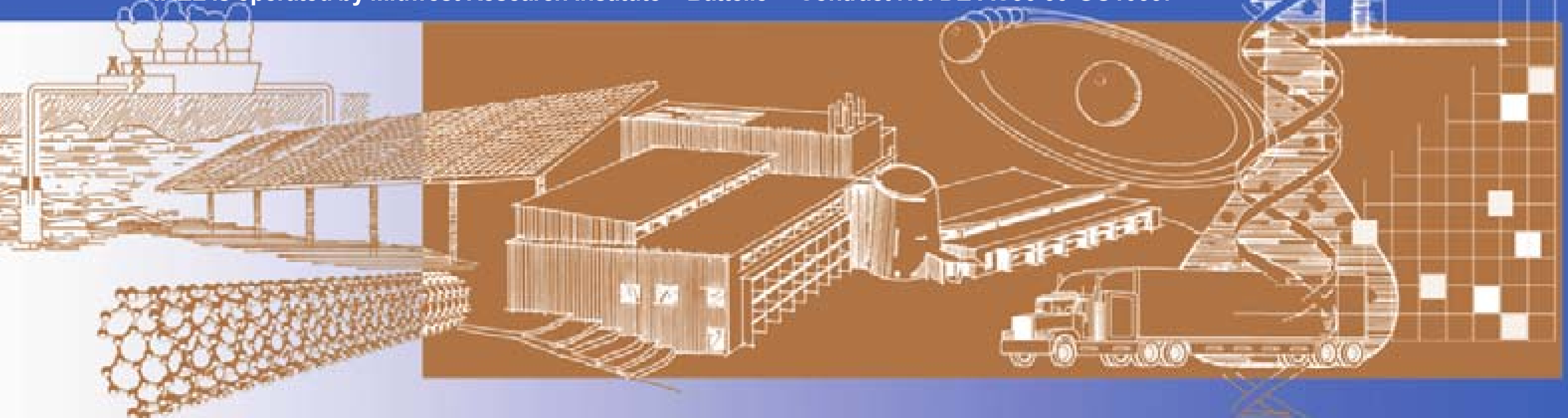

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Executive Summary

The Advanced Power Electronics Interfaces for Distributed Energy Workshop, sponsored by the California Energy Commission Public Interest Energy Research (PIER) program and organized by the National Renewable Energy Laboratory, was held Aug. 24, 2006, in Sacramento, Calif.

The workshop provided a forum for industry stakeholders to share their knowledge and experience about technologies, manufacturing approaches, markets, and issues in power electronics for a range of distributed energy resources. It focused on the development of advanced power electronic interfaces for distributed energy applications and included discussions of modular power electronics, component manufacturing, and power electronic applications.

The workshop was organized into four sessions:

- Experience With Modular Power Electronics
- Advanced Concepts and Components
- Modular Power Electronics
- Power Electronics for Distributed Energy Applications.

Each session included multiple presentations, and subsequent discussion periods allowed attendees to ask questions and share thoughts on power electronics issues.

The presentation and discussion sessions revealed several themes:

- The need for a standardized interface for power electronics
- The importance of scalability in power electronics
- The importance of modularity in power electronics
- The need for power electronics to perform with high reliability and mean time between failure
- The need to reduce the cost of power electronics components and address the increasing cost of current designs
- The reluctance of industry to forfeit proprietary designs for a standardized interface and the threat/opportunity of commoditization
- The need for longer warranties for power electronics products
- The need for improved certification scenarios and lower-cost certification methods
- The need to plan for power electronics early in system designs to reduce cost and increase effectiveness.
- The recognition that power electronics interface manufacturing will compete in a global market.

The information collected from this workshop is a resource for organizations that plan to submit proposals in response to an upcoming California Energy Commission PIER request for proposals for an advanced power electronic interface.

Information about the workshop was posted on the California Energy Commission PIER Web site (see http://www.energy.ca.gov/pier/notices/2006-08-24_workshop_power_elect.html). Forty-one people—representing industry, state and federal government, and national laboratories—attended.

Acronyms

APEI	Advanced Power Electronics Interface
CBEMA	Computer Business Equipment Manufacturers Association
CPES	Center for Power Electronics Systems
DER	distributed energy resources
EPS	electric power system
ETO	emitter turn-off
IEEE	Institute of Electrical and Electronics Engineers
NREL	National Renewable Energy Laboratory
ONR	Office of Naval Research
PEBB	Power Electronics Building Block
PIER	Public Interest Energy Research
PV	photovoltaics
R&D	research and development
UL	Underwriters Laboratories
UPS	uninterruptible power system

Definitions

Distributed energy resources (DER): DER are electric power sources located at or near the point of use or load center. DER include distributed generation, distributed energy storage, and demand response efforts. The energy generation resources include a range of technologies, such as photovoltaics, wind turbines, fuel cells, microturbines, combustion turbines, reciprocating engines, gas- and steam-powered turbines, Stirling engines, biomass systems, and solar thermal systems. Related systems and supporting technologies include integrated storage systems, power electronics, and control technologies.

Plug and play: An approach in which hardware and software work together to automatically configure devices and assign resources. This allows hardware changes and additions without large-scale adjustments or modifications. The goal is to be able to plug in a new device and immediately use it, without complicated or significant setup modifications or adjustments.

STATCOM: An abbreviation for "static compensator." This device is a shunt-connected voltage controller typically used to limit reactive power fluctuations or harmonic content. It does not contain energy storage but can actively inject or draw reactive power.

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1 Introduction

The Advanced Power Electronics Interfaces for Distributed Energy Workshop, sponsored by the California Energy Commission Public Interest Energy Research (PIER) program and organized by the National Renewable Energy Laboratory (NREL), was held Aug. 24, 2006, in Sacramento, California.

The purpose of the workshop was to create a forum for a diverse range of distributed energy resource (DER) industry stakeholders to learn about experiences and related technologies and explore the issues and options for DER power electronics. It focused on the development of advanced power electronic interfaces for distributed energy applications and included discussions of modular power electronics, component manufacturing, and power electronic applications.

1.1 Workshop Sponsor

The California Energy Commission, California's energy policy and planning agency, forecasts energy needs, keeps historical energy data, licenses thermal power plants, promotes energy efficiency, develops energy technologies and renewable energy, and plans for and responds to energy emergencies. In 1996, the Electric Utility Industry Restructuring Act of 1996 expanded the commission’s responsibilities by establishing the PIER Program. The act required that at least $62.5 million be collected each year from investor-owned utility ratepayers to fund public interest energy research.

The PIER Program partners with individuals, businesses, utilities, and public and private research institutions to conduct research on promising technologies, products, and services. It focuses on:

- Buildings end-use energy efficiency
- Energy innovations small grant program
- Energy-related environmental research
- Energy systems integration
- Environmentally preferred advanced generation
- Industrial/agricultural/water end-use energy efficiency
- Renewable energy technologies.

Power electronics fall within the purview of the PIER Energy Systems Integration group. This group takes a systems engineering approach to the electricity delivery system and focuses on transmission research, distribution research, and the integration of DER into the power system. A significant part of this group’s $42 million research portfolio is committed to demonstrating the benefits of DER integration for utilities, regulators, and ratepayers. Power electronics, a key technology in this area, can reduce the costs of interconnection and improve the integration of DER technologies.

Toward this end, PIER has partnered with the NREL to address power electronics issues. Called the Advanced Power Electronics Interface (APEI) Initiative, this six-year, $20-million-plus effort is a coordinated plan to develop a modular architecture for standardized, highly integrated power electronics interconnection technologies that will come as close as possible to "plug-and-play" for DER platforms.

The goal of the APEI Initiative is to develop power electronics technology that improves and accelerates the use of DER systems. The objective is to reduce costs for DER and interconnections by developing standardized, high-production-volume power electronic modules.

NREL is the U.S. Department of Energy's premier research facility for renewable energy and energy efficiency research. As part of its mission, NREL has established a Distributed Energy Systems Integration group to facilitate the interconnection of DER with the electric power system (EPS). The Distributed Energy Systems Integration group focuses on testing and certification, standards and codes, technology development, DER applications, and regulatory issues.

1.2 Workshop Structure

The workshop provided a status update on DER power electronics designs, manufacturing approaches, and issues. PIER will use the information gathered to determine issues its research could address and strategies for the APEI Initiative. The information will also be used to develop a future California Energy Commission PIER request for proposals for an advanced power electronic interface.

The workshop was organized into four sessions:

- Experience With Modular Power Electronics
- Advanced Concepts and Components
- Modular Power Electronics
- Power Electronics for Distributed Energy Applications.

Sections 3 through 6 provide summaries of the workshop presentations. The full presentations are included in Appendix D. As an additional resource, a presentation by Dr. Alfred Engler, Institut für Solare Energieversorgungstechnik, is included in Appendix E.

2 Workshop Introduction

Mark Rawson, program lead of the PIER Energy Systems Integration team, opened the workshop by welcoming participants and providing background information about the APEI Initiative.

The PIER Energy Systems Integration team uses a systems engineering approach in its work to integrate energy efficiency, demand response, DER, renewable energy, and energy storage into the EPS. It focuses on science and technology advancements in sensors and monitoring, power electronics, communications and controls, intelligent automated systems, and real-time operations.

Two of PIER's seven strategic objectives are addressed by the advancement of power electronics:

- Enable optimal integration of renewables, distributed generation, demand response, and storage to the power system.
- Improve cost and functionality of components to integrate demand response, distributed generation, and electricity storage into the system.

The APEI Initiative, under the direction of PIER Energy Systems Integration and NREL, will facilitate the advancement of the power electronics industry by enabling the production of more cost-effective products.

2.1 "Power Electronics for Utility Applications at the Department of Energy," Imre Gyuk, Department of Energy

Power quality is critically important to today's digital economy. In fact, common nominal power quality events cost the nation about $52 billion each year. To address power quality issues, the Energy Storage program within the Department of Energy's Office of Electricity Delivery and Energy Reliability has researched a number of advancements in energy storage technologies and power electronics, including a large-scale uninterrupted power system (UPS) that could be factory-integrated, tested, and used in plug-and-play installations.

Based on CBEMA curves (which were developed by the Computer and Business Equipment Manufacturers Association to simplify the modeling of system response and evaluate all factors in voltage deviations from the norm) from the Electric Power Research Institute, researchers determined that a system that could provide power for 15–30 seconds would cover 95% of all outages. A mobile, 2-MW, 15-second battery system was designed to meet these requirements. This system won an R&D 100 award and is now used throughout the country. A later generation, which provides 10 MW for 30 seconds, is now in service in a microchip plant in Arizona. Another, which uses a sodium sulfur battery rather than a lead acid array, provides peak shaving at a substation.

Other areas of research have included optically isolated inverters; advanced heat exchangers; low-cost, modular, highly-reliable inverters; emitter turnoff switches; and transmission stabilization devices.

The emitter turn-off (ETO) switch, developed by Virginia Tech and North Carolina State, was conceived from the need for a faster, more powerful, and cheaper switch. The resulting product is 15–20 times faster than a gate turnoff thyristor and has three times the power of the more-expensive insulated gate bipolar transistor. This technology also was awarded an R&D 100.

The transformerless STATCOM with energy storage was created through a collaboration of organizations with the goal of providing four quarter control with both real and reactive power. Although two-thirds of an example trailer-mounted installation employed supercapacitors, one-third made use of the ETO.

Finally, a more recent project has addressed the power quality issues associated with a 48-MW Bonneville Power Administration wind farm. Customer complaints and variable voltage led the administration to seek solutions. A trailer-mounted ETO STATCOM couple with grid power was one suggestion. The group is currently pursuing this option.

Projects such as these are showing the potential of power electronics. In fact, a recent meeting that brought together representatives of the national laboratories, renewable and electricity research groups, and the Office of Science determined that power electronics and energy storage should be priority areas for investment.

Future research plans include work with advanced materials, ETO deployment, thermal management systems, novel materials, silicon carbide switches, high-temperature materials, ionic fluids for electrolytes, advanced wideband gap system deployment, nano-structured materials, and diamond switches.

2.2 "Power Electronics Research Assessment," Forrest Small, Navigant

In 2004, Navigant Consulting Inc. worked with PIER's Energy Systems Integration team on research assessment and planning for power electronics. The goal was to identify research activities the commission could support to increase the penetration of DER in California.

To do so, Navigant first surveyed stakeholders to identify their key business needs. It found that the expense of power electronics—as much as 40% of DER system cost—has inhibited the use of DER. It also found that the current performance of power electronics was lacking and hindering long-term commercial application.

Navigant then analyzed the technology challenges related to these needs. It found:

- A lack of standardization and inter- and intra-operability of power electronic systems, components, and the grid
- A need for power electronic devices that are modular and scalable
- A need for improvements in power electronic system packages.

Navigant next identified 10 potential research initiatives to address the technology challenges. It ranked the initiatives based on their relative impact to DER systems, their relevance to the public interest, and the existing gap between current and necessary research. Based on the rankings, it identified three key initiatives:

- Standardize the interface between power electronics systems and the grid.
- Standardize and improve the interoperability of power electronics components and systems.
- Improve the scalability/modularity of power electronic systems and components.

Navigant believes these initiatives offer the greatest potential to affect future development and recommended that the PIER team pursue them with a systems approach. These findings were the basis for the California Energy Commission to proceed with the APEI Initiative.

2.3 Workshop Introduction Discussion

- *Who manufactures the ETOs in Dr. Gyuk's projects?*

  The ETO is not being commercially manufactured. At this time, it is made only at the university. However, there is some interest, and manufacturers are being pursued.

- *It was mentioned that power electronics correspond to up to 40% of the cost of DER systems. Does that include motors and generators as part of power electronics?*

  Navigant performed a round buildup of the cost of a representative DER system to determine what percentage of the cost would belong to power electronics components. Forrest Small, of Navigant, believes this counted only inverter and control systems.

3 Session 1: Experience With Modular Power Electronics

3.1 "Power Electronic Building Blocks: Office of Naval Research Experience and Observations," Terry Ericsen, Office of Naval Research

In 1994, the Office of Naval Research (ONR) instituted the Power Electronics Building Blocks (PEBB) program, an effort to develop a universal power processor capable of changing any electrical power input into any voltage, current, and frequency output. The goal was to create a product that would enable high-volume production of small power electronics to reduce their cost and development time. The resulting PEBB is envisioned to be software-reconfigurable, multi-purpose, "smart," and universal (i.e., it replaces specialized devices such as power conditioners, inverters, and circuit breakers). However, numerous advances are still necessary.

The ONR has identified several challenges to its overall ship design process. These include rule-based design, standard parts, increasing complexity, specifications and documents, and small sample statistics.

However, there are other, more general, challenges as well. One example is the role of simulation. Today, as in the past, simulations are developed as an analysis tool. They are based on models of a real product to study variations in design. However, simulations can play a synthesis role in the process. In the future, simulations should be based on specifications and performed in the early stages of design to determine the final real product.

Another example is the effect of the design cycle—or the lack of one. Because power electronics do not function in a vacuum, they should be developed in an iterative design cycle in which requirements influence products and vice versa. It was noted that the use of general models in the design process is more productive than the use of specific ones because they help developers avoid overly constrained problems.

Then there is complexity. Complexity is a result of emergence. That is, complex systems display a behavior that cannot be predicted based on the behaviors of their individual parts. Complexity is not a product of the number of parts. Complex systems can be simplified through physics-based partitioning, the addition of intelligent active devices, and the creation of controlled and predictable system states at physics-based partitions. However, reducing complexity increases the detail, size, weight, and cost of the power electronics. Therefore, these traits must be reduced to enable practical application and overall simplification of complex systems.

Three recent innovations will influence the future development of power electronics: (1) increased computing power; (2) the development of high-speed, low-cost controllers; and (3) system-simplifying concepts. These are important innovations that will touch on multiple aspects of development and enable new advances.

An additional problem relates to investor influence. Up to a point, if money is invested into a development process, the final cost of the product will decrease and performance will improve. Obviously, at some point, more money must be invested to extract diminishing performance returns. Between these is an optimal point, at which the balance between investment and performance is ideal. For investors, their influence is very high early in the development process, when their investments garner big returns on performance. But as progress is made, changes become more difficult, and investor influence weakens. Therefore, for effective development and maximum influence, investors must become involved early in the process, and developers must employ modeling and simulation to guide the process.

All of these issues have influenced the vision and development of PEBBs. Other important influences include the concepts of partitioning, concurrent engineering, early validation, and universal, or “plug and play” components.

Today, a working group headed by Narain Hingorani is developing an IEEE standard using the PEBB concept for electrical power systems. There are also some examples of PEBBs already in use. Three to five megawatts have been installed for a variety of applications.

Finally, future needs also include modeling standards, benchmark models, a library of models, and a body of international volunteer experts for these efforts.

3.2 “Integrated Power Electronics Building Block Modules, Converters, and Systems,” Fred Wang, Virginia Tech

The Center for Power Electronics Systems (CPES), a National Science Foundation engineering research center, is focused on the development of integrated power electronics modules. Its vision is to follow the example of micro-electronics by achieving integrated functionality, a standardized interface, and a versatile product suitable for mass production.

Power electronics interfaces are a key enabling technology for DER. They offer the potential of lower costs, higher reliability, and improved performance. To achieve this, other organizations are pursuing the conventional approach of improving the components, devices, and circuits of power electronics. CPES, however, has adopted an alternative approach of modularization, standardization, and integration to achieve economies of scale. It also emphasizes a system perspective in its work.

CPES’ specific approaches include integrated load converters (including motor-converter integration and microprocessor-converter integration), power distribution converters, and integrated source converters. For each, CPES begins with basic research on the devices, materials, and technology and then moves to developing enabling technologies and, finally, engineered systems. Already, through research funded by ONR’s PEBB program and other sponsors, CPES has developed numerous integrated power electronics modules ranging from 10 W to 10 MW. CPES researchers are now addressing the issues of a building block approach, architecture and partitioning, and interface characterization.

CPES starts at the bottom with a topology and builds from that foundation up to application layer control in a hierarchical structure. This requires the correct control architecture and communication protocols.

Finally, CPES has realized additional benefits to integrated power converter functionality. These include power flow control; power management; power quality control; monitoring, diagnosis, and online mitigation; and protection.

3.3 "Bricks and Buses," Giri Venkataramanan, University of Wisconsin

The largest markets for power electronics today are in relatively large-volume areas such as motor drives, power supplies, UPSs, and compact fluorescents. However, these are segmented markets, and it is unclear if DER can establish itself as a new market segment.

To create a new market segment, DER power electronics must overcome challenges. For example, a typical inverter is a complicated piece of equipment. The power electronic, filter, transformer, and controller components form a jungle of wires and electronics. Because of this, power electronics applications are assembled by hand—even in mass production scenarios. This production process is expensive and inhibits cost reductions. If significant cost reductions are to be realized, automated assembly, fabrication, and compilation are necessary. Other constraints include low reliability, custom designs, and long design cycles. Therefore, the future of power electronics must include standardized input, output, and functionality; "compilable" cabinets; and fail-safe and plug-and-play capabilities as well as units compatible with multiple geometries.

Modular systems are in production. Eaton has developed a molded case circuit breaker board into which input and output breakers, transient voltage surge suppressor modules, and card and voltage sensors can be plugged. Therefore, minimum assembly is involved. Rockwell has introduced a product line of several drives that are pre-engineered to work together. These incorporate control and communication cables interfaced through a bus and a line interface module that is pre-engineered for ease of integration. These are models for DER market development.

Several years ago, with support from the California Energy Commission and other sources, the University of Wisconsin – Madison began to develop a "bricks and buses" converter. This work involved demonstrating a concept prototype with electrical performance comparable to that of classically designed products, increased power density, modular packaging, and improved manufacturability.

One result of this work was a 3.2-kW, single-phase inverter. The inverter integrates the switch gear, rectifier module, capacitor, inductor, and output. On the bottom, mechanical, power, and control buses are positioned for "brick" interconnection. Each of its modules is independently thermally managed. However, other models are also possible.

The "bricks and buses" example offers standard depth and height dimensions but varied widths. In addition, it has variable volume, proportional scaling of the surface area, a decoupled power bus and signal bus, and a contained interconnect electromagnetic interference.

However, there are still challenges. The cost, size, and lack of modularity of the many components are major barriers. For example, the prices of copper and steel, which are used for the magnetic elements, have increased substantially over the past 5 years. Many of these components can be produced with less expensive materials and in more modular structures.

Such advances could make possible alternatives. An example is a system that could include a switch, throw capacitance, pole magnetics, and thermal management. These cells can be combined to increase power rating and number of phases. Other advanced concepts include air- and liquid-cooled designs and bus-centered assemblies.

3.4 Session 1 Discussion

- *The initial PEBB program focused on Navy ship power systems. For that program, how many eventual manufacturers are there? And are their products compatible with one another's, or are they just compatible within each company?*

  The Navy is not a mass buyer, and it does not buy these types of systems frequently. So it is not an industry. To create an industry and bring down costs for the Navy, utilities and others must be involved. ONR has employed a spin-on/spin-off strategy to spin off its investments to companies such as ABB and Rockwell. So far, several PEBBs—including one aboard a GLIB, or Great Lakes Icebreaker—have been put into use through this arrangement.

  Manufacturers have an incentive to adopt the PEBB process because of economies of up to five- to ten-time reductions in engineering costs. ONR's next development will be plug-and-play units. At that point, it is expected that costs will start to be driven from the customer side. The question remains of how to provide incentives for this step.

- *How realistic is it that PEBBs can accommodate distributed generation and storage in increasingly large power classes? More specifically, is the PEBB approach one that focuses within classes, or can it be used to cross classes of power electronics packages?*

  The idea is to do both. In fact, as the various markets and industries progress, they are becoming more similar. For example, they are losing fuses and breakers as solid state becomes more common. The ABB SCS 5000, a medium-voltage system for ship drives, is a 20-MW system with no fuses or breakers.

  However, this may be a challenge for utilities that want to visually check switch gear and relays. In the ship system, this is not an issue because there are no uncontrolled generation sources and so no reason to employ fuses and breakers to protect the system from such threats.

- *The business paradigm also must change, and it is. In the past, the manufacturers have associated themselves with a particular application segment (e.g., drives or wind generation). But with converter modules or PEBBs, they must associate with a line based on power level rather than application.*

  Eventually, this will mean original equipment manufacturers will be able to offer application solutions within short time frames, much like the computer industry. This is a difficult move for industry, but it is beginning to happen.

- *If there is a failure in a module, is there some type of diagnostic to identify which module needs attention? Can that module be replaced, or must the entire block be discarded?*

  At this point, this is not possible. However, it is the intent for the future. Upon failure, the module would shut itself off and electrically isolate itself from the other units. The long-term goal is modules that are "hot swappable," meaning that they can be replaced without shutting the system down.

  This type of functionality will require a definition of an architecture, and the IEEE working group is working on one now. Another idea for such functionality uses "agents" located inside each PEBB. When the system is activated, the agents would communicate with one another to determine the incorporated functions and operate appropriately. This could lead to the development of dynamically reconfigurable systems.

- *What are the biggest barriers to industry adoption of a bricks and buses approach?*

  In approximately 2003, Dr. Venkataramanan held a workshop of power electronics industry representatives in Madison, Wisconsin. The feedback he received revealed hesitations to dismantle practices and systems designed for established industries (e.g., power supplies or motor drives).

  However, there has been change since that time, and some of the new thinking is being incorporated into new designs. Further, this workshop is focused on power electronics for DER, which is a new industry. It will likely be easier to work with all the players early on, before they are entrenched in practices and systems.

4 Session 2: Advanced Concepts and Components

4.1 “Advanced Topologies for Distributed Energy Interface,” Ned Mohan, University of Minnesota

The University of Minnesota has performed power electronics research at the detailed level of topologies. This work has included an ultra-compact, high-efficiency, hybrid converter for photovoltaics (PV) and fuel cells and a multi-port DC-DC converter. The multi-port DC-DC converter is a compact unit that works as an interface between two or more energy sources and a load. It allows power flow from different energy sources to a load and bidirectional flow for all sources (e.g., for a battery). The converter is intended for use in hybrid vehicles and residential homes/buildings.

More recently, the university has been working to simplify the control of matrix converters to control motors and generators. It has found that silicon carbide-based converters, which can operate at very high temperatures, are particularly promising.

The voltage-link power electronic system is common, but there are problems with its storage capacitor—and particularly with weight, cost, and reliability. In addition, the capacitor has problems with in-rush current, and it is difficult to integrate with motors.

Matrix converters, however, have no energy storage element. They operate AC-AC and offer bidirectional power flow. The university used ideal transformers to simplify how switching signals are generated and therefore simplify matrix converter control.

The university’s study then pushed the technology by incorporating an AC machine to improve its performance. It found it could almost double it. By taking an AC machine’s Wye-connection and opening it up and feeding it from matrix converters from both sides, it found it could eliminate bearing currents, deal with isolated voltages, reduce slab insulation, control input power factor, and increase power capability. In addition, because the converters take advantage of the new silicon carbide materials, they have the potential for reduced costs because they do not require expensive copper and steel. And finally, functionally, they are PEBBs. They eliminate the need for bulky storage capacitors.

Future research on matrix converters will analyze the efficiency of the system, explore how to make the current ripple smaller, and determine ways to operate at lower frequencies.

4.2 “Integrated Modules Simplify Systems Design,” John Mookken, SEMIKRON Inc.

Power modules have evolved significantly since their introduction in the 1960s. Each generation has introduced improved power densities and new components, and each generation has evolved to integrate more components into the modules. Today, power modules integrate diodes, switching devices, gate drives, current sensors, voltage sensors, and temperature sensors.

The trend toward integration has several drivers, including a shorter time to market, easier system design and assembly, improved economics, and a reduced number of components. In addition, integration offers benefits such as customized solutions for regular prices, standard interfaces, and standard platforms.

At SEMIKRON, the latest design is the SKAI, which also includes the digital signal processor controller, a move toward intelligence in the module. (However, the module is not yet fully "intelligent" because the software is not included.) This programmable module was developed with U.S. Department of Energy funding over a 3-year period that began in 1999. It is an advanced design that begins to blur the boundary between power modules and motor drives.

The SKAI consists of a core platform (which consists of the semiconductors and capacitor) and customizable components (i.e., the insulated gate bipolar transistors, digital signal processor, controller, power supply, gate driver, protection, and heat sink). SEMIKRON designed the module to work with various applications but incorporated flexibility into the design based on its customer experience. It found that its customers liked the product, but, because of its general design, it was not optimized for their needs. The customizable components offer them the flexibility to build an optimized solution while taking advantage of the benefits of standardization. Today, only about 5% of SKAI sales are for unmodified units.

The SKAI can be configured using 600 V or 1,200 V insulated gate bipolar transistors with continuous AC output currents of 400 A rms or 300 A rms, respectfully. The module includes either a liquid-cooled or air-cooled heat sink. It is about the size of shoebox and can be manufactured in large quantities. All customizations are additions to the manufactured unit, so they do not affect manufacturing costs. The SKAI can be used for a variety of applications, depending on the customer's need and software.

SEMIKRON has experienced varying reactions to the standardized platform. It has generally found that its customers like the standardization concept—for their own product ranges. But most do not want outside products to be able to plug into their architecture. However, this is the general growth pattern in the industry and is likely to be overcome. For example, earlier power module designs from one company were eventually adopted by others so they could serve the replacement market. Customers especially like this situation because it results in competition. However, it makes the product a commodity, and power module manufacturers have incentives to resist this situation.

4.3 "Distributed Energy Advanced Power Electronic Interfaces," Ben Kroposki, National Renewable Energy Laboratory

Distributed energy applications include wind turbines, PV arrays, fuel cells, microturbines, and reciprocating engines. Although they are not new technologies, they are receiving increased attention today because of their ability to provide combined heat power, peak power and demand reduction, backup power, improved power quality, and ancillary services to the power grid.

One concern with distributed energy applications is their interconnection with the grid. Interconnection technologies have the potential to simplify this issue by performing the integration for all DC generation technologies as well as for generators. However, in addition to the basic integration, they can provide broader functions. Many small distributed energy systems already incorporate these functionalities in their inverter technology. Larger systems, however, generally incorporate these functions through separate pieces of equipment.

Power electronics have the potential to improve the interconnection of distributed energy applications and the power grid. In one scenario, they are used as an interface between the DER unit and the grid. In another, they are used to facilitate the creation of "islands" or "microgrids" by replacing circuit breakers.

Such applications can have many benefits. For example, the use of power electronics to interconnect DER can improve operating efficiencies, improve power quality, provide Var support and voltage regulation, reduce distributed energy fault currents, allow interoperability of multiple sources, and provide for standardization and modularity.

Key to the interconnection of distributed energy applications are the ongoing efforts of the IEEE 1547 working groups. These groups are developing a series of standards to address the technical requirements interconnection. IEEE 1547 Standard for Interconnecting Distributed Resources With Electric Power Systems, the first of the series, was approved in 2003, and 1547.1 Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources With Electric Power Systems was approved in 2005. These standards provide a foundation for efforts to develop power electronics-based interconnection equipment. Five more standards in the series are under development and will provide more guidance. In the future, a possible standard may address power electronics interface specifications. NREL, through support from the Department of Energy Office of Energy Research, is leading these efforts.

Further, the tests outlined in IEEE 1547.1 to ensure proper interconnection have been incorporated into Underwriters Laboratories (UL) 1741 Inverters, Converters, Controllers, and Interconnection System Equipment for Use With Distributed Energy Resources. This provides manufacturers of power electronics or other interconnection equipment with a consistent set of testing requirements for their products. UL 1741 was updated to include these requirements last November, and manufacturers have 18 months from that date to comply.

NREL also performs testing and evaluation of DER systems and components at it Distributed Energy Resources Test Facility in Golden, Colo. This facility will be used for testing and evaluation of equipment developed as a result of the upcoming PIER Advanced Power Electronics Initiative solicitation.

4.4 Session 2 Discussion

- *Presentations in the first session focused on the different functional modules in the PEBB concept and their standardization, but John Mookken focused on standardizing only the power module. What cost savings can be realized from standardizing only that piece?*

  The standard power module includes the driver and controller, but both can be replaced, if the customer desires. The biggest cost contributors are the capacitor, the current sensor, and the silicon.

- *Five percent of SEMIKRON's orders for the SKAI were for off-the-shelf units. What is the cost increase for changes to those units?*

  Because no manufacturing modifications are necessary to accommodate the changes, the cost on a per-unit basis is virtually insignificant. The only changes that significantly affect cost are adding more capacitance into the module or scaling up the power level.

- *Does the SKAI come with a warranty, and if so, do customizations affect the warranty?*

  SEMIKRON offers a 2-year warranty for the SKAI. Customized models are also covered.

- *First, manufacturers have until May 2007 to comply with the requirements of 1547.1 and UL 1741, and UL is not yet prepared to certify to 1547. However, utilities are beginning to require 1547.1 certification. This is, in effect, locking the manufacturers out of some utility districts. Second, 1547.1 introduced new requirements that resulted in manufacturers having to redesign and recertify their equipment. This is a very expensive process. Will the other standards in the 1547 series have similar effects?*

  IEEE 1547 and IEEE 1547.1 are actual standards, but the rest of the series consists of guides and recommended practices. Therefore, few or no requirements should be developed as part of their introduction (with the possible exception P1547.6 and operation on distribution secondary networks). Unfortunately, for the 1547 and 1547.1 requirements, meeting them is a cost of doing business in the DER market. UL1741 provides a way to certify products to those standards.

- *There has been a lot of discussion of standards. Are the future PEBB standards for consumers or application suppliers?*

  The consumer likely has the most to gain from a standard. As mentioned earlier, this would eventually result in a commodity product and lower prices. This is why some manufacturers resist the concept of standards.

- *There is resistance to standardization, but there are benefits also. The market increases with commoditization because of lower costs and standardization.*

  However, it can also work the other way. Consumers want the lowest possible price. In some instances, they may want a custom solution (e.g., they do not need a standard part) to further lower costs.

- *Have the matrix converters discussed by Dr. Mohan been tested to confirm the doubling of power?*

  Not yet. The idea is only in the conceptual and analytical stages at this point.

- *Is the NREL test facility able to implement and test microgrid configurations?*

  The facility is flexible and includes a variety of distributed generation sources. It can be used for low-voltage configurations of less than 600 V. Additional equipment would be necessary for medium-voltage configurations.

- *Are their problems with the 60-Hz harmonics in the matrix converter because there aren't any passives?*

  No. Matrix converters can synthesize any frequency desired at the output. In the past, a drawback was that the output voltage was only 86% of the input voltage. The new configuration achieves 186%. It also allows control of the input power factor. However, this is all analytical at this time. It has only been simulated through software.

- *One problem with matrix converters is their lack of fault tolerance. How will this be addressed for interconnection applications?*

  There must be protection against spikes, but matrix converters are in some ways more benign than others.

- *What is the IEEE standard for microgrids and intentional islanding?*

  IEEE P1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems With EPS is currently under development. It is not a full standard but rather a guide of how to intentionally island parts of the power system correctly and safely.

5 Session 3: Modular Power Electronics Distributed Energy Applications

5.1 "Modular and Scalable Power Converters in the Uninterruptible Power Supply Industry," Ian Wallace, Eaton

Sensitive (e.g., data centers, servers, and clinical laboratory equipment) and critical (e.g., broadcast transmitters, industrial process, and government facilities) power applications require high quality. Even brief interruptions in power supply or quality can severely affect function and profits.

The EPS typically provides 99.9%, or three "nines," reliability to its users, which is equivalent to roughly 9 hours of outage per year. However, for mission-critical applications, this is often not sufficient. These applications require "high nines" reliability, or reliability on the order of 99.9999% or more.

To achieve "high nine" reliability, most of these systems rely on two elements. The first is multi-source power, or the use of some combination of utility power, generators, batteries, flywheels, ultracapacitors, etc. The second is a UPS, located between the power sources and the load. In the event of a power quality or availability problem, the UPS switches the load's source to avoid a power outage or equipment damage.

To be effective, UPSs must employ parallel redundancy to ensure availability and avoid single-point failures. They must be easily expanded to accommodate increased capacity and growth, and they must have a low mean time for repairs.

Today, the UPS market is growing. It is projected the industry will achieve 10% growth in revenue per year and a 4% reduction in UPS price. In the market, the drivers for UPS technology and market growth include:

- Low installation cost
- Low operating cost
- High power quality utility interface
- High power density
- Serviceability
- Multi-source compatibility
- Monitoring, diagnostics, and prognostics
- Maintenance services.

Past UPSs were positioned to meet these needs, but they faced two technical hurdles: the control of two or more paralleled AC power sources and the elimination of all systems-level single points of failure. These systems were limited to six "nines" or less.

Today, Eaton uses Hot Sync technology, a communicationless parallel system, to achieve seven "nines." The elimination of communications enables the use of multiple units connected together and eliminates single points of failure. The identical modules operate together as peers to share and balance the power. This modular system provides flexibility and scalability to Eaton's UPS systems.

Based on this technology, Eaton has developed product lines that can be expanded incrementally for capacity, redundancy, and volume. In one approach, the control contains overhead to accommodate the incorporation of future modules, and the modules are standardized "bricks." In another, full modular products are hot-swapped on a standard rack.

5.2 "Distributed Energy Applications Leverage High-Volume, Modular Power Converters," Perry Schugart, American Semiconductor

Regardless of the size of the system, power electronics are often the last component to be designed. Frequently, the power electronics designers are forced to accommodate the rest of the system by squeezing their product into whatever space is left. Often, however, there are significant benefits to planning for the power electronics early in the design process.

American Superconductor has developed a PEBB with support from the ONR. The PM1000 is a programmable building block power converter designed for high-volume production and rapid development. Each module is fully contained with controls and power supplies. The PM1000 uses a power pole architecture and can be air- or liquid-cooled. It is designed to accommodate customer special needs without converter board modifications. The PM1000 offers two digital signal processors and four operating programs as well as a configurable graphical user interface.

The modularity of the PM1000 allows rapid development of power converters and power conversion systems. In addition, its standard power pole enables high-volume production, low cost, and increased reliability. The use of the PM1000 allows developers to avoid the time and cost of design, development, iteration, integration, and production. American Superconductor estimates this saves developers 1 year of development time and approximately $2 million.

Another product offered by American Superconductor is a developer kit, which includes a PM1000, a converter interface, a graphical user interface, a software package, and fiber optic cable with a connector. The software can be changed out to change functionality. For example, a unit may first be used as an active rectifier but later switched to a DC-DC converter. No hardware changes are required.

These developer kits cut time to operation even more. For example, a fuel cell manufacturer bought two of these kits to demonstrate a new concept for providing power to the grid. The demonstration was operational in less than a week.

A related development kit is designed for multiple-converter systems and can use any converter type (e.g., three-pole or six-pole). This system also allows the use of proprietary control algorithms. This kit is particularly applicable to DER applications. American Superconductor also offers the PM2000, a higher-power version of the PM1000.

5.3 "Modular Inverters for Distributed Generation," Matt Zolot, UQM

UQM's focus is on high-performance, power-dense, energy-efficient motors and power electronics for vehicle electrification. Over the past few years, interest has increased in the potential to connect hybrid vehicles to the power grid. These vehicles could conceivably provide peak-shaving power or other grid support and charge themselves from grid power to achieve true electric hybrid status.

However, the automotive industry has different requirements for DG converters if they are to be packaged within vehicles. To be successful, the converters would need to be high-voltage, high-density, lightweight, rugged, and low-cost.

UQM's general specifications for a grid-connect inverter include an input voltage of 150–360 V, a power output of up to 5 kW, 90% or more efficiency, galvanic isolation, and a grid and standalone operation of 50/60 Hz. In addition, the unit must meet appropriate UL and IEEE standards.

UQM uses a Mathworks autocoding setup that takes advantage of existing in-house capabilities to simplify the control design process. This approach also allows researchers to perform simulations to test the code before it is downloaded to hardware. This setup will be used for the DER work to allow for advanced signal processing, true sine wave generation, and various phase operations.

After analyzing the trade-offs between the performance, cost, and packaging of higher-integration modules and discrete component and the benefits of component-, board-, and package-level modularity, UQM chose to pursue smaller modular products.

The UQM modular inverter allows incremental additions of 1.7 kW to a 1.7-kW base, up to 5 kW. There is also a package design in which the modularity comes from components added to a board. A DC front end provides 5 kW and interfaces with the inverters. The whole system can then be duplicated and multiple systems coupled together. The output voltage can be configured in various ways.

The goal of a modular system is to prevent redesign to enable high-volume production and reduce costs. However, to reach this goal, some challenges must be overcome. One challenge is the actual interconnection. To be truly useful, it must be simple enough for non-specialists to accomplish. Another involves communication between modules and packages. IEEE standards do not currently address this, so there is no standard for communication between different products. Another challenge is anti-islanding. Although it is not a challenge for the DER industry, it is a new concept for the automotive industry and must be considered. Finally, there must be a market. At this point, it is unclear if or how the market for such applications may develop.

5.4 Session 3 Discussion

- *Why are the automotive units only 5 kW?*

  For light-duty vehicles, this is about right. Traction and heavier-duty uses would require more.

- *Approximately what volumes of the PM1000 are being produced?*

  American Superconductor is producing hundreds of the converter per year.

- *What sort of list price, in dollars per watt, does the PM1000 have? And what is smallest power increment?*

  Currently, there is essentially one power size. The three-phase unit is 175 kilowatts. The six-pole is about twice that.

  The developer kit, which is for three-pole configuration, is just less than $20,000. However, a volume purchase of the three-pole converter would garner a lower price per unit. The developer kit is intended for small volumes. Overall, however, the biggest cost savings come from the avoidance of development costs.

- *Do these products have warranties, and if so, what is the length?*

  The Eaton UPS products carry warranties of 1–2 years. The American Superconductor products come with base warranties of 1 year and offer the option of an extended warranty. The UQM product is still under development.

- *It seems 1–5 years seem to be the lifespan of warranties. What components are failing?*

  Electrolytic capacitors and fans often have the shortest lifetimes, but warranties are not necessarily indicative of lifespan. In addition, service contracts are an important offering to extend performance.

  Another consideration is the trade-off between lifespan and cost. Longer life spans will require increased costs. There is a balance that must be determined.

6 Session 4: Power Electronics for Distributed Energy Applications

6.1 "Power Electronics Conversion for Distributed Energy Applications," Alex Levran, Magnetek Inc.

Magnetek is a power electronics company that develops products for various applications, including DER. Its DER products serve wind turbines, PV arrays, energy storage, fuel cells, variable speed generation, and microturbines. Magnetek serves both residential and commercial markets.

DER applications have specific requirements that must be considered in the design of power electronics. For example, they must meet grid connection and anti-islanding standards and technical requirements. They must achieve high efficiencies in both power conversion and energy harvesting, and they must have compact designs. In addition, power electronics for DER must be reliable and cost-competitive, and they must be capable of communications and remote monitoring.

Magnetek's strategy is to lead the power electronic interface market for alternative energy systems. Its approach employs a common platform and building blocks into a scalable, modular, compact design that can be used for multiple DER sources. It uses high-efficiency, reliable converters; primary energy source control; high power densities; and system-level control.

Magnetek anticipates several trends in the future of DER technologies. For inverters, new topologies and improved control algorithms will improve performance. Improvements will also be realized in thermal management devices, driver and sensing circuits, and capacitors and magnetic devices. In addition, silicon will be used for more components, and medium voltage will become more common. Magnetek also predicts the expansion of modular designs and more flexibility, scalability, and cross-technology platforms.

6.2 "Xantrex Power Electronics for Renewable Energy System Applications," Ray Hudson, Xantrex

Xantrex is a power electronics company that is focused on the renewable power, portable and mobile power, and programmable power markets. It offers products for the solar, wind, and backup power areas of DER.

For solar, the function of the power electronics is to convert the DC source power to AC power for use by loads or the electricity grid. The solar grid-tied inverters do not include backup power capability; they only allow the provision of PV power to the electricity grid. Off-grid inverters, in contrast, can provide backup power or primary power in locations without access to the grid. Xantrex offers battery-based, single-phase grid-tied, and three-phase grid tied inverter lines. It also offers a charge controller product.

These inverters are crucial elements of solar array systems. They provide the user interface and key safety features. However, they are also very complicated and are often perceived as a weak link in the overall system because of past reliability issues. For example, solar array panels come with 20–30 year warranties; inverters come with 5–10 years.

Xantrex's key requirements for solar application inverters include high efficiency, advanced communication capabilities, low weight and part count, a sealed design, and standards compliancy.

For wind applications, the role of power electronics is to convert the variable frequency and voltage AC power from the turbine(s) into grid-compatible AC power. Unlike PV systems, wind-based generation must meet Federal Energy Regulatory Commission ride-through requirements. Xantrex offers products for both the commercial and residential scales.

In addition, Xantrex has developed power electronics for other DER technologies, including fuel cells, microturbines, advanced energy storage systems, and hybrid systems. However, this work has been relatively small-volume.

In the future, Xantrex forecasts that power electronics manufacturers will move toward optimal system design that includes the balance-of-system components. The market will also see improved performance, with higher reliability, higher efficiency, longer life spans, lower costs, and simplified installation. For DER, Xantrex anticipates higher penetration levels on the EPS and a merger between the conflicting requirements for grid-tied wind turbine and PV applications. It also projects a "feed in" tariff incentive to reward the delivery of electricity and encourage the optimization of all DER system components.

6.3 "Power Electronics for DER and Renewable Applications," Jonathan Lynch, Northern Power Systems

Northern Power Systems works on systems integration and engineering procurement, but it is steadily expanding its products and services, including those for renewable DER applications.

Through market observation and experience gained from its own installations, Northern recognized a need for power electronics. It also recognized that power electronics were often the last part of the system to be considered and that this hindered performance. It saw opportunities for advanced power electronics to enable simpler interconnections, advanced power system architectures, utility distribution system support, increased DER ancillary support, and increased DER penetration.

Based on these observations, Northern determined its power electronics focus. The company works primarily on applications of 500 kW or more and uses its PowerRouter control system to enable advanced power system architectures. It is also developing a line of products to support these systems.

Northern's FlexPhase power converter platform is a modular converter system that accommodates applications from 500 kW to multiple megawatts. It is available in 480 V and 690 V and contains configurable, rack-in power modules. The modules can be quickly replaced, and they contain intelligence. A system controller provides overall coordination.

The benefits of the FlexPhase platform include its modularity, performance, size, and cost. The modular design of the system enables a low mean time to repair, which is particularly important in remote applications. It also allows serial production, which decreases manufacturing costs, and standard sizing.

Northern is now using power electronics with conventional DER to standardize the grid interface, eliminate fault current contributions, add variable speed capability, and enable advanced architectures. Other recent efforts include the Power Distributor, which uses a power converter to provide distributed generation to multiple services; a DER utility interface switch, and the SmartView DER management system.

6.4 "SMA America: Advanced Power Electronic Interfaces Workshop," Kent Sheldon, SMA

SMA America focuses on solar technology but also has product areas in communications and control, railway technology, and advanced energy systems. Within the solar division, about 80%–85% percent of SMA's business is for grid-tied units. SMA's product line includes residential PV, small wind, and hydro; commercial PV; and backup power and off-grid inverters.

SMA believes that inverters are becoming a commodity, much like solar panels have. Maximum achievable efficiencies of 97%–98% are being reached, so cost is the only area for development and improvement. However, products can be differentiated based on strengths. At SMA, the strength is communications and control.

SMA offers a Web box communication hub and system logger. This product logs every inverter on a system and stores the information in data files for customer use. This technology will be especially useful as renewable energy credit trading becomes more common, and it enables services such as performance analysis and system alarms.

Another SMA differentiation is its use of AC coupling. In the United States, most off-grid and backup power systems are connected through battery storage. In AC coupling, SMA connects the system through an inverter that controls power quality to the load. This design provides an adaptable system and achieves 96% efficiency to loads.

Recent innovations in SMA power electronics include optic-cooled forced air cooling, an integrated aluminum enclosure and heat sink, Ethernet communication, and a load-break rated DC fused disconnect. SMA has also introduced a transformerless, 8-kW grid-tied PV inverter in Europe that has achieved 98% peak efficiency. Future products include a power balancer to correct imbalance of multiple inverters on three-phase systems.

SMA identified several challenges in today's power electronics market. These include pressure to further reduce prices, high competition, high certification costs, and increasing material costs. However, it also sees promising developments for the future. For future success, SMA believes there must be a shift to performance-based incentives, an acceptance of transformerless inverter technologies, and easing of regulatory and certification requirements.

6.5 Session 4 Discussion

- *Are the megawatt-scale inverters for the large wind projects UL-listed? Do they conform to UL 1741, or are there other requirements that they must meet?*

  They do not go through UL, and there is not a specific standard for them other than safety requirements. Generally, at these sizes, the turbines are "behind the fence" of the utility and are not subject to UL authority.

- *What is the longest warranty offered on the DER-type inverters?*

  The standard warranty is 5 years, although some companies also offer extended warranties for a fee. The 5-year standard was influenced by California Energy Commission requirements.

- *There was a reference to ride-through in wind installations versus anti-islanding in PV installations. Is the PV is on the distribution system and the wind on the transmission system?*

  Yes, that is a difference. Because these systems interconnect at different levels of the EPS, they may have different interconnection rules.

- *Is there any standard to qualify digital signal processor software?*

  Yes, UL 1998.

  For a utility application, is there any standard requirement for validation of the code?

  No attendees were aware of any such requirements.

  Are there standards for electromagnetic compatibility of internal components of digital signal processor chips or power electronics?

  There are no standards, but there are techniques that can be used to check for this.

- *Where do you think price points can be on megawatts-size power electronics if you produce 100 MW per year?*

  Price points are variable and depend on the product and its specifications.

- *Have the inverter companies considered their future business plans? Perhaps the commoditization of inverters will not be a bad thing if it is approached correctly.*

  Not everyone agrees that inverters will become a commodity. However, much of the future will depend on the degree that the industry moves to vertical integration, the level of competition and the number of competitors, and the variations allowed in the products while meeting standards requirements.

  It is difficult for companies in this industry to create long-range plans because the market environment is very fluid. The regulatory climate and incentives change frequently, and so do material prices. One option to avoid all of these challenges may be pre-competitive cooperation, but this is not the way the industry is currently headed.

- *What could increase the reliability of your product lines?*

  Several things could and do help, including improvements in installation and installer knowledge, inverter technology maturation, the use of proven reliability techniques, improved simulation, and service contracts.

- *Other than cost, is there anything about the semiconductors that limit inverter performance?*

  Yes, the actual losses in the power electronics. They can be about 3%–4%.

- *Can inverters be designed in such a way that testing costs can be reduced?*

  The UL requirements are not yet known, and how the tests will be performed is not know. Easier test points can be added, but the standards must be known first.

  In addition, IEEE 1547.1 addresses testing of the black box, the whole package. Even if individual components of the unit have passed testing individually, it requires that they be tested again as part of the full system.

7 Conclusions

The Advanced Power Electronics Interfaces for Distributed Energy Workshop was organized to gather information about the status of power electronics technologies. Through workshop presentations and discussion, several important themes emerged. These included:

- The need for a standardized interface for power electronics
- The importance of scalability in power electronics
- The importance of modularity in power electronics
- The need for power electronics to perform with high reliability and mean time between failure
- The need to reduce the cost of power electronics components and address the increasing cost of current materials
- The reluctance of industry to forfeit proprietary designs for a standardized interface and the threat/opportunity of commoditization
- The need for longer warranties for power electronics products
- The need for improved certification scenarios and lower-cost certification methods
- The need to plan for power electronics early in the system design processes to reduce cost and increase effectiveness
- The recognition that power electronics interface manufacturing will compete in a global market.

PIER will use the information gathered to determine issues its research could address and strategies for the APEI Initiative. The information will also be used to develop a future California Energy Commission PIER request for proposals for an advanced power electronic interface.

Appendix A: Agenda

Advanced Power Electronics Interfaces for DE Workshop

Thursday, August 24, 2006

Sponsor: California Energy Commission

Location: 1516 9th Street Sacramento, CA

A WORKSHOP TO FOCUS ON THE STATUS OF DEVELOPMENT OF ADVANCED POWER ELECTRONIC INTERFACES FOR DISTRIBUTED ENERGY APPLICATIONS AND A DISCUSSION OF MODULAR POWER ELECTRONICS, COMPONENT MANUFACTURING, AND POWER ELECTRONIC APPLICATIONS

8:00 - 8:10	Welcome and Introductory Remarks, *Mark Rawson, California Energy Commission*
8:10 - 8:25	Power Electronics for Utility Applications at the Department of Energy, *Imre Gyuk, DOE*
8:25 - 8:40	Power Electronics Research Assessment, *Forrest Small, Navigant*
Session 1: Experience with Modular Power Electronics - Chair: Bernard Trenton, CEC	
	EXPERIENCE WITH MODULAR POWER ELECTRONICS FROM THE POWER ELECTRONICS BUILDING BLOCK PROGRAM, INTEGRATED POWER ELECTRONICS MODULES AND BRICKS AND BUSES APPROACH
8:40 - 9:00	PEBB Program Experience, *Terry Ericsen, Office of Naval Research*
9:00 - 9:20	Integrated PEBB Modules, Converters, and Systems, *Fred Wang, Virginia Tech*
9:20 - 9:40	Bricks and Buses, *Giri Venkataramanan, University of Wisconsin*
9:40 - 10:00	***General Discussion***
10:00 - 10:30	***BREAK***
Session 2: Advanced Concepts and Components - Chair: Dick DeBlasio, NREL	
	ADVANCED CONCEPTS FOR POWER ELECTRONICS CONVERTER DESIGNS INCLUDING MATRIX AND MULTI-PORT CONVERTER, MANUFACTURING POWER ELECTRONIC COMPONENTS AND ADVANCED FUNCTIONALITY FOR DISTRIBUTED ENERGY APPLICATIONS.
10:30 - 10:50	Advanced Topologies, *Ned Mohan, University of Minnesota*
10:50 - 11:10	Integrated Modules Simplify Systems Design, *John Mookken, SEMIKRON Inc.*
11:10 - 11:30	Power Electronic Interfaces, *Ben Kroposki, NREL*
11:30 - 12:00	***General Discussion***
12:00 – 1:00	***Lunch (on your own)***
Session 3: Modular Power Electronics Distributed Energy Applications - Chair: Jose Palomo, CEC	
	HIGH VOLUME POWER ELECTRONICS DESIGN AND MANUFACTURING CHALLENGES AS WELL AS CURRENT DISTRIBUTED ENERGY APPLICATIONS THAT USE THE MODULAR APPROACH
1:00 – 1:20	Modular and Scalable Power Converters in the UPS Industry, *Ian Wallace, Eaton*
1:20 – 1:40	Distributed Energy Applications Leverage High Volume, Modular Power Converters- *Perry Schugart - American Superconductor*
1:40 – 2:00	Modular Inverters for Distributed Generation, *Matt Zolot, UQM*
2:00 – 2:30	***General Discussion***
2:30 – 3:00	***BREAK***
Session 4: Chair: Power Electronics for Distributed Energy Applications - Chair: Holly Thomas, NREL	
	CURRENT POWER ELECTRONICS IN THE RENEWABLE AND DISTRIBUTED ENERGY MARKETS
3:00 – 3:20	Magnetek Power Electronics - *Alex Levran, Magnetek, Inc.*
3:20 – 3:40	Xantrex Power Electronics for Renewable Energy System Applications – *Ray Hudson, Xantrex*
3:40 – 4:00	Power Electronics for DER & Renewable Applications, *Jonathan Lynch, Northern Power Systems*
4:00 – 4:20	SMA Power Electronics – *Kent Sheldon, SMA*
4:20 – 5:00	***Wrap-up for the day and general discussion***

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Appendix C. Speaker Biographies

Imre Gyuk, U.S. Department of Energy

Dr. Imre Gyuk is program manager of the U.S. Department of Energy's Energy Storage and Power Electronics Research Program in the Office of Electricity Distribution and Energy Reliability. The program funds work on a variety of technologies, such as advanced batteries, flywheels, supercapacitors, and power electronics. The program works with California Energy Commission on a joint $9.6 million energy storage initiative.

Forrest Small, Navigant

Forrest Small is an associate director in the Energy Practice of Navigant Consulting. His professional focus is on the development and implementation of technology-based solutions for electric power delivery through work with utilities, equipment suppliers, and public sector agencies. Mr. Small has more than 15 years of experience in the electric power industry and has worked in consulting, open access transmission operations, transmission and distribution planning, and advanced power system engineering.

Terry Ericsen, Office of Naval Research

Terry Ericsen is the program manager for the ONR. He has led the development of the Power Electronic Building Block Program for the office.

Fred Wang, Virginia Tech

Dr. Fred Wang is an associate professor and the technical director at CPES, Virginia Tech. Prior to joining CPES five years ago, he worked for GE for 10 years as a power systems application engineer, a motor drive design engineer, and a power electronics R&D manager. His interests are power converters, power systems, and motor drives.

Giri Venkataramanan, University of Wisconsin

Giri Venkataramanan studied electrical engineering at Government College of Technology, Coimbatore, India; Caltech; and the University of Wisconsin, Madison. After teaching electrical engineering at Montana State University, Bozeman, he returned to the University of Wisconsin, Madison, as a faculty member in 1999, where he continues to direct research in various areas of electronic power conversion as an associate director of the Wisconsin Electric Machines and Power Electronics Consortium. He holds five U.S. patents and has co-authored more than a hundred technical publications. His interests are in the areas of microgrids, wind energy, power converter topologies, dynamics and control, and community engineering projects.

Ned Mohan, University of Minnesota

Ned Mohan is Oscar A. Schott Professor of Power Electronics at the University of Minnesota in Minneapolis, Minnesota, where he has been teaching for the past 31 years. He has numerous patents and publications in the fields of power electronics, electric machines and drives, and power systems, in which he has written five books.

John Mookken, SEMIKRON Inc.

John Mookken's career in power electronics began in 1999 as an applications and test engineer working on a U.S. Department of Energy-funded automotive power electronics program. In 2004, he joined SEMIKRON USA as a product manager for advanced integrated power modules. He is also the project director of the U.S. Department of Energy-funded AIPM program at SEMIKRON. He completed his MS in electrical engineering at the University of South Carolina.

Ben Kroposki, NREL

Ben Kroposki is the Distributed Energy Systems Integration supervisor at NREL. His expertise is in the design and testing of renewable and distributed power systems, and he has produced more than 40 publications in this area. Kroposki received his BS and MS in electrical engineering from Virginia Tech and is pursuing his Ph.D. in electrical engineering at Colorado School of Mines. He is a senior member of the IEEE and a registered professional engineer in Colorado.

Ian Wallace, Eaton

Ian Wallace is a senior specialist at Eaton Corp.'s Innovation Center, a research and development center in Milwaukee, Wisconsin. He has 16 years experience in electric power conversion designing and developing power electronics and control systems for industrial, aerospace, and power quality markets.

Perry Schugart, American Superconductor

Perry Schugart joined American Superconductor in December 2000 as director of Sales and Marketing of the company's Power Electronics Business Unit. In this position, Schugart is responsible for the development, marketing, sales, and distribution of the company's power electronic converter products. Prior to joining American Superconductor, Schugart held increasingly senior positions with International Rectifier, most recently as director of Sales Development. An Illinois native, Schugart holds a bachelor's of science degree in physics from the University of California, Santa Barbara.

Matt Zolot, UQM

Matt Zolot is a power electronics engineer at UQM, where he works on the development of modular inverter designs. Prior to working at UQM, Matt was with NREL, where he worked on power electronics for the transportation sector. Matt graduated from Georgia Tech with a BS in electrical engineering and is currently pursuing a master's degree in electrical engineering at the Colorado School of Mines.

Alex Levran, Magnetek Inc.

Alex Levran is the executive vice president and chief technology officer for Magnetek. He manages engineering activities in the design of power supplies, generators and motors, military and commercial power conversion, and alternative energy products. He also coordinates engineering activities in Europe and the United States, creates technology roadmaps, and engages in acquisitions. Prior to his work at Magnetek, he worked for Marlin Gernin and Teledyne. Levran has also been a visiting professor at the University of California, Los Angeles, and is currently on the board of directors for the Power Sources Manufacturers Association.

Ray Hudson, Xantrex

Ray Hudson is the vice president of Advanced Technology for Xantrex.

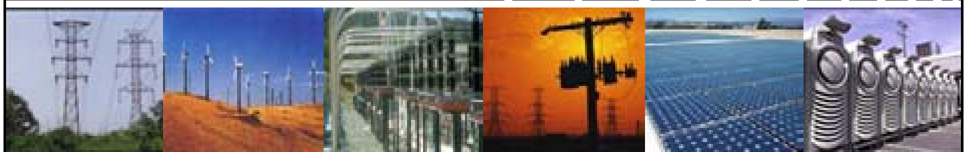
Jonathan Lynch, Northern Power Systems

In his role as chief technology officer of Northern Power, Mr. Lynch manages R&D and new product development efforts. Lynch is responsible for the identification and development of new technology and products to aid Northern's growth across its business areas, which include products and services for remote industrial, onsite generation, and renewable-based power systems. Prior to joining Northern, Lynch was employed as a design engineer at Carrier Corp., where he modeled and designed high-performance refrigeration systems and controls for transportation applications. Lynch graduated from Stevens Institute of Technology with a BSME degree with honor.

Kent Sheldon, SMA America

Kent Sheldon has been involved in the renewable energy industry for 10 years with Kenetech Windpower, Trace Technologies, Xantrex Technologies, and SMA America. During this time, he has worked as a project engineer for a variety of three-phase, grid-tied photovoltaic and large hybrid power centers; an engineering manager for the PV Series inverter family; and, currently, as a sales support manager.

Appendix D. Workshop Presentations



Advanced Power Electronics Interfaces
for
Distributed Energy Workshop

August 24, 2006

Energy Systems Integration Research Program
California Energy Commission
and
National Renewable Energy Laboratory

Mark Rawson
Energy Systems Integration Research Program
California Energy Commission

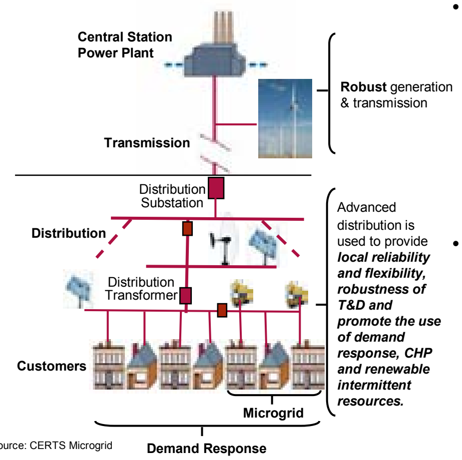
California's PIER Program

- **Public Interest Energy Research (PIER)**
  - Established in 1996 as part of deregulation of electric utilities
  - At least $62.5M collected annually from investor-owned utility ratepayers for "public interest" energy R&D
  - Focuses on R&D not adequately provided by competitive and regulated markets
- **Comprised of 7 research areas**
  - Environmentally Preferred Advanced Generation
  - Renewable Generation
  - Building End Use Efficiency
  - Industrial, Agricultural and Water End Use Efficiency
  - Environmental
  - Transportation
  - **Energy Systems Integration**
- **New, complementary natural gas public interest program established in 2005 that is expected to grow to $24M by 2009**

2

ESI Approach

ESI uses systems engineering approach that requires looking at the big picture in a holistic fashion.



Source: CERTS Microgrid

- Addressing T&D and load growth issues necessitates a coordinated effort
  - Integrate EE, DR, DG-CHP, renewables (large and DG), and storage into local energy system designs
  - Demonstrate the benefit to utilities, regulators and ratepayers
  - Optimize integration strategies to target peak load and grid utilization
- Advances in the T&D system and on the load side can get us to this new vision for the future
  - Sensors and monitoring
  - Power electronics
  - Communication and controls
  - Intelligent automated systems
  - Real time operations of the T&D system

Science and technology can transform the 19th century electricity system into the 21st century information age if we dare to make it happen.

3

ESI Strategic Objectives Aligned with Policy Drivers

IEPR, EAP, California Solar Initiative, RPS all identify needs that ESI is focused on finding solutions for.

Integrated Electricity System that is Reliable and Secure	
PIER Strategic Objectives	**1. Enable optimal integration of renewables, distributed generation, demand response, and storage to the power system.** 2. Improve capacity, utilization, and performance of transmission and distribution system. **3. Improve cost and functionality of components to integrate demand response, distributed generation, and electricity storage into the system.** 4. Improve security and reliability of electricity system. 5. Support improvement of tariffs and regulations for demand response, distributed generation, storage, and renewables. 6. Facilitate transmission siting process. 7. Develop knowledge base for future decision-making and informed delivery, integration, and infrastructure policy relative to electricity.

Source: PIER 2007-2011 Electricity Research Investment Plan

Our comprehensive portfolio of T, D, DR, DER Integration, Storage and Security research projects is supporting these strategic objectives.

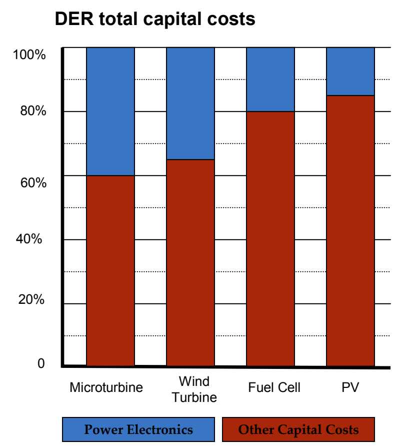
4

Cost of Power Electronics

Power electronics are part of key DER technologies, and represent a significant portion of the capital costs.

DER Type	DER Capital Cost $/kW	Power Electronics % of DER cost
Microturbine	$900 - $1,800	35% - 45%
Wind Turbine	$1,000 - $4000	25% - 40%
Fuel Cell	$3,000 - $6,000	10% - 30%
Photovoltaics	$6,000 - $10,000	10% - 25%

Cost reductions in power electronics will reduce the overall cost of DER.

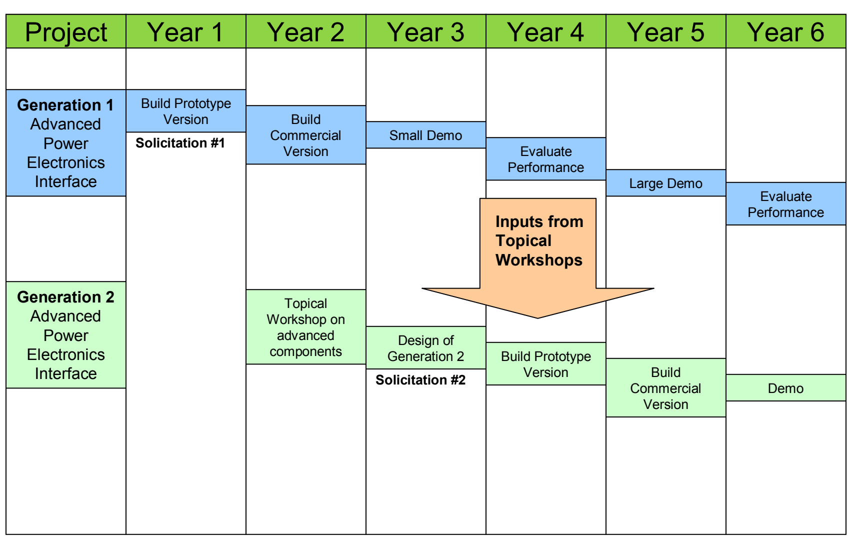


Source: NREL

5

APEI Initiative Timeline

APEI Initiative is anticipated to be a collaborative ~$20M, 6 years effort.



6

Purpose and Focus of Workshop

Purpose

- To provide industry stakeholders with an update of the status of technologies and issues in power electronics

Focus

- Development of advanced power electronic interfaces for Distributed Energy Applications

Results from this workshop will help PIER and NREL structure our strategies for the upcoming APEI Initiative.

7

Power Electronics for Utility Applications at the Department of Energy

IMRE GYUK, PROGRAM MANAGER
ENERGY STORAGE AND POWER ELECTRONICS RESEARCH, DOE

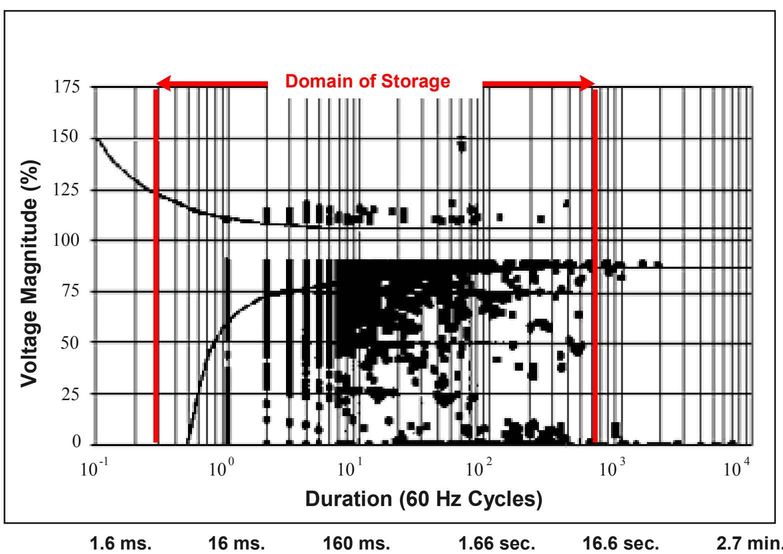
CEC-PE 8-24-06

Office of Electricity Distribution and Energy Reliability DOE

Utility Power Electronics funded through the Energy Storage Program but relevant for all Distributed Generation.

THE PQ PROBLEM:

- The Digital Economy is vulnerable to Power Quality (PQ) events such as micro-outages of a few milli-seconds and voltage sags of a few percent
- PQ events are common and cost the U.S. economy an estimated $52 billion
- System should be factory integrated and tested and allow plug and play installation



CBEMA Magnitude - Duration Scatter Plot (EPRI Data)

- Full power must be available in 4 milliseconds = 1/4 cycle for seamless power supply
- Energy should last for 15 -30 sec to cover 95% of outages and allow backup generation to ramp up
- Required development of a compact 250kW inverter (Omnion, S&C)
- Testing at PG&E facility. R&D 100

2 MW – 15 sec Mobile Battery System

10 MW - 30 sec System at AZ Microchip Plant

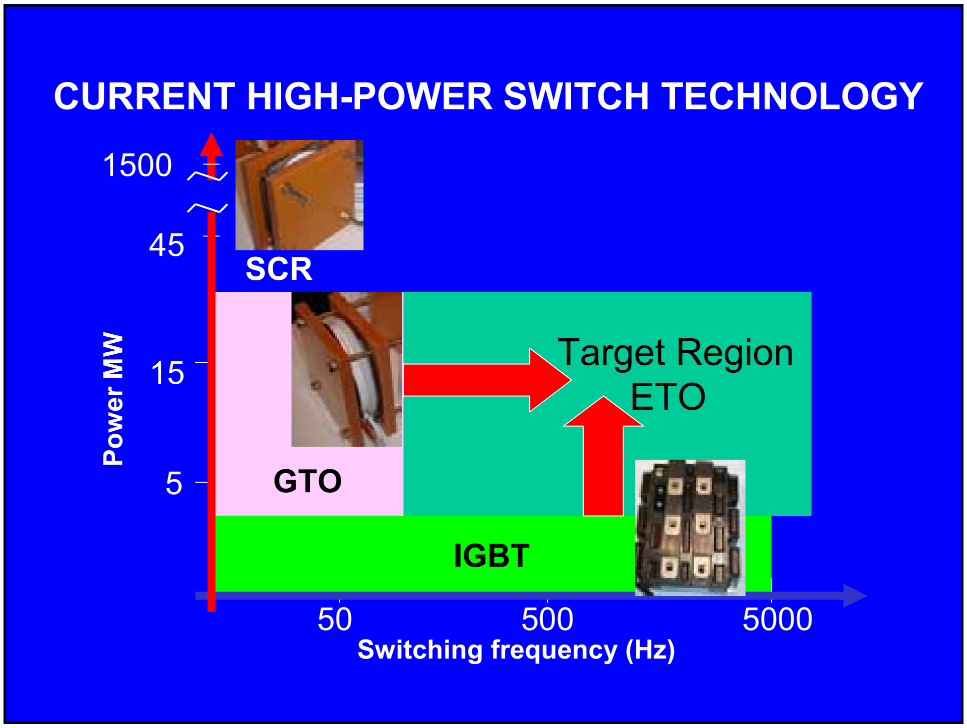
S&C Power Conditioning System for a
1.2 MW – 6 hour NaS System for Peak Shaving

SBIR Projects :

- Optically Isolated Inverter, (ONR co-funding)
  R&D 100 Award
- High Current Inverter with Advanced Heat Exchanger
- Low Cost Modular Highly Reliable Inverter

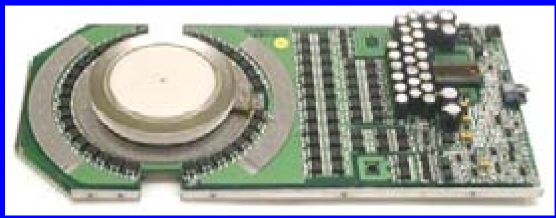
Development of Emitter Turn-off (ETO) Switch

Need for a Switch that is Faster, More Powerful, and Cheaper than Conventional Switches



16 MW ETO Switch

- Developed at Virginia Tech – NC State
- 15-20 times faster than GTO
- 3 times the power and less expensive than IGBT
- Development of Transmission Stabilization Device Planned with TVA

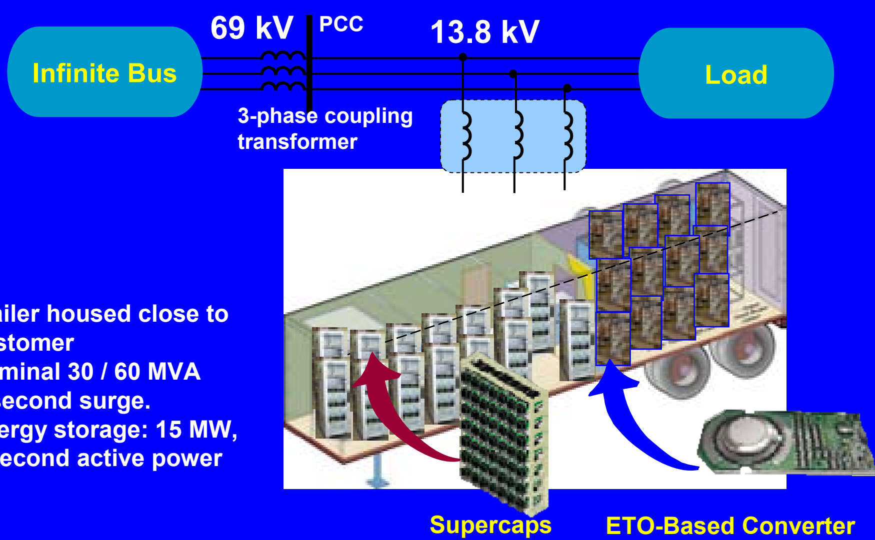


Emitter Turn Off Thyristor
R&D 100 Award Winner

Transformerless STATCOM
with Energy Storage

DOE, TVA, NC State University,
EPRI, EPRI-Solutions, Sandia

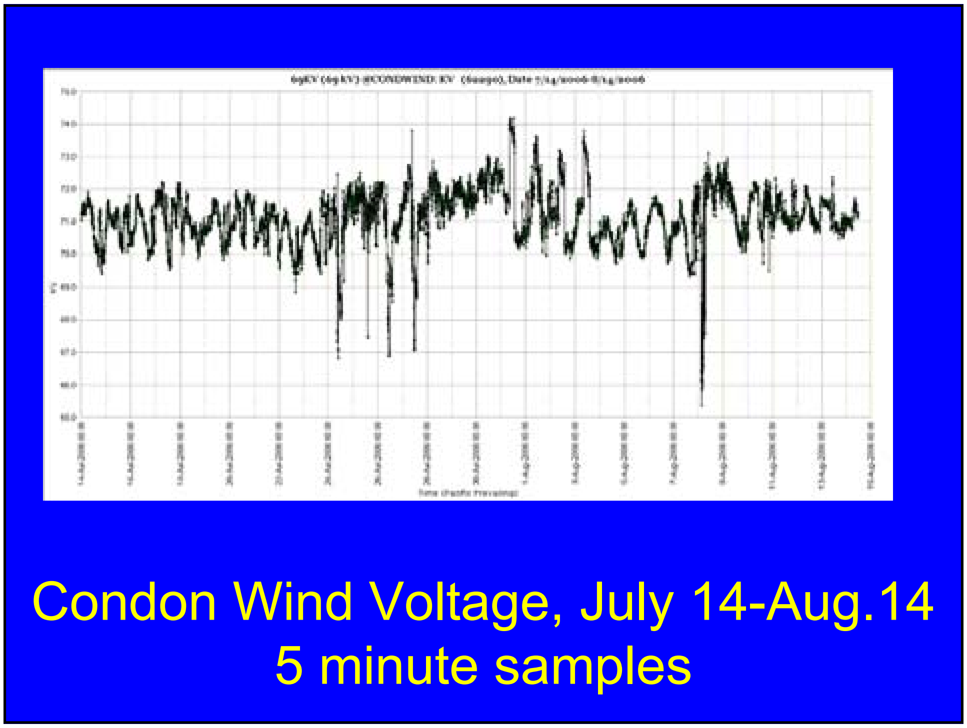
To provide 4-quarter control with Real and
Reactive Power

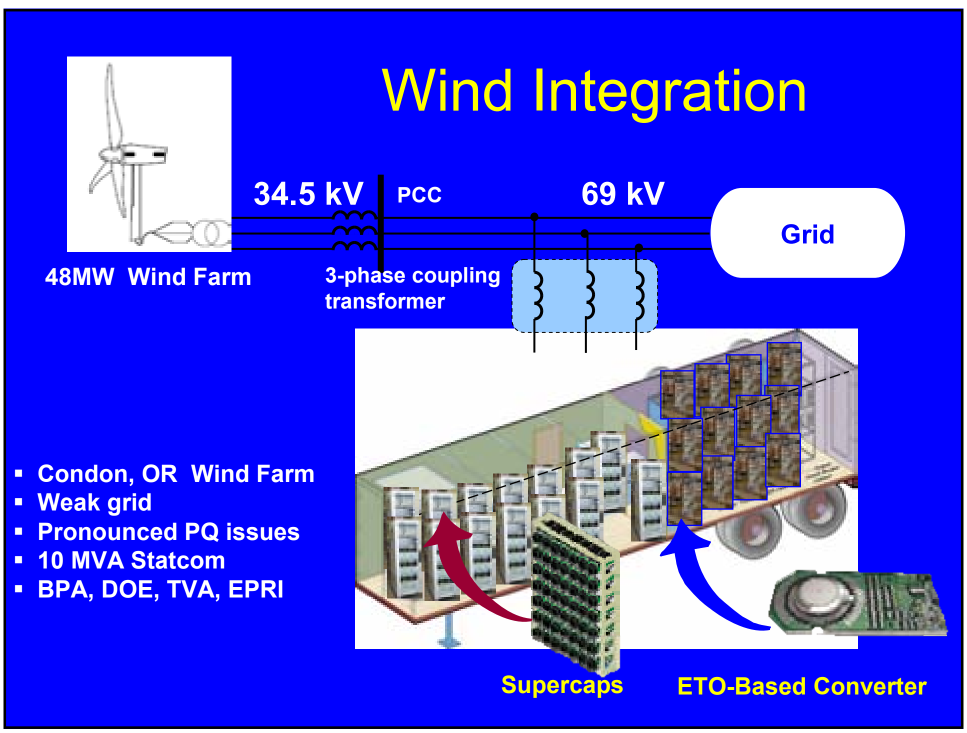


- Trailer housed close to customer
- Nominal 30 / 60 MVA
  2 second surge.
- Energy storage: 15 MW,
  2 second active power

The BPA Wind Project:

- A 48 MW Wind Farm on the BPA Grid
- Extensive Complaints by other Customers about poor PQ
- Proposed Solution by ETO Statcom


Condon Wind Voltage, July 14-Aug.14
5 minute samples


Wind Integration
34.5 kV
PCC
69 kV
Grid
48MW Wind Farm
3-phase coupling transformer
Condon, OR Wind Farm
Weak grid
Pronounced PQ issues
10 MVA Statcom
BPA, DOE, TVA, EPRI
Supercaps
ETO-Based Converter

FY 2008 Science, Technology, and Environment Briefing

Specific Areas for Investment and Management Attention – Plus ups

- Electricity storage
- Carbon capture & storage
- Unconventional fossil
- Bioenergy
- Adaptive grid controls
- Power electronics
- Superconductivity
- Solar energy utilization
- Buildings systems
- Complex systems assessment

Power Electronics and Advanced Materials

Near Term Options < 2010

- ETO deployment
- Improved thermal management systems with novel materials

Through 2015

- Silicon carbide switch
- High temperature materials
- Ionic fluids for electrolytes

Through 2025 & beyond

- Advanced wide band gap systems deployment
- Nano-structured materials and devices
- Diamond switch

SBIR Projects :

- High Power Densit y (100 kW) Silicon Carbide (SiC) Three Phase Inverters, Arkansas Power Electronics (FY06)
- Advanced Power Converter System Using High Temperature, High Power Density SiC Devices, Aegis Technology (FY06)
- Wide Band Gap, High Voltage, High Frequency Switches (FY07)

Energy Storage and Power Electronics Program Peer Review

Nov. 2 – 3, 2006, Washington, DC

http://www. sandia.gov/ess/

DER Integration Research Program

Power Electronics Research Assessment Executive Summary

Advanced Power Electronics Interfaces for DE Workshop
August 24, 2006

Public Interest Energy Research Program

California Energy Commission

Research Assessment Scope

In 2004, the CEC asked NCI to provide input into the Distributed Energy Resources Integration research agenda for power electronics.

- Objective
  - To identify gaps in the research programs being conducted by government organizations and private industry in order to provide guidance to the PIER DER Integration Research Program as it develops its research agenda in the area of Power Electronics technologies used in DER applications.
- Scope
  - Included the identification and assessment of research gaps in Power Electronics technologies used in DER applications. The analysis focused on Power Electronics technologies used in distributed generation systems (e.g., fuel cells, PV and microturbines) and distributed energy applications (e.g., inverters, uninterruptible power supplies and energy storage).
  - Included recommendations for specific research initiatives and approaches.

Power Electronics Research Assessment Executive Summary, 08/24/2006 2

Summary of Recommendations

NCI recommended that the CEC support three research initiatives and act as a catalyst for a systems approach to power electronics.

High Priority Research Initiatives

- Standardize the interface between power electronics systems and the grid
- Standardize and improve the interoperability of power electronics components and systems
- Improve the scalability and modularity of power electronic systems and components

Catalyst for Systems Approach

CEC should drive for a systems approach:

- Large projects should include all stakeholders that develop the various components and systems rather than just the final integrator/packager of the technologies.
- Smaller projects should be encouraged to exchange research needs ideas and results. These projects should be coordinated to effect the larger PE systems.
- CEC should begin by supporting the development of a forum to encourage a dialogue between different stakeholders. The initial topic could discuss how to move toward common standards and modularity.

Key Business Needs and Technology Challenges

The key business needs for DER power electronics are reducing costs and improving reliability. To support these an effective R&D program must address three technology challenges.

Key Business Needs

- Reduce costs – power electronics can account for up to 40% of the costs of a DER system
- Improve reliability – current level of performance may prevent the long term commercial penetration of DER using power electronics

Technology Challenges

- Lack of standardization and the inter- and intra-operability of power electronic systems, components and the grid
- Need power electronic devices that are modular and scalable
- Need for improvements (R&D) in power electronic system packages

Key Research Initiatives

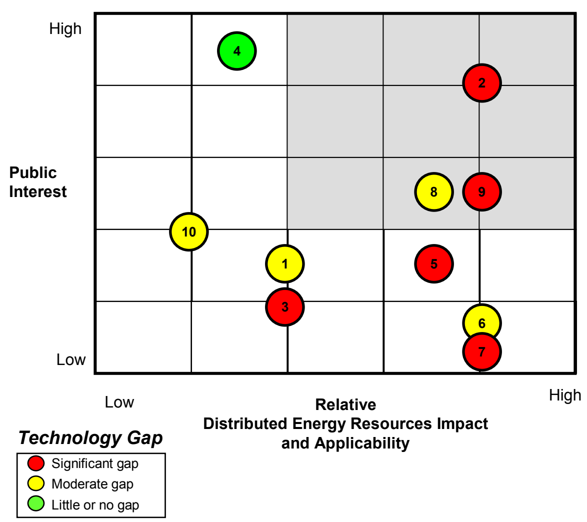
The technology challenges can be overcome by supporting ten key research initiatives.

1. Increase the efficiency of power electronic systems
2. Standardize the interface between power electronics systems and the grid
3. Improve the thermal management characteristics of power electronic systems
4. Minimize the harmonic distortions of power electronic systems
5. Improve the durability of power electronic systems and components
6. Reduce the complexity of power electronic systems
7. Improve the manufacturability of power electronic systems and components
8. Standardize and and improve the interoperability of power electronics components and systems
9. Improve the scalability / modularity of power electronic systems and components
10. Minimize the system package size of power electronics

Power Electronics Research Assessment Executive Summary, 08/24/2006 5

Initiative Mapping

Initiatives that the CEC should consider are those that have a large technology gap, high public benefit and high DER applicability.



Research Initiatives

1. Increase the efficiency of power electronic systems
2. Standardize the interface between power electronics systems and the grid
3. Improve the thermal management characteristics of power electronic systems
4. Minimize the harmonic distortions of power electronic systems
5. Improve the durability of power electronic systems and components
6. Reduce the complexity of power electronic systems
7. Improve the manufacturability of power electronic systems and components
8. Standardize and improve the interoperability of power electronics components and systems
9. Improve the scalability / modularity of power electronic systems and components
10. Minimize the system package size of power electronics

Power Electronics Research Assessment Executive Summary, 08/24/2006 6

Top Three Initiatives for the CEC

Of the ten research initiatives identified, three are the most attractive for the CEC:

2 **Standardize the interface between power electronics systems and the grid**

- A significant research and funding gap exists
- This initiative is very important for both DER and Public Benefit
- PIER could play an instrumental role in bringing together the key stakeholders to develop necessary and acceptable interface standards for DER power electronics

8 **Standardize and improve the interoperability of power electronics components and systems**

- A moderate research and funding gap exists, and this was raised as a critical issue for power electronics
- Private industry would likely have great difficulty organizing itself to address this challenge
- PIER could facilitate the bringing together of key stakeholders to develop interoperable components and systems

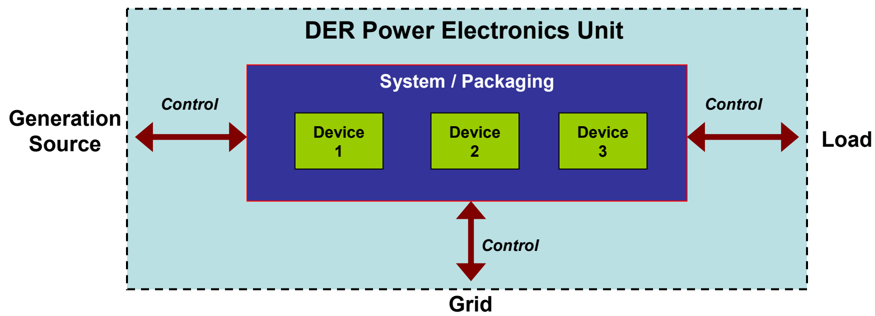
9 **Improve the scalability / modularity of power electronic systems and components**

- A significant research and funding gap exists
- This is initiative is very important for DER and moderately so for increasing public benefit
- The impact of this research initiative is cross-cutting as increased scalability and modularity should lead to improvements in the reliability and cost of DER power electronics

End of Executive Summary

DER Power Electronics Context

A DER power electronics unit is a system that incorporates packaged devices and controls. The level of complexity depends on the application.



9

Activity Areas

The power electronics activity can be classified into three fundamental areas: Devices, System / Packaging, and Controls.

	Devices	System / Packaging	Controls
Description	• The discrete switching devices themselves • Current technology is silicon-based, with silicon-carbide technology the most likely successor in the coming years.	• The arrangement of devices • Devices can be can be used individually or in combinations depending on the application	• Hardware and software to manage the power electronics system as well as monitor and respond to changing conditions
Examples	• Metal Oxide Semiconductor Field Effect Transistor (MOSFET) • Insulated Gate Bipolar Transistor (IGBT) • Gate Turn-Off Thyristor (GTO)	• Rectifier • Inverter • Converter	• Sensors • Processors • Communications • Software
Current R&D	**Devices:** • IGCT switch • Super GTO switch • ETO switch **Materials** • Silicon Carbide • Diamond	• ETO • Advanced topologies utilizing higher voltage/capacity devices • Thermal management • Packaging	• Plug and play interconnection of DER • Autonomous control • Peer to peer communications

10

The degree to which individual research initiatives are currently being pursued was categorized based on comments and feedback.

- **Significant gap**: Few companies or entities are adequately pursuing this strategy at a level that will likely ensure the strategy has a reasonable chance of success to help resolve the issue it is addressing. This could indicate an area that has been overlooked or just emerging as a viable strategy.
- **Moderate gap**: There are several companies and/or entities pursuing this strategy. Continued *and* additional activity is likely required to ensure the strategy has a reasonable chance of success to help resolve the issues it is addressing. Strategies were also given a moderate gap rating if it is deemed a strategy that is not appropriate or feasible to pursue at this time.
- **Little or no gap**: There are many companies and/or entities pursuing this strategy. The current level of activity is likely appropriate to ensure the strategy has a reasonable chance of success to help resolve the issue it is addressing. *Little* additional work beyond what is currently funded is needed.

Research Initiative 1

(1) Increase the efficiency of power electronic systems

Increasing the efficiency of power electronic systems is a key concern given its impact on the effectiveness of power electronics solutions, and there are multiple projects currently underway that are addressing this issue. Nevertheless, given the fundamental importance of this top, additional support may be warranted.

Public benefit: This initiative could provide a competitive advantage, but benefits are primarily to the manufacturer.	2
Relative DER Applicability: This initiative is a crosscutting issue, but there is little room left for economic or reliability improvements to occur as a result of increased efficiency.	2.5

Estimated Total Funding Needed	$20 M	Estimated Current Public Support	$1.9 M

Research Projects That Address Initiative

A	*Optically Isolated 5MW Inverter.* Improve reliability by developing a new, highly efficient (99%+) inverter design that utilizes optical sensing and control, DSP control algorithms and HVIGBT devices.	J	*High Reliability Inverter Development.* Reduce the cost and improve reliability by developing an inverter that operates like a convention hard-switched inverter with no limitations on switching timings or additional control complexity.
C	*Compact Diode-Clamped Multilevel Converter.* Improve reliability and efficiency by developing a diode-clamped multilevel inverter that share a common DC bus	L	*Digital Control of PWM Converters.* Improve reliability by minimizing the power dissipation of the converter by dynamically adjusting parameters such as the synchronous rectification dead time and the current sharing in multi-phase converters.
H	*Silicon Carbide Power Electronics for Utility Application.* Improve the reliability of power electronics by researching the benefits and applications of SiC.	O	*Diamond Tip Emitters.* Improve the reliability and efficiency of power electronics through the use of diamond tipped emitters

● Significant gap ● Moderate gap ● Little or no gap

Research Gap Analysis Research Initiative 2

Research Initiative 2

2	Standardize the interface between power electronics systems and the grid

Standardization of a power electronic grid interface for DER is critical to increasing the penetration of DER. Several projects are developing technology that will support this initiative, but only one project directly addresses the issue of standardization. Moreover, the current public support is a small fraction of the estimated total funding required.

Public benefit: Very limited incentives, and all classes of stakeholder (including ratepayers) will benefit.	4.5
Relative DER Applicability: This initiative is unique to DER and there could be a significant impact to DER through reduced installation costs and improved reliability.	4.5

Estimated Total Funding Needed	$15 M	Estimated Current Public Support	$1.5 M

Research Projects That Address Initiative	
C	*Compact Diode-Clamped Multilevel Converter.* Improve reliability by developing a diode-clamped multilevel inverter that share a common DC bus Their unique structure allows them to span high voltage without the use of transformers and with no voltage sharing problems.
G	*Distributed Energy Interface.* Improve the reliability of power electronics by improving the power flow between energy resources and the grid through the use of power electronic interfaces.
J	*High Reliability Inverter Development.* Reduce the cost and improve reliability by developing an inverter that operates like a conventional hard-switched inverter with no limitations on switching timings or additional control complexity.
N	*ETO Thyristor Development.* Reduce cost and improve reliability by utilizing integrated power electronic modules composed of standardized components (instead of custom designed systems) in the development of ETO Thyristors.
V	*Static Inverter Type Testing.* Improve reliability by developing a procedure type and verification testing of static inverter.

Significant gap Moderate gap Little or no gap

13

Research Gap Analysis Research Initiative 3

Research Initiative 3

3	Improve the thermal management characteristics of power electronic systems

There are only a few projects addressing the thermal management issue, yet this is a major issue surrounding power electronics. Several of the people interviewed raised this topic as an area requiring further research. Thermal management can be controlled or improved through both material and mechanical advances and should increase both performance and reliability.

Public benefit: This initiative is more of a product attribute, and the benefits are not widespread.	1.5
Relative DER Applicability: This initiative could reduce package size and manufacturing costs. Reliability is increased through the reduction in failures associated with poor thermal management.	2.5

Estimated Total Funding Needed	$10 M	Estimated Current Public Support	$2 M

Research Projects That Address Initiative	
H	*Silicon Carbide Power Electronics for Utility Application.* Improve the reliability of power electronics by researching the benefits and applications of SiC.
R	*Thermal Management for Power Electronics.* Increase the reliability of power electronics by improving the thermal characteristics with a combination of high--temperature materials and advanced cooling strategies
O	*Diamond Tip Emitters.* Improve the reliability and efficiency of power electronics through the use of diamond tipped emitters

Significant gap Moderate gap Little or no gap

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Research Initiative 4

4	Minimize the harmonic distortions of power electronic systems

There was only one project identified that is focusing on reducing the harmonic distortions of power electronics, yet a significant amount of research has been done in this area in the past. Industry standards already exist to address this issue.

Public benefit: There is significant public interest and multiple stakeholder classes will benefit.	5
Relative DER Applicability: There is minimal impact on DER applications.	2

Estimated Total Funding Needed	$2 M	Estimated Current Public Support	$0.5 M

Research Projects That Address Initiative	
D	*Multilevel Universal Power Conditioner.* Improve the reliability of power electronics through the development of a multilevel universal power conditioner.
I	*Harmonic Elimination Technique and Multilevel Converters:* Control a multilevel inverter in such a way that it is an efficient, low total harmonic distortion (THD) inverter that can be used to interface distributed dc energy sources to a main ac grid.

Significant gap Moderate gap Little or no gap

Research Initiative 5

5	Improve the durability of power electronic systems and components

A significant research gap exists as relatively few projects are actively concentrating on increasing the durability of power electronic components and systems. While power electronics system manufacturers are likely to be actively conducting internal research to improve the reliability of their products, a more systemic approach with public funding support may yield benefits that can be shared industry-wide.

Public benefit: This initiative benefits primarily manufacturer and customer.	2
Relative DER Applicability: This initiative has high applicability to DER, and improves reliability.	4

Estimated Total Funding Needed	$20 M	Estimated Current Public Support	<$0.5 M

Research Projects That Address Initiative	
	None

Significant gap Moderate gap Little or no gap

Research Gap Analysis Research Initiative 6

Research Initiative 6

6	Reduce the complexity of power electronic systems

The DOE is funding several research projects to reduce the complexity of power electronics, but many comments were raised about the significance of this issue. This is a cross-cutting issue that will help reduce costs, ease manufacturing, and facilitate standardization.

Public benefit: Commercial incentives already exist, and this initiative primarily benefits the manufacturer.	1
Relative DER Applicability: This initiative is very applicable to DER and significant cost reductions could occur.	4.5

Estimated Total Funding Needed	$10 M	Estimated Current Public Support	$2.0 M

Research Projects That Address Initiative

F	*Soft Switching Snubber Inverter.* Reduce the cost and improve reliability through the development of advanced inverter designs that utilize fewer components and modular electronics.	N	*ETO Thyristor Development.* Reduce cost and improve reliability by utilizing integrated power electronic modules composed of standardized components (instead of custom designed systems) in the development of ETO Thyristors.
J	*High Reliability Inverter Development.* Reduce the cost and improve reliability by developing an inverter that operates like a convention hard-switched inverter with no limitations on switching timings or additional control complexity.	O	*Diamond Tip Emitters.* Improve the reliability and efficiency of power electronics through the use of diamond tipped emitters
		P	*Standard Power Electronic Interfaces.* Reduce the cost and improve the reliability of power electronics by developing standardized approaches for integrating power converter components.
M	*PV Inverter Products Manufacturing and Design Improvement.* Design a large number of products based on small number of functional modules to achieve high manufacturing efficiencies and enhanced product reliability		

Significant gap   Moderate gap   Little or no gap

17

Research Gap Analysis Research Initiative 7

Research Initiative 7

7	Improve the manufacturability of power electronic systems and components

There is a need for additional research to improve ease of manufacturing. Although the DOE is supporting projects focused on reducing manufacturing costs, there is still a great deal of research needed. Manufacturing costs are a major part of total power electronic system costs, and so improving the ease of which a component is manufactured could have a substantial impact on the attractiveness of power electronics based DER.

Public benefit: Commercial incentives exist, and this initiative primarily benefits the manufacturer.	1
Relative DER Applicability: This initiative is very applicable to DER and significant manufacturing cost reductions could occur.	4.5

Estimated Total Funding Needed	$15 M	Estimated Current Public Support	$1.2 M

Research Projects That Address Initiative

B	*Cascade Multilevel Inverter for Utility Applications.* Reduce the manufacturing cost and improve reliability and efficiency of multilevel inverter through the utilization of modular and compact circuit topology
J	*High Reliability Inverter Development.* Reduce the cost and improve reliability by developing an inverter that operates like a convention hard-switched inverter with no limitations on switching timings or additional control complexity.
M	*PV Inverter Products Manufacturing and Design Improvement.* Design a large number of products based on small number of functional modules to achieve high manufacturing efficiencies and enhanced product reliability
N	*ETO Thyristor Development.* Reduce cost and improve reliability by utilizing integrated power electronic modules composed of standardized components (instead of custom designed systems) in the development of ETO Thyristors.
P	*Standard Power Electronic Interfaces.* Reduce the cost and improve the reliability of power electronics by developing standardized approaches for integrating power converter components.

Significant gap   Moderate gap   Little or no gap

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Research Gap Analysis Research Initiative 8

Research Initiative 8

8	Standardize and and improve the interoperability of power electronics components and systems

Standardization of interfaces was identified as a significant barrier surrounding power electronics. There are public and privately funded projects addressing the standardization / interoperability issue, but research is still needed.

Public benefit: Limited incentives exist, and this initiative could benefit multiple stakeholders.	3
Relative DER Applicability: This is a crosscutting initiative that could yield significant cost and reliability benefits.	4

Estimated Total Funding Needed	$5 M	Estimated Current Public Support	$1.0 M

Research Projects That Address Initiative	
C	*Compact Diode-Clamped Multilevel Converter.* Improve reliability by developing a diode-clamped multilevel inverter that share a common DC bus Their unique structure allows them to span high voltage without the use of transformers and with no voltage sharing problems.
J	*High Reliability Inverter Development.* Reduce the cost and improve reliability by developing an inverter that operates like a conventional hard-switched inverter with no limitations on switching timings or additional control complexity.
N	*ETO Thyristor Development.* Reduce cost and improve reliability by utilizing integrated power electronic modules composed of standardized components (instead of custom designed systems) in the development of ETO Thyristors.

Significant gap Moderate gap Little or no gap

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Research Gap Analysis Research Initiative 9

Research Initiative 9

9	Improve the modularity / scalability of power electronic systems and components

Scalability and modularity were identified as major barriers to improved adoption of power electronics based systems due to the potential impact on flexibility and cost. There are few projects addressing these issues and significant research is still needed.

Public benefit: Limited incentives exist, and this initiative could benefit multiple stakeholders.	3
Relative DER Applicability: This initiative is highly applicable to DER and could yield significant cost benefits.	4.5

Estimated Total Funding Needed	$10 M	Estimated Current Public Support	$1.3 M

Research Projects That Address Initiative	
J	*High Reliability Inverter Development.* Reduce the cost and improve reliability by developing an inverter that operates like a convention hard-switched inverter with no limitations on switching timings or additional control complexity.
P	*Standard Power Electronic Interfaces.* Reduce the cost and improve the reliability of power electronics by developing standardized approaches for integrating power converter components.
Q	*New Power Electronic Technologies.* Reduce costs and improve reliability by developing power electronics products using cutting edge technology.

Significant gap Moderate gap Little or no gap

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Research Gap Analysis Research Initiative 10

Research Initiative 10	
10	Minimize the system package size of power electronics

A moderate research gap exists as several projects identified are trying to minimize the system footprint, and this topic of obvious concern to manufacturers. The size of the power electronics package impacts the attractiveness of DER technologies and the ease of integration.

Public benefit: Limited incentives exist, yet this initiative benefits the manufacturer and customer only.	2.5
Relative DER Applicability: This initiative has limited applicability to DER and could actually increase costs.	1.5

Estimated Total Funding Needed	$5 M	Estimated Current Public Support	$0.8 M

Research Projects That Address Initiative	
A	*Optically Isolated 5MW Inverter.* Improve reliability by developing a new, highly efficient (99%+) inverter design that utilizes optical sensing and control, DSP control algorithms and HVIGBT devices.
B	*Cascade Multilevel Inverter for Utility Applications.* Reduce the manufacturing cost and improve reliability and efficiency of multilevel inverter through the utilization of modular and compact circuit topology

NOTE ON MANUFACTURERS: Given that many of the research initiatives are manufacturing or packaging related, it is likely that many DER power electronics equipment suppliers are actively pursuing internally-funded research supporting many of the research initiatives identified well beyond research activities co-funded by public sector entities. However, due to competitive nature of the business, very little is known about these internal research activities.

Significant gap **Moderate gap** **Little or no gap**

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Literature Search and Interviews

The first stage of this project was to conduct literature searches and telephone interviews with research stakeholders.

- Literature search of projects and activities by various stakeholders
  - DOE and National Labs
  - State based R&D funding entities (e.g., CEC, NYSERDA, etc.)
  - Universities
  - Manufacturers
  - Industry organizations and standards bodies
- Telephone interviews with stakeholders and researchers such as:
  - Alex Huang of Virginia Tech
  - Giri Venkataramanan of University of Wisconsin
  - Keith White and Richard Zhang of GE
  - Leon Tolbert of Oak Ridge National Laboratory and the University of Tennessee
  - Matt Lazarewicz of Beacon Power
  - Nag Patibandla of NYSERDA
  - Stan Atcitty of Sandia National Laboratory
  - Tim Zgonena of UL
  - Bill Erdman of DUA
  - Ben Koproski of NREL
  - Bob Panora of Tecogen
  - Greg Ball of PowerLight
  - Ian Wallace of Eaton
  - Jim Davidson of Vanderbilt University
  - Perry Schugart of American Superconductor
  - Scott Samuelsen of UCI
  - Syed Ahmed of Southern California Edison

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Power Electronic Building Blocks, PEBB
ONR Experience and Observations

Terry S Ericsen
Program Office for Electrical Science and Technology
Office of Naval Research
ericset@onr.navy.mil

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Recent Innovations

- Computing Power Increase
- High-Speed and Low-Cost Controllers
- System Simplifying Concepts

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"System of Systems" Design Challenges

Today

- Rule Based Design
- Standard Parts
- Increasing Complexity
- Specifications, Documents
- Small Samples Statistics

Tomorrow

- Relational Based Design
- Standard Processes
- Increasing Detail
- Model is the Specification
- Physics Based Analysis
- Statistics from All of Industry

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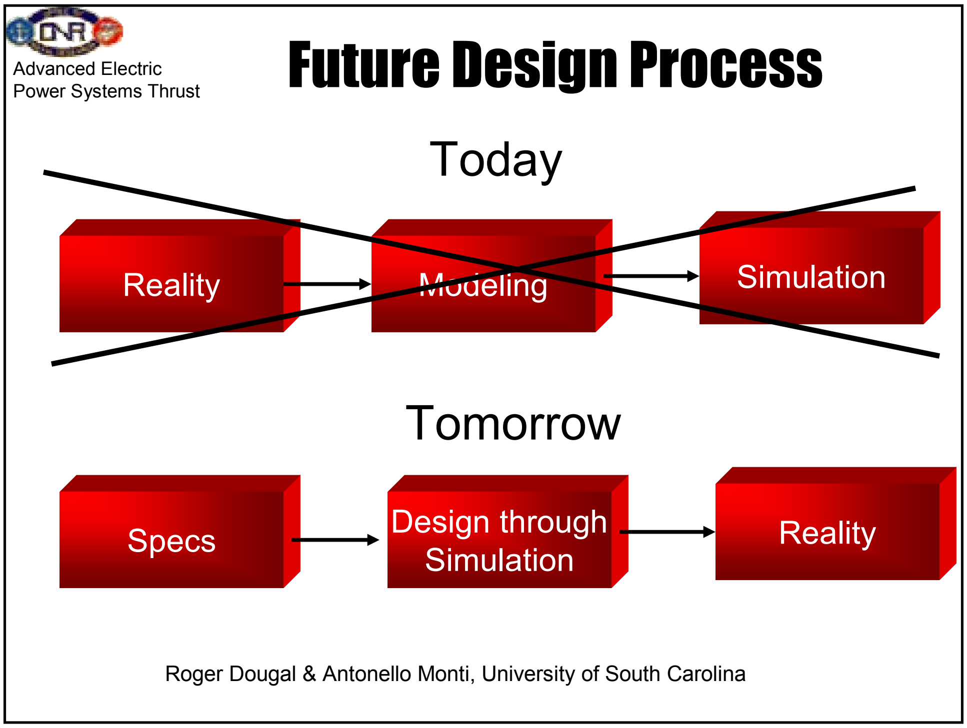
The Changing Role of Simulation

- **Today,** simulation is used for evaluation -- **Analysis**.
  - Simulation programs require detailed design information
    - Circuit parameters are entered before simulation begins.
    - Variations in design can be analyzed
- **Tomorrow,** simulation will become part of the design process -- **Synthesis**.

The Model Will Be The Specification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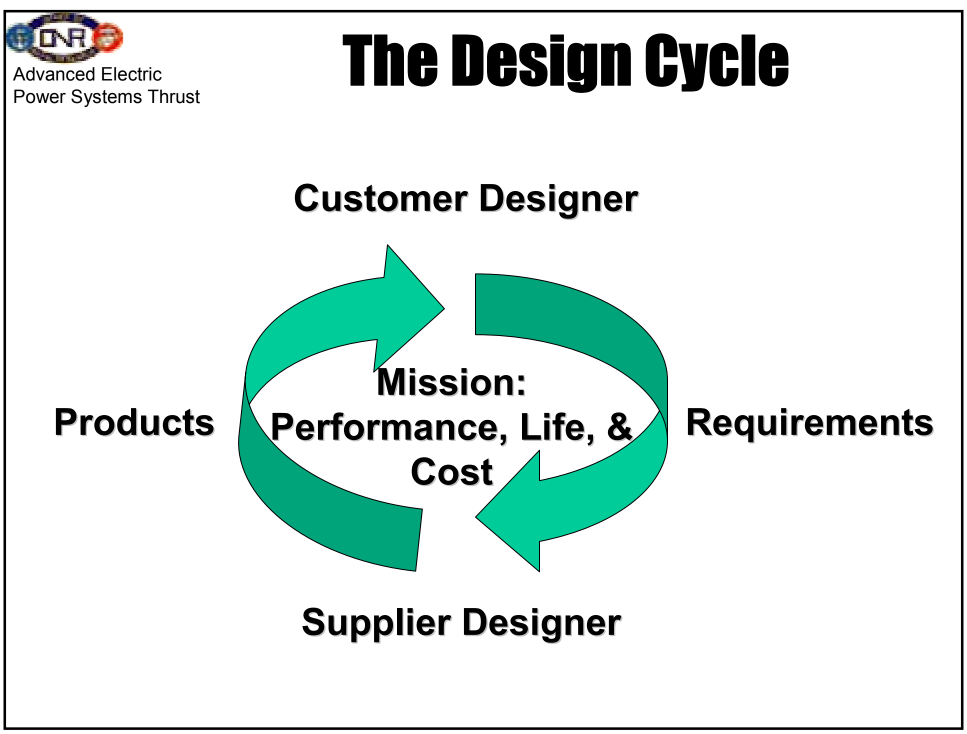
Future Design Process
Today
Reality
Modeling
Simulation
Tomorrow
Specs
Design through
Simulation
Reality
Roger Dougal & Antonello Monti, University of South Carolina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The Design Cycle
Customer Designer
Products
Mission:
Performance, Life, &
Cost
Requirements
Supplier Designer

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Changing World of Models -- Dynamics

- Model is the Specification
- Model is the Control
- Model is the Machine

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Physics-Based Models are Required

- Product models must be specific
- Requirement models can be general
  - In fact, requirement models with very specific details, in the design phase, can lead to an overly constrained problem.

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Complexity

(From "Modeling and Simulation in System Engineering: Whither Simulation Based Acquisition?" By Andrew P. Sage and Stephen R. Olson, George Mason University)

- The more identical that a model must be to the actual system to yield predictable results, the more complex the system is.
- Complex systems "…have emergence … the behavior of a system is different from the aggregate behavior of the parts and knowledge of the behavior of the parts will not allow us to predict the behavior of the whole system."
- "In systems that are 'complex,' structure and control emanate or grow from the bottom up."
- A system may have an enormous number of parts, but if these parts "interact only in a known, designed, and structured fashion, the system is not complex, although it may be big."
- Although a physical system maybe not be complex, if humans are a part of the system, it becomes complex

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Complexity and Simplification

- Complex systems can be simplified by:
  - Physics-based partitioning
    - Based on the nature of the materials, components, and manufacturing methods
  - Adding intelligent active devices
  - Creating controlled and predictable system-states at physics-based partitions
- All of this increases detail, size, weight, and cost.
- Therefore:
  - The size, weight, and cost of these technologies have to be reduced to enable practical application and simplification.
  - Computational abilities and new modeling and simulation tools are needed to allow for design with increased detail.

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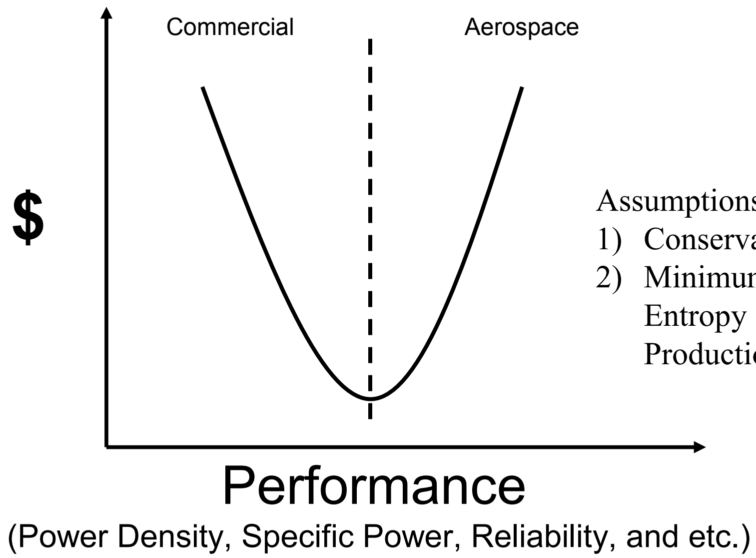
Development Processes



Assumptions:
1) Conservative
2) Minimum Entropy Production

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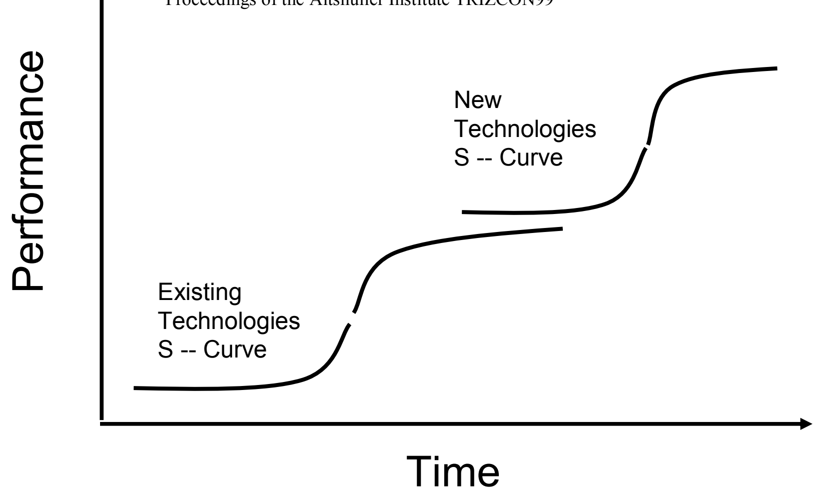
Technology Maturity Based on the Micro-Evolution of Biological Systems

Michael S. Slocum, "Technology Maturity Using S-curve Descriptors," Proceedings of the Altshuller Institute TRIZCON99



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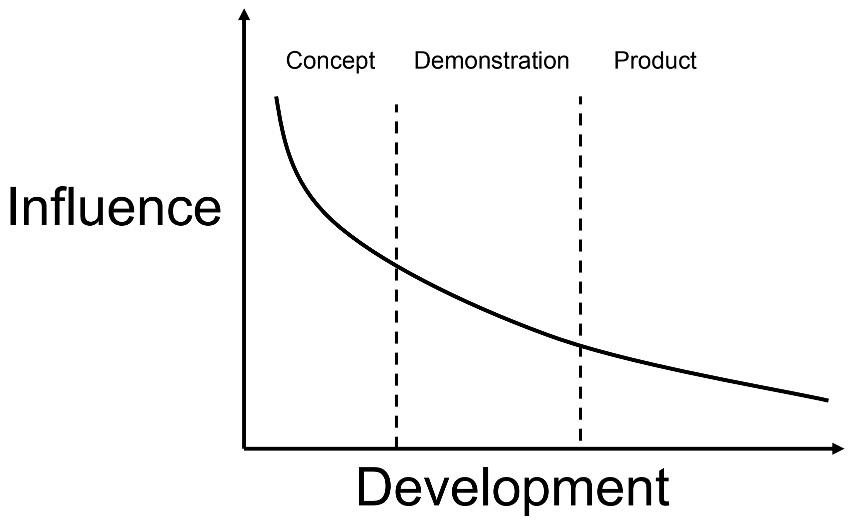
Management Influences



Modeling and Simulation as Early as Possible in a Project

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Example: The Electrical System and The Power Electronics Thesis

- Present electrical power systems are complex.
  - At equilibrium, 60Hz. Supplies power to 60Hz loads the system is stable and predictable.
  - If perturbed, the system can become unstable and unpredictable – bifurcation can occur.
  - Humans are needed to operate the system
- Future PEBB based power electronic systems will not be complex.
  - Automation is possible -- reduced operating costs
  - Progressive integration -- reduced system costs
  - Higher availability due to physics-based health prediction – reduced maintenance costs
  - Increased reliability and life by controlling overstresses

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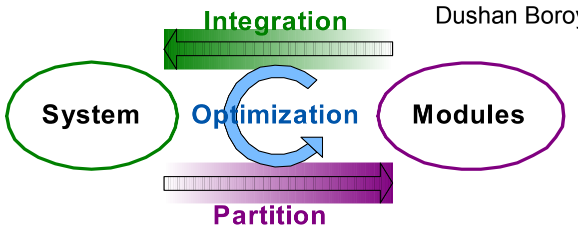
Modularization/Integration Process: CPES Example

CPES

Dushan Boroyevich, VA Tech



Partition

- Optimization techniques
- Spatial and functional, then temporal
- Facilitate manufacturing, achieve volume

Integration

- Interaction of components: energy, control
- Spatial, then temporal and functional
- Manufacturing volume

Non-desired interactions are non-desired, non-useful, energy exchanges among system components

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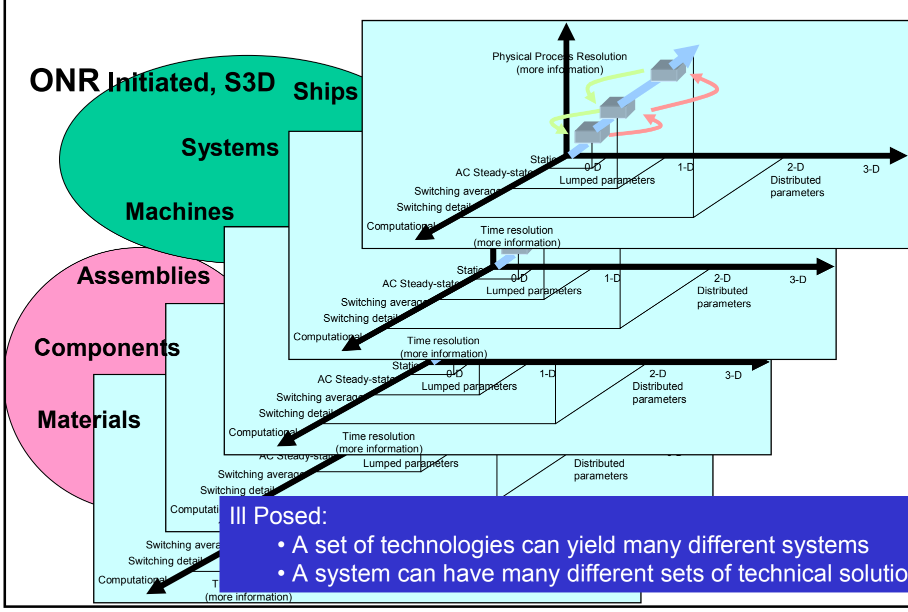
Design Challenges, Partitions and Standard Interfaces



Ill Posed:
- A set of technologies can yield many different systems
- A system can have many different sets of technical solutions

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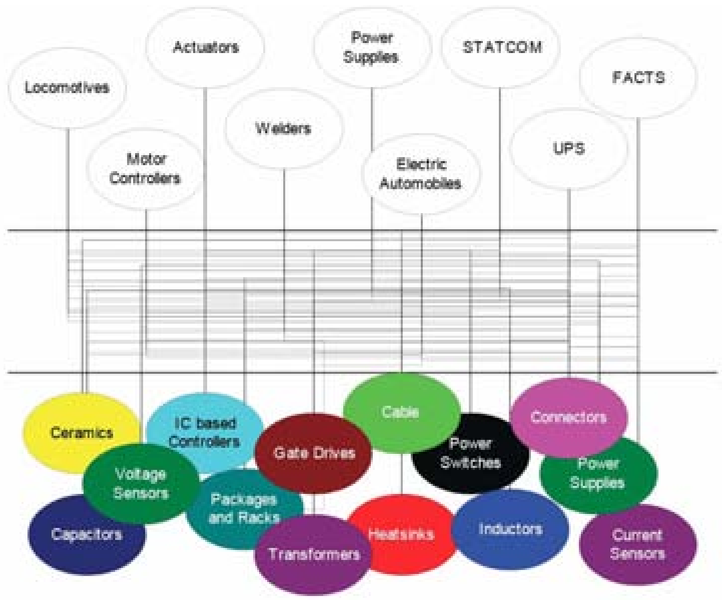
Traditional Power Electronics Industry



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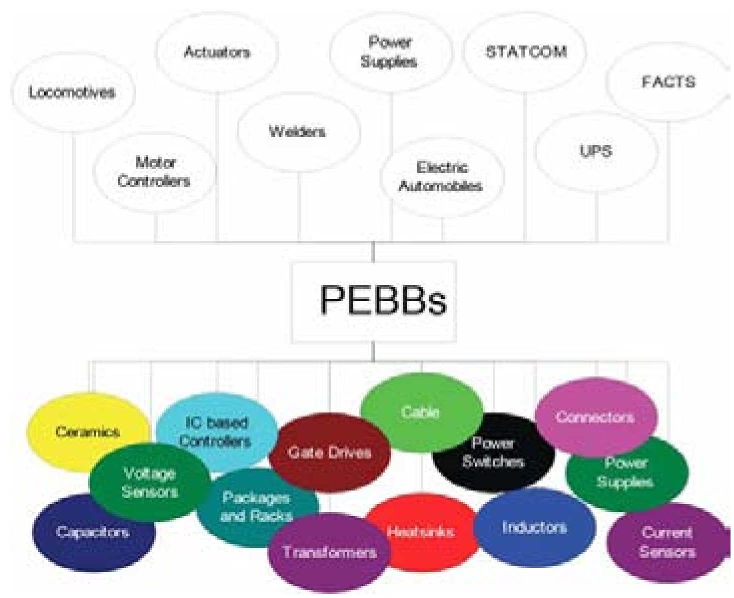
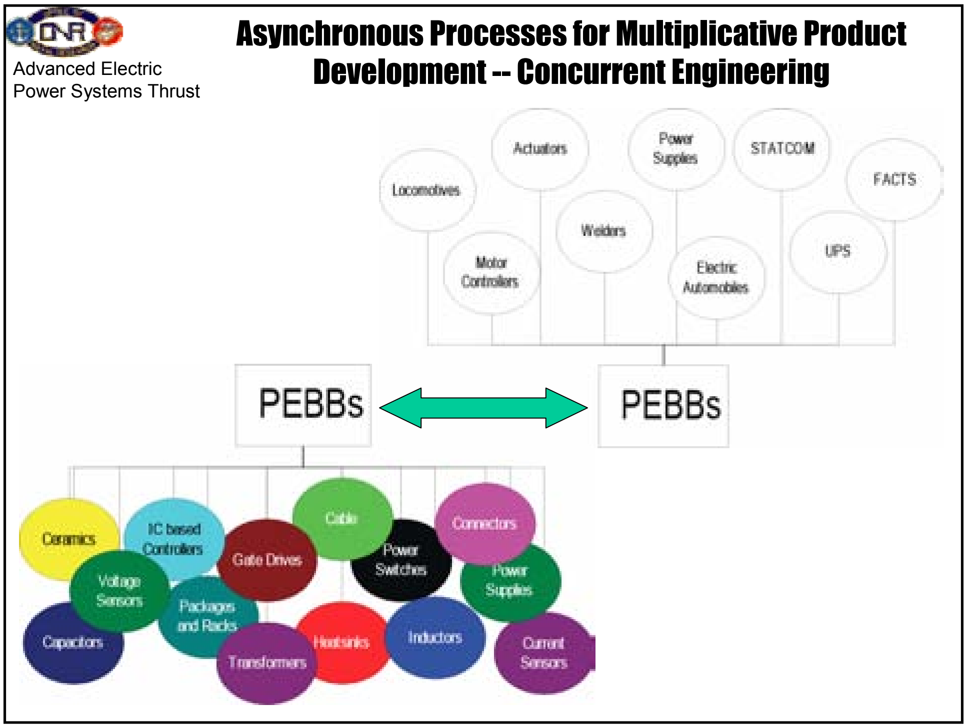
PEBB Based Power Electronics Industry

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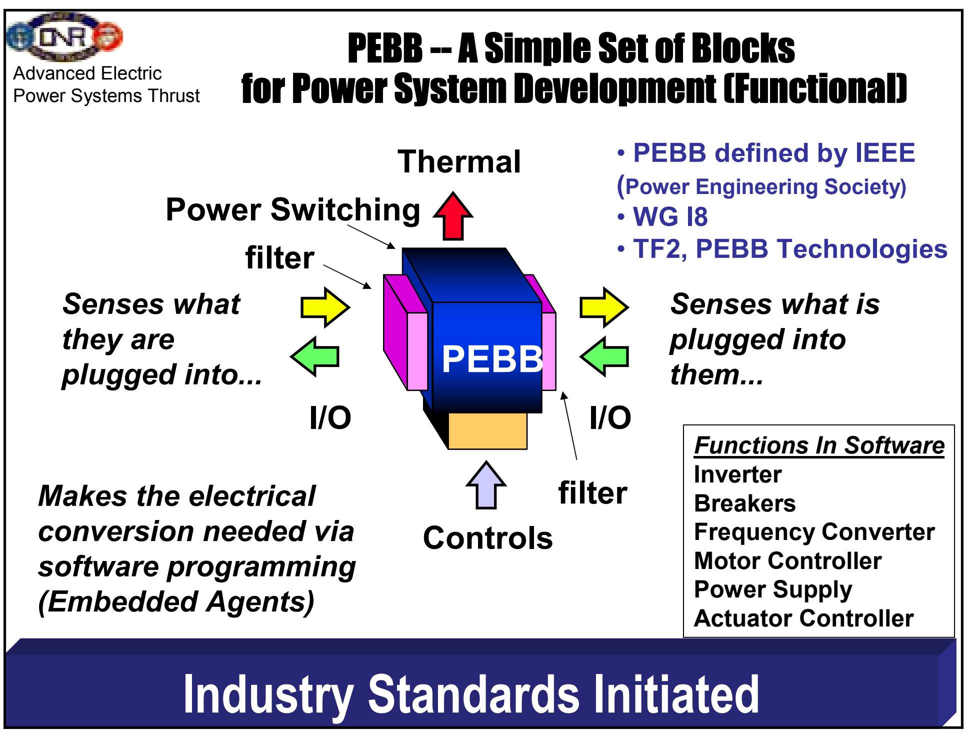
Asynchronous Processes for Multiplicative Product Development -- Concurrent Engineering
Locomotives
Actuators
Power Supplies
STATCOM
FACTS
Motor Controllers
Welders
Electric Automobiles
UPS
PEBBs
PEBBs
Ceramics
IC based Controllers
Gate Drives
Cable
Power Switches
Connectors
Power Supplies
Voltage Sensors
Packages and Racks
Capacitors
Transformers
Heatsinks
Inductors
Current Sensors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PEBB -- A Simple Set of Blocks for Power System Development (Functional)
Thermal
Power Switching
filter
Senses what they are plugged into...
I/O
PEBB
I/O
Senses what is plugged into them...
filter
Controls
Makes the electrical conversion needed via software programming (Embedded Agents)
• PEBB defined by IEEE (Power Engineering Society)
• WG I8
• TF2, PEBB Technologies
Functions In Software
Inverter
Breakers
Frequency Converter
Motor Controller
Power Supply
Actuator Controller
Industry Standards Initiated

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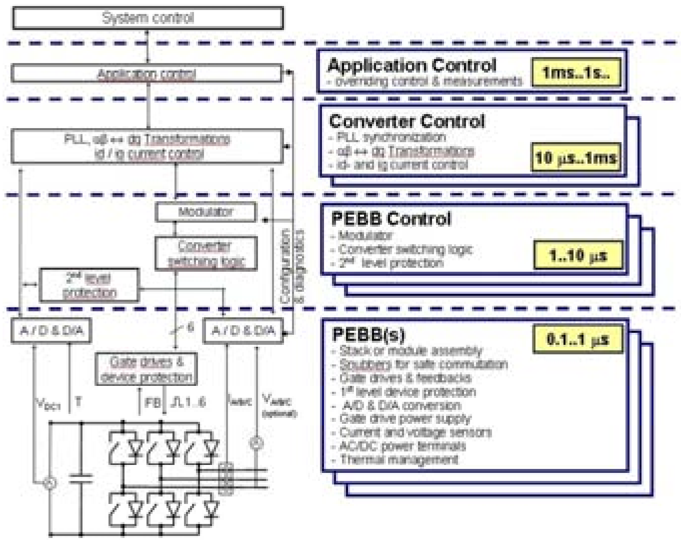
Universal Control Architecture for Control Interfaces (temporal) , IEEE Guide Initiated

PEBB Concept for Power Electronics



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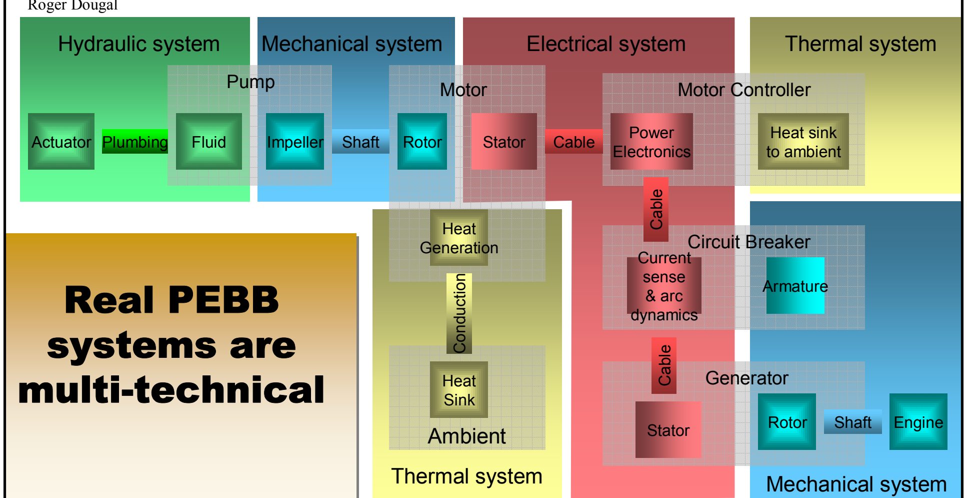
VTB Simulation Environment

Roger Dougal



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Validation, Emulation, and Incremental Prototyping

- Validation of models
  - Controller In the Loop
  - Processor In the Loop
  - Hardware In the Loop
- Real-time simulation is needed for real hardware
- High speed real-time simulation is need for high-speed controllers
- Multi-rate simulation for distributed simulation environments

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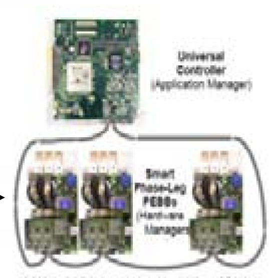
PEBB Examples

ABB Lopak5 IGBT based PEBB with 12 capacitor DC bank

ABB ANPC IGCT PEBB (16 MVA PowerStack)

Virginia Tech Universal Controller



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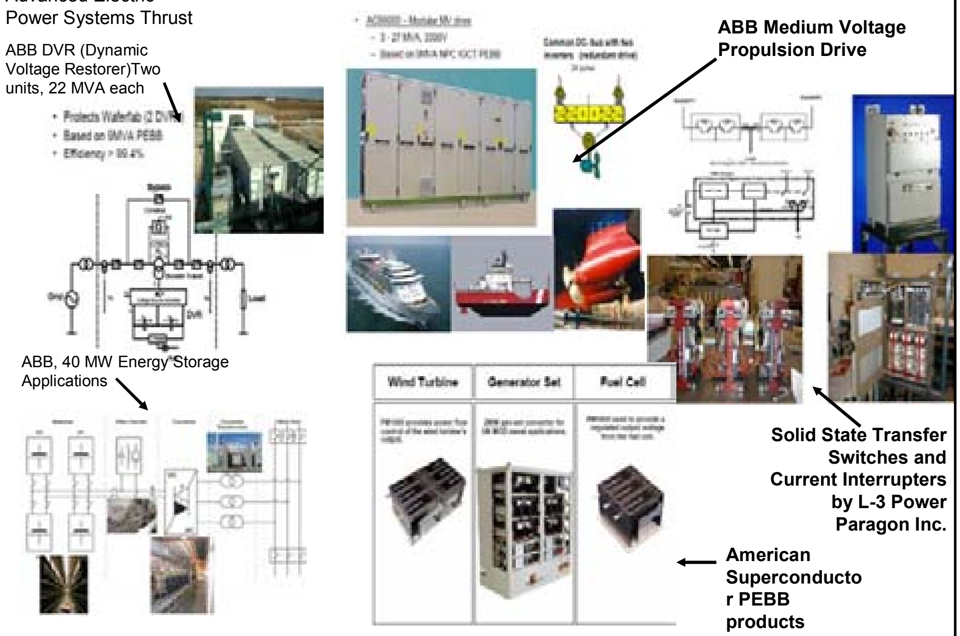
PEBB Applications



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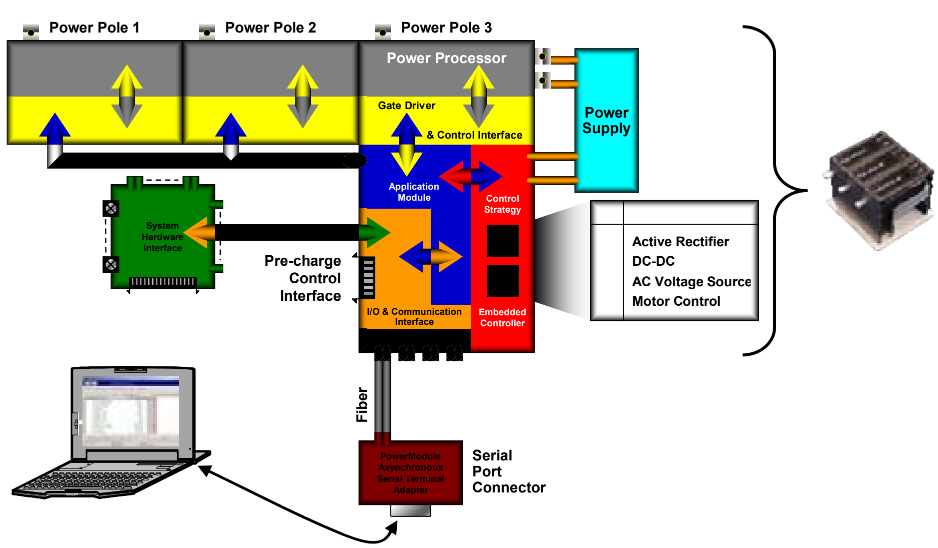
PM1000 Developers Kit



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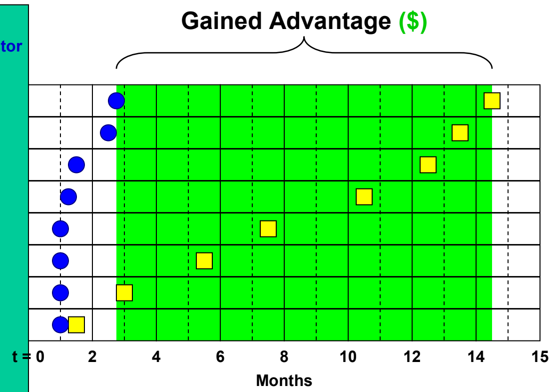
Rapid Product Development Benefits

	Typical OEM In-house Development	American Superconductor PM1000
Production	1 m	.25 m
System Integration	1 m	1 m
Iteration	2 m	.25 m
S/W Development	3 m	.25 m
H/W Development	2 m	0
S/W Design	2.5 m	0
H/W Design	1.5 m	0
System Design	1.5 m	1 m
Product Dev. Time	14.5 m	2.75 m
Labor & Overhead	$2,175,000	$412,500
Materials	$100,000	$10,000
Testing	$100,000	0
Product Dev. Cost	$2,375,000	$422,500



PEBB concept leads to a 5 times reduction in design cost!

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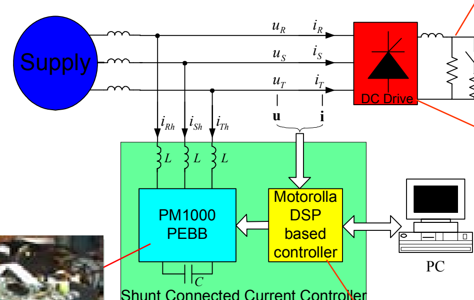
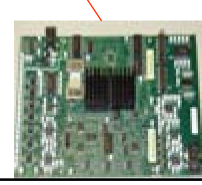
Simple APF Hardware Test Bed

Herbert L. Ginn III

1) Power supply, 208V, 60A
2) 6RA70 thyristor control rectifier (TCR) from SIEMENS
3) PM1000 PEBB
4) DSP56F807 based Controller





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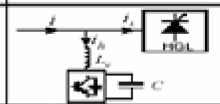
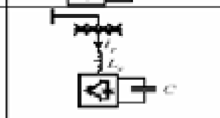
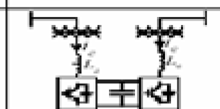
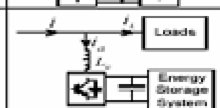
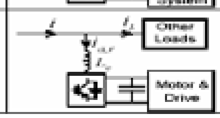
Shunt Current Controller Applications

Herbert L. Ginn III

Converter System Description	Function	Power Electronics Type	Simple One-line Diagram
Active Filter	Cancel harmonic currents by injecting appropriate current into the node	Bi-directional voltage source converter	
Static Synchronous Compensator (STATCOM)	Provide desired reactive current for VAR compensation, voltage regulation and stability enhancement	Bi-directional voltage source converter	
Mini-HVDC	Provide interconnection between two ac nodes for active and reactive power flow control	Bi-directional voltage source converter	
Energy Storage System	Provide active power for load leveling or UPS function	Bi-directional voltage source converter and DC/DC converter	
Active Front End for Motor Drives	Provide active and reactive power for motor VSD	Bi-directional voltage source converters	

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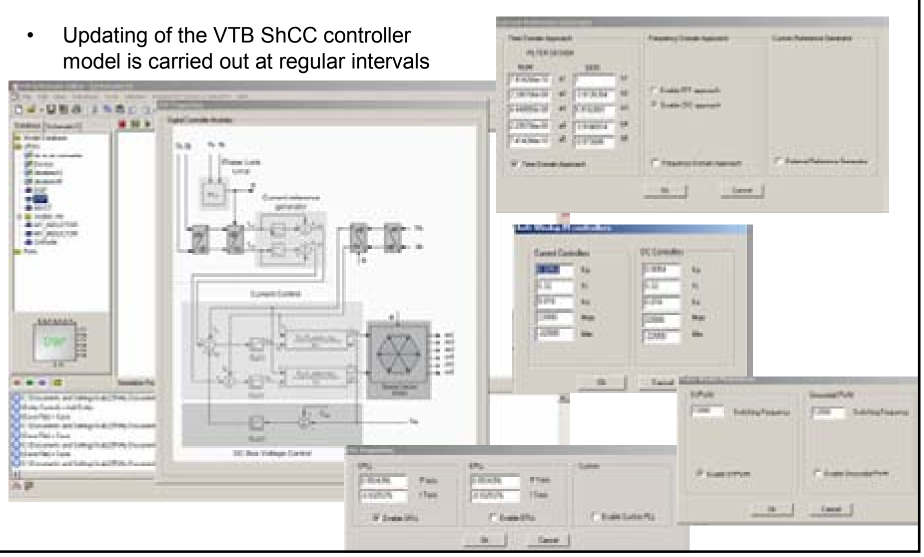
Herbert L. Ginn III

Generalization of ShCC Digital Controller Model in VTB

- Updating of the VTB ShCC controller model is carried out at regular intervals



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Vehicle Power Problem

$$p = \varepsilon \frac{dw}{dt}$$

w = **energy which is equal to the ceiling amount of the installed generation capacity (may increase over time with technology – <u>fractionally</u>)**
p, **power requirements are increasing <u>multiplicatively</u> by 10x to 100x**
ε = **efficiency**

Conditions:
1) Size, weight, cost stay the same or decrease
2) Open architecture, plug and play

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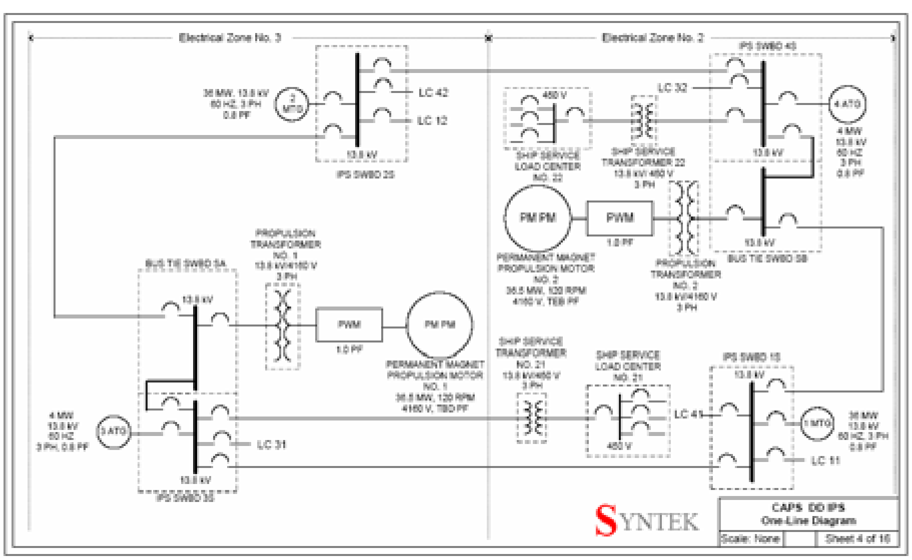
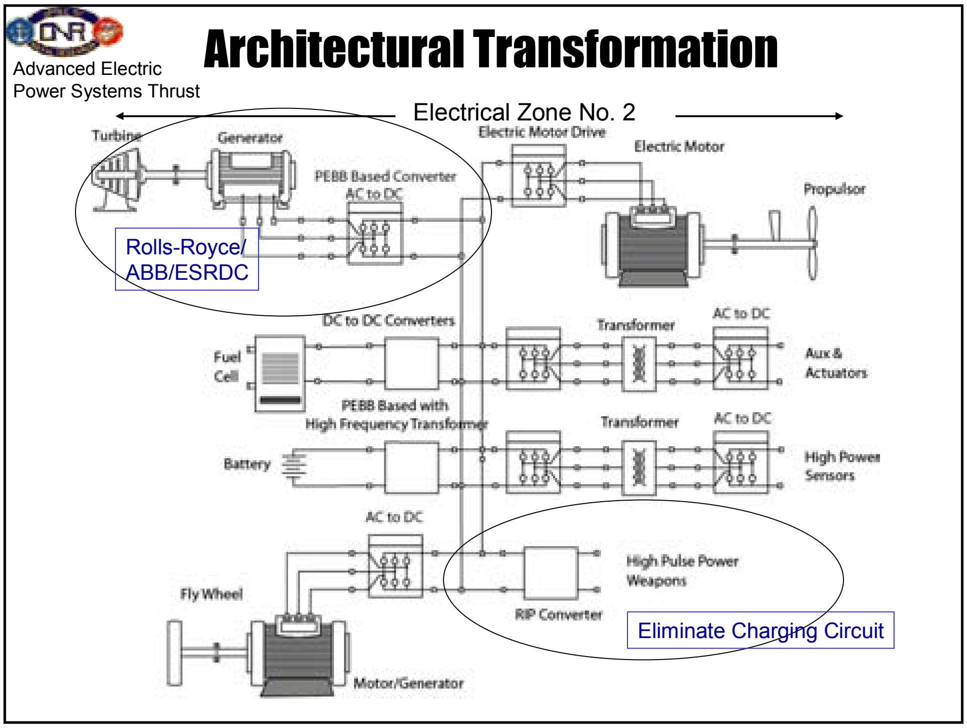
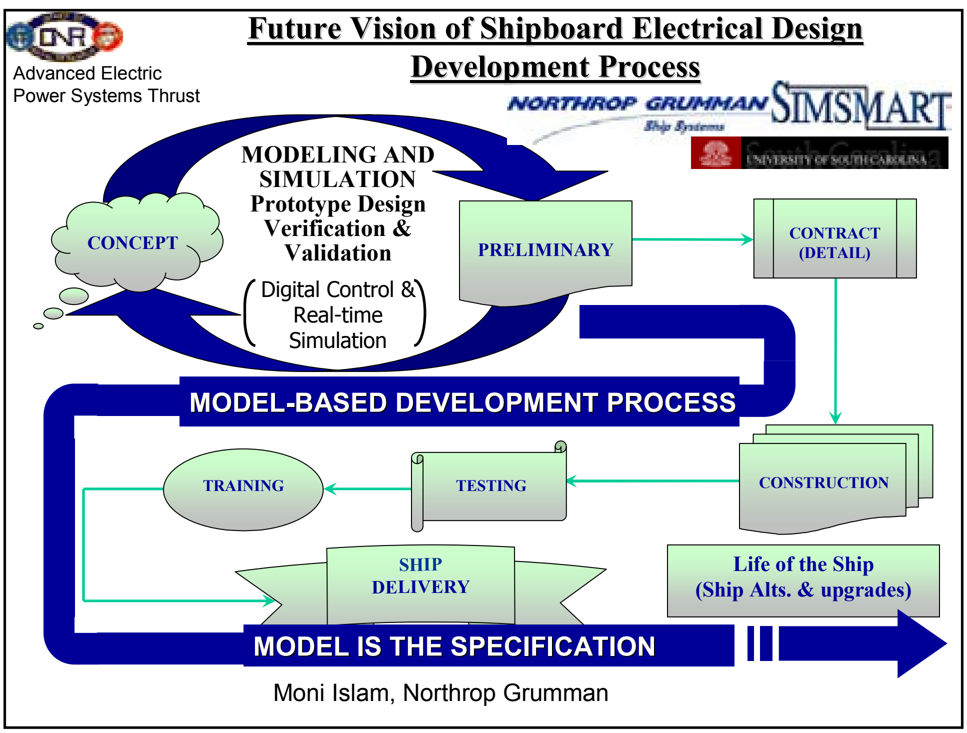
Power Systems Thrust

Notional Integrated Power System (IPS)




Advanced Electric
Power Systems Thrust
Architectural Transformation
Electrical Zone No. 2
Turbine
Generator
PEBB Based Converter
AC to DC
Electric Motor Drive
Electric Motor
Propulsor
Rolls-Royce/
ABB/ESRDC
DC to DC Converters
Fuel Cell
PEBB Based with
High Frequency Transformer
Transformer
AC to DC
Aux & Actuators
Battery
Transformer
AC to DC
High Power Sensors
AC to DC
Fly Wheel
High Pulse Power Weapons
RIP Converter
Eliminate Charging Circuit
Motor/Generator


Advanced Electric
Power Systems Thrust
Future Vision of Shipboard Electrical Design
Development Process
NORTHROP GRUMMAN
Ship Systems
SIMSMART
UNIVERSITY OF SOUTH CAROLINA
MODELING AND SIMULATION
Prototype Design
Verification &
Validation
Digital Control &
Real-time
Simulation
CONCEPT
PRELIMINARY
CONTRACT
(DETAIL)
MODEL-BASED DEVELOPMENT PROCESS
TRAINING
TESTING
CONSTRUCTION
SHIP
DELIVERY
Life of the Ship
(Ship Alts. & upgrades)
MODEL IS THE SPECIFICATION
Moni Islam, Northrop Grumman

Advanced Electric
Power Systems Thrust

Needs Continued – Social Structure

- Modeling Standards
- Benchmark Models
- Public Library of Models
- A body of international volunteer experts for all of the above
- And …

CPES
Center for Power Electronics Systems
A National Science Foundation Engineering Research Center
Virginia Tech, University of Wisconsin - Madison, Rensselaer Polytechnic Institute
North Carolina A&T State University, University of Puerto Rico - Mayaguez

Integrated Power Electronics Building Block Modules, Converters, and Systems

Fred Wang
Virginia Tech, Blacksburg, VA
fred.wang@vt.edu

Advanced Power Electronics Interfaces for DE Workshop
Sacramento, CA, USA

August 24, 2006

Distributed Energy Resources

- Wind
- Bio
- Microturbines
- Others
- Solar
- Fuel cells
- Energy storage

Power Electronics Interface a Key Enabling Technology

- ***Lower cost***
- ***Higher reliability***
- ***Better performance***

Improving DE Power Electronics Interfaces

- Conventional approach
  - components, circuits, control, processes, design optimization
- Modular building blocks
  - high volume, standardization
- Integration
  - reliability, performance, manufacturing
- System
  - added functionality and values

CPES focus on IPEMs and IPEM building blocks based systems

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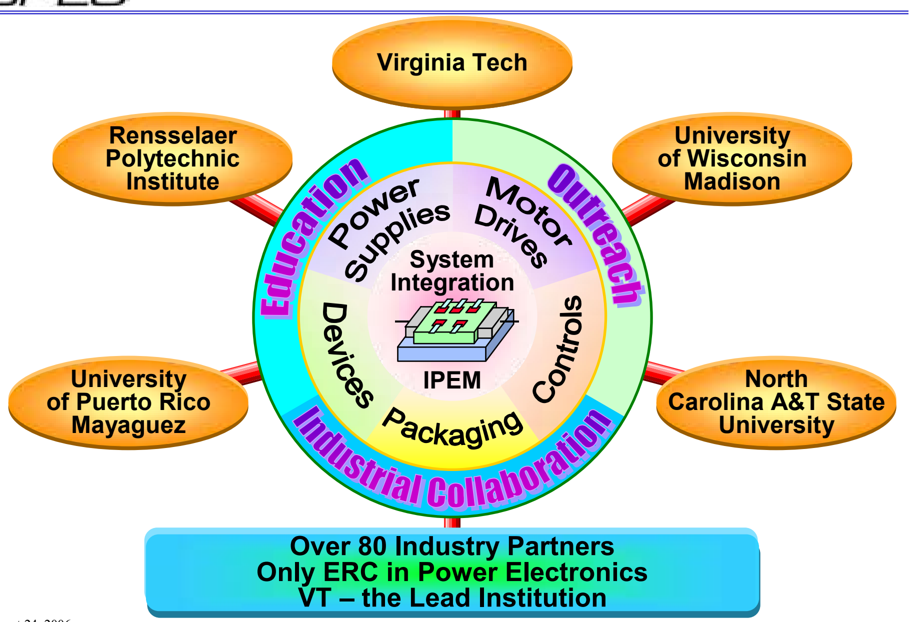
Center for Power Electronics Systems

A National Science Foundation Engineering Research Center



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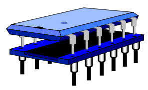
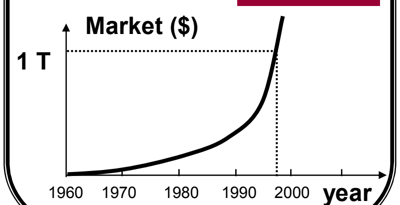
CPES Research Vision and Objectives
– Power electronics to follow microelectronics –

Moore's Law Prevails

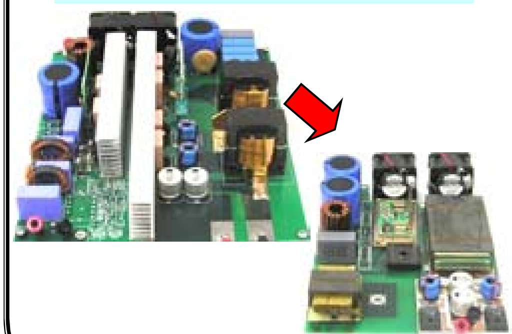
- **Standardization**
- **Manufacturability**
- **Volume production**
- **Cost reduction**



Signal Processing IC



- **Integrated Power Electronics Modules (Standardized building blocks)**
- **Reduce labor content**
- **Low cost**



Power Processing IPEM

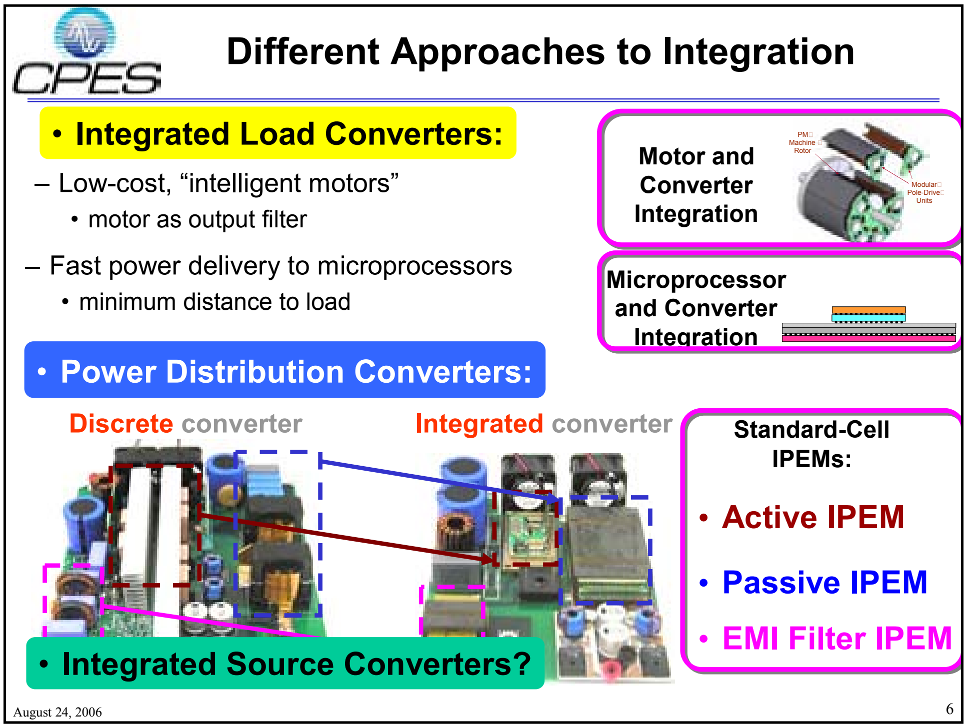
Vision and Focus

Enable dramatic improvements in the performance, reliability, and cost-effectiveness of energy processing systems by developing an integrated system approach via Integrated Power Electronics Modules (IPEMs).

IPEM Concept:

A concept for design of electronic energy processing systems with improved performance, reliability, manufacturability, and reduced cost, based on the integration of a set of building blocks with:

- **Integrated functionality,**
- **Standardized interfaces,**
- **Suitability for mass production, and**
- **Application versatility.**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Different Approaches to Integration
• Integrated Load Converters:
– Low-cost, "intelligent motors"
• motor as output filter
– Fast power delivery to microprocessors
• minimum distance to load
Motor and Converter Integration
Microprocessor and Converter Integration
• Power Distribution Converters:
Discrete converter
Integrated converter
Standard-Cell IPEMs:
• Active IPEM
• Passive IPEM
• EMI Filter IPEM
• Integrated Source Converters?
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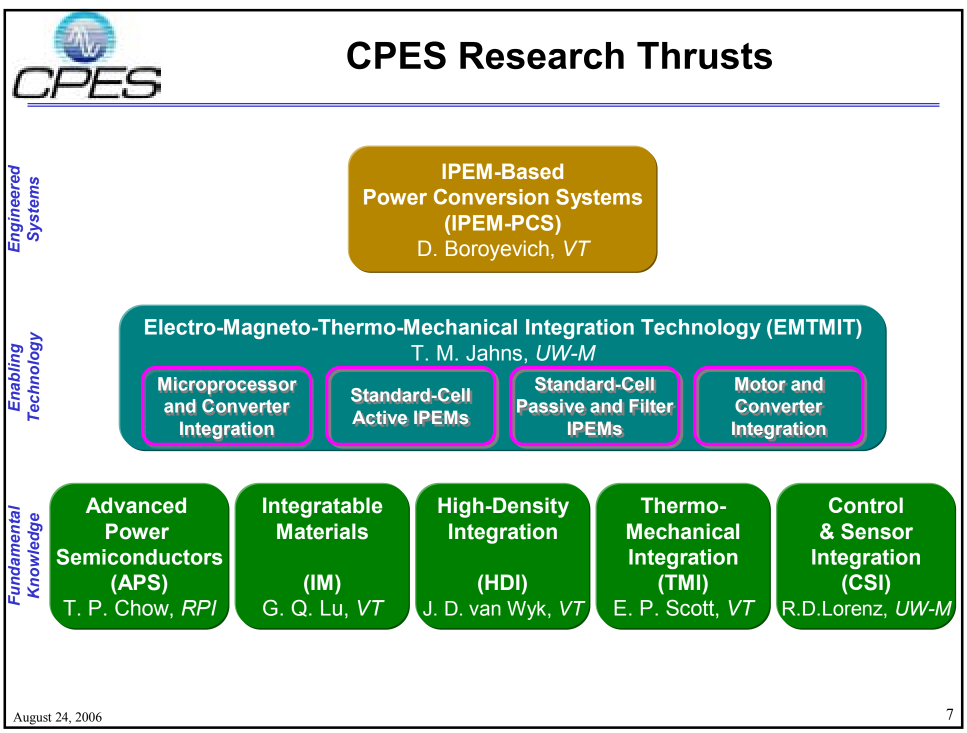
CPES
CPES Research Thrusts
Engineered Systems
IPEM-Based Power Conversion Systems (IPEM-PCS)
D. Boroyevich, VT
Enabling Technology
Electro-Magneto-Thermo-Mechanical Integration Technology (EMTMIT)
T. M. Jahns, UW-M
Microprocessor and Converter Integration
Standard-Cell Active IPEMs
Standard-Cell Passive and Filter IPEMs
Motor and Converter Integration
Fundamental Knowledge
Advanced Power Semiconductors (APS)
T. P. Chow, RPI
Integratable Materials (IM)
G. Q. Lu, VT
High-Density Integration (HDI)
J. D. van Wyk, VT
Thermo-Mechanical Integration (TMI)
E. P. Scott, VT
Control & Sensor Integration (CSI)
R.D.Lorenz, UW-M
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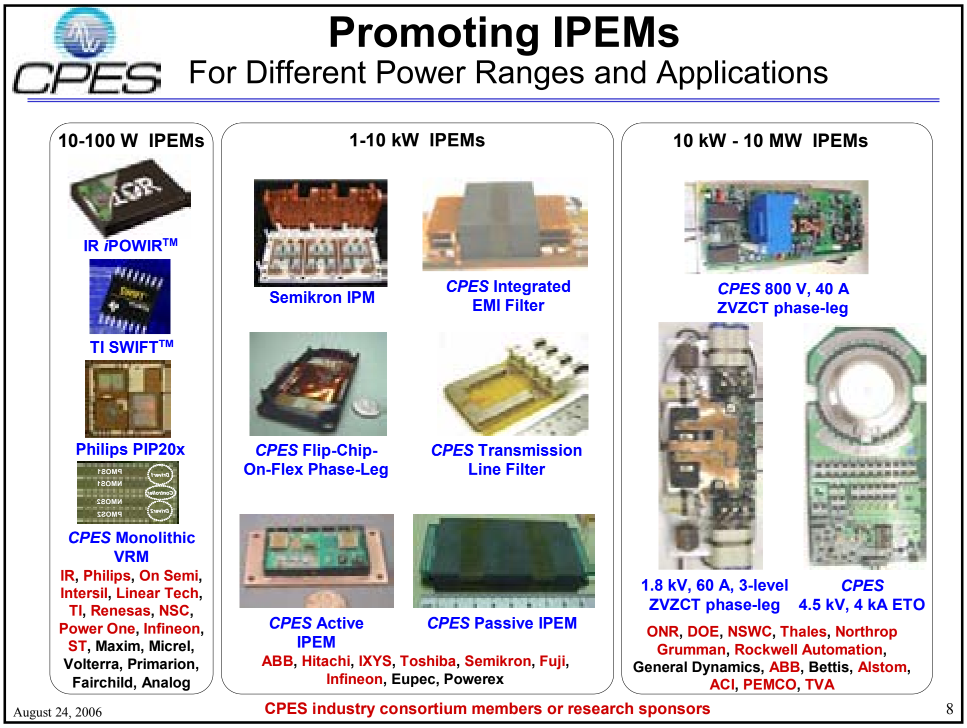

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Issues for IPEM Building Block Approach

- **Basic building blocks**
  - **"A minimum set of building blocks with integrated functionality, standardized interfaces, suitability for mass production, and application versatility."**
- **Architecture & Partitioning**
  - **How to build a power system application with application-independent PE modules?**
- **Interface Characterization**
  - **What are interface characteristics and requirements for a selected architecture?**

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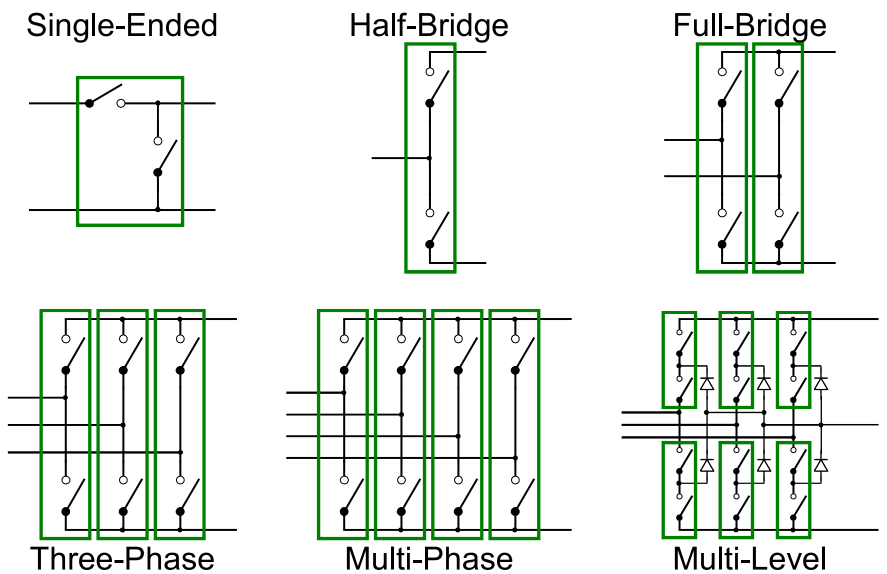
Topologies Based on Totem-pole Phase-leg Modules



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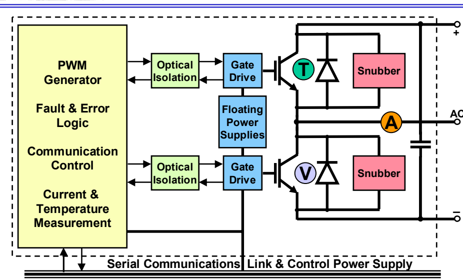
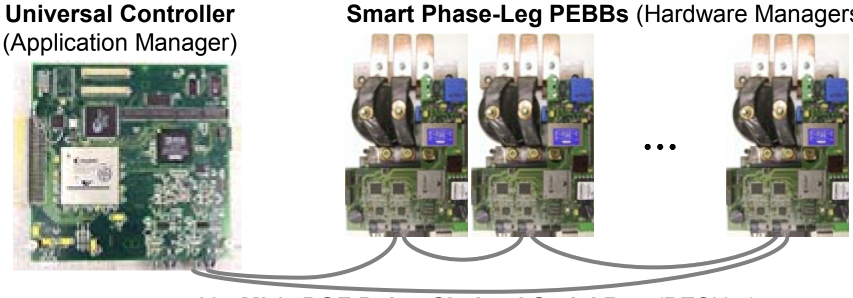
Integrated Phase-leg PEBB + "Plug & Play" Control Architecture



35 kVA, 800 V, 20 kHz

Universal Controller (Application Manager)

Smart Phase-Leg PEBBs (Hardware Managers)



125 Mb/s POF Daisy-Chained Serial Bus (PESNet)

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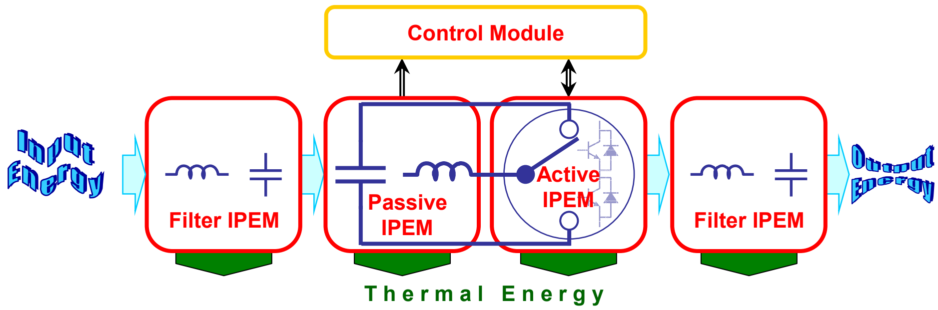
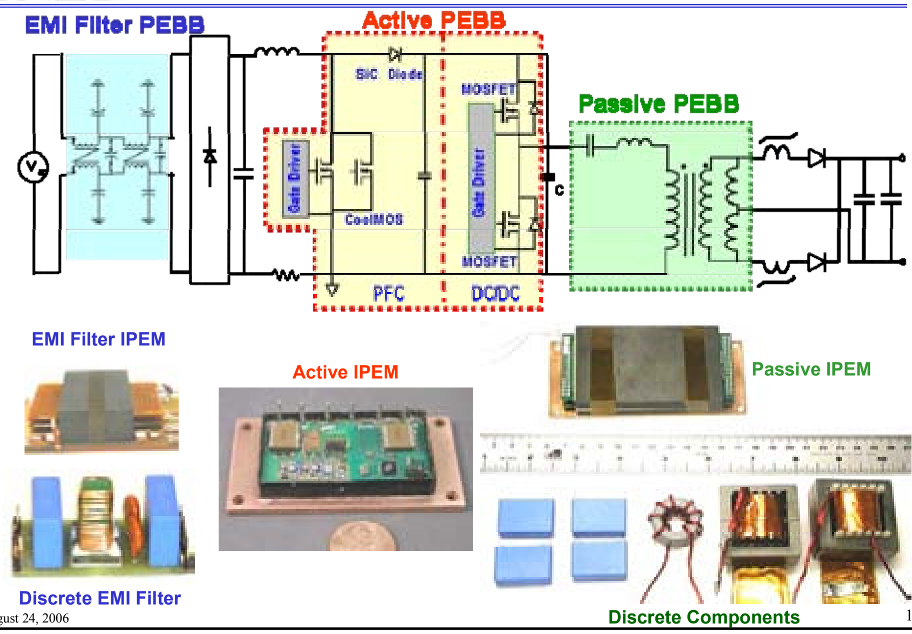
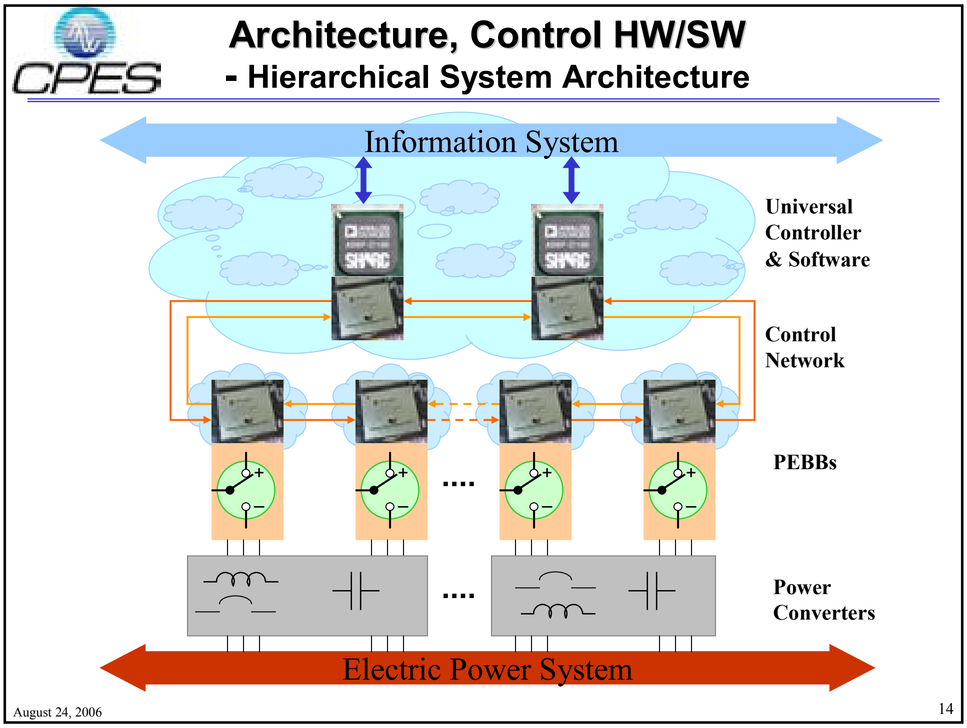
Passives and Filters Need to be Integral Part of the Converter



- **Active IPEM**
  Controls the energy flow (switching)
- **Control Module**
- **Passive IPEM**
  Absorbs high-frequency energy (temporary storage)
  Size reduces with increasing switching frequency
- **Filter IPEM**
  Blocks high-frequency energy (size independent of switching frequency)

1 kVA, 1-AC (90-260 V) to DC (48 V) Isolated Converter




CPES
Architecture, Control HW/SW
- Hierarchical System Architecture
Information System
Universal Controller & Software
Control Network
PEBBs
Power Converters
Electric Power System
August 24, 2006
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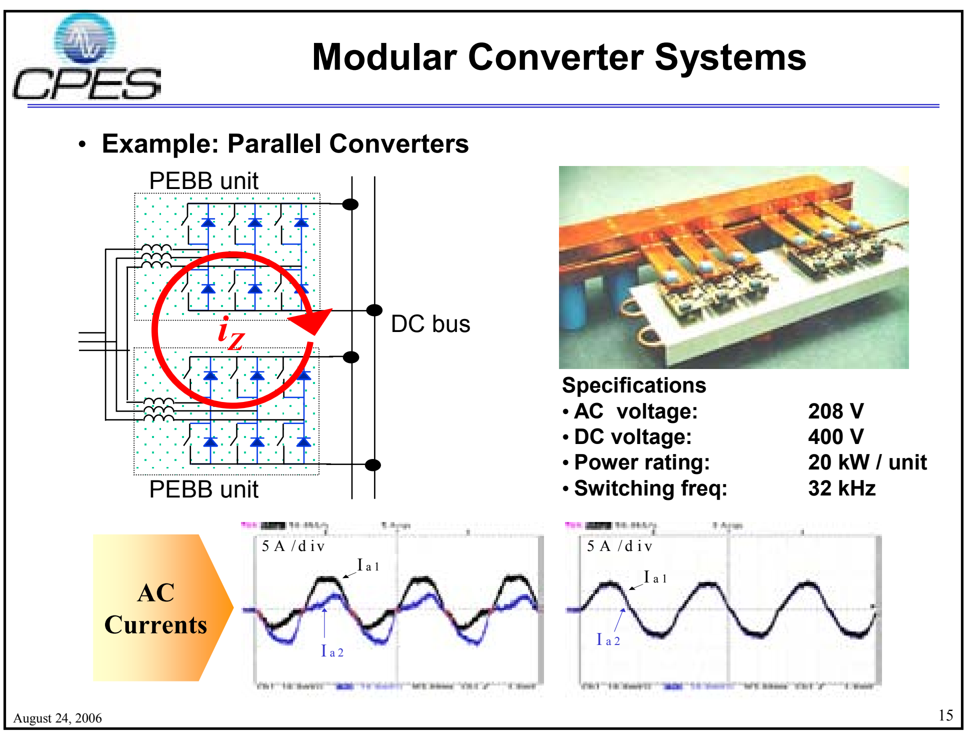
CPES
Modular Converter Systems
• Example: Parallel Converters
PEBB unit
DC bus
PEBB unit
Specifications
• AC voltage: 208 V
• DC voltage: 400 V
• Power rating: 20 kW / unit
• Switching freq: 32 kHz
AC Currents
5 A /div
Ia1
Ia2
5 A /div
Ia1
Ia2
August 24, 2006
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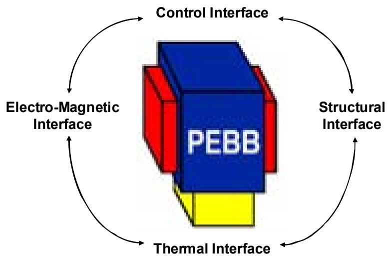
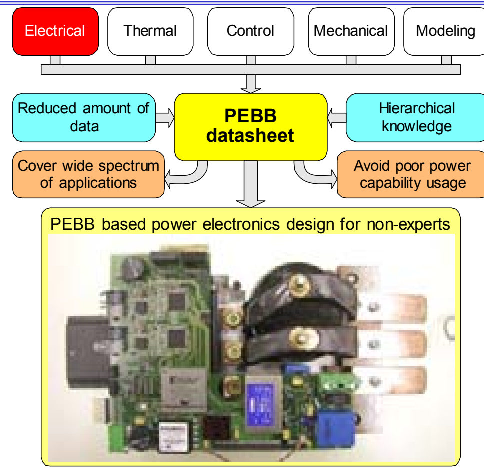
Modeling and Characterization - Standard cell interface characterization

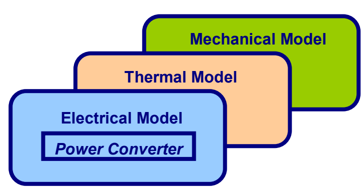




PEBB modules with standardized interfaces

Modeling and Simulation as Partition Evaluation Methodology

- Physics-based modeling
  - Takes into account (within and without)
    - Energy fields
    - Materials
    - Assembly
- Enables system-level evaluation
  - Terminal models of subsystems
    - Power: v, i
    - Control: u
    - Thermal: θ, p
    - Structural (mechanical)



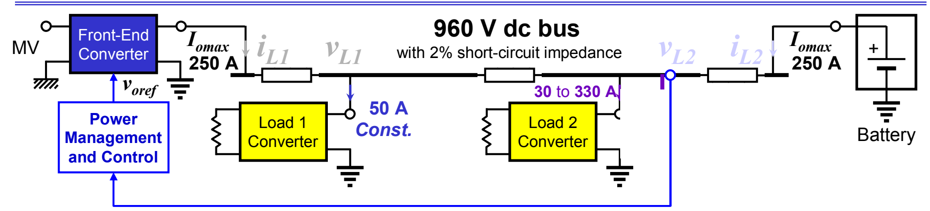
- Explicit relationships between terminal variables, while indirectly capturing internal physics
- Hierarchical reduction of modeling detail

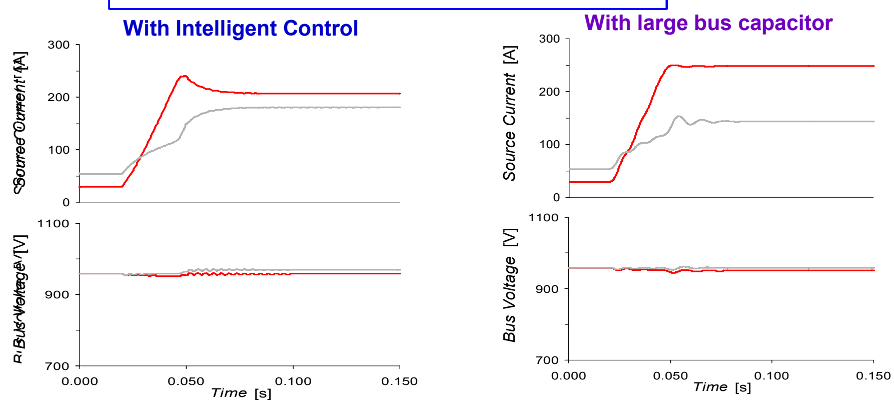
PCS with Integrated Functionality

- **With active control and built-in intelligence, power converters can change the dynamics of the sources and loads to:**
  - Reduce system complexity by decoupling the dynamics (benefits in design & operation)
  - Reduce the oversize margin for sources and loads
  - Replace/eliminate bulky passive filters
- **Functionalities:**
  - Power flow control
  - Power management (continuous)
  - PQ control, active filtering
  - Monitoring, diagnosis, and on-line mitigation
  - Protection

Subsystem Interaction Example

– models with input & output impedances –





CPES

Summary

- CPES promotes an integrated system approach via Integrated Power Electronics Modules (IPEM) concept to improve performance, reliability, and cost-effectiveness of power converters
- IPEM building blocks need passive and filter modules in addition to active modules
- Benefits can be achieved, and researches are needed at module, converter, and system levels
- There is a strong need for consistent, physics-based, system architecture analysis and evaluation methodology

CPES

Acknowledgement

The work and contributions are result of many CPES faculty, students, and staff.

National Science Foundation

Office of Naval Research

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Many other US government and industrial sponsors of CPES research are gratefully acknowledged.

Bricks and Buses

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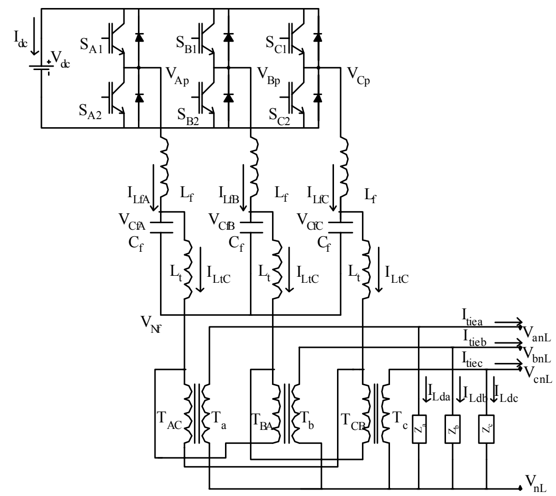
24th Aug 2006
California Energy Commission
Sacramento, CA

Power Electronics Applications

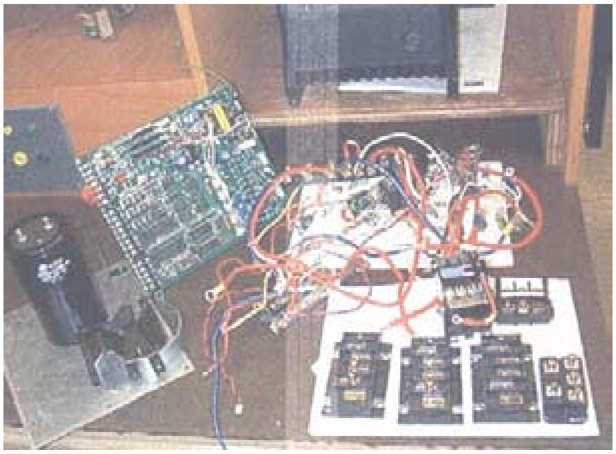
- Motor drives 1 h.p. – 5000 h.p.
- Power supplies 10W – 5 kW (and >)
- UPS systems 100W – 100kW
- Compact fluorescents 5W – 50W

- Segmented markets
- DG as a new market segment?

Typical schematic



State of the art



Power Electronics Assembly

CEC, 24th Aug 2006 GV -5

Restraints

- Barriers to growth
  - High cost
  - Low reliability
  - High complexity
  - Custom design
  - Long design cycle
  - High manufacturing cost
  - Low volume
  - Custom interfaces
  - Lack of scalability
  - Multi-geometric assembly

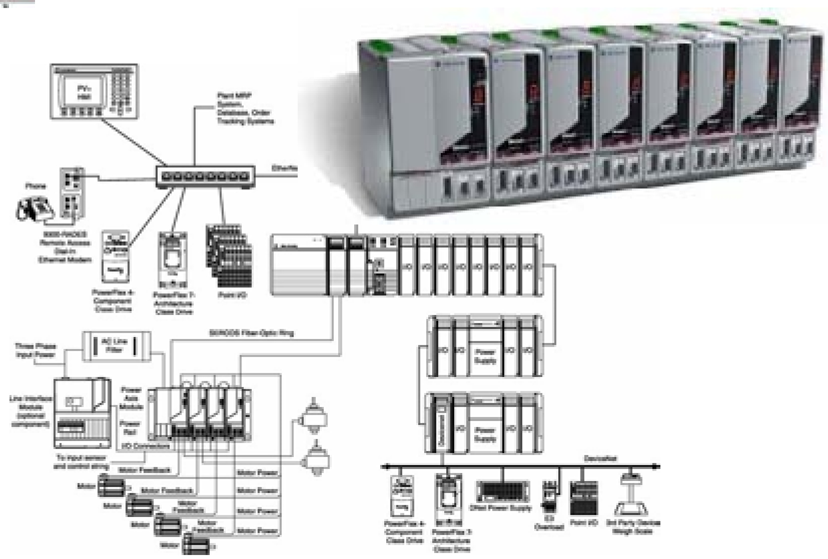
CEC, 24th Aug 2006 GV -6

Desirable scenario

- Standardized input, output, functionality
- ‘Compilable’ cabinets
- Fault tolerant, fail safe capability
- Plug and play
- Geometries for:
  - Thermal
  - Electrical & Magnetic
  - Mechanical & Industrial design

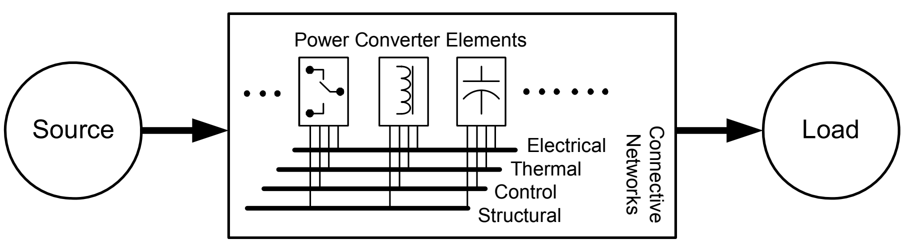
MCCB Panel Boards (EATON)

Modular servo drives (Rockwell)



CEC, 24th Aug 2006 GV -9

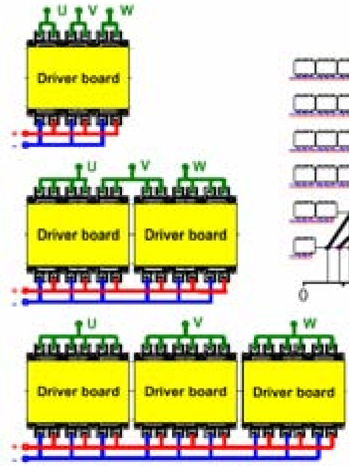
Components

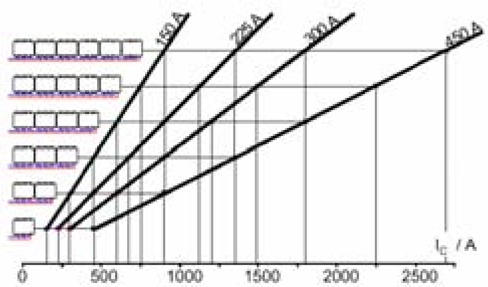


Electronic Power Converter

CEC, 24th Aug 2006 GV -10

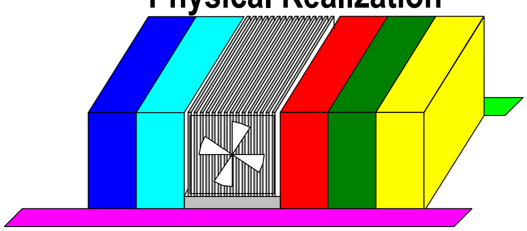
Silicon scaling

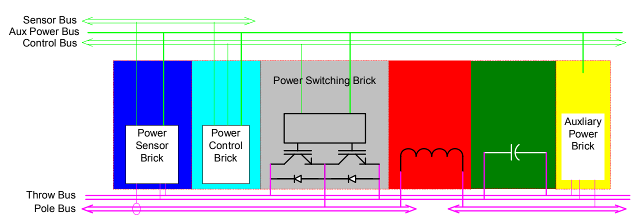




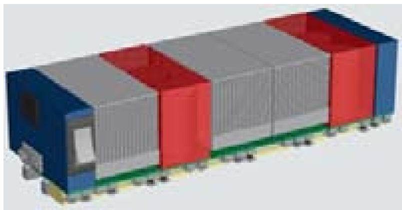
Bricks & Buses Concept

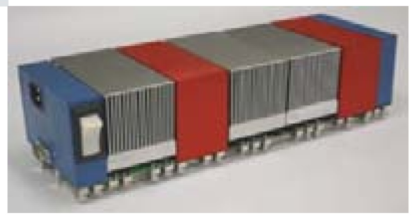
Physical Realization





Bricks and Buses Converter





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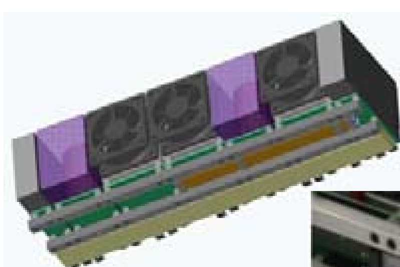
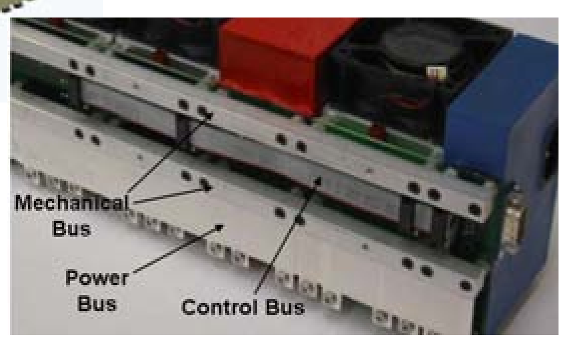
Bricks and Buses Converter





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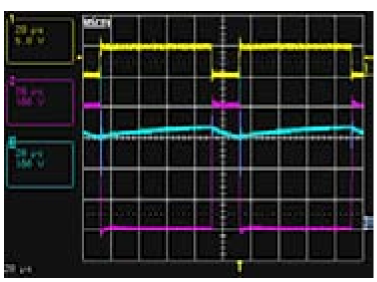
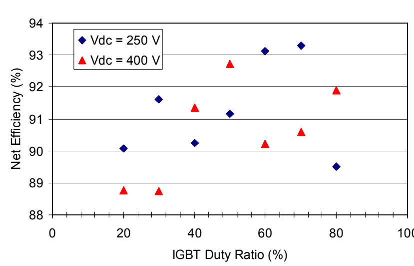
Bricks and Buses Converter

CEC, 24th Aug 2006 GV -15

Test results





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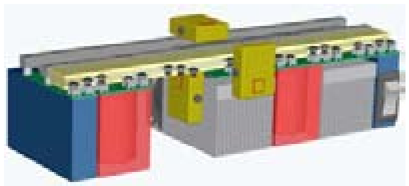
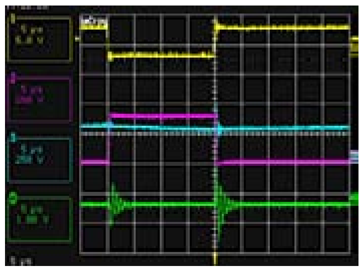
Radiated Coupling



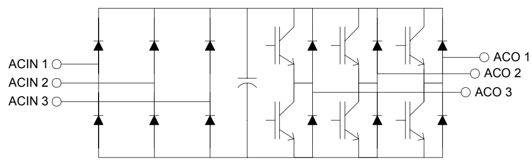


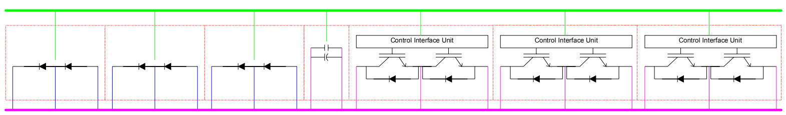
Location	$V_{PK\text{-}PK}$ / Area (mV/cm^2)
A	0.413
B	0.263
C	0.620

Bricks & Buses

- Standardized dimensions – depth and height
- Incremental scaling of width
- Each brick thermally self managed
- Variable volume
- Proportional scaling of surface area
- Decoupled power bus and signal bus
- Contained interconnect EMI

3 phase ac-dc-ac converter





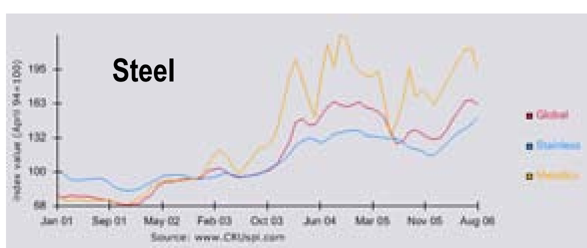
Accomplishments to date

- $70k demonstration seed through CERTS DG Integration (2001-2004)
- Demonstrated a concept prototype
- Adhoc design
- Comparable electrical performance
- Increased power density
- Modular packaging
- Improved manufacturability

Challenges

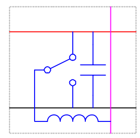
- Electronics – Silicon
- Capacitors – Film, Foil
- Magnetic elements – Copper, Iron
- Cooling – Heat-sink, Cold plates
- Auxiliary – Switchgear
- Interconnections – Printed circuits, busbars
- Design, manufacturing, applications

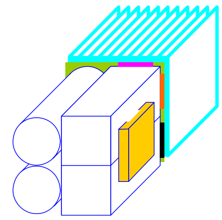
Magnetics - trends

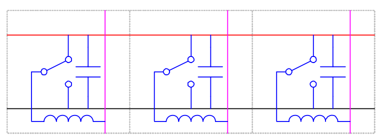


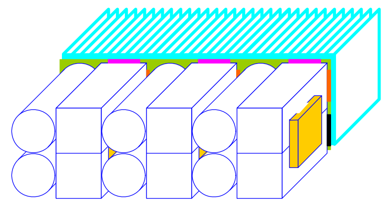
Beyond Si - Cellular design

- Cell definition
  - Switch
  - Throw capacitance
  - Pole magnetics
  - Thermal



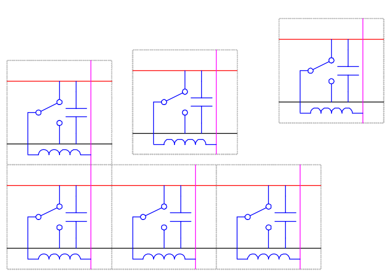


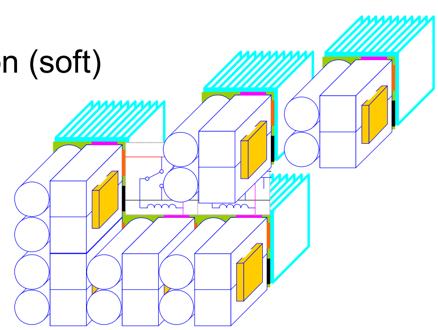




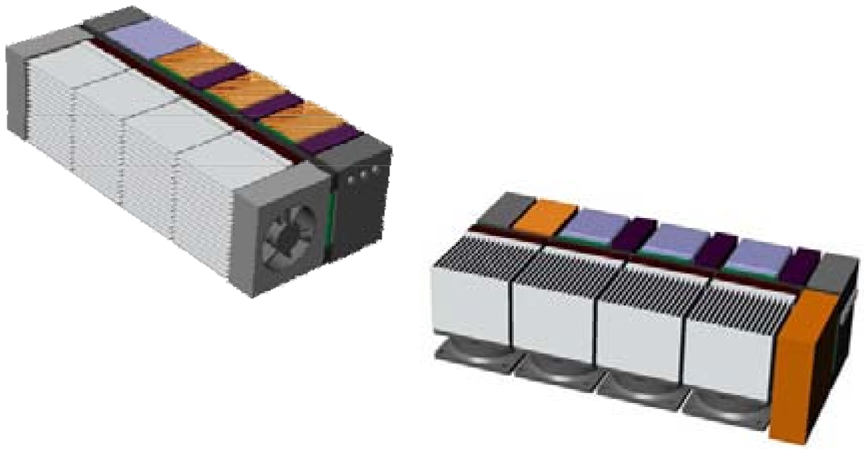
Step and repeat process

- Conforming and compatible layers
  - Thermal management
  - Switching electronics
  - Reactive elements
  - Control/communication (soft)





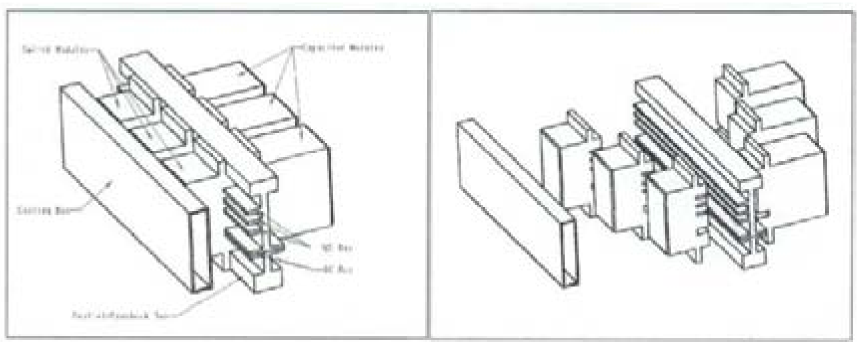
Air-cooled concept designs



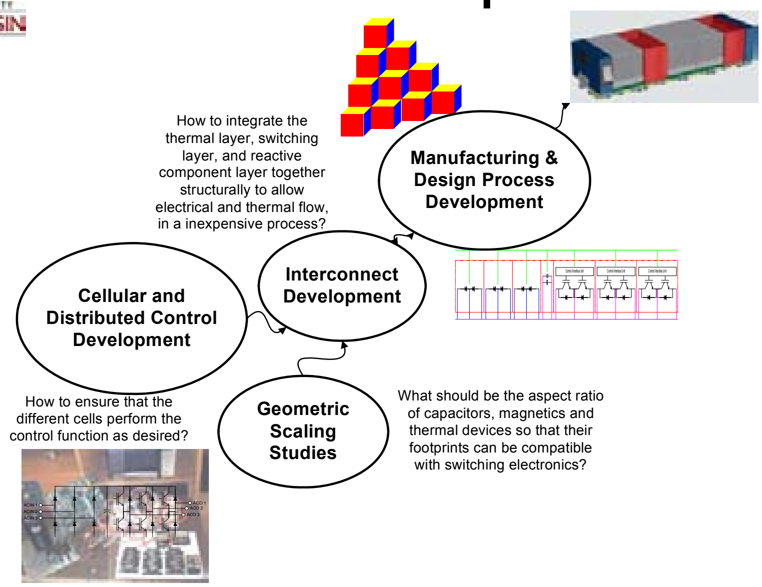
Liquid-cooled concept designs

Bus Centered Assembly

- Electrical and structural interconnection
- Similar to MCCB panel-boards



Roadmap



Advanced Topologies for DE Interface

Ned Mohan
University of Minnesota
Distributed Energy Workshop
Sacramento, CA
August 24, 2006

1

Workshop on Renewable Energy for Minnesota

McNamara Alumni Center, University of Minnesota, Minneapolis
Thursday October 12, 2006

Objectives:
- Discuss renewable energy prospects in Minnesota
- Bring renewable energy curriculum into K-12
- Describe the research being conducted in this field in the Department of Electrical and Computer Engineering (funded by XcelEnergy, National Science Foundation and ONR)

Who should Attend: Everyone concerned with energy, particularly the technical issues, and its impact on the environment and society.

Tentative Schedule:

7:30-8:00 **Registration, Coffee and Rolls**

8:00-8:30 **Welcome and Introduction**
- Welcoming Remarks: *Steven Crouch*, Dean – Institute of Technology, U of M
- Workshop Objectives and Agenda: *Ned Mohan*, ElectE, U of M
- Renewable Energy Development Fund: *Michelle Swanson*, XcelEnergy

8:30-10:00 **Renewable Energy Overview**
- A Power Grid for the Hydrogen Economy: *Thomas Overbye,* Professor, University of Illinois
- Lessons From Norway: *Terje Gjengedal*, Vice President - STATKRAFT, NORWAY, in charge of renewable energy projects
- What is Happening in Minnesota?: *Michael Bull*, Assistant Commissioner, Minnesota Department of Commerce (invited)

10:00-10:30 **Coffee Break**

10:30-11:30 **Wind Energy**
- Present Projects and Potential in Minnesota: *John Dunlop*, American Wind Energy Association
- Transmission Planning in Minnesota – CapX 2020: *Gordon Pietsch,* Great River Energy

11:30-12:00 **Research in Renewable Energy at the ECE Dept, University of Minnesota**
- Results of Research funded by NSF, XcelEnergy and ONR: *Ned Mohan*, ElectE, U of M

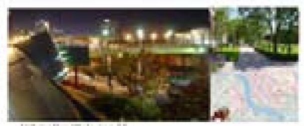
12:00-1:00 **Lunch** (buffet lunch provided)

1:00-2:00 **Hydrogen and Fuel Cells: Making the Connection**
- Hydrogen From Wind: *Lanny Schmidt*, Regents Professor, ChemE, U of M
- Research in Fuel Cells: *Brad Palmer*, Cummins Power Generation, Fridley, Minnesota

2:00-3:00 **Bringing Renewable Energy and Conservation Curriculum into K-12 Courses**
- Sustainable Architecture: Virajita Singh and John Carmody, U of M
- Group Discussion led by: *Steven Pullar*, Woodbury Math and Science Academy, MN and *Michael Maas*, Eden Prairie High School, MN

Posters on Display: Research being conducted in this field in the Department of Electrical and Computer Engineering, funded by XcelEnergy, National Science Foundation and ONR.

2



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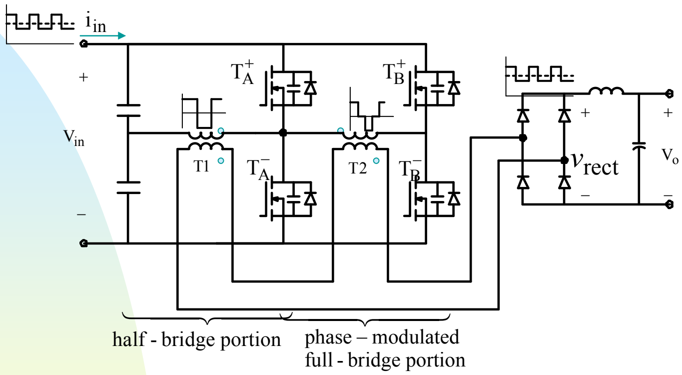
Sources of Distributed Energy

- Photovoltaic
- Fuel Cells
- Wind
- Micro-Turbines

4

An Ultra-Compact High-Efficiency DC-DC Soft-Switching Converter for Photovoltaic and Fuel Cells

(US Patent:6,310,785 University of Minnesota)

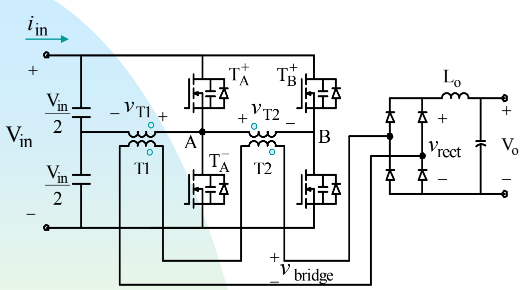


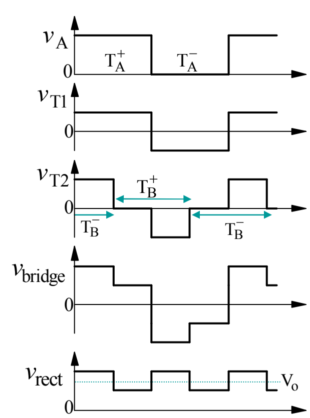
- Combination of uncontrolled half-bridge and phase shifted full-bridge
- Uses 4 switches with combined VA ratings identical to PMC

✓ ZVS down to no load
✓ Reduced magnetics
✓ Smaller conduction loss compared to PMC
✓ Better dynamic response

5

Operating principles





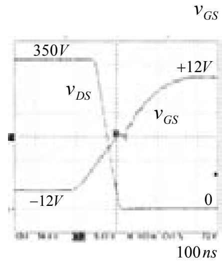
- all switches switch at 50% duty-ratio and constant switching frequency

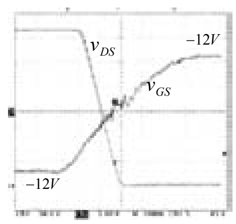
$$\frac{V_o}{V_{in}} = \frac{n_1}{2} + D\, n_2$$

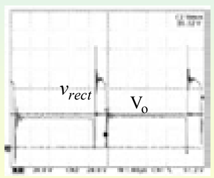
6

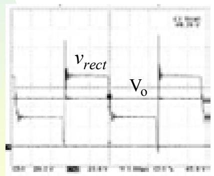
Experimental waveforms

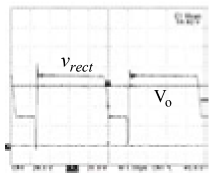
V_{in} : $350V - 400V$
V_o : $36V - 60V$
@ $20\,A$
f_{sw} : $100\,kHz$











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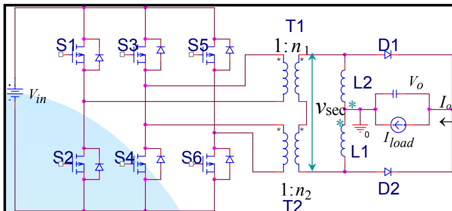
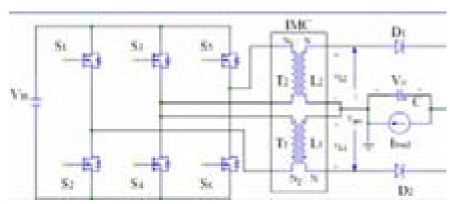
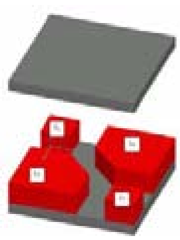
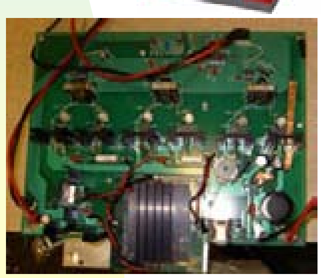
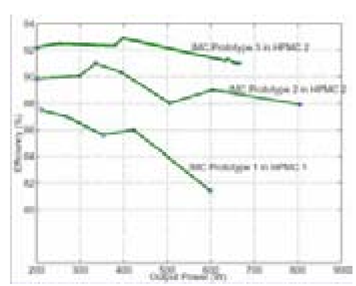


HPMC with Current Doubler









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Hariharan Krishnaswami, Ned Mohan, Department of Electrical & Computer Engineering, University of Minnesota

Objective:

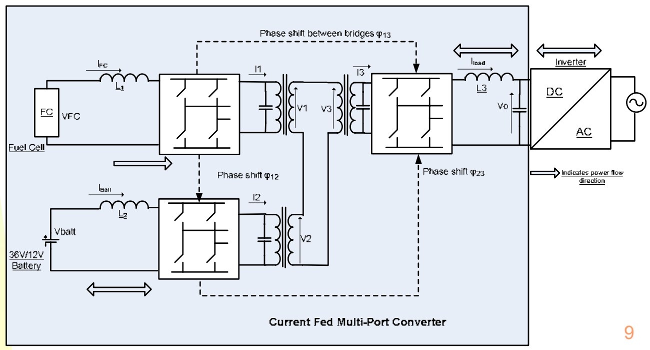
The goal of this project is to develop a compact & efficient dc/dc converter that can serve as an interface between 2 or more energy sources (e.g., Fuel cells, PV array, batteries) and the load. Such a converter is termed a multi-port converter with each port connected to a source or a load.

Characteristics of the multi-port converter:

1. A single converter interfacing with several energy sources leads to part count reduction.
2. Power flow can be controlled from different energy sources to load.
3. Each port of the converter is bidirectional in nature, for example, a battery needs a bidirectional port.
4. Applications are in hybrid vehicles, pluggable hybrids and residential homes/buildings.

Proposed converter topology

The block diagram shows two sources Fuel cell and battery interfacing with a motor drive inverter. The battery and inverter ports are bi-directional.



A Multi-Port DC/DC Converter

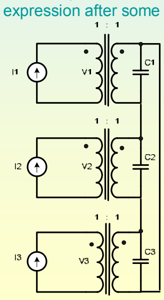
Hariharan Krishnaswami, Ned Mohan, Department of Electrical & Computer Engineering, University of Minnesota

Advantages of proposed converter topology:

1. The proposed converter circuit is the dual of the existing voltage fed multi-port converter
2. The source current ripple is reduced due to the inductor at the input.
3. High step-up of voltage possible due to the inverse topology.
4. Power flow control is by varying the phase shift between the full bridges as shown in the block diagram.
5. By appropriately selecting the turns ratio and matching the voltage levels of the sources and the load, Zero Current Switching (ZCS) can be achieved over a significant range of load and input voltage variations.

Principle of operation:

The equivalent circuit for analysis can be reduced to high frequency square wave current sources I_1,I_2 & I_3 derived from the input dc currents I_{FC}, I_{Batt} and I_{load} respectively. The capacitors are reflected to the secondary of the transformers. The resultant power flow equations between ports 1(Fuel cell), 2(Battery) and 3(Load) are given in eqn.1. The final load voltage expression after some algebra is also given in eqn. 2.



I1, I2, I3 are high frequency square wave current sources. I2 lags I1 by an angle φ12. I3 lags I1 by an angle φ13. I3 lags I2 by φ23=φ13-φ12

$$C_1' = \left(\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}\right)C_1C_3$$

$$C_2' = \left(\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}\right)C_1C_2$$

$$C_3' = \left(\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}\right)C_2C_3$$

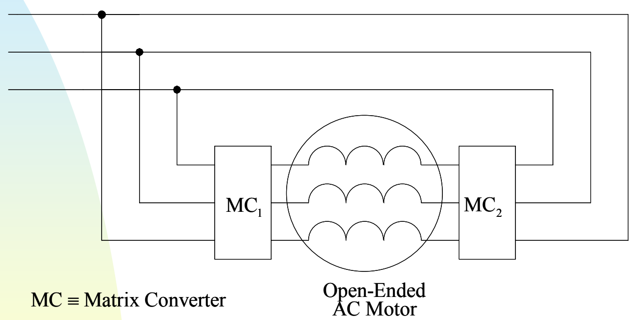
$$P_{13} = \frac{I_{FC}I_O}{C_1'}\phi_{13}\left(1-\frac{\phi_{13}}{T_s/2}\right)$$

$$P_{21} = \frac{I_{Batt}I_{FC}}{C_2'}\phi_{21}\left(1-\frac{\phi_{21}}{T_s/2}\right) \quad \longrightarrow (1)$$

$$P_{32} = \frac{I_{Batt}I_O}{C_3'}\phi_{32}\left(1-\frac{\phi_{32}}{T_s/2}\right)$$

$$V_O = \frac{C_2'}{\phi_{12}\left(1-\frac{\phi_{12}}{T_s/2}\right)}\left[\frac{V_{FC}}{C_3'}\phi_{23}\left(1-\frac{\phi_{23}}{T_s/2}\right)-\frac{V_{Batt}}{C_1'}\phi_{13}\left(1-\frac{\phi_{13}}{T_s/2}\right)\right] \quad \longrightarrow (2)$$

SiC-Based Matrix Converters for Open-Ended AC Drives for Wind Generators and Micro-Turbines



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Advantages of SiC Devices

- Closer to an ideal switch
- Lower Losses; Higher Efficiency
- High Temperature; Compact Design

Press Release 2006

- 110 kVA SiC-based Inverter by Kansai Electric and CREE
- 50% less conversion losses compared to Si inverters

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Power Electronic Systems

- Voltage-Link

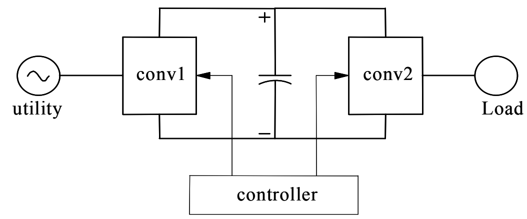

Figure 1-19 Load-side converter in a voltage-source structure.

- Current-Link

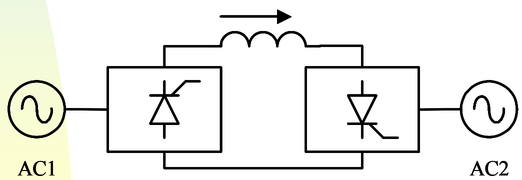

Figure 1-17 Current-link structure of power electronics interface.

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- Voltage-Link

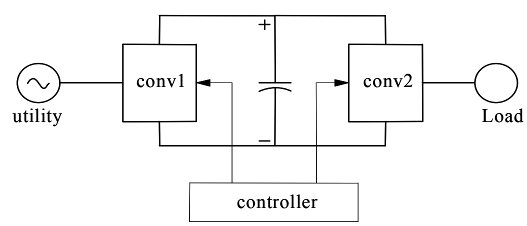

Figure 1-19 Load-side converter in a voltage-source structure.

Problems with the Storage Capacitor:

1. Weight and cost
2. Reliability
3. Inrush Current at switch-on
4. Additional currents under input unbalance
5. Difficult to integrate motor and the inverter

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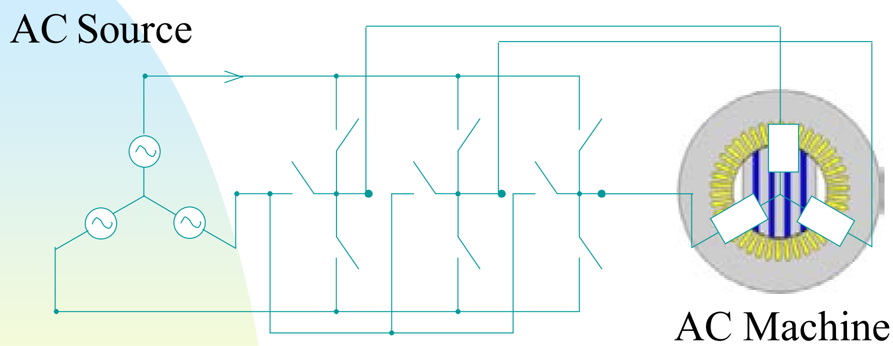
Matrix Converters



- Direct-Link (no energy storage)
- Ideal with SiC Devices

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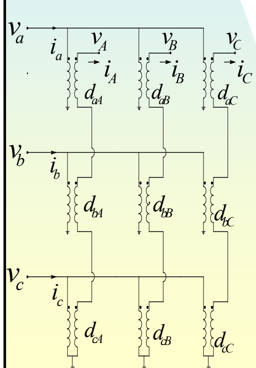
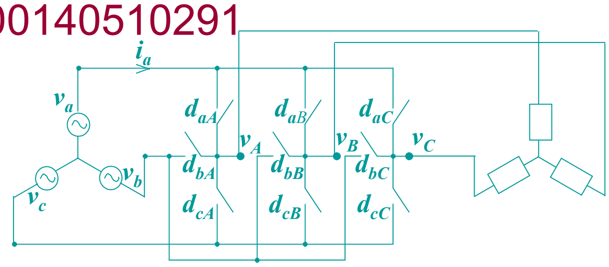
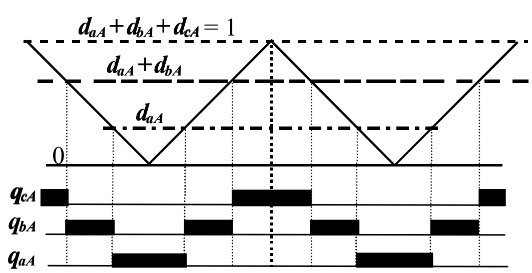
Highly Simplified Control of Matrix Converters

ONR Grant: N000140510291







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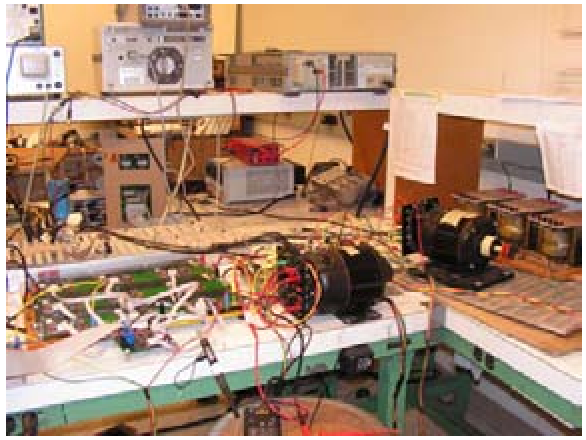
Laboratory Demonstration



- Novel : Intellectual Property Disclosure
- Papers Attached
  - IEEE-PESC 2006 and IEEE-APEC 2006

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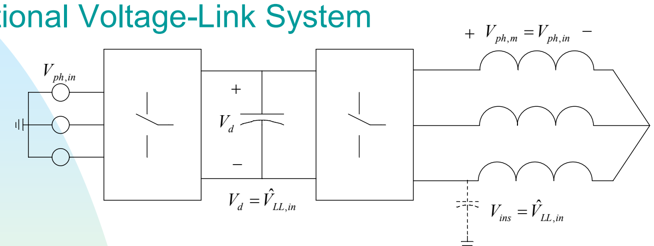
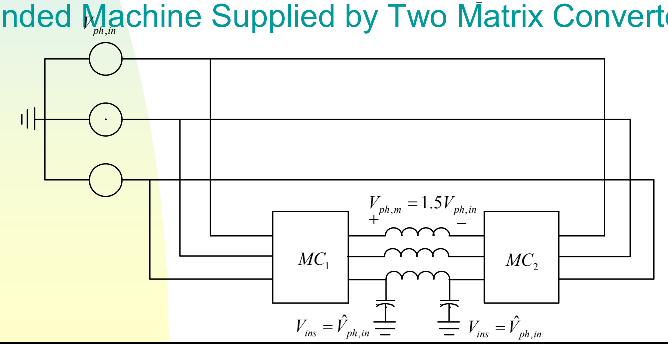
Nearly Doubling (1.876) the Drive Output

Conventional Voltage-Link System



Open-Ended Machine Supplied by Two Matrix Converters



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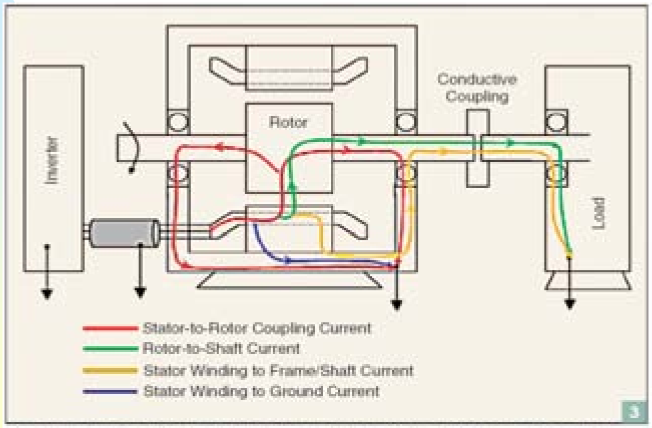
Switching of Common Mode Voltages Results in Bearing Currents

- SiC devices will make this more acute



Capacitively coupled current paths in an inverter driven induction motor system.

Source: Prof. Gopakumar, IISc

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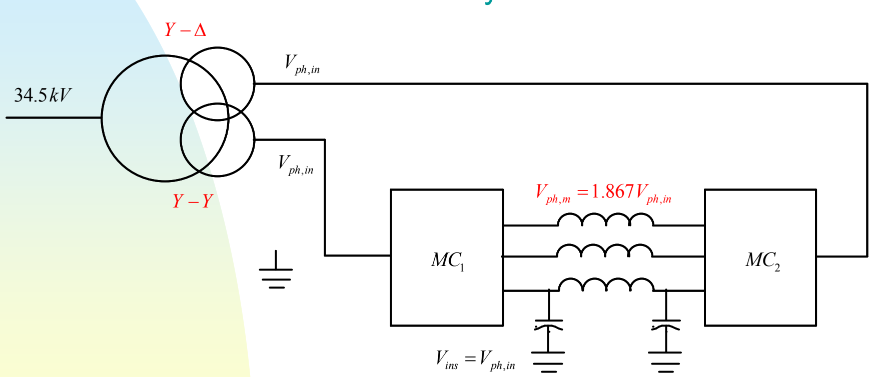
Isolated Inputs with 30 deg phase shift

- Power Capability increases to 186.7%
- Ideal for Wind Electric Systems as shown below



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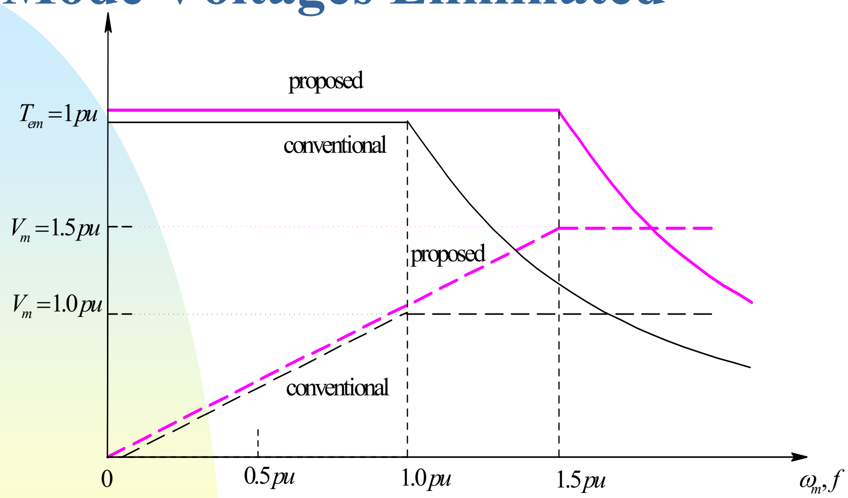
Capability Curves with Common Mode Voltages Eliminated*



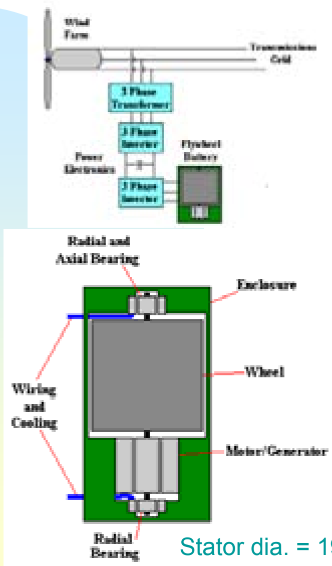
* Extended to 1.867 pu if input voltages at two sides are isolated from each other and 30 deg phase shifted

Simultaneous Benefits

1. Increases available voltage to 150%*
   - rated torque up to 150%* of the rated speed
   - 150%* power output capability
2. Bearing currents are eliminated
3. Slot insulation reduced by a factor 1.73
4. Comparable efficiency at the rated power?
5. Smaller current ripple?
6. Input power factor is controllable
7. Elimination of Energy Storage Capacitor
   - Bulky, inrush current, current under unbalance

* 186.7% if isolated inputs and 30 phase shifted

Flywheel Battery



Stator dia. = 19 in
Length = 42 in

- Objectives of Flywheel Battery
  - Firm up wind resources on a short-term basis
  - Interface with alternative generation
  - Voltage support to the transmission grid
- Flywheel Battery Components
  - Wheel – made with lightweight composites
  - Enclosure – designed to maintain a low windage loss environment
  - Magnetic Bearings – used for low rotational loss
  - Motor/Generator – charges and discharges the battery
  - Power Electronics and Controls – Control the Motor/Generator and Magnetic Bearings
- Flywheel Battery Specifications
  - Power = 2 MW
  - Energy = 100 kWhrs
  - Speed range = 7,500 to 15,000 rpm
  - High in-out efficiency
  - Lowest cost possible

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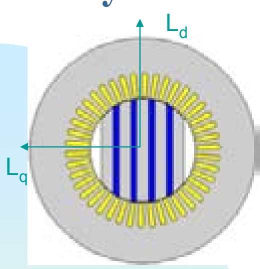
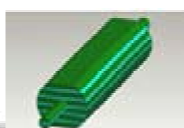
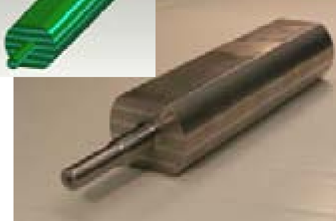
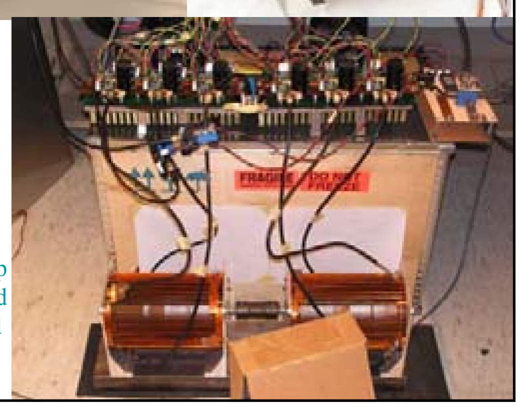
Synchronous Reluctance Motor/Generator



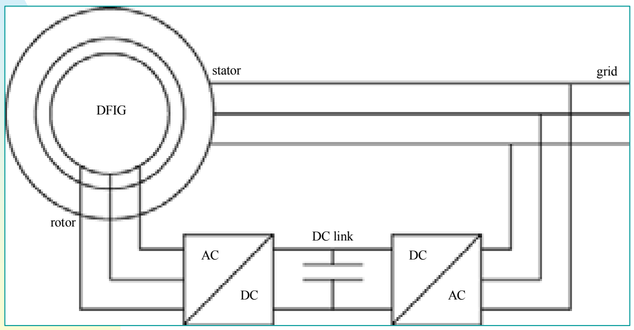






- Synchronous reluctance machine
  - Low cost and no loss at idle
  - Relatively low rotor loss
  - High rotor operating temperature of 250 °C (Most important)
- Large ratio of L_d to L_q inductance
- Axial Laminated small-scale rotor designed due to high L_d/L_q ratio
  - Machines tested in back to back setup
  - Machine able to operate at high speed
  - Due to thickness hot rolled steel used for magnetic layers

Control of a Doubly-Fed Induction Wind Generator Under Unbalanced Grid Voltage Conditions



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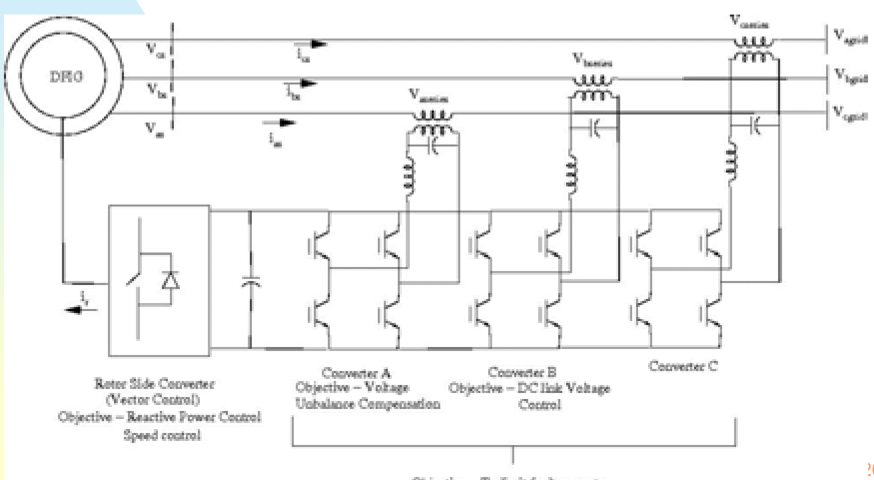
Application of Series Compensation in Wind Power



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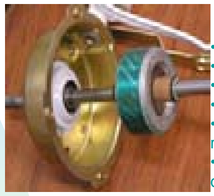
Innovative Methods to Triple Efficiencies of FAN Motors

(*a*)



(*b*)

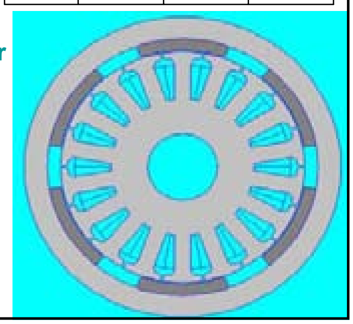
Present FAN motor

- **Max Efficiency = 30%**
- Starting Problem
- Poor Power Factor
- Pulsating Torque
- Low efficient speed regulator
- Efficiency goes further down at low speed

	Speed Setting	Input Power (W)	Efficiency
Fan 1	High	118.81	28%
	Mid	91.4	26%
	Low	67.69	14%
Fan 2	High	56.2	31%
	Mid	43.17	26%
	Low	35.82	21%
Fan 3	High	51.86	29%
	Mid	34.12	18%
	Low	25.97	11%

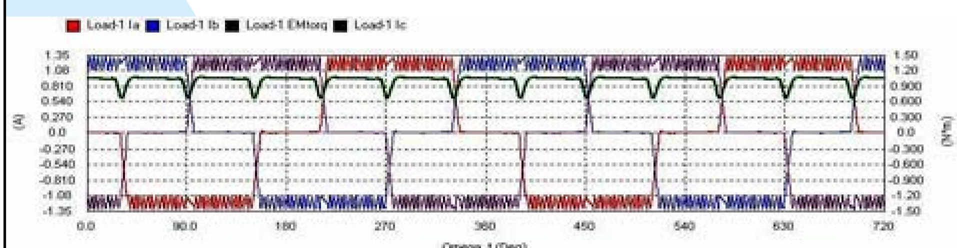
Proposed FAN motor

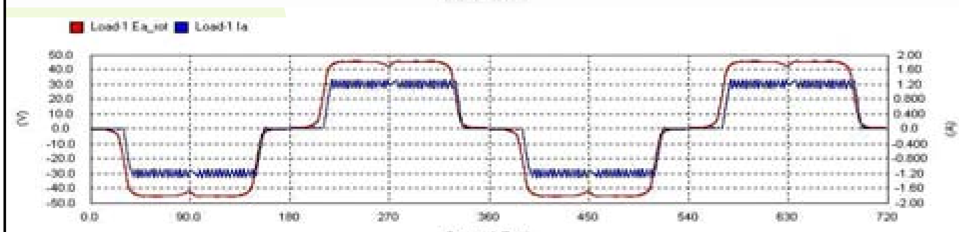
- **High Efficiency (close to 90%)**
- Power factor close to 0.9 (Design dependent)
- Can be wound with the available winding technology for AC machine
- Easy to manufacture, small size, ease in winding (Outer rotor)
- Low cost, readily available ferrite magnet as permanent magnet
- Low assembly cost and not a multi-step process

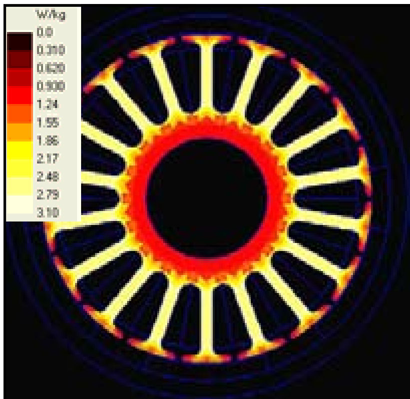


SIMULATION RESULT : Outer Rotor Configuration

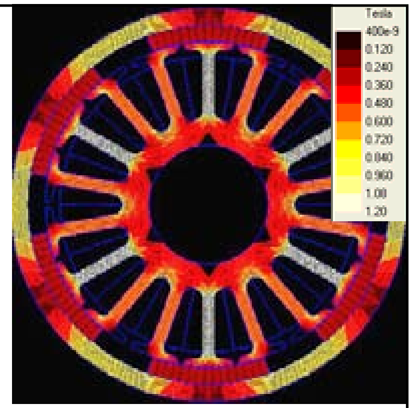
Torq	RPM	Freq	P_in	P_out	P_loss	VA	P.F.	Effic	CktVs	PwmIndx	AF_ang
(N-M)	(Rpm)	(Hz)	(W)	(W)	(W)	(VA)	(PU)	(PU)	(V)	(PU)	(deg)
0.966	1000	50	108.7	101	7.68	123.2	0.88	0.93	165	1	0







FEM
RESULTS



Iron Loss density

COST ANALYSIS

Flux density

Material	Volume required (PM in cm3)	Cost of PM ($)	Cost of Steel ($)	Cu Cost ($)	Size of machin e (mm)	Cu Loss (W)	Iron Loss (W)	Total (Loss, W)	Total Cost ($)
Neo (NdFeB)	22.12	11.06	2.79	2.39	100	4.36	4.22	8.58	16.24
Hybrid (60% Neo,40% Ferrite)	24.63	7.17	3.102	2.99	110	4.86	3.8	8.66	13.26
Ferrite	66.6	2.71	3.34	4.4	122	4.03	3.65	7.68	10.45

A compromise in efficiency (by 5- 8%) can reduce the total cost of motor by 20-30%, Present target is to achieve the highest efficiency possible at low cost

***** For a fair comparison, analysis is done at almost equal losses***

29

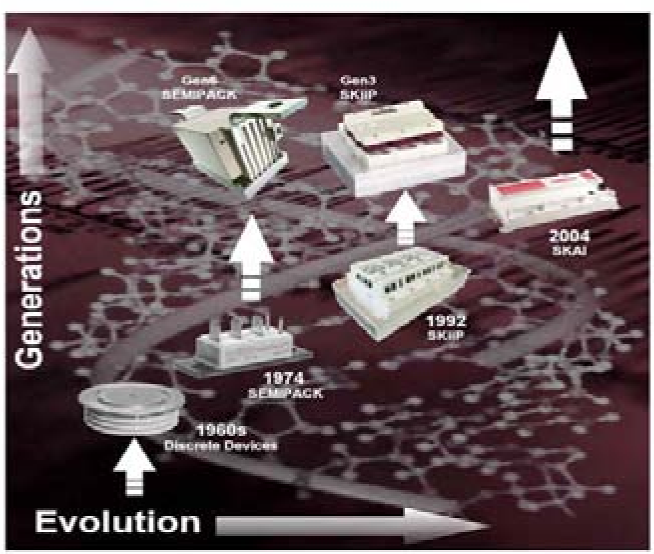
Integrated Modules
Simplify Systems Design

By: John Mookken
SEMIKRON USA

8/24/06

Advanced Power Electronics DE Workshop
Sacramento, CA

Evolution of the Power Module

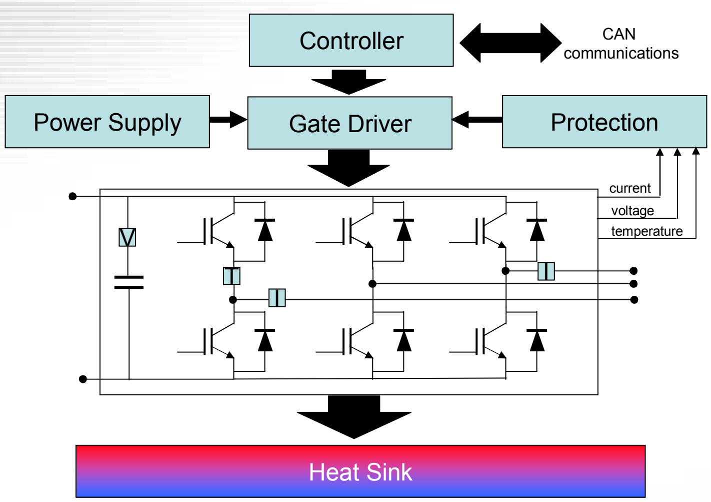


Why Integrate?

- Shorter time to market
- Easier system design & assembly
- Economical
- Reduced number of components
- Customized solution without the custom pricing
- Standard Interface
- Commonality or standard platform

3

SKAI: Block diagram



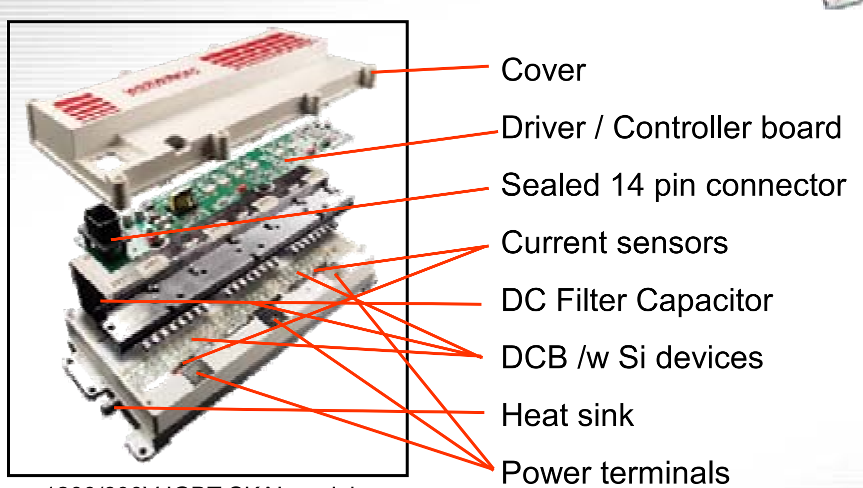
4

SEMIKUBE

- « A 390A rectifier + inverter into a 400mm cube »(*)
- Includes all sensing (current, voltage, temperature)

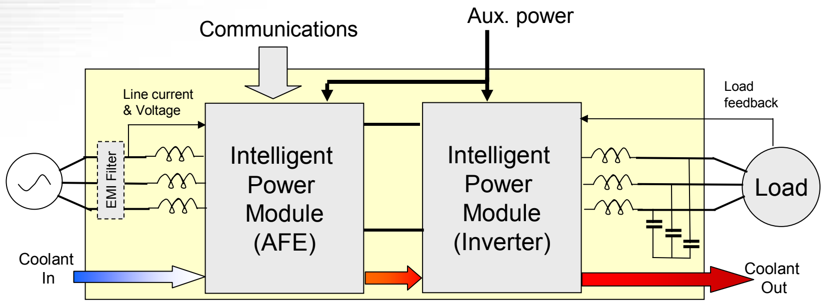
(*) actual max dimensions are 412 x 435 x 380

SKAI: Components

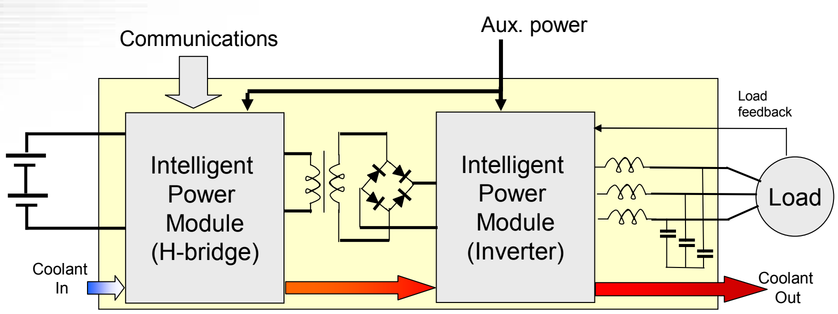


1200/600V IGBT SKAI module

AFE / Inverter Example



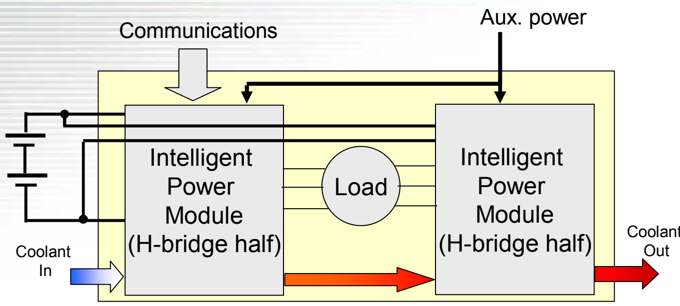
DC/DC Example



Example Systems

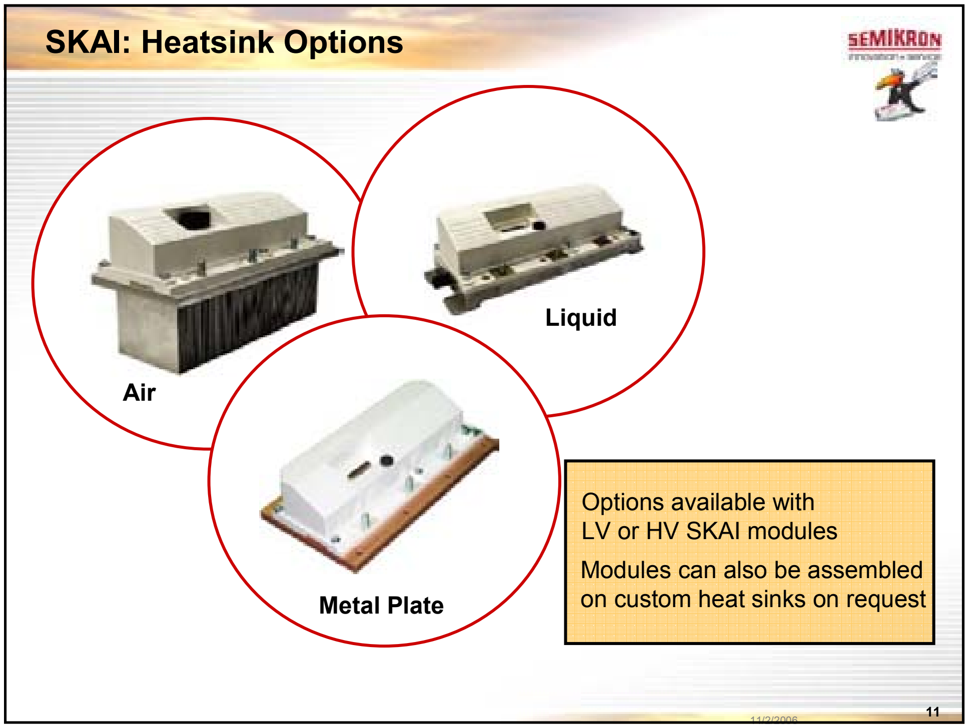
9

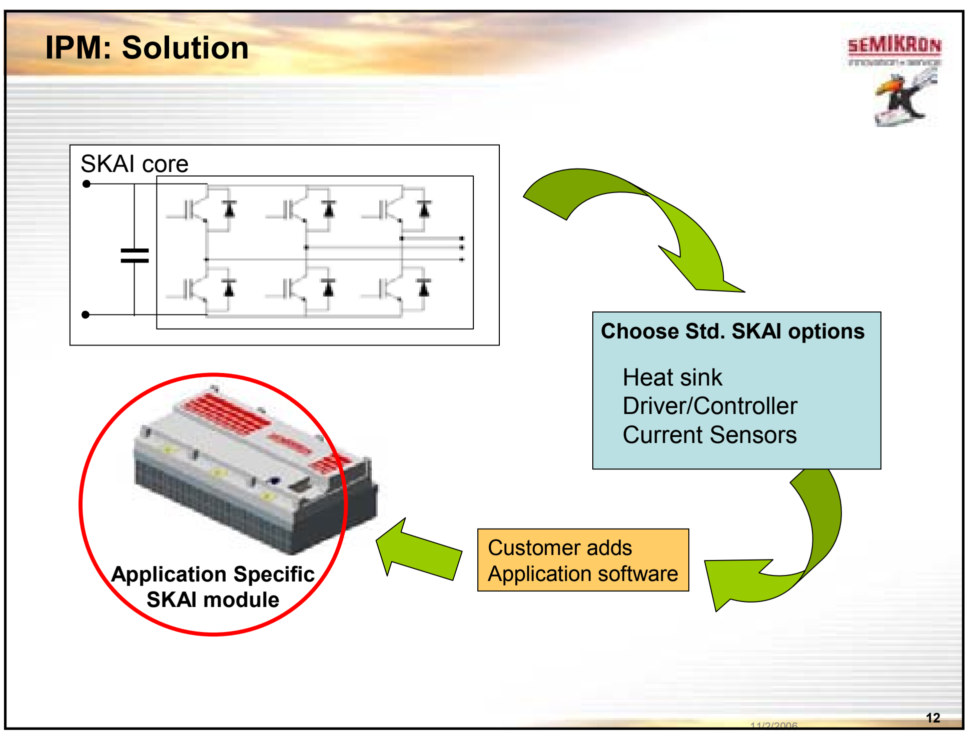
H-Bridge Example



Dual modules assembled on motor end bell / heat sink

10


SKAI: Heatsink Options
SEMIKRON
Air
Liquid
Metal Plate
Options available with
LV or HV SKAI modules
Modules can also be assembled
on custom heat sinks on request
11


IPM: Solution
SEMIKRON
SKAI core
Choose Std. SKAI options
Heat sink
Driver/Controller
Current Sensors
Customer adds
Application software
Application Specific
SKAI module
12

SEMIKRON

Thank you for your attention

Questions or Comments ?

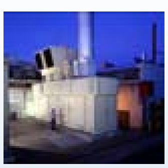
John Mookken
John.mookken@semikron.com

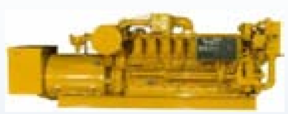
Distributed Energy

Advanced Power Electronic Interfaces

Ben Kroposki
National Renewable Energy Laboratory

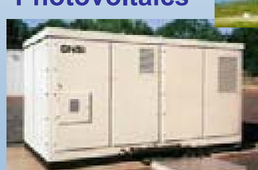
Distributed Energy (DE) Applications


Advanced Turbines


Reciprocating Engines

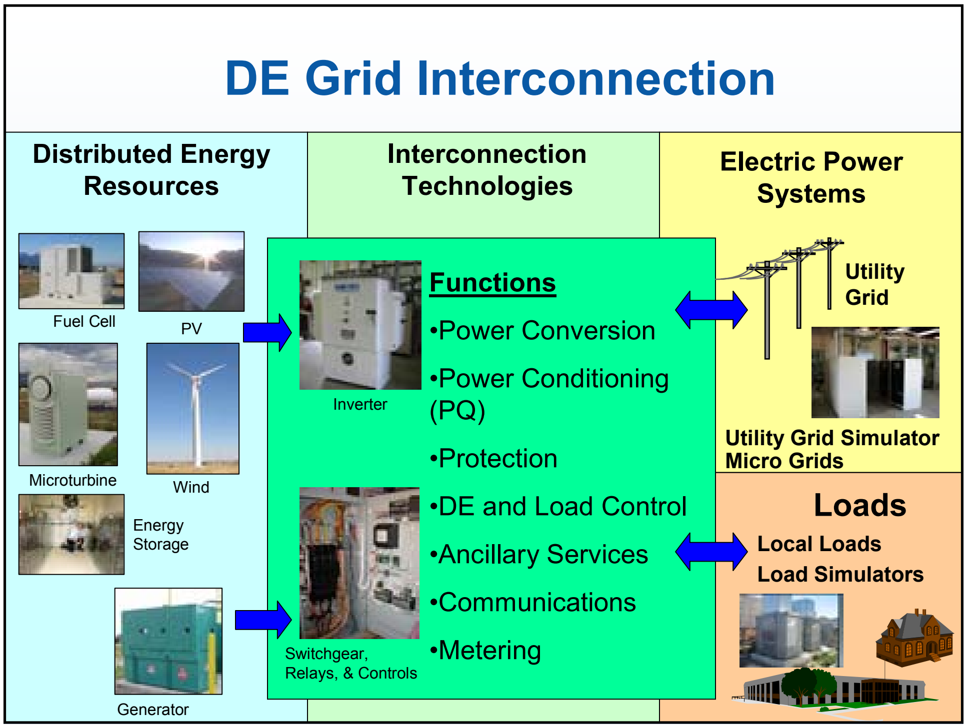

Wind

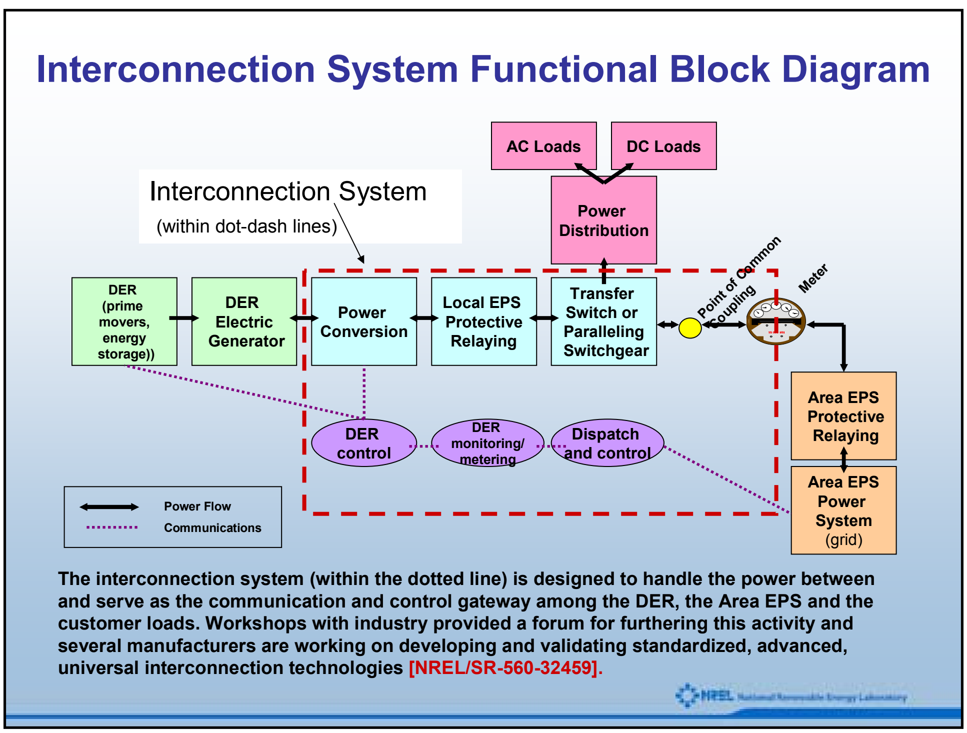

Photovoltaics


Fuel Cells

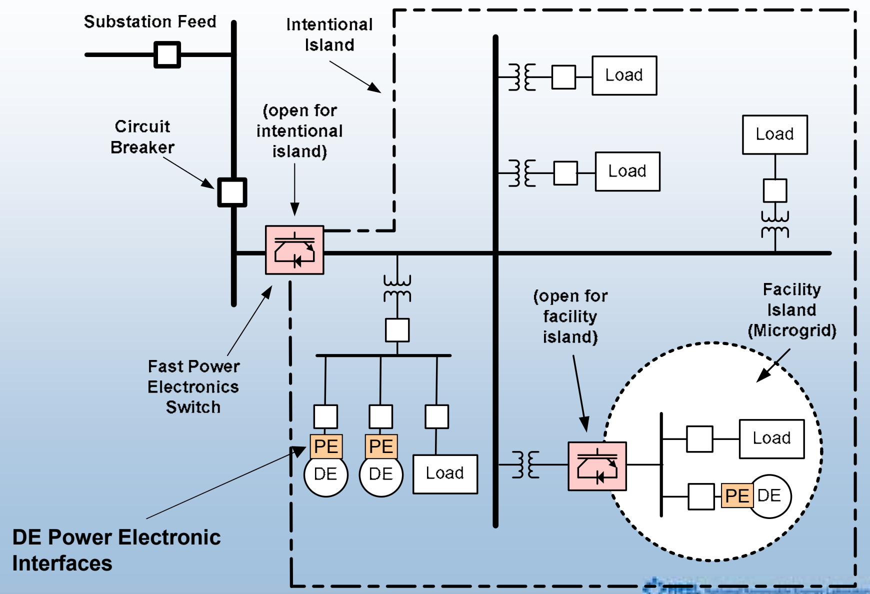

Microturbines

- Energy Management
- Electricity to Grid
- Baseload/CHP
- Peak/Demand Reduction
- Reliability/Backup Power
- Power Quality
- Grid Ancillary Services


DE Grid Interconnection
Distributed Energy Resources
Interconnection Technologies
Electric Power Systems
Fuel Cell
PV
Microturbine
Wind
Energy Storage
Generator
Inverter
Switchgear, Relays, & Controls
Functions
•Power Conversion
•Power Conditioning (PQ)
•Protection
•DE and Load Control
•Ancillary Services
•Communications
•Metering
Utility Grid
Utility Grid Simulator
Micro Grids
Loads
Local Loads
Load Simulators


Interconnection System Functional Block Diagram
AC Loads
DC Loads
Power Distribution
Interconnection System
(within dot-dash lines)
DER (prime movers, energy storage))
DER Electric Generator
Power Conversion
Local EPS Protective Relaying
Transfer Switch or Paralleling Switchgear
Point of Common Coupling
Meter
Area EPS Protective Relaying
Area EPS Power System (grid)
DER control
DER monitoring/ metering
Dispatch and control
Power Flow
Communications
The interconnection system (within the dotted line) is designed to handle the power between and serve as the communication and control gateway among the DER, the Area EPS and the customer loads. Workshops with industry provided a forum for furthering this activity and several manufacturers are working on developing and validating standardized, advanced, universal interconnection technologies [NREL/SR-560-32459].

PE Applications with DE Systems

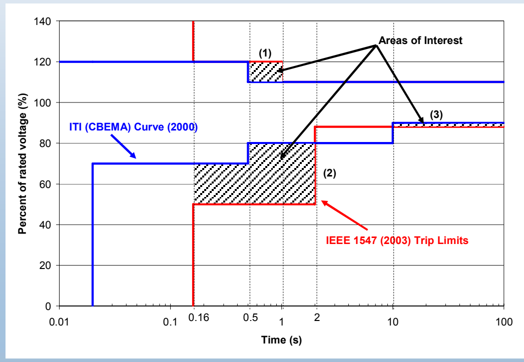


Benefits of Power Electronic Interfaces for DE

- Improved Operating Efficiencies
  - Variety of topologies for power electronic interfaces can improve conversion efficiencies
  - Allow for variable speed operation of internal combustion engine DG

Benefits of Power Electronic Interfaces for DE

- Power Quality
  - Harmonic Control
  - Power for Sensitive Loads

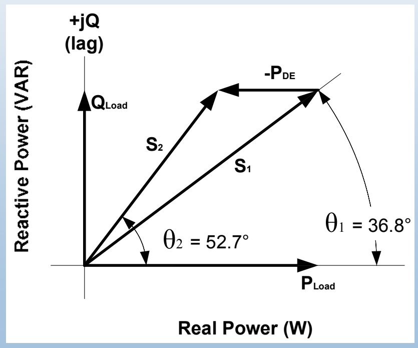


- **Sustained Interruptions** – DE can provide backup power if designed to do so. This may improve reliability if designed and operated properly.
- **Voltage Regulation** – DE can provide voltage regulation if allowed. This can also be a limiting factor as to penetration on a feeder.
- **Harmonics** – There are harmonic concerns with both rotating and inverter based DE.
- **Voltage Sag** – DE may be able to help keep voltage up, but only if allowed to do so.

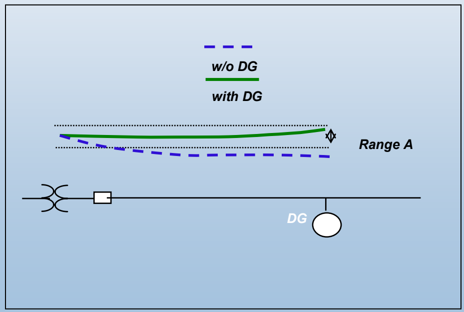
Benefits of Power Electronic Interfaces for DE

- VAR Support and Voltage Regulation

Power Factor



Voltage Regulation



Benefits of Power Electronic Interfaces for DE

- Reduced DE Fault Currents
  - Ability to recognize dI/dt of fault currents and clamp or disconnect
  - This allows for use of DE on networked systems and easier integration with protection system
- Interoperability with a variety of other DE sources
- Standardization and Modularity
  - High volume manufacturing techniques

IEEE 1547 Series Standards

1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems

1547.1-2005 Conformance Test Procedures for Equipment Interconnecting DR with EPS

Current Projects

- **P1547.2** Application Guide for IEEE 1547 Standard for Interconnecting DR with EPS
- **P1547.3** Guide for Monitoring, Information Exchange and Control of DR
- **P1547.4** Guide for Design, Operation, and Integration of DR Island Systems with EPS
- **P1547.5** Guidelines for Interconnection of Electric Power Sources Greater Than 10 MVA to the Power Transmission Grid
- **P1547.6** Recommended Practice for Interconnecting DR With EPS Distribution Secondary Networks

Future Projects

- DG Specifications and Performance
- Guide for Grid/DG Impacts Determination
- Interconnection System Certification Guide
- Power Electronic Interface Specifications for DR

Covers IEEE 1547 Section 4.3.2

Covers IEEE 1547 Section 4.1.4

IEEE 1547.1 Interconnection Tests have been incorporated into UL 1741 for product certification

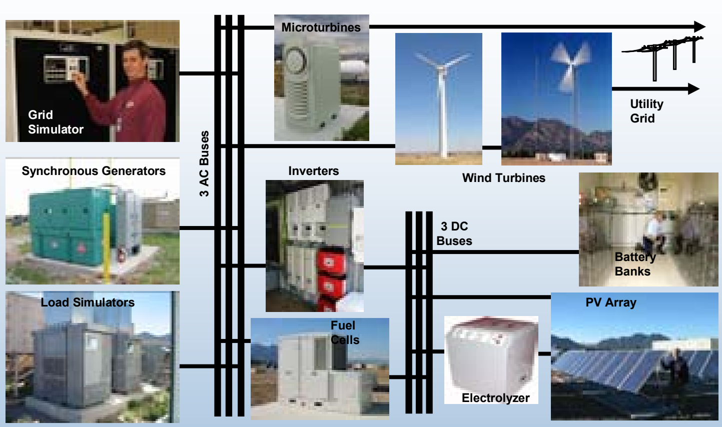
DE Interconnection Equipment Certification Approach

IEEE 1547
Interconnection System Requirements
- Voltage Regulation
- Grounding
- Disconnects
- Monitoring
- Islanding

IEEE 1547.1
•Interconnection System Testing
- O/U Voltage
- and Frequency
- Synchronization
- EMI
- Surge Withstand
- DC injection
- Harmonics
- Islanding
- Reconnection

UL 1741
Interconnection Equipment
- Construction
- Protection against risks of injury to persons
- Rating, Marking
- Specific DR Tests for various technologies

NREL DER Test Facility



- Test Systems up to 200kW
- Natural Gas on site
- All DER Technologies
- Full IEEE 1547.1 testing

Modular and Scalable Power Converters in the UPS Industry

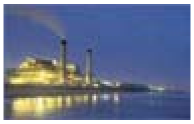
Ian Wallace
Eaton Corporation, Innovation Center

Content

- Eaton Overview
- Eaton Electric – UPS Business
- Today's Critical Power Systems
- UPS Market Drivers
- Modern UPS converter technology
  - Design for reliability
  - Scalability & Redundant Systems for high 9's reliability
  - Topology and control
- Modularity : Power Control
  - Two examples:
  - 9390 UPS power / control structure
  - Blade UPS modularity / power density.

2

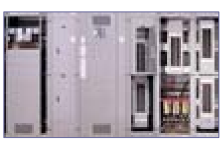
Eaton Overview

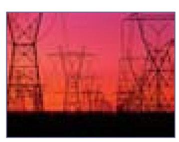
Electrical	Fluid Power	Automotive	Truck
			

- A global diversified industrial manufacturer
  - 2005 sales: $11.1 billion
- A leader in:
  - **Electrical power quality and control**
  - Fluid power systems
  - Automotive engine air management
  - Intelligent drivetrain and safety systems for trucks & heavy vehicles

3

What Markets Does Eaton Serve?

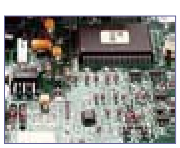


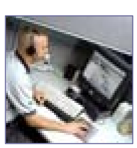


Industrial Facilities & Utilities

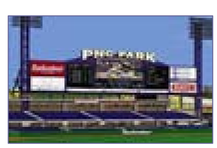
Residential

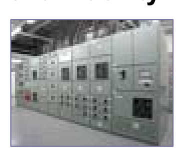
Telecom / Data Centers





Commercial/Institutional Facility





4

Eaton Business Segment – Electrical

$3.7 billion sales in 2005.
14,000 employees, 57 factories in 19 countries

→ electrical control, power distribution, UPS, industrial automation products & services, …

- **Power Quality Systems**
- Power Component & Systems
- Electrical Components / Industrial Control

1893	1979	1994	2003	2004
Founded in Milwaukee	C-H Acquired By Eaton	Acquired DCBU Westinghouse	Acquired the Electrical Group Of Delta, plc	Acquired Powerware
	EATON		ELEK, HOLEC, MEM, TABULA	POWERWARE

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5

Eaton Electrical – Power Quality Systems

- Mission Critical UPS systems for highest power reliability (emergency back-up)
- Single phase & three phase UPS Modular, transformerless up to 160 kVA
- Industrial & Rack-mount UPS
- Sag Ride-through Power Conditioner
- Active and Passive Harmonic Filters
- Static Transfer Switches
- Advanced Battery Management
- Integration & Global Service Support

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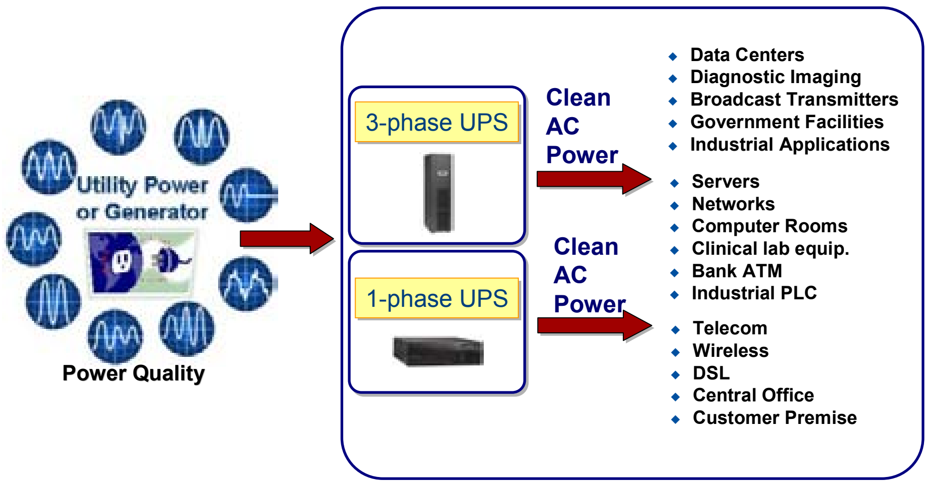
6

UPS Systems – Key to 24/7 Daily Life



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7

Eaton UPS Market Position

- Eaton is an industry leader and globally recognized provider of innovative, effective power quality solutions, delivered under the Powerware brand
  - Power protection revenue ~ $900M
  - #1 in worldwide UPS sales above 5 kVA
  - #2 in worldwide UPS sales at and under 5 kVA
  - Total volume: >1.5 million units / year
  - 3-Phase volume: ~ 7,000 3-phase units / year
  - Large installed base of more than 45,000 3-phase UPSs worldwide

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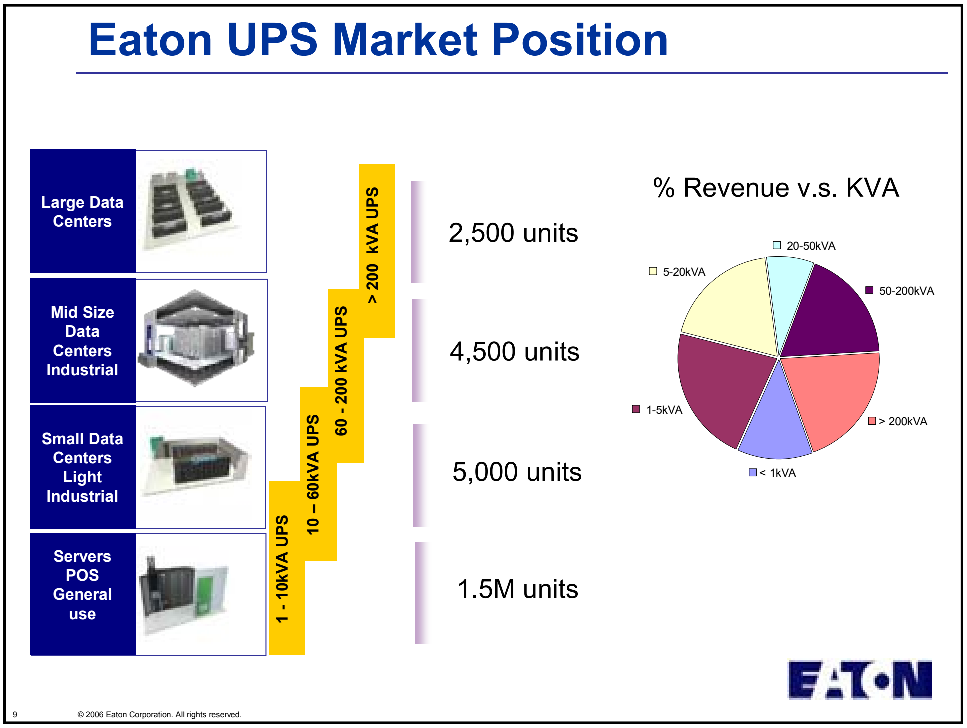
Eaton UPS Market Position
Large Data Centers
Mid Size Data Centers Industrial
Small Data Centers Light Industrial
Servers POS General use
> 200 KVA UPS
60 - 200 KVA UPS
10 – 60kVA UPS
1 - 10kVA UPS
2,500 units
4,500 units
5,000 units
1.5M units
% Revenue v.s. KVA
20-50kVA
5-20kVA
50-200kVA
1-5kVA
> 200kVA
< 1kVA
9
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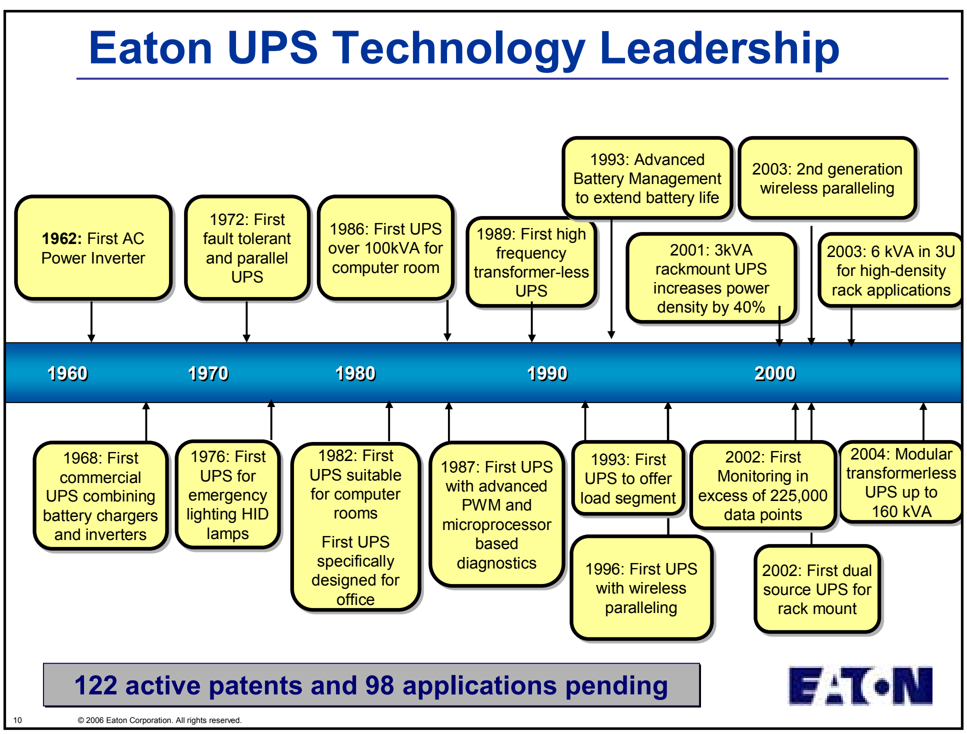
Eaton UPS Technology Leadership
1962: First AC Power Inverter
1972: First fault tolerant and parallel UPS
1986: First UPS over 100kVA for computer room
1989: First high frequency transformer-less UPS
1993: Advanced Battery Management to extend battery life
2001: 3kVA rackmount UPS increases power density by 40%
2003: 2nd generation wireless paralleling
2003: 6 kVA in 3U for high-density rack applications
1960
1970
1980
1990
2000
1968: First commercial UPS combining battery chargers and inverters
1976: First UPS for emergency lighting HID lamps
1982: First UPS suitable for computer rooms
First UPS specifically designed for office
1987: First UPS with advanced PWM and microprocessor based diagnostics
1993: First UPS to offer load segment
1996: First UPS with wireless paralleling
2002: First Monitoring in excess of 225,000 data points
2002: First dual source UPS for rack mount
2004: Modular transformerless UPS up to 160 kVA
122 active patents and 98 applications pending
10
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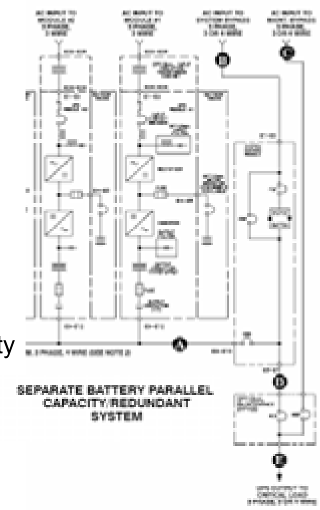
Today's Critical Power Systems

- Main elements of Critical Power systems
  Measured by 9's of availability
  - Multi-source / storage systems
    - Utility (single / multiple feeds)
    - DC Batteries
    - AC Generator
    - DC Flywheels & ultra capacitors
  - UPS – one element in high 9's system
    - System design for redundancy
    - UPS paralleling for redundancy and capacity
    - Static UPS bypass
    - Manual / Maintenance bypass



Today's UPS Market Drivers

- Power quality under utility disturbances
- Flexible architectures for high 9's reliability
  - Parallel redundancy
  - Expandable for capacity
- High system reliability, MTBF
  - No single point failure

Interruption Costs	
Business / Industry	Cost
Paper Industry	$10,000 – $30,000 / event
Textile Industry	$10,000 – $40,000 / event
Data Processing	$10,000 – $40,000 / event
Plastics Industry	$10,000 – $50,000 / event
Semiconductor Industry	$10,000 – $50,000 / event
Automotive Manufacturing	$15,000 / event
Air Traffic Control	$15,000 / minute
Office Building	$22,000 per 500 kVA of critical load
Broadcast Facility	$100,000 / 30 minutes

Source: EPRI - *Power Quality Applications Guide for Architects and Engineers*

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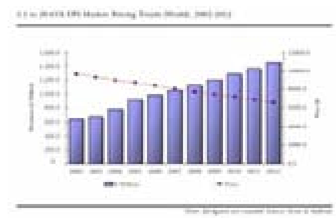
Today's UPS Market Drivers

- Low installation cost
- Low operating cost - high efficiency
- High power quality utility interface
- High power density
- Serviceability – MTTR
- Multi - power source compatibility
- Global sourcing and manufacturing
- Monitoring, diagnostics & prognostics
- Maintenance services



- Revenue → ~10% growth / yr
- Price → ~ 4% $ reduction / yr

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Today's UPS Technology

- Market drivers are addressed by:
  - Design for reliability
  - Scalable multi-unit operation for high 9's architectures
    - Elimination of single point failures
    - Fault identification and selective trip
  - Power module topology and design
  - Converter modulation and control techniques
  - Modular power and control modules
    - Build a scalable product line via modularity

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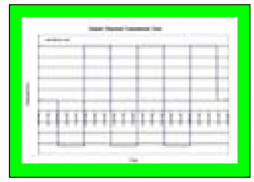
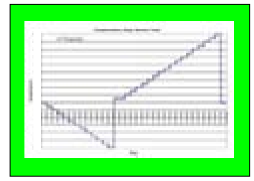
Converter Design for Reliability



▪ HALT: Highly Acceleration Life Test
  - Thermal cycling, rapid thermal transitions, load cycling …
  - Identify weakest link via product destruction



▪ HASS: Highly Accelerated Stress Screen
  - Ongoing production screening.
  - Verify production units continue meet reliability objectives

▪ MTBF targets
  - UPS Converter > 60,000 hrs
  - Parallel redundant systems > 300,000hrs

System Level Modularity and Scalability

System Level Drivers:

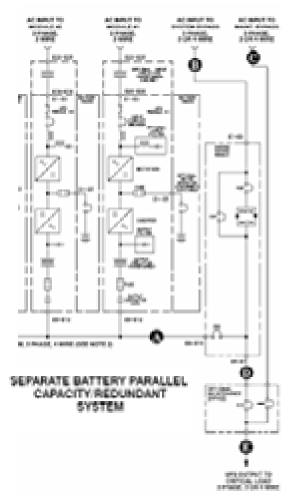
▪ Key to achieving high 9's of reliability
  - parallel for redundancy

▪ Parallel for capacity - load expansion

Enablers

- Eliminate single point failure
  - power & controls
- Communication less paralleling

  Hot Sync™ Technology
- Fault location detection



Power Availability for Mission Critical Apps

The power grid typically provides 3 - 9's, or 99.9% reliability. This equates to almost 9 hours of downtime per year. 'High 9's' are generally considered to mean 6 - 9's and above.

9's		Downtime per Year
3	99.9%	8 hr, 45 min, 36 sec
4	99.99%	52 min, 33.6 sec
5	99.999%	5 min, 15.36 sec
6	99.9999%	31.5 sec
7	99.99999%	3.15 sec

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Increasing Availability of Power

Parallel redundant systems offer substantially increased availability

- Can provide "high 9's" availability
  - The best opportunity to increase availability at the source
- There are two fundamental technical issues to solve for parallel redundant power systems
  - Control and stability of two or more AC power sources being paralleled
  - Elimination of all potential system-level single-point-of-failure
- The resulting performance is depending on design implementation of:
  - Load sharing
  - Fault isolation

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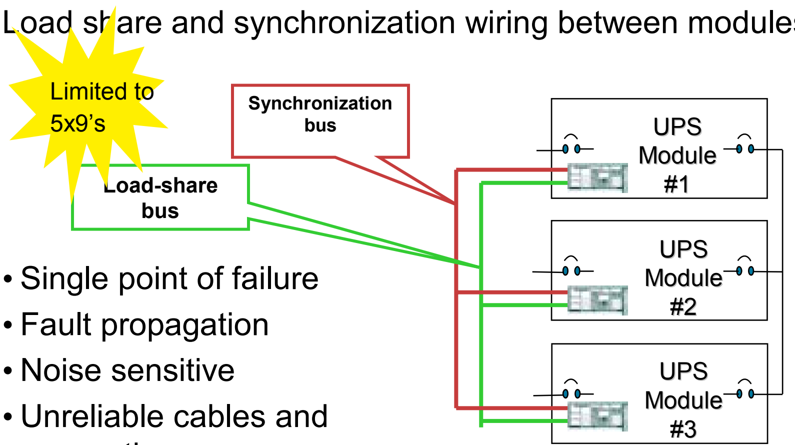
Legacy Systems

Load share and synchronization wiring between modules



- Single point of failure
- Fault propagation
- Noise sensitive
- Unreliable cables and connections

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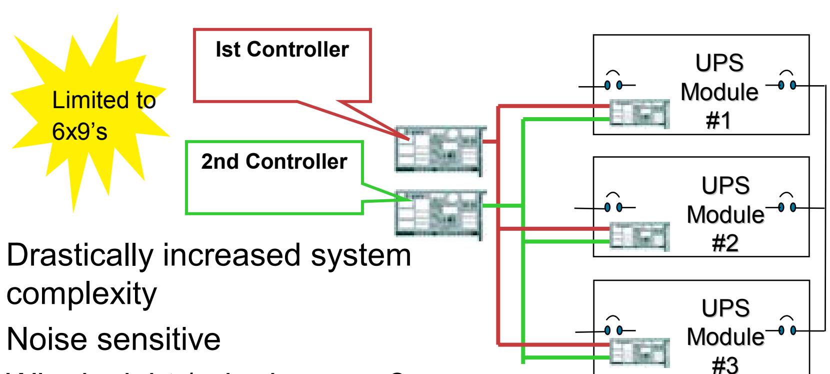
Legacy Systems

Master / redundant controllers



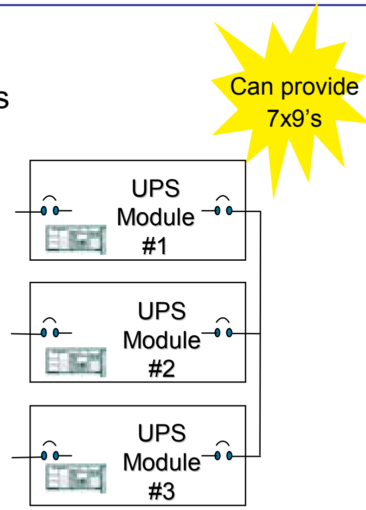
- Drastically increased system complexity
- Noise sensitive
- Who is right / who is wrong?
- Unreliable cables and connections

EATON

20

Powerware Hot Sync™

"Wireless" paralleling of AC sources



- Reduced system complexity
- No single point of failure
- Modules are identical
- Modules act as peers
- No Primary / Secondary relationship
- No "Main Intelligence Module" required

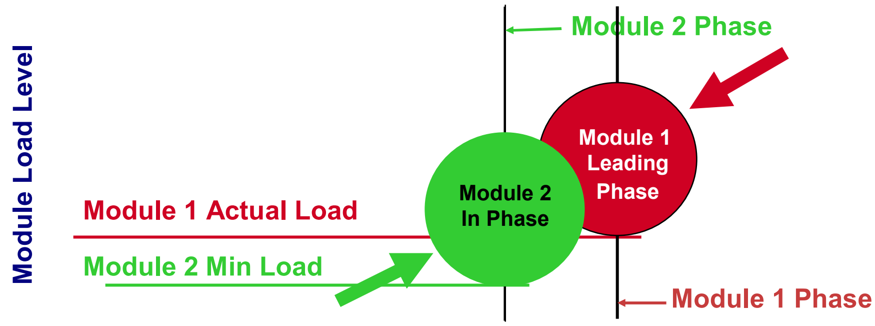
Powerware Hot Sync™

Hot Sync™ provides automatic load sharing and selective tripping in a parallel system.

- No control wiring required between modules for current sharing or selective tripping
- Designed to share load with any power source, including the utility
- Provides flexibility and scalability
- The UPS can be decentralized into the server equipment and still operate in parallel with additional server racks
- Ideal for distributed power system applications

Hot Sync™ Load Share Pictorial

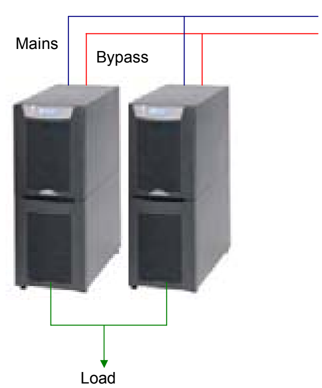
Parallel load share control algorithm constantly drives the module to carry the least amount of load. This will drive Module 1 back in Phase with Module 2.



•Eaton developed technology – US patents #5,745,356 & 5,745,355

Hot Sync™ Benefits

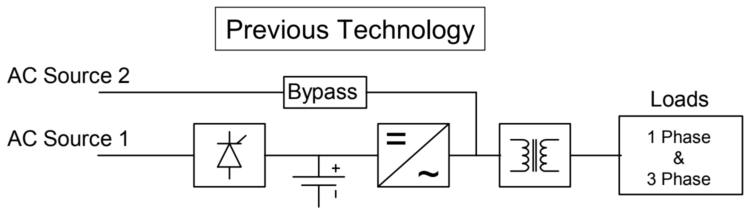
- Can provide up to 7x9's availability of power
- Ultimate scalability with no additional controls
- Modules in Parallel:
  - are absolute peers
  - have absolute autonomy
  - use 100% intrinsic components
- Seamless transition from capacity to redundancy
- Increased serviceability



Direct extension to autonomous operation of grid interface Scalable DG converters

Input Power Quality and Efficiency

- Online UPS: maximum protection from utility disturbances
- Source 3-wire and 4-wire loads.
- Maintain efficiency > 95%
- Manage battery lifetime

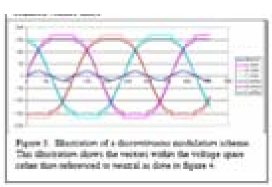


Low power density
- Input line filters
- Output transformers

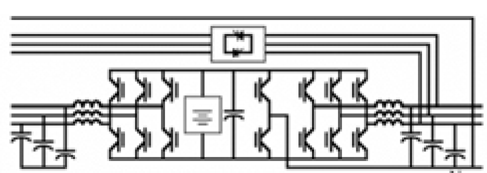
Limited battery management

Input Power Quality & Efficiency

- Active front end IGBT Converters (10-200kVA) improve:
  - Power quality, grid and generator interface
- Transformerless Double-Conversion UPS Topology
  - Elimination of distribution transformers (4 wire source / loads)
  - Novel modulation scheme for 4 leg inverters
  - Maximized DC bus utilization to maintain efficiency
  - Ultra small filter size: optimization of magnetic component & switching frequency

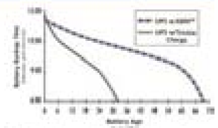


Increased power density



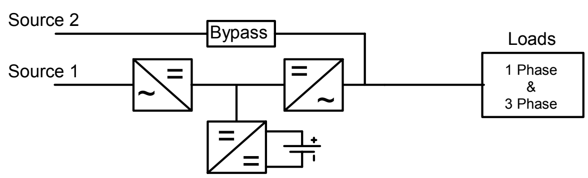
Complete UPS with modulated neutral.

Battery Management



Data based upon tests performed by an independent battery manufacturer.

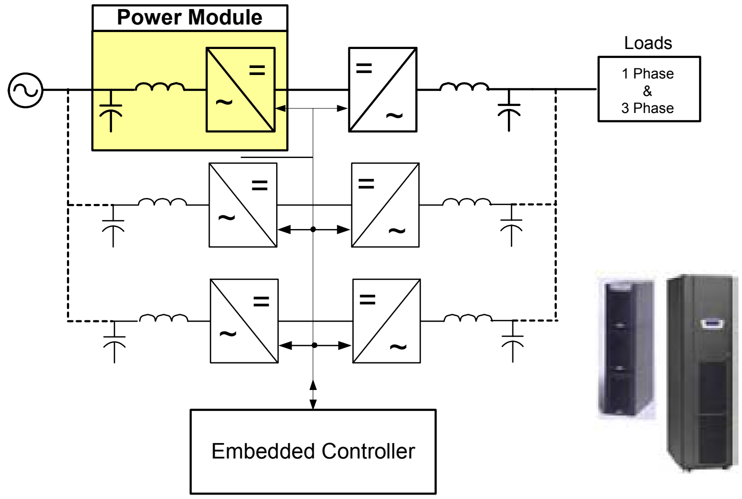
- Battery Systems
  - Advanced Battery Management:
    - 3 stage charging technique - doubles battery life & optimizes battery recharge time.
    - Prognostics / Diagnostics- provides up to 60-day advanced notification of the end of useful battery life.
- ProActive Service – max uptime via 24x7 corrective maintenance, remote monitoring



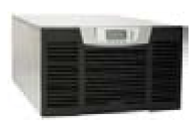
Modular Product Approaches

- Motivation
  - Build a product line to cover wide power range
  - Maintain low cost and high reliability
  - Enable N+1 redundancy: high MTBF
  - Serviceability - Maintain low MTTR
- Where is the appropriate division and extent of modularity ?

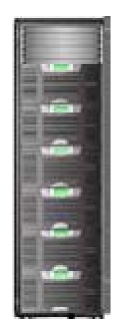
Modular Power Block Approach



Rack Mount Modular UPS



- **BladeUPS:**
  - 12-60 kW modular, rack-based N+1 power protection
- **Features:**
  - Very compact design, high power density (6U)..
  - Highest power density on the market
  - No single points of failure in system
  - Mounts in any industry standard rack
  - Each module is autonomous - establishes peer-to-peer relationship when paralleled.
  - Hot Sync reliability, redundancy, and scalability
    - Scalable from 12kW to 60kW
  - High Efficiency up to 97%
  - Features hot-swappable battery modules and electronics
  - Advanced Battery Management (ABM)



Thank You

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Presentation for:

California Energy Commission

REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY™

American Superconductor™

Presenter

Distributed Energy Applications Leverage High Volume, Modular Power Converters

Advanced Power Electronic Interfaces for DE Workshop

Sacramento, CA

August 24, 2006

Perry Schugart
Director, Power Converter Products
12 years, Power Semiconductors
9 years, Power Electronic Systems
Bachelor of Science, Physics

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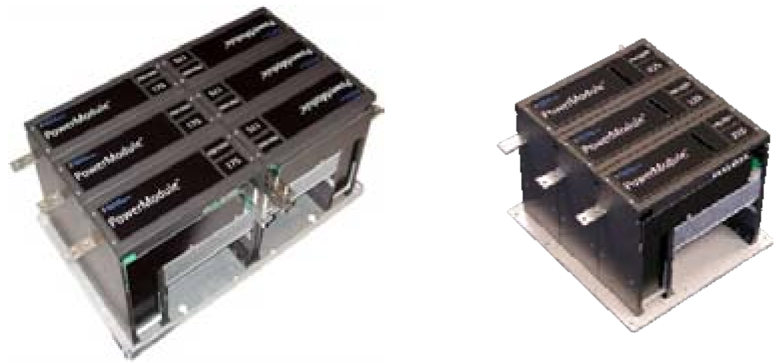
Phone: +1.262.901.6036
Fax: +1.262.901.0104

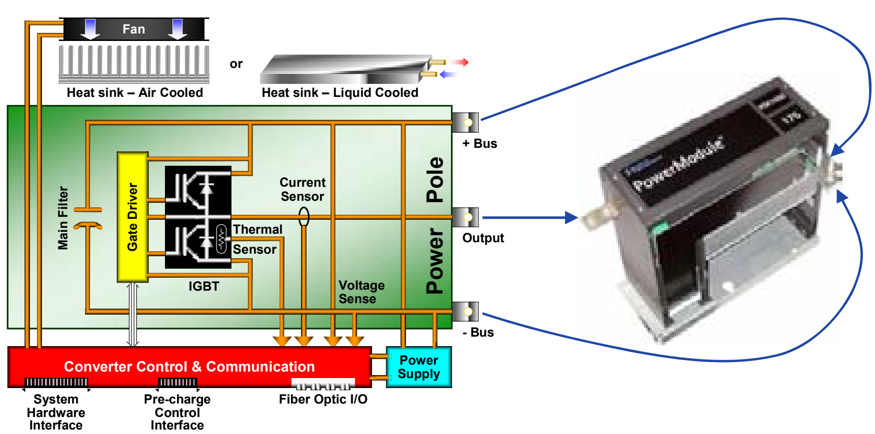
American Superconductor

Modular & Configurable High Power Converters

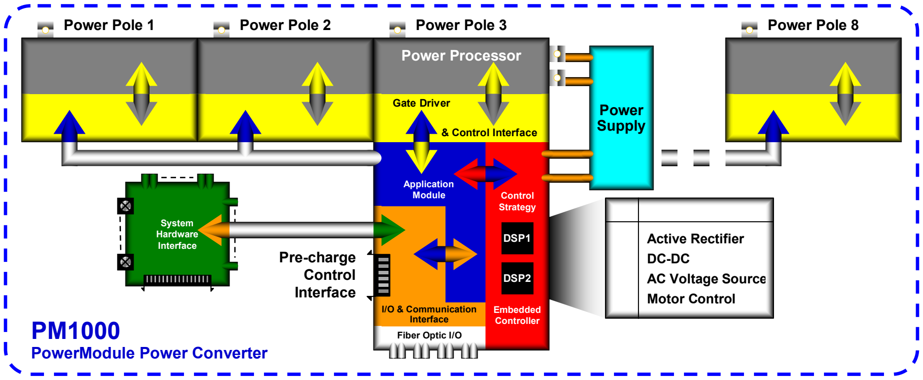


- Programmable Electronic Building Blocks (PEBB)
- Configurable for different power conversion needs
- High volume, modular architecture
- Rapid product development

Integrated Modularity with Power Pole Architecture



PM1000 – Configurable Power Converter



- Analog and digital I/O
- Dual digital signal processors
- Fiber optic communications
  - CAN, asynchronous serial
- Gate drivers
- Auxiliary power supply
- Cooling
  - Liquid & air

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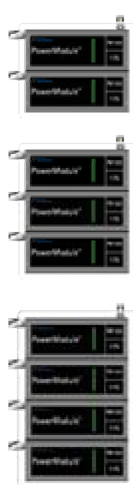
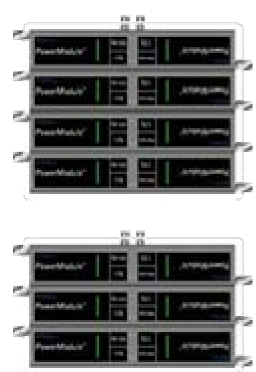
Rapid Product Development



From Concept
to Converter



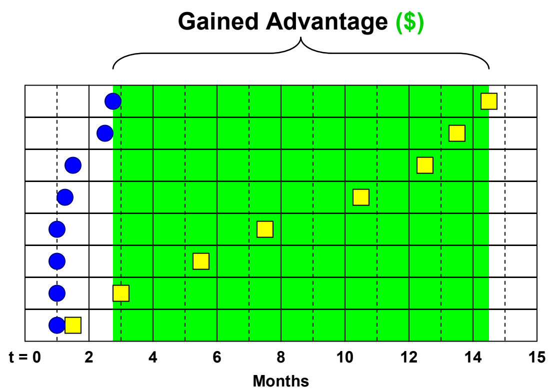
PM1000
Rapid Product Development
Makes it happen the quickest

American Superconductor

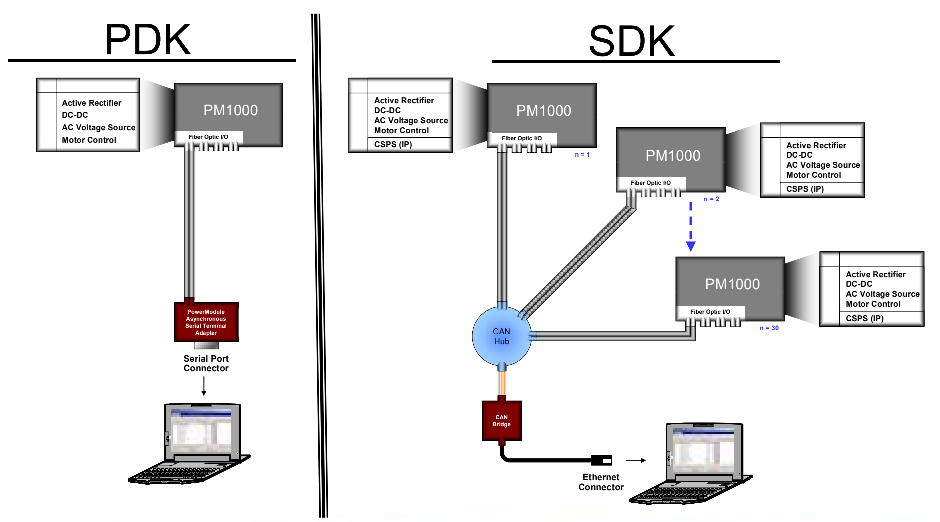
PM1000 Rapid Product Development Benefits

	Typical OEM In-house Development	PM1000
Production	1 m	.25 m
System Integration	1 m	1 m
Iteration	2 m	.25 m
S/W Development	3 m	.25 m
H/W Development	2 m	0
S/W Design	2.5 m	0
H/W Design	1.5 m	0
System Design	1.5 m	1 m
Product Dev. Time	14.5 m	2.75 m

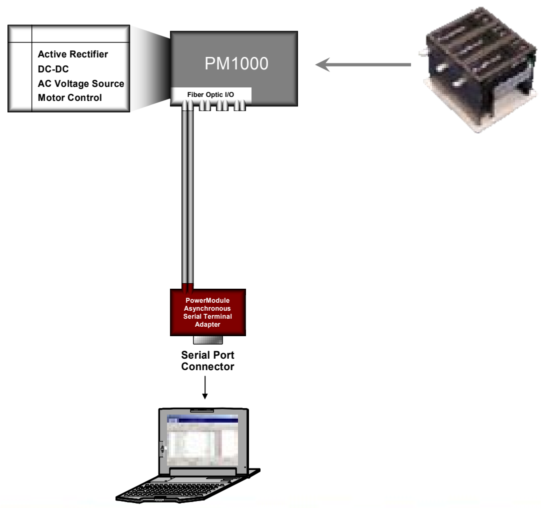
Δ = 11.75 m



Simplify Power Electronic System Development



PM1000 Product Developer Kit – PDK

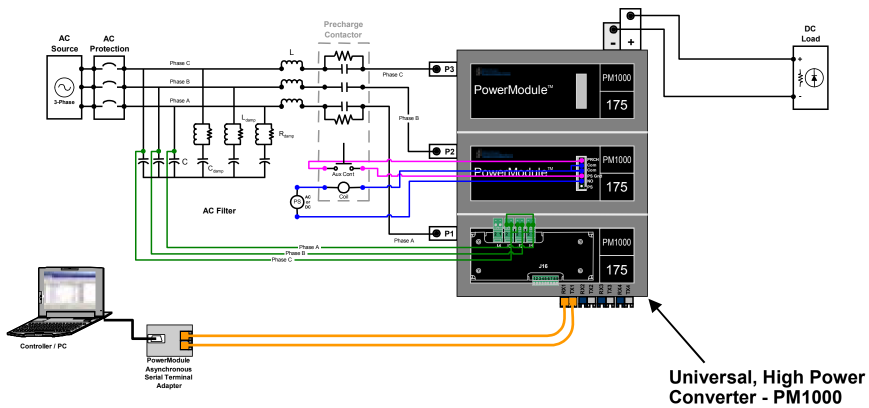


9 American Superconductor

PM1000 PDK

10 American Superconductor

PM1000 PDK – Active Rectifier



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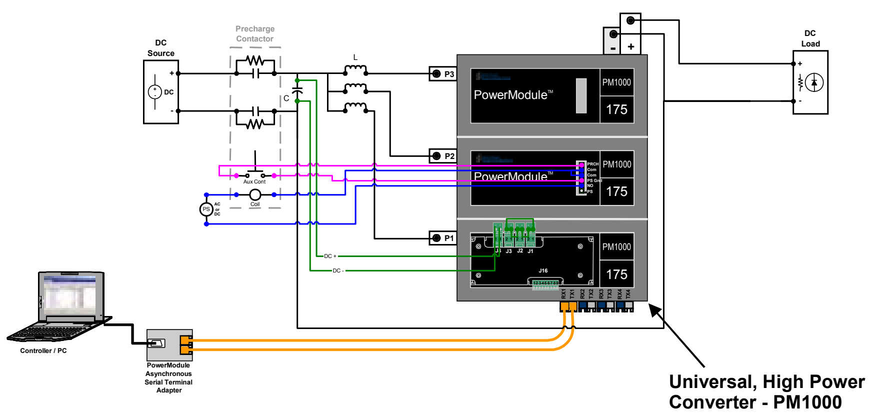
PM1000 PDK – DC/DC Boost



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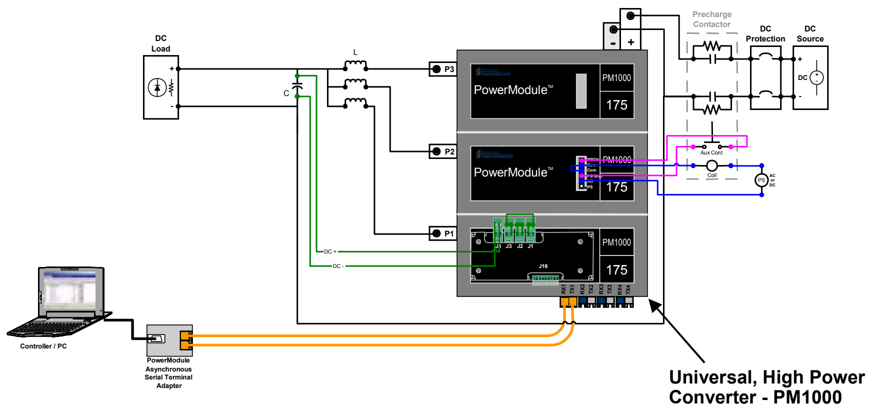
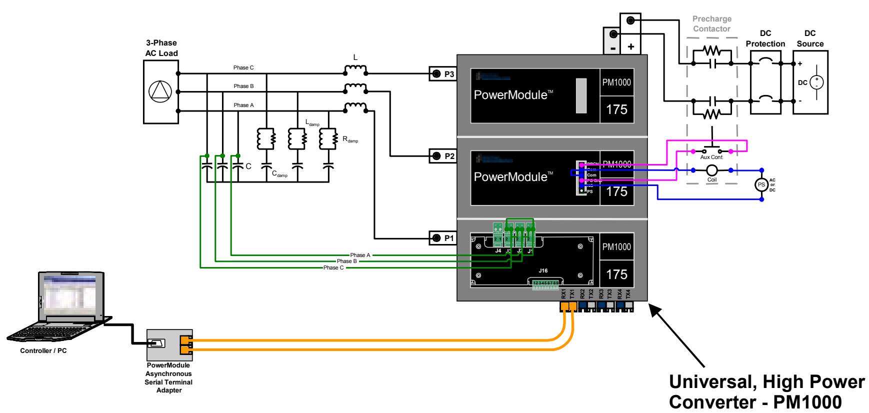
PM1000 PDK – DC/DC Buck

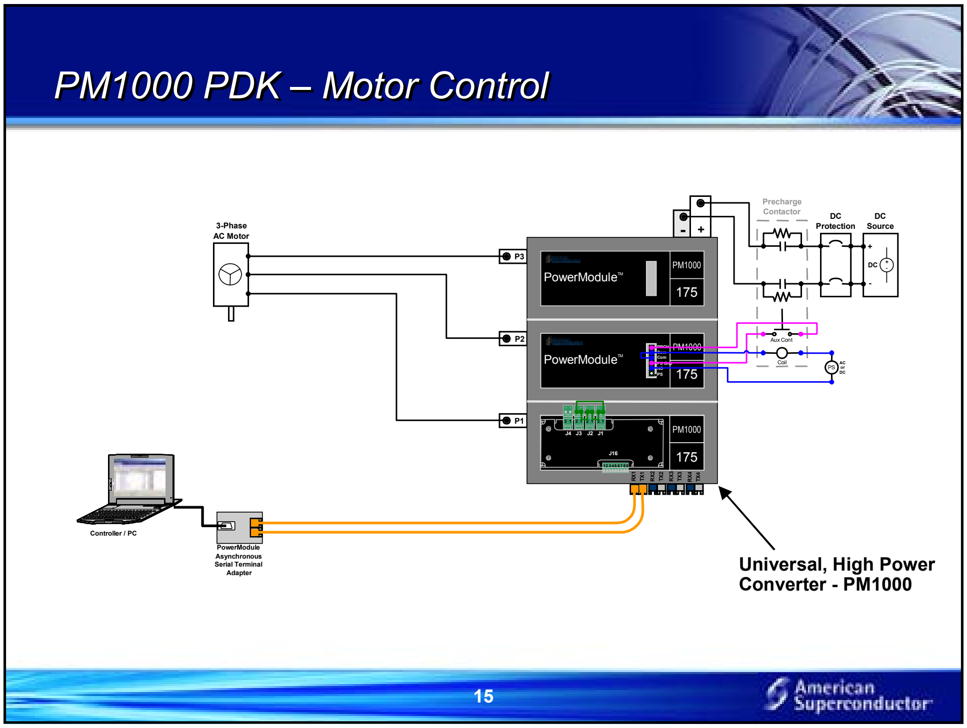


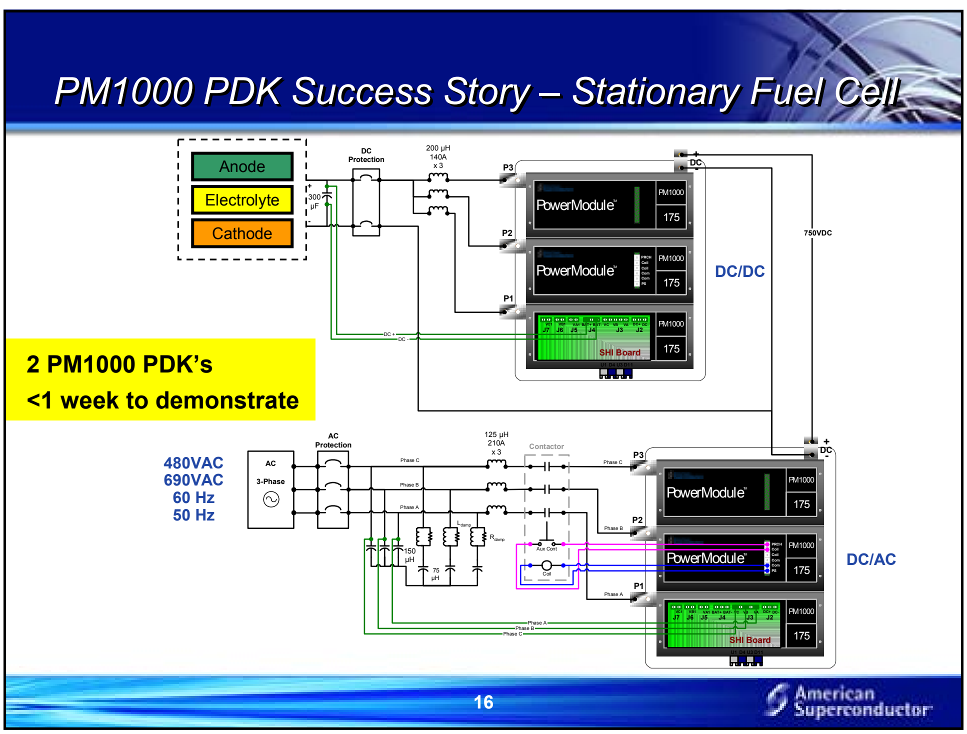
13

PM1000 PDK – AC Voltage Source



14

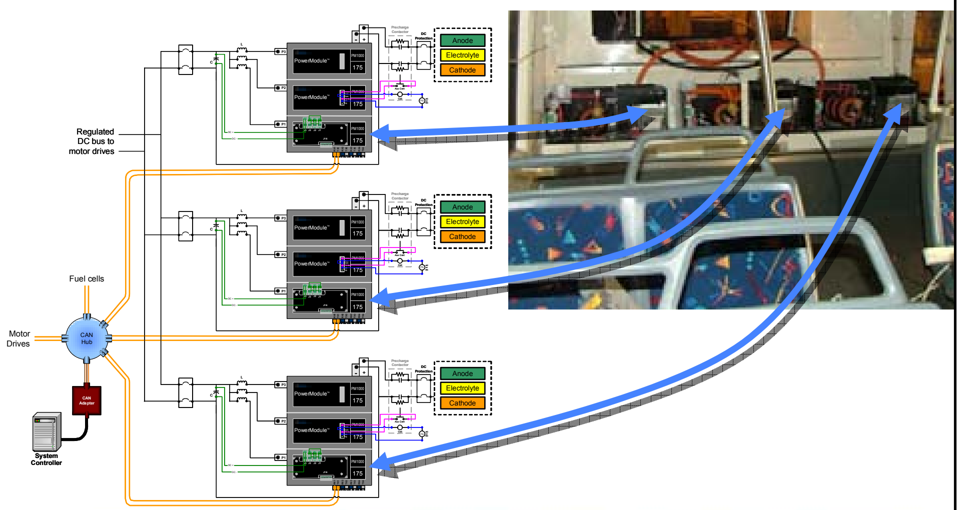

PM1000 PDK – Motor Control
3-Phase
AC Motor
Precharge
Contactor
DC
Protection
DC
Source
P3
P2
P1
PowerModule™
PM1000
175
Controller / PC
PowerModule
Asynchronous
Serial Terminal
Adapter
Universal, High Power
Converter - PM1000
15
American
Superconductor


PM1000 PDK Success Story – Stationary Fuel Cell
Anode
Electrolyte
Cathode
DC
Protection
200 µH
140A
x 3
300
µF
P3
P2
P1
PowerModule™
PM1000
175
SHI Board
750VDC
DC/DC
2 PM1000 PDK's
<1 week to demonstrate
480VAC
690VAC
60 Hz
50 Hz
AC
3-Phase
AC
Protection
125 µH
210A
x 3
Contactor
DC/AC
16
American
Superconductor

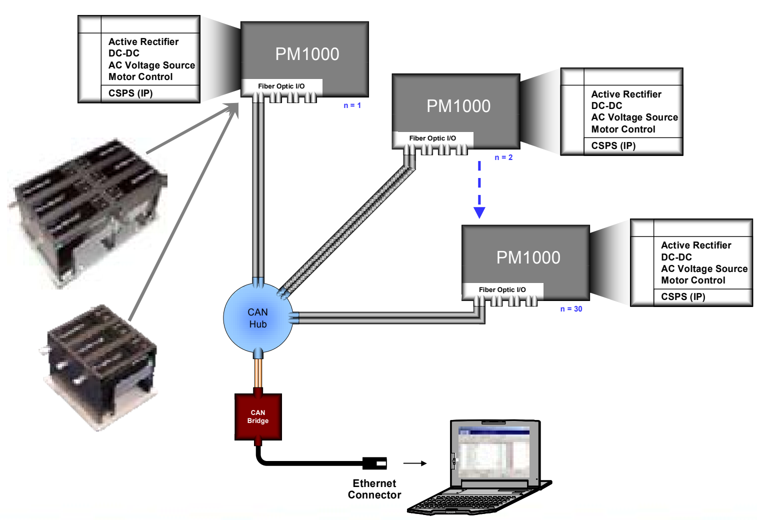

PM1000 PDK Success Story – Fuel Cell Bus
3 PM1000 PDK's
DC/DC boost converters
AMSC
17
American Superconductor

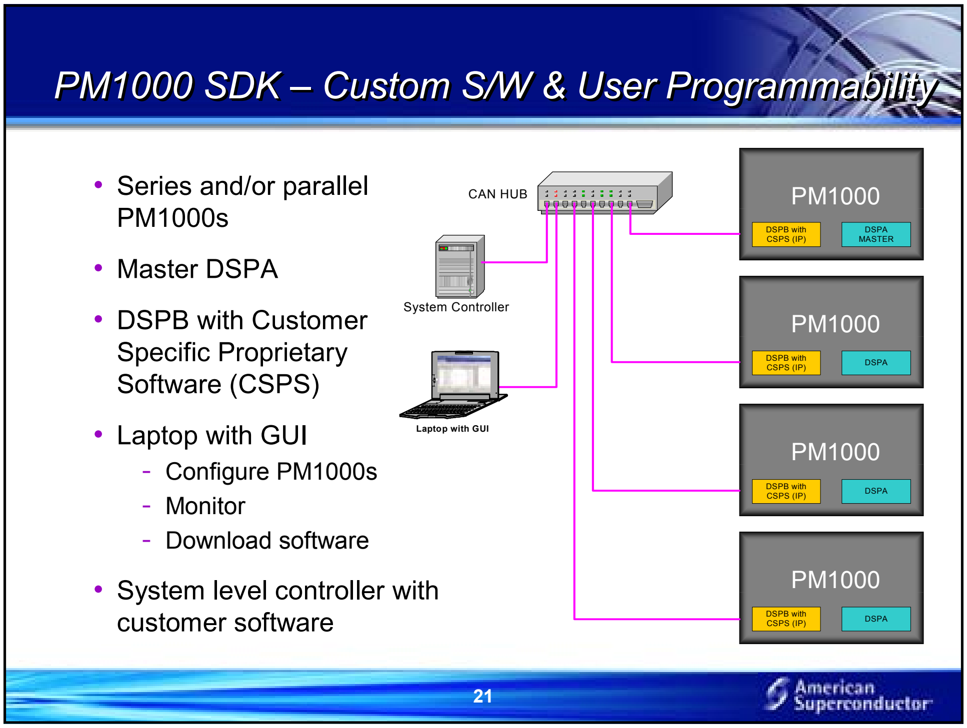

PM1000 PDK Success Story – Fuel Cell Bus
Anode
Electrolyte
Cathode
PowerModule
175
18
American Superconductor

PM1000 PDK Success Story – Fuel Cell Bus



PM1000 System Developer Kit – SDK




PM1000 SDK – Custom S/W & User Programmability
• Series and/or parallel PM1000s
• Master DSPA
• DSPB with Customer Specific Proprietary Software (CSPS)
• Laptop with GUI
– Configure PM1000s
– Monitor
– Download software
• System level controller with customer software
CAN HUB
System Controller
Laptop with GUI
PM1000
DSPB with CSPS (IP)
DSPA MASTER
PM1000
DSPB with CSPS (IP)
DSPA
PM1000
DSPB with CSPS (IP)
DSPA
PM1000
DSPB with CSPS (IP)
DSPA
21
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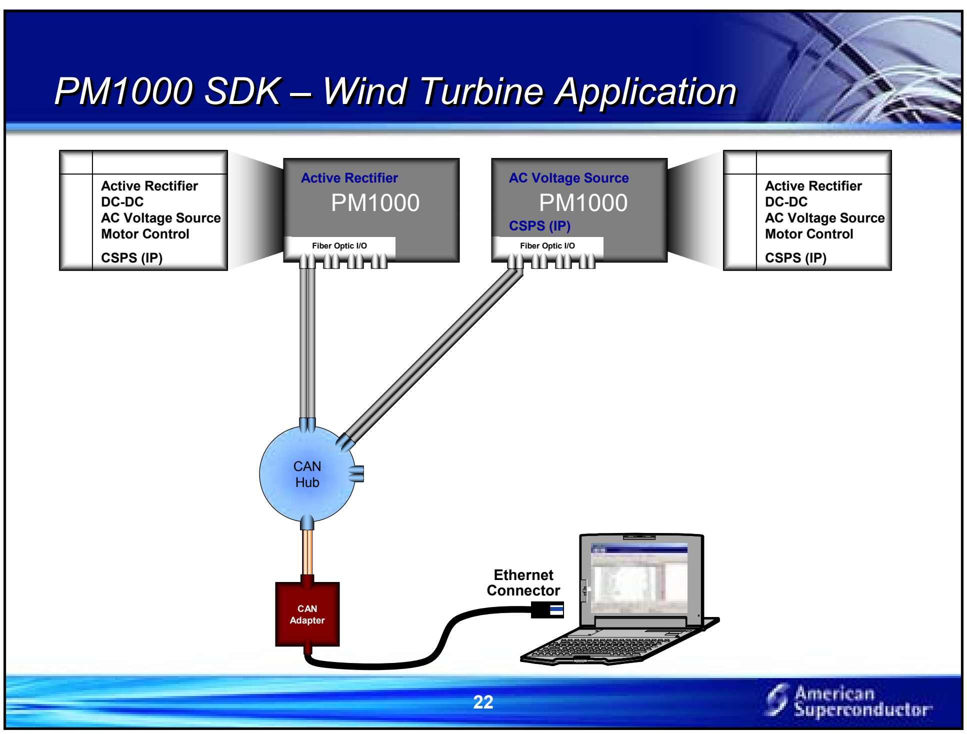
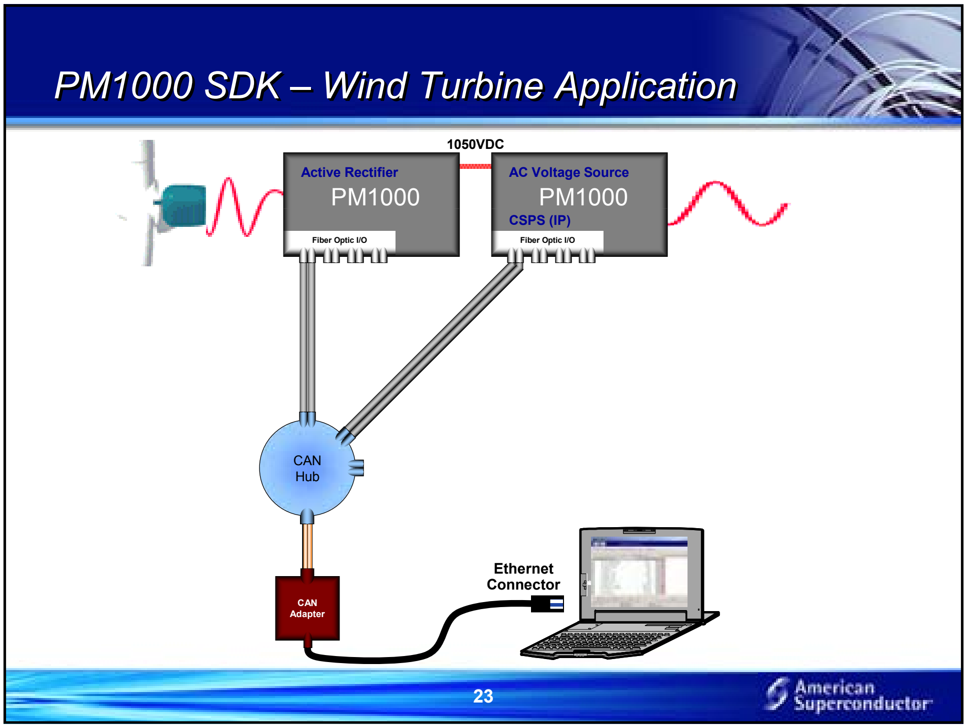
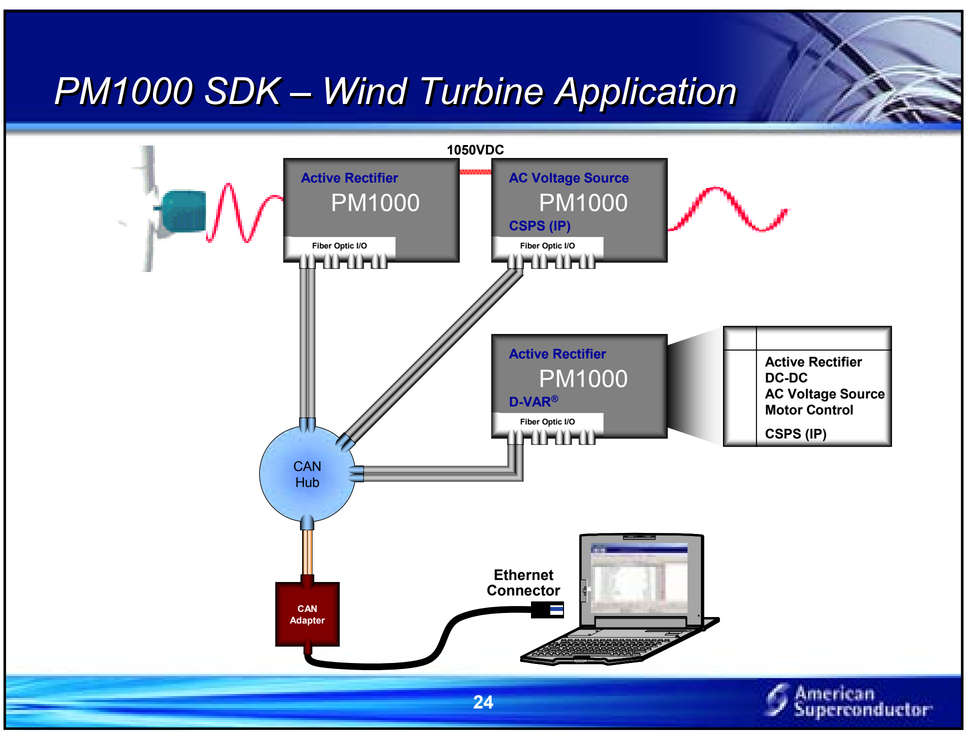

PM1000 SDK – Wind Turbine Application
Active Rectifier
DC-DC
AC Voltage Source
Motor Control
CSPS (IP)
Active Rectifier
PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
Active Rectifier
DC-DC
AC Voltage Source
Motor Control
CSPS (IP)
CAN
Hub
CAN
Adapter
Ethernet
Connector
22
American Superconductor


PM1000 SDK – Wind Turbine Application
1050VDC
Active Rectifier
PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
CAN
Hub
CAN
Adapter
Ethernet
Connector
23
American
Superconductor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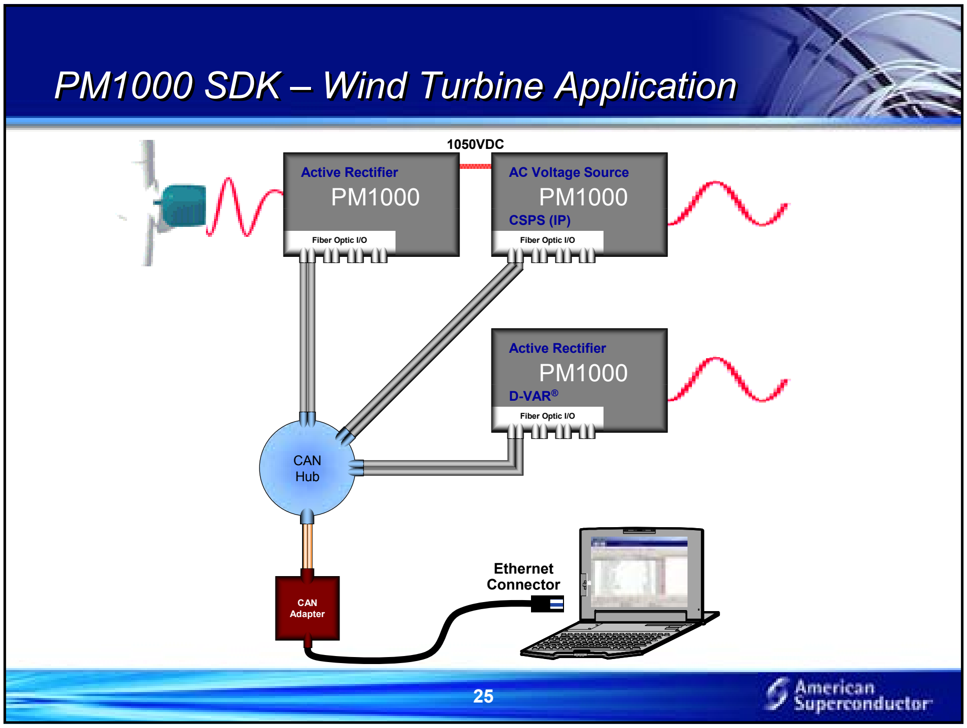
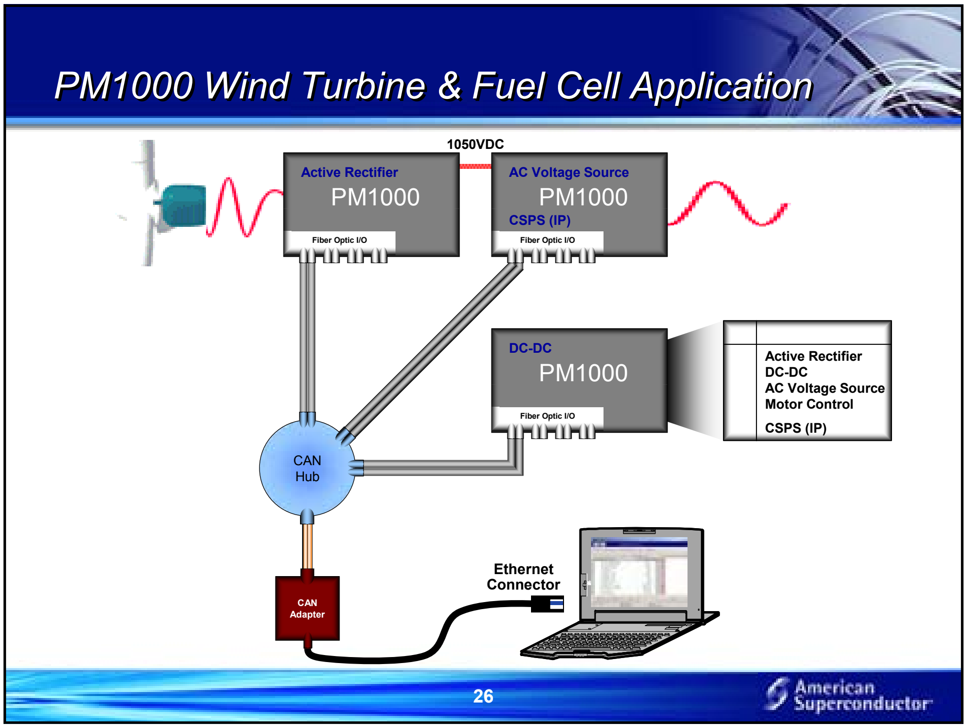
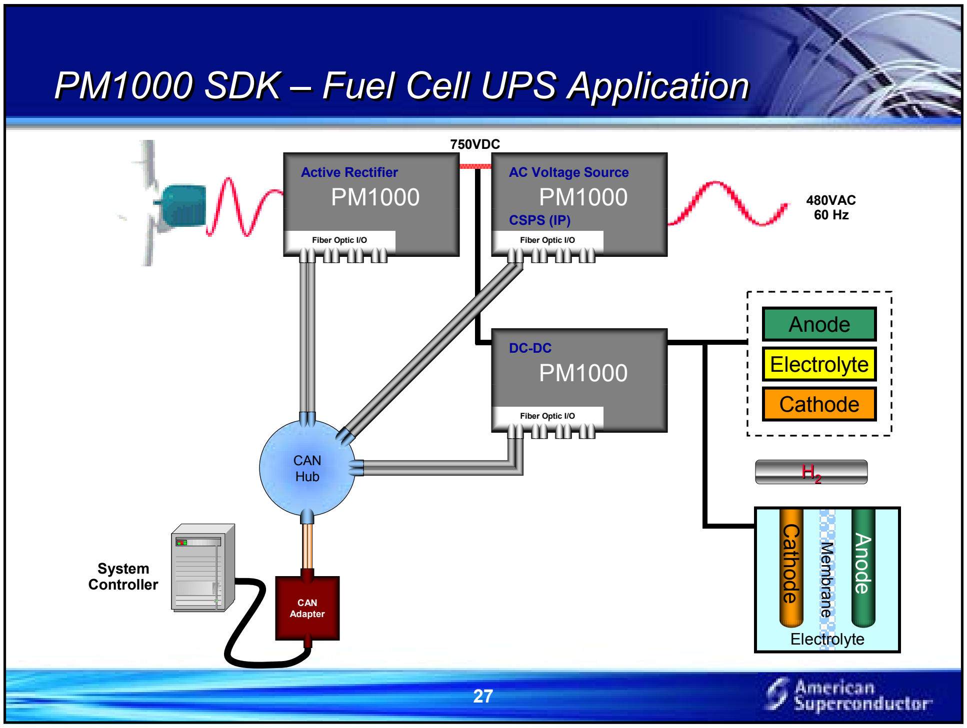
1050VDC
Active Rectifier
PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
Active Rectifier
PM1000
D-VAR®
Fiber Optic I/O
Active Rectifier
DC-DC
AC Voltage Source
Motor Control
CSPS (IP)
CAN
Hub
CAN
Adapter
Ethernet
Connector
24
American
Superconductor


PM1000 SDK – Wind Turbine Application
1050VDC
Active Rectifier
PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
Active Rectifier
PM1000
D-VAR®
Fiber Optic I/O
CAN
Hub
CAN
Adapter
Ethernet
Connector
25
American
Superconductor


PM1000 Wind Turbine & Fuel Cell Application
1050VDC
Active Rectifier
PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
DC-DC
PM1000
Fiber Optic I/O
Active Rectifier
DC-DC
AC Voltage Source
Motor Control
CSPS (IP)
CAN
Hub
CAN
Adapter
Ethernet
Connector
26
American
Superconductor


PM1000 SDK – Fuel Cell UPS Application
750VDC
Active Rectifier
PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
480VAC
60 Hz
DC-DC
PM1000
Fiber Optic I/O
Anode
Electrolyte
Cathode
H2
Cathode
Membrane
Anode
Electrolyte
CAN
Hub
System
Controller
CAN
Adapter
27
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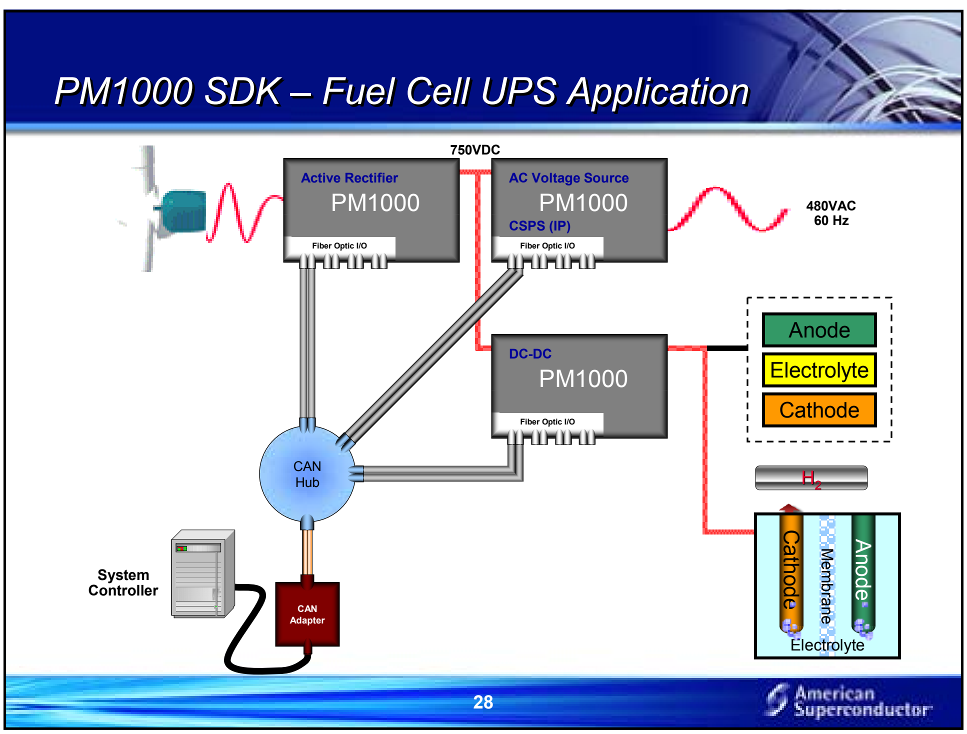
Superconductor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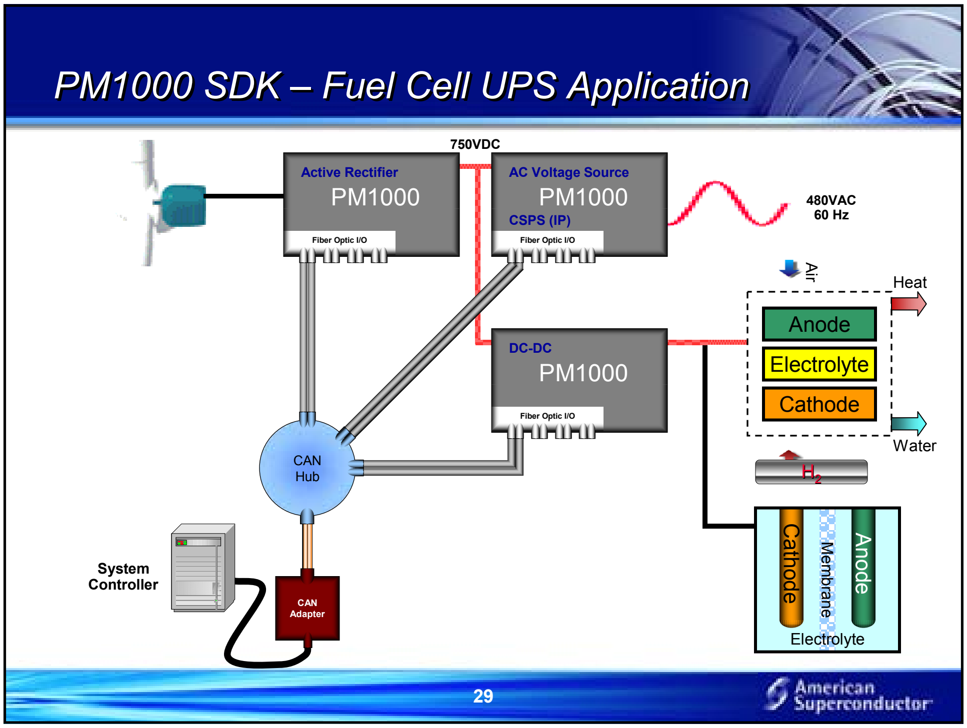
PM1000
CSPS (IP)
Fiber Optic I/O
480VAC
60 Hz
DC-DC
PM1000
Fiber Optic I/O
Anode
Electrolyte
Cathode
H2
Cathode
Membrane
Anode
Electrolyte
CAN
Hub
System
Controller
CAN
Adapter
28
American
Superconductor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750VDC
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PM1000
Fiber Optic I/O
AC Voltage Source
PM1000
CSPS (IP)
Fiber Optic I/O
480VAC
60 Hz
Air
Heat
Anode
Electrolyte
Cathode
Water
DC-DC
PM1000
Fiber Optic I/O
CAN
Hub
H2
Cathode
Membrane
Anode
Electrolyte
System
Controller
CAN
Adapter
29
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Superconductor


PM1000 2MW Generator Set Application
30
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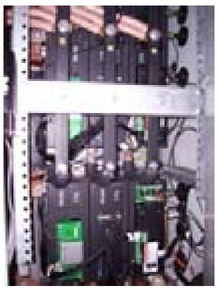
Superconductor

PM1000 Distributed Generation Applications

Wind Turbine	Generator Set	Fuel Cell
PM1000 provides power flow control of the wind turbine's output.	2MW gen-set using a high speed alternator and PM1000 for UK Ministry of Defense naval applications.	PM1000 used to provide a regulated output voltage from the fuel cell.
		

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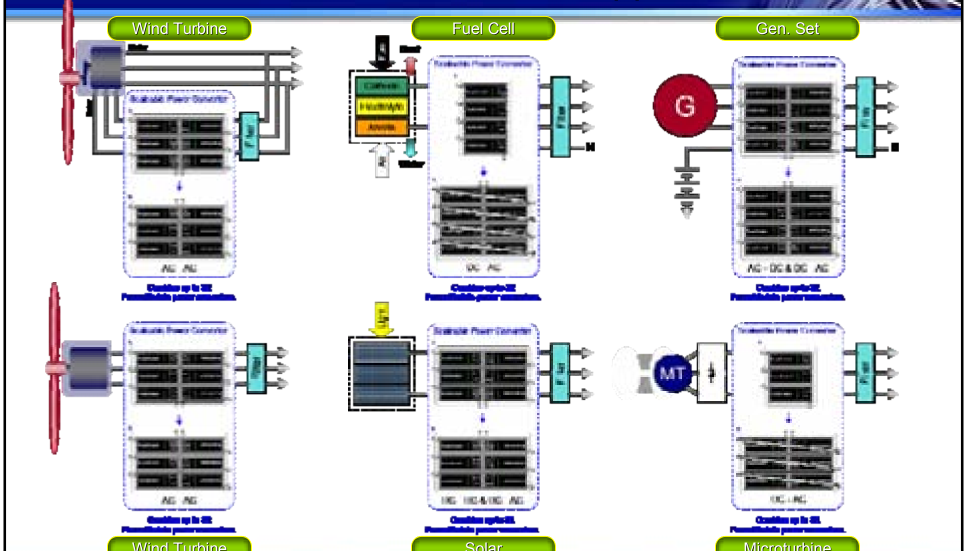
PM1000 Distributed Generation Applications



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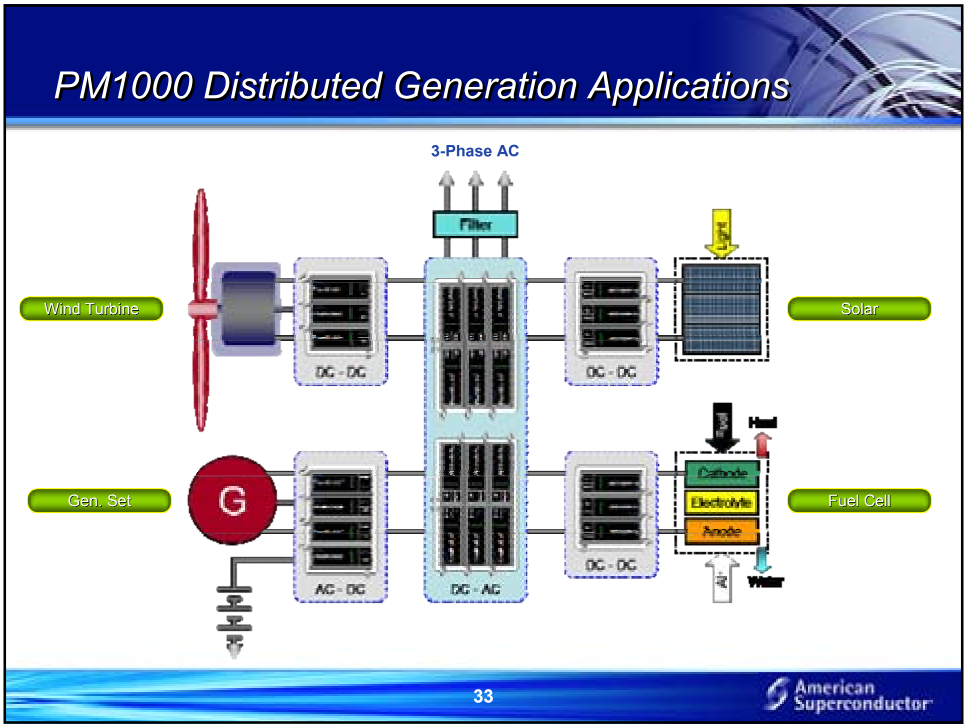

PM1000 Distributed Generation Applications
3-Phase AC
Filter
Wind Turbine
Solar
Gen. Set
G
Fuel Cell
DC - DC
DC - DC
AC - DC
DC - AC
DC - DC
Cathode
Electrolyte
Anode
Heat
Water
33
American Superconductor


PM2000
34
American Superconductor

Modular Inverters for Distributed Generation

Matthew Zolot

UQM Technologies

Presented at the Advanced Power Electronics Interfaces for DE Workshop

August 24th, 2006

Outline

- UQM Specialization
- Functional Specifications
- Design for Modularity
- System Integration Issues

Company Overview

UQM THE POWER IN POWER TECHNOLOGY

UQM Technologies is a technological leader in the development and manufacture of very high performance, power dense and energy efficient:

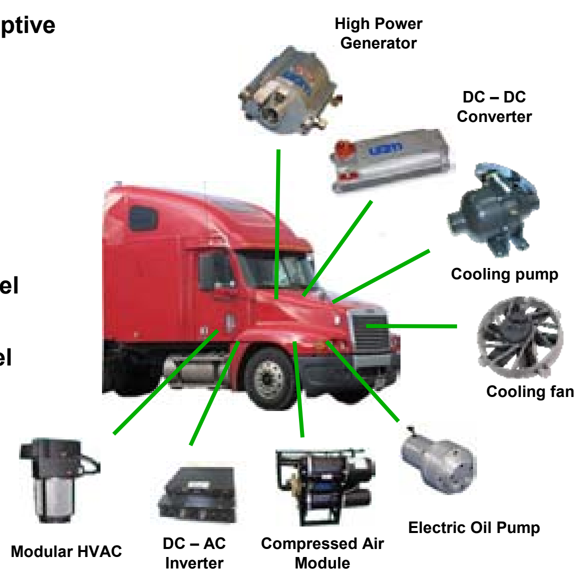
- **electric motors**
  - **generators**
    - **power electronic controllers**

for vehicle electrification.

Electrification of Engine-Driven Auxiliaries

UQM THE POWER IN POWER TECHNOLOGY

- **Easily adapted, non-disruptive**
- **Improved controllability**
- **Improved reliability**
- **More easily serviced**
- **Flexible architecture**
- **Available export power**
- **Key strategy to meet diesel emission mandates**
- **7-15% improvement in fuel economy**



UQM Core Competencies

- UQM products have technology advantages over conventional systems
  - *Power density*
    – smaller and lighter weight
  - *Efficiency*
    – consume less energy
  - *Performance*
    – eliminate gearing
    – adaptive software control
  - *Rugged*
    – automotive & military grade packaging

Motor Controller Example

UQM's experience with small, lightweight vehicle electronics helped us win this SBIR award

CD40-400L Controller

- DC to AC 3-phase motor / generator controller (4 quadrant)
- 140 kW maximum input (350 VDC, 400 ADC)
- 380 x 365 x 120 mm dimensions
- 16 kg weight
- Liquid (water/glycol) cooled

Outline

- UQM Specialization
- Functional Specifications
- Design for Modularity
- System Integration Issues

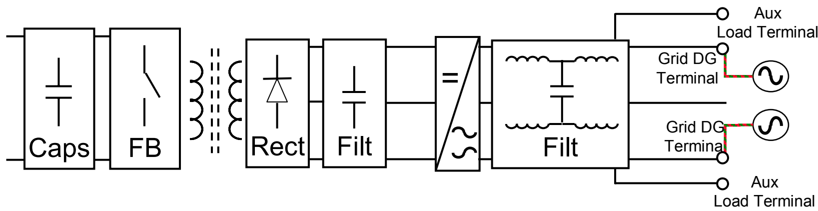
Bringing Unique Perspective to DG

- Plug-in varieties of Hybrid Electric Vehicles are getting a lot of attention these days.
- Automotive requirements for DG products will differ from stand-alone implementations.
  - High voltage
  - High density
  - Light weight
  - High efficiency
  - Rugged packaging &
  - Low Cost (key to automotive)

UQM DG Inverter Specifications:

- V_{in}: 150 – 360 V
- P_{out}: 250 – 5000W (3 - 1.7kW modules)
- Efficiency: >90%
- Galvanic Isolation
- Grid & Stand-alone operation, 50/60 Hz
- Standards: UL 1741, IEEE 1547, IEEE 519

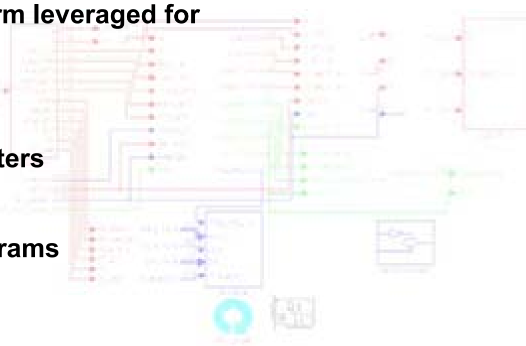
Overall Layout



Automated Control Code Generation

Mathworks Autocoding with DSP platforms

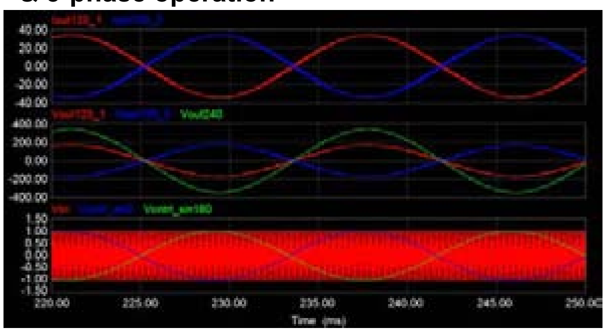
- **Existing and customized MATLAB blocks are used selectively to quickly develop new systems**
- **Popular Mathworks platform leveraged for system simulation**
- **Embedded safety features**
- **OEM configurable parameters**
- **Successfully used within several development programs**

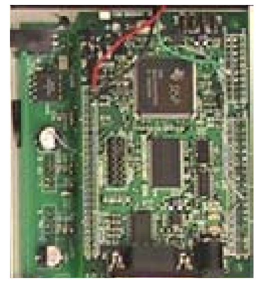


True Sine Wave AC Generation

Texas Instruments DSP platforms

- **Enables the use of advanced signal processing**
- **PWM based True Sine wave generation**
- **Software configurable for split-phase, in-phase, & 3-phase operation**





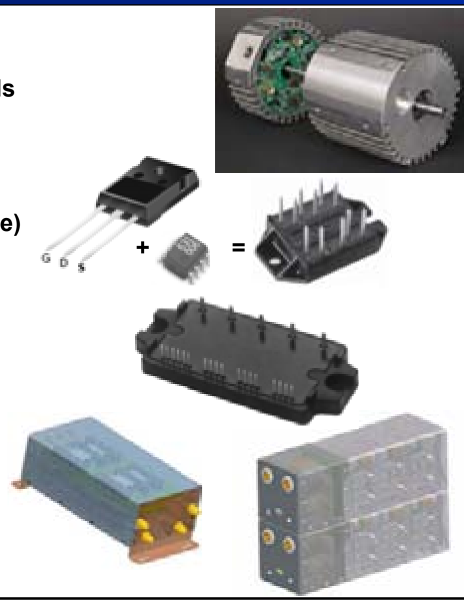
Outline

- **UQM Specialization**
- **Functional Specifications**
- **Design for Modularity**
- **System Integration Issues**

Modular Inverter – Design Trade-offs

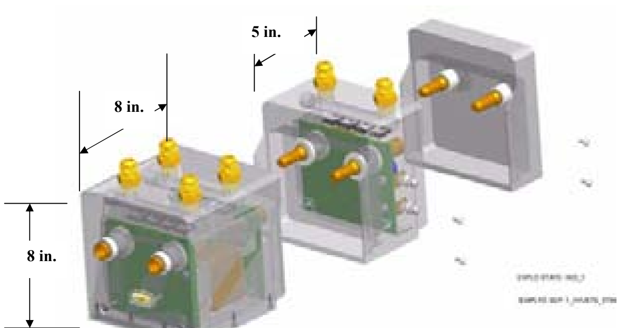
THE POWER IN POWER TECHNOLOGY

- Higher component integration levels vs. discrete components on FR4
  - Highly dependant on operating specifications (P, I, V)
  - Cost (top priority for Automotive)
  - Packaging density
  - Performance (High frequency, inductance, trace lengths, etc.)
- Level of Modularity {PEBB}
  - Component Level
  - Board Level
  - Package Level



Modular Inverter – Initial Design (Base Package)

THE POWER IN POWER TECHNOLOGY



DC-DC module 8x8x8”   Inverter modules 8x8x5” respectively

- High frequency, Isolated DC-DC front end: 5kW
  - Capable of stand-alone operation
- Modular Inverter (up to 3 modules, each 1.7kW)
- Liquid Cooled (automotive variety)

Modular Inverter – Interconnection Potential

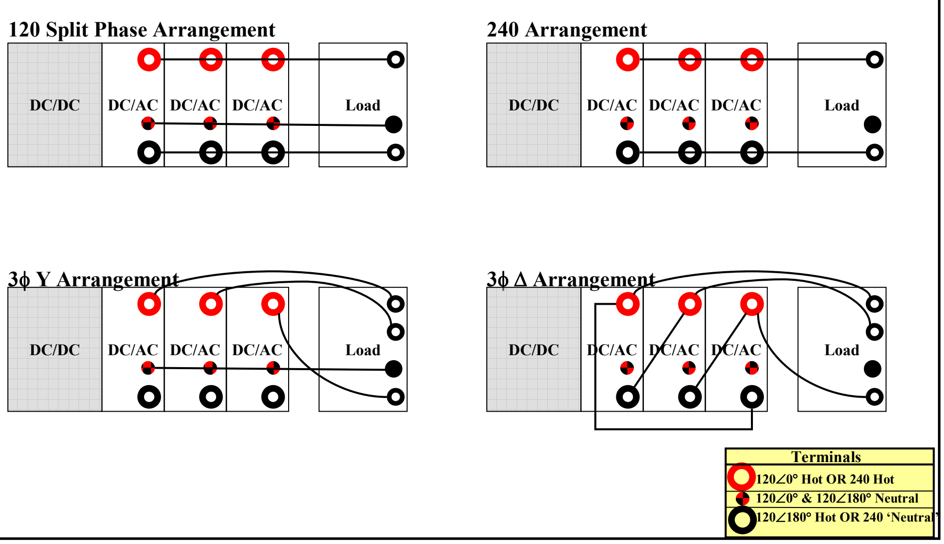
1.67 kW Inverter

5 kW Inverter

10 kW Inverter

- **Sub-Block Modularity**
  - 1.7 kW, 3.4 kW, or 5 kW at 120/240 VAC 60 Hz single phase, or 5 kW 3-phase
- **Block Modularity**
  - 5 kW, 10 kW, etc… operation

Functional Modularity



Outline

- UQM Specialization
- Functional Specifications
- Design for Modularity
- System Integration Issues

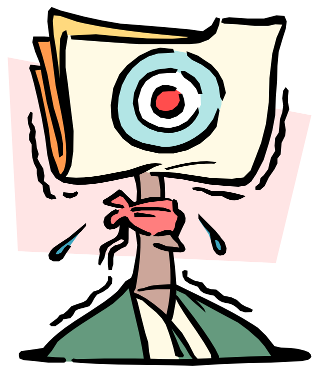
Challenges to Going Modular

- Goal: prevent redesign/modifications for every unique implementation
  - Enable higher volumes and reduced costs

Challenges:

- Evaluate mechanical connections for all types of terminal requirements (Input & Output)
- Communication: between modules & packages
- Anti-Islanding: Identification and prevention
- New market: will the egg grow into a Chicken?

Questions?



MAGNETEK UNCOMMON POWER

Power Electronics Conversion for Distributed Energy Applications

By: Dr. Alex Levran
EVP & CTO, Magnetek Inc
CEC & NREL

www.alternative-energies.com

Overview:

- **Technology**
- **Applications and Products**
  - Wind
  - PV
  - Variable Speed
  - Energy Storage
  - Fuel cells
- **Future Trends**

Magnetek Inc - Fast Facts

Headquarters: Los Angeles, CA (USA)

Listed on NYSE, ticker MAG

Sales >$250M

1,500+ Associates worldwide

7 plants in Europe, North America, Asia

Core Technology: Power Electronics Conversion

Embedded products and Systems

Distributed Energy Technologies

- **Wind**
  - Large farms compete with central generation
  - Residential applications <10kW
- **Photovoltaic**
  - Growing Commercial and residential applications.
  - Lower cost materials and manufacturing processes for PV panels key to increased market penetration
- **Energy Storage**
  - Full range of batteries, flywheels and ultra-capacitors evolving for managing transients, compressed air,SMES
- **Fuel Cells**
  - Automotive applications key to small-scale FC economics
  - Limited success in commercial and telecom
- **Variable Speed Generation**
- **Microturbines**
  - Lower cost, higher reliability critical for market expansion

Power Electronic Conversion - Requirements

- Grid Connection
  - Anti Islanding, kVAR control, Unbalance/Nonlinear Loads
  - Low and medium voltages
  - Power Quality and Harmonic Distortion (IEEE 519)
  - IEEE 1547 Standard for Interconnecting Distributed Resources with EPS.
  - DC current injection (w/o transformer)
- Higher Efficiencies
  - Power Conversion
  - Energy Harvesting
- Mechanical Packaging
  - Parallelable, scalable designs
  - Indoor and outdoor applications
  - Thermal management : air and liquid cooling
  - Compact designs, higher power densities
- Improved Reliability
- Cost competitiveness
- Communication and Remote Monitoring
  - Power Line and/or RF Communication
  - SCADA and GIS interfaces

Power Electronic Inverters Technology

- **Converters/Inverters Topology:**
  - Voltage source for stand alone. Current Source for grid connected operation
  - Sinusoidal PWM,multi(three) level or space vector modulation.
  - Low or high frequency galvanic isolation
  - Non-controlled and active rectifiers. Buck /Boost Converters.
  - Unidirectional and bidirectional architectures/operations.
  - System integration configurations: cascade inverters, cascade rectifiers, cascade total conversion systems
- **Control Circuits and Algorithms (digital):**
  - Voltage, Current and Frequency Control
  - Power Flow Control
  - Real and Reactive Power Sharing
  - Protection Circuits
- **Local and Remote Communication Protocols** (supervision, controls, and monitoring)

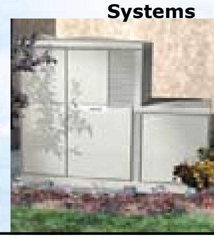
Strategy: To lead the market of power electronic interfaces for alternative energy systems.

- High reliability and efficiency power converters
- Primary energy source control
- Grid interface know-how (grid tied, stand alone, hybrid)
- High power density and compact size
- System level control
- Modular design for multiple sources (PV, wind,FC).
- Scalable design. common building blocks & platforms

Photovoltaic Systems

Wind Generators

Fuel Cell Systems



Microturbines and Variable Speed Distributed Generation

Wind Power Conversion

COMPLETE POWER INTERFACE FOR SMALL POWER WIND SYSTEMS

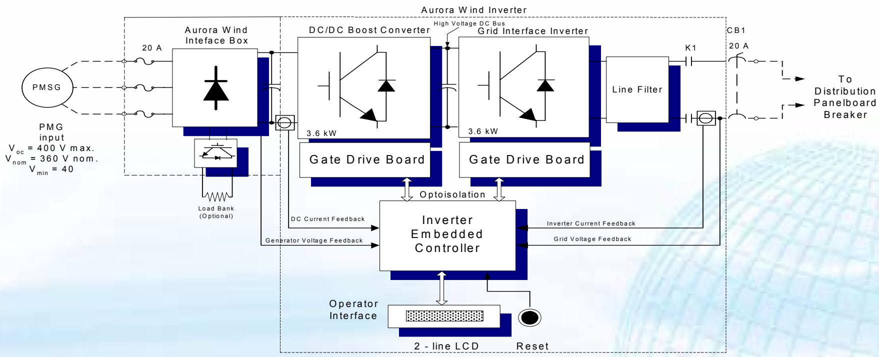
- Up to 10kW
- Most compact design available on the market
- Stand Alone and Grid-tied operating modes
- Optional Photovoltaic and Genset inputs
- Split phase inverter for worldwide 110V/60Hz or 220V/50Hz operation
- Aurora PV platform with minor change.
- Parallelable.
- Advanced communication

POWER CONVERTER FOR LARGE POWER WIND SYSTEMS

- Up to 3.0 MW
- DSP based digital control
- Parallel multiple 625 kW inverters

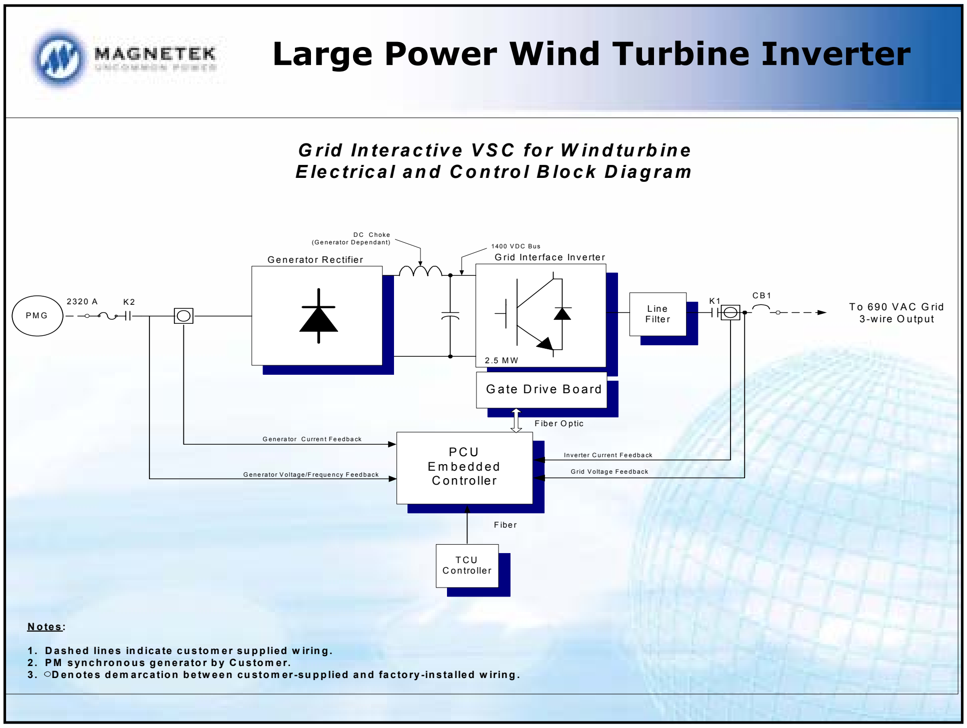
Small Power Wind Inverter Topology

Grid Interactive Inverter System for Small Wind Turbine Electrical and Control Block Diagram



Large Power Wind Turbine Inverter

- **Typical Characteristics:**
  - Output Voltages: Low to medium
  - Grid Connection: UL1741 or Stand Alone
  - Indoor and outdoor designs. Air and water cooled designs.
- **Topology:**
  - Full bridge rectifier
  - Voltage fed three phase inverter with adjusted current
  - Three Level Inverter or Space Vector Modulation
  - Bi-directional conversion for doubly fed generators.
- **Features:**
  - High efficiency (>97%)
  - Low THD meets IEEE 519
  - Modular and scalable designs
  - Enhanced voltage regulation
  - Compact design
  - Advanced communication
  - Closed loop controls with the turbine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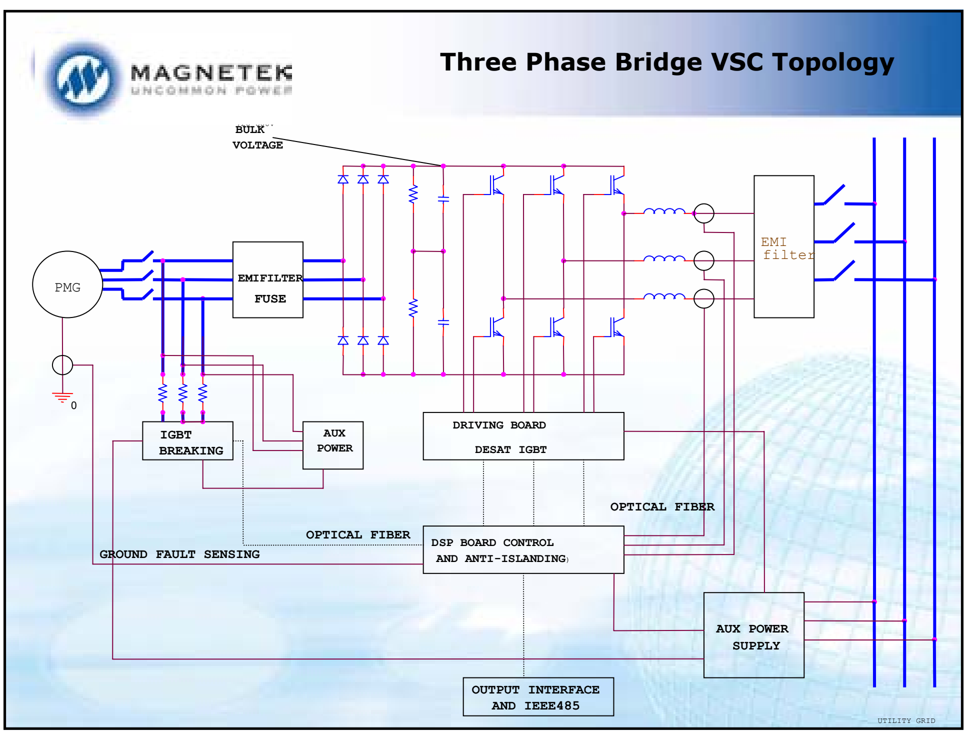
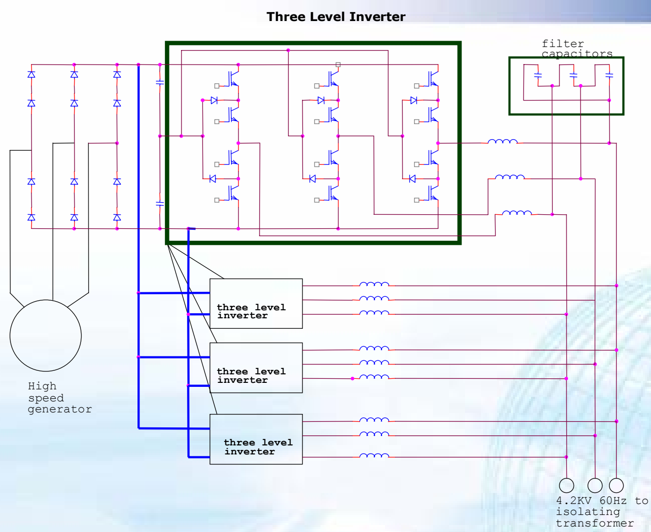
UNCOMMON POWER
Large Power Wind Turbine Inverter
Grid Interactive VSC for Windturbine
Electrical and Control Block Diagram
DC Choke
(Generator Dependant)
1400 VDC Bus
Generator Rectifier
Grid Interface Inverter
PMG
2320 A
K2
K1
CB1
Line
Filter
To 690 VAC Grid
3-wire Output
2.5 MW
Gate Drive Board
Fiber Optic
Generator Current Feedback
Generator Voltage/Frequency Feedback
Inverter Current Feedback
Grid Voltage Feedback
PCU
Embedded
Controller
Fiber
TCU
Controller
Notes:
1. Dashed lines indicate customer supplied wiring.
2. PM synchronous generator by Customer.
3. ○Denotes demarcation between customer-supplied and factory-installed wiring.


MAGNETEK
UNCOMMON POWER
Three Phase Bridge VSC Topology
BULK
VOLTAGE
PMG
0
EMIFILTER
FUSE
EMI
filter
IGBT
BREAKING
AUX
POWER
DRIVING BOARD
DESAT IGBT
OPTICAL FIBER
OPTICAL FIBER
GROUND FAULT SENSING
DSP BOARD CONTROL
AND ANTI-ISLANDING
AUX POWER
SUPPLY
OUTPUT INTERFACE
AND IEEE485
UTILITY GRID

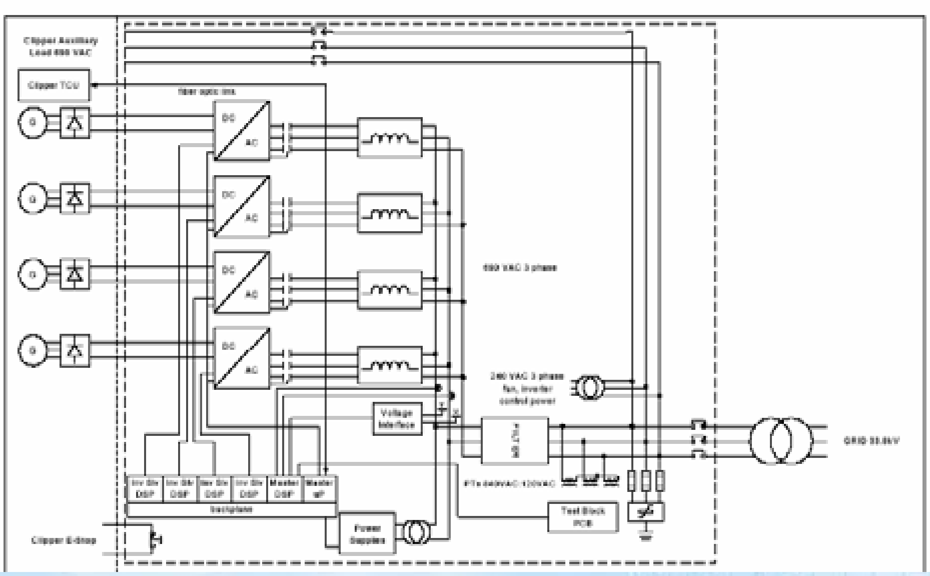
Three Phase Tri-level Inverter

MAGNETEK



Large Power Wind Turbine Inverter(>2.5MW)

MAGNETEK



Advantages of Large Wind PMG Turbine- Up to 5.0 MW

Variable Speed Converter (VSC) Value Proposition

Advantages of Full Scale Conversion with PMG (Permanent Magnet Generator):

Increase efficiency of 7 1/2% over wound rotor technology for variable speed:

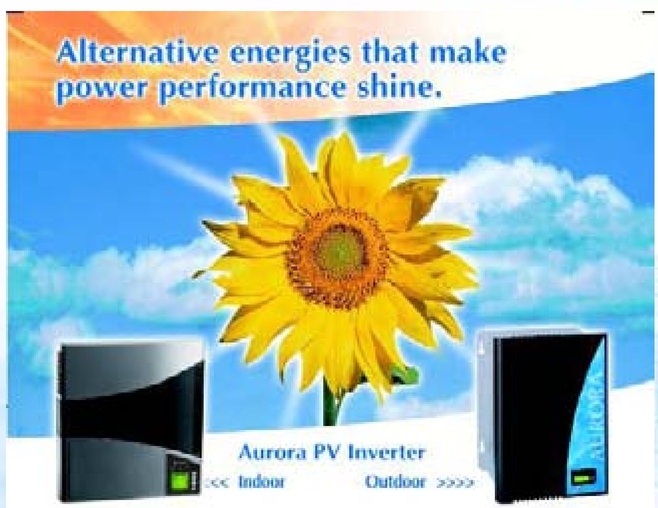
- PMG Generator 3% more efficient than the Wound rotor induction generator
- PMG is 1/3 the size and cost
- Gear box 1/2 the size and cost, while 2% more efficient
- Converter is 2 1/2 % more efficient and 1.5 x cost
- Wound rotor systems in the 2 MW range are $.047 kWh vs. $.032 kWh with Full conversion utilizing PMG
- Avoids infringements of current IP
- No brushes as with wound rotor generators for higher reliability

.

Photovoltaic Power Conversion

AURORA PHOTOVOLTAIC INVERTERS

- Up to 6000W
- Top level performance
- Indoor and Outdoor models
- Advanced remote communications

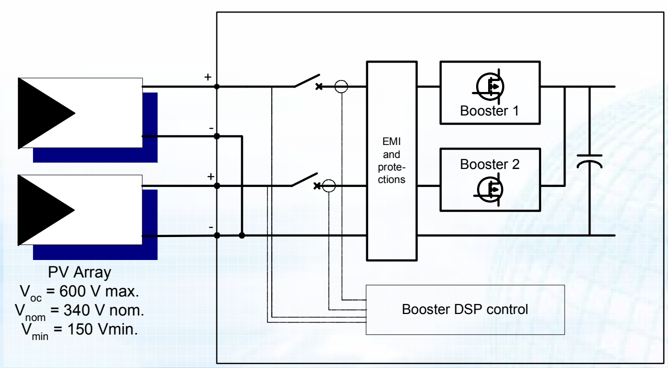


Residential Photovoltaic Inverters

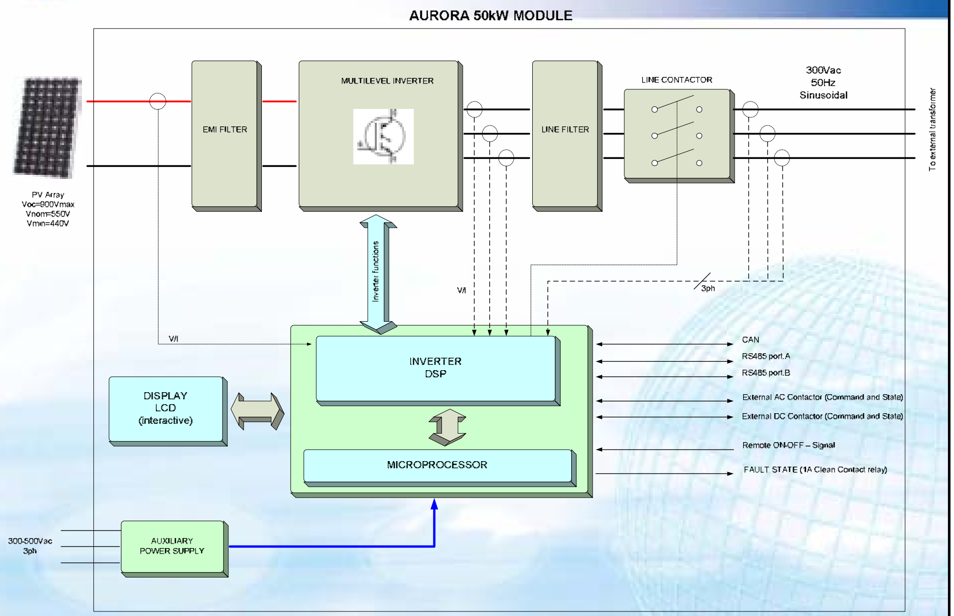
- **Topology:**
  - Single or multi-string conversion
  - Typical Architectures:
    - Boost converters with DC link and PWM full bridge inverter with or without low frequency transformer isolation (grounded PV panels)
    - Single inversion stage with low frequency transformer for galvanic isolation and voltage adjustment.
- **Typical Performance:**
  - Power Ratings: 500W to 8000W
  - Wide open circuit voltage range from 90VDC to 600VDC
  - High efficiency: Exceeding 96%
  - Cost competitive, high power density design
  - Harmonics: meets IEEE 519 spec
  - Grid connected operation: Meets UL 1741 and VDE requirements.
  - High overload capabilities, operates at high temperatures, and anti-islanding protection
  - Packaging: Indoor meets Nema2(IP21) and outdoor meets Nema4(IP65)
  - Advanced local and remote communications and continuous data logger

Optimal Performance

Aurora higher power models are Multistring inverters with two independent and fast Maximum Power Point Tracking (MPPT) inputs



Commercial PV Inverter



Commercial Photovoltaic Inverters

- **Topology:**
  - Full Bridge with PWM or multilevel controls and topologies.
  - Parallel-able with advanced master/slave assignment algorithm
- **Typical Performance:**
  - Power Ratings: 30kW to 250kW. 50kW modules
  - Wide open circuit voltage range from 300VDC to 600VDC or 400VDC to 900VDC
  - High efficiency: Exceeding 97%
  - Advanced MPPT algorithm to harvest higher energy
  - Cost competitive, high power density design
  - Harmonics: meets IEEE 519 spec. Low DC current components.
  - Grid connected operation: Meets UL 1741 and VDE requirements.
  - High overload capabilities, operates at high temperatures, and anti-islanding protection
  - Packaging: Indoor meets Nema2(IP21) and outdoor meets Nema4(IP65)
  - Advanced local and remote communications and continuous data logger
  - Output transformer section (low frequency, low and medium voltages)

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Multimode Wind Converters

- **Typical Characteristics:**
  - Multi mode operation: Grid Connected, Stand-alone, UPS
  - Universal Inverter: Single phase 230VAC, 110VAC, 50Hz and 60Hz
  - Multi Source: Wind, PV (max 420VDC), Gen-sets (115VAC split phase 230VAC, 10%), batteries (48V/110A or 110V/50A).
- **Topology:**
  - Two stage conversion: DC/DC converter and single phase full bridge inverter.
- **Typical Performance:**
  - Power Ratings: 2500W to 6000W
  - High efficiency: Exceeding 90% from renewable source and 92% from Battery.
  - Cost competitive compact design
  - Harmonics: meets IEEEE 519 spec
  - Grid connected operation: Meets UL 1741 requirements
  - Advanced local and remote communications

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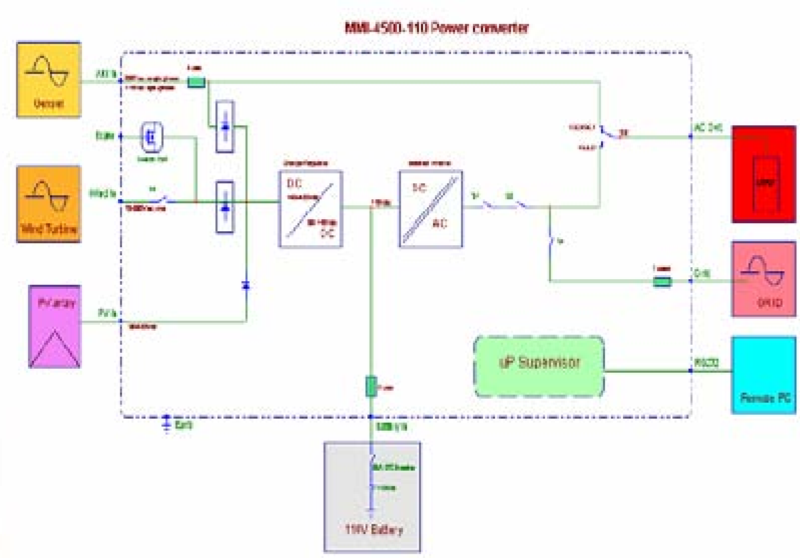
Stand-Alone Single Phase Converter



Microturbine - Compact Power Generator

- 50kW and 100kW
- Easily Transportable (light and small)
- High Reliability
- High Power Quality
- Reduced emissions
- Cogeneration
- Versatile

Fuel Cell Inverters

COMPLETE POWER INTERFACE FOR FUEL CELL SYSTEMS – RESIDENTIAL AND AUTOMOTIVE APPLICATIONS

- PCS – 2000W to 7400W
- Stand Alone and Grid-tied operation
- Auxiliary output for start-up phase of fuel cell stack
- Split phase inverter for worldwide 110V/60Hz or 220V/50Hz operation

COMPLETE POWER INTERFACE FOR FUEL CELL SYSTEMS – INDUSTRIAL APPLICATIONS

- PCS-3: 300 kW
- Grid tied and stand alone operating modes
- MULS (Multiple unit load sharing) up to six units
- Seamless transition with optional static switch

MAGNETEK UNCOMMON POWER

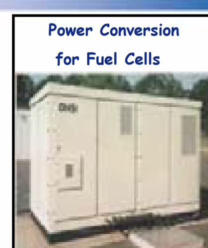
Fuel Cell Inverter Technology

- **Typical Characteristics:**
  - Convert DC output voltage from fuel cell module to three phase AC voltage.
  - Supports different fuel cell source technologies: Phosphoric Acid, Proton Exchange Membrane, Molten Carbonate, and Solid Oxide.
- **Topology:**
  - Two stage conversion. Three phase inverter PWM inverter.
  - Space vector modulation or sinusoidal PWM
- **Features:**
  - Indoor or outdoor designs.
  - Water cooled or air cooled
  - Efficiency over 93%
  - Harmonics: meets IEEE 519
  - Parallelable, scalable designs
  - Connection: stand-alone or grid connected UL 1741
  - Remote monitoring an control

MAGNETEK UNCOMMON POWER

Large Scale Fuel Cell Inverters > 200kW

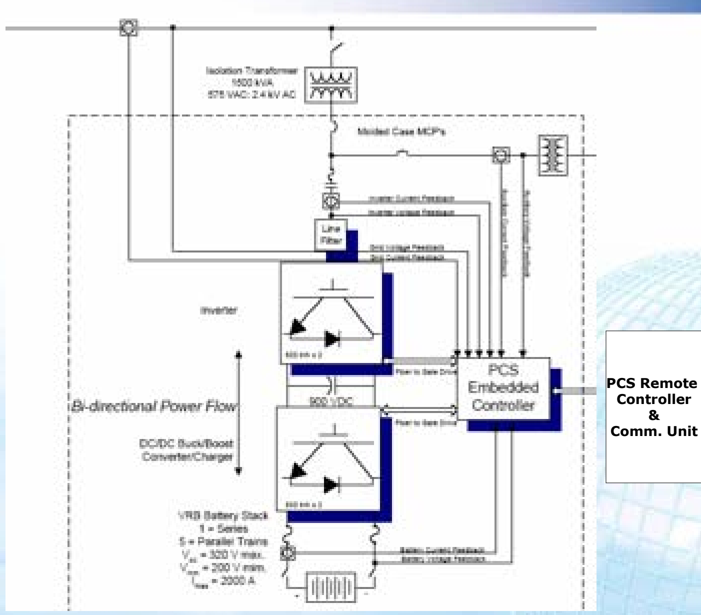
- UTC Fuel Cells: 200 kW, (160)
- Installed base exceeds 32 MW
- Other customers: 300kW modules



Energy Storage Converters

- **Applications:**
  - Load Leveling
  - Power Quality and Energy Management
  - Integration with renewable energy sources for enhanced efficiency and higher capacity
- **Sources:**
  - Batteries: Lead Acid, Sodium Sulphur-NAS, Nickel Cadmium(Ni-Cd), Nickel Metal Hydride(Ni-MH), Vanadium Redox (VRB), Lithium Ion(Li-Ion)
  - Flywheels,Compressed air storage
  - Superconductive Energy Storage
- **Typical Topology:**
  - Bi-directional Two stage conversion: Back/Boost DC Converters and PWM Inverters with transformer isolation.
- **Performance Features and Controls:**
  - Power range: 200kW to 10MW
  - Charging/discharging control algorithms to extend battery life
  - High efficiency
  - Low harmonic distortion

Energy Storage Converters



Future Trends (>3years)

- **Inverter Technology:**
  - New Topologies (tri-level inverters) and improved control algorithms.
  - Higher voltage and current rating of IGBTs, and SiC components.
  - Improved thermal management devices (heat-sinks,
  - Improved driver and sensing circuits(fiber optical)
  - Improved capacitors and magnetic devices
  - Will drive:
    - Higher conversion efficiency, higher power density, higher reliability
    - Higher voltage (Medium), higher power, lower cost
- **Expansion of Modular designs:**
  - Flexibility of installation and application
  - Scalability
  - Multiple sources of energy, similar platforms (Topologies)
- **Improved Communication:**
  - Enhanced maintenance and service
- **Hybrid Systems:**
  - Combination of PV and Wind with advanced energy storage devices for better power quality and back-up power applications

Smart choice for power

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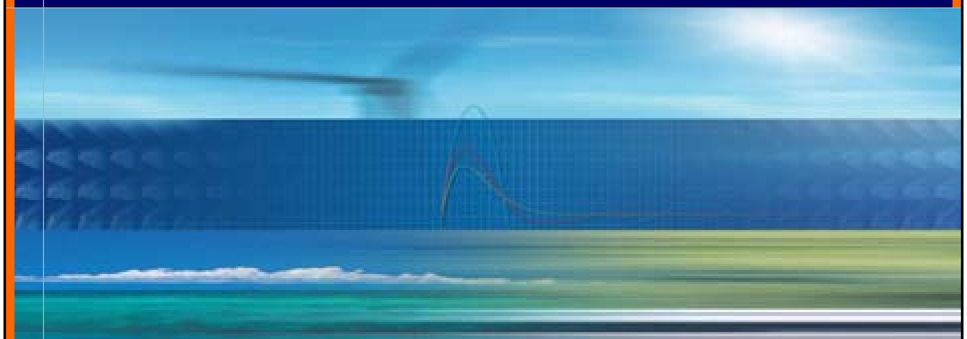

Xantrex Power Electronics for Renewable Energy System Applications

Ray Hudson
Vice President Advanced Technology
ray.hudson@xantrex.com

xantrex

Outline

- Xantrex Overview
- Renewable Energy Power Electronic Converter Products
  - Residential Solar – Grid Tied
  - Residential Solar – Off-Grid/Backup
  - Industrial/Commercial Solar – Grid Tied
  - Wind
  - Others
- Future Direction

2

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Xantrex Overview

Offices	Livermore, CA, San Luis Obispo, CA, Burnaby BC, Arlington WA, Elkhart IN, Barcelona Spain, Reading England, Beijing China
Manufacturing	Livermore CA, Burnaby BC, Arlington WA, Dominican Republic, China (4 Outsourced Locations)
Employees	500
Revenue	US$143 Million in 2005
Patents	79 patents with 97 more in progress
Ownership	Public, Traded on Toronto Stock Exchange (XTX)
Established	1983

3

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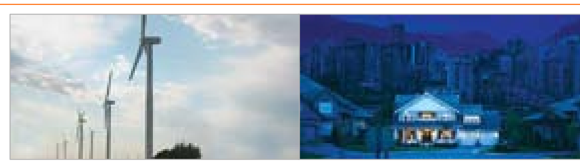
ADVANCED POWER ELECTRONICS Target Markets

Renewable Power



Portable & Mobile Power

Programmable Power

4


Mobile Power
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Mobile Power – Product Portfolio
Recreational Vehicles
RS2000/MS2000
Inverter/Chargers
Prosine
Inverters & Inverter/Chargers
Freedom Marine 458
Inverter/Chargers
TrueCharge
Chargers
Xantrex Battery
Chargers
Commercial Vehicles
Railmount
Inverter/Charger
Fleetpower
Inverter/Chargers
Prosine
Inverters & Inverter/Chargers
Portable Power
XPower
Powerpack 150
XPower
Powerpack 400
XPower Powerpack 300
Micro Inverters
XPower Plus Inverters
XPower Chargers
XPower Jumpchargers
5


Programmable Power
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Programmable Power – Product Portfolio
Design & Development
XFR 1.2 – 2.8kW
Full Rack Programmable
DC Power Supply
XDC 6-12kW
Digitally Controlled Programmable
DC Power Supply
Value Line (XDL, XPF, XPL, XPH)
Digitally Controlled Programmable
DC Power Supply
Manufacturing Test
XFR 1.2 – 2.8kW
Full Rack Programmable DC
Power Supply
XHR
Half Rack Programmable
DC Power Supply
XPD
Quarter rack Programmable
DC Power Supply
Precision Equipment
XDC 6 – 12kW
Digitally Controlled Programmable
DC Power Supply
XMP
Multiple Output Programmable
DC Power Supply
XT
Quarter rack Programmable
DC Power Supply
6

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Renewable Power Examples

7

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Power Electronics for Solar Applications

- Convert DC from PV Array to AC
- Grid Connected Inverters
  - Only source power to utility grid
- Off Grid/Backup Inverters
  - Include storage for operation when grid not available
- Charge Controllers for battery interfacing
- Often included in "Balance of System"
- Is a very key system component
  - User interface
  - Implements safety features
  - "Heart and Brain" of the system
  - Sometimes viewed as system weak link

8

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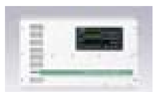
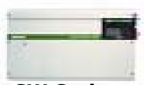
Solar Portfolio

Battery Based Inverters

DR Series



SW Plus Series



SW Series

Single Phase Grid Tie

GT Series
Residential
Grid-tie Inverter
2.5 to 3.8 kW

3-Phase Grid Tie

PV Series
10 kW to 225 kW
NA 3 Phase
Commercial Grid Tie

9

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GT3 Series Residential

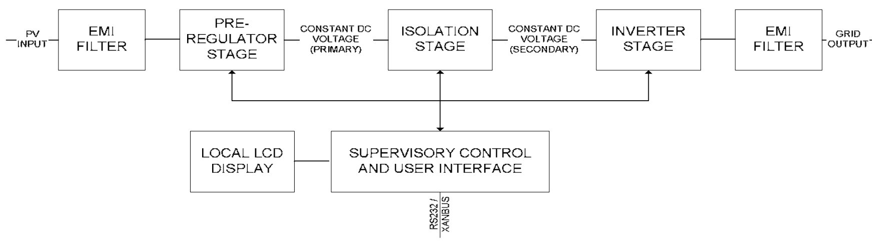
Grid Tied Inverter Features

- True 2.5kW, 3kW, 3.6kW power rating
- High efficiency (CEC 94.5%)
- Wide PV DC MPPT range
- Faster and less expensive to install
  - Light weight and compact
  - Integrated DC/AC disconnect
  - Wiring box
  - Split chassis design (easy to service)
- Communications:
  - LCD display
  - Communication ports and software
- Attractive industrial design
- Passive cooling
- Demonstrated reliability

10

GT 3 Design Topology

- High frequency design
  - Reduces copper losses
  - Smaller, lighter magnetic components = compact/low weight
- Uses new, state-of-art power devices
  - Takes advantage of newer/more advanced semiconductors



11

SW Series

- Off Grid / Primary Power
- Backup Power
- Sell PV power back to utility / provide backup power
- Battery charger standard
- Sine wave output power
- Low frequency design topology
- 2.5, 4.0 & 5.5 kW 120 VAC 60 Hz
- 3.0 & 4.5 kW 230 VAC 50 Hz
- Most features of any inverter in the world – complex, but many variable programming options
- Over 30,000 sold worldwide

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xantrex

DR Series

- Off Grid / Primary Power
- Backup Power
- Battery charger standard
- Modified sine wave output power
- Low frequency design topology
- 1.5, 2.4, 3.6kW 120 VAC 60 Hz
- 1.5, 2.4 230 VAC 50 Hz
- 12 & 24 Volt
- High Surge Capacity
- Simple to install and use

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xantrex

C Series Charge Controllers

- Interface between DC and battery for charging
- 12, 35, 40, or 60 amps
- Solid state, electronically controlled, pulse width modulated (PWM) controllers
- Stand-alone lighting system controller (C12)
- Charge and diversion controllers (C35, C40, and C60)
- Optional temperature compensation
- Adjustable charge control set points
- Rugged & reliable

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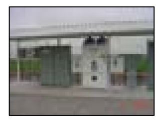
xantrex

PV Series Product Overview

- Three-phase grid connect PV inverter for commercial, industrial and utility scale applications
- Three product platforms comprising 10 distinct models
- Single Stage DC to AC Inversion





- Single, "central" inverter minimizes installation and maintenance costs in large commercial applications

15

xantrex

Real-World Installations

PV150 (34) 5.1MW - Tucson Electric Power
99.92% Inverter Availability in 2005

16

Key Requirements

		Xantrex
High efficiency	• Maximizes rebates and minimizes PV	✓
Sealed design	• No external contaminants, no filters to clean, higher reliability	✓
Communication capabilities	• Flexible options including free GUI to maximize uptime	✓
Low part count	• Better reliability and maintainability	✓
Low weight	• Easier to transport and install	✓
AC Disconnect on transformer output and soft start circuit	• Reduce tare loss and transformer inrush	✓
Wide MPPT Voltage Range	• Covers all temperature conditions and module types	✓
Negative & Positive Ground Arrays	• Allows use with positive ground modules	✓
FCC Part B compliant	• Less potential interference with communication, radio, and consumer electronics	✓
Meets all applicable codes including UL1741 and IEEE 1547	• Inverters can be installed in any jurisdiction	✓

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Power Electronics for Wind Applications

- Convert variable frequency and Voltage AC from generator to grid compitible AC
- Commercial scale – MW
  - Typically installed in North America in large "windplants" – similarities to central generation
  - Ride-Through – FERC requirements
  - Communications – utility SCADA
- Small Wind <30KW
  - Residential
  - Systems sometimes incorporate storage for off-grid or backup applications

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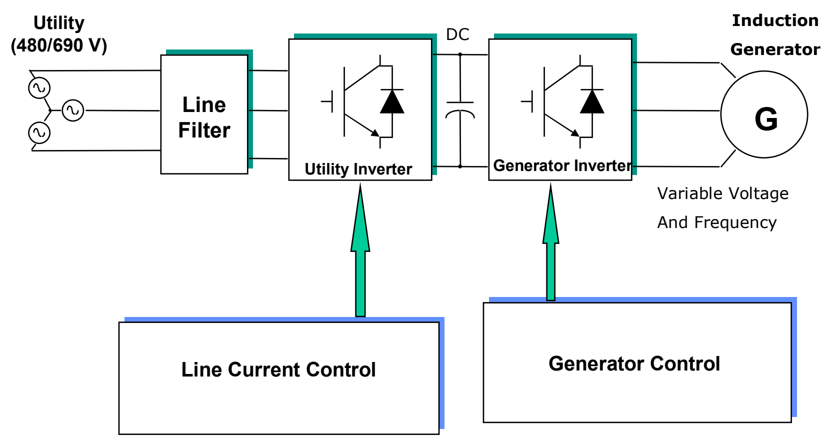
xantrex

Xantrex Converter Technology For Induction Generator



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xantrex

Xantrex Wind Converter Products

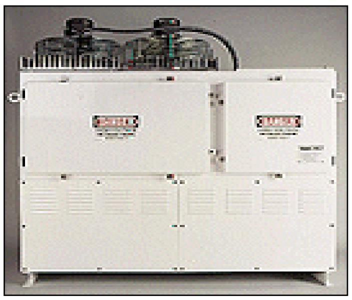
410kW Windturbine and Converter 33 Meter Blade Diameter

20

xantrex

Xantrex Wind Converter Products

750kW Windturbine and Converter 50 Meter Blade Diameter



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Xantrex Wind Converter Products

1.5MW Windturbines and Converter 70 Meter Blade Diameter

22

xantrex

Xantrex Wind Converter Products

2.5MW Windturbine and Converter 93 Meter Blade Diameter

23

xantrex

Power Electronics for Other DER Applications

- Xantrex has Experience with Power Electronics for other Distributed Energy Resource Applications
  - Fuel Cells
  - Microturbines
  - Advanced Energy Storage
    - Flow Batteries
    - Superconducting Magnetic Energy Storage
    - Fly Wheels
  - Large Hybrid Systems
- Relatively small volumes
- Xantrex approach is to leverage from wind and solar

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xantrex

Xantrex R&D

- Internal development activities
  - Wind is OEM product designed for each turbine
  - Advanced solar products
  - Other DER applications based on practical business case
- Sandia High Reliability Inverter Program
  - Residential Solar inverter incorporating storage
- NREL PV Manufacturing R&D Program
  - 500kW Solar Grid Interactive product
- We support DOE Systems Driven Approach and Solar America Initiative goals
- Goal of reducing cost of energy ($/kWhr) is key!

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xantrex

Future DER Power Electronics Direction

- Optimal SYSTEM design
- Including "Balance of Systems" components
- Higher Performance Systems
  - Higher Reliability
  - Higher Efficiency
  - Longer Life
  - Lower Levelized Cost of Energy (LCOE)
  - Easier Installation
- CEC leading in setting high expectations for system performance requirements

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Future Direction

- Support for Higher Penetration Levels
- Wind must meet FERC interconnect standards
- Wind – Ride Through and Grid Support (VARS)
- Solar UL 1741 and IEEE 1547
- Solar – Anti-Islanding and Unity Power Factor
- Likely to come together
- Other DG sources will follow – eventually
- Possibility to move to "Feed-In Tariff" incentive model in US more broadly
  - Maximize Energy Delivered (kWHrs)
  - Incentive to optimize all system elements

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Thank You!

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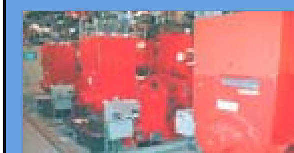
Power Electronics for DER & Renewable Applications

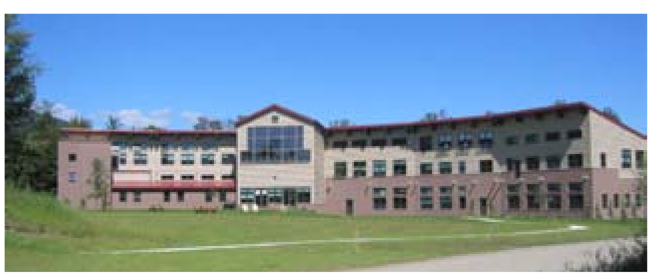
Northern Power Systems
CEC DE Workshop
August 24, 2006




NORTHERN POWER SYSTEMS

Northern Power Systems

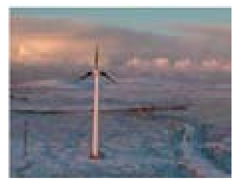
- Subsidiary of Distributed Energy Systems (DESC)
- High reliability power systems, products, and services
- 225 employees
- HQ and manufacturing facilities in Vermont
- Regional domestic and international offices for sales and service



Northern

Northern Power Business Segments

- Distributed Generation
  - Commercial
  - Industrial
- Remote power systems
  - Oil & Gas
  - Industrial infrastructure
  - Village Power
- Renewable power systems
  - Wind
  - PV
  - Biofuels



Northern

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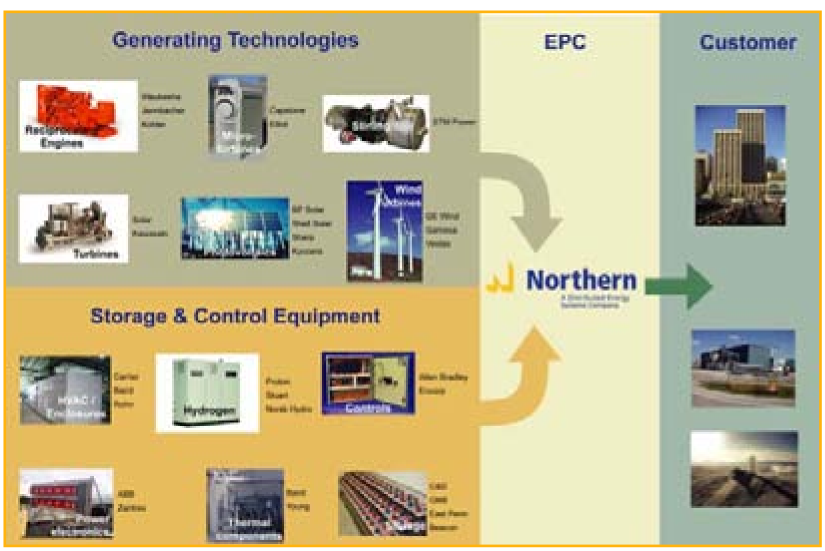
Northern EPC Approach



Northern

4

Power Electronics for DER Applications

Drivers for increased PE use

- New DER technologies require PE interface
  - DC, variable speed, non 50/60Hz generation and storage devices
- Use of advanced PE enables additional features and value across applications
  - Standardized interface for simpler interconnect approval
  - Advanced power system architectures
  - Utility distribution system support
  - Increased DER ancillary support capabilities
  - Increased DER penetration levels on distribution system

Northern

5

Northern's Power Electronics Focus

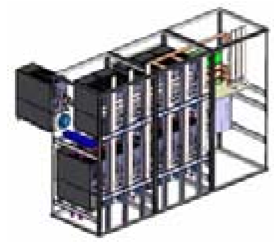
- Flexible power converter platform for multiple markets
  - MW Wind
  - DER generation and storage assets
  - Utility support
- Control capabilities to enable advanced architectures
  - PowerRouter® control system
- Family of products to support advanced power systems
  - Fast DER switch for critical load support and microgrid applications
  - Site and fleet level energy management systems

Northern

6

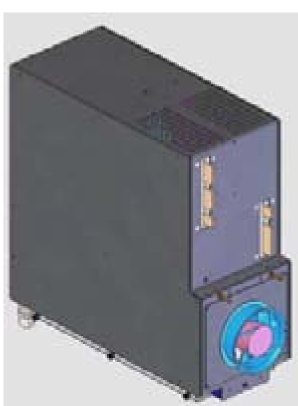
FlexPhase™ Power Converter Platform

Developed for wind and DER markets



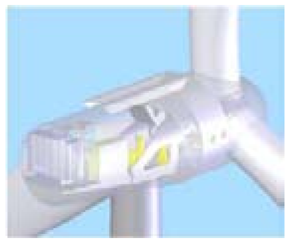
- Modular converter system for 500kW to multi-MW applications
- Liquid and air cooled versions
- 480Vac, 690Vac versions
- Rack-in power modules
- Configurable power modules
  - DC-AC, AC-DC, DC-DC,
  - uni- or bi-directional power

FlexPhase™ Power Module Features



- Bi-directional DC-AC or DC to DC power conversion
- Small footprint & high power density: 2.2 kVA/kg (1,956 kVA/m3) liquid cooled
- Flexible universal control architecture
- Include filtering and magnetics
- EMI controlled at module level
- Internal sensing with built in calibration
- Install and extract like draw-out circuit breakers
- Low mean time to repair

FlexPhase™ Converter Platform Applications



Northern

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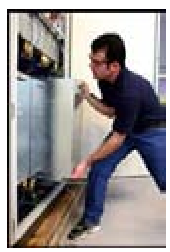
FlexPhase™ Platform Features & Benefits



- Modularity
  - Configurable for multiple applications and power ranges
  - Exchangeable modules for easy service and support
  - Low Mean Time To Repair
- High performance
  - Full grid support capabilities
    - Ride-through, VAR support, harmonic correction
  - Very low harmonics (<1%THD capability)
  - Reduced stress, longer life for generator and motor windings
  - PowerRouter® control system enables microgrid operation
    - Peer to peer aggregation of DER generation and storage assets
    - No high speed communication required
    - Modeless transition between grid & isolated operation
- Cost
  - FlexPhase design allows reduction in power switch costs
  - Modular design well suited for reduced manufacturing cost
- Size
  - High power density for reduced footprint

Northern

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Northern Current DER Applications

Trend to use PE with conventional DER assets

- Standardized grid interface across applications
- Elimination of fault current contribution
  - Simplifies interconnect approval
  - Allows interconnection to constrained systems
- Adds variable speed capability
- Enables advanced power system architectures
  - PowerRouter® controls
    - Microgrid and critical load support applications
  - PowerDistributor™ system
    - Interconnect DER asset(s) to multiple service entrances

Northern

11

MicroGrid Power Network Test System

Northern

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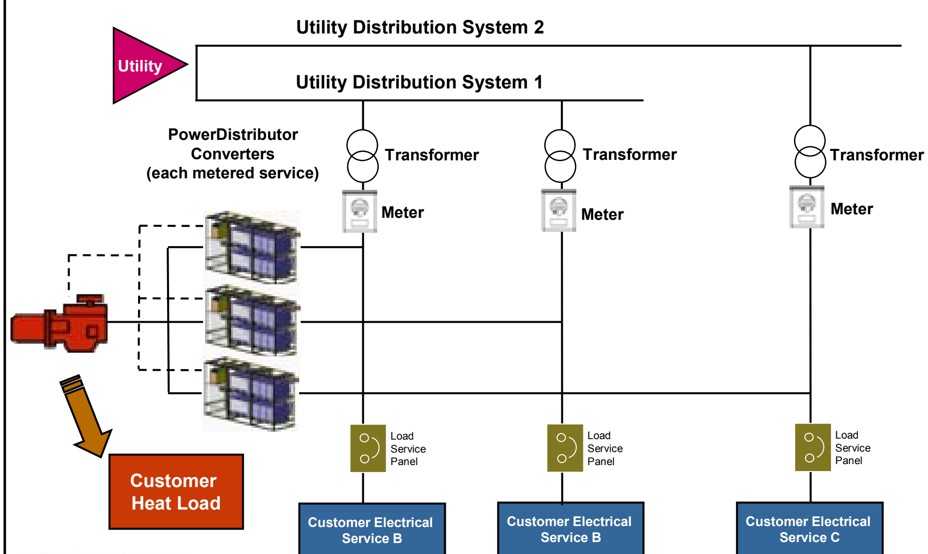
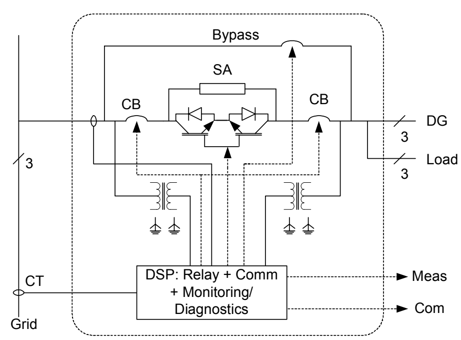
PowerDistributor™ DER System

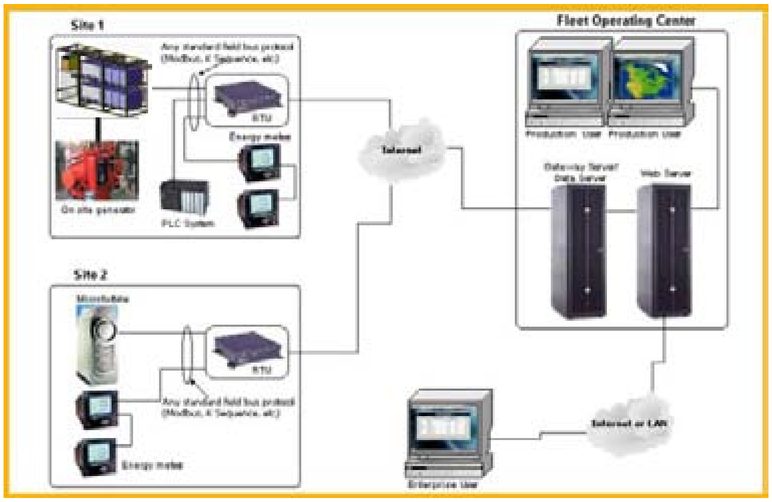


DER Utility Interface Switch

- Flexible, universal interface for connecting single or multiple DER systems
- Controls for CB, SCR, or IGBT switching modules
- Enables
  - Critical load support
  - Intentional islanding
  - Enhanced power quality
  - Anti-islanding protection



SmartView® DER Management System



Northern

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For more information, contact:

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Waitsfield, Vermont 05673 USA
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Northern

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SMA America
Advanced Power Electronics Interfaces Workshop

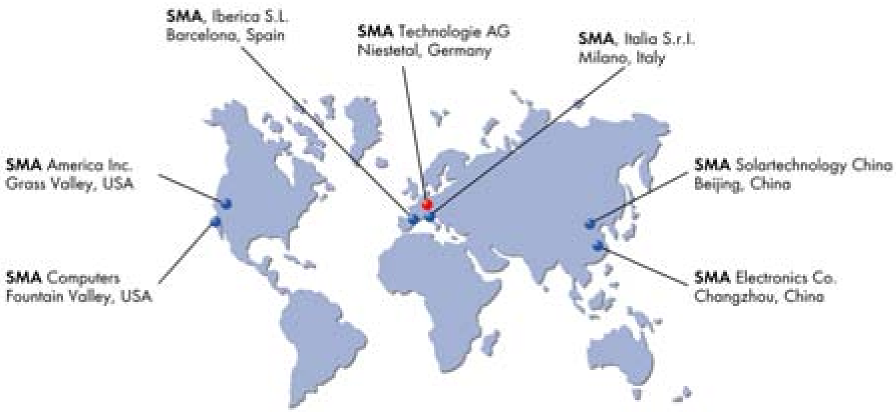
August 24, 2006

Who We Are And What We Do

- Founded in 1981
- Headquartered in Niestetal, Germany
- Approx. 1,200 employees worldwide, more than 15 % are engineers
- Technology leader and trend-setter
- Privately held Ag corporation

2

Where We Are



- Office recently opened in Korea

3

Product areas

4

Synergies of key competence areas

5

US Inverter Products and Applications

- **Residential PV, Small Wind, Hydro**
  - SB1800U, SB2500U
  - SB700U, SB1100U
  - SB3300U, SB3800U, SB6000U
- **Commercial PV**
  - SC125U
- **Back-up Power and Off-grid**
  - SI4248U (partially funded by PIER)
- **AeroSmart Wind Turbine**
- Further expansion of product family by 2007

6

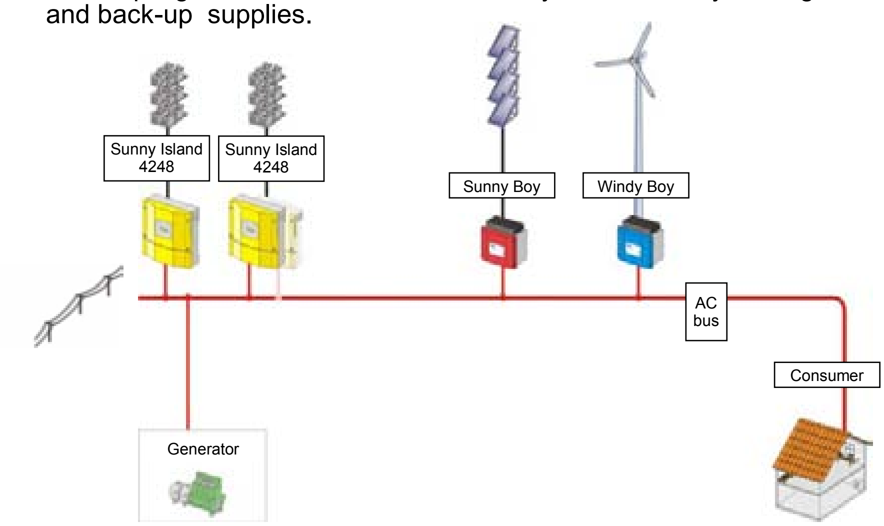
Trendsetting Communication Services

- Communication products
  - Web Box
    - Communication hub and system data logger
  - Sunny Portal
    - Free internet system performance server
- Services
  - Automated notification of performance and system alarms.
  - Automated performance analysis and notification

7

The Future of Distributed Energy

AC coupling: The best solution for flexibility and efficiency of off-grid and back-up supplies.



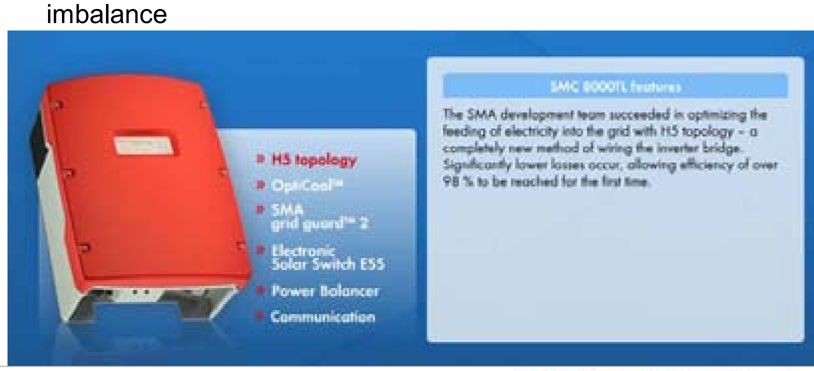
8

Design Improvements

- Opti-Cool forced-air cooling
- IGBT skip-packs
- Integrated aluminium enclosure and heat-sink
- Ethernet communication
- Load-break rated DC fused disconnect
- HALT/HASS testing

New Inverter Family Introduction

- Over 98% peak efficiency inverter topology
- Advanced communication and control features
- System performance analysis
- Intelligent off-grid & back-up power integration
- Intelligent three-phase integration to prevent generation imbalance



Recent History in the PV Market

- PV module prices increase 30% in 2 years.
- Inverter competition is high due to PV module shortages.
- IEEE-1547.1 has doubled regulatory certification costs (apr. $100,000 per inverter).
- One time CEC rebate system rewards on name-plate ratings rather than system performance.
- CEC rebate continues to decline ($2.60 per Watt).
- Copper, steel, specialty metals increased 40% in the last year.

- SB1 passed, rebate may return to $2.80 per Watt.
- CEC Pilot Performance-Based Incentive Program is a step in the right direction.

11

Recent History at SMA

- SMA has reduced inverter prices by 20% over 2 years.
- Our aim is 5% per price reduction per year.
- Reliability and functionality has dramatically improved with new products.
- Advanced communication products positioned to:
  - Energy reporting for performance based incentives.
  - REC recording and trading

12

Moving Forward

- Shift to performance based incentives
  - Define equipment and metering requirements.
- Acceptance of transformerless inverter technologies by AHJ's
  - Immediate adoption of the NEC-2008 Article 690 upon publication.
- Ease regulatory requirements
  - UL has become a barrier to flexibility, responsiveness and innovation.
- Streamline accounting/reporting requirements for PIER funding to attract established companies.

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Kent Sheldon
Sales Support Manager

SMA-America, Inc.
12438-C Loma Rica Drive
Grass Valley, CA 95945
530.273.4895 ext 107
www.sma-america.com

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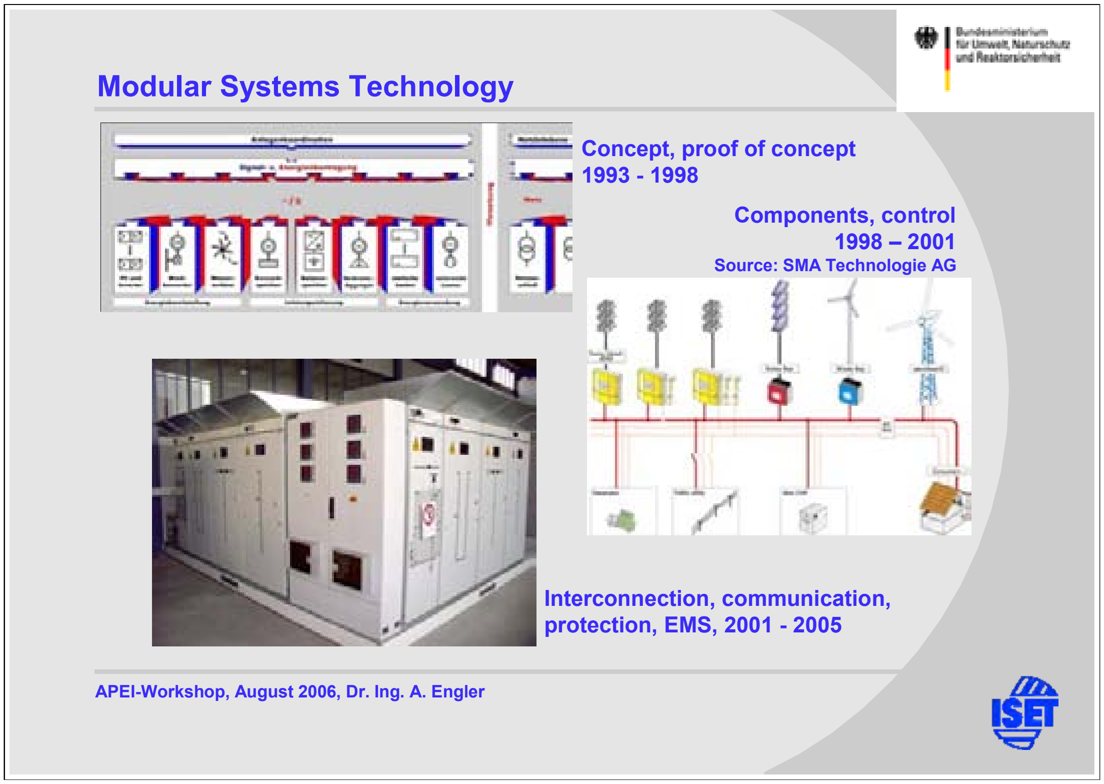
Appendix E. Additional Resources

Power Electronics Activities at ISET

Power Electronics for Grid Interfacing
Power Quality
Microgrids
Stand-alone Systems

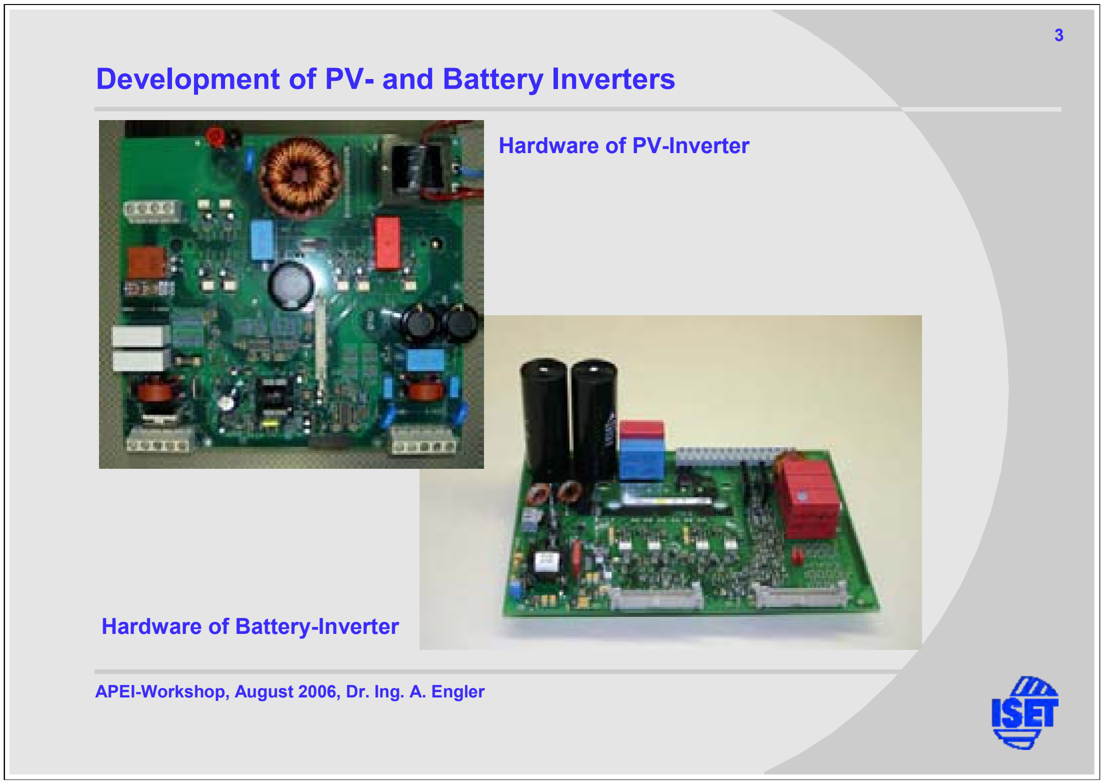
Dr.-Ing. A. Engler

This presentation gives an overview about ISETs power electronics activities with regard to DER and grid integration



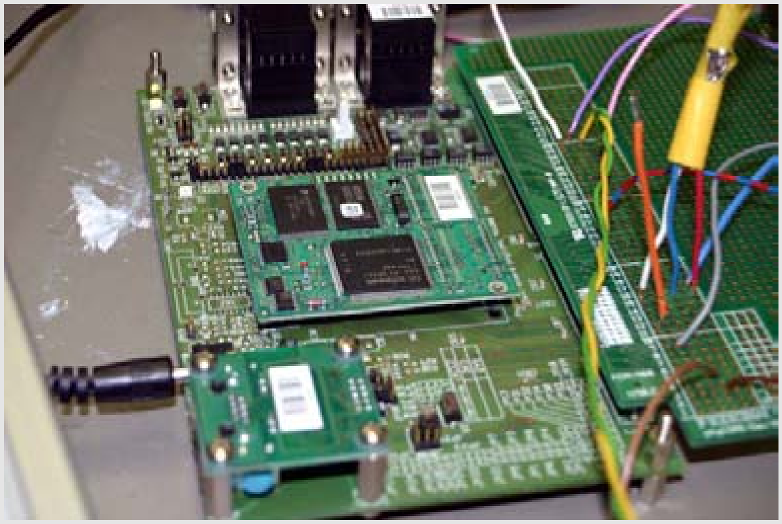
„Modularity" has been a major topic at ISET for about 15 years!

E. g. within the frame of three national projects a modular concept has been developed. A whole DER-component family has been developed and transferred to commercial products (SMA). The next step have been the integration and interconnection issues.



Development of commercial inverters in the kW-range for major PV-companies as SMA, KACO, etc.

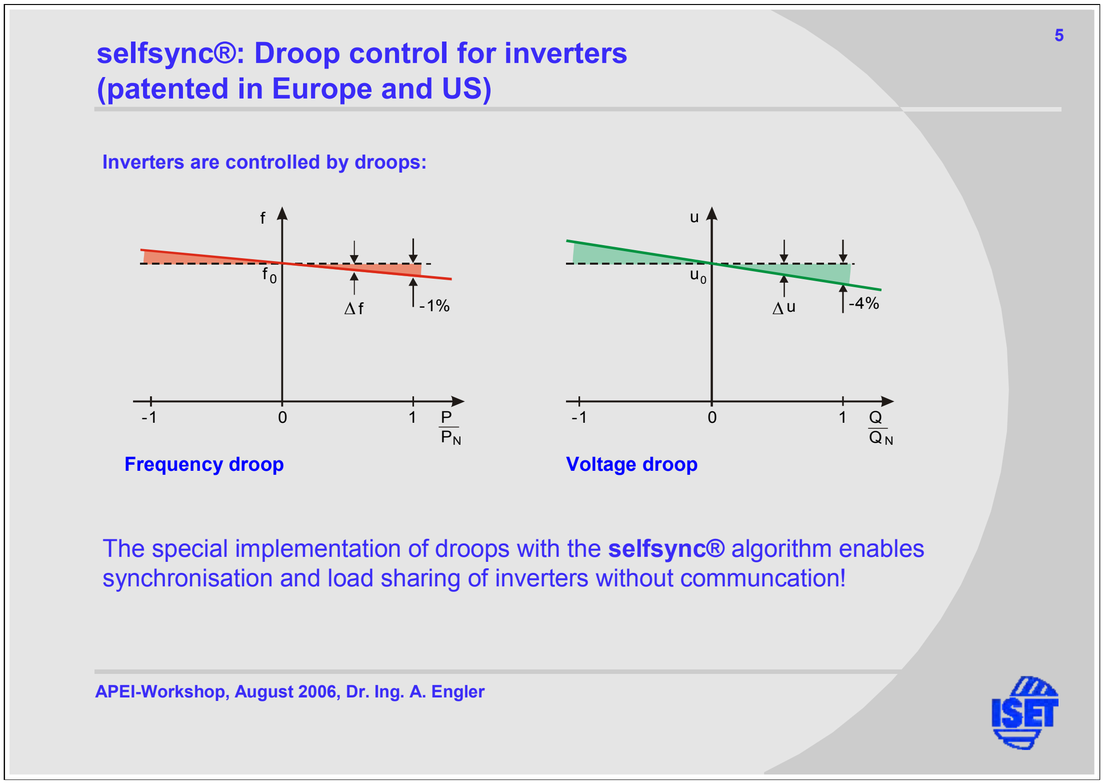
Code Generation for Embedded Controllers



APEI-Workshop, August 2006, Dr. Ing. A. Engler

ISET

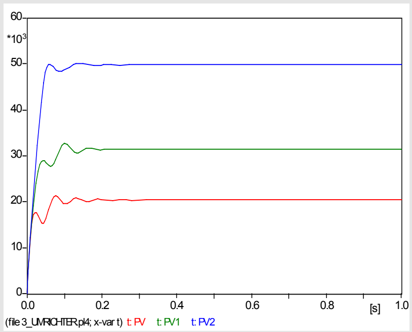
Embedded code generation by means of modern development tools enabling partially graphical implementation.



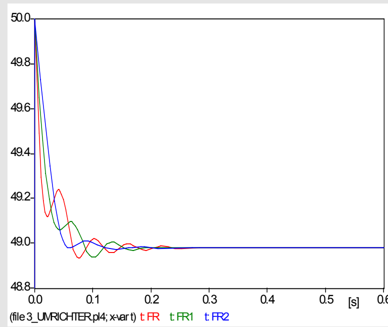
Development of efficient control algorithms especially for stand-alone systems and Microgrids.

6

Load sharing and frequency change (selfsync®)



Loadsharing: contribution depends on set-point of the idle frequencies

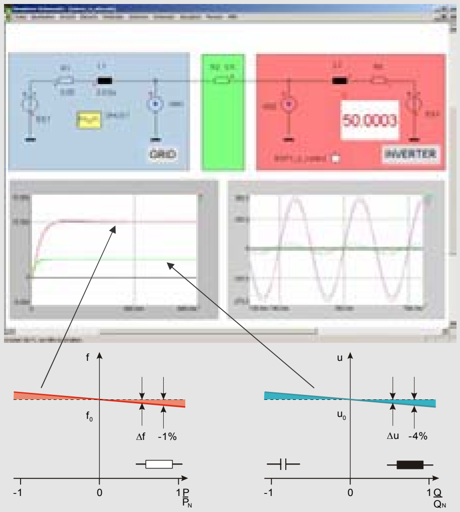


Frequency could be restored by a secondary control

APEI-Workshop, August 2006, Dr. Ing. A. Engler

Selfsync® enables load sharing between inverters bettern than 1 %!

„Indirect operation“ of droops in case of resitive coupling (LV-case)

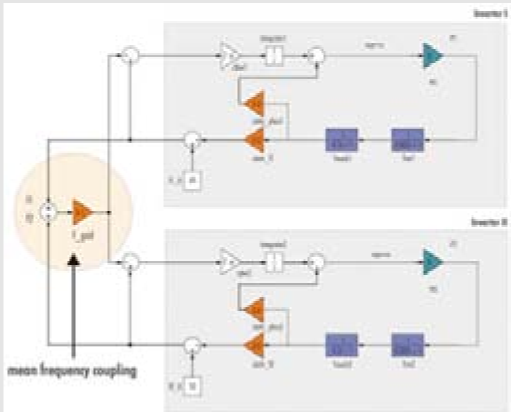


- Applied droop concept is based on inductive coupled voltage sources.
- In a LV-grid components are coupled resistively, thus voltage determines the active power distribution
- There are two effects of droops
  - direct (inductive coupling)
  - indirect (resitive coupling)
- The „indirect“ effect requires droops, which have the same sign for the frequency as well as the voltage droop and therefore the stable operation point is „in phase“.

Selfsync® is applicable in LV-, MV and HV-Grids!

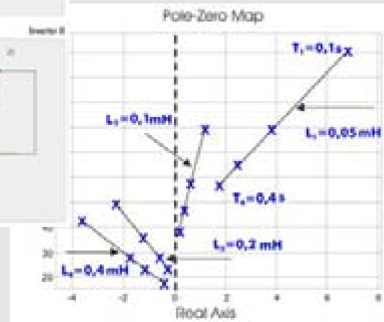
Stability assessment of multi-inverter systems (selfsync®)

8



MatLab/Simulink model based on mean frequency coupling

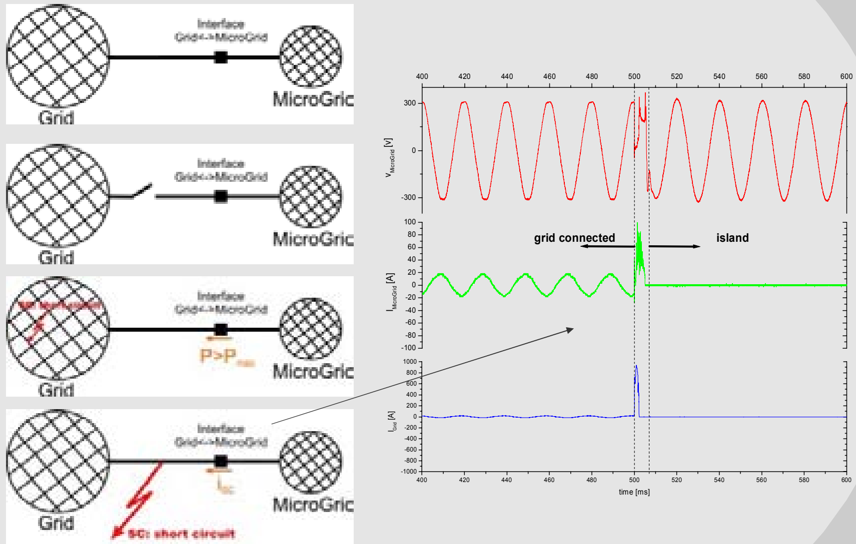
Stable and unstable operating points



APEI-Workshop, August 2006, Dr. Ing. A. Engler

Inverters co-ordinated with selfsync® are scalable: One can operate as many inverters in parallel as necessary. They can be of different size (practically a ratio of 1 : 100 shouldn‘t be exceeded). By special means even dynamical loadsharing can be ensured.

Electronic switch: possible faults (selfsync®)



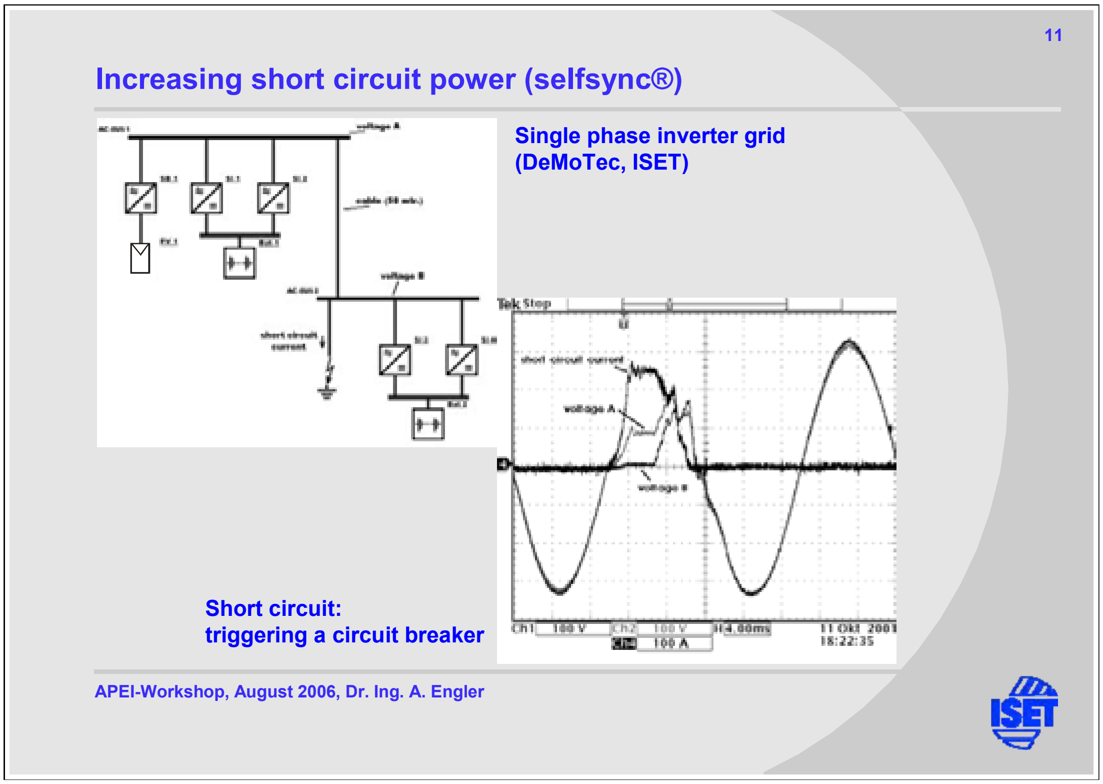
APEI-Workshop, August 2006, Dr. Ing. A. Engler

Selfsync® masters all possible grid faults, even near short circuits. A fast disconnection device is required.

High Impedance Grid fault (selfsync®)

Principally the suggested control mode also continuous operation even in case of a line interruption. A grid failure mostly results not in an interruption but in a short-circuit and therefore motivates the development of a disconnection device!

As the operation mode is not changed between island und grid operation, there is almost no transition time.

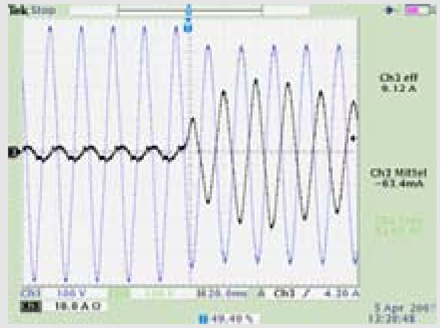


Standard protection devices can be used with Selfsync® .

Parallel operation of an ASG and Sunny Islands (selfsync®)

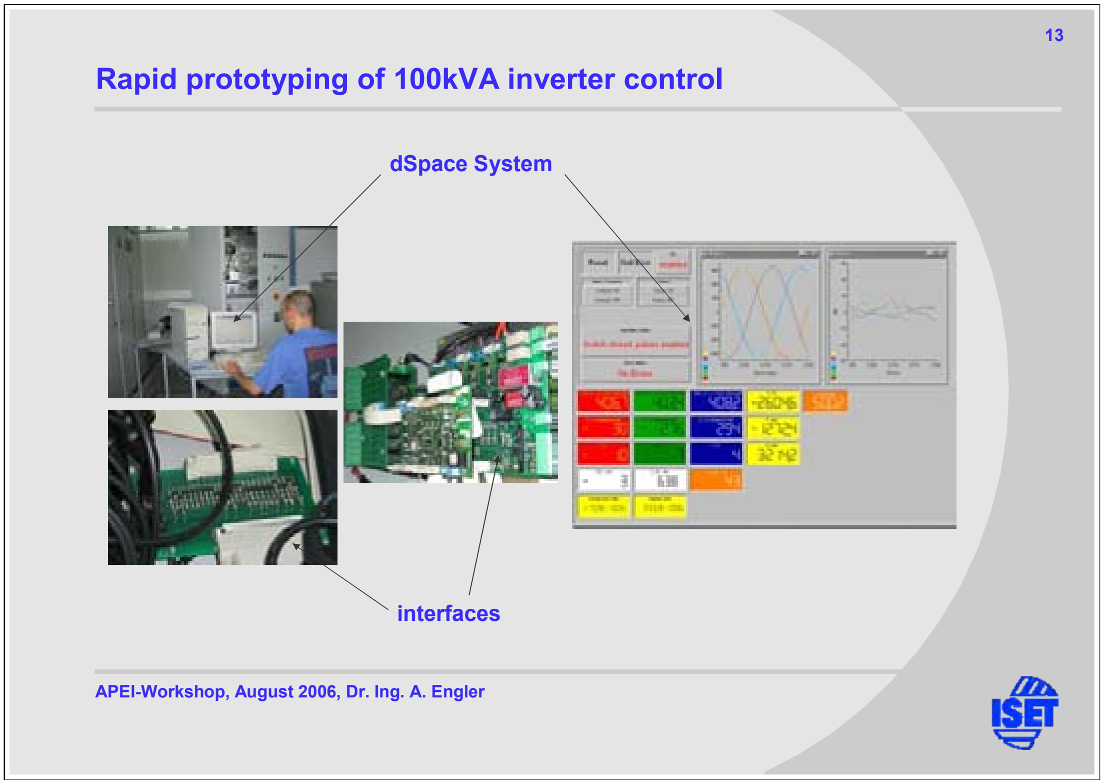
Load sharing between Sunny Island and genset is possible due to the inherent frequency / active power characteric of the genset (slip, mechanical controller)

Single phase genset with ASG and capacitor (Fa. Kirsch)



Synchronising a Sunny Island onto the genset (idle frequency set for charging)

Selfsync® is compatible with standard diesel gensets.



ISET develops advanced control algorithms for 100 kVA to 1 MVA inverters.

General Advantages of „Rapid Prototyping“:

• Control algorithms are developed using MatLab/Simulink simulation software. Tested and working models can directly be used in the prototype.

• Automatic code generation for the architecture of the Rapid-Prototyping-System.

• Integration of custom C-code possible

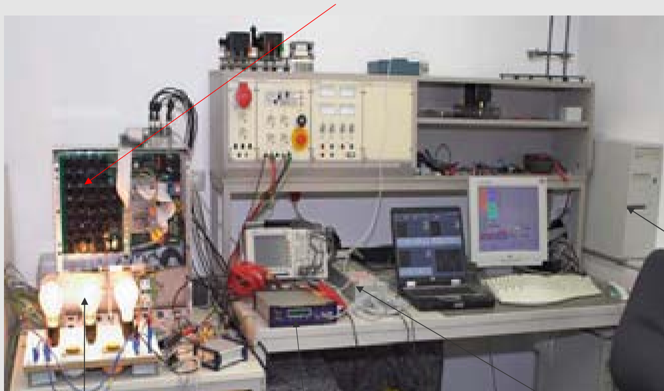
• Quick and effective development even of advanced control algorithms due to high computing power of the Rapid-Prototyping-System.

• Online visualization of all variables

• Adjustment of variables i.e. controller parameters during operation

Development of Power Quality Equipment with rapid prototyping

Prototype, 3.3 kVA, 16 kHz switching frequency, usable energy storage 470 Ws



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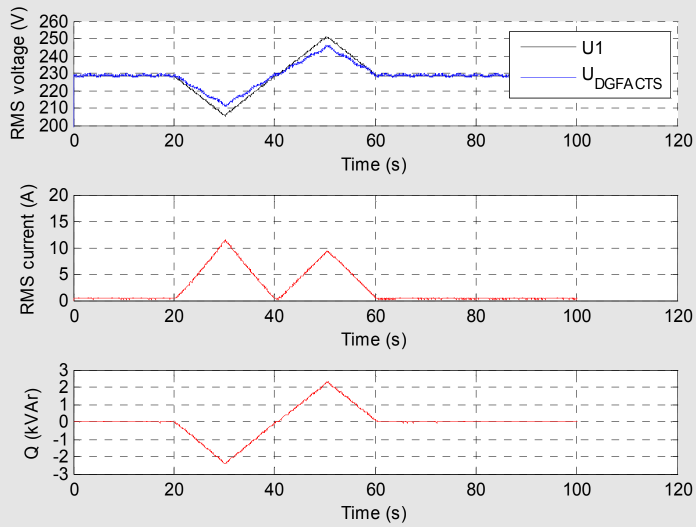
ISET

Realised functions:

- Voltage dependent supply of reactive power (Q droop)
- Dynamic reactive power compensation of dedicated loads
- Dynamic harmonics compensation of dedicated loads
- Flicker reduction
- Local improvement of voltage quality by inductively decoupled sub-networks

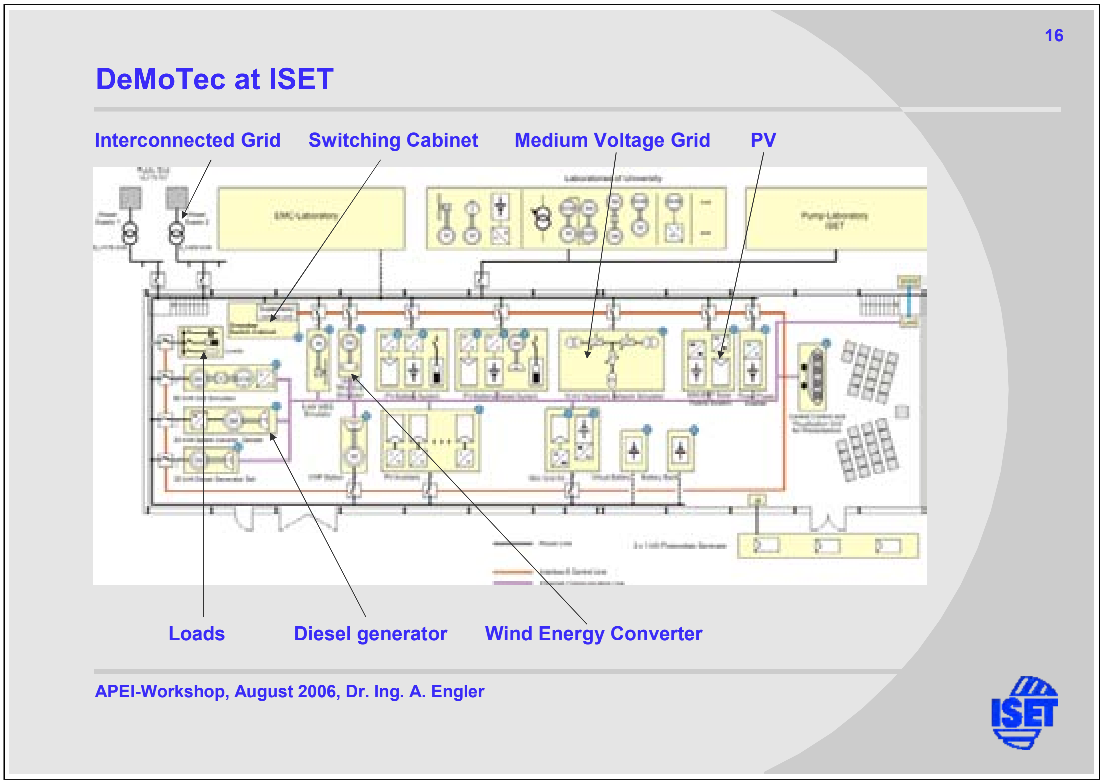
Development of Power Quality Equipment:
Q-Droop: Grid Support with Reactive Power



Inverter injects reactive power according to the line line voltage and supports it depending on the line impedance

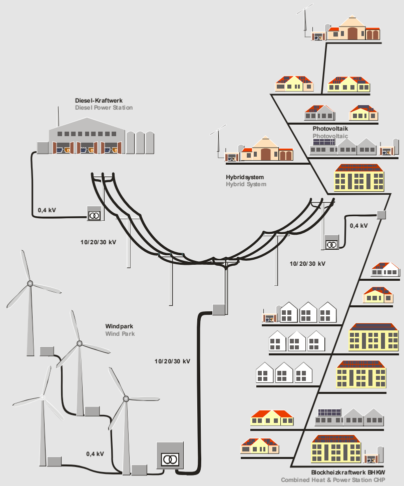
<u>Realised functions:</u>

- **Voltage dependent supply of reactive power (Q droop)**
- Dynamic reactive power compensation of dedicated loads
- Dynamic harmonics compensation of dedicated loads
- Flicker reduction
- Local improvement of voltage quality by inductively decoupled sub-networks



The design, demonstration and test center (DeMoTEC) at ISET enables a variety of relevant tests for DER-components.

Interconnecting distribution systems (MV- and LV-Grids)



Medium-voltage grid emulator

Line equivalent

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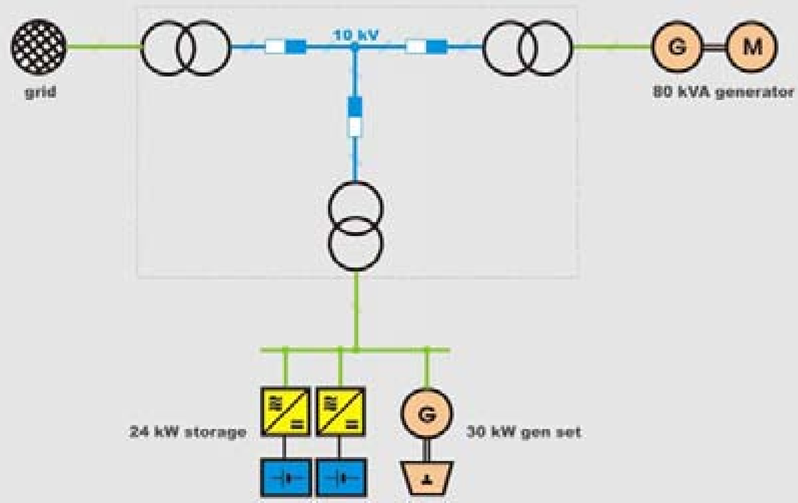
ISET

The Medium voltage grid emulator enables test of equipment for MV-distribution systems.

Example for laboratory installation



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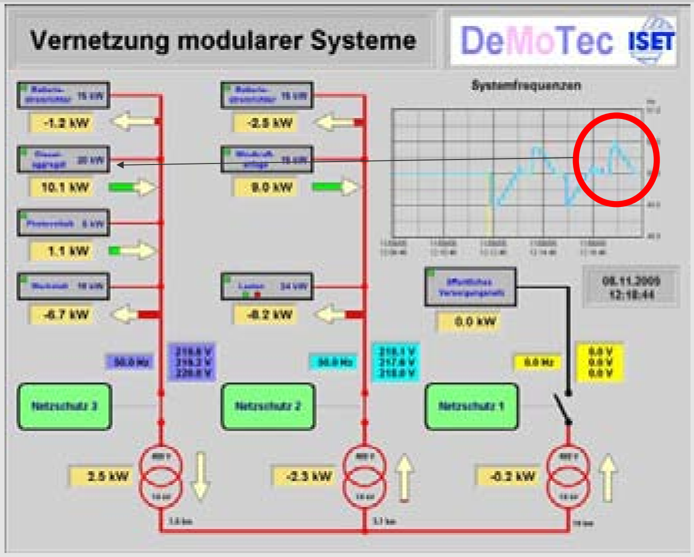
Laboratory demonstration
- Starting diesel genset (tertiary control) -



Screenshot
Of
SCADA-System

APEI-Workshop, August 2006, Dr. Ing. A. Engler

The development of SCADA-Systems and supervisory control algorithms enables energy management of grid connected or remote hybrid systems.

Example of small hybrid system installed by ISET and SMA.

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Greek Island Kythnos

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ISET

Example of small hybrid system installed by ISET and SMA.

Conclusion

- ISETdevelops power electronics for commercial production
- ISET develops advanced control algorithms for grid interfacing
- ISET is able to test equipment in laboratory and field tests
- ISET is a non-profit organisation

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14. ABSTRACT *(Maximum 200 Words)*
The Advanced Power Electronics Interfaces for Distributed Energy Workshop, sponsored by the California Energy Commission Public Interest Energy Research program and organized by the National Renewable Energy Laboratory, was held Aug. 24, 2006, in Sacramento, Calif. The workshop provided a forum for industry stakeholders to share their knowledge and experience about technologies, manufacturing approaches, markets, and issues in power electronics for a range of distributed energy resources. It focused on the development of advanced power electronic interfaces for distributed energy applications and included discussions of modular power electronics, component manufacturing, and power electronic applications.

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