SAND2018-9689

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SAND201X-XXXX
Unlimited Release
Printed September 2018

Enabling Advanced Power Electronics Technologies for the Next Generation Electric Utility Grid

Workshop Summary Report

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Prepared by
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Abstract

The role of power electronics in the utility grid is continually expanding. As converter design processes mature and new advanced materials become available, the pace of industry adoption is poised to accelerate. Looking forward, we can envision a future in which power electronics are as integral to grid functionality as the transformer is today. The *Enabling Advanced Power Electronics Technologies for the Next Generation Electric Utility Grid Workshop* was organized by Sandia National Laboratories and held in Albuquerque, New Mexico, July 17-18, 2018. The workshop helped attendees to gain a broader understanding of power electronics R&D needs—from materials to systems—for the next generation electric utility grid. This report summarizes discussions and presentations from the workshop and identifies opportunities for future efforts.

ACKNOWLEDGMENTS

The authors would like to thank all of the presenters and session chairs who prepared insightful and informative briefings on next generation electric utility grid and power electronics R&D challenges & opportunities and all the participants for their contributions to the workshop. The authors would like to thank Satish Ranade of New Mexico State University, as well as M A Moonem, Jack Flicker, Jason Neely, and Jon Bock of Sandia for sharing their unique perspectives and extensive notes from the workshop.

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1. EXECUTIVE SUMMARY

The electric utility grid is a massive interconnected system that provides consumers with safe, reliable, and affordable access to electrical energy. Functionally, the grid consists of two electrical networks. A high-voltage transmission system transfers power efficiently over great distances. At the point of energy consumption, a distribution system delivers power safely into homes, businesses, and public spaces at voltage levels suitable for general utilization. Together, the American transmission and distribution grids connect millions of customers to thousands of generating stations through millions of miles of power lines.

Today, however, the ways we generate, exchange, and consume electric power are rapidly changing. The driving force behind this change is the field of power electronics. Power electronics enable efficient conversion between different forms of electricity. Whereas transformers are limited to conversion between synchronous AC sources, power electronics enable direct conversion between AC sources, DC sources, and any combinations thereof.

Power electronic converters are already ubiquitous in society, hidden inside computers, cell phones, and nearly all other consumer electronics. While power electronics are widespread in low to medium power applications, materials and technologies capable of withstanding the stresses of high-power conversion are relatively new. These recent innovations are fueling the expanse of power electronics into new applications in transmission and distribution systems.

Power electronics provide two potentially transformative advantages for power delivery systems. First, advanced efficient energy converters enable a more diverse set of energy resources, including wind energy, photovoltaics, electrochemical energy storage, and more. While many of these new resources create challenges due to their distributed and variable nature, they also present the possibility of a cleaner, cheaper, and more sustainable energy supply. The second advantage of power electronic conversion is an unprecedented level of control over electrical energy. In the existing grid, control is exerted either at the point of generation or through switchgear, which enable or bypass physical connections. Power electronic conversion inherently provides direct control over electrical characteristics, and can be leveraged at the generation site, point of consumption, or anywhere in between. This increased degree of control translates to improvements in power flow management, voltage/frequency stability, and response to contingency events.

The purpose of the *Enabling Advanced Power Electronics Technologies for the Next Generation Electric Utility Grid Workshop* was to gain a broader understanding of power electronics R&D needs for the next generation electric utility grid. Topics of discussion ranged widely in scope, from basic materials to full system architectures. The workshop provided a unique opportunity for experts from a variety of research entities (electric utilities, academia, industry, and government) and areas (materials, devices, circuits, and systems) to exchange new ideas, perspectives, and experiences. The goal of the workshop was to explore the key challenges in power electronics R&D needed to enable a more reliable, adaptable and resilient electrical grid. To do this, the workshop focused on five objectives.

1. Understand how readily available (low cost, high reliability, high performance) power electronics can change the electric utility industry.
2. Explore state-of-the-art power electronics, including their current potential and future prospects for utility grid applications.
3. Identify research opportunities in the following power electronics components:
    - Wide bandgap (WBG) semiconductors
    - Advanced circuit topologies
    - Magnetic components and materials
    - Capacitors and dielectrics
    - Packaging solutions
4. Explore advanced controls for a smarter grid and the role of power electronics in changing how we deliver energy.
5. Gain a better understanding of developing standards for grid-tied power electronics and the role standards play in ensuring converter safety and reliability.

The meeting was structured to encourage interaction and discussion of enabling advanced power electronics technologies for the next generation electrical grid.

This report provides an overview of the workshop contents and summarizes the key discussion and outputs. Presentation titles are linked to downloads of the presentation files.

2. NOMENCLATURE

AC	Alternating Current
DC	Direct Current
DOE	U.S. Department of Energy
DSO	Distributed System Operator
EPRI	Electric Power Research Institute
ES	Energy Storage
FACTS	Flexible AC Transmission System
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IGBT	Insulated-Gate Bipolar Transistor
IPM	Integrated Power Module
kV	Kilovolt
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MV	Medium Voltage
R&D	Research & Development
Si	Silicon
SiC	Silicon Carbide
SST	Solid-State Transformer
WBG	Wide Bandgap

3. PRESENTATION SUMMARIES / WORKSHOP CONTENT

3.1. Session 1: What does the electric utility grid look like if power electronics are readily available?

Chair: Stan Atcitty, *Sandia National Laboratories*
Panelists:

- Manuel Avendano, *Southern California Edison*
- Dushan Boroyevich, *Virginia Tech*
- Kerry Cheung, *DOE Office of Electricity*
- Deepak Divan, *Georgia Tech*

What is the future of the electric grid? In the first session of the workshop, speakers from industry, government, and academia outlined ambitious visions for modernized power systems. All panelists, regardless of affiliation, shared a common belief that power electronics will be fundamental to the operation of future grids. Building from this common premise, the session considered ongoing efforts to improve the existing grid using power electronics and explored the potentially transformative long-term impacts of practical utility-scale power electronic conversion. The panel described a future grid in which power electronics are utilized as the building blocks in entirely new paradigms for power generation, transmission, and distribution. In this scenario, existing grids are transformed into hierarchical collections of electronically interconnected and dynamically decoupled subsystems, which deliver power in the ideal form for each application they serve. This future grid offers plug-and-play support of distributed energy sources and contains sufficient energy storage to accommodate high percentages of generation from renewable resources.

Establishing a clear vision for the future electric grid was a relatively simple task. It was more difficult, however, to delineate a course of action that would make this vision a reality. The panel identified several critical obstacles. Some were technical in nature, while others were concerned with economic issues or regulatory challenges. Panelists observed that “rip-and-replace” strategies are economically infeasible. They suggested that intermediate solutions which have well-defined economic benefits and limited operational risks could help facilitate the widespread introduction of power electronics in the grid. For instance, designing solid state transformers (SSTs) to fail normal, or default to conventional operation with existing 60 Hz transformers, could ease the growing pains of SST deployment.

Generally, the technical challenges were presented as solvable problems. The channels for developing and distributing innovative technical solutions are already in place. Economic and regulatory issues are more problematic. Grid modernization is a massive task, and will require coordinated efforts between researchers, regulators, and utilities. Regulatory change is needed, but change happens slowly, and regulators are not accustomed to changes so fundamental and far-reaching. Meaningful regulatory change is not possible without an understanding of technical constraints and capabilities. Likewise, technological developments must be informed by a holistic understanding of the modernization problem. The absence of open lines of communication between all parties involved is a barrier to forward progress. In the panel session, the need for careful coordination between grid participants was further emphasized, and it was suggested that this multi-disciplinary challenge is best addressed from a systems engineering perspective. It was also observed that progress may be accelerated by delegating more authority to local operators. By tasking distributed system operators (DSOs) with handling the distribution market and market products, more control is effectively placed in the hands of those closest to infrastructure assets, potentially speeding the adoption of new technologies.

Despite the abundance of challenges and obstacles, the panelists were optimistic about the future. Hard problems must be solved to build an electrical grid based on power electronic conversion, but the benefits of this future power system are simply worth the effort.

3.2. Session 2: What is the state-of-the-art of power electronics today?

Chair: Kaushik Rajashekara, *University of Houston*
Panelists:

- Ram Adapa, *Electric Power Research Institute*
- Anant Agarwal, *Ohio State University*
- Subhashish Bhattacharya, *North Carolina State University*
- Madhu Chinthavali, *Oak Ridge National Laboratory*

The second session focused on establishing a clear picture of current state-of-the-art power electronics technologies. The panel described successful deployments of flexible AC transmission system (FACTS) devices and presented new developments in SST technologies. In both cases, the need for high voltage devices was apparent. Discussions emphasized the developing capabilities of WBG devices, which are the driving force behind the expansion of power electronics into utility applications. In particular, several prototypes and demonstration projects described by the panel indicate that Silicon Carbide (SiC) based MOSFET and IGBT modules are ready to handle the stresses of medium voltage (MV) applications. Despite the strengths of WBG materials, market acceptance remains low due to their high costs and lack of established reliability. The panel characterized this challenge as a “chicken and egg” scenario: price remains a barrier for new SiC applications, but without greater demand, material and substrate costs cannot decrease. While dedicated R&D efforts have advanced the physical limits of WBG technology, the market and supply chain have yet to fully mature.

Power electronics comprise many individual components and subsystems, each with their own state of development. The panelists’ depictions of the current state of power electronics technology show uneven rates of growth in the field. Semiconductors continue to act as the trailblazer in the advance of power electronics technology. However, the rapid progress in WBG devices has outpaced the development of other parts of the field such as gate drivers, passive components, and packaging, creating significant gaps in the practical maturity of state-of-the-art power converters. The constraints of these auxiliary components limit the performance of WBG converters to well below maximum theoretical capabilities.

Gate drivers were a particular point of concern. The absence of commercial integrated power module (IPM) solutions and self-powered driver boards create an additional barrier to new SiC applications. Nearly all auxiliary components of high-power, high switching frequency converters require improvement. Considering these issues, the panel pointed to the importance of a system-level mindset. The value of new component technologies should not be assessed solely as a function of their merits in isolation, but also in how they advance the capabilities of the integrated system. This perspective will ensure that the field progresses as a cohesive whole, rather than a collection of parallel technologies.

3.3. Session 3: What components are needed to achieve the Session 1 vision?

Chair: Bob Kaplar, *Sandia National Laboratories*
Panelists:

- Jim Cooper, *Sonrisa Research, Inc.*
- Abhijit Gurav, *KEMET Corporation*
- Paul Ohodnicki, *National Energy Technology Laboratory*
- Brandon Passmore, *Wolfspeed*

Session 3 focused on the technological developments needed at the individual component level. Semiconductors were again a key point of the discussion and the panel began with a review of state-of-the-art semiconductor devices. Material properties favor the use of SiC over Silicon (Si) for grid applications due to the high blocking voltages required. Additionally, the need for bipolar devices such as IGBTs at very high voltages suggests that SiC, which is an indirect-gap semiconductor, may be preferable to direct-gap WBG semiconductors. At lower voltages, the performance of SiC Super-Junction MOSFETs may be competitive. However, Super-Junction fabrication complexity increases with blocking voltage, so SiC IGBTs are likely the best long-term solution for utility-scale applications. To support the development of new semiconductor devices, the panel highlighted a need for new modeling and design techniques. Furthermore, the semiconductor device package is extremely important as it is the interface between the semiconductor device and the outside world. More comprehensive tools are needed for predicting package reliability over time, such as models that describe the electric fields in high-voltage power modules and their effects on device and package degradation.

The panel also considered developments in passive device technology and shared the belief that a system-level design perspective is needed. Dielectric and magnetic components are no less critical than semiconductors to high-performance converter solutions, but magnetics and dielectrics are consistently treated as an afterthought in the design process. From a magnetics perspective, traditional transformer design and characterization is based on sinusoidal excitation, but a disparity exists between sinusoidal loss characterization and the loss profiles observed in modern power electronic converters due to the variety of switching patterns and excitation waveforms present in real converters. New modeling and characterization tools are needed and many research opportunities exist in the emerging field of permeability engineering. Magnetic component R&D has not yet reached a critical mass of engineering talent. Innovative educational programs are needed to build a larger community of power electronics engineers with specializations in magnetic design.

Capacitors for high frequency and high-power density converters are a current target for component manufacturers. High frequency and temperature requirements preclude the use of electrolytic and Class II ceramic capacitors (due to AC losses) as well as polymer capacitors (due to temperature). Class I ceramic capacitors, however, are a possible solution due to low AC losses and temperature stability. The panel highlighted these points and discussed strides to overcome the low capacitance of Class I ceramic capacitors. It was shown that stacking capacitors using liquid phase sintering pastes can increase the capacitance range significantly, but novel capacitor mounting schemes are needed to minimize inductance losses at high frequencies.

3.4. Session 4: What power electronics topologies are needed to achieve Session 1 vision?

Chair: Satish Ranade, *New Mexico State University*
Panelists:

- Martin Becker, *Princeton Power*
- Rajib Datta, *GE Global Research*
- Adel Nasiri, *University of Wisconsin-Milwaukee*
- Kaushik Rajashekara, *University of Houston*

Converter topologies were discussed in Session 4. In keeping with the general theme of previous sessions, panelists characterized the need for new topologies as a system integration challenge. The value of novel and complex hardware configurations has diminished. The more pressing need is to extract the full performance potential from simple converter designs. Panelists identified three key elements of successful converter topologies: cost, reliability, and efficiency. All these attributes are a function of the number of power-processing components in a converter, but the most well-established relationship applies to reliability. The real benefit of WBG devices is that they make possible the use of simpler topologies (especially in higher power rated applications) thereby decreasing the number of components and increasing system reliability. For instance, high-voltage SiC IGBTs expand the range of DC-AC applications for which two-level inverters are a viable solution. Rugged and reliable converters are the main building block of the power electronic grid envisioned in Session 1, and reliability was described as the single most important attribute for enabling utility adoption of power electronic assets. At least for now, simplified designs are an effective tool for improving system reliability while decreasing cost.

The merits of simplified designs notwithstanding, the panel also agreed that more complex and innovative solutions are justified in specialized applications. While simple solutions exist for many common converter applications, the challenges of new application domains may require entirely new designs. As an example, the panel discussed the challenges of subsurface applications in the oil and natural gas industry. Many specialty applications involve conditions outside typical operating ranges, and require components which are robust to environmental influence, such as high temperatures or electromagnetic interference. As a result, the unique problems encountered in new applications may lead to new solutions with more general impact.

3.5. Session 5: What role do power electronics play in making the grid smarter?

Chair: Charles Hanley, *Sandia National Laboratories*
Panelists:

- Leo Casey, *X (formerly Google[x])*
- Brandon Grainger, *University of Pittsburgh*
- Tom Jahns, *University of Wisconsin-Madison*
- Hariharan Krishnaswami, *DOE Solar Energy Technology Office*

The future grid described in Session 1 is "smarter" than our current power systems. More precisely, the future grid implements more sophisticated management and control systems to provide new services to both customers and utilities. In Session 5, panelists discussed the ways in which power electronics contribute to grid intelligence. The cost of microcontrollers, digital signal processors, and field programmable gate arrays is low, but the value of the functions they enable is high. The panel observed that all issues related to power quality are within the scope of inverter control, particularly if the control system is capable of decomposing AC measurements into symmetrical components. Fast acting measurement and control systems also provide potential solutions to the reliability challenges of power electronic devices. While power converters are still fragile and short-lived in comparison to electromechanical equipment, soft fault detection and mitigation may extend converter life span and increase their long-term value to the grid.

The panel illustrated the importance of intelligent control in two ways. First, they enumerated the benefits of new grid functionality. Second, they warned of the potential issues caused by large-scale adoption of converters without advanced control systems. In the absence of intelligent control strategies, power electronics may have a destabilizing effect on power distribution systems. As an example, the panel described the inadequacy of grid-following control in systems with high penetration of distributed energy resources. Grid-following operation is a simple control strategy. It assumes a stiff grid connection and exports maximum possible power from the local energy resource. However, when the amount of distributed generation is large enough, inverter power exports affect grid inertia (as power converter systems with low inertia have displaced high-inertia traditional synchronous generators). This results in larger variations in system frequency during contingency events and may cause conventional generating units to trip. In contrast, grid-forming control mimics the behavior of synchronous machines and allows inverters to share load requirements without communication. Only a small difference in control complexity separates grid-forming and grid-following inverters, but that small increase has enormous implications for system performance.

3.6. Session 6: What role do power electronics play in system integration, standards, and safety?

Chair: Adel Nasiri, *University of Wisconsin-Milwaukee*
Panelists:

- Wei-Jen Lee, *University of Texas at Arlington*
- Andy Rockhill, *Eaton Corporation*
- Charlie Vartanian, *Mitsubishi Electric Power Products*

The last session of the workshop considered progress and challenges in system integration, standards development, and safety. The panel presented practical efforts to make microgrids work in the real world. At present, equipment compatibility is a challenge. In the absence of standard interconnection and communication protocols, comprehensive single-manufacturer solutions are the most viable options for early microgrid deployments. These systems are important first steps toward implementing the future electric grid; they help researchers and manufacturers to understand practical microgrid problems. Key among these are issues related to safety and system protection. In addition to the challenges of converter protection, the preponderance of power electronics in the grid may reduce the effectiveness of existing system protection schemes. For instance, a power electronic system may limit fault current, preventing traditional protection devices from actuating. More detailed understanding of the system-level effects of widespread use of power converters is needed.

Microgrids are just one example of the influence of power electronics on existing power grids. However, microgrids and distributed generation systems are an important test case for more general power electronics applications in utility systems. Lessons learned in early microgrid deployments and demonstration projects help inform new standards, which in turn provide a safe pathway for widespread adoption of new technologies. The panel described this process using IEEE 1547 as an example. In the ideal case, standards protect existing systems and ensure safety, but provide enough flexibility to support innovation. However, standards develop slowly, and their usefulness depends on how they are adopted.

4. ELECTRIC UTILITY GRID WORKSHOP AGENDA

Tuesday July 17, 2018		
8:00	Welcome and Workshop Overview	Stan Atcitty, *Sandia National Laboratories*
8:10	Sandia National Laboratories Overview	Carol Adkins, *Sandia National Laboratories*
8:30	Energy Storage Impact on the Grid	Imre Gyuk, *DOE Office of Electricity*
8:40	Session 1: Future Vision for Power Electronics	Chair: Stan Atcitty, *Sandia National Laboratories* Panelists: Manuel Avendano, *Southern California Edison* Dushan Boroyevich, *Virginia Tech* Kerry Cheung, *DOE Office of Electricity* Deepak Divan, *Georgia Tech*
10:00	Break	
10:15	Session 2: Power Electronics Today	Chair: Kaushik Rajashekara, *University of Houston* Panelists: Ram Adapa, *Electric Power Research Institute* Anant Agarwal, *Ohio State University* Subhashish Bhattacharya, *North Carolina State University* Madhu Chinthavali, *Oak Ridge National Laboratory*
11:15	Lunch	
12:45	Session 3: Power Electronics Components Needed for Future Vision	Chair: Bob Kaplar, *Sandia National Laboratories* Panelists: Jim Cooper, *Sonrisa Research, Inc.* Abhijit Gurav, *KEMET Corporation* Paul Ohodnicki, *National Energy Technology Laboratory* Brandon Passmore, *Wolfspeed*
1:50	Session 4: Power Electronics Topologies Needed for Future Vision	Chair: Satish Ranade, *New Mexico State University* Panelists: Martin Becker, *Princeton Power* Rajib Datta, *GE Global Research* Adel Nasiri, *University of Wisconsin-Milwaukee* Kaushik Rajashekara, *University of Houston*
2:50	Break	
3:05	Poster Session	
4:05	Reception	
6:30	Adjourn	

Wednesday July 18, 2018		
8:30	Welcome and Day One Recap	Babu Chalamala, *Sandia National Laboratories*
8:45	Session 5: How do Power Electronics Make the Grid Smarter?	Chair: Charlie Hanley, *Sandia National Laboratories* Panelists: Leo Casey, *X (formerly Google[x])* Brandon Grainger, *University of Pittsburgh* Tom Jahns, *University of Wisconsin-Madison* Hariharan Krishnaswami, *DOE Solar Energy Technology Office*
9:45	Break	
10:15	Session 6: Power Electronics role in System Integration, Standards, and Safety?	Chair: Adel Nasiri, *University of Wisconsin-Milwaukee* Panelists: Wei-Jen Lee, *University of Texas at Arlington* Andy Rockhill, *Eaton Corporation* Charlie Vartanian, *Mitsubishi Electric Power Products*
11:15	Wrap-up and closing comments	Stan Atcitty, *Sandia National Laboratories*
11:30	Lunch	
1:00	Adjourn	

5. ELECTRIC UTILITY GRID WORKSHOP ATTENDEEE LIST

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