

# Projecting the Evolution of Power Electronics

*Highlights from FEPPCON VIII*



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by Ashok Bindra

Last September, during the eighth International Workshop on the Future of Electronic Power Processing and Conversion (FEPPCON VIII 2015), more than 50 power electronics experts from around the world gathered at the Grand Hotel Majestic in scenic Lago Maggiorie, Verbania, Italy, to jointly predict the evolution of power electronics in the next ten-plus years. The aim was to identify technological opportunities and obstacles for applications of power electronics in generation, storage, transmission, distribution, and conversion of electric energy, while concurrently looking for new directions for future research and development.

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In recent years, the electric grid and transportation systems have greatly benefited from advances in power electronics based components, which has brought us to the point where smart grids and electrical transportation have become a reality, says Prof. Braham Ferreira of Delft University of Technology, The Netherlands, IEEE Power Electronics Society (PELS) president and cochair of FEPPCON VIII. Although power electronics has made new system features possible while concurrently creating opportunities for the components industry, it has also created problems that are at the center of this evolution. Hence, the need for a workshop to better understand power electronics in systems, adds Prof. Ferreira.

In essence, based on their understanding of the rapidly changing landscape of power processing and conversion from the grid to the consumer, the participants identified fundamental issues for pushing the application boundaries by the year 2025 and beyond.

The workshops were organized from 4 to 6 September by PELS under the chairmanship of Prof. Frede Blaabjerg of Aalborg University, Denmark and cochairs Prof. Ferreira and Prof. Daan Van Wyk of Rand Afrikaans University, South Africa. While Prof. Dushan Boroyevich of Virginia Polytechnic Institute and State University (Virginia Tech) was the long-range planning chair, Prof. Paolo Mattavelli of the University of Padova, Italy, acted as the local advisor and organizer for the conference.

On day 1 (4 September 2015), there were three technical sessions, “Power System Infrastructure,” “Converter Networks/Systems,” and “Transportation Electrification.”

### Power System Infrastructure

The “Power System Infrastructure” session, chaired by Prof. Johan Enslin of the University of North Carolina, Charlotte, featured five papers. The paper “Challenges for Developing the Integrated Grid” kicked off the session. Since the paper’s author, Mark McGranaghan, Electric Power Research Institute’s (EPRI’s) vice president, was not at the workshop, Prof. Enslin presented it.

With the rapid rise of distributed energy resources, EPRI has been studying the transformation of the electric grid. In other words, EPRI has been investigating ways to integrate these emerging resources into the conventional grid so that customers can tap the benefits of both the central power system and distributed resources in the most cost effective way. EPRI’s paper proposed an integrated grid as a power system that is highly flexible, resilient, and connected, with the ability to optimize energy resources (Figure 1). In addition, the integrated grid would allow lo-

cal energy optimization to become part of the global energy optimization.

The presentation indicated that EPRI started working on this concept in February 2014 (phase 1). A benefit/cost assessment of an integrated grid was conducted in January 2015 (phase 2). The project is now in phase 3 of this development, with ongoing demonstrations of pilot projects. There has been extensive industry coordination in all three phases. While addressing the integration issues, the study has also been focusing on how much to integrate with hosting capacity that ensures voltage control and thermal limits. Speaking of capacity, the study suggests that, in the future, capacity and ancillary services will become more important with an integrated grid.

The paper identified a few game changers for the integrated grid. They include distributed solar, energy storage and associated power electronics, distributed intelligence, and model-based management, including new models for power electronics controls. To realize this vision, there are many challenges to confront. According to McGranaghan’s paper, key among them are research collaboration and coordination, cross-cutting approaches, standards, and new approaches to education and training.

Demonstrating the critical role of power electronics at the utility grid, Prof. Deepak Divan of the Georgia Institute of Technology, Atlanta, and the founder and chief scientist of Varentec, presented the second paper, “Grid-Edge Control—Distributed Control of Power Systems.” Calling grid-edge control a new paradigm for distributed control of power systems, Prof. Divan argued that the conventional centralized volt-var control is complex and slow, with a limited number of operations and challenging implementation of fault detection, isolation, and load restoration. Moreover, there is no secondary voltage control, and photovoltaic (PV) integration is difficult, while conservation voltage reduction performance is poor. Prof. Divan’s paper

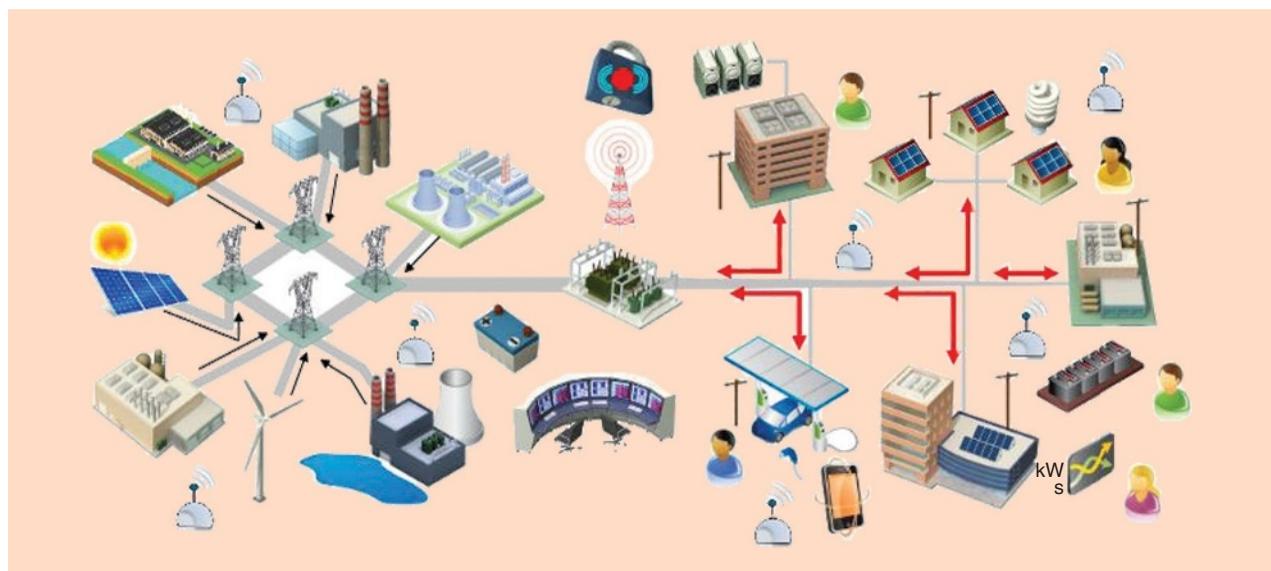
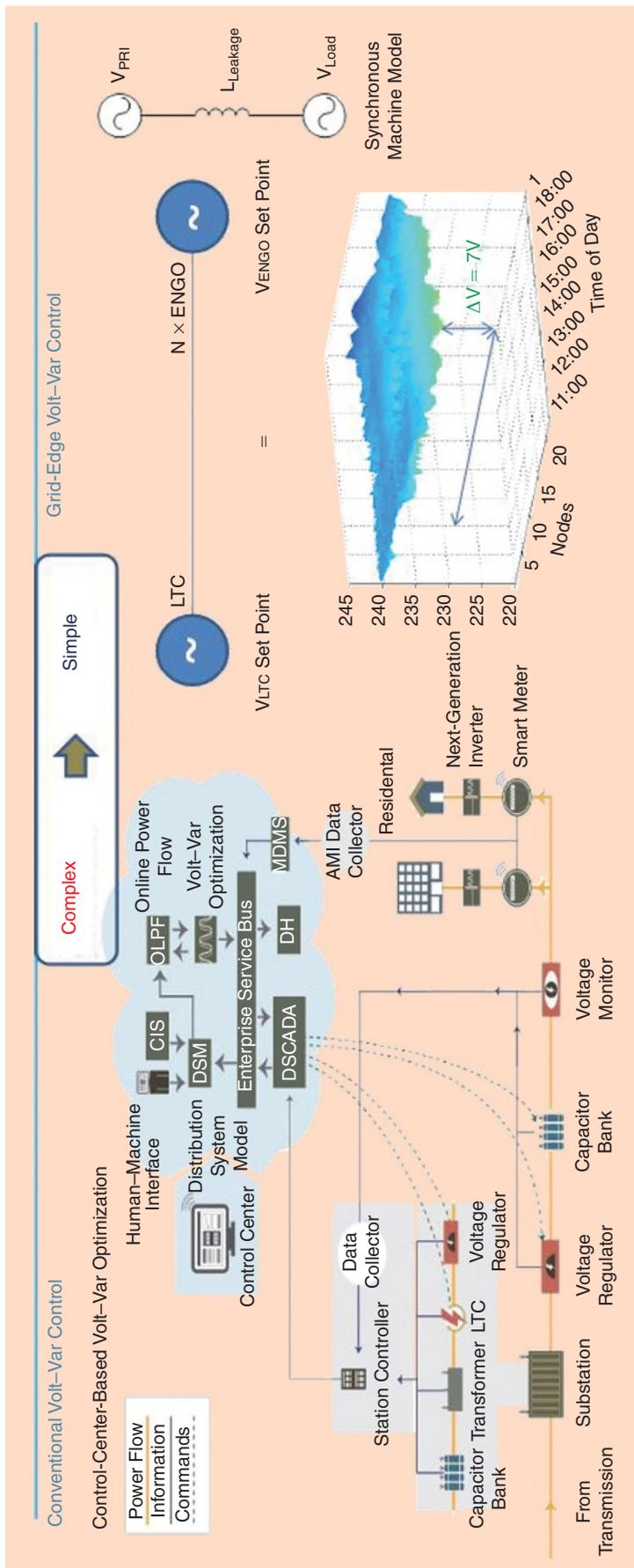


FIG 1 EPRI’s vision of an integrated grid. (Figure courtesy of EPRI.)



**FIG 2** Unlike conventional centralized volt-var control, grid-edge volt-var control is simple coordinated LTC and ENGO control with automatic regulation of load voltages and self-balancing regulation of primary voltage. (Figure courtesy of Varentec.)

showed that, unlike the conventional volt-var control, the grid edge volt-var control is simple coordinated load tap changer (LTC) and edge-of-network grid optimization (ENGO) control with an automatic regulation of load voltages and self-balancing regulation of primary voltage (Figure 2). It also provides control of feeder-level power factor and vars, and its dynamic response enables PV integration.

For this application, Varentec has developed a shunt var-injection device, the ENGO-V10. It is built using capacitors controlled by smart switches for injecting varying levels of reactive power into the grid [1]. Approximately 15 utilities in the United States, deploying hundreds of ENGO devices across their respective feeder lines, are studying the benefits of grid-edge control using the ENGO-V10. Figure 3 shows graphical field data from the southeastern United States for a 5-MW, 12-mi feeder using the ENGO-V10.

It shows a 5% voltage reduction while keeping all endpoints within the low-voltage (LV) limits of American National Standards Institute (ANSI), effectively increasing the overall system's capabilities and achieving 5% energy savings. Furthermore, according to the paper, the results also suggested that grid-edge control improves energy control range by  $2.5 \times$  versus the conventional control.

In short, field data suggest that grid-edge control offers many benefits, including

- unexpected voltage drop across the service transformer
- the ability to operate paralleled autonomous var devices with zero droop
- self-balancing regulation
- automatic compensation for PV volatility, increasing hosting capacity
- decoupled volt-var control at the system level through feeder aggregation.

Consequently, grid-edge control can be transformative for utilities.

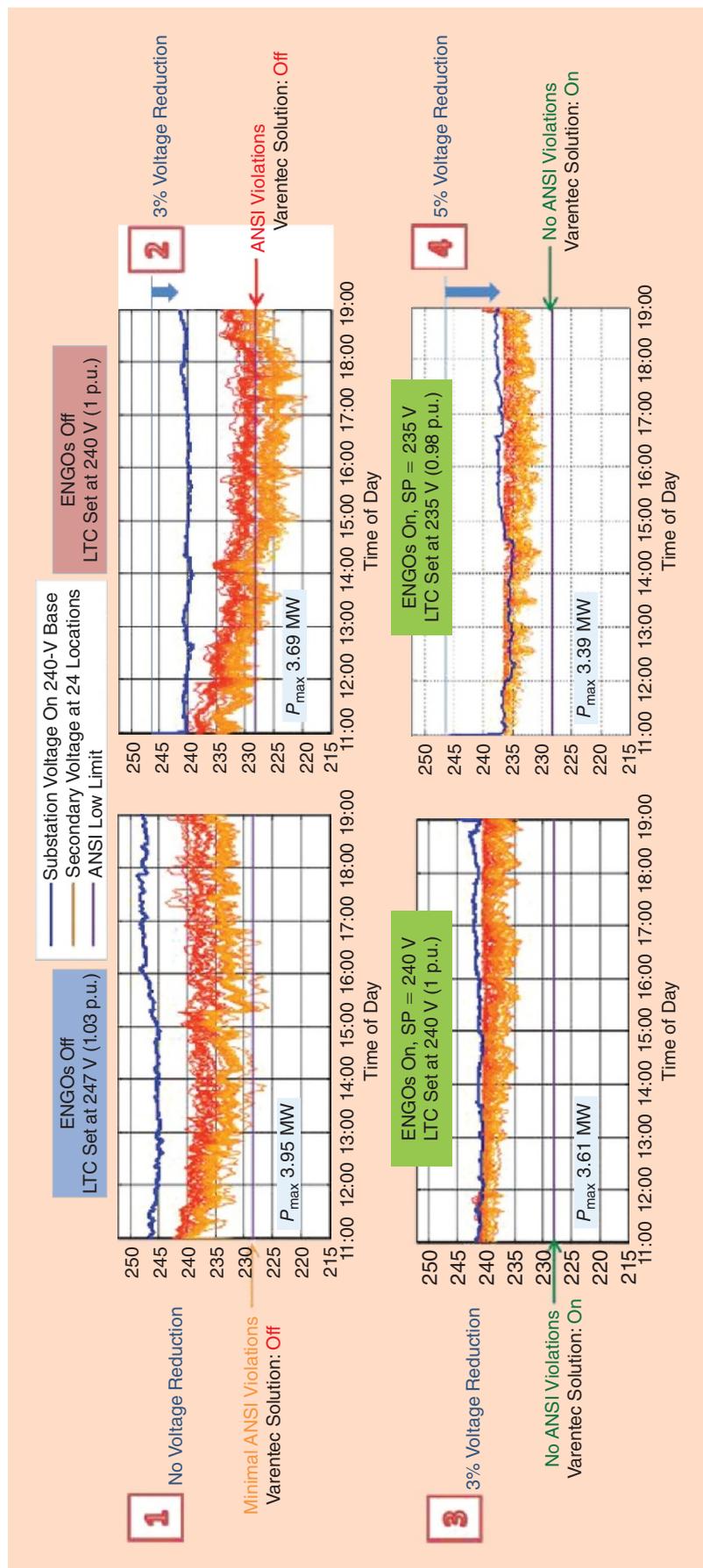
### Energy Storage and System Stability

The next paper, "Power Electronics and Storage Systems for Flexible Distribution Networks," was presented by Prof. Rik W. De Doncker of RWTH Aachen University, Germany. The talk focused on the future electricity grid, which is slowly moving in the direction of dc transmission for several reasons, including lower distribution losses as compared with ac distribution and more efficient integration of

renewables to substantially increase the mix of clean energy sources with the standard grid in the next ten-plus years. During the presentation, Prof. De Doncker argued that comparing the standard ac grid versus the dc grid is like comparing beer and wine. Unlike a glass of beer, which has significant amount of foam at the top, a glass of wine is flat at the top. A dc grid is like wine, with very minimal disturbance on the line.

In addition, as medium-voltage (MV) dc grids gain popularity, electronic transformers, also known as solid-state transformers (SSTs), will gain momentum. This, in turn, will simplify the use of energy-storage systems. Also, in-house dc distribution grids will further improve cost savings and reliability with less maintenance.

Subsequently, Prof. Ron Hui of the University of Hong Kong and Imperial College London presented his paper, "Use of Power Electronics Technology for Power System Stability." He noted, "While the trend toward renewable energy sources is gaining momentum worldwide for backup and clean energy, its intermittent behavior is initiating destabilization of electric grids, causing potential blackouts." Consequently, Prof. Hui added, "The grand challenge is how to increase wind/solar power substantially and simultaneously while achieving power balance and voltage and frequency stability." His solution to stabilize the power system is to use grid-connected power inverters as a stabilizing force. In other words, Prof. Hui is proposing grid-connected inverters mimicking electric springs (ESs) for demand response. By his definition, an ES is a power electronics system that can be used like an active suspension device, distributed over the power grid to stabilize the mains voltage in the presence of a large percentage of intermittent renewable power generation. Consequently, he continued, many small but distributed ESs should provide a collectively robust stabilizing effect on the future smart grid (Figure 4).



**FIG 3** The field data from a 5-MW, 12-mi feeder in the southeastern United States compare the performance of the conventional centralized volt-var control with grid-edge volt-var control. (Figure courtesy of Varentec.)

Based on these talks, note-taker Marcelo L. Heldwein presented his views on what some of the major challenges posed by the emerging integrated grid are. According to Heldwein, power converters need a more integrated design approach, including system-level control that is reliable and low cost. Power electronic and power system engineers must communicate effectively. Although the integration of distributed renewable resources is accelerated with low cost, it will bring challenges to distribution network operation. For example, the networks must be rated for thermal overloads and be capable of handling bidirectional power flow. Volt-var control and distributed energy-storage integration must also be considered, and excess intermittent resources might lead to system-wide stability problems.

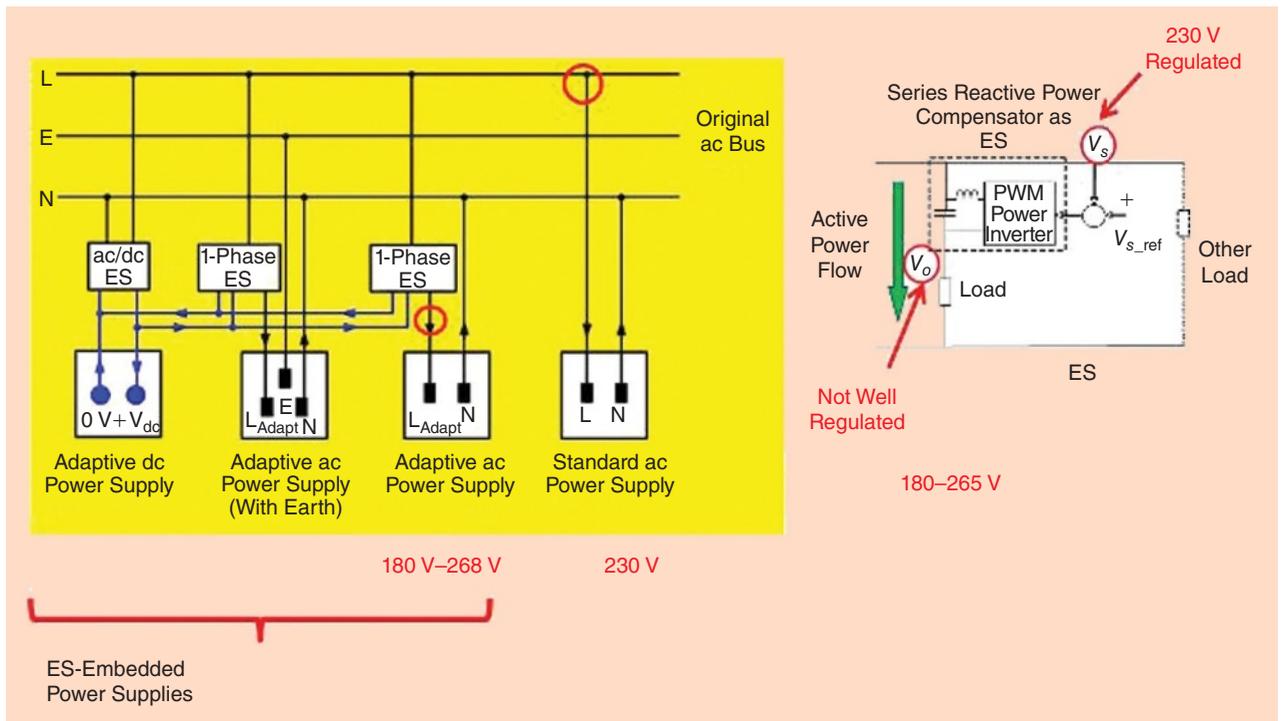
In addition, stated Heldwein, widespread use of multiple power electronics in the transmission and distribution grid leads to system resonances, and grid protection needs to be redesigned with power electronics in mind. With an integrated grid, better utilization of distribution network capacity is also going to be challenging.

Other challenges highlighted by Heldwein include cyber- and physical security risk with power-electronics-rich networks; underutilized advanced metering infrastructure by the power electronics community; modeling of large numbers of converters, grid impedances, energy resources, and loads; and energy-storage optimization and applications. Furthermore, he added that there is a need for better interaction between filters and systems of converters at high populations and for developing optimum value propositions using power electronics in distribution networks.

Regarding the solutions offered in this session, Heldwein indicated that power electronics is well positioned to mitigate intermittent sources at the LV grid edge as well as manage power flow, increase capacity utilization, and provide ancillary services, such as demand response and regulation. Similarly, distributed intelligence with communication and supervisory control can optimize distribution network operation through converters. While improving ac grids with distributed power converters, it can provide an intermediary step to future dc grids. Furthermore, to gradually improve the overall system, dc systems could be built on top of ac systems, and power electronics could play a more dominant role in integrating thermal and electric networks. With this growing integration, protection methodology and solid-state protection at all levels (ac and dc) are needed in the power electronics strategy. With respect to cost, Heldwein concluded that the power electronics community is close to the breakeven point between solid-state and conventional (copper and iron) 50-/60-Hz distribution systems.

### Converter Networks/Systems

Before starting the session “Converter Networks/Systems,” session Chair Prof. Braham Ferreira quickly highlighted the challenges confronting power electronics converters in the emerging power systems. According to Prof. Ferreira, power converters increasingly have to work together in systems while walking a tightrope to balance and control the interaction they have with each other. Concurrently, these power converters have to collectively provide the desired system performance. As a result, there are new challenges in control and communications, he noted.



**FIG 4** Two ESs embedded in a power supply infrastructure provide regulated output despite fluctuations in the input. (Figure courtesy of The University of Hong Kong/Imperial College London.)

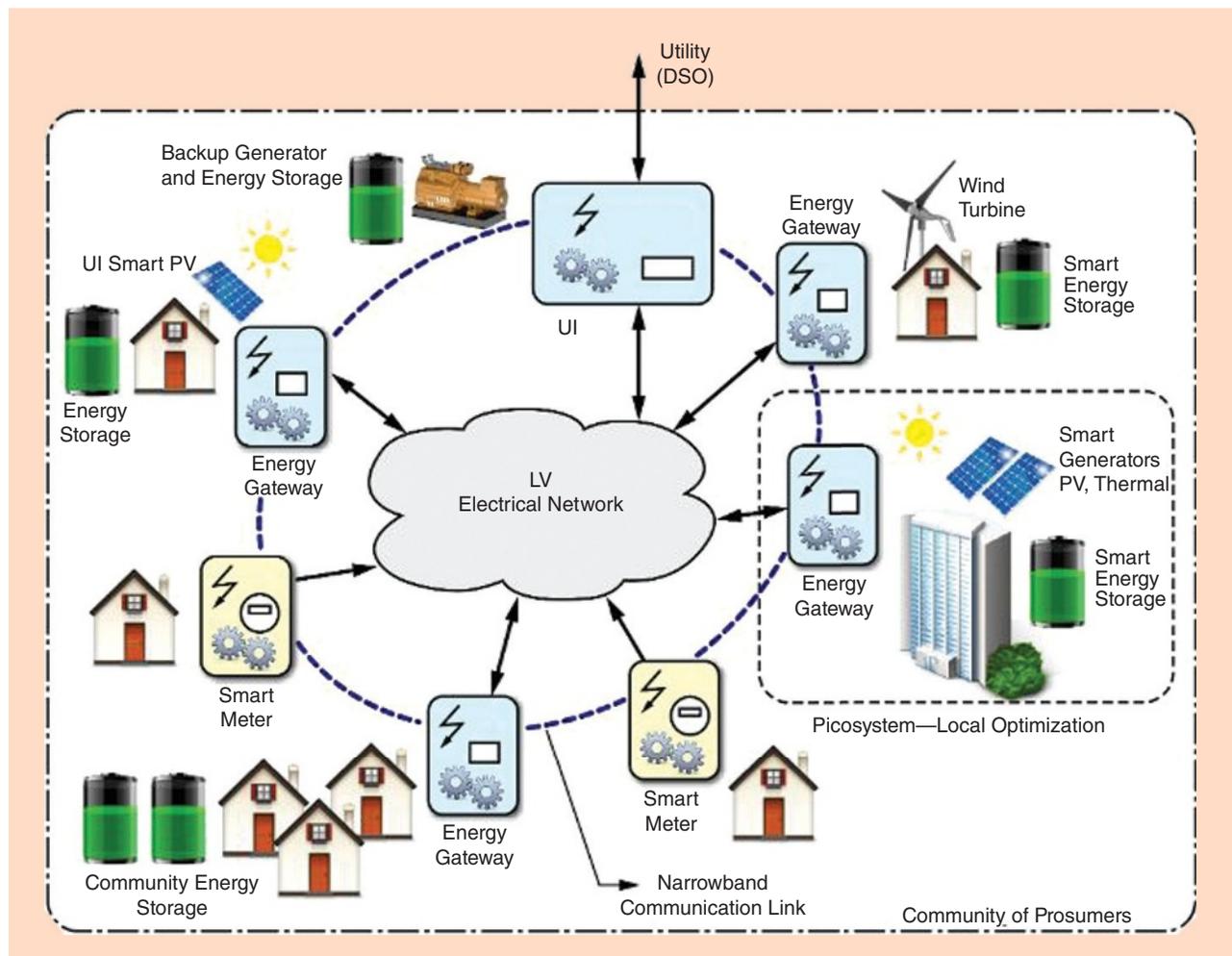
The first paper in this session, “Interactions of Power Electronics Converters in Distribution Grids: Some Issues and challenges” by Prof. Paulo Mattavelli, examined the interactions of power electronics converters at different levels of distributed networks and LV microgrids. Presenting a typical LV microgrid architecture (Figure 5), the paper highlighted utility interface (UI) as a key element of the architecture that ensures safe dynamic operation of the microgrid and its effective interaction with the mains. Besides allowing optimum microgrid operation in the steady state (minimum losses and maximum power quality), UI also enables soft transition to/from islanding and black start.

Although UI has solved the problem of transition from grid-connected to islanded operation and vice versa for the LV microgrid, there are still issues when it returns to grid-connected operation with a large number of UIs in operation. The challenge is how to guarantee small interaction when a large number of UIs are operating, says Prof. Mattavelli. The protection complexity also rises with this number, according to the paper.

Investigating interaction with a large number of parallel inverters in a multimewatt PV farm, the study found

that current stability tools were inadequate for the task and that MV automated reclosing switches were not designed to close with voltage at the load side when unintentional islanding occurs. The paper also indicated that anti-islanding schemes (which are not mandatory in some countries) may not work with multiple PV systems. Concurrently, the paper also proposed active power–frequency ( $P/f$ ) and reactive power–voltage ( $Q/V$ ) droop methods for addressing instability during unintentional islanding of microgrids. In addition, such methods can also help enlarge the nondetection zone. However, for accurate results, better load models are needed for this study, as noted in the paper.

Finally, the paper presented a distribution power generation load power sharing model that could fit in the existing infrastructures. The talk concluded that radical innovations are expected in the LV microgrid arena as there are no technology bottlenecks that could limit the development of microgrids. Furthermore, Prof. Mattavelli added, power electronics interactions may increase with large renewable distributed power sources for several reasons, which include internal converter control, grid functions



**FIG 5** UI is a key element in the LV microgrid architecture. It ensures safe dynamic operation of the microgrid as well as effective interaction with the mains. (Figure courtesy of The University of Padova, Italy.)

imposed by standards, and coordination in reactive/active power distributed control. The interactions can be minimized by ensuring protection coordination, developing load models, and analytical tools and methodology to create modularity approach.

Similarly, investigating “Future Requirements for Reliable Networks of Converters,” Prof. Rainer Marquardt of the Institute for Power Electronics and Control, the University of Bundeswehr, Munich, Germany, proposed modular converter systems that use multiple voltage levels. He explored safe behavior under fault conditions, redundant operations after faults, and network expandability. Several problems were identified under these scenarios along with steps proposed to overcome them. For example, for safe behavior under fault conditions, the paper identified five main problems and proposed measures as follows:

- 1) An isolation fault of one partner disturbs the whole network.
  - *Proposed measures:* disconnection by means of mechanical switches, a double isolation system with intermediate voltage sensing and isolated data, and auxiliary power transmission (wireless transmission).
- 2) A defect of one partner results in shorting the bus.
  - *Proposed measures:* disconnection by means of mechanical switches and using redundant topology [i.e., a modular multilevel converter (MMC)].
- 3) A defect of one partner results in a surge or high resonant currents in the bus (with defects in other converters possible).
  - *Proposed measures:* no capacitors are allowed at the bus, and use fast (electronic) protection switches.
- 4) A defect of one partner results in self destruction, including explosion and arcing.
  - *Proposed measures:* mechanical pressure-proof housing to protect the environment and press-pack semiconductors.
- 5) A defect of one partner results in extreme surge currents (mechanical destruction and arcing in the whole network).
  - *Proposed measures:* limit allowable capacitor size, and use fast (electronic) protection switches and damping resistors.

Likewise, for redundant operation after faults, four problems were presented.

- 1) Power semiconductors are neither safely shorted nor open.
  - *Proposed measures:* use press-pack devices, bypass switches, and fuses.
- 2) The power circuit topology necessitates rearranging the circuit.
  - *Proposed measures:* employ mechanical switches for rearranging and a topology with inherent redundancy, including series connections of power electronic building blocks (PEBBs).
- 3) Data transmission is disturbed.
  - *Proposed measures:* redundancy and error correction of (duplex) transmission channels.

- 4) Measurement signals and auxiliary power are lost.
  - *Proposed measures:* redundancy and monitoring of redundancy.

Figure 6 shows a typical PEBB of high integration level recommended for the aforementioned measures.

For the third issue, expandability of the network, three problems were recognized.

- 1) The resulting impedance of the network is changing (protection levels must be adapted).
  - *Proposed measures:* a concept with self-protecting converters (including overvoltage clamping, current limitation at ac and dc side).
- 2) There are electromagnetic interference (EMI) compatibility changes.
  - *Proposed measures:* a concept not relying on passive filters.
- 3) The resulting resonance frequencies of the network are changing.
  - *Proposed measures:* a concept not relying on passive filters.

In a graphical presentation of bus impedance versus frequency at a converter terminal (Figure 7), the paper showed that filters at the bus lead to multiple series and parallel resonances. In short, Prof. Marquardt’s talk suggested that the future measures would require converters with inherent redundancy and reduced  $dv/dt$ , self-protected converters, and no passive filters at the network side (bus).

In the same session, Kamiar J. Karimi, a senior technical fellow at Boeing Co., investigated the bottlenecks and opportunities of power-electronics-based power systems in more-electric airplane (MEA) architecture. His slides presented power electronics as a pervasive technology in the MEA architecture, but he cautioned that there are many design challenges for the integration of power electronics equipment in the aircraft environment. These include the following.

- Very high power densities are needed to meet size/weight constraints.
- High efficiency is necessary as a very limited amount of heat can be rejected.
- Converters must operate in challenging environmental conditions.
- Constraints on emission and susceptibility of electromagnetic fields make filtering an important part of power electronic systems.
- Controls must be designed to ensure source/load stability—limited source sizes combined with many power electronic loads in parallel can impact system stability.
- Power electronics introduces new failure modes, so power system protection and coordination is becoming more challenging.

Key bottlenecks highlighted by Karimi included complexity, meeting stringent requirements like power density/efficiency/reliability/thermal management at low cost, and conservative industry. The penalty is severe when these systems are not reliable. Despite these hurdles, there are many opportunities, he noted.

A session summary provided by Prof. Robert Balog indicates that there are currently limitations in global system optimization (top-down and bottom-up) and technoeconomic optimization. Models are currently not good enough. Although component models offer electrical static and dynamic characteristics, they do not capture the thermal, lifetime, reliability, and cost that are needed for system-level optimization.

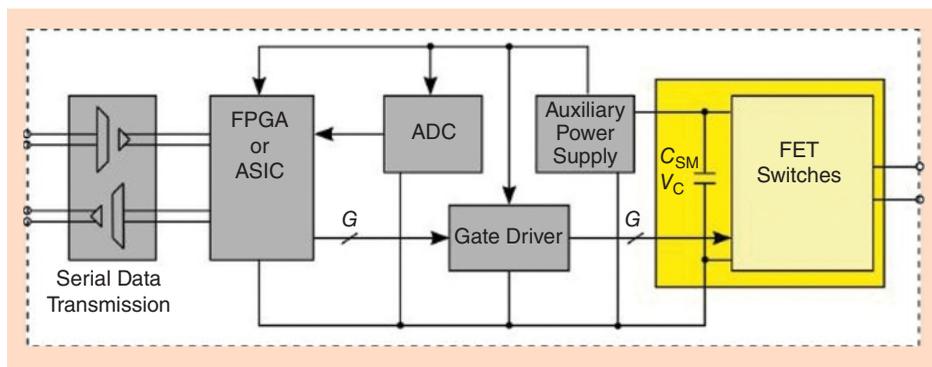
Likewise, he continued, codes and standards lag behind technology development and may not embrace the capabilities of power-electronics-enabled power systems. There is a “need to address standards for power electronics integration into electrical systems,” stated Prof. Balog. He further suggested that protection is a technical area that is under-represented in power electronics. Design for reliability and cost are not addressed in academia and, therefore, must be elevated in priority.

Based on his observation, Prof. Balog suggested a few directions for the power electronics community. These include the development of standard test case systems with sufficient and appropriate dynamics to be a validation and design tool for power converter integration; the development of appropriate system-oriented models, including dynamic load models, that contain a rich set of multiphysics, including electrical, thermal, cost, reliability, and so on; and the development of a society-wide mechanism to share lessons learned. Furthermore, Prof. Balog highlighted the importance of understanding the dynamics of at-scale power-electronics-enabled power systems, developing a mutual understanding/common language for protection technology and system coordination between power electronics and power systems, including protection as integral to power electronics, and coordination at the system level. He also hinted at developing a common vocabulary (lexicon) to describe features and capabilities of power-electronics-enabled power systems, for example, common definitions for reliability, resiliency, and availability.

### Transportation Electrification

The discussion of power electronics in MEA continued into the third technical session of the day, Transportation Electrification, chaired by Don Tan of Northrop Grumman Aerospace Systems, the immediate past president of PELS. In his paper, “Power Electronics for the More-Electric Aircraft,” Prof. Pat Wheeler of the University of Nottingham, United Kingdom, explored both the challenges and motivations of integrating power electronics in MEA architecture.

According to Prof. Wheeler’s talk, motivations include

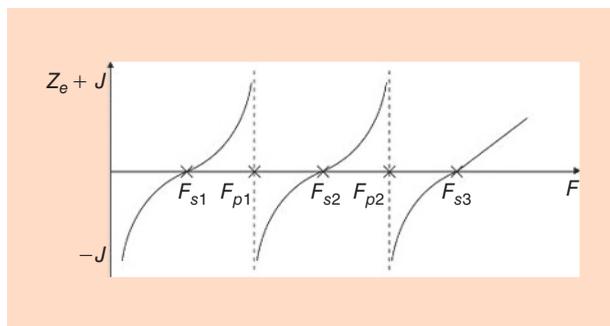


**FIG 6** A typical schematic of a PEBB with a high level of integration. FPGA: field-programmable gate array; ASIC: application-specific integrated circuit; FET: field effect transistor. (Figure courtesy of the University of Bundeswehr Munich, Germany.)

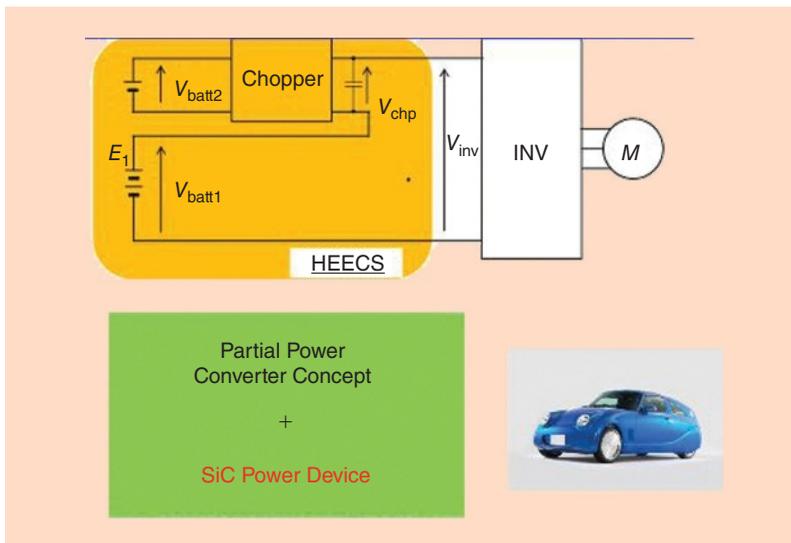
- the removal of hydraulic systems (for reduced system weight and ease of maintenance)
- a bleedless engine (for improved efficiency and simplified design)
- desirable characteristics of electrical systems, like
  - controllability (for power on demand)
  - reconfigurability (maintaining functionality during faults)
  - advanced diagnostics and prognostics for more intelligent maintenance and increased aircraft availability.

The overall goals for these motivations were reduced operating costs, fuel burn, and environmental impact. The challenges outlined by Prof. Wheeler include optimization of system-level design and integration, power-converter topologies, functionality, thermal design, size and weight, and reliability of device packaging and bonding techniques. Newer device materials, such as silicon carbide (SiC) and gallium nitride (GaN), must deliver more power at high efficiencies.

The session shed some light on electric vehicles (EVs), high-speed railway systems, spacecraft, and ships. Prof. Atsuo Kawamura of Yokohama National University, Japan, examined a very high-efficiency energy-conversion system (HEECS) for EV power trains. Prof. Kawamura’s paper, “A Very High-Efficiency Chopper” presented a new power train for EVs with longer driving range. The paper described a superhigh-efficiency chopper (>99%) for an EV power train.



**FIG 7** The filters at the bus lead to multiple series and parallel resonances. (Figure courtesy of the University of Bundeswehr Munich, Germany.)



**FIG 8** A two-battery-based HE ECS incorporating the proposed series chopper. (Figure courtesy of Yokohama National University, Japan.)

Figure 8 shows the proposed series chopper incorporated in a two-battery-based HE ECS.

The result is a very high-efficiency, compact, and light-weight system and simple output stabilization control. In addition, it delivers higher output power against fluctuations of input voltage for the EV power train. The concept was verified in a 10-kW chopper using 1,200-V, 180-A SiC MOSFET power modules. Figure 9 shows experimental test results for a 20-kW back-to-back HE ECS system. It shows that the 20-kW HE ECS prototype achieved 99.3% efficiency at 15-kW output, which increases to 99.5% at 5-kW output.

Zhixue Zhang of CSR Zhuzhou, China, uncovered some significant challenges of incorporating power electronics

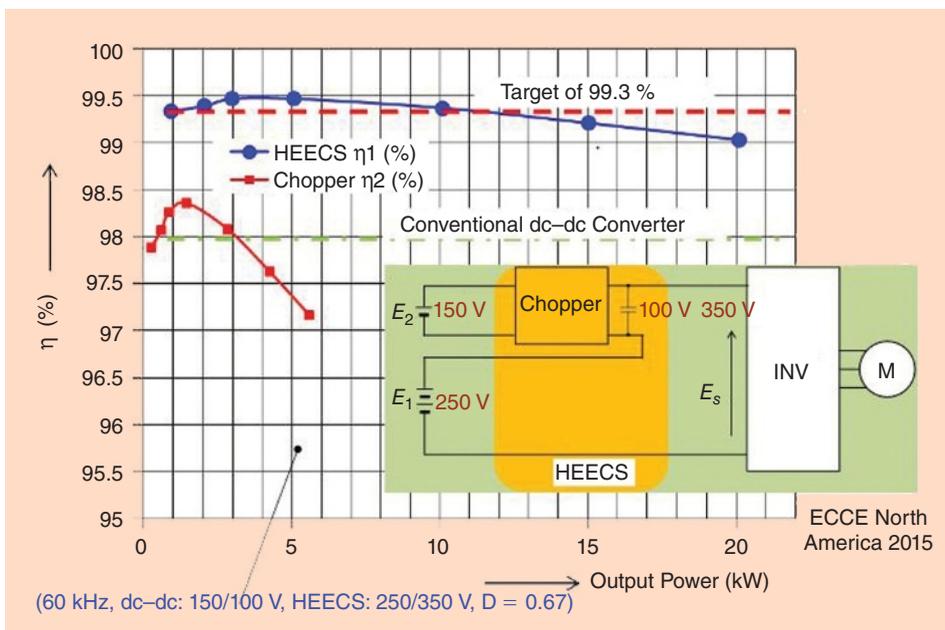
technology in high-speed railways. Currently, third-generation high-speed trains (HSTs) in China, with a speed of 350–430-km/h, are now ready for production. According to Zhang, key challenges for power electronics in the next-generation HSTs are achieving high reliability of power devices in traction converters, higher power density, and high intelligence.

“Power devices are the weakest point of the traction drive system,” says Zhang. Therefore, he added, they must be subjected to much harsher test conditions as compared to power devices used in common converters. While improving the performance of the next-generation IGBTs, Zhang’s engineers are also concurrently advancing packaging technology for power devices and modules.

Meanwhile, plans for fourth-generation HSTs (with speeds of 500 km/h) are on the drawing board. Chinese researchers are exploring new converter topologies, such as power electronic transformers (SSTs), energy-storage technologies, multilevel converters, high-voltage SiC IGBTs rated at 10 kV/200–300 A, better packaging technologies, and intelligent protection systems.

Disclosing the future role of power electronics in “Electric Propulsion in Space,” session Chair Don Tan explored upcoming metrics for solar arrays and emerging high-power thrusters. His presentation indicated that in-space electric propulsion for human space exploration calls for 250-kW thrusters and new solar arrays that will increase the specific power by 3–4× and packaging density 2.5–4× over current solar arrays (Figure 10). The new high-power thrusters will reduce the number of units needed.

Next Prof. Dushan Boroyevich, the director of the Center for Power Electronics Systems (CPES), Virginia Tech, educated the workshop attendees on the evolution of electrical infrastructure in ships. Besides showing the integrated power systems used on modern cruise ships today, Prof. Boroyevich described the world’s first all-electric battery-powered ferry with two electric motors offering 450-kW output each. The batteries weigh 10 tons, with a capacity of 150 kWh. He also presented a four-zone



**FIG 9** Experimental test results for a 20-kW HE ECS system. (Figure courtesy of Yokohama National University, Japan.)

1,000-V dc distribution system deployed in the U.S. Navy's latest stealth-guided missile destroyer, USS *Zumwalt* (DDG-1000). The system includes MV ac power generation and propulsion with LV dc zonal electrical distribution. According to Prof. Boroyevich's presentation, future combat-ready shipboard power systems will be designed for reconfigurability and survivability with the ability to isolate the damaged section and reconfigure the electric plant in fewer than 100 ms. The presentation further highlighted the developments in SiC power devices and MV dc distribution for future applications (Figure 11).

Challenges identified in this session, according to note taker Robert Pilawa, include designing and building large power thrusters (>250 kW) for in-space electric propulsion for human space exploration, better understanding of reliability and failure modes of components and how to improve modeling of component reliability, improving the reliability of power devices and their packaging, continued improvements in battery technologies, and rapid charging and discharging of batteries. For MEA, improvements in inverters and motors are needed, in addition to storage.

Furthermore, he added, effective heat removal is critical in many transportation systems, while electric transportation requires system-level thinking. In addition, continued Pilawa, power electronics designer must concurrently work with other experts (mechanical, materials, software, and so on) at the system level.

### New Power Devices, High Temperature

During this presentation, Prof. John Shen from the Illinois Institute of Technology (IIT), Chicago, suggested that one future direction might lie in the convergence of nanotechnology and power electronics. He calls it "big power on a small scale" and cited a few early examples that his research group is currently looking into—a nanoscaled silicon IGBT with three times more current capability, a nanoscaled superjunction device with five times reduction in on-resistance, and power devices based on GaN nanowire arrays jointly investigated by Tyndall National Institute in Ireland, Illinois Institute of Technology, and Queen's University Belfast in Northern Ireland (Figure 12).

Similar projections were also made by Prof. T. Paul Chow of Rensselaer Polytechnic Institute, Troy, New York. In his paper "Living in a Wide-Bandgap World in 2025: What Conquered and What Next?" Prof. Chow investigated wide-bandgap (WBG) developments worldwide by 2025 and also presented a ten-year road map for SiC and GaN devices (Figure 13).

Based on improvements in materials, structure, and processes, Prof. Chow sees SiC MOSFETs handling up to 10 kV, with a current rating as high as 300 A, and SiC IGBTs going up to 25-kV blocking voltage with a current rating of up to 300 A. Likewise, the SiC gate turn-off thyristor (GTO) is also expected to handle voltages as high as 25 kV and 300-A current. The GaN HEMT/MOSFET is projected to offer a voltage range of 30–6,500 V, with a current rating of up to 300 A. GaN power ICs and optoelectronic ASICs are also

Solar Array Metrics	Current	Next Generation
Cell Efficiencies	29–33%	29–33%
Special Power (W/kg)	40–60	130–160+
Power (kW)	<20	30–50+
Special Volume (kW/M <sup>3</sup> )	8	~20–30+

(a)

Thruster Metrics	BPT–4,000	NASA TDU
Input Power (kW)	1–4.5	1–13
Thrust (mN)	50–280	25–685
Specific Impulse (s)	1,100–2,500	1,000–3,200
Thruster Efficiency	35–55%	20–61%

(b)

**FIG 10** The (a) solar array and (b) thruster metrics for next-generation electric propulsion in space. (Figure courtesy of Northrop Grumman Aerospace Systems.)

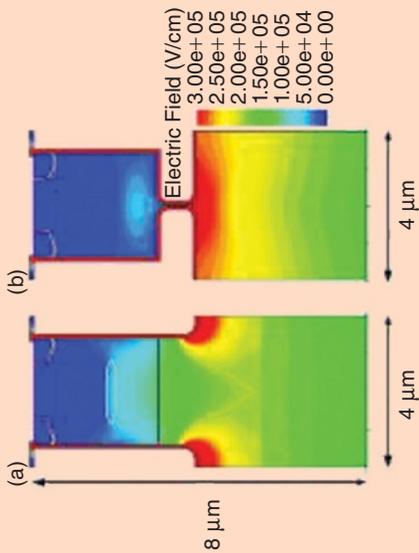
expected to emerge, as well as bidirectional power transistors in silicon, GaN, and SiC technologies. Bidirectional power transistors under development include the 1,200-V Si BD-IGBT, 600-V GaN BD-IGBT, and 10-kV SiC BD-IGBT. Furthermore, diamond-based MOSFETs and aluminum nitride (AlN) HFETs are also expected to challenge silicon in the next ten years.

Despite challenges from WBG devices, silicon is not going away any time soon. Franz-Josef Niedernostheide of Infineon Technologies AG confidently showed "Where Silicon Will Survive and Thrive in 2025." His paper indicated that there is still room for improvement for silicon. Superjunction MOSFETs, for instance, will continue to scale for the next few years and deliver improved  $R_{DS(on)} \times A$  specs, as well as reduce the stored charge. Simultaneously, evolution in silicon IGBTs will continue to improve switching losses and  $V_{CE(sat)}$  characteristics at high temperatures for the next five-plus

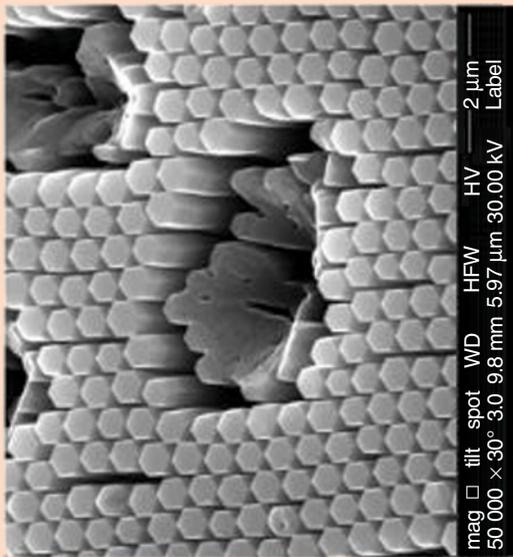
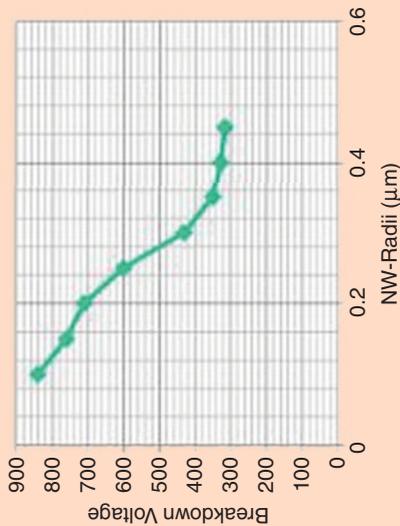
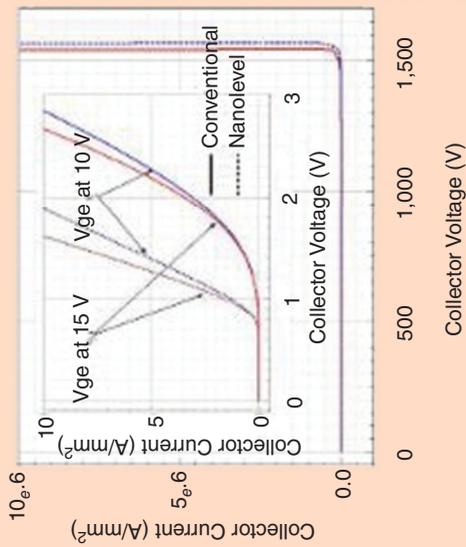
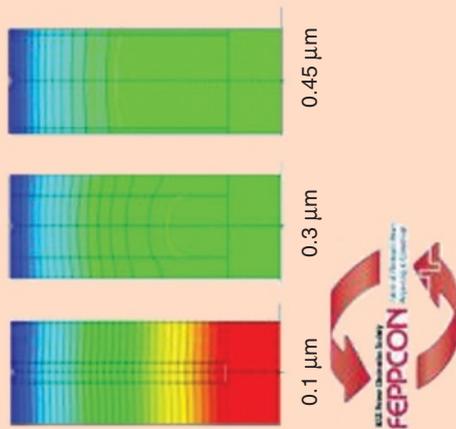


**FIG 11** The developments in SiC power devices and MV dc distribution for future shipboard applications. (Figure courtesy of CPES, Virginia Tech.)

**Nano IGBT: Three Times More Current?**



**Nano CoolMOS: Fivefold Reduction of  $R_{DS(on)}$ ?**



NanoGaN Research by Tyndall/IT/QUB (NSF)

**FIG 12** The nanoelectronics-driven power devices of the future. (Figure courtesy of John Shen and Peter Parbrock.)

years (Figure 14). In addition, the paper showed that IGBT advances such as the reverse-conducting IGBT with diode control (RCDC IGBT), when combined with advanced low-inductance packages, will further significantly cut switching and conduction losses at high voltages and power to meet the new power density, efficiency, and reliability goals of the future at low system costs. The paper demonstrated a working 6.5-kV RCDC IGBT fabricated by Infineon.

In another paper from Infineon Technologies, “Basic Potentials in Power Electronics,” Reinhold Bayerer, Infineon fellow of physics of power modules, demonstrated how lowering parasitic inductance can further cut losses and improve the turn-on characteristic of an IGBT. He also highlighted the high-temperature benefits of copper bonding and diffusion assembly of dies, resulting in operation as high as 200 °C. This, in turn, simplifies cooling and saves materials, noted Bayerer.

In a joint paper with Prof. C. Ó'Mathúna of Tyndall National Institute, Prof. W.G. Hurley of the Power Electronics Research Center, National University of Ireland, reminded the attendees that “Without Better Passives We Are Nowhere.” In this paper, the authors highlighted the important role of magnetics as switching frequencies and power densities, along with efficiencies, go higher. To realize true power supply on chip (PwrSoC), an integrated magnetics process, in which discrete magnetic devices are processed together with other components in an ultralow profile, must be compatible with IC process technology, says Prof. Hurley. To achieve future goals in efficiency and power density, the paper suggested new materials like nanocrystalline for magnetics and graphene, nanotubes, and ceramics for capacitors.

Fraunhofer Institute’s Eckart Hoene predicted issues for heterogeneous integration of power systems in a package (PSiP). These include thermal performance with a higher number of substrate interconnections, soldering (electrical and mechanical component assembly), flexibility/package standardization, and the availability of copper metalized chips.

According to session note taker Juan Carlos Balda, the session identified several challenges facing high-temperature power devices in the next ten-plus years. These include high-quality WBG material to make cost effective devices, high-voltage packaging (>10 kV) to allow hot swaps of grid-connected power electronic systems, meeting basic insulation level requirements, improving silicon IGBT performance by working on plasma profiles, and advancing protection and gate control of silicon RCDC IGBTs. Also on the radar was building heterogeneous processes that can handle materials with different coefficients of thermal expansion (CTEs), processing and reliability specs, and tackling thermal stresses due to CTE mismatch and developing controller ICs for switching at 10 MHz.

### Projected Road Map – Ten Years

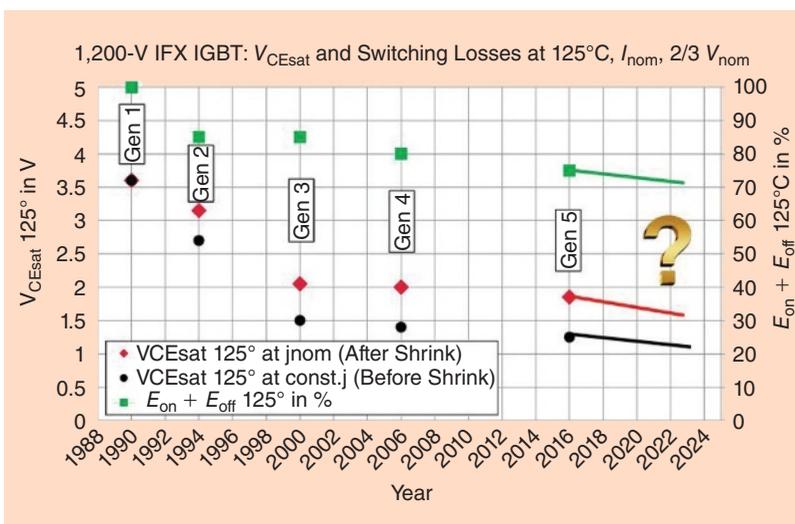
- SiC Schottky Rectifiers 600–5,000 V, 300 A
- SiC Junction Rectifiers 5,000–25,000 V, 300 A
- SiC MOSFET 600–10,000 V, 300 A
- SiC IGBT 5,000–25,000 V, 300 A
- SiC GTO 5,000–25,000 V, 300 A
- GaN HEMT/MOSFET 30–6,500 V, 300 A
- GaN Power IC
- GaN Optoelectronic LEIC
- Diamond MOSFET?
- AlN Diode?

**FIG 13** The ten-year road map for SiC and GaN power transistors. (Figure courtesy of Prof. Paul Chow.)

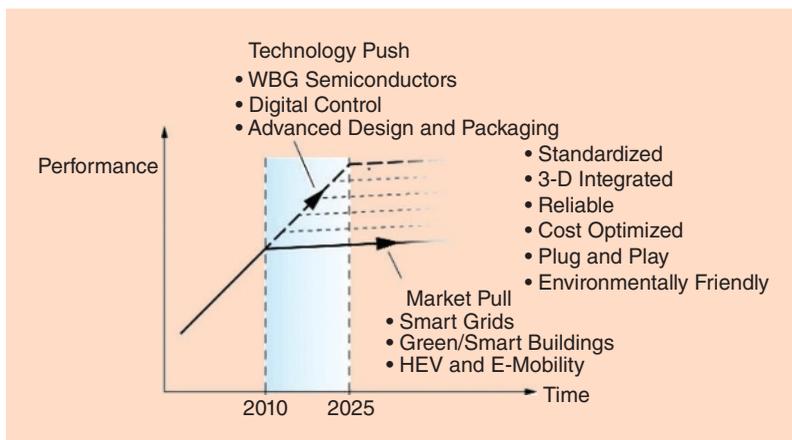
Balda also pointed to future research and development directions for such devices. It includes the development of high-voltage bidirectional SiC IGBTs and GaN MOSFETs, and up to 25-kV SiC power devices. Likewise, efforts are needed to push silicon devices for 200 °C operation and three-dimensional (3-D) printing to cut manufacturing costs. New materials are also needed for magnetics and capacitors for integration and high-temperature operation. New conductor materials are needed to replace maturing copper. Also required are smart power modules with built-in gate drivers for WBG devices. Furthermore, added Balda, better software tools are needed for designing advanced integrated packages and exploiting nanotechnology to enable higher current densities or reduced conduction losses.

### Power Electronics Integration

It is well understood that integration will play a crucial role in further pushing the performance envelop of power electronics circuits and systems. However, to simultaneously combine performance metrics such as power density, efficiency, weight, and failure rate with relative costs, power



**FIG 14** The improvement in silicon IGBT performance will continue for the next five-plus years. (Photo courtesy of Infineon Technologies AG.)



**FIG 15** Predicting the next level of integration by 2025. (Photo courtesy of ETH Zurich.)

electronics integration will confront many hurdles. Hence, key challenges of system-level integration were further discussed and debated in the last session of the workshop Power Electronics Integration chaired by Prof. Johann W. Kolar of ETH Zurich, Switzerland. While advances in packaging and passives, including magnetics, will be vital for achieving improvements in integration, Prof. Kolar's presentation hinted that raising the bar of system-level integration in the future would require new design and test and measurement tools, along with dedicated power electronics fabs (Figure 15).

With WBG devices gaining momentum, Dan Kinzer, chief technology officer of start-up Navitas Semiconductor, took a quick look at integration in the GaN arena. In his paper "Integrated GaN Technology for High-Frequency Converters," Kinzer indicated that GaN power ICs will redefine tradeoffs between energy savings versus switching frequencies to deliver dramatic improvements in energy savings, size, weight, and cost. Toward that goal, Navitas is developing all GaN power ICs incorporating power, driver, and control on a single chip based on the GaN-on-silicon technology. Concurrently, the company is also pushing the switching performance of 650-V GaN power devices to a new high (>27 MHz). However, details were not provided.

Continuing the discussion on integration, Bernhard Wicht of Robert Bosch Center for Power Electronics and Reutlingen University, Germany, explored the challenges of integrating fast-switching high-input-voltage inductive and capacitive dc-dc converters. Wicht's paper argued that modern high input voltage ( $V_{in}$ ) inductive converters are operating at <5 MHz, but advances in technology and circuit design can push this limit to 30 MHz. Wicht and his team are investigating a zero-voltage switching topology, in combination with integrated passives and low-inductance interconnects and EMI reduction techniques to work concurrently in harmony to achieve the end results. The ultimate goal is to switch at 100 MHz. Likewise, similar efforts are underway at Robert Bosch and Reutlingen University to enable capaci-

tive dc-dc converters with high input voltage switching at higher frequencies.

Furthermore, this session also explored integration challenges for MV converters. A paper by Wim Van der Merwe of ABB Corporate Research investigated integration technologies for a fully modular and hot swappable MV multilevel concept converter. The modularity in this MMC included scalability (voltage, power, number of levels, etc.), configurability (functionality, features, applications, etc.), and pluggability (assembly, commissioning, servicing, etc.). The integrated technologies investigated include inductive power transfer for auxiliary power, thermosiphon cooler in air-cooled cabinets, solid-insulated PEBB

enclosures, and control and communications for adaptable and reconfigurable converters. Combining the modular topology and the integration technologies outlined in the paper, Van der Merwe demonstrated the feasibility of the concept converter with  $P_{out} = 0.55$  MW,  $V_{dc} = 3.3$  kV, and  $I_{out\_rms} = 460$  A.

In short, the presenters envisioned the future integrated grid to be driven by a large amount of resources enabled by power electronics and distributed intelligence. To get there, a number of converter networks/systems challenges must be addressed. Future transportation electrification requires huge onboard power processing, as well as improved reliability of power devices and their respective packages, and energy storage poses a big challenge. Moreover, high-voltage, high-temperature power devices will be needed, including bidirectional devices. Three-dimensional printing will enable cost reductions, and new materials will improve passives integration and challenge copper. Finally, advances in software tools will be needed to advance system level integration and nanotechnology must be tapped to enable high current densities.

According to the organizers, FEPPCON is a biannual PELS strategic planning conference. Approved presentations from FEPPCON VIII will be available on the PELS website; <http://www.ieee-pels.org/>.

### About the Author

**Ashok Bindra** ([bindra1@verizon.net](mailto:bindra1@verizon.net)) is the editor-in-chief of *IEEE Power Electronics Magazine* and a veteran writer and editor with more than 30 years of editorial experience covering power electronics, analog/RF technologies, and semiconductors. He has worked for leading electronics trade publications in the United States, including *Electronics*, *EE Times*, *Electronic Design*, *Power Electronics Technology*, and *RF Design*.

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[1] D. Divan, R. Moghe, and A. Prasai, "Power electronics at the grid edge," *IEEE Power Electron. Mag.*, vol. 1, no. 4, pp. 16–22, Dec. 2014. 