The Future of Power Electronics Circuits

New technologies and managed complexity will drive the future

by Robert Pilawa-Podgurski

The field of power electronics advances through a number of different innovations, ranging from new and better semiconductors (e.g., power MOSFET, insulated-gate bipolar transistor, gallium nitride, silicon carbide), to improved passive components enabled through material science breakthroughs. Moreover, through improved integration and packaging, higher performance and more complex circuits can be implemented. Thanks to digital control and improved simulation tools, new circuit topologies that better utilize the active and passive devices can be implemented in practical designs. At the 10th IEEE Future of Electronic Power Processing and Conversion (FEPPCON X), several invited speakers and participants presented viewpoints and discussed ideas in the session "Future of Power Electronics Circuits." The two invited speakers were Prof. Johann Kolar of Power Electronic Systems Laboratory at ETH Zurich, Switzerland, and Prof. David Perreault of the Power Electronics Research Group at the Massachusetts Institute of Technology, Cambridge. The session also included two invited panelists, Dr. Isik Kizilyalli of the Advanced Research Project Agency for Energy (ARPA-E), Washington, D.C., and Prof. Cian O'Mathuna of Tyndall Institute, University College Cork, Ireland. In addition, Prof. Yan-Fei Liu of Queen's University, Canada, served as note-taker and panelist. Finally, serving as session organizer and panelist was Prof. Robert Pilawa-Podgurski of the University of California, Berkeley.

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In the first session, Prof. Kolar presented his vision for identifying and addressing important development of power electronics core technologies. His presentation focused on the five areas of topology, components, control, design, and manufacturing. Following a discussion on the required performance improvements in power density, costs, failure rates, and more, Prof. Kolar provided a brief historical review of the key technologies that have yielded dramatic improvement in power electronics (Figure 1). The key question discussed in this session was what new technology or solution will bring another 10× improvement in performance ("moon-shot" technologies). Wide bandgap (WBG) power semiconductors appear to be one such promising technology, but the increased switching speed also brings significant challenges in packaging and electromagnetic interference, making WBG technology a double-edged sword. A key message of this presentation was that to fully reap the benefits of faster devices, more advanced designs must be considered that mitigate some of the drawbacks of higher *di/dt* and *dv/dt*.

Another approach that may bring significant performance improvements is the general concept of series and parallel interleaving. Examples of multilevel and multiphase designs were discussed to highlight the performance benefits, with examples from the Google Little Box Challenge supporting this case. It was also noted that much of the cost and power-density improvement relies on advanced packaging, and that 3D packaging and heterogeneous integration are important technologies for future research directions, with some questions of how research in this area should best be carried out in university laboratories.

Prof. Perreault's presentation highlighted how the requirements for future power electronics vary with applications, and in addition to lower cost, greater performance is required. To date, passive components still dominate size, weight, and loss of many power electronics systems, and magnetics are especially challenging to miniaturize. Consequently, design of improved high-frequency power magnetics remains a high-impact research challenge, where both better high-frequency magnetic materials and designs that address skin and proximity effects can yield greatly improved performance (Figure 2).

What new technology or solution will bring another 10× improvement in performance ("moon-shot" technologies).

Another important trend identified by Prof. Perreault was the judicious utilization of higher complexity to leverage technology advances (managed complexity). Thanks to advances in semiconductor devices, integrated circuits, controls, and passive integration techniques, more sophisticated and complex power conversion approaches are becoming feasible. This breaks from the traditional approach of desiring the simplest solution possible. Examples from the hybrid switched-capacitor power-converter architectures were presented to illustrate this trend. Finally, Prof. Perreault provided a perspective of other potential energy storage mechanisms, such as piezoelectrics, which offer fundamentally higher energy densities than inductors and capacitors, but have yet to be captured in practical designs.

Prof. O'Mathuna addressed opportunities and challenges for power electronics at smaller physical scales, driven by edge computing, the Internet of Things (IoT), wearable electronics, and fully on-chip integration of power electronics. Here also, magnetics prove to be difficult to miniaturize, where both printed circuit board embedded magnetics and magnetics on silicon remain active research topics. Finally, Prof. O'Mathuna cautioned that with the expected dramatic increase in the number of IoT devices, sustainable IoT must be considered, where also power electronics components must be recyclable or even dissolvable as they spread in our environment.

Dr. Kizilyalli provided an important government and society perspective on the challenges that we face in terms of decarbonization, global emissions, and the increased amount of electric power that flows through power converters. He highlighted the many applications, in particular at voltage levels above 600 V, that would benefit from WBG devices. However, circuit topologies, application-specific architectures, control, and packing are all areas that are lacking for fully taking advantage of the new WBG devices. Areas of risk that must be retired before WBG devices can be widely adopted include system integration, device design and fabrication, proven reliability, and cost. Dr. Kizilyalli concluded by presenting several ongoing U.S. government initiatives that are trying to solve these problems and presented the participants with the challenge of achieving truly high-voltage (20+ kV) semiconductors.

In the follow-up discussion, participants were invited to share their views and perspectives on the future of power electronics circuits. A key theme that was voiced several times

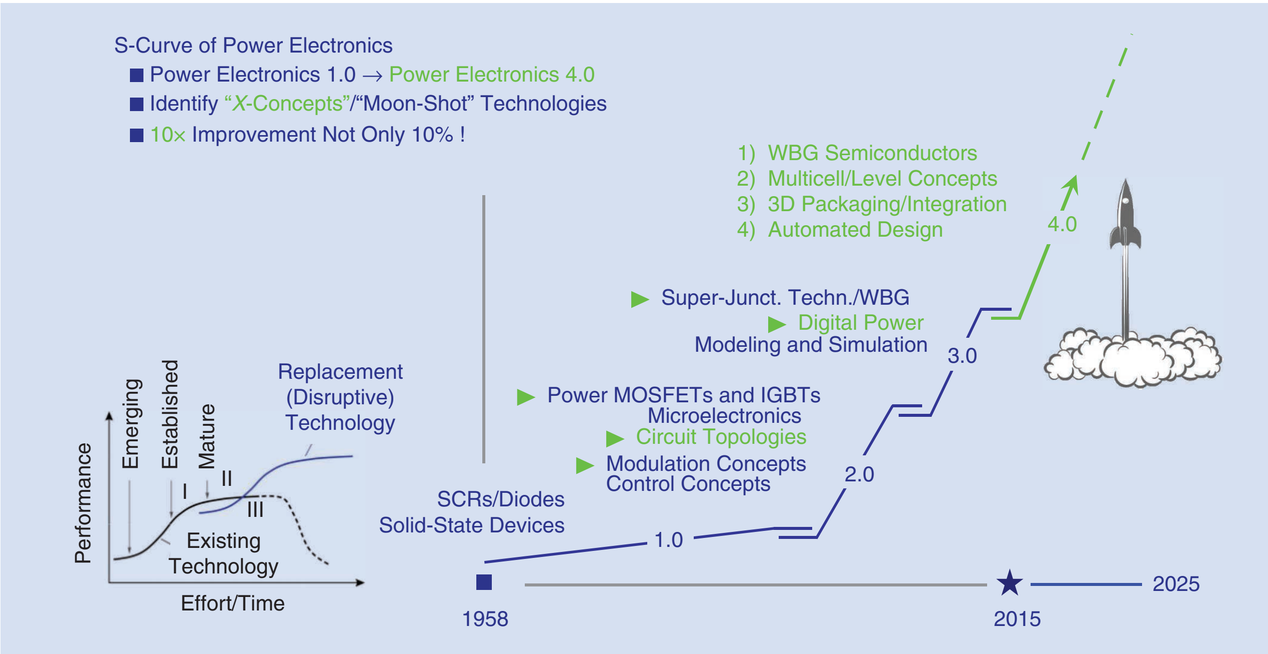

FIG 1 A historical review of key technologies and future 10× technologies. SCR: silicon-controlled rectifier; Junct.: junction; Techn.: technology. (Source: Prof. Johann Kolar; used with permission.)

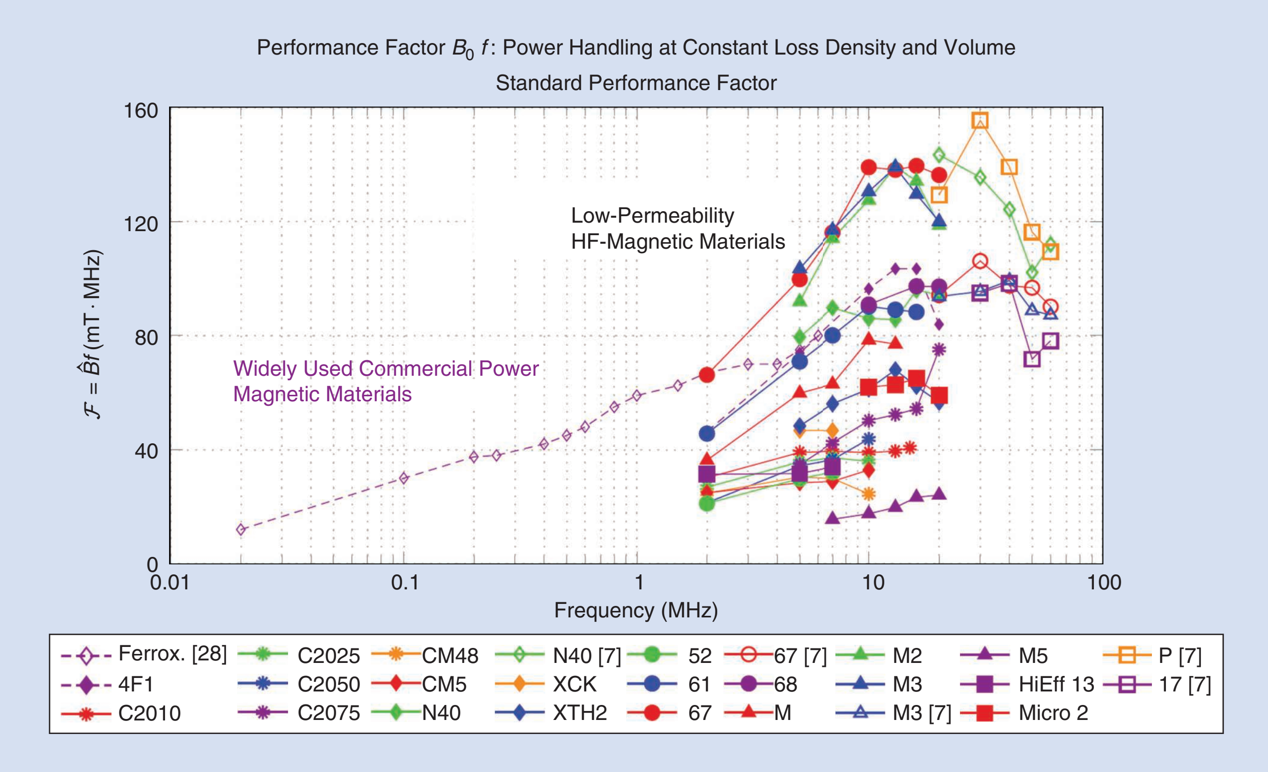

FIG 2 Design of improved high-frequency power magnetics continues to challenge researchers. (Source: [1].)

was the challenges of magnetics. In addition to continued improvement in magnetic material and transformer/inductor structures, circuit topologies that inherently rely less on magnetic components were viewed as a promising path forward. Hybrid switched-capacitor converters and, in general, multilevel converters follow the trend presented by several panelists, where the designers judiciously leverage circuit complexity to obtain performance improvements. Key technology drivers or successful implementations of such solutions are digital control, integration, and improved active and passive devices.

Another challenge that was identified by many participants was that of research in packaging, integration, and manufacturability. This area was viewed by many as critical for performance improvements, yet difficult for many university research groups to participate in. There is a concern that only the most well-connected research groups and largest companies have the scale to be at the forefront of technology development in this area. In addition to the importance of new design tools suitable for academic research, there may be a need for shared/pooled resources, similar to what is done in CMOS integrated circuits. Standard process design kits and foundry approaches have served the integrated circuit community well, and may well be on a path worth pursuing for power integration as well.

Finally, the participants agreed that for power electronics, form fits function, and a key opportunity is identifying the right applications where dramatic system performance can be realized through power electronics. In terms of true moon-shot technologies, the participants were looking forward to identifying and developing new active switches and exploring new passive components such as piezoelectrics for potential use in power conversion. Entirely new approaches to power conversion were also viewed favorably, but likely best identified and pursued by the next generation of power electronics engineers.

About the Author

Robert Pilawa-Podgurski (pilawa@berkeley.edu) received his B.S., M.Eng., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge. He is an associate professor in the Electrical Engineering and Computer Sciences Department at the University of California, Berkeley. Previously, he was an associate professor in electrical and computer engineering at the University of Illinois, Urbana-Champaign. He received the IEEE Power Electronics Society Richard M. Bass Outstanding Young Power Electronics Engineer Award, in 2014, and the IEEE Education Society Mac E. Van Valkenburg Award for outstanding contributions to teaching unusually early in one's career, in 2018. He is a coauthor of nine IEEE prize-winning papers.

Reference

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