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Wired and Wireless Charging Technologies.

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Despite global efforts, CO₂ emissions, along with other harmful gases, continue to rise and transportation is a big contributor to this global warming concern. As a result, to reduce these harmful emissions, governments and policymakers around the world are pushing the adoption of electrified vehicles (EVs) via a variety of incentives. Subsequently, for passenger vehicles only, EVs are forecasted to reach 80 million cars in the U.S. and around 500 million globally by 2040.

In the cover feature “Charging Electric Vehicles: Wired and Wireless Power Transfer” of this issue of IEEE Power Electronics Magazine, written by Hua(Kevin) Bai, Daniel Costinett, Leon M. Tolbert, Ruiyang Qin, Liyan Zhu, Ziwei Liang, and Yang Huan, the authors identify key enablers for such rapid EV adoption. These include improvement of battery energy density, life span and safety, and drastic cost reduction of batteries and power electronics. With advances in power electronics, EV charging technologies, both wired and wireless power transfer (WPT), have also evolved over the years. This cover article explores developments in EV charging technologies, as the industry works to expedite the charging speed of the battery to compete with the short time it takes to fill the tank of conventional vehicles. In the wired arena, the article investigates improvements in on-board and off-board chargers, as well as fast and extreme fast chargers with power ratings.

Likewise, in the wireless section, it summarizes the state-of-the-art WPT systems for EV charger applications, and investigates interest in integrating charger with other on-board systems to save the cost and size. Lastly, with power demand increasing for EVs, it projects 800 V battery will become the mainstream in the near future.

The next feature “Practical Realization of GaN’s Capability: GaN-Fast Power ICs Introduce Lossless Sensing and Autonomous Protections.” The authors John Stevens, Tom Ribarich, and Stephen Oliver jointly examine the short-circuit protection and cycle-by-cycle current limit in the lossless current sensing of GaNFast IC with integrated GaN-Sense technology. It demonstrates the added benefit of local protection at the power switch with improved accuracy and drastically reduced response time to an overload current event. Plus, it displays the thermal benefits of efficiency improvements with lossless current sensing.

Similarly, in the third feature “Transformative Role of Power Electronics in Solving Climate Emergency” by Rajendra Singh, Prahalad Paniyil, and Zheyu Zhang, the authors show that power electronics has the potential to achieve the goal of electrifying almost everything by green sustainable electric power and provide a cost effective solution to our shared climate emergency. The article argues that a large amount of green electric dc power generated by photovoltaics and/or wind turbines and stored in batteries is wasted in current ac electricity infrastructure. Based on silicon carbide power electronics, it proposes HVDC transmission of bulk power by dc-dc power converters. In conclusion, the authors say “power electronics with higher performance, higher reliability, and low-cost power has the potential to provide transformative transformation of power transmission, distribution, and utilization.”

Microgrids is the focus of the next feature titled “Microgrids in a Smart Low-Voltage Distribution System.” In this article, authors Ramanuja Panigrahi, Santanu Mishra, S C Srivastava, Prasad Enjeti propose converting a smart low-voltage distribution system (LVDS) following a distribution transformer into a three-phase ac microgrid. Thus, segregating the existing LVDS into a smart LVDS with as many microgrids as the number of distribution transformers. Furthermore, it proposes replacing the low-voltage distribution transformers with solid-state transformers (SSTs) to enable the LVDS to control the power exchange between the phases within a microgrid as well as power exchange between different microgrids.
• Aluminium Electrolytic Capacitors Screw terminal Type

• Aluminium Electrolytic Capacitors Snap in Type

• Metallized Polypropylene D.C. link Capacitors

• Electrolytic Capacitors Screw Terminals from 16 VDC to 600 VDC
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This approach will also support smart homes and their interactions within a microgrid.

The final article of the issue provides an overview of the IEEE Applied Power Electronics Conference and Exposition (APEC) 2022. Besides highlighting the talks of the seven distinguished speakers of the plenary session, it also explores developments in bidirectional silicon carbide and gallium nitride FETs and new products announced on the exhibit floor.

**Columns, Society News and More**

The hybrid format of IEEE APEC 2022, held 20–24 March in Houston, Tx, USA, was a refreshing change from the virtual conferences of the last two years due to the COVID-19 pandemic, stated IEEE Power Electronics Society (PELS) president Liuchen Chang in his column President’s Message “Hope for Resuming our In-Person Events.” Thanking the tremendous efforts of hundreds of organizers and volunteers, he said that APEC 2022 signals the return to our in-person events. Likewise, in the “Expert View” column, Dinesh Ramanathan reveals the avalanche and short circuit robustness of vertical GaN FETs. Likewise, in the “White Hot” column “To Ph.D. Or Not To Ph.D.?” Bob White recommends questions to consider before making a decision.

Next, the “Women in Engineering” (WiE) column “Women in IEEE PELS: Progress and Opportunities” by Katherine A. Kim, Lauren E. Kegley, Stephanie Watts Butler, Christina DiMarino, Mariam Rasheed, and Radha Sree Krishna Moorthy, the authors track statistical data on the participation and progress of women engineers in PELS over the last decade across the board and suggest ways to become part of the solution.

Society News brings activities from PELS Chapters around the world, and previews the upcoming IEEE Energy Conversion Congress and Exposition 2022. Finally, the “Event Calendar” provides a year’s listing of PELS sponsored conferences and workshops.

As we transition out of the pandemic phase, we are hoping normalcy will return. Thanks to you, IEEE Power Electronics Magazine continues to bring timely articles, columns and news items of interest and value to practicing power electronics engineers worldwide. To serve you better and keep this magazine a valuable resource for working power electronics engineers around the world, we look forward to your feedback and suggestions. Now we have a website (https://pelsmagazine.ieee.org/) where you can easily provide your feedback. Stay safe and healthy!
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Hope for Resuming Our In-Person Events

The hybrid format of IEEE Applied Power Electronics Conference and Exposition (APEC) 2022, held 20–24 March in Houston, TX, USA, was a refreshing change from the virtual conferences of the last two years due to the COVID-19 pandemic. Thanks to the tremendous efforts of hundreds of organizers and volunteers, APEC 2022 signals the return to our in-person events. It was a joyful reunion of IEEE Power Electronics Society (PELS) members, volunteers and exhibitors. The breakfast event of “WiE, YP, and You: How to become involved with PELS and PSMA too” was a huge success, the fruit of the tireless work of the PELS Women in Engineering (WiE) and Young Professionals (YP) Committees. You can find detailed materials including FAQs of many programs of the PELS, prepared by dozens of PELS volunteers on the WiE events website: https://www.ieee-pels.org/membership/wie/wie-events. The “YP Reception at APEC 2022” cosponsored by PELS and Industry Applications Society (IAS) attracted over 100 young professionals and students to a social gathering at The Grotto, Houston. Our hybrid Spring Administrative Committee (AdCom) Meeting and several PELS standing committee meetings held during APEC 2022 presented a venue for our volunteers and friends to catch up.

APEC 2022’s great success is representative of PELS conferences, as reported by Dr. Jian Sun, VP Conferences. Thanks to many dedicated volunteers, PELS has maintained an active conference program during the pandemic. The total number of conferences sponsored by PELS in 2021 has recovered from the dip in 2020, and is comparable to the peak number reached in 2019. As travel restrictions ease in more countries and regions, we hope more and more members will be able to attend our conferences in-person this year. To make PELS conferences more attractive to industry, a new award called “Value to Industry and Practitioners (VIP) Best Papers” has been initiated by the Conference Committee. The annual award, targeting papers presented at all PELS-sponsored conferences, is currently under review by IEEE TAB Awards and Recognition Committee (TABARC) and is expected to start in 2023.

As reported by Dr. Mark Dehong Xu, VP Membership, the PELS membership reached 11,187 in 111 countries as of February 2022, a record high after a full recovery from the drop in 2020 due to pandemic. Last year, 42 new chapters and student branch chapters were added to a total of 213. We are enhancing our membership ecosystem with a significantly increased funding program for our chapters and student branch chapters for grassroots activities, and close interactions among members, chapters, regions, and PELS leadership. In recent years PELS has developed Regional Distinguish Lecturer (RDL) programs, building on the success of our excellent Distinguish Lecturer (DL) programs. RDL programs are welcomed in many countries, for short travel distances, topics pertinent to local interests, and lectures in local languages. To elevate our service to members around the world, we will expand our collaborations with national and international associations and institutes around the world.

To achieve our goals set by our Strategic Plan (2021–2025), the society has developed numerous new programs, adding more values, benefits and services for the PELS members. Starting 2023, PELS members will have an option of selecting fully digital publications at substantially reduced membership fees, while enjoying the same full services as before. The Education and Digital Committee has been diligently working on the ambitious “PELS Tube” program, the educational videos on power electronics, recently released for your review and contribution at https://ieeepelstube.org.

Recently, two long-time PELS members received the prestigious IEEE medals. Prof. Ned Mohan

(continued on page 12)
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To help equip the power electronics industry to deal with the future, Power Sources Manufacturers Association (PSMA) (www.psma.com) publishes the Power Technology Roadmap (PTR). The most recent edition was published at IEEE Applied Power Electronics Conference and Exposition (APEC) 2022 reporting on key trends and forecasts affecting the fast-growing industries of power conversion technologies, electrical components, and applications.

At APEC 2022, longtime PSMA member Ritu Sodhi gave a plenary talk on the history and future of the Power Technology Roadmap. She also examined how the community anticipated industry trends such as efficiency, digital control, and the adoption of wide bandgap materials, as well as – displaying a uniquely valuable PSMA approach and tradecraft – an analysis of which predictions did not materialize as expected.

History of the PTR
The first PTR released in 1994 was the result of a one-day, in person workshop with a power supply focus. The introduction of the PTR webinar series some years later provided a real-time dynamic element to the roadmap activity. The webinars keep the roadmap active with immediate inputs coming from industry experts about current challenges, new research, and new solutions.

Over time the number of contributors, attendees, and range of topics has increased. Figure 1 illustrates the range of presentation topics from 1994 through 2022. An examination of the range of presentations over time provides an indication of emerging trends, challenges, and new solutions. As an example, the most common and well-attended webinars from 2013 through 2022 included those on wide bandgap switches, magnetics, integration and standardization, packaging, and reliability.

Projected Trends – Hits & Misses
When reviewing past product technology roadmaps, some of the topics that the PTR predicted quite well were the trends for system efficiencies, power density, and increasing switching frequency. Some of the topics for which there was more of a disconnect included the rate of adoption of new component technology and the specific adopters of the new component technology. Digging into the reasons for these misses enables PSMA to improve sources and methods for the next PTR. Key items identified include the fact that users develop innovative ways to continue to use existing technology as well as some underestimation of the challenges and roadblocks to adoption. With any new technology, it is not just the device itself that drives adoption, a new technology also needs to overcome the challenges of cost constraints, performance optimization, reliability, packaging, and ecosystem development.
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- POWER: to 720 watts
- AC INPUT: 90 to 265 VAC/110 to 350 VDC
- OUTPUT VOLTAGE: 3.3 VDC to 135 VDC
- OUTPUT CURRENT: 3.3 A to 70 A

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- AC INPUT: 105 to 125 VAC
- OUTPUT VOLTAGE: 1.5 VDC to 150 VDC
- OUTPUT CURRENT: 350 mA to 13.2 A

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In addition, finding the so-called ‘killer app’ for a new technology that can drive volumes is critical to speed adoption and it is not always the application you think it will be! This was certainly the case with silicon carbide. In the early PTRs that discussed trends for wide bandgap components, the forecast assumptions were that solar and telecom would drive widespread adoption of SiC FETs. In reality, it has been electric vehicles. This is a market few would have predicted would be willing to be an early adopter of a new technology using a new material and higher cost, yet the performance and system cost improvements were compelling enough to overcome these barriers.

Highlights from 2022 PTR

The most recent edition of the PSMA PTR was published at APEC 2022 and provides a three-dimensional cross-cut look at technology, components, and applications. Some highlights include the following:

- The latest update on wideband gap standards for testing, qualification, and reliability from the JEDEC team
- The latest solutions and future trends for integrated GaN
- Packaging advancements for wide bandgap semiconductors
- Advances in magnetics and the modeling of these devices to better predict losses
- Electric vehicle trends impacting power electronics including new materials for batteries, vehicle charging using SiC devices, and how new semiconductors enable and improve the performance of EV battery packs.

Looking Forward

The PSMA PTR has evolved from a single, one-day, in-person roundtable to a multidimensional, multimedia, multiyear activity to track key trends across a broad variety of power conversion markets. As we move forward, continued collaboration with multiple organizations will provide a broader perspective and using new technologies to create a more interactive resource will give users contextual and relevant information real-time for their specific areas of interest, easily accessible within the roadmap.

About the Author

Renee Yawger is the director of marketing at Efficient Power Conversion Corp. (EPC) and director corporate marketing at EPC Space. She has over 25 years of sales and marketing experience within the semiconductor industry. Prior to joining EPC, she was at Vishay Siliconix for nearly 15 years in various positions in sales support, customer service, and regional marketing. At EPC, Yawger is responsible for the product marketing and marketing communication functions globally. Yawger is also the vice president of the board of directors, PSMA.

President’s Message (continued from page 8)

received the IEEE James H. Mulligan, Jr. Education Medal for leadership in power engineering education by developing courses, textbooks, labs, and a faculty network. Prof. Thomas M. Jahns (the 5th PELS president, 1995–1996) received the IEEE Medal in Power Engineering for contributions to the development of high-efficiency permanent magnet machines and drives. Congratulations!

Lots more are happening in our society. At the PELS AdCom meeting in March 2022, many initiatives were proposed and approved. Please stay tuned for the exciting programs and projects in the near future. To strengthen the industry services and engagements, our VP Standards was changed to VP Industry and Standards, along with the formation of a new standing committee—the Industry Committee. We have started the process of seeking our members’ input to the idea of elevating the educational programs within the PELS organization, and thereby expanding the professional education products and services for students and practitioners. I’d love to hear your thoughts (My e-mail is LChang@unb.ca).
Since motors appeared in the early 19th century, they have been used in all types of electrical appliances and are now an indispensable part of our daily lives. Today, a huge number of motors are used in a wide range of applications, and it is claimed motors account for more than 55% of the world's power consumption. Therefore motor research is extremely important if we are to maintain our affluent lives while also perpetually conserving the global environment.

We created these Nagamori Awards to bring vitality to technological research of motors and related fields, such as generators and actuators, and also to support the researchers and development engineers who strive each day to fulfill their dreams.

Nagamori Foundation decided six winners of the 8th Nagamori Awards, from whom the Grand Nagamori Award winner will be chosen on September 4th. The Grand Nagamori Award winner will receive 5 Million JPY and each Nagamori Award winner, 2 Million JPY.

**The 8th Nagamori Awards Winners:**

**Huijun Gao**  
Professor and Director, Research Institute of Intelligent Control and Systems, Harbin Institute of Technology  
For contributions to the advanced control for mechatronic systems

**Yunwei Ryan Li**  
Professor and Acting Department Chair, Department of Electrical and Computer Engineering, University of Alberta  
For contribution to the PWM, control and converter topology of medium voltage high power industrial drives

**Burak Ozpineci**  
Section Head, Vehicle and Mobility Systems Research Section, Building and Transportation Science Division, Oak Ridge National Laboratory  
Low cost, high efficiency, compact electric motor drives for more electrified transportation systems

**Gianmario Pellegrino**  
Full Professor, Department of Energy "Galileo Ferraris", Politecnico di Torino  
Synchronous and PM-synchronous reluctance motor drives - theory, design, and control methods

**Maryam Saeedifard**  
Associate Professor, School of Electrical and Computer Engineering, Georgia Institute of Technology  
For contributions to highly-efficient, power-dense and fault-tolerant multilevel converter-based medium-voltage drives

**Akio Yamamoto**  
Professor, Graduate School of Frontier Sciences, The University of Tokyo  
Pioneering research and development on theoretical models and applied systems for electrostatic film actuators

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Due to the environmental concerns about CO$_2$-caused global warming, policymakers are pushing electrified vehicles (EVs) to reduce these emissions. For passenger vehicles only, the electrified fleet is forecasted to reach 80 million in the U.S. and 500 million globally by 2040. Key enablers for such rapid EV adoption include the improvement of battery energy density, lifespan and safety, and drastic cost reduction of batteries and power electronics. The technology of power electronics nowadays can be found in many aspects of EVs. It alters and transforms the energy from the power source to different forms to feed the loads. For example, the on-board charger (OBC) accepts ac input and converts it to high voltage (HV) dc to charge the propulsion battery. An auxiliary power module (APM) steps down the HV battery voltage to low voltage (LV) to charge the LV battery [1].
The HV dc bus voltage is converted to an ac form to drive the propulsion motor, forming the motor drive inverter. Putting the power electronics system and the batteries together, the typical structure of an EV is shown in Figure 1. In addition, power electronics can be found in other onboard auxiliary circuits, such as LED lighting and battery management system (BMS).

As shown in Figure 2, a typical OBC includes a power factor correction (PFC) stage and an isolated dc/dc stage. Such a two-stage design can effectively decouple the grid from the vehicle. Certainly the efficiency, weight and size will all receive the penalty of this two-stage design, particularly given the existence of the dc-link capacitors and galvanic transformer. Therefore it is not hard to understand why in recent years both academia and EV industries put vast efforts into its potential improvement.

The PFC stage maintains unity power factor at the ac input port and reduces the injection of harmonics and reactive power to the grid. Otherwise, the utility company will tax this “dirty power” drawn from the grid. While specifications might vary due to different companies’ requirements, usually it is demanded that at full power the grid power factor is >0.99 while the grid current total harmonic distortion (THD) is <5% or even lower. A dc/dc stage is then inserted between the PFC stage and batteries, to provide isolation and accommodate the wide output voltage range. Depending on the state of charge (SOC), the terminal voltage of a 400 V-rated battery can vary from 250 V to 450 V [2], or 550 V to 850 V for an 800 V-rated battery [3]. The isolation is necessary by the regulation of standard IEC 61851-1 for safety concerns [4]. Different from the data-center ac/dc power supply which also has a similar topology, EV battery chargers usually face wider output voltage, and sometimes wider ac input voltage range. A recent trend is the emergence of universal OBCs, which accommodates both single-phase (100–260 Vac) and three-phase (208–500 Vac) input. Such requirements usually yield redundancy of the design. Given that the automotive industry is very cost sensitive, engineers must find a balance between performance and cost, particularly when designing such universal chargers.

The charging technology, in the long term, needs to expedite the charging speed of the battery in order to compete with the short time it takes for fuel pumping to fill the tank in conventional vehicles. The OBCs can then be classified into several levels in terms of their power ratings. Essentially, it is based on the grid voltage and current rating of the circuit breaker. In the U.S., the charging power from the residential power outlet can be classified into three levels according to SAE J1772 [5]. The commonly used rating series are 3.3 kW, 6.6 kW, 11 kW, 19.2 kW and 22 kW for OBCs only. When going to higher power, the large size and cost will become an obstacle to place the OBC inside the vehicles. Therefore chargers with much higher power rating, say >22 kW, are placed outside the vehicle and categorized as off-board chargers, e.g., dc fast charging, where a dc instead of ac input is provided. Fast chargers and extreme fast chargers (XFC >150 kW) are usually off-board chargers. Lead by Chinese and Japanese companies, a super charging technology to provide 900 kW charging power (Chaoji) can be expected in the near future, which allows customers to complete charging in a few minutes instead of hours. Due to its high power, such charging infrastructure is serving for public purpose.

As a global EVSE supplier, Brusa has been developing a series of EV chargers, from 3.3 kW to 22 kW. Their 22 kW OBC (NLG664) exhibits 94% efficiency and 2 kW/L power density. Academic effort in recent years is trying to improve both efficiency and power density. Shown in Figure 3(a) below is a 22 kW EV offboard charger prototype, developed by the University of Tennessee, Knoxville (UTK) power electronics group. Its charging I-V curve is shown in Figure 3(b).

The internal view of the charger reveals that a significant volume of EV charger is occupied by passive components (capacitors, inductors, electromagnetic interference (EMI) filters, heatsink, etc). One solution lies in the recent rapid adoption of wide-bandgap (WBG) devices, such as silicon carbide (SiC) and gallium nitride (GaN). Such semiconductor switches compared to the traditional silicon (Si) devices have faster switching transitions and less switching loss, which cuts the loss and thereby reducing the heatsink size and can be operated at higher switching frequency resulting in less inductor and capacitor usage. This directly benefits the power density. On the other hand, we also need to understand WBG devices are not the solution to all challenges. For instance:

1) Universal AC input. When the grid side is single-phase ac input, we can assume the grid voltage is

\[ v_g(t) = V \cos(\omega t) \]  

With unity power factor, the ac current is

\[ i_g(t) = I \cos(\omega t) \]  

Therefore the input power is

\[ p_g(t) = VI \cos^2(\omega t) \]  

which can be translated into

\[ P_g = \frac{V^2}{2} \left[ 1 + \cos(2\omega t) \right] \]  

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Therefore the grid power exhibits a double-line frequency component, e.g., 120 Hz when operated with 60 Hz grid. Filtering out such low-frequency component cannot be answered by WBG devices, but instead a large dc-link capacitor. Some attempts have been made to minimize the dc-link capacitance and let such double-line-frequency power flow toward the battery, which usually is not welcome by EV original equipment manufacturers (OEMs). Therefore the single-phase and universal chargers yield much lower power density than a three-phase charger, even with WBG devices.

2) Magnetics design. EV chargers provide opportunities to magnetics (inductor and transformer) companies. The desire of having compact, light, and efficient magnetics is increasing, which imposes new challenges. Theoretically, the higher the switching frequency, the smaller the inductance. When inductance is small enough, we can then lay out the inductor/transformer windings on printed circuit boards (PCB), wrapping a small core, forming a so-called planar transformer. Such technology greatly flattens the transformer footprint thereby saving overall volume. The challenge, however, is once the windings are stacked closely, the turn-to-turn capacitance, and the capacitance between primary and secondary windings will be increased significantly. Shown in Figure 4(a) is an equivalent circuit of a transformer when considering all such parasitic capacitance. Coupled with fast switching transitions of WBG devices, such capacitance can generate some unexpected electrical waveforms; also, a large capacitance between primary and secondary windings \( (C_{ps}) \) forms a path of EMI noise to flow between the grid side and the battery side.

Authors have integrated a planar transformer into a non-resonant circuit, dual active bridge (DAB) converter when the switching leg output is directly tied to the transformer. When the dc/dc stage input voltage is 400 V, Figure 4(b) shows the experimental waveform. Here, the brown curve is the primary voltage, the blue one is the secondary voltage, green is the primary current and the purple is the secondary current. A significant current oscillation is observed at the transformer secondary-side current. It turned out that the winding capacitance is the reason. A 3 nF capacitance is measured across the secondary-side winding of the physical transformer. Such high-frequency oscillation creates concerning EMI and additional loss to both switches and the transformer.

Therefore, WBG devices are not the only answer to EV charger improvement. In some cases, a mismatch between WBG and other peripheral components can yield even worse performance. Particularly in recent years, low power OBC development has matured significantly. Convincing OEMs to use different switches with a new design can face obstacles.

On the other hand, when we step back and consider the whole EV system, another approach to save cost and size can be traced back to better system-level integration and optimization. One typical example is integrating the OBC.
with the APM. The APM in an EV is mainly used to replace the alternator in a conventional internal combustion engine (ICE) vehicle. It bridges the HV system with the LV system, say 12 V. Essentially, it is another isolated dc/dc converter, with the typical structure very similar to the isolated dc/dc stage of the OBC[6], except that the terminal voltage varies from 10 V to 14 V [7], [8]. This provides opportunities for two units to share the same components aiming at cost saving and size reduction.

In addition to the system integration, recent EV users tend to treat the battery not only as the load, but also as a generation source. While vehicle-to-grid (V2G) has concerns for EV OEMs in regards to battery degradation due to overuse, vehicle-to-load (V2L) feature is useful during grid blackout particularly when in recent years natural disasters have happened more frequently. This, however, requires the battery charger to be bidirectional and have the ability for grid forming control, which will add cost to the charger design. Such a feature allows the battery together with the OBC to form a local microgrid.

The third element is the transformer-less design for XFCs. Such high charging power, e.g., >150 kW, imposes high current stress on the distribution-level power grid, particularly when considering several EVs are being charged at the same time. Therefore the latest research attempt is to draw power directly from medium voltage transmission lines, say 13.4 kVac. Instead of stepping down such voltage to three-phase 480 Vac using bulky and heavy 50/60 Hz transformer, high-voltage semiconductor devices with multilevel topologies offer the chances to eliminate the grid-side transformer thereby saving size and weight.

Last but not the least, wireless power transfer (WPT) is another hotspot emerging in recent years. The wireless charging coils can be buried underground, allowing the charging station footprint to be reduced. Charging plugs, which cause safety concerns without supervision and can be easily damaged, are no longer required. In October 2020, SAE International published its first standard J2954 on WPT for EVs, allowing charging power up to 11 kW over a
250 mm air gap with up to 94% system efficiency. The standard also outlines the parking assistance for EV that makes autonomous parking and charging available. Together with J2954, J2847/6 is also published recommending the communication protocols between EVs and charging stations. Based on the different coupling mechanisms between transmitter side and receiver side of the WPT system, there are two types of candidate WPT techniques for high-power, near-field wireless EV applications: Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT), which will be compared in this paper in a later section.

High-level System Integration

Take the integration of OBC+APM as an example. Different from OBC only working at the charging mode, the APM usually works continuously. Even when the vehicle is fully stopped, the APM still needs to power the LV system for the nonpropulsion loads, such as control units and cooling system[9]. One typical structure of the integrated charger is shown in Figure 5, using a three-winding transformer. In this way, grid, HV and LV batteries are all isolated from each other. Active bridges then allow the power to flow through three ports freely.

An exemplary design is shown in Figure 6(Fig 6a), forming a phase-shift (PS)-triple port converter (TPC). Three active bridges are connected to three isolated power sources through a three-winding high-frequency transformer, respectively. The power flow of each port is then controlled by the phase difference among all ports. The two-level voltage generated from the bridges together with the leakage inductance network forms an equivalent circuit shown in Figure 6(b). Phase shifts and impedance among sources are the two key factors to determine the power flow.

One key challenge for such an integration approach is that the power of one port is coupled with the other two. The second challenge lies in the LV side. Assuming 2.5 kW is needed for the 12 V battery, the LV bridge will conduct >200 A average current, with the peak current of the related winding being >400 A. While more semiconductor switches can be paralleled to offset the conduction loss, switching off such large current can be the challenge, particularly considering the switching loss and the accompanying EMI. Last but not least, the turns ratio of the transformer can be high, say 400 V:400 V:12 V.

To overcome all the shortcomings mentioned above, UTK power electronics team worked with Hella and proposed a novel current-fed three-port converter, as shown in Figure 7(a) [12]. Without considering the ac/dc stage, the converter has three ports: the primary side, HV side, and LV side, being connected to the PFC output, HV battery, and LV

![FIG 4](image) (a) Equivalent circuit of the transformer. (b) Transformer oscillation (experiments).

![FIG 5](image) Integration of OBC and APM.

FIG 7 (a) Topology of the UTK/Hella converter for the integrated charger. (b) Prototype of the integrated OBC+DCDC.
battery, respectively. $L_{s1}$~$L_{s3}$ are the leakage inductances of the three windings of the transformer, respectively. $L_{01}$ and $L_{02}$ are negatively coupled inductors for HV output filter. The same design applies for $L_{03}$ and $L_{04}$ at the LV output. $C_{hv}$ and $C_{hv}$ are clamping capacitors and used to maintain a high dc voltage to reduce current stress on both transformer secondary sides. An exemplary prototype is also shown in Figure 7(b). The rationale behind this design is that the current-fed port boosts the LV side voltage to a much higher value, which significantly reduces the turns ratio thereby facilitating the transformer design. In addition, duty cycles are introduced as additional control freedoms, enabling the possibility of further optimization, e.g., realizing zero-voltage-switching (ZVS) in most of the power range. Even though the debate of pros and cons of voltage source and current source converter continues, and the current-fed topology is nothing new, such integration attempt actually brings two types of converter technologies together by maximizing their potential at the same time.

**Using Battery and OBC for V2L**

When the grid loses power during a blackout, one mission of the EV battery and OBC is to form the local grid and provide minimum energy usage. It then requires the energy to flow from vehicle to the grid created by the vehicle power supply; this operation can be called vehicle to load (V2L). A typical topology is shown in Figure 8(a). At the ac side, a conventional three-phase four-wire inverter is a promising candidate. At the dc-bus side, there are split dc-link capacitors $C_{N1}$ and $C_{N2}$, where the midpoint of the split dc-link capacitors serves as the neutral point. The fourth leg is formed by $S_{N1}$ and $S_{N2}$, should a two-level topology be preferred. $L_{N}$ aids in the regulation of the neutral-point voltage caused by the load imbalance. $L_{v}$ and $C_{v}$ are the grid-side filter inductor and capacitor, respectively. Note the fourth leg might not be necessary such as in the case where the dc-link capacitor tank is large enough to cope with a large neutral current. With the fourth leg stabilizing the neutral point, each phase can be essentially equivalent to a buck converter and controlled independently with conventional SPWM, with the equivalent circuit of each phase shown in Figure 8(b). In this way three independent phases, A, B and C are formed. Each phase can then undertake balanced or unbalanced load, should the neutral point be controlled well.

Potentially, when $R_{L} \to \infty$, i.e., no-load, the overall grid inverter part of the OBC is supplying just the LC circuit, which has a natural resonant frequency. If the OBC output at the ac side happens to have a voltage component around such resonant frequency, large voltage and current harmonics are expected on the phase output, deteriorating the grid power quality. Note such operational mode is not V2G, which has the normal utility power grid connected. V2L function requires the battery and charger to form its own microgrid, therefore from the control point of view it can be more challenging than V2G. One approach is controlling the effective output impedance of the converter, which

![Image of EV charger circuit diagram](image-url)
assumes a virtual resistor $R_v$ is in parallel to the load resistor $R_L$, as highlighted in Figure 8(b). The essence of employing such an imaginary resistor is optimization of the system transfer function by adding a notch filter to suppress the harmonics. Simulation results are shown in Figure 9. With the virtual resistance, the quality of both grid voltage and current is improved.

**Transformerless XFC Design**

To complete battery charging in a short time period, power levels of at least 350 kW and up to 1 MW are needed for conventional passenger vehicles. In North America, Electrify America, a subsidiary of Volkswagen Group of America, was established in late 2016. It opened California’s first 350 kW charger location in December 2018. 350 kW chargers are now available in front of more than 120 Walmart stores. Electrify America now offers stations widely available so that 96% of Americans live within 120 miles of a charger.

Take Tesla Model 3 as an example. The vehicle is equipped with a 75 kWh battery, which requires >12 hr to charge if only a 6.6 kW OBC is utilized. However, with a 500 kW XFC, the charging time can be shortened to ~10 mins, which certainly helps to expedite EV adoption and use of these vehicles for longer trips. These high-power levels, however, are comparable to small electric utility substations, especially for a location that has multiple XFCs to charge multiple vehicles simultaneously. Therefore, most proposed designs involve the primary of the charger system connected to an electric utility’s distribution system at a medium voltage (MV) (e.g., 12.4, 13.2, 13.8 kV). The XFC then must step down the MV to a voltage level compatible with the battery pack (200 to 400 V) and regulate the voltage and current in the charging process. At the present time, >500 kW XFC is still uncommon. EVs capable of accepting 350 kW charging power typically use an 800 V battery, for instance, Porsche Taycan and Audi e-tron GT started

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**FIG 9** Simulated grid voltage for 2 kW output power. (a) without virtual resistance, (b) with virtual resistance [13].
to have this capability in 2020, and have delivered more than 20,000 vehicles in 2020 (Figure 10).

Because of the costs required to upgrade the utility system’s infrastructure to accommodate the power levels expected with XFC, most designs require multiple XFCs to be deployed per charging site so that utility costs are spread over several charging stations. This also allows for ease in scheduling the charge demanded to avoid drawing too high peak power from the utility, creating the power cluster. On the other hand, to maximize the profitability of XFC stations, significant up-front modeling will be required to assess where to locate these within the electric system such that minimum system modifications are needed. Many have also pointed out that because of the large power required at these locations, power sources such as photovoltaics (PV) and energy storage (batteries) will need to be integrated to help reduce the demands on the grid [13], as shown in Figure 11. Some researchers have also proposed using bidirectional chargers to transfer charge among vehicles or to provide grid support when needed, but this option may face opposition from vehicle OEMs as the additional battery cycling may reduce the overall battery lifetime.

One recent mission is to eliminate the MV/LV transformer (shown in Figure 11), given such high-power 50/60 Hz transformer is bulky and heavy. Thanks to the recent breakthrough with HV SiC MOSFETs (devices with voltage ratings of 10 kV), a modular design is a promising candidate such that voltage blocking can be divided among multiple devices/modules. In addition to the two-level design using >6 kV devices, [16] proposed a multilevel converter as shown in Figure 12(a). Both the PFC stage and dc-dc stage use a three-level topology as shown in the figure. 1200 V SiC MOSFETs or Si IGBTs can be used at the secondary side to save cost.
FIG 12 (a) Modular design using the multilevel (three-level) topology [16]. (b) Block diagram of an ISOP XFC [17]. (c) Exemplary design of ISOP XFC station for two vehicles [18].
Given the voltage limits of power semiconductors nowadays, input series and output parallel (ISOP) is a popular candidate as shown in Figure 12(b) [17]. Since such dc-dc stage still engages the HF transformer, here “Transformerless” actually means that no 50/60 Hz transformer is used, but instead still incorporates a high frequency (>10 kHz) transformer that is much more compact in size and weight. One exemplary ISOP XFC is presented in Figure 12(c) [18], proposed by the UTK team and Wolfspeed, under the sponsor of U.S. Department of Energy. To transfer the power, the ac voltage at the grid is first rectified and transferred to the primary side dc link, such as 4.3 kVdc which allows 6 kV SiC MOSFETs to be adopted. The number of series-connected H-bridges on the grid side is determined by the ac-grid voltage and the switch voltage rating. Then, the high-frequency inverter converts the dc voltage to high-frequency ac voltage and transfers power from the dc link to the resonant network formed by compensation components (resonant inductor and capacitors).

A MV HF transformer is needed for voltage isolation purposes. If only one car is charged from the XFC, the transformer secondary side only needs one winding. In this particular case, the XFC is designed to charge two cars simultaneously, so two secondary-side windings are used. The secondary windings then induce a stepped-down ac voltage, which will be rectified by the LV H-bridges with output voltage being paralleled forming the LVDC bus (e.g., 1.3 kVdc). To charge regular EV batteries of 200–450 Vdc, another buck converter is needed to step-down the 1.3 kVdc to the battery voltage. Note using XFC technology to charge the battery still needs to secure high quality output voltage/current at the battery side, for instance output voltage 200 – 920 V with ripple of ±5% or ±5 V, and output current up to 500 Adc with ripple <1.5 A and frequency <10 Hz, based on IEC 61851-23.

To alleviate the switching loss and transformer stress thereby avoiding the scenario in FIG 4, a typical resonant-type isolated MVDC-LVDC converter can be a good choice, e.g., an LC type also called dc transformer (DCX) converter. The resonant network only incorporates series-connected capacitors C and transformer leakage inductance L on the secondary side. The transformer mutual inductance is much larger than the leakage inductance. Therefore, it has little effect on the resonance. At the resonance frequency, this topology behaves as a constant voltage source. The transformer turns ratio can be accurately designed to transform the 4.3 kVdc bus to a 1.3 kVdc output. Essentially, such DCX topology is made to eliminate the switching losses, given the switching moments all happen around current zero crossing points, which helps in natural ZVS turn-on and zero-current switching turn-off for both primary side and secondary side switches as shown in Figure 13. In addition, the resonant topology avoids the transformer windings from having to accommodate the high dv/dt of the switches, further facilitating the transformer design.

The first major concern with this topology is its resonant capacitors. High voltages at resonant frequency are induced across the resonant capacitor. Such high voltage stress, usually multiple times of the dc-bus voltage, requires a large number of film capacitors in series and parallel, resulting in large capacitor banks. Meanwhile, such high-voltage voltage is also subject to significant EMI issues. The second major concern lies in the MV high-frequency transformer, which has issues of partial discharge. In recent years, researchers are aware of the challenge of such MV transformer design. The high dv/dt of SiC devices requires the larger distance among turns, which enlarges the size of the MV transformer.

Nevertheless, with the operating frequency of a transformer increasing, reduction of the transformer size and weight is still expected, given its core cross section is reduced inversely proportionally to the frequency. Nanocrystalline cores, for instance, can be produced with sheet thicknesses as low as 13 μm, in contrast to the 350 μm thickness of conventional grain-oriented electrical steel used at the line frequency. However, for MV insulation, the miniaturization of the transformer creates a direct challenge for the dielectric design, given increasing frequency does not reduce the clearance distance required for insulation. Meanwhile, because of the MV ratings required, the insulation material layer, which encapsulates the MV-winding and isolates it from the LV-winding and the core, has to be rather thick, which increases the transformer size again.

**FIG 13** Voltage and current waveforms of the primary side of the DCX transformer [18].
Two main families of cores are available for MV transformer design: the powder type and the tape type. Although the powder types are generally referred to as ferrites, a variety of materials can be used in terms of loss and saturation levels. One challenge is that ferrite cores are not easily manufactured in larger sizes. Therefore, nowadays such materials are mainly applied in low-power applications. Additionally, ferrites usually have relatively low flux density saturation levels (e.g., ~0.3–0.5 T). Tape type cores, in theory, have unlimited size. Therefore, they can be produced in much larger sizes than ferrites. The main material types for these cores are amorphous, nanocrystalline, nickel iron, and cobalt iron. The main core parameters are shown in Table 1. As a summary, the XFC design challenges nowadays are more on the materials instead of power electronics control.

Wireless Charging
In 2007, a group of scientists in MIT successfully delivered 60 W at 40% efficiency over a 2 m distance between coupled coils of 30 cm radius [19]. They co-founded WiTricity later which has been working closely with major automakers like BMW and Hyundai by licensing its technology and has demonstrated a series of wireless charging prototypes for next generation vehicles. In 2018, BMW introduced the 530e iPerformance, the world’s first electric sedan that is factory equipped with a wireless charger using WiTricity’s techniques. Meanwhile, Qualcomm’s Halo collaborated closely with the University of Auckland and has developed a number of coil pad geometries suitable for wireless EVs, including the patent for the double D coil pad [20]. In 2019, it was acquired by WiTricity with its over 1500 patents or patent applications. Plugless Power provides wireless chargers with 3.6 – 7.2 kW power rating and allows customers to directly install the charger on their vehicles. The supported models include Tesla Model S, BMW i3, and Nissan Leaf. In 2021, HEVO licensed a series of wireless charging technologies from Oak Ridge National Laboratory (ORNL), including a unique polyphase coil structure that enables a very high coil surface power density at 1.5 MW/m². HEVO is working with ORNL to build a 300 kW system to meet the 15-min charging goal for EVs with 100 kWh battery packs [21].

Images of wireless chargers from different companies are given in Figure 14, with their specifications compared in Table 2. All IPT systems use inductive coupling of a magnetic field between two coils. Controlled

<table>
<thead>
<tr>
<th>Core type</th>
<th>Ferrite MnZn</th>
<th>Amorphous (iron-based)</th>
<th>Amorphous (cobalt-based)</th>
<th>Nano crystalline</th>
<th>Nickel iron (79%)</th>
<th>Cobalt iron (50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation induction at 20 °C (T)</td>
<td>0.43 Powder</td>
<td>1.56 Tape</td>
<td>0.57 Tape</td>
<td>1.23 Tape</td>
<td>0.88 Powder/tape</td>
<td>2.1 Tape</td>
</tr>
<tr>
<td>Curie temperature (°C)</td>
<td>140</td>
<td>395</td>
<td>225</td>
<td>600</td>
<td>450</td>
<td>940</td>
</tr>
<tr>
<td>Core losses at 10 kHz (W/kg)</td>
<td>70.0</td>
<td>250.0</td>
<td>4.0</td>
<td>28.7</td>
<td>50.0</td>
<td>400.0</td>
</tr>
<tr>
<td>Saturation magnetostriction (ppm)</td>
<td>-0.6</td>
<td>27.0</td>
<td>1.0</td>
<td>0.5</td>
<td>12.0</td>
<td>70.0</td>
</tr>
</tbody>
</table>

**Table 1. Comparison of Main Core Parameters.**

![Images of wireless chargers](a) Commercially available prototype from WiTricity. (b) Manhole-like charger from HEVO. (c) Electric bus from Momentum. (d) Customized charger from Plugless Power.
by a varying current source in the primary side coil, a predominantly magnetic time-varying field is generated between the coils. Both the coil-to-coil distance and the coil size are generally much smaller than the operating frequency’s wavelength. For most of the current coil designs, Litz wire is used extensively instead of the conventional solid AWG wire for its capability of reducing high frequency eddy current loss. Usually, magnetic cores like ferrite plates or bars are applied to better channel the flux around the coil.

The typical structure of an IPT charger is shown in Figure 15. Compared to the wired charger of Figure 2, the main difference is the pair of loosely-coupled \((k \ll 1)\) coils \(L_p\) and \(L_s\) that replace the transformer of the wired charger. Due to the low coupling resulting from the air gap between transmitter and receiver, impedance matching networks (IMN) are used to cancel out the large uncoupled series reactances on both coils and limit the circulating reactive power. Each IMN can be as simple as a single capacitor designed to resonate with the coil inductance, either in series or in parallel. In either event, the IMN gives the system a bandpass characteristic and results in a dominantly single-frequency magnetic field between the two coils. Differences in series or parallel compensation, resonating with coil self-inductance or uncoupled inductance, or the use of more complex IMNs such as LCC of LCL networks will influence the charger’s dynamics, harmonic attenuation, and loading of the inverter and rectifier over varying output power levels and misalignment conditions [23], [24].

Different coil pad structures have been explored in the literature, mainly including circular, rectangular, DD, and DDQ pads. To have a fair and comprehensive comparison on the system performance using different coil pad structures, a multi-objective optimization is developed in [22] considering the tradeoffs between conflicting design parameters to evaluate and compare the performance of different coil pad structures. The main conclusions are:

a) Circular pads have the highest coupling coefficient and efficiencies for the same gravimetric power density under the perfectly aligned condition.

b) Circular pads use the most ferrite and the least copper for the same system performance.

c) Polarized pads including DD and DDQ give better misalignment performance in the longitudinal direction.

d) Both circular and rectangular pads have lower stray field densities compared to polarized pads.

In CPT, energy is delivered through coupled metal plates instead of coupled inductors. Compared with IPT, CPT features favorable characteristics including lightweight and cost-effective design. It does not require expensive high-frequency Litz wires or heavy magnetic cores, which aids the high frequency design to reduce the weight of passive components. However, CPT suffers from two major issues: low coupling capacitance and high fringing field. Capacitive coupling requires a relatively large coupling area to achieve large coupling capacitance, imposing a design challenge on high power density. For high power EV applications with a large air gap, the transmission efficiency is low due to the low coupling capacitance between the paralleled plates. To compensate, MHz operating frequencies are required to reduce the impedance, which directly imposes a design challenge for the high power, high frequency converters. In addition, relatively large-valued microhenry-range inductances are required for resonant matching networks in the MHz frequency range, leaving a design challenge for high value, high quality factor inductors at high frequency. The high fringing field at the edge of coupled metal plate pairs is another concern for CPT because of electric field exposure limits on the human body.

Whether using CPT or IPT, maximum power and coupler design are constrained by electromagnetic compliance and human exposure. EMC requirements, both regulatory and system-level, are similar in WPT systems to traditional wired chargers. The near-field electric and/or magnetic fields used to transfer power are minimally radiative, though the long coils and large conductors used may make radiated compliance difficult when higher harmonics are

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Table 2. Industrial Wireless EV Charger Specifications.

<table>
<thead>
<tr>
<th>Company</th>
<th>Frequency [kHz]</th>
<th>Airgap [mm]</th>
<th>Power rating [kW]</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiTricity</td>
<td>145</td>
<td>180</td>
<td>3.3–11</td>
<td>90–93%</td>
</tr>
<tr>
<td>Momentum</td>
<td>NA</td>
<td>610</td>
<td>50–200</td>
<td>NA</td>
</tr>
<tr>
<td>HEVO</td>
<td>85</td>
<td>305</td>
<td>1–10</td>
<td>&gt;85%</td>
</tr>
<tr>
<td>Plugless Power</td>
<td>20</td>
<td>152</td>
<td>3.3–7.2</td>
<td>89%</td>
</tr>
<tr>
<td>WiPowerOne</td>
<td>85</td>
<td>200</td>
<td>27</td>
<td>80%</td>
</tr>
</tbody>
</table>

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**FIG 15** Typical structure of an IPT charger for EVs.
present. The risk of human exposure, however, is unique to WPT. Incidental exposure can occur near the sides or bumper of the vehicle during charging. Guidelines set forth by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) give reference levels for general public exposure to time-varying fields, including a limit of $27 \mu T_{\text{rms}}$ magnetic field exposure in the frequency range from 3 kHz to 10 MHz [25], with additional considerations required for frequencies above 100 kHz [26]. The geometric design of the coil, ferrites, and conductive shielding elements (including the vehicle underbody) are required to ensure any possible human exposure remains below safe reference levels, even under misalignment.

Particularly for IPT, foreign metallic objects present an additional concern. Eddy currents induced in metallic objects due to the magnetic fields can cause dangerous heating and ignition risk, e.g., gum wrappers, cans, or staples. If the system cannot be designed with sufficiently small magnetic fields to prevent ignition, foreign object detection (FOD) sensing and control schemes are required [27].

The SAE J2954 specifies a multitude of design, communication, and testing procedures for light-duty wirelessly-charged EVs. Standardization facilitates interoperability of dissimilar coil geometries and designs, and provides a common reference assessment for safety, EMC, and performance under misalignment. These benefits come at the cost of a limited design space, in particular due to the 85 kHz frequency used for powers below 11 kW. Compliance with SAE J2954 is not required, however, proliferation of wireless charging in EVs will benefit from the interoperability afforded by standardization.

Figure 16 summarizes the state-of-the-art WPT systems for EV charger applications from both the industry and academia. The color of dot represents the WPT technique applied. Critical performance specifications are also labeled, including system dc–dc efficiency, coil power density and power transfer distance. Compared to CPT, IPT is a relatively mature technology for WPT systems for EV chargers with air gap up to dozens of centimeters with power rating up to tens of kilowatts. Most use frequencies below 100 kHz, many of which use 85 kHz following SAE J2954. The highest coil surface power density of the reviewed works is 250 kW/m² achieved by the 88.5 kHz, 50 kW three-phase series-compensated coil in [28].

**FIG 16** State-of-the-art WPT systems for EV charging.
High frequency WPT system designs at frequencies above 1 MHz have also been explored, enabled by wide bandgap devices. High frequency operation does not inherently benefit the system, but enables the use of new self-resonant (SR) passive component designs, which have the potential to reduce weight and volume of the system. Compared to coils made of Litz wires, the SR coil has many advantages including its compact structure without need for lumped compensation capacitors [29], [30].

For the further adoption of WPT for EVs in the industry, there are still economics challenges brought by the infrastructure costs including the magnetic couplers, power electronics, and energy consumption [23]. The unique requirement of high power delivery over 100 – 250 mm airgap makes WPT system efficiency relatively low compared to the wired EV chargers with similar power ratings. The state-of-the-art EV WPT charger products exhibit only 90 – 93% efficiency, which brings challenge in both energy costs and thermal management design of the system. For a better power transfer with higher efficiency, the couplers’ size is often larger than 50 cm in diameter, inevitably increasing the material cost and total weight. Considering all the factors above, more innovative coil structures and more advanced WPT system design methods are still needed. High efficiency, high power density, lightweight WPT systems with low cost are imperative for increased adoption of wireless EV charging in the future.

Conclusions
Authors have been engaged in EV charging techniques for more than a decade. While witnessing the low-power charger development is approaching the design plateau, power electronics engineers now must examine other parts of the EV for further optimization, such as integrating charger with other on-board systems to save the cost and size, to engage the charger more with the power grid, and to further increase the charging power or efficiency of WPT systems.

In addition to what has been discussed in this paper, there are many other aspects of EV charging technologies to explore; for instance, the impact of various charging algorithms on the battery lifespan, and selection of the cables and associated cooling techniques for the XFC.

While this article is focused on 400 V battery charging, in reality charging a 48 V battery in electric shuttles or >800 V battery for heavy duty vehicles are not rare cases. In fact, with power demand increasing for EVs, it is projected 800 V battery will become the mainstream in the near future. Even for a conductive XFC station, during non-charging period the PFC converter can provide grid services such as reactive power generation for voltage regulation. The charger development then becomes more interdisciplinary, diverging from conventional power electronics design to interacting with power system and material science.

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The system-level value of wide bandgap power semiconductors of higher efficiency, smaller size and weight, and more sustainable energy usage in our power supplies and motor drives is being demonstrated now. Gallium nitride (GaN) power FETs are replacing silicon (Si) power MOSFETs in applications from 48 V to 800 V. Silicon carbide (SiC) is replacing legacy IGBTs in applications >800 V. The previous barriers to implementing what was theoretically possible with these
technologies included manufacturability, reliability, system complexity, and cost (Table 1). But over just the last few years with numerous advancements, it’s clear that those challenges have been addressed as 10's of millions of units of GaNFast power ICs have been shipped in mass production in applications from fast mobile chargers to gaming systems to notebook computer adapters, and more.

For offline ac/dc, dc/ac, and isolated dc/dc power applications where user safety is paramount, N-channel silicon power MOSFETs (normally-off power switches that require a positive gate voltage, relative to source to conduct) have been the most popular power switch (compared to their P-channel counterpart that requires a negative gate voltage relative to its source to conduct). The N-channel devices are easier to use, easier to interface to controllers, safer and more reliable, and lower cost to manufacture and design with and have become ubiquitous in the industry while the P-channel power switches are more of a niche component for unique application use cases.

Similarly, GaN power switch technology is now in production from many vendors, and we see two types of approaches battling it out for market adoption. The earliest GaN power devices were depletion-mode (d-mode, normally “on” devices). ‘Normally-on’ d-Mode devices require a negative $V_{GS}$ to turn off – not a practical solution for off-line or high-voltage applications. This characteristic was mitigated by the addition of a second, low voltage ‘cascode’ Si FET used to turn the GaN power device on and off. This essentially converts the d-Mode device into an enhancement-Mode (e-Mode) device, required to block high bus voltages when a power converter is first turned on. The cascode FET allows for a standard gate drive signal to be used ($0 \ V = \text{OFF}$). However, the Si FET frequency characteristics are inferior to GaN and compromise the switching performance of the combined device. Another cascode variant uses the low voltage Si FET simply as an on/off switch for the circuit, and then drives the GaN transistor directly with a negative voltage drive from an inverting buck-boost controller or similar, leading to a complex double gate-drive solution with two supply rails. Cascoding requires at least a two-chip package that presents a variety of other concerns including complex (multiple and/or stacked die) packaging, high parasitic inductance, ceramic interposers for isolation, tendency for oscillation and internal overvoltage stress due to ac and dc mismatch of the GaN device and the Si device, as well as additional internal passives to mitigate these effects. This results in a reduced overall yield and ultimately a higher cost.

Later, e-Mode (normally “off” devices) GaN discrete devices came about with more reliable normally off

| Table 1. Traditional Challenges of Adoption of GaN in High-Volume Products. |
|---------------------------------|---------------------------------|---------------------------------|
| **Legacy challenge to practical implementation of GaN power supplies** | **Status as of February 2022** |
| **Manufacturability and Yields** | • GaN power device companies already achieving stable >90%+ yields, leveraging proven, low-cost GaN-on-Silicon in mature, underutilized 6” and 8” wafer Fabs. |
| | • Many GaN power suppliers available today |
| | • Multiple generations of GaN products have been launched and ramped in production |
| **Reliability** | • Some GaN companies have already shipped >40 million units individually with zero failures and >116 billion device hours in the field. |
| | • Devices available with protected gates capable of 2 kV ESD |
| | • 650 V ratings moving even to 700 V continuous $V_{GS}$ ratings with 800 V surge capability showing strong data and confidence in their guaranteed robustness |
| **System Complexity** (gate drive circuitry, number of components, parasitic elements, high frequency design, EMI, etc.) | • Easy-to-use GaN building blocks available with integrated gate drive, bias, UVLO, dV/dt, etc. in low inductance QFN package launches high frequency designs to production |
| | • Continued advancements in integration and features reduces external components and improves performance still further |
| | • Planar magnetics for AC/DC and HV DC/DC become more widely available and designed with |
| **Cost** (Device and System-level) | • GaN-based systems approaching cost parity with silicon |
| | • Shipment volumes drive down cost |
| | • Many GaN suppliers available today create competitive cost environment |
| | • Multiple generations of GaN products released to production accelerate cost reductions |
capability but then had vulnerable exposed gates and a very low threshold voltage. This made them very susceptible to noise and voltage spikes due to high-frequency and high dv/dt noise from the surrounding switched-mode converter circuit, so required complex and expensive control and gate drive circuits and introduced further parasitic circuit elements like resistance and inductance. Both implementations of d-Mode and discrete-FET e-Mode GaN restricted the high-frequency performance of the GaN switch, to the point where there was minimal, if any, advantage over Si, so limiting market adoption to date.

**Introducing Monolithic GaNFast Power IC**

The key to improved performance (reduced loss, higher switching frequency) and rapid market adoption (simple, cost-effective designs) is to create what approaches the ‘ideal switch’, i.e. a circuit building block which translates a minimum energy digital input signal into lossless power delivery. Using lateral e-Mode GaN, a proprietary technology platform – GaNFast – has been created which enables the monolithic integration of drive, logic, protection, and FET into a GaNFast power IC [4], [5]. This single die can then be packaged into industry-standard, low-inductance, low cost, QFN packages for off-line ac or 400 V dc applications. Integration enables virtually zero loss in turn-off because the gate drive loop has essentially zero impedance.

With GaNFast, the GaN FET gate is driven safely, precisely, and efficiently by the integrated GaN driver. Simple, robust, low-current 3.3 V, 5 V or 15 V signals, from standard, low cost, low voltage ‘no driver’ control ICs are fed directly into the GaNFast power IC for an easy, low component count design. The waveforms exhibit a true “textbook” waveshape with very clean rising and falling edges, no ringing, and extremely fast turn-on and turn-off propagation delays. Integration eliminates gate overshoot and undershoot, while zero inductance on-chip insures no turn-off loss. This lack of ringing and overshoot makes tight control of deadtime easy in half-bridge circuits. This exceptional level of fast and quiet switching performance, together with the integrated gate drive and simple PWM input, allows for the design of a variety of different high-frequency power converters, raising practical switching speeds more than 10x from typical mass production 65/100 kHz to 1 MHz+.

The single-device monolithic GaNFast power IC seen in Figure 1 was a huge step for the industry, and rapidly accelerated the adoption of GaN in production for high density flybacks and PFC circuits in mobile-device chargers starting in 2018. The next challenge was half-bridge power stages. Half-bridge circuits are essential building blocks in the power electronics industry, used in everything from smartphone chargers and laptop adapters, motor drives, TVs, solar inverters, data centers and electric vehicles (EVs). Operating these half-bridge circuits – i.e. providing bias power and signal to a floating high-side switch – at very high frequencies can shrink magnetics and enable a dramatic reduction in size, cost and weight while delivering faster charging. However,
such frequency increases have eluded the industry as silicon devices have been too slow and suffer from parasitic impedances between the driver and FET, high-capacitance silicon FETs and poorly performing level-shifter/isolators. Because of this, most converters previously ran at 65-100 kHz.

With the fully integrated half-bridge GaNFast power IC as seen in Figure 2, the evolution continued as further components were integrated such as the high-side bootstrap diode, the high voltage level-shift (allowing for low-side ground referenced PWM input signals), and logic with shoot-through protection; truly allowing for a "digital-input, power-output" capability in a small-size standard 5x6 mm and 6x8 mm QFN package seen in Figure 3.

**Enter GaNSense Technology**

With the advent of the fully integrated GaNFast power IC, power supply designers could do more immediately, and quickly released ground-breaking products to the market with higher efficiency and power densities even three times higher than best-in-class previous solutions. But the fight to extract all the capability out of GaN continued, and in late 2021, GaNSense technology with still further integration and expanded features was released.

As seen in Figure 4, in its simplest form GaNSense is lossless current sensing in-circuit, removing the shunt current-sense resistor and its associated headaches and improving the overall efficiency of the system while also increasing robustness with fast, internal, <100 ns short-circuit protection. This "lossless" current sensing in the current-sense (CS) block is implemented through a popular parallel current-mirror technique as seen in Figure 5.

As seen in Figure 5, within the CS block the main power FET device is connected to the common drain and gate connections. For simplicity’s sake, we will show the source’s connected commonly as well. By using well-matched devices and using a high on-resistance sense-FET (maybe >1000 times higher $R_{DS(ON)}$ than the main power FET), a small portion of the load current branches off to the sense FET and can be measured accurately through a variety of techniques. $R_{DS(ON)}$ and temperate affects are also cancelled out naturally. Because of the matching the current is based on the ratio of the resistances of the devices. As the sense FET is much higher $R_{DS(ON)}$ than the main power FET, the loss from this approach is negligible, especially compared to alternatives like shunt current sense resistors in the main power path.
Other features and advancements were also included in GaNSense as system designers demanded new capabilities as they released generation after generation of GaN-based power supply products. The progression can be seen in Figure 6.

At first glance, removing the shunt current sense resistor doesn’t seem all that ground-breaking, but let’s discuss the ripple-effects from this advancement starting with Figure 7.

Any reduction or elimination of series loss elements helps efficiency. When comparing GaNSense technology versus an existing external series resistor sensing method (Figure 7), the total ON resistance, $R_{\text{ON(TOT)}}$, can be substantially reduced. For a 65 W high-frequency Quasi-Resonant (HFQR) flyback circuit, for example, $R_{\text{ON(TOT)}}$ is reduced from 340 mΩ to 170 mΩ. Even when...

**FIG 5** Simplified diagram of Current-Sense (CS) block in GaN-Sense technology.

**FIG 6** Evolution of GaNFast power IC.

**FIG 7** Total on-resistance reduction through lossless sensing.
comparing to a high efficiency GaN solution without lossless sensing, the power loss savings by eliminating the external resistor results in a +0.5% efficiency benefit for the overall system at the most critical thermal conditions at 90 V\textsubscript{AC} input as seen in Figure 8. The improvements over a silicon solution would be even more significant. Alternatively, designers may opt to use higher $R_{\text{DS(ON)}}$ power switches which offers an even more cost-effective solution while achieving the same efficiency they were achieving previously with the reduction of total series resistance in the power path.

In Figure 9, you can see how removal of the $R_{\text{CS}}$ hotspot component and improving the efficiency ultimately affects the thermal performance of the power supply.

**FIG 8** Efficiency improvements over series-shunt current-sensing GaN solution.

**FIG 9** Thermal effects of efficiency improvements with lossless current sensing.
The GaN power device temperature is reduced, the hotspot moves from the $R_{CS}$ to the transformer as the limiting factor with the removal of the hot $R_{CS}$ component, and overall board temperature is reduced.

As designers push the frequency even higher in these designs and push the limits of thermal capabilities, overload protection becomes increasingly important. Thankfully, through the integration of short-circuit protection and cycle-by-cycle current limit in the lossless current sensing, the system with GaNSense technology achieves the added benefit of local protection at the power switch. This improves accuracy but also drastically reduces the response time to an overload current event. This can be seen in Figure 10.

As seen in Figure 10, even with a dedicated high-frequency controller, due to filter, controller, and system response times, the signal to turn-off the power switch during a short-circuit event can be 300 ns typically with a standard controller shunt-resistor current-sensing method as seen in the red waveform. Note that we also need to add the reacting time of the downstream device to this figure. Alternatively, with the lossless localized current sensing, you can see in the green waveform that the FET not only reacts but turns off fully very quickly in 100 ns.

In these high-density power systems, every component matters to meet size requirements. Every mW of power loss matters to meet standards, sustainability, and thermal
Every feature and operating condition hold potential for improvements to make the designer’s life easier. When activating standby low-power mode, previously, designers would use logic to pull down on the Enable (EN) pin of the GaNFast power IC. But this added additional cutoff circuitry and layout considerations. With the addition of autonomous standby power mode, now these fully integrated GaN power stages can identify when they need to go into low-power mode on their own, and when they need to start switching again. This not only reduces external components but also further reduces the standby power loss itself. This can be seen in Figure 11.

With some of these feature integrations, and further component savings mentioned in Figure 6 previously, the net results in terms of efficiency and power density of fast-charging mobile device chargers, as an example, are significant. As seen in Figure 12, even when operating at 2.5x higher switching frequency, the high level of integration and performance of GaN-Sense technology allows designers to realize a product that’s 1.6% higher efficiency and 12 degrees cooler at the most critical thermal operating point.

A highly-autonomous, lossless, self-protecting power stage is the ideal building block all designers need in power electronics. As generational innovations are introduced,
we come closer to that full realization in everyday products in our daily life of the capability of wide bandgap semiconductor power switches, like GaN. We are on the right path through cost-effective and reliable e-Mode, focusing on high integration, and working together with the leading designers in the world to solve their toughest challenges. Now that we see proof in the capability in real high-volume production as seen in mobile travel adapters and chargers available, the industry should expect to see these capabilities of GaNFast power ICs make their way into other USB charging wall and furniture outlets, EV charging, server and telecom datacenters, and renewable energy among others.

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Transformative Role of Power Electronics

by Rajendra Singh, Prahaladh Paniyil, and Zheyu Zhang

Long term shifts in weather patterns and temperature are referred to as climate change. Hotter temperatures, more severe storms, increased droughts, food and water insecurity, and economic disruption, etc. are all due to climate change. According to NASA, “Human activities (primarily the burning of fossil fuels) have fundamentally increased the concentration of greenhouse gases in Earth’s atmosphere, warming the planet” [1]. One of the most difficult challenges faced by humanity is to solve the climate emergency [2]. In addition to the climate...
emergency, the drive to transition from fossil fuel to renewable energy has taken on a new urgency as a result of Russia’s assault on Ukraine [3]. The recent Glasgow summit left a huge hole in addressing the challenges of climate change [4]. In order to avoid more than 1.5°C of eventual warming, the 2030 goal of greenhouse gas (GHG) emissions must be further reduced by approximately 17–20 bn tones [4]. Daring and transformative economic transformations are required to save humanity. There are fundamental differences between green and clean energy sources. Free fuel and renewable green energy sources such as solar and wind have negligible negative impact on the environment and require minimum use of water in electric power generation. On the other hand, clean energy source such as nuclear energy does not produce GHG emission during electric power generation, but mining, extraction, and long-term radioactive waste storage are threats to the environment, and Uranium is a nonrenewable resource. In addition, nuclear energy requires massive amount of water in electric power generation. Thus, renewable, and free fuel-based solar and wind power that have minimal negative impact on the environment are considered as green sustainable power. From safety (death rate from accidents and pollution) [5], minimum GHG emissions [5], negligible use of water in electric power generation [6], photovoltaics (PV)

**FIG 1** Global GSG Emissions by sectors [9].
and wind power provide lowest cost [5] of electric power generation. In 2020, the International Energy Agency (IEA) announced that solar power is now the cheapest form of energy [7]. The cost of electric power generation by photovoltaics has reached as low as $0.0104/kWh [8]. The use of these green sustainable energy sources in place of fossil fuels is the only economical solution to address climate emergency. The objective of this article is to show that power electronics has the potential to achieve the goal of electrifying almost everything by green sustainable energy sources and providing a solution to our shared climate emergency.

**An Analysis of Greenhouse Gas Emissions**

Figure 1 [9] shows global GHG emissions data for various sectors. The livestock-related agriculture emissions can be reduced by making a personal choice either by becoming a vegan or eating synthetic meat. Thus, other than livestock related agriculture emissions, energy is the root cause of all GHG emissions. Recent data have shown that energy use accounts for 83% of the GHG emissions across energy and land-use systems [10]. In the following sections we have discussed the role of electrifying almost everything to solve the global climate emergency.

**Electrify Almost Everything**

The Introduction section has discussed the economic superiority of green sustainable electric power. In addition to the use of green sustainable energy for generating electric power, thermal power must be produced by green electric power. A number of industries rely on dirty energy sources to generate the required thermal power. GHG emissions by concrete and steel industries account for as much as 16% of humanity’s annual carbon dioxide emissions [11]. As an example, virtually every thermal power step in cement and steel manufacturing can be replaced by green electric power. Figure 2 [12] shows various steps used in cement manufacturing. Other than the use of sustainable green energy for all power needs of manufacturing (including transportation of raw material and finished product), power electronics will play an important role in providing highest energy efficiency for various electrical machineries and equipment used in manufacturing.

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**FIG 2** Various steps used in cement manufacturing [12].
**Sustainable Sources of Green Electric Power Generation and Storage**

Based on abundance, free fuel, minimum amount of GHG emissions, minimum use of water in power generation, highest safety, access to all, and ultra-low cost, solar and wind energy are the only two energy sources for generating green sustainable electric power [13]–[15]. Due to advancements in technology and ultra-large-scale manufacturing, lithium-ion batteries (LIBs) are emerging as a cost-effective solution of electric power storage due to its constantly reducing cost as seen in Figure 3 [16]–[17]. In addition to consumer products and electric vehicles, LIBs are also emerging as a low-cost practical solution at utility scale to address the intermittency of solar and wind energy [14]–[15]. Free fuel-based solar and wind electric power generation combined with batteries for storing electric power has the potential to electrify almost everything.

**Myths and Facts about DC vs AC Power**

Except for few inductive loads, virtually all our loads (electronics, solid-state lighting, efficient motors etc.) need dc power as the input power. However, based on the outcome of the “war of currents” in the beginning of the last century, the entire world is using ac power-based electricity infrastructure. Power industry has realized the importance of semiconductor-based electronics but has used it only to facilitate the control, conversion, and distribution of ac power. Solar energy-based photovoltaics generates dc power. Batteries and fuel-cells store dc power. Erratic wind power is first converted to dc power before converting to ac power for transmission and distribution. Thus, dc power generated today by free fuel sources is first converted to ac power. After transmission and distribution, the ac power is converted back to dc power internally in all dc loads. More than 30% power and capital is wasted in this process [18]. Extremely fast charging of electric vehicles (EVs) requires dc power. As shown in Figure 4 [19], the ac power supplied by the grid is first converted to dc power inside the charger. The components shown in blue color in Figure 4 will not be required if the power source is dc. Another aspect of ac power is that a fortune is invested to regulate the frequency of the ac grid. Thus, from the point of view of capital cost and overall cost of generated electric power, we need to devise a plan that can be implemented for dc-based electricity infrastructure. However, an immense amount of capital, research, and time has been invested in the current ac-based infrastructure. Thus, we are not proposing to dismantle the existing ac power infrastructure. Other than the existing loads, new loads (e.g., charging of electric vehicles, desalination plants, etc.) are emerging that can be served at a lower cost with a dc power network as compared to the existing ac grid. After retirement of the existing ac infrastructure, new infrastructure can be based on dc power. The power networks architecture proposed in the next section has the potential to transform the global electricity infrastructure and provide a solution to climate emergency by providing efficient dc-dc conversion to achieve an edge over the ac power-based grid.

**Power Electronics as an Enabler**

The growth of semiconductor-based switching transistors in the integrated circuits (IC) industry has become a boon to the power electronics industry. The availability of high frequency switching transistors has enabled higher efficiency converters to convert dc power to ac power in inverters and transformers. Silicon (Si) based insulated-gate bipolar transistor (IGBT) has been the workhorse of the power electronics industry. The fundamental limits of silicon power electronics can be overcome by the utilization of silicon carbide (SiC) transistors in place of silicon transistors. SiC modules are providing higher power density of motor drive of electric vehicles [20]. The ac power network has sustained so far due to the ability of effective voltage conversion by transformers enabling long distance transmission of ac power with minimal losses. However, due to the advent of SiC power electronics, dc-dc voltage conversion can also be efficiently implemented. The following sub-sections explain our proposed dc power-based network for the most efficient utilization of green sustainable electric power through solar, wind, and batteries. Sub-section A illustrates a local dc power network, and sub-section B includes transmission for a DC network at a larger scale. Key aspects of SiC-based power electronics for high voltage dc-dc conversion are described in sub-section C.
A. Local DC Power Network

With the advent of solar energy-based PV and wind energy as sources of generation and battery banks for storage, it is possible today to realize Edison’s vision of dc generation and distribution. If the physical distance between power sources (generation and storage) and loads is small (power loss less than about 4–5%), an interconnected local dc power network can satisfy these loads with maximum efficiency. Figure 5 illustrates the local dc power network.

The first part of Figure 5 is the low-power load (48 V) fulfillment through the PV, wind, and battery bank-based dc network. These loads are typical household appliances with low power consumption like LED lights, ceiling fans.
The importance of novel dc loads can be seen in reference [21]. The importance of novel dc loads with high energy efficiency must be taken into consideration for under-developed and developing nations where the power infrastructure is still in nascent and developing stages.

The second part of Figure 5 is the medium to high-power loads (380 V) like data centers, commercial centers, and residential buildings, etc. The 380 V dc distribution network is already being used by several data centers in the United States and other countries. However, in most cases the ac power is converted to 380 V dc before entering in the building. The third and most important part is the emergence of dc fast charging networks as loads. With the rapidly growing trend of electrification in the transportation industry, dc fast charging is going to be dominant source of power consumption. The viability of a sustainable dc-based power network for EV charging is elaborated in reference [22]. The last part is the interconnectivity of such a local dc power network with similar local networks to form a microgrid. Such a dc network can be realized only through efficient dc-dc converters which is discussed in the next section.

**B. High Voltage DC (HVDC) Power Network for Current and New Electricity Infrastructure**

In addition to local dc microgrids, the design for a sustainable power network must encompass the capability to transmit over long distances. Figure 6 illustrates the current transmission network with high voltage ac (HVAC) and HVDC methodologies. The idea of using power networks for sending green sustainable electric power over a distance of thousands of miles has been around for a number of years [23]. Backed by the United Kingdom, India led International Solar Energy Association has a plan to create a network to connect the power markets of 120-plus countries [23]. With advancements in various aspects of technology, it is possible to realize such power networks today. As an example, at the low-cost of $0.013/kWh HVDC will be used to connect a 10.5 GW solar/wind complex in Morocco to the UK grid [24]. In current practice, dc power generated from the PV, wind, and battery banks is first converted to medium voltage ac (MVAC) in order to transmit via HVAC. Generation level inverters are utilized for this purpose. The HVDC transmission is carried out utilizing converter stations at the HVAC transmission-level. However, the majority of the system cost in a HVDC transmission system comes from the converter stations. The details of the cost per mile for a HVAC transmission system vs a HVDC transmission system are discussed in reference [14]. For a dc power generation source and a HVDC transmission system, the current practice registers significant losses in conversions.

Our proposed dc network with dc-based power generation and storage and HVDC transmission with new dc loads can be seen in Figure 7. In this system, the generated LVDC power is converted to HVDC power using high efficiency dc-dc converters and transmitted through HVDC transmission. The transmitted dc power can be utilized to power emerging dc loads like EV fast charging and can also serve in the utilization of a dc distribution bus in industrial loads like cement factories, desalination plants, etc. The significance of dc bus in industrial loads like desalination plants is discussed in reference [15]. However, capital and time invested in the current ac infrastructure cannot be ignored just at the cost of energy efficiency. Therefore, the current practice of utilizing a converter station to convert HVDC to HVAC can be incorporated in our proposed network but this reduces the high voltage conversion stage from 2 to 1, thereby reducing converter costs. Existing HVAC transmission lines can be converted to be used with a HVDC

**FIG 6** Conceptual diagram representing the current practice of the utilization of green sustainable electric power in the ac power-based grid-tied network.
transmission system, and the new HVDC system would have a higher capacity of electric power transmission than the HVAC system with the same insulation level.

C. Silicon Carbide-based Power Electronics

In both our proposed systems, dc-dc converters play a vital role. As discussed earlier, with the growth and development of power electronics, it is possible to design high efficiency dc-dc converters. The advent of high frequency transformers or solid-state transformers (SSTs) have made it possible to achieve high efficiency ac-ac converters. Implementation of conversion stages in SSTs utilize power electronics. In our system, the LVDC and MVDC conversions can be handled by Si IGBT transistors as they have adequate performance in the 1–2 kV range. As the breakdown voltage increases, due to limited performance, the highest voltage rating of the state-of-art commercial Si IGBT has been 6.5 kV for the last 15 years. These intrinsic physical limits become a barrier to achieving higher performance power conversion. Therefore, the implementation of HVDC conversion will require transistor ratings that are much higher than commercially available Si IGBT ratings. SiC transistors have a higher breakdown voltage as compared to their Si counterparts. However, Si IGBTs have a significant cost advantage over SiC transistors [25]. Significant manufacturing advances that have been established in the Si industry will be required in the SiC industry as well. Due to the emerging demand for SiC electronics in the power and EV industries, SiC manufacturing can follow a similar roadmap to the Si industry at a much faster rate due to the existing knowledge from the Si based semiconductor industry. Thus, SiC transistors can be potentially cost competitive with Si IGBTs enabling their adoption at a larger scale than the current scenario.

Therefore, SiC transistors are at the heart of our proposed dc-dc power conversion system by utilizing a SST, as shown in Figure 8. There are extensive research activities in the implementation of SSTs for ac-ac, dc-ac or ac-ac conversions [26], [27]. There are various topologies in consideration for employing the best ac-ac conversion design for grid-based applications based on SSTs. Bidirectional power flow is a key required feature for implementation in our proposed power network. Due to the wide range of dc-dc voltage converters in our proposed system, a highly scalable and modular converter is required. There are various transformer-coupled and direct-coupled conversion topologies in active research. Direct-coupled converter topologies require heavy filtering components and are suitable for MV-to-MV conversions. Transformer-coupled converter topologies are suitable LV-to-MV conversions. We will be extrapolating the transformer-coupled topology for MVDC-to-HVDC conversion to facilitate the end-to-end dc power network illustrated in Figure 7. The topology utilized in our system will be the bidirectional soft switching resonant converter as shown in Figure 8. The modularity of this topology as well as elimination of heavy filtering components reduce system complexity as well. We will be focusing on the power electronics aspect of the

FIG 7 Proposed concept of the end-to-end dc power-based architecture for existing and new loads.
transformer-coupled topology hereon. As seen in Figure 8, the LVDC (1–2 kV) power generated from green sources undergoes an initial high frequency switching stage in the order of a few kHz. Since this stage faces a LVDC/MVDC input, the switching transistors can be Si IGBTs or SiC transistors depending on the trade study between cost and performance as both transistor types have breakdown voltages up to 1.7 kV. The generated high frequency MVDC output acts as the primary input for a high-frequency transformer (SST) which has superior characteristics in terms of weight, volume, and modularity over the conventional line-frequency transformer. High-frequency suitable magnetic core materials, such as nanocrystalline core, are utilized for this application. The turns ratio can also be designed according to the input voltage from the generation side. The turns ratio cannot be manipulated to achieve HVDC outputs due to the breakdown voltage limitations of the output power transistors. Taking 10 kV SiC MOSFET as an example, the output must be less than 10 kV (~7–8 kV). However, the output power electronics module can be replicated in a series arrangement to achieve the desired HVDC output. The number of SiC power electronics output modules N is directly correlated to the required HVDC output. The modular proposed model will face some challenges at the power electronics level and system level. The details about the power electronics-based challenges like inadequacy of a single device to interface HVDC, switching losses at HVDC operation, device-level isolation and control, high-frequency transformer tradeoff design between insulation and thermal management; and system level challenges like reliability issues, system isolation and dc protection, and system complexity have been extensively discussed [28] and some of them are still ongoing research topics.

**Conclusions**

Electrification of almost everything by green sustainable electric power is an economic solution to address climate emergency. A large amount of green electric dc power generated by photovoltaics and/or wind turbines and stored in batteries is wasted in current ac electricity infrastructure. Based on silicon carbide power electronics, we propose HVDC transmission of bulk power by dc-dc power converters. Power electronics with higher performance, higher reliability, and low-cost power has the potential to provide transformative transformation of power transmission, distribution, and utilization.

**About the Authors**

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References


Invention of the transistor in 1947 made a radical change to the path of the development of electronic products and systems. In the mid-1950s, integrated circuits (ICs) started evolving rapidly, creating miniaturized analog, digital, and mixed-signal circuits. By the 1960s to 1970s, microprocessors, memories, and power semiconductors entered the electronic marketplace. During the 1980s and 1990s, power supplies required to power the high-performance digital circuits kept dropping towards 2 V and below. By the year 2000, complex digital and mixed-signal circuits required for portable gadgets were powered by very low...
dc rails as low as 1 V and sub-1 V. Very large-scale ICs and ultra-large scale ICs proliferated after 2000, integrating millions to billions of sub-micron feature transistors. The ultimate result of this massive progress came with the unique problem of vulnerability of modern electronics to transient surges. A detailed background to this is presented in Chapter 1 of reference [1].

Figure 1(a) provides a pictorial view of transients and noise present on a 230 V 50 Hz utility ac power, and Figure 1(b) depicts the difference between differential mode and common mode transient voltage sources superimposed on the ac mains and the associated ground connection.

**Circuit Designer’s View to Surge Protectors**

All surge protector devices (SPD) basically work on the simple concept of voltage divider [2]. Figure 2 illustrates this concept in three steps. In Figure 2(a), the superimposed surge appears on the load represented by $Z_L$ based on the voltage division network comprising the compound series impedance $Z_S$ and the value of $Z_L$. For the transient high voltage surge to have a minimal effect on the load represented by $Z_L$, ohmic value of the $Z_S$ should be very much greater than $Z_L$. On the other hand, for 50 Hz power line frequency energy feed, value of $Z_S$ at 50 Hz, should be very much smaller than the ohmic value of $Z_L$.

Figure 2(b) depicts how an additional series non-linear resistance can come into play in safeguarding the load. For the frequency components of the surge, $|Z_{\text{block}}|$ should be very much higher than $|Z_L|$. Figure 2(c) shows how a non-linear shunt device can help reduce the impact of transient surge on the load, by $Z_{\text{shunt}}$ becoming very small value due to the effect of the transient on the inserted non-linear device.

Figure 3 shows a typical case of a traditional surge protector designed to cater for both differential mode and common mode surges, where the simple concepts discussed in relation to Figure 2 are applied, using metal oxide varistors (MOV), bidirectional break-over diodes (BBD) and L-C filters combined. The MOVs and BBDS, when fired due to high transient surge voltage, they show very low shunt impedance, as depicted in Figure 2(c). Series path inductors act as high impedances at frequencies associated with the surge pulse in the order of microsecond duration, based on $2\pi f L$, where $f$ represents the harmonic frequencies of the surge transient waveform. Shunt capacitances similarly act to show low shunt impedances at harmonic frequencies of the surge based on $1/2\pi f C$. A detailed explanation is available.

**Surge Protection Standards and Practices**

In most countries, the equipment connected to power lines has to be certified by nationally accredited testing laboratories. Most of these national standards are based on the international standards of the International Electrotechnical Commission (IEC). In North America the international standards of the IEC are not valid; instead, standards by
the American National Standards Institute (ANSI) and the Institution of Electrical and Electronic Engineers (IEEE) are used, together with the safety standards developed by Underwriters Laboratories Inc. These standards cover the areas such as SPD specifications for different locations, SPD test procedures, and test waveforms. Table 1 lists some of these institutions and their standards in relation to SPDs [1], [3].

**Locations and Categories**

When a transient propagates through power lines, data lines, or other branched circuits, its energy gets dissipated in several ways. While wire resistance, flashovers, and SPDs in the surge path dissipate part of the energy, the branch circuits divide the energy to smaller quantities depending on the branch impedances and transfer these into individual branches. Due to this fact, facilities are divided into different location categories and specific protection levels are defined based on locations. Figure 4 shows IEEE C62.41 and UL 1449 defined standard location [4]–[6]. The standards classify surge protector types based on the potential impact of the transient surge, and location.

As we see from Figure 4, categories A to C are based on how far the protected equipment is from the power line entry area of the building. It shows that the closest area to power line entry point is category C and furthest areas are defined under category A. More details, and how IEEE C 62 series standard categories relate to UL 1449 types are summarised in [1].

**Surge Test Waveforms**

The IEC 61000-4-5 standard specifies a combination wave consisting of two waveforms, which are shown in Figure 5. The 1.2/50 μs open-circuit voltage waveform and the 8/20 μs short-circuit current waveform are shown in Figure 5(a) and 5(b) respectively. These impulse waveforms are defined by their rise times and half-amplitude duration. For example, an 8/20 μs impulse current would have an 8 μs rise time from 10% of the peak current to 90% of the peak current. The 20 μs decay time is measured between half amplitude points.

Commercially available lightning surge simulators could generate these standard live

**Table 1. Test Agencies and Their Recommended Standards for Surge Protection.**

<table>
<thead>
<tr>
<th>Standard Agency</th>
<th>SPD-Related Standards</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC</td>
<td>IEC 61000-4-5</td>
<td>Provide a model to simulate surges and then to be able to check if the equipment is able to survive them. General rules for Product standards Selection and application guide.</td>
</tr>
<tr>
<td>IEC</td>
<td>IEC 60364</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>IEC</td>
<td>IEC 61643-11</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>IEC</td>
<td>IEC 61643-12n</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>UL</td>
<td>UL 1449</td>
<td>Devoted to surge protection manufacturers, defines the parameters as well as the test procedure to qualify an SPD.</td>
</tr>
<tr>
<td>UL</td>
<td>UL 1449 3rd Ed</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>ANSI/IEEE</td>
<td>IEEE C62.41.1</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>ANSI/IEEE</td>
<td>IEEE C62.41.2</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>ANSI/IEEE</td>
<td>IEEE C62.45</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>ANSI/IEEE</td>
<td>IEEE C62.62</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
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<tr>
<td>ANSI/IEEE</td>
<td>IEEE C62.72</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
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<tr>
<td>NEC</td>
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<tr>
<td>NEC</td>
<td>Article 285</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
<tr>
<td>NEMA</td>
<td>LS1 Low-voltage surge protective devices</td>
<td>PRIMARY CONCERN IS SAFETY.</td>
</tr>
</tbody>
</table>

waveforms, where peak value of the voltage or the current is adjustable as required.

Mathematical representation of these waveforms are available in relevant standards, and Table 2 provides the details of standard test waveforms used in different location categories. Effect of external transients in ‘A’ location is negligible due to the protection provided by the inductance of the building wiring.

Category B location is exposed to both internally created and lightning created transients and hence both ring wave and combination wave test parameters are defined. Category C has the highest exposure for lightning and utility switching transients. Combination waveform with high current and voltage, 3–10 kA and 6–20 kV waveform parameters are specified for category C locations.

![Diagram](image)

**FIG 4** Locations and categories of surge protectors in a building and associated standards.
Supercapacitors Capability to Absorb Transient Surges

Authors have set up a high voltage transient test laboratory with several transient surge simulators and tested several commercial families of supercapacitors to confirm that the devices themselves can withstand transient surges with peak voltages up to several kilovolts and the results are presented in [7]. This section provides an overview of the theoretical foundations related to these encouraging test results which led to the development of the supercapacitor assisted surge absorber (SCASA) technique [8], [9], which culminated multiple international patents.

Supercapacitors can be simply summarised as a device family where you could achieve over one million times larger capacitance for the same canister size as electrolytic or film capacitors. New commercial devices come in three different variations, namely (i) symmetrical electrical double layer capacitors (ii) hybrid devices where one electrode is similar to electrodes used in Li rechargeable batteries, and (iii) pseudo-capacitance based [9]. These commercial single cell devices are in the range of 1 F to over 70,000 F and in the SCASA technique, symmetrical double layer capacitances in the range of 1 to 100 F are used, given their very low cost [10].

Given the very large capacitance of a SC, and most types with a very low ESR in the order of 1 mΩ to over 100 mΩ, a SC in a practical circuit creates a large time constant circuit. For example, a 1 µF electrolytic capacitor in a resistive circuit with a total loop resistance of 1 Ω creates a circuit with a time constant of 1 µs. If this RC circuit is fed by a dc voltage source after about 5 µs it will reach the dc supply's voltage. This means that if the dc rail is a step voltage source of over 5 µs duration, the capacitor could reach its maximum voltage, while storing 0.5 CV² Joules. If the capacitor was starting with a zero charge, the resistive parts of the loop will dissipate the same amount of energy.

However, if the electrolytic capacitor is replaced by a SC of 1 F, the circuit will take over 5 seconds to charge the capacitor fully, if the dc source is steady. Now if the SC based RC circuit is fed by a step dc source lasting only 5 µs, capacitor charge will be pretty low, and the energy stored in the SC will be also very low. During this time the loop resistance wastes the energy based on the squared value instantaneous loop current and the total loop resistance. The energy stored in capacitor during the step voltage will be every much lower than the energy dissipated in the cumulative resistance of the loop.

Based on the above qualitative explanation, we can analyse the case of an RC circuit based on a SC subjected to a high voltage transient of limited duration. Figure 6(a) depicts this case with a capacitor of value C, and its ESR of value R and the total parasitic loop resistance of Rp. If a step dc voltage of duration of T is given as v_in, applying Kirchhoff's voltage law to Figure 6(a),
\[ v_{in} = iR + iR_p + \frac{1}{C} \int_0^t i \, dt \quad (1) \]

\[ i(t; 0 < t < T) = \frac{V_{max}}{R^2} e^{-t/CR} \quad (2) \]

\[ v_c(t; 0 < t < T) = V_{max} (1 - e^{-t/CR}) \quad (3) \]

where, \( R_T = R + R_p \) and \( V_{max} \) is the pulse voltage as depicted in Fig 6(b).

Assuming that the capacitor is initially fully discharged, energy dissipated in the capacitor ESR, \( E_R \), is given by,

\[ E_R = \int_0^T i^2 R \, dt = \frac{CR}{2R^2} V_{max}^2 (1 - e^{-2TCR}) \quad (5) \]

At time \( T \), the capacitor has accumulated an energy, \( E_C \), of

\[ E_C = \frac{1}{2} CV_c^2 \quad (6) \]

Where \( V_c = V_{max} (1 - e^{-t/CR}) \).

Figure 6(c) shows the development of current in the loop and voltage across the capacitor for a case of pulse duration of 50 µs, and a maximum current from a transient surge source of 3000 A (such as a lightning surge simulator, discussed later). Figure 7 depicts the effect of above analysis in Equations (1) to (5) when the surge is equivalent to a 6 kV step dc source of duration 50 µs. While the lower right hand side of Figure 7 shows the cases of three different SCs of values 1 F, 5 F and 100 F, upper left hand side of the Figure shows the cases with the supercapacitors replaced by 100 µF, 470 µF and 1500 µF.

What Figure 7 shows in summary is the case that supercapacitors in an RC loop fed by a HV transient pulse does not damage or destroy SCs, compared to an electrolytic capacitor set of similar can size (and price), since the SCs do not charge beyond their rated dc voltage. More details are available in [1], [10]. As Figure 7 indicates, while supercapacitors maintain the voltage within their dc ratings, in electrolytic capacitors, they get charged up to several 1000 volts.

In Figure 8 we see a different, but a more useful interpretation of this concept. In a real world situation, charging loop will have the capacitor which offers a farads order supercapacitor, with a finite, but small ESR (larger the SC smaller the ESR) together with its parasitic loop resistance, where theory related to the Figure 7 still applies. Under this situation, energy dissipated in the SC loop is of importance, since it can create heat within the device (due to the effect of the ESR), and push the capacitor beyond its safe temp range. It can be shown that [12] energy dissipated in ESR of the SC as a ratio of energy absorbed by the SC is given by,

\[ \frac{E_R}{E_C} = \frac{1}{2} \left( \frac{CR}{R^2} \right) \frac{V_{max}^2}{(1 - e^{-2TCR})^2} \]

\[ = \frac{R}{R^2} \left( 1 + e^{-2TCR} \right) \left( 1 - e^{-2TCR} \right) \quad (7) \]
These mathematical relationships in summary indicates the case of a supercapacitor’s capability to dissipate short-term surge energy in path resistances and/or ESR of the device, compared to an electrolytic capacitor of a similar can size. Based on the same theory, Figure 9 depicts what happens to the voltage across the capacitor, with repeated surges applied from a lightning surge simulator such as Noiseken LSS 6230. It is important to note that the vertical axis is in the units of millivolts, and hence do not tend to exceed the rated dc voltage of the device.

In summary this discussion provides the background to use a SC based sub-circuit to develop a more effective SPD.

Problems with Supercapacitors as Shunt Devices
Referring to Figure 3, in a surge protector application, critical load is safeguarded by the action of shunt devices such as the MOVs and the BBDs. Given these conditions of the MOV/BBD are kept in parallel to the ac utility mains line, they should have a voltage rating that under nominal line voltage and its worst case (RMS voltage) variation, they do not fire into conduction, and they can withstand the instantaneous line voltage.

Compared to this essential requirement, since supercapacitors have very low voltage dc ratings in the range of 2 to 4 V (for single cell cases), they cannot directly replace MOVs or BBDs in a surge protector. Also, at 50 or 60 Hz of power line frequency, if you place a SC between live and the neutral of the ac mains, it will show a very small shunting impedance determined by $1/2\pi fC$ which will in turn create an effective short circuit across the line and the neutral. For example, 1 F SC will show an impedance of approximately 3.1 mΩ at 50 Hz. However, a 1 µF film capacitor, will show a shunt impedance of 3.1 kΩ. This simply argues about the difficulty of using a SC based shunt sub-circuit to absorb transient surge voltages superimposed on the power line.

Supercapacitor Assisted Surge Absorber Concept
Power electronics research group at the University of Waikato, launched a PhD thesis completed by the first author [10]–[14], based on the preliminary investigations which lead to the first patent [8]. As per detailed research published in [12]–[16], a uniquely new circuit topology as per Figure 10(d) was successfully developed by the team at Waikato. This was based on a step by step analysis of Figures 10(a) to 10(c). Following paragraphs provide a summary of the applicable theoretical concepts, and the associated design and development process.

Based on the summaries provided in the above sections (Supercapacitors’ Capability to Absorb Transient Surges and Problems with Supercapacitors as Shunt Devices), while a SC and a resistor based circuit can be used to dissipate transient energies associated with high voltage transients superimposed on the power line, the low voltage dc rating and the extra-low ac impedance...
(at line frequency) is a major issue to replace a MOV or BBD directly. Another useful information is the joules order energy absorption capability of the SCs based on 0.5 CV^2. For example, a 5 F SC with a dc rating of 2.7 V could safely-store 18.2 Joules. A 100 F SC with same dc voltage rating could store 364 Joules. A typical class A/B type SPD is expected to handle few joules to over 100 J surge energy, based on a combination wave or a current waveform generated by a lightning surge simulator.

As per Figure 10(a), a simple inductor and a MOV type surge absorber can be combined to provide protection against transient surge voltages of microsecond durations. When the transient surge voltage exceeds the firing voltage of the surge absorber (MOV or the BBD) parallel to the protected load, a current is induced in the input loop, and inductor develops a voltage of \( L \frac{di}{dt} \) maintaining the following relationship,

\[
V_{in} = V_{var} + L \frac{di}{dt}
\]

where \( V_{in} \) is the instantaneous input voltage due to superimposed surge, and \( V_{var} \) is the instantaneous voltage across the MOV which will be the same as the instantaneous voltage at the load. Under normal 50 or 60 Hz only line voltage, MOV is under off condition and with a very small inductor, load will see the rms ac voltage approximately. Once the MOV enters into conduction, until the transient surge disappears, \( V_{var} \) will be approximately equal to the clamping voltage of the MOV.

Figure 10(b) depicts how we could extend this into a coupled inductor wound on a suitable magnetic core, to perform the function of a loosely coupled transformer where primary winding is in series with the MOV and the secondary winding in series with the protected load, while input ends of both windings are connected to the input ac mains. This two winding loosely coupled magnetic component (with coupling coefficient \( k = 0.74 \)) is purposely selected so that it creates a high leakage inductance to attenuate the surge voltage. By the inductor placement and the polarity arrangement of the coupled inductor, it is possible to:

- Trigger the coupled inductor to carry a primary current when the varistor (MOV) fires at the event of transient voltage superimposed at the input power line.
- Reduce the load voltage (transient related) during the high voltage transient surge
- Store part of the transient surge energy in the inductive elements of the coupled inductor (where self and magnetizing inductances of the non-ideal transformer comes into play)

To analyze the coupled inductor circuit, assume the perfect coupling to describe the transformer turns ratio, which allows the desired operation. SC is connected between the load side ends of the two coils so that it helps creating a closed loop via the SC for absorbing part of the surge energy. Input side end of the two coils are connected together and the common point is attached to the live wire of the input power source. Common point of the SC and the secondary

**FIG 10** Conceptual development of the SCASA protector (a) a series inductor with a high voltage clamping device (b) use of a coupled inductor instead of the case in part (a) (c) a SC based sub-circuit to form a closed loop with the primary and the secondary windings (d) commercially produced version with two MOVs and one low-cost SC.
coil terminal forms the output node, which is connected to the critical load.

From varistor current, $i_{\text{var}}$ and load current branches in Figure 10(b).

$$v_{\text{in}} = v_{\text{var}} + v_p = v_s + v_{\text{load}} \quad (9)$$

If the transformer has $n_p$ primary turns and $n_s$ secondary turns, turns ratio, $n = n_s/n_p$, then $v_s = n v_p$. Hence the load voltage can be expressed as:

$$v_{\text{load}} = v_{\text{var}} + v_p - n v_p = v_{\text{var}} - (n - 1)v_p \quad (10)$$

Because the design should lower the voltage seen by the load to a voltage less than the varistor clamping voltage.

$$v_{\text{load}} < v_{\text{var}} \Rightarrow (n - 1)v_p > 0 \quad (11)$$

Because $v_p > 0$ for a positive transient,

$$n - 1 > 0 \Rightarrow n > 1 \quad (12)$$

To provide a complete analysis with design calculations leading to a testable prototype of the SCASA is beyond the scope of this paper. These details are available in [1, 12-16]. A summary useful for a designer is given below, based on the preliminary prototypes build and the first commercial product developed which will be discussed later.

i) The coupled inductor’s secondary should work as a step-up winding to lower the transient related voltage appearing at the load.

ii) Technique provides the unique advantage of transient related load voltage will be less than the varistor’s clamping voltage.

iii) There is a limit to increasing the turns ratio, to prevent transient load voltage reaching a negative value.

iv) Coupled inductor’s windings should not create any excessive series inductance into the load loop at the 50 Hz line frequency.

v) Supercapacitor sub-circuit shown in Figure 10(c) assists the dissipation of the surge energy by forming a closed loop due to SC path, without any unwanted ringing waveforms related to the transient surge energy.

For readers to gain more insight into this technique in terms of theoretical concepts, Ref [10] is suggested.

**Selection of Supercapacitor and the Magnetic Core**

To achieve a practically useful SPD based on the SCASA technique, correctly selecting the supercapacitor and the core for the coupled inductor are the most important key design decisions. At the early development stage of the technique, research team considered using a film capacitor in the order of tens of nano-Farads, instead of a SC. This was to justify the value of using a small supercapacitor, to assist the absorption and dissipation of the transient surge energy, so that SPD’s ability to survive without major degradation of the MOVs, when subjected to repeated surges under UL 1449-3rd Edition tests.

Figure 11 depicts the case where the SC is replaced by a similar can size 47 nF capacitor. Figure 11(a) shows the experimental results and Figure 11(b) depicts the simulation results. In both cases, it can be observed that the voltage across the load creates a ringing effect with an approximate frequency around 120 to 125 kHz.

Figure 12 shows the transient performance of the actual SCASA circuit based on a 1 F SC and a resistor subjected to C62.41 standard based surges, where peak voltages at 1 kV and 6.6 kV were supplied from a lightning surge simulator. In both experimental and simulated results, it can be observed that the transient related load voltage does not create any ringing effects, as in the case of using film capacitors in the sub-circuit.

This discussion indicates clearly that the supercapacitor assisted new topology helps in the surge absorption, based on a coupled inductor approach at the input end. In developing this new topology, the coupled inductor acts as a loosely coupled transformer, when the MOV enters into conducting stage. Design of this coupled inductor was based on a permeance (inductance per square turns) based approach, as detailed in [10], [16]–[19]. Without a detailed discussion, at the first stage of research and development, the research team had a concluding result that powdered alloys work effectively in the SCASA design while ferrite cores were not effective. Due to high permeability/permeance of ferrites (Figure 13), they cannot be used in their original form for SCASA design. But, in the gapped form (single-gapped or double-gapped), ferrites perform satisfactorily. More

**FIG 11** Effect of sub-circuit capacitor on load voltage during the surge (a) experimental results for 47 nF capacitor (b) simulation results for 47 nF capacitor.
FIG 12 Experimental and simulation results for different surge voltage inputs on a SCASA prototype (a) Actual oscillogram for a 1 kV surge (b) simulated results for a 1 kV surge (c) Actual oscillogram for a 6.6 kV surge (d) simulated results for a 6.6 kV surge.

FIG 13 Comparison of magnetic properties of different powdered-iron and ferrite based alloys used in SCASA prototype design.
investigations about air-gapped ferrites and other suitable magnetic materials are found in [20].

In summary, out of various commercially available magnetic materials, the optimum range of core permeability was found to lie within $\mu_r = 26 - 60$, and the wound magnetic component should be such that the magnetic coupling coefficient lies within $0.56 < k < 0.74$. Moreover, as X Flux toroid shows ~60% better saturation flux capacity (16,000 gauss) compared Kool $\mu_u$ (10,500 gauss) as illustrated by Figure 13, functional limitations of SCASA circuit at high-magnitude surge currents can be prevented. Since a detailed discussion about the magnetic component selection of SCASA is beyond the scope of this paper, we highlight essential properties of various magnetic materials used for prototype design in Figure 13.

Development of a Commercial Prototype, and testing under UL 1449 Standard-3rd Edition

SCASA technique is a unique new way to design a high endurance capability SPD, using a supercapacitor sub-circuit to improve its ability to withstand repeated surges, with minimal or no degradation to its components. In a typical MOV dominated traditional surge protector, with repeated transient surges absorbed by the internal components such as the MOVs, the effective performance degrades over time. UL 1449 3rd Edition specifies the requirements of a commercial SPD, subjected to repeated surges, and the respective abilities of internal components of a SPD to survive without any disastrous failures. SCASA technique summarised in Section on “Supercapacitor Assisted Surge Absorber Concept”, and its design calculations summarised in [1], [12] led to the design of a commercial version, as shown in Figure 14.

Product shown in Figure 14(a) is aimed at protecting indoor appliances such as LCD TVs, computers and high-fidelity systems and therefore it is designed to safeguard against differential mode transients. As shown in Figure 14(b), the overall circuit carries two MOVs, one powdered alloy based coupled inductor and a supercapacitor-resistor based sub-circuit. For readers interested in the design calculations, Ref [10] is recommended. A powdered core from Magnetics, USA with a relative permeability of 60 and a permeance value of around 81 nH/Turns$^2$ was used, since most ferrites with large relative permeability were not useful [16]. While maintaining the confidentiality of commercial details, the overall implementation achieved the following essentials required in a commercial SPD adhering to the UL 1449 3rd Ed.

- Showing very low series impedance at 50/60 Hz to allow power flow to the load side
- At the occurrence of a transient, first MOV (Var 1) in Fig 14(b) fires and creates a activation of the coupled inductor to develop a secondary voltage opposing the imposed surge voltage
- SC sub-circuit absorbs part of the transient surge energy due to the closed loop formed by the two windings creating opposite voltages, where the difference creates a loop current via the SC sub-circuit attempting the charge the SC, while dissipating part of the surge energy in the cumulative resistance of the inductive loop.
- Energy of the transient surge is shared among (i) Var1, loop inductances, and the supercapacitor sub-circuit. Stored energies in the SC and the inductive elements are dissipated with some delays.
- In case the remaining (transient related) output voltage is over the firing point of the Var2, it fires and reduces the impact on the critical load protected by the SPD.
- Over 100 repetitions of 6 kV, 3 kA surges were applied as per UL 1449 guidelines and no deterioration of the components were observed.

<table>
<thead>
<tr>
<th>Component Type</th>
<th>High End</th>
<th>Low End</th>
<th>SCASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOVs</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Inductors</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>X-type capacitors</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
The most unique property is the transient related peak appearing at the load is always less than the MOV’s clamping voltage.

Table 3 provides a comparison of number of components for differential mode section in two commercial version (sold in New Zealand) and the number of components in the SCASA based commercial product. This clearly shows, that SCASA uses much lower number of components, than a high-end commercial SPD.

Table 4 depicts another key performance related characteristic of SCASA technique. By the introduction of the coupled inductor into the SCASA technique, with a SC based sub-circuit, it increases the lifetime of the varistors used inside the circuit significantly. Table 4 compares the cases of failures of MOVs used as Varistor 1 and Varistor 2 [Figure 14(b)] and the required number of repeated surges to destroy them. For 6 kV surges both versions (when individually tested) failed even before 40 repeats, whereas overall SCASA system could withstand much above 100 repeated surges, without any degradation of the components.

Appendix B1 in Ref [1] is a summary of commercial test report on Smart TVIQ2 product subjected to UL 1449 3rd Edition recommendation. It also gives an overview of how to interpret test data created by the test procedure, utilizing a commercial lightning surge simulator (LSS) of the type Noiseken LSS 6230 and Tektronix TPS 2014 oscilloscope.

Figure 15 depicts the measured performance of the SCASA implementation, where Figure 15(a) compares its performance with two common commercial products and Figure 15(b) depicts the unique property of load seeing a lower transient related peak voltage than the clamping voltage of the varistors used.

### Ongoing Developments

SCASA’s commercial success has led us to develop the basic technique further to absorb high transient joules and also to have significant surge-repeat-endurance. One area where significant ongoing research is in the selection of magnetic cores including the gapped ferrite cores of high relative permeability, with lower costs than powdered alloys. The other area will be the advanced versions of SCASA topology based on complex core combinations. References [17], [18] provide our early results, in ongoing Ph.D projects.

### Conclusion

Supercapacitor assisted surge absorber (SCASA) technique is a new technique useful for surge protectors where a SC based sub-circuit is effectively combined with traditional surge absorber devices such as MOVs. This work proves the capability of SC based long time constants in surge absorbers, as a unique new family of surge protectors adhering to UL 1449 3rd Ed standard. A unique property of the SCASA technique is to achieve a lower transient related peak voltage at the load, compared to the Varistor’s clamping voltage in a commonly used SPD techniques. With repeated surge applications, as per UL 1449, the MOVs in SCASA protectors do not deteriorate with the applied number of surges. Proper selection of a magnetic core is key requirement for the successful implementation in a commercial SPD.
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Sadeeshvara Silva Thotabaddurage holds a Ph.D in electronic engineering from the University of Waikato, New Zealand (2021) and a B.Sc. (Hons. -1st class) from University of Sri Jayewardenepura, Sri Lanka (2014). Soon after his doctoral study, he joined Electric Power Engineering Centre, University of Canterbury, New Zealand as a research engineer. He acts as a reviewer for IEEE Transactions on Industrial Electronics, IET Power Electronics and for IEEE conferences such as APEC, IECON, and TENCON. He is also a Member of Engineering NZ, IEEE and IET. He is passionate in research on power quality & surge protection, supercapacitor applications, transformer theory & design, frequency domain modelling and magnets.

References

Smart low-voltage distribution system (LVDS) is an essential component in realizing smart electricity grids. In countries like India and other energy-deprived regions of the world, researchers are looking for a holistic approach to integrate millions of small Renewable-powered homes in the LVDS and make the system smart. Restructuring the existing distribution system to form clusters of microgrids is an important step in achieving a smart LVDS. The realization of microgrids in LVDS can take different shapes in different countries depending on the structure of the distribution grid. This article envisions a possible approach to implement microgrids in a smart LVDS with radial distribution.

The article proposes that radial LVDS following a distribution transformer can be converted into a three-phase ac microgrid. Thus, segregating the existing LVDS into a smart LVDS with as many microgrids as the number of distribution transformers. However, this approach leads to many issues so far as microgrid operation is concerned. To address these issues, this article envisions replacing the low-voltage distribution transformers with solid-state transformers (SSTs). It will enable the LVDS to control the power exchange between the phases within a microgrid as well as power exchange between different microgrids. This approach will also support smart homes and their interactions within a microgrid. Various existing microgrid related grid codes are also reviewed to complete the discussion.
**Traditional LVDS**

Electric power has been traditionally generated in generating stations far away from load centers. The transmission network takes care of transporting this power from generating stations to high voltage substations, and the distribution network is responsible for distributing it to the end-users. The distribution system is further divided into primary and low-voltage (secondary) distribution systems (LVDS). The primary distribution system is easy to analyze as it electrically resembles with the transmission system and is mostly a balanced network. However, the LVDS networks are usually unbalanced and predominantly resistive in nature, with a high R/X ratio. The LVDS architecture varies depending on its geographical location. For example, the LVDS is mesh-structured in urban North America, as shown in Figure 1(a). It offers redundancy to loads and is referred to as ‘Secondary Networks.’ The architecture of the LVDS is typically radial in most distribution systems, as shown in Figure 1(b). The LV side of the distribution transformer supplies household single-phase loads connected between a phase and the neutral.

For the realization of a smart-grid, it is imperative that the existing LVDS is made smart instead of restructuring the complete LVDS. Successful integration of a smart LVDS to the overall power grid will demand voltage control, frequency stability, reverse power flow, and protection system coordination. Different protection aspects associated with the deployment of distributed energy resources (DERs) and microgrids on secondary networks are discussed in the literature. The primary protection challenges arise due to the bidirectional power flow caused by the DERs and limited fault current due to inverter-interfaced generators.

The smart LVDSs in most of the places, especially in developing countries, are relatively unplanned and unregulated. To add to this complexity, a considerable proportion of solar photovoltaic (PV) installations are consumer driven causing the power injection to the grid at different nodes unsymmetrical. The second issue faced by the present secondary distribution network is that the distribution transformers (11 kV/415 V) are not able to directly control the voltage and power. This limits the operation of the existing LVDS as supervisory control can’t be implemented.

**Definition of A Microgrid**

According to the US Department of Energy (DoE), a group of sources and loads can be considered a ‘microgrid’ if they satisfy the following four conditions.

- A clearly defined electrical boundary.
- It includes a controller to control the DERs and loads to behave as a single controllable entity.
- The installed generation capacity is greater than the peak critical load.
- An active switch to connect and disconnect it from the distribution network to shift between the grid-connected and islanded mode.

A typical microgrid is shown in Figure 2. Now the question is, how to make the existing secondary distribution grid smart by incorporating microgrids into it? Due to the diverse nature of the LVDS, a standard development template cannot be applied everywhere. The distribution system can be segmented to form a set of independent-interconnected microgrids with different energy resources, energy storage capacities, load requirements, and network configurations. The potential of the DERs can be better utilized by taking a system approach and amalgamating them to form microgrids. This approach also enables extensive research in the field of microgrids to be used directly.
in making the LVDS smart. The microgrid controller controls the operation of the microgrid, and the balance between generation and demand is met from or supplied to the electricity grid.

A Microgrid in Existing LVDS
As shown in Figure 3 (a), the network after the distribution transformer can be defined as a microgrid. This approach limits the operation of the system as a microgrid in the following ways.

1) **Control Switch:** The distribution transformer cannot be operated as a controlled switch to toggle between grid-connected and islanded mode (Figure 3 (a)).

2) **Reverse Power Flow:** Traditional transformers are rarely used to carry reverse power without modification in associated protection circuit nor to regulate the power flow. Due to this limitation, power cannot be transferred from one microgrid to another in a controlled manner.

   A tie line converters or interlinking converters can be used as a bypass link to enable power transfer between two microgrids, as shown in Figure 3(a). The tie-line converter approach is equivalent to interconnecting two ac microgrids. However, it is not an optimal solution for connecting many microgrids as the required number of tie-line converters will be exceedingly high.

3) **Interphase Power Transfer:** Renewable power-sharing is possible between the houses connected to the same phase (Figure 3 (b)) but not between different phases (Figure 3 (c)). This is due to the presence of a grounded neutral conductor.

4) **Voltage Control:** Due to the intermittent nature of generation from the PV system, the voltage of the distribution grid can vary significantly in high PV integration scenarios. A traditional transformer may use an on-load tap changer (OLTC) to control voltage. However, they are slow and affect the life of the transformer.

Microgrids using SST
A SST can be a possible candidate to eliminate the limitations imposed by the traditional transformers. SST is an ac-to-ac converter with high-frequency galvanic isolation having a smaller size and weight. The basic structure of an SST module is shown in Figure 4. It is being explored for next-generation locomotive and intra-microgrid power flow interface. SST can be utilized as a smart grid building block due to its modularity and controllability property.

The special properties of SST can be exploited to replace the existing distribution transformers, as shown in Figure 5. This will have several advantages as given below:
1) Controlled power exchange between microgrids through the SST as reverse power flow is possible.
2) High degree of controllability of voltages, currents, power flows.
3) Power transfer between the phases within a microgrid is possible as the SST has a dc interface.
4) SST has a much faster response compared to a transformer and can be controlled to limit fault current and for fault isolation. This leads to a robust smart LVDS.
5) The ability of SSTs to control power flow can be used to implement energy budgeting between microgrids during disasters and extreme events.

The SST can also facilitate ancillary grid services such as reactive power support, harmonic mitigation, sag mitigation and short-circuit protection, and dc connectivity. However, the development of SST technology is limited due to the unavailability of switching devices in the voltage range of 13 kV. Issues such as implementation, control, protection, reliability, and isolation are still to be addressed. SST is an evolving technology and its cost as well as operational comparison to a commercially available power transformer is a valid concern. Over the years, SST has seen significant augmentations in features, operation, and efficiency. For example, an SST from GE is reported to have 99.2% peak efficiency at 60 kW power level [11]. With gradual innovation and technological advancements, the cost of SST will go down and performance will be better. Some other challenges of SST in LVDS will include protection co-ordination with existing relays.

**SST: A Smart Homes Enabler**

To enable the smart home compatible with demand side management (DMS), some non-essential loads can be interfaced to the grid using solid-state relays (SSRs). This will allow independent control of these loads by a central microgrid controller, which also dictates the operation of SST. However, critical and essential loads can still be interfaced to the LVDS/microgrid using miniature circuit breakers (MCBs) or fuses. Figure 6 shows a smart home architecture supplied from an SST which enables these features. Renewable power can support critical loads. Apart from supplying home loads, the power electronics in the smart home will be responsible for power exchange within the microgrid, energy arbitrage, and reactive power support. Instead of connecting the home directly to the power lines, a power electronic router such as PINE can be employed [12]. The power electronic

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**FIG 4** Basic block diagram of a solid-state transformer.

**FIG 5** SST as building blocks to make the existing LVDS smart.

**FIG 6** Architecture of smart homes in SST interfaced smart LVDS.
router in the smart homes will be responsible for powering the home loads, power exchange within the microgrid, energy arbitrage, and reactive power support. Inclusion of commercial storage system (e.g., Tesla powerwall) or EV with V2G capability adds a new dimension to the microgrid operation. Several recent research work have discussed the microgrid operation with distributed storage and its challenges [13].

### Standards and Grid Codes

Few popular standards related to the operation and control of microgrids are listed in Table I. These standards discuss functional specifications, protection configurations, and testing procedures relevant to the microgrid deployments in LVDS.

#### Conclusions

A vision to convert the existing radial LVDS to a smart LVDS is presented in this paper. As LVDS is heterogeneous, consumer driven, and unbalanced in nature, specifically in the developing countries, incorporating distributed generation will require carefully defining energy islands or microgrids. The article proposes that the network supplied by a distribution transformer can be demarcated as a three-phase ac microgrid. The LV distribution transformer can be replaced by an SST to enable power exchange between different phases of the microgrid and with other microgrids. The realization of a smart home in smart LVDS is also discussed. Using this reconfiguration, a smart home allows an un-interrupted supply of essential loads and smart interaction of non-essential loads to a central microgrid controller using DMS. A review of various grid codes and standards for microgrids is also summarized.

### Acknowledgement

This work is supported by the Indo-US Science and Technology Forum in partnership with Department of Science and Technology, Government of India, under grant no. IUSSTF/JCERDC-Smart Grids and Energy Storage/2017. The authors will like to thank Prof. S. S. Venkata and Prof. Sukumar Brahma for their valuable suggestions to improve this work.

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**Table I. Popular Standards Related to Operation and Control of Microgrids.**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Title</th>
<th>Description</th>
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<tbody>
<tr>
<td>IEEE 2030.5-2018</td>
<td>IEEE Standard for Smart Energy Profile Application Protocol</td>
<td>Providing functions to enable utility management of end-user energy environments, including demand response, load control, time-of-day pricing, management of distributed generation, electric vehicles, etc.</td>
</tr>
<tr>
<td>IEEE 2030.7-2017</td>
<td>Standard for the Specification of Microgrid Controllers</td>
<td>Provides all the functional specifications for microgrid energy management system (MEMS) regardless of topology, configuration, or jurisdiction.</td>
</tr>
<tr>
<td>IEEE 2030.8-2018, (Under development)</td>
<td>Standard for the Testing of Microgrid Controllers</td>
<td>To develop a set of testing procedures allowing the verification, quantification, and a comparison of the performance with expected minimum requirements of the different functions of the microgrid controllers.</td>
</tr>
<tr>
<td>IEEE P2030.11, (Under development)</td>
<td>Distributed Energy Resources Management Systems Functional Specification</td>
<td>Functional specifications for DER management systems will be important factors in designing and deploying protection for DERs and microgrids.</td>
</tr>
<tr>
<td>IEEE P2030.12, (Under development)</td>
<td>Draft Guide for the Design of Microgrid Protection System</td>
<td>Will facilitate the deployment of protection systems through different approaches to detect problems and protect microgrids. The standard will address protection configuration and challenges, protection system structures, modes of operation, system coordination, requirements for microgrid energy management, and communication system structures.</td>
</tr>
<tr>
<td>UL 1741</td>
<td>Standard for Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resource</td>
<td>These requirements cover inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for use in stand-alone or grid-connected power systems. Provides specifications for characteristics that can impact interconnection operations and safety. Supplement-A: Grid support—Utility interactive equipment Supplement-B: Compatibility with IEEE 1547.1</td>
</tr>
<tr>
<td>UL 3001 (Under development)</td>
<td>Safety Standard for Distributed Energy and Storage Systems</td>
<td>Product safety standard for DERs and storage systems. Will provide insight into the characteristics of DER and microgrid functionalities that facilitate protection.</td>
</tr>
<tr>
<td>Indian Electricity Grid Code</td>
<td>IEGC lays down the rules, guidelines, and standards to be followed by various persons and participants in the system to plan, develop, maintain, and operate the power system, in the most secure, reliable, economic, and efficient manner.</td>
<td></td>
</tr>
</tbody>
</table>
degrees in electrical engineering from the Indian Institute of Technology Kanpur, India in 2016 and 2021, respectively. His research interests include design and control of power converters, topology synthesis, energy harvesting, power electronics for advanced grid functionality, and integration of photovoltaics in secondary distribution network.

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**References**


For the last two years, the IEEE Applied Power Electronics Conference and Exposition (APEC) was organized in a virtual format due to the COVID-19 pandemic. This year, the leading international conference was delivered in a hybrid format in Houston, Texas, 20–24 March at the George R. Brown Convention Center. Because some overseas and domestic participants in our community, including domestic, were unable to physically attend due to travel restrictions and other COVID-related concerns, the organizers made a decision to provide select recorded conference content (Plenary, Technical, and Industry Sessions) in an on-demand format for a period of time (March 28–April 29) after the conference ended in Houston on 24 March.

As usual, APEC2022 was co-sponsored by the IEEE Power Electronics Society (PELS), Industry Applications Society (IAS), and Power Sources Manufacturers Association (PSMA). This year’s industry partners included Mentech, Power Integrations, Mouser Electronics, STMicroelectronics, West Coast Magnetics, Wolfspeed, Transphorm and Texas Instruments Inc. The organizers took the necessary steps to assure safe

Distinguished Plenary Speakers Chart
Future Technology Path for APEC 2022

Researchers unveil advances in bidirectional wide bandgap FETs
and healthy conference environment for some 3,004 attendees representing 38 countries.

While the Industry Sessions presented new ideas on current topics ranging from magnetics to wide bandgap bidirectional switches and applications, as well as market and technology trends, the Technical Sessions offered peer-reviewed papers in all areas of technical interest for the practicing power electronics professionals. On the exhibit floor, some 198 vendors displayed the latest in passive components, semiconductor devices, test & measurement tools, including simulation, and system level solutions.

APEC 2022 general chair was Dr. Omer C. Onar of Oak Ridge National Laboratory, Tennessee, USA, and plenary session chair was Dr. Stephanie Watts Butler, president of WattsButler LLC, Texas, USA. Dr. Pradeep Shenoy, manager in Power Design Services at Texas Instruments, Dallas, TX, USA, was the conference program chair. Tim McDonald, senior consulting advisor, CoolGaN Program, Infineon Technologies, was assistant program chair and also co-chair of the plenary session.

**Distinguished Plenary Speakers**

Continuing its long-standing tradition of addressing issues of immediate and long-term interest to the practicing power electronics engineers, APEC 2022 invited seven distinguished professionals from industry and academia to predict the course of technology in the coming years. Also, per recent tradition, IEEE TV broadcasted the plenary live and a recording of each presentation can be found at https://ieeetv.ieee.org/event/apec-2022. The distinguished speakers at APEC 2022 were:

- **Alexander Gerfer**, CTO, Würth Elektronik eiSos Group, Waldenburg, Germany
- **Prof. Jelena Popovic**, IEEE Empower a Billion Lives (EBL) II Vice-Chair and Associate Professor at the University of Twente, The Netherlands
- **Prof. Liuchen Chang**, IEEE Power Electronics Society (PELS) President and Professor Emeritus, University of New Brunswick, Fredericton, Canada
- **Dr. Gideon (Don) van Zyl**, Technical Fellow, Advanced Energy, Denver, CO
- **Dr. Ritu Sodhi**, PSMA Roadmap Committee, and Consultant, Power Transistor R&D ROHM Semiconductor, Santa Clara, CA, USA
- **Prof. Deepakr (Deepak) Divan**, Professor, John E Pippin Chair, GRA Eminent Scholar, and Director, GT Center for Distributed Energy, ECE, Georgia Institute of Technology, Atlanta, GA, USA

Welcoming the power electronics nerds, Dr. Shenoy kicked off the plenary session on Monday 21 March, 2022 with a focus on powering space and enabling power on earth while looking at powering new frontiers. In keeping with the theme of the conference, he invited the first speaker Alexander Gerfer, CTO at Würth Elektronik eiSos Group, to talk about the huge magnetics universe and the challenges confronting the technology. In his talk “Space M: The Magnetics Universe & Challenges,” Gerfer presented new and emerging design tools for magnetics, while highlighting the importance of increased co-operation between research institutes, manufacturers and consultants to overcome existing design barriers. Gerfer’s talk suggested that AI and 3D printing are making inroads into the magnetics world to enable designers to build low loss and volume optimized magnetic components.

“On the Moon to Stay: Challenges Presented to Power Electronics Technology by Sustained Operations on the Lunar Surface” was the topic of the second speaker John H. Scott, the principal technologist for power and energy storage in the Space Technology Mission Directorate at NASA Headquarters in Washington, D.C. Besides returning humans to the moon for the first time since the 1970s, NASA’s Artemis program will also provide the technological basis for infrastructure that will enable permanent and expanding scientific and industrial exploitation of the lunar surface, said the keynote speaker. While the primary aim of this infrastructure is to generate and distribute power to a diverse and growing range of scientific and industrial assets, the keys to success for this function are power management and control circuits that are highly reliable and maintainable for a decade of operation in the extreme thermal, radiation, and dust environment of the lunar surface. While various combinations of wide bandgap semiconductors, electronic devices, circuit topologies, and shielding schemes have been successfully developed for mission environments ranging from low Earth orbit to the Jovian system, power management technology has not been optimized to meet the full combination of mission requirements for the lunar surface. To accomplish this, NASA is looking for dedicated support and collaboration with the power electronics industry, added Scott. With the efforts underway, concluded Scott, NASA scientists are aiming to bring to TRL 6 by 2030 a suite of power management, control, and regulation circuits and software operating at up to 1000 V and at maximum specific power, which are maintainable in the lunar dust environment and 0.99 reliable for 10 years in the relevant lunar radiation and thermal environments and in the lunar hard vacuum and Mars atmospheric environments.

“Energy Access: Challenges, Opportunities, and our Contributions” was the third topic of the session that was jointly presented by Prof. Jelena Popovic, associate professor with the University of Twente, The Netherlands and vice chair of IEEE EBL II and Prof. Liuchen Chang, IEEE PELS president and professor Emeritus with the University of New Brunswick, Fredericton, Canada. While decentralized approaches, such as solar home systems and minigrids have emerged in response to the shortcomings of centralized grid extension, which are increasingly being integrated in national electrification plans, there are still many challenges to overcome, stated Prof. Popovic. These include affordability, scalability, quality, interoperability, business models, technology obsolescence
and lifecycle sustainability. Prof. Chang highlighted PELS flagship initiatives, such as the IEEE Empower a Billion Lives (EBL), a recurring global competition aimed at fostering innovation to develop technically, economically, and socially viable energy access solutions and IEEE Global Energy Access Forum, a platform to facilitate multistakeholder engagement in discussions on how rapid technology developments, forward leaning policies and new financing mechanisms intersect and can accelerate the development and deployment of scalable solutions for energy access.

Dr. Gideon (Don) van Zyl, Technical Fellow at Advanced Energy Industries, presented the fourth talk on “Driving Plasma: Advancing Power Conversion in Critical Semi and Medical Applications.” His talk indicated that plasma processing is well known in semiconductor wafer manufacturing and for creating highly engineered coatings in advanced industrial applications. Plus, he added, “The ability to precisely power and drive plasma loads has also enabled electrosurgical applications.” For the power electronics engineer, Dr. van Zyl said that plasma loads present unique challenges, including wide swings in load impedance, the highly nonlinear and time-varying nature of the load, arcing, and the difficulty in precisely measuring and controlling power delivery. While highlighting the challenges of power delivery and control with varying plasma loads, Dr. van Zyl’s talk showed how advances in power electronics devices, such as SiC and GaN, circuits, and measurement and control are enabling advanced plasma processing.

Next, Dr. Ritu Sodhi, PSMA Roadmap Committee executive and a consultant with ROHM Semiconductor’s Power Transistor R&D Group, presented the history of PSMA Power Technology Roadmap (PTR), starting from 1994 to the present time. In her talk “History of PSMA Power Technology Roadmap: from AAA TripTik to Google Maps,” she walked down memory lane and tracked the evolution of the PSMA PTR— from a single, in-person, roundtable event in the early years to a multidimensional, multimedia, multiyear activity to track key trends across a broad variety of power conversion markets. In her concluding remarks, Dr. Sodhi said that the power electronics community should come together to help PSMA chart the next 30 years of the industry!

The final talk “Inverters for the Future Grid—Challenges and Opportunities” was given by Prof. Deepakraj (Deepak) Divan, John E Pippin chair, GRA eminent scholar, and director of GT Center for Distributed Energy, ECE, Georgia Institute of Technology, GA, USA. In his presentation, Prof. Divan highlighted the increasing role of power electronics in the grid. With the wide spread proliferation of solar PV, wind and storage in the utility eco-system, his talk indicated that over the next five to ten years, millions of geo-dispersed inverters will replace the traditional rotating synchronous generators that form today's grid. As a result, he added, “These inverters will have to work together collectively and autonomously to also form and sustain the grid as an ecosystem and will have to do so without causing stability issues or interacting with each other or with other grid elements.” This will require new hardware, software and control principles (Figure 1), stated Prof. Divan. Investigating the future grid, his talk suggested that at the current rate of progress, the industry move towards multiport power converters that are flexible, modular and scalable, and which can simultaneously and safely interface with solar PV, batteries, generators and loads, managing power flows between various sources/loads and ensuring stable operation under normal, transient and fault conditions. In his concluding remarks, Prof. Divan said that fast-moving technologies, lagging standards, diverse communications protocols, cybersecurity issues, hundreds of inverter vendors, and hundreds of grid codes to comply with, will pose many challenges, but they must be addressed soon. However, he was optimistic that the next generation inverter for the future grid can be a key factor in addressing climate change and saving the only planet that we have.

**Bidirectional FETs**

In the professional education seminars and industry sessions, several researchers unveiled advances in monolithic bidirectional switches with SiC and GaN FETs (BDS or BiDFETs), also known as four-quadrant switches. Dr. Subhashish Bhattacharya of FREEDM Systems Center, PowerAmerica Institute, North Carolina State University, delivered a paper titled “Monolithic SiC-based Bidirectional FET: Vehicle Electrification Opportunities.” In his presentation given in session IS09, Dr. Bhattacharya focused on the four

![FIG 1 Coordinated control of millions of inverters on the grid is challenging.](image-url)
quadrant switch: SiC BiDFET (Figure 2), characterization of SiC BiDFET, applications of BiDFET for vehicle electrification, and experimental results of SiC BiDFET enabled grid-connected PV converter. This paper indicated that the SiC BiDFET was a monolithic device (1200 V, 20 A) that offered lower conduction voltage drop and higher switching frequency for CSI and direct ac-ac matrix or cyclo converter based power conversion systems. A 2.1 kW, 1-phase grid connected converter prototype enabled by 1200 V, 20 A SiC BiDFET was discussed in this paper.

In a joint paper (#S09) titled “Wide-Bandgap Bidirectional Switches and Their Impact on Future AC Power Converters and Applications,” researchers from NCSU, ETH Zurich, and WEMPEC University of Wisconsin-Madison, presented WBG based technology of monolithic bidirectional (M-BD) switches and the performance improvement they bring to matrix converters and CSIs, including CSI based integrated motor drives (see “The Incredible Shrinking Motor Drive” by Thomas M. Jahns and Bulent Sarlioglu, IEEE Power Electronics Magazine, September 2020, p.18). Similarly, Transphorm is also developing a 600 V GaN based four-quadrant M-BD switch. Preliminary details were presented in a paper titled “GaN Four Quadrant Switches: Ready for Prime Time?”. This paper was presented in the Industry Session (ISS02.3) by Dr. Rakesh Lal, Technical Fellow and principal scientist at Transphorm.

GaN FETs and Technologies

Soon after the plenary session, the exposition was officially opened to attendees, and about 198 companies demonstrated their cutting-edge products and technologies for a wide range of applications over the next two days. Wide bandgap (WBG) devices dominated the show and it was evident that both gallium nitride (GaN) and silicon carbide (SiC) based power transistors were making rapid progress in terms of adoption in mainstream applications. Although, consumer electronics, datacenters, automotive, industrial, medical and renewable energy applications were initial targets for WBG devices, space is the next frontier for them.

In the wide bandgap arena, several new entrants demonstrated their respective capabilities in GaN technologies. U.K. based fabless semiconductor company Cambridge GaN Devices Ltd (CGD) was one of them to launch the 650 V ICEGaN HEMTs with the ability to operate like a MOSFET. As a partner in the European GaNext project, consisting of 13 companies, it will be supplying its 650 V GaN devices to create an intelligent power module (IPM) comprising the controller, driver and protection circuits, all co-packaged with the power GaN devices. (Figure 3)

According to CGD, the first GaNext IPM is assembled and ready for testing and encapsulation. It contains the half-bridge power stage with ICEGaN 650 V HEMTs and employs individual heat spreaders on top of the transistors to improve power dissipation. Also, the GaN transistors are driven by Infineon’s silicon-on-insulator (SOI) gate drivers at high switching frequencies, while the controller is RISC-V from Fraunhofer.

Likewise, Tagore Technology demonstrated several reference designs using its 650 V GaN HEMT with integrated driver. They include 65 W active clamp flyback (ACF) ac-dc converter, 65 W quasi-resonant flyback (QRF) ac-dc converter, and 240 W totem-pole PFC (TPFC) + LLC ac-dc converter.

Unlike others using lateral structure, NexGen Power systems is betting on vertical technology. Utilizing its patented vertical GaN-on-GaN technology, the company has developed a 1200 V GaN HEMT with robust avalanche capability and >10 µs short-circuit protection rating. In addition, based on its vertical GaN FET, it has also crafted a power platform for developing power systems for a variety of applications. Called Merlin Power Engine, it incorporates novel power management algorithm, including software controllable proprietary controller, advanced magnets and thermal management. The platform allows vertical GaN devices to switch at frequencies over 1 MHz. Utilizing its vertical GaN FET, NexGen Power Systems demonstrated a 240 W gaming power supply with unprecedented power density and efficiency.

Another GaN supplier readying 1200 V FETs is Transphorm. The manufacturer claims that the 1200 V GaN device delivers greater than 99% efficiency and performs well against a leading SiC MOSFET of similar on-resistance. Partially funded by the ARPA-E CIRCUITS program, the company is developing the technology for EV mobility and infrastructure power systems as well as industrial and renewable energy systems. The initial 1200 V GaN device in a TO-247 package offers an $R_{DS(on)}$ of 70 mΩ and easily scales to lower resistance and higher power levels, said the supplier. Transphorm said the 1200 V GaN FET will be sampled in 2023, and will be in direct competition with SiC MOSFETs.
Similarly, GaN Systems displayed several GaN-based chargers from leading and innovative brands such as Samsung, Philips, Harman, and Greenworks. Additionally, in collaboration with Rompower, the company demonstrated compact 65 W and 100 W GaN chargers, which the company claimed to be the world’s smallest GaN chargers for smartphones, laptops, and other consumer devices. “Supporting Rompower’s achievements in size and performance is GaN technology, which is quickly replacing traditional silicon transistors used in legacy chargers and adapters,” stated Jim Witham, GaN Systems CEO.

Silanna Semiconductor and Smarter Living collaborated to display world’s smallest in-wall 65 W GaN charger. Measuring just 42 × 42 × 30-mm, the new 3510PDFE charger is built around Silanna’s SZ1131 ACF controller and is the first in a series of small form factor wall sockets that Smarter Living will be providing for global markets.

Ultrafast charging is also the forte at Efficient Power Conversion Corp. (EPC), who announced the availability of the EPC9171, a 90 – 265 V universal ac input to 15–48 V dc output power supply. Designed for USB-PD3.1 ultra-fast chargers, this reference design can deliver 240 W maximum output power and features that provide an extremely flexible and easy to use chip and helps to design a highly efficient offline power supply circuits. The GNE10xxTB series is offered in a highly versatile package featuring superior heat dissipation and large current capability, facilitating handling during the mounting process.

Entering the medium-voltage arena was ROHM Semiconductor. ROHM has developed 150 V GaN devices with rated 8 V gate voltage. As a result, according to ROHM, degradation is prevented, even if overshoot voltages exceeding 6 V occurs during switching—contributing to improved design margin and higher reliability in power supply circuits. The GNE10xxTB series is offered in a highly versatile package featuring superior heat dissipation and large current capability, facilitating handling during the mounting process.

Employing its 650 V GaN HEMT, STMicroelectronics introduced a high voltage converter, labeled VIPerGaN50. Designed for medium power quasi-resonant ZVS flyback converters, it is, capable of providing an output power of up to 50 W in wide range. It integrates a complete set of features that provide an extremely flexible and easy to use chip and helps to design a highly efficient offline power supply. VIPerGaN50 comes in a compact and low-cost 5-mm × 6-mm package. The speed of the integrated GaN transistor allows a high switching frequency with a small and lightweight flyback transformer. Minimal additional external components are needed to design an advanced, high-efficiency SMPS supply.

Speaking of fast and ultra-fast chargers, Navitas Semiconductor continues to strengthen its hold on the mobile phones and consumer markets. With more than 40 million units shipped, 174 billion hours in the field and zero reported GaN-related field failures, plus 5.8 billion equivalent device hours testing, Navitas is now able to offer a 20-year warranty for GaNFast power ICs. “As we describe in our sustainability

![FIG 4 Fully assembled demonstration board for EPC9171.](image)
report, each GaN IC saves 4 kg of CO₂. So, the faster customers can adopt GaN, the better it will be for our environment. GaN could save up to 2.6 Gtons CO₂ per year by 2050, stated Anthony Schiro, Navitas’ VP Quality and Sustainability."

The unprecedented 20-year limited warranty is founded on Navitas’ holistic approach to product reliability through design, testing, characterization and certification. As the pioneer in GaN power ICs and a founding member of the industry’s JEDEC JC-70.1 GaN standards committee, Navitas developed proprietary high-speed production and qualification testing to set new standards in GaN reliability.

Lastly, Texas Instruments demonstrated high power density 800 V, 11-kW three-level, three-phase, GaN-based active neutral-point clamped inverter using its 600-V LMG3422R030 GaN FET and C2000 real-time MCU, which enables high switching frequency to reduce magnetics size, increase power density, and achieve 98.5% peak efficiency in EV charging and solar-power applications, according to TI. This converter was designed for EV powertrain components, such as onboard chargers (OBCs), which are facing the formidable challenge of increasing power rating without a proportionate increase in size and volume. Consequently, TI’s OBCs offer power ratings of 6.6 kW through 11 kW with power densities of 4 kW/liter while adding new features such as bidirectional operation and support for 800 V batteries.

**Expanding SiC Portfolio**

On the silicon carbide (SiC) front, Microchip Technology Inc. announced the expansion of its SiC portfolio with the release of the industry’s lowest on-resistance (25 mΩ) 3.3 kV SiC MOSFETs and 3.3 kV, 90 A rated SiC Schottky barrier diodes (SBDs). The designers can take advantage of the ruggedness, reliability and performance of these devices to develop smaller, lighter and more efficient power systems for electrified transportation, renewable energy, aerospace and industrial applications, said the maker. The 3.3 kV MOSFETs and SBDs join the company’s comprehensive portfolio of 700 V, 1200 V and 1700 V die, discretes, modules and digital gate drivers.

Both MOSFETs and SBDs are available in die or package form. In a statement, Leon Gross, vice president of Microchip’s discrete product business unit said, “Our new family of 3.3 kV SiC power products allows customers to move to high-voltage SiC with ease, speed and confidence and benefit from the many advantages of this exciting technology over silicon-based designs.”

Concurrently, ROHM Semiconductor displayed its fourth generation 1200 V SiC MOSFET for Lucid, an advanced luxury electric vehicle (EV) company headquartered in California. This OBC unit is designed for Lucid Air. It integrates a dc-dc converter and the bidirectional OBC, where an advanced PFC circuit is capable of operating at high switching frequencies because of the high performance of the SiC MOSFET, said ROHM. The improved performance at high frequency and high temperature of ROHM’s SCT3040K and SCT3080K SiC MOSFETs have helped Lucid to reduce the size of the design, and to reduce power losses, which results in high charging efficiency.

Meanwhile, GeneSiC Semiconductor disclosed its fourth generation 750 V SiC MOSFET with further drop in on-state resistance at operating temperatures and excellent performance in short circuit withstand capability and avalanche ruggedness. The fourth generation 750 V SiC MOSFET is also automotive qualified.

**Advanced Silicon Solutions**

Concurrently, silicon vendors were also busy exhibiting their technologies and products that offered leading-edge solutions. Eggtronic, for instance, demonstrated a number of technologies aimed at improving the performance and efficiency of power conversion and wireless power transfer. The company showed how ZVS can be combined with a proprietary controller to create a novel architecture (Figure 5) that replaces the conventional boost PFC input stage and LLC stage with a single-stage converter capable of controlling both input current and output voltage. Known as SmartEgg and designed for applications in the 100 W to 1 kW range, the new high-performance solution offers the promise of reduced energy consumption and smaller form factors in applications ranging from adapters and chargers for high-performance laptops to power adapters for PCs, home appliances and TV panels.

In addition, Eggtronic also demonstrated its capacitive wireless power technology called Eden, which ensures total positional freedom for wireless charging. Thanks to the proprietary Eden capacitive wireless matrix, this incredible feature has been made a reality by Eggtronic.

Empower Semiconductor, Inc. displayed what it claims to be the industry’s smallest and fastest integrated voltage regulator (IVR), integrating all the necessary elements in a single device. In essence, it is a multioutput dc-dc voltage regulator system that requires no external components on the PCB. According to Empower, IVRs are high-performance power management chips designed to provide efficiency, size, and cost benefits to energy-hungry, data-intensive, electronics applications. Joining the family was a new digitally configurable EPT1xx series that can deliver complete voltage regulation and protection functionality without the need for external discrete components (Figure 6). Rated for 12 A of continuous current with up to four voltage regulators in a single FcCSP package that measures just 5-mm × 7-mm and only 0.7-mm in height! Other features include
ultra-fast transient response, express DVS-on-demand with up to 6 mV/ns capability. According to the manufacturer, this feature is more than 1000x faster than other competing technologies and enables rapid, lossless, processor state changes that can significantly reduce processor power.

In addition, the company also revealed its innovative silicon-based alternative to conventional capacitors. Providing the most compact and flexible capacitor solution, Empower E-CAP is a high-performance, configurable silicon-based alternative to multi-layer ceramic capacitors (MLCCs). E-CAP devices offer a capacitance density that is over five times that of leading MLCCs with improved equivalent series inductance (ESL) and equivalent series resistance (ESR) characteristics that dramatically reduce parasitics.

Power supply in package (PSiP) was also the focus of Murata’s 48 Vin charge pump step-down dc-dc converter that boasted a power density of 5.4 kW/in³. Capable of delivering 72 W with peak efficiency of around 97%, the interleaved switching capacitor architecture employs Murata’s unique lossless charge pump technology.

Other exhibitors demonstrating their respective capabilities in power electronics include Analog Devices, Infineon Technologies, Power Integrations (PI), Pre-Switch, Halo Microelectronics, and Menlo Microsystems amongst others.

In a press conference, PI’s Doug Bailey, vice president of marketing, introduced an advanced quasi-resonant PFC controller IC with integrated 750 V PowiGaN switch (HiperPFS-5), and an off-line LLC switcher IC chipset HiperLCS-2. Designed for high-power USB-PD adapters, TVs, game consoles, all-in-one computers and appliances, the HiperPFS-5 ICs can deliver up to 240 W without a heat sink and can achieve a power factor of better than 0.98. According to the PI executive, “by pairing HiperPFS-5 ICs with our new HiperLCS-2 chipset, designers can easily beat even the most aggressive efficiency regulations while cutting the bill of materials by half and achieving extremely attractive form factors for ultra-fast chargers.

Similarly, Pre-Switch demonstrated a 200 kW inverter reference design using its proprietary AI based soft switching controller, capable of delivering 99.5% (peak) efficiency for industrial applications while simultaneously reducing size and weight.

Conclusions
Taking all the adversities into account, APEC 2022 organizers and vendors did a great job in creating a successful in-person event with online service for those who could not physically attend. From tutorials to technical and industry sessions, as well as display of latest products and technologies on the exhibit floor, the conference provided a stimulating environment that offered five days of excitement. Next year, hope to see you all at APEC 2023 in Orange County Convention Center, Orlando, FL, USA, 19–23 March, 2023.

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“PELS embraces the imperative to encourage and assure the diversity and inclusion in our membership, volunteers, local and AdCom leadership. We shall respect each other’s needs and values with honesty and transparency.” ~ First Core Value of the PELS 2021-2025 Strategic Plan [1].

As we discussed in the last issue, IEEE Power Electronics Society (PELS) is undergoing a significant shift to encourage stronger support from our members during their professional career [2]. In the last few years, the general awareness of the importance of diversity has increased, but how has diversity, equity, and inclusion (DEI) permeated throughout IEEE PELS specifically? In what ways are we doing well, and where do we see gaps that still need to be addressed? Do we see any improvements or further gaps compared to the DEI analysis one year ago [3]?

The IEEE PELS Women in Engineering (WiE) committee is committed to annually reporting on the status of our society’s gender diversity statistics to enable our membership to understand one of the many diversity statistics, which helps to shape our society. This annual report is meant to be an informative call to action, enabling all members to understand how to support their female-identifying colleagues and to be active change agents able to support a more overall diverse technical society. Additionally, IEEE PELS has also created a new strategic initiative to form a DEI Committee to ensure that the society’s policies and procedures integrate best practices to support all of the various diversity identities which make our society unique [2].

Before diving into the statistics, it is essential to note that diversity is a multi-faceted concept which includes gender, region, affiliation, race, ethnicity, and cultural identity—among other diversity identities. Women in the field of electrical engineering have historically been an underrepresented group, and IEEE has tracked gender statistics over many years making it a readily available diversity identity to track over time. Hence, this article focuses on the representation of female-identifying members as an indicator of diversity within IEEE and PELS. In the future, IEEE PELS hopes to create a sustainable demographic reporting infrastructure to be able to track other diversity identities as well.

The goal of analyzing these gender statistics is to shine a light on the representation and recognition of women in PELS, to identify areas with strong representation and those that still need improvement. Specifically, we are examining the representation of women for membership, positions of leadership, awards, Fellow elevation, and distinguished lecturers within PELS. This is a follow-up article to the first gender statistics review, which was published last year [3].

Representation of Women in IEEE PELS—Membership

Data on the number of women in IEEE has been collected since 1998, but data on gender statistics within each society was only available starting in 2010 [2]. Gender statistics within IEEE are self-reported within each member’s profile with options of male, female, other, and prefer not to answer. Within this article, the term women will be used for members who self-identify as female within their IEEE membership profile. The historical data of women in IEEE, PELS, Industry Applications Society (IAS), Power and Energy Society (PES) and Electron Devices Society (EDS) from 2000 to the present are shown in Figure 1.

Over the last 20 years, the percentage of women in IEEE has generally increased. However, the rate of change is staggeringly slow. Women members in PELS has historically been below the IEEE percentage of women. Although, the gap has begun to close in the past few years, women’s representation in PELS membership (11.8%) is still 3% points below that of IEEE (14.8%). To put this representation
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data into perspective, it means that for a woman in a room full of 10 PELS members, the probability of being the only woman is still very likely. Nevertheless, the increase in PELS and IEEE representation of women in the last 5 years is promising for further growth, but still lags behind sister societies Industry Applications Society (IAS) and Power & Energy Society (PES).

The continued efforts of IEEE and PELS to improve DEI will be a key factor in the slope of these trends. While the data in Figure 1 gives a sense of the overall membership, we need to dive deeper into the data to understand where the growth is actually occurring.

Next, we analyze the distribution of women per membership level by year. This analysis was not performed a year ago and provides some new insightful information. The membership levels are Fellow, Senior Member, Member, Graduate Student Member, and Student Member (non-graduate students, primarily undergraduate students). Within PELS, the number of women in each of these membership grades is shown in Figure 2(a), starting from 2010. As of 2021, the most significant number of women are undergraduate Student Members (54.5%), followed by regular members (23.4%), Graduate Student Members (11.4%), Senior Members (10.0%), and Fellows (0.7%). The percentage of women in each membership grade for PELS, starting from 2010, is shown in Figure 2(b).

The largest area of growth has been in undergraduate Student Members, which has steadily increased since 2015. After these undergraduate students graduate, we should expect the number of women graduate students and regular members to also increase proportionally over time. However, the trends of the graduate members and regular members have only increased very gradually. This indicates that undergraduate women are joining PELS, likely in student chapter groups where gender representation is more inclusive, but many are not continuing after graduation. The attrition of student members after graduation is a challenge that IEEE Societies face for all members (regardless of gender), but the problem is
particularly stark for women members. It is important to bridge the gap from student to graduate student or professional membership to ensure women members are included and gain value from being a PELS member.

Another important trend is the percentage women of Fellow and Senior Members over time. Although the number of women Senior Members has increased gradually over time, the percentage of women members that are Senior Members was 10% in 2010 and is still 10% in 2021. For Fellows, the trend declines, starting from 1.5% in 2010 and decreasing to 0.7% in 2021 [Figure 2(a)]. In terms of percentage of women, only 1.9% of Fellows in PELS were women in 2010 and, after some variation over the last decade, the percentage is still only 2.9% in 2021. This means that the many young women members joining PELS have few senior women role models within PELS and even fewer recognized at the highest level of Fellow. Recognizing the accomplishments of senior women in PELS through Fellow elevation continues to be an area of improvement for our society.

Representation of Women in IEEE PELS—Leadership & Recognition

Next, we examine the representation of women in PELS leadership positions. The percentage of women on the PELS Administrative Committee (AdCom, the governing body for PELS) since 2010 is shown in Figure 3, compared to the IEEE and PELS membership as a baseline. The PELS AdCom has consistently had representation of women at the same level as IEEE membership. In 2022, AdCom representation increased to 23%, with eight women out of 35 voting members. One reason for the increase is that four of the six incoming Members-at-Large...
The slate of candidates included 5 women and 7 men. MAL are elected by popular vote of the PELS membership. The jump in representation of women MAL is excellent for creating a diverse governing body and important for setting up women to continue on to senior leadership positions, including vice-president and president. That said, representation of women in AdCom alone is not enough to ensure women continue to senior leadership positions, as PELS has never had a female president or vice president. In this year’s election for vice president positions (Membership, Global Relations, and Standards), two women were on the slate of nine nominees, but none were elected.

While we undoubtedly want to see women in senior leadership positions, it is important that women 1) assume leadership positions that eventually lead to senior leadership positions and 2) are being recognized and advocated for by the current senior leadership and AdCom. Both of these factors have been improving, particularly in the last couple of years and we hope to see women in senior leadership positions soon.

The recognition of women members in PELS was previously identified as an area in need of improvement, particularly in Fellow elevations and awards [3]. Although elevation to Fellow is an IEEE-level recognition decided upon by the IEEE Fellow Committee, each nomination first goes through a society- or council-level evaluation. The number of members elevated to Fellow depends on the size of that specific society. For 2022, among the eight people elevated to Fellow through PELS, Dr. Maryam Saeedifard was recognized for her contributions to modulation, control and protection of multilevel converters for high-voltage DC transmission. Figure 4 shows the percentage of women Fellows elevated by PELS compared to all of IEEE (note that overall data for 2022 was not yet available at the time of publication). At least one woman being elevated per year would be a par with the representation of women in PELS membership, but this also means that more women need to be recognized for their contributions and consistently nominated for Fellow through the PELS Technical Committees.

As for awards, Figure 5 shows the percentage of women receiving PELS-sponsored awards since 2010. In 2021, Rose Abramson, graduate student at the University of California, Berkeley, USA, was awarded the IEEE Joseph John Suozzi INTELEC
Fellowship Award in Power Electronics. She was the only woman recipient out of 11 PELS awards (equivalent to 9.1%). While this is better than in 2020, when there were no women PELS award recipients, over the past 11 years there have only been five women recipients (equivalent to less than 1 every two years). Further, if we look at the specific awards received, two women have received the IEEE Joseph John Suozzi INTELEC Fellowship Award in Power Electronics and two women have received the Richard M. Bass Outstanding Young Power Electronics Engineer Award, which is focused on student and young professional members, respectively. The other PELS-sponsored award received by a woman was the IEEE Transportation Technologies Award in 2017, but the awardee’s field was not power electronics; this award is co-sponsored by multiple societies, including PES and IAS—both of which have a higher representation of women members (both at 16% in 2021) than PELS (12% in 2021).

The PELS Distinguished Lecturer (DL) program is another honor awarded to a number of accomplished individuals in power electronics each year. In 2020, a regional distinguished lecturer program was started to recognize accomplished individuals within local IEEE regions. The percentage of women DLs since 2017 is shown in Figure 6, compared to the membership baseline. Since 2020, the representation of women DLs has been at par with that of PELS membership, while the Regional Distinguished Lecturers (RDLs) have exceeded it by threefold. This increased recognition of women for their technical contributions is critical to paving the way for greater recognition in the future and proves strong engagement of female PELS members internationally.

Overall, the last year has shown increases in the representation of women in PELS membership, AdCom, Fellow elevations, PELS awards, and DLs. However, strong trends of diverse representation have not yet been established for PELS Fellow elevation (Figure 4) and PELS awards (Figure 5), which are two areas of future improvement. As evidenced by the significant recognition of female RDLs, there is a strong population of female members active in technical activities; awareness of the gap in recognition for their achievements in all forums is a call to action for all members of our society to help improve the overall diversity of PELS. The breakdown of women PELS members by grade (Figure 2) also shines a light on the problem of decreasing representation of women at higher membership grades and increased loss of undergraduate female students transitioning to...
professional grade levels. Efforts to ensure equal recognition across diversity identities, including gender, may help reduce this attrition rate moving forward. PELS is committed to diversity and inclusion at multiple levels of the society. We will continue to track the resulting progress in the coming years.

**How to Be a Part of the Solution & Get More Involved**

Although, diversity and inclusion are systemic challenges facing our field, inclusion is often felt at a personal level. One individual—of any gender—can make a positive impact to support underrepresented groups. Here are a few suggestions on how to be part of the solution and get involved. These points focus on women, but the same applies to individuals of any underrepresented group:

- **Learn** about the specific challenges women face in their professional careers and ways to be an ally by utilizing the resources available from past PELS WiE events [5].
- **Volunteer** and become involved with the PELS WiE Committee by emailing us at pelswie@ieee.org.
- **Invite** women colleagues to join you in a PELS Technical Committee or other PELS activities.
- **Advocate** for recognition of female colleagues, including nominating them for awards or Fellow elevation, by learning of their work and accomplishments.

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**References**


GaN power semiconductor devices have been the recent focus of intense development efforts due to the promising material properties of GaN for next-generation power electronics applications. For power switching and rectifying applications, the ruggedness in breakdown is a critical requirement as addition of snubber circuits reduce the performance and efficiency of the system. Lateral GaN high-electron mobility transistors (HEMTs) have been commercialized up to 900 V class recently, but they lack avalanche capabilities. Vertical GaN transistors demonstrate several advantages over lateral GaN HEMT: 1) higher breakdown voltage (BV) and current for a given chip area, 2) higher reliability, 3) easier thermal management, 4) avalanche capabilities, and 5) short-circuit robustness.

Among the various possible approaches to GaN based power electronics systems, vertical devices on GaN substrates offer the advantage of better area efficiency due to the ability to grow thick drift regions and improved reliability due to the reduced defect density. The devices demonstrate a non-destructive BV with positive temperature coefficient robust avalanche under the unclamped inductive switching conditions. Double pulse tests reveal significantly less than ~10 ns switching times and small turn-on/off switching losses. The body diode shows almost no reverse recovery. These results present a significant performance advancement in vertical GaN transistors.

An avalanche event in a semiconductor is a form of electric current multiplication that can allow very large currents within materials which are otherwise good insulators. When a power semiconductor device exceeds the breakdown voltage, the resulting electric field becomes strong enough to create additional carriers. In this case, free carriers collide with and dislodge carriers from the lattice. These newly dislodged carriers create new additional free carriers and an immediate increase in free carriers, resulting in avalanche breakdown. In other GaN technologies, like the GaN-on-Si HEMT, the leakage gradually increases through sub-surface conduction and, thus, avalanche behavior is not realized. This results in power system engineers having to put expensive clamping circuits to ensure the power semiconductor behaves appropriately under unexpected voltage fluctuations.

Unlike GaN-on-Si, the NexGen Vertical GaN (Figure 1) has a P-N junction and this enables the device to show both single and repeated cycle avalanche robustness. It allows reverse biased voltage to exceed the maximum breakdown voltage value for a specified energy and current limitations. This means that when faced with a situation where the system voltage exceeds the breakdown voltage of the device, the vertical GaN power semiconductor avalanche circuits don’t require external voltage clamping components. In-house tests have shown that the 1200 V rated Vertical GaN device can consistently avalanche at 1400 V [Figure 2(a)].

In typical power electronic systems, number of overload operational conditions must be considered to ensure the device and system/circuit robustness. Typically, these conditions are managed by system-level failure-detection and shut-down mechanisms to avoid destructions. Therefore, a crucial device withstand capability is required, to guarantee their intervention. A short circuit (SC) event can occur in a variety of ways in an industrial or automotive environment. This is especially true for all power electronic systems, where different kinds of protection circuits were proposed to avoid catastrophic failure during overload and SC events in the power stage. Therefore, in this scenario a device should be designed to have reasonable SC withstand time prior to the intervention of the protection circuitry. Nevertheless, this could not be achieved without an understanding of the
**Basic Function of a Switch**

- **Normay Off**
- **Current Flows From Drain to Source**
- **Gate Action Causes Switching**

**GaN-on-GaN Fabrication**

Grow GaN Drift Layer in Syracuse Fab on GaN Wafers

**3D Roadmap**

- **Increased Area for Higher Current**
- **Thicker Growth for Higher Voltage**
- **Uses All Three Dimensions to Create a Scalable Product Roadmap**

**FIG 1 Vertical GaN structure**
underlying physical mechanisms that bring the device to failure. The SC robustness is a very important feature of power transistors, strictly required by several applications (e.g., motor drives, power trains, inverters and more). The common minimum requirement is to withstand a short-circuit duration of 10-μs. During a SC the device must be capable of a high-power dissipation, that eventually leads to an excessive self-heating related failure. For transistors, the most commonly occurring extreme condition is the hard-switching short circuit when the device voltage is up to the circuit bus voltage.

A short circuit (SC) test is a widely used criteria for power device, and 10 μs is the usual minimal time that most over-voltage protection circuits can step in to protect (e.g., commercial gate driver for HV Si IBGT). Hence, it is desired that the power semiconductor device has the capability to withstand 10-μs SC under the same bus voltage for device switching. So far, no wide bandgap material has ever demonstrated this capability and the only semiconductor device is a silicon based IGBT that shows >10 μs SC. SiC is generally believed to be not able to meet this standard.

**FIG 2** (a) Avalanche robustness of vertical GaN devices.1 (b) Vertical GaN devices meeting >10 μs short-circuit2 capability.

**FIG 3** The NexGen scalable and software configurable power platform.
unless adopting special designs (which compromise the device performance under normal operation). All GaN commercial HEMTs cannot withstand $>10\mu s$ SC at a bus voltage higher than 300 V; this fundamentally limits their applications in EV powertrain applications (current 400 V bus voltage, future 800 V bus voltage). Only Vertical GaN has demonstrated $>10\mu s$ SC capability at voltages exceeding its breakdown voltage [Figure 2(b)].

To fully utilize this power device, NexGen has developed a power platform called Merlin Power Engine (Figure 3) that incorporates innovative power management algorithm, including software controllable proprietary controller, advanced magnetics and thermal management, allowing Vertical GaN to switch at frequencies above 1 MHz. This novel, scalable, software-configurable power platform can scale across different wattages to deliver power systems for a wide variety of applications, ranging from computing to datacenters and electric mobility.

**About the Author**

Dr. Dinesh Ramanathan co-founded NexGen Power Systems in 2017. Prior to co-founding NexGen, Dr. Ramanathan was the CEO of Avogy Inc. where he oversaw the development of vertical GaN technology. He also served as the executive vice president at Cypress Semiconductor for almost 9 years, where he managed the Programmable Systems Division and the Data Communications Division.

In addition, he held senior marketing and engineering positions at Raza Microelectronics, Raza Foundries, an incubating venture capital company and Forte Design Systems, an electronic design automation company. He started his engineering career at Synopsys, Inc. Dr. Ramanathan holds a Ph.D. and an M.S. in Information and Computer Science from the University of California, Irvine, USA. He also holds an M.S. in Mathematics and a B.E. in Computer Science from BITS, Pilani, India. He has been awarded two patents.

**References**


On 16 March 2022, the IEEE Power Electronics Society (PELS) Student Branch Chapter (SBC) at the New Horizon College of Engineering (NHCE) and IEEE PELS Bangalore Chapter in India organized a virtual Distinguished Lecture (DL) program with the topic “Long-horizon Finite Control Set Model Predictive Control (FCS-MPC): Theory, Implementation, and Applications.” The presentation was given by Dr. Tobias Geyer (ABB, Switzerland), who introduced FCS-MPC, which is very popular in academia, and showed how FCS-MPC performs well when adopting long prediction horizons (Figure 1). The event also helped to bring researchers and academic experts from reputed institutes in India together to exchange and share knowledge about recent developments and research challenges in model predictive control in power electronics. Over 140 participants attended this event, all who found the event informative and became more enthusiastic about the power electronics industry. The PELS SBC at NHCE would like to thank Dr. Geyer for his informative presentation.
On 30 March, the joint IEEE Power Electronics Society (PELS)/Industry Applications Society (IAS) Student Branch Chapter (SBC) at the University of Sheffield in the United Kingdom hosted a lecture entitled “The Critical Role of Power Electronics in the Delivery of Net Zero.” The lecture was delivered by Dr. Iain Mosley, a world-renowned technologist in power electronics who is also an alumnus of the University of Sheffield (Figure 1).

During his presentation, Dr. Mosley covered the fundamentals, critical elements, and tools of power electronics design, which includes power semiconductors, power topologies, magnetics design, digital electronics, control theory, and simulation. He simulated both a 15 W flyback converter and a GaN-controlled flyback converter using PLECS software and PSpice to illustrate the process of power electronics design and its practical implementation. Afterwards, he did a comparison of both in terms of computational efficiency and waveform visualization. Dr. Mosley emphasized the need to control the energy stored in the gap of the inductor to design and

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implement an effective power converter, which can only be facilitated with skills and knowledge of magnetics design. He recommended the use of Finite Element Method Magnetis free software to achieve this. To end his presentation, Dr. Mosley offered a tip to the audience: only by practicing and playing with simulations regularly would help one to develop a mastery in power electronics design.

The joint IEEE PELS/IAS SBC at the University of Sheffield would like to thank Dr. Mosley for his informative presentation that helped spark the interest of undergraduate students in power electronics.

by Yong Ding and Meiqin Mao

IEEE PELS SBC at HFUT Hosts Virtual Lectures in 2021

From September to December 2021, the IEEE Power Electronics Society (PELS) Student Branch Chapter (SBC) at Hefei University of Technology (HFUT) in China organized multiple virtual lectures with the support of the IEEE Distinguished Lecturers (DL) and the Regional Distinguished Lecturers (RDL) programs. The goal of these events was to provide members and other students an opportunity to access the latest developments and accomplishments in the power electronics field during the COVID-19 pandemic.

During the events, the presenters delivered lectures that covered multiple themes of power electronics, including motor control, EV charging technology, advanced converter control, microgrid control, and microgrid management. The SBC hosted three IEEE DLs (Prof. Udaya K. Madawala, Dr. Tobias Geyer, and Prof. Kai Sun), eight IEEE RDLs (Prof. Kan Akatsu, Dr. Noriko Kawakami, Prof. Rukmi Dutta, Prof. Xu Yang, Prof. Wuhua Li, Prof. Meiqin Mao, Prof. Jun-ichi Itoh, and Prof. Dong-Choon Lee), and one Chapter Chair (Prof. Dong Jiang, IEEE PELS Wuhan Section).

Over 2,400 individuals attended and participated in the event, ranging from PELS members to graduate students and faculty members. The IEEE PELS SBC at HFUT would like to thank all who presented for their presentations and are glad to have access to the IEEE DL and RDL programs to offer a high-quality academic exchange for its members and attendees.
IEEE PELS SBC at SJCE Host Multiple Events to Begin New Year

To begin 2022, the IEEE Power Electronics Society (PELS) Student Branch Chapter (SBC) at St. Joseph’s College of Engineering (SJCE) in India organized multiple events for its first quarter, including a mathematical quiz on 18 January and a live technical quiz on 24 March.

On 27 February, the PELS SBC at SJCE hosted a virtual gathering called “Bright Reds Bash” to develop bonds and connections with other SBCs in the area. The other SBCs included in this event were from the Knowledge Institute of Technology, Jeppiaar Engineering College, Panimalar Institute of Technology, and Saveetha Engineering College. This event sparked a discussion of future collaborations and members engaged with each other during a gaming session with three different games hosted on the Gathertown platform.

The PELS SBC at SJCE also hosted a technical webinar on 20 March. The event had Mr. Nikhil Mathew James (Danfoss, India) deliver a presentation with the topic “Introduction of AC Drives.” Mr. James explained working concepts of the power electronics and some basics of ac drives while also displaying MATLAB simulations.

Overall, the PELS SBC at SJCE is pleased with the results of its events and would like to thank all who made them a success.
From 13 to 25 March 2022, the non-governmental organization Committee on the Status of Women (NGO CSW66) conference was held at the United Nations headquarters in New York, NY, USA. During this time, the Women in Science of China Power Supply Society (WIS-CPSS) organized its own conference on 20 March 2022 with the theme “Promoting the Proportion of Women in Participating Scientific and Technological Activities in Developing Countries.” The virtual event was co-organized by the IEEE Power Electronics Society (PELS) Beijing Chapter and the Chinese Association of Women Scientists.

To begin the event, Xie Xin, the Secretary General of the Chinese Women Scientists Association, delivered an opening speech. Afterwards, six speakers from China, Denmark, Italy, Nigeria, and the United States shared their views and cognition on the theme of the event, which allowed the exchange of development status of female scientists in different countries. This conference helped to build exchange and cooperation bridges with colleagues both at home and abroad while also providing a platform for female scientists and technical workers to show their talents and offer suggestions. Over 150 participants attended the conference and the PELS Beijing Chapter would like to thank all who made this event successful.

In December 2021, the Joint IEEE Power Electronics Society (PELS)/Industry Applications Society (IAS) Chapter at the Federal University of Rio Grande do Norte (UFRN) in Brazil organized a webinar on the topic “Electric Power System: Changes, Challenges, and Opportunities.” The webinar contained two parts: a lecture from Prof. Dr. Thiago Rocha (UFRN, Brazil) and a roundtable with three electrical engineers, which was moderated by Chapter Chair Jose Raimundo. The panelists discussed their views on the power sector and the needs of the companies in the job market.

The virtual event had over 70 attendees, including undergraduate students, graduate students, and full-time engineers. Attendees enjoyed interacting with the electrical engineers during the roundtable and raised questions for the panelists to discuss. The Joint PELS/IAS Chapter at UFRN would like to thank all who made this webinar successful and is looking forward to holding more events like this in the future.
After a successful introduction of the IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE) in 2020, the Industry Applications Society (IAS)/Industrial Electronics Society (IES)/Power Electronics Society (PELS) Joint Kerala Chapter organized and hosted the second edition of PESGRE virtually from 2 to 5 January 2022. PESGRE focuses on the challenges, latest developments, and upcoming technologies in power electronic systems, electric drives, renewable energy resources, and smart-grid operation. Since this edition of PESGRE was virtual, the theme selected was “Power Electronics and Renewable Energy for Sustainable Development”.

PESGRE 2022 saw over 300 submissions from 20 countries that went through a review committee that had 36 technical program chairs and over 300 reviewers. Out of all the papers submitted, 176 papers were accepted and presented at the conference.

On 2 January 2022, Prof. Liuchen Chang (IEEE PELS President) presented an inaugural address to begin the event. Over the course of the conference, there were four tutorial sessions, four keynote lectures, one student forum, and 25 technical tracks. Some of the well-known experts who delivered presentations include Prof. Fei Gao (University of Technology of Belfort-Montbéliard, France), Dr. Uday Deshpande (D&V Electronics, Canada), Dr. Amitkumar KS (Opal-RT, Canada), Prof. Kaushik Basu (Indian Institute of Science, India),
Dr. Anirban Pal (University of Nottingham, UK), Prof. Sandeep Anand (Indian Institute of Technology, India), Prof. Kaushik Rajashekara (University of Houston, USA), Prof. Deepak Divan (Georgia Institute of Technology, USA), Prof. Joydeep Mitra (Michigan State University, USA), and Prof. HM Suryawanshi (National Institute of Technology, India).

All attendees enjoyed that the conference allowed for technical exchange among researchers from academia, research groups, and industries. The IAS/IES/PELS Joint Kerala Chapter would like to thank the IEEE IAS, IEEE IES, IEEE Kerala Section, IEEE PELS, and IEEE PES for sponsoring PESGRE 2022 and are looking forward to hosting the next edition.

by Harish Sarma Krishnamoorthy, Nayara Brandao de Freitas, and Joseph P. Kozak

PELS Students and Young Professionals—Marching Towards Normalcy!

From a world largely isolated by the COVID-19 pandemic, 2022 is turning out to be a year of hope with a slow, but steady, march towards normalcy. This has brought a widespread sense of optimism among IEEE members and volunteers, particularly those of the IEEE Power Electronics Society (PELS). We at the PELS Students and Young Professionals (SYP) committee are taking a flexible approach towards the future with a combination of in-person and virtual events for the benefit of the PELS members.
While we are back to conducting in-person SYP events and receptions, we are also continuing to offer virtual programs, considering that such online platforms help reach out to a diverse audience. In addition, as the IEEE PELS Day 2022 is soon approaching, we are planning a list of exciting celebrations and competitions that aim to bring our worldwide PELS members and volunteers together once again.

It was a great feeling coming back together at the 2022 IEEE Applied Power Electronics Conference and Exposition (APEC) in March in Houston, TX, USA. There was excitement in the air with the chance to meet and greet fellow colleagues and friends in-person after two long years. This was reflected even more at the PELS and IAS Young Professionals reception conducted in the evening of 22 March at ‘The Grotto’ restaurant adjacent to the convention center (Figure 1). The venue was packed with well above 100 attendees who had a great time networking over food and drinks. The event started with an address from Harish Krishnamoorthy, followed by the PELS President, Liuchen Chang. Representatives from IAS and PSMA also gave brief overview of their respective societies. Students and young professionals got a chance to informally interact with several experts from industry, national labs, and academia. Overall, the event was a great success. Stay tuned for the upcoming in-person SYP receptions at other major PELS-sponsored conferences as well–such as ITEC+EATS, ECCE-Europe (EPE), etc.

New volunteers were recently selected for the PELS SYP committee. The selected volunteers encompass a diverse group where four out of the 11 new volunteers are women. Additionally, three volunteers are located in India, three are in the United States, and one each in Algeria, Canada, Germany, Spain, and Sri Lanka (Figure 2). The SYP leadership will continue to prioritize the gender and geographic diversity of the team to provide a strong representation for our community.

One of the plans of SYP leadership is to reorganize and formalize the structure of the committee. Since March 2022, the SYP committee is organized into sub-teams. The Marketing & Communication sub-team deals with the SYP website and social media presence. The Webinars team leads the organization of webinars and similar initiatives. The Outreach team organizes the SYP reception, PELS Day celebrations and communications.

This year, the PELS SYP committee will coordinate the 2022 PELS Day festivities. It will include supporting local chapters in their own celebrations, as well as hosting a virtual program for a global
celebration with a variety of keynote speakers. Continuing the tradition from previous years, a global photo competition will be held with prizes for the chapter who celebrates PELS together. Additionally, since this is the 35th anniversary of PELS, a logo competition will be held before the PELS Day celebrations. The winning logo will be used for the special PELS Day celebrations in the following year.

About the Authors
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Joseph P. Kozak (jpkozak@vt.edu) is a senior electrical engineer at the Johns Hopkins Applied Physics Laboratory, in Laurel, Maryland, USA. He is the current vice-chair of the IEEE PELS SYP committee.

A
fter two years of virtual events, the 14th annual IEEE Energy Conversion Congress and Exposition (ECCE) 2022 is ready for in-person event in Detroit, Michigan. Cosponsored by the IEEE Power Electronics Society (PELS) and the IEEE Industrial Application Society (IAS), the flagship ECCE 2022 will be held from 9 to 13 October at the Huntington Place, the new name for Detroit’s world class convention center. “We are excited to meet again in person and catch up with our old friends and colleagues and meet new ones in Detroit in October,” said ECCE 2022 general chair Prof. Emmanuel Agamloh (Figure 1), an associate professor of electrical engineering at Baylor University, Waco, TX, USA. In a greeting message to the community, he wrote that ECCE 2022 will be designed to provide outstanding networking opportunities for both emerging and seasoned specialists in the field, as well as new entrants who are seeking to join this exciting field of energy conversion.

Promising to make this conference a highly engaging and memorable professional event, Prof. Agamloh is planning to deliver high quality peer-reviewed technical program with special panel sessions, tutorials, as well as

**Fourteenth Annual IEEE ECCE 2022 Comes to the Motor City**
plenary talks and an interactive exposition. Exhibitors at ECCE will showcase state-of-the-art technologies, products, and solutions, creating a highly interactive networking environment, mixed with technical poster sessions and student project demonstration competitions on the same floor.

According to the organizers, special sessions are solicited focusing on emerging technologies and industry-oriented topics. Industry and government organizers or speakers are of particular interest. Guest speakers will be invited on the day their session is scheduled. No written papers are required. Materials presented in the special sessions will not be included in the conference proceedings. Each session will be assigned either one or two 100-minute slot(s), subject to conference program scheduling.

For the plenary session, three keynote speakers were confirmed at the time this article was submitted to print. While Linda Zhang, F-150 chief nameplate engineer at Ford Motor Company, will talk on “From Concept to Road: The F150 Lightning Story,” Prith Banerjee chief technology officer at ANSYS will deliver a presentation on “Future of Simulation-Based Product Innovation.” Prof. Deepak Divan, Georgia Institute of Technology, Atlanta, GA, USA, will present a talk on the “Grid as an Ecosystem. In addition, all registered attendees will be invited to a welcome reception at the Henry Ford Museum, where attendees can explore American innovations, starting with the Wright brothers’ achievements, or make themselves at home inside Buckminster Fuller’s circular Dymaxion House. Besides exploring the movers and shakers who blazed the trail to where we stand today, you will have an opportunity to mingle with the movers and shakers of this generation!

On 10 April, 2022, IEEE Power Electronics Society (PELS) Wuhan Chapter, China and the Singapore Student Branch Chapter (SBC) conducted a joint online webinar, which was held successfully.

The forum is co-sponsored by IEEE PELS Wuhan Chapter and Singapore SBC, and co-hosted by School of Electrical and Electronic Engineering (SEEE), Huazhong University of Science and Technology (HUST) and IEEE PELS HUST SBC. The purpose is to provide a platform for academic exchange for scholars in Wuhan and Singapore.

This forum consists of two parts, which includes invited professor lectures and young professional talks. Prof. Mark Dehong Xu, vice president of IEEE PELS Membership, gave an introduction of IEEE PELS to the audience at first. Professor Zhiqiang “Jack” Wang briefly introduced the 70 years’
The purpose is to provide a platform for academic exchange for scholars in Wuhan and Singapore.

history of SEEE in HUST. Professor Sanjib K. Panda, regional coordinator, IEEE PELS R-10 Asia & Pacific Region and associate professor at the National University of Singapore (NUS), introduced the PELS Singapore SBC. While Dong Jiang, chair of IEEE PELS Wuhan Chapter, professor of HUST, presented the information on PELS Wuhan Chapter.

Professor Tang Yi of Nanyang Technological University (NTU) gave a report entitled “Smart Grid and Power Electronics Research”, which introduced the NTU’s research in smart grid and power electronics, and successful applications in related key research laboratories. Prof. Han Peng of HUST provided a report on the topic of “High Frequency, High Power Density Gate Drivers for WBG Devices”, which explained resonant drive, including drive speed, drive loss and other advantages based on high frequency, high power density, as well as presented a novel time segmented analysis methodology.

Dr. Hasmat Malik of NUS gave a speech on the topic “Intelligent Data Analytics for Renewable Energy Sources.” Dr. Zhen Tian of Wuhan University, presented a report entitled “Synchronization Stability of Grid-tied Converters from Energy Perspective.” Dr. Fawen Shen of NTU gave a speech on the topic “Analysis of Vernier Machine with Stator-V-Shaped Permanent Magnet Arrangement.” Dr. Yingbiao Li of HUST gave a report entitled “Concept and Dynamic Symmetrical Components with Time-Varying Amplitude/Frequency”.

For the first, PELS Wuhan Chapter co-hosted a webinar with a trans-regional PELS Student Branch Chapter, the Singapore section, which provided a great opportunity to promote the academic exchange of ideas between regions during the pandemic.
2022

14–17 June
Cappadocia, Turkey
4th Global Power, Energy and Communication Conference (GPECOM)
https://gpecom.org/2022/

15–17 June
Anaheim, CA, USA
IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)
https://itec-conf.com/

20–23 June
Tel Aviv, Israel
IEEE 23rd Workshop on Control and Modeling for Power Electronics (COMPEL)
https://www.compel2022.org/

21–23 June
Newcastle, United Kingdom
11th IET International Conference on Power Electronics, Machines and Drives (PEMD)

22–24 June
Sorrento, Italy
International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)
http://www.speedam.org/

26–29 June
Kiel, Germany
13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)
https://pedg2022.org/

5–7 September
Eindhoven, Netherlands
International Conference on Smart Energy Systems and Technologies (SEST)
https://sest2022.org/

5–9 September
Hannover, Germany
24th European Conference on Power Electronics and Applications (EPE’22 ECCE Europe)
http://www.epe2022.com/

8–11 September
Santa Clara, CA, USA
IEEE Global Humanitarian Technology Conference (GHTC)
https://ieeeghtc.org/

18–20 September
Coventry, United Kingdom
IEEE Workshop on Wide Bandgap Power Devices and Applications in Europe (WiPDA Europe)
https://warwick.ac.uk/fac/sci/eng/wipda2022/

9–13 October
Detroit, MI, USA
IEEE Energy Conversion Congress and Expo (ECCE)
https://www.ieee-ecce.org/2022/

17–19 October
Puebla, Mexico
International Symposium on Electromobility (ISEM)
http://escueladeingenieria.itesm.mx/workshops/electromobility-2022/

4–7 November
Guangzhou, Guangdong, China
IEEE International Power Electronics and Application Conference and Exposition (PEAC)
http://www.peac-conf.org/

7–9 November
Redondo Beach, CA, USA
IEEE 9th Workshop on Wide Bandgap Power Devices & Applications (WiPDA)
https://wipda.org/

9–11 November
Banja Luka, Bosnia and Herzegovina
XIV International Symposium on Industrial Electronics and Applications (INDEL)

23–25 November
Cassino (FR), Italy
Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)
https://smart-conf.com/

29–30 November
Regensburg, Germany
12th International Electric Drives Production Conference (EDPC)
https://edpc.eu/
6–9 December
Nadi, Fiji
IEEE 6th Southern Power Electronics Conference (SPEC)

16–18 December
Karunagappally, Kollam, India
IEEE International Power and Renewable Energy Conference (IPRECON)
https://iprecon.org/

2023

19–23 March
Orlando, FL, USA
IEEE Applied Power Electronics Conference and Exposition (APEC)
http://www.apec-conf.org/

22–25 May
Jeju-do, Korea (South)
11th International Conference on Power Electronics and ECCE Asia (ICPE 2023—ECCE Asia)
http://www.icpe-conf.org/

5–8 June
Shanghai, China
IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)

25–28 June
MI, USA
IEEE 24th Workshop on Control and Modeling for Power Electronics (COMPEL)

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in industry, I think it is important to understand what a Ph.D. brings over just a Master's degree. What distinguishes a Ph.D. from a Master's degree is a significant program of original research. Ph.D. programs generally have some minimum requirement for publishing journal articles (and not just conference papers) as well as writing and defending a dissertation (aka thesis).

So how valuable to industry is this documented ability to do original research? Again, it depends. For most product development, system engineering, applications engineering, or technical marketing positions original research ability has, in my experience, minor importance. Most commercial products are not developed in research labs. Instead each new generation of product is developed by making incremental, not revolutionary, improvements to existing products.

For example, consider the evolution of the server power supply. In the 1990 time frame a 1–2 kW server type power supply with single main output would have an efficiency in the high 80s percent, a power conversion density of 5 watts/in², and cost perhaps US$0.50 per watt. Today those power supplies are 96–98% efficient, have a power conversion density by a factor of 10, and a 1% improvement there. No companies that for each new design worked on a 1% improvement here and a 1% improvement there. No company created these great new power supplies in a single leap in a research lab. Yes, there were a couple of notable improvements along the way. The adoption of various bridgeless active rectifiers (power factor correction (PFC) stages) and LLC resonant converters were vital. But these circuits had been known for some time and they were adopted as needed and then continuously improved. Most of this work was done by engineers with bachelor's and Master's degrees—not Ph.D.s.

There is, in my experience, one sector of industry that seems to prefer candidates with Ph.D.s—semiconductor manufacturers. I don't know why but it seems that the semiconductor manufacturers prefer to hire people with Ph.D.s even for positions that would not seem to need a Ph.D., such as applications engineers.

There is another career path and that is pursuing a career in research at government or major corporate research labs. Working in these positions offers one the chance to do leading edge research without the burdens of chasing tenure at a university and once tenured, the need to split one's time between teaching, research, and other university duties such as serving on any number of faculty committees. These positions generally do require a Ph.D. These kinds of positions can offer exciting and fulfilling careers with good compensation but are limited in the number of positions available.

So my answer to "Is a Ph.D. needed for a career in industry?" is "Generally, no".

My next question to these students asks about how they like to work. For example, do they prefer working by themselves or in small teams on focused technical problems? Or do they like working with larger groups of people that might be working things like product definition or working with customers to solve customer problems? Understanding one's working preferences can be used to choose career directions. Those who want to be highly technical might want to look at roles in product or technology development. If they are someone that really enjoys deep technical challenges and likes to spend a lot of time at the lab bench, then a Ph.D. has more benefits. It is not so much the Ph.D. itself but the mindset that drives one to the challenge of original research and solving deep technical problems that carries over to the workplace.

Those that like working more with people and bigger picture problems might look more to roles in technical marketing, applications engineering, or even sales. For those looking at moving their careers in this direction, a Ph.D. does not seem to me to be a clear advantage.

The next question I ask is how much they want to be a leader in their organization or even the industry? And if they want to be a leader, do they see themselves as being a technical leader or leading through a management role? If they do see themselves as wanting to be a technical leader then a Ph.D. has some value. It is somewhat the additional deep problem solving skills refined as part of the doctoral research but as one advances towards the CTO's office companies do value a doctorate.

If on the other hand they see themselves as wanting to lead from a management role then the Ph.D. in today's finance driven organizations has less value. I think their time would be better spent pursuing an MBA rather than a Ph.D.

Next, I ask why they are in engineering. Did they take up engineering because they thought it would be a good way to earn a good salary to support themselves and perhaps a family? Or did they become an engineer out of some drive to create, to invent, to make the world a better place?

If they entered engineering because they thought it would offer good opportunities for continued
employment and to build financial security, then I don't think a Ph.D. adds much. Consider that a power electronics engineer in the United States with a bachelor's degree and a couple of years' experience is probably making US$60-80,000 per year. An engineer with a Master's degree is probably making US$80-100,000 per year. For the student with a bachelor's degree to get a Ph.D. is probably going to take 4–6 years. Even if they entered a Ph.D. program with full support that means they are sacrificing US$250–500,000 in income while they work on their degree. An engineer with a Master's degree might need more like 3–4 years to complete a Ph.D. which means they are sacrificing about the same amount of money.

How long does it take to earn that money back? A Ph.D. does not double one's salary over those with a Master's degree. Depending on the company and the position, a Ph.D. increases one's salary by 10–20%. So, if a student with a Master's degree takes only 3 years to complete a Ph.D., graduates with no student loan debt, and takes a job at 20% higher pay than if they only had a Master's degree it would take 15 years to catch up the earnings sacrificed while in school. One may argue with my assumed numbers but the result remains the same—it takes a long time to make up the financial sacrifice of a few years regular salary to get the Ph.D.

When I point this out sometimes I am asked “What if I work full time and work on my Ph.D. part time?” This is a fair question as this is how I earned my Master’s degree. However, it is exponentially harder to get a Ph.D. in engineering while also working part time. I encourage students considering this to have a detailed discussion with the faculty at the schools they are considering. In general, I think the chance of success for a part time engineering Ph.D. is low. I urge students who are determined to get a Ph.D. to just make the sacrifice and go full time.

If the answer to the question is that the student became an engineer to design and create and make the world a better place then a Ph.D. can further those ambitions, mainly by enabling a more research oriented career.

The next question I ask is where in the world do you want to work? Does it matter? Are you strongly interested in working in a particular place, such as your home country? Since all of my students went to school at the University of Colorado—Boulder in
the United States and many are from outside the US, I ask if working in the US is important to them. Are they open to working in Europe or Asia? For the student considering the Ph.D. there is excellent power electronics research going on in companies and research centers all over the world. To pursue the best opportunities could mean being open to international locations to pursue advancement in one’s career.

A couple of final questions are more about their outlook and desires in general. I ask them to think about their thoughts and plans for a family. Pursing a Ph.D. while starting a family is more than doubly hard. Simultaneously, managing the demands of the Ph.D. program and the demands of a young child can be overwhelming. So to pursue a Ph.D. may mean putting off starting a family for several years. Does that match with what the student envisions for his/her life?

And my last question—how important is it to you to make a lot of money? Engineering can provide a good career with steady employment and a chance to build financial security now and for retirement. But, not many engineers become really wealthy. If pursuing wealth is important then a career on the management side, pursing a CEO position or leveraging one’s engineering training in the investment world would offer a better chance to become wealthy. In this case a business degree would be more beneficial than an engineering Ph.D.

These questions generally leave the student reeling a bit. None of the students that have sought my advice about going on for a Ph.D. had considered even half of these questions—and none had considered the implications of giving up several years’ salary to earn the Ph.D. I think in the end it comes down to one’s goals and one’s personal desires. For some, the prestige of introducing themselves as “Doctor” or as having a Ph.D. is important for their own sense of self and perhaps even as a matter of family pride. Others may be more concerned about being able to consistently find work that is interesting and challenging. Others may be more worried about financial security. In the end, each person has to weigh their own goals and desires to answer for themselves the question “To Ph.D. or not to Ph.D.?”

**About the Author**

Robert V. White (bob.white@ieee.org) has more than 40 years of industry experience as a power electronics engineer. He has worked in product design, systems and applications engineering, technical marketing, and technology development. He has been an active volunteer with the IEEE Power Electronics Society, serving several years on the Administrative Committee, two terms as technical vice president, and as a Chapter chair. He earned a B.S.E.E. degree from the Massachusetts Institute of Technology and an M.S.E.E. degree from Worcester Polytechnic Institute. He is currently pursuing a Ph.D. degree in power electronics at the University of Colorado, Boulder. Presently, he is the chief engineer of Embedded Power Labs, a power electronics consulting company in Highlands Ranch, CO 80130, USA. He is a Life Fellow of the IEEE.
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Some of my former project lab students have reached out to me in the past few months seeking career advice. These former students, who all have a Master's degree, have been working for two to three years now and are trying to figure out the next step in their career. One of the common questions I get is “Should I get a Ph.D.?”

Like a lot of questions in life there is no one right answer. To help these students think about whether getting a Ph.D. is right for them or not, I developed a list of questions for them to consider. They don’t have to give me the answers to these questions, although I invite them to discuss them with me if they wish, but they do need to think about each one as they make their decision. In this column, I share those questions, and my thoughts, with the hope that this will be helpful to other young power electronics professionals who may be considering the pursuit of a Ph.D.

Before discussing the questions, I would like to address the question of getting a Master’s degree. This question most always comes up when I talk with undergraduates or recent graduates with bachelor’s degrees. My answer in this case is that if you are going to work in the industry then do all you can to get your Master’s degree. I earned mine mostly by taking night classes at the Worcester Polytechnic Institute while working full time. The bachelor’s degree, even at the best schools, only offers the very basics of engineering. After taking the required physics, mathematics, and humanities, there is just enough time to cover the basics of engineering. In a typical four year program, one can often only take two to four elective engineering courses that offer some additional depth or breadth. The two years of a Master’s program, even without a thesis, allows one to substantially broaden and/or deepen one’s engineering education. The eight to ten graduate level engineering classes go a long way towards enabling you to take on more challenging work assignments—and thus advance faster in both promotions and compensation. So yes, I always recommend getting a Master’s degree for those working in industry.

Questions to Consider
When it comes to pursuing a Ph.D. the first, and most important question, is “Why?”

One motivation for getting a Ph.D. is simply a personal drive for achievement. These students want to earn a Ph.D. for their own personal satisfaction or personal pride—much like a mountain climber wanting to climb Mount Everest. If this is the reason for getting a Ph.D. then that is sufficient to make the decision to go for it. It is better to pursue one’s dream and ambition than spend the rest of your life wondering “What if?”

Most of the students seeking my advice, however, are generally less motivated by the personal satisfaction of earning a Ph.D. and more about pragmatic concerns about their career. The common question is “Will a Ph.D. help me advance my career?” This raises the question of what they mean by advancing their career. Are they interested in more interesting and satisfying work, more recognition, or earning more money?

Given that the student asking about a Ph.D. is thinking pragmatically about whether a Ph.D. would help them advance their career, the next question I have is “Where do you see yourself working for most of your career, industry or academia?” If the answer is academia, then a Ph.D. is mandatory for any tenured faculty position. One could consider working in academia as an instructor or lecturer without a Ph.D. but such positions are limited in number, career growth, and compensation.

If the answer is “Industry” then it is my opinion that a Ph.D. is not generally required and may, or may not, help advance your career. To think about the need for a Ph.D. for a career

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