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High Frequency Power Electronics at the Grid Edge: A Bottom Up Approach towards the Smart Grid

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High Frequency Power Electronics at the Grid Edge: Motivations

Currently, solar energy systems are supplying 2% of US electricity generation and their use is rapidly growing. Data centers make up 2% of the US total energy consumption. By 2030, 40% of the overall worldwide energy consumption is expected to be in the form of electricity. The future development of transportation electrification and smart grids requires grid-scale energy storage. These emerging and high-impact applications locate in the distribution grid. They represent exciting opportunities in developing fundamentally new principles for high performance power electronics that are smaller, smarter, more efficient, and are capable of performing new functions (Fig. 1).

Power electronics systems are pervasive in many aspects of our daily lives, including renewable energy, transportation electrification, data communication, and industrial electrification. These applications all locate at the distribution level, near the edge of the electric grid. “Grid edge” is an emerging and important opportunity for power electronics. Power converters usually do not perform active grid forming functions at the distribution level. This, however, is rapidly changing following the emergence of renewable energy, transportation electrification, and smart grids, where power electronics serve as the main energy gateway. One common attribute of many of these grid-edge energy systems is that they comprise numerous classic power converters designed simply for voltage conversion. They also typically do not contribute to grid stability or resiliency. Moreover,

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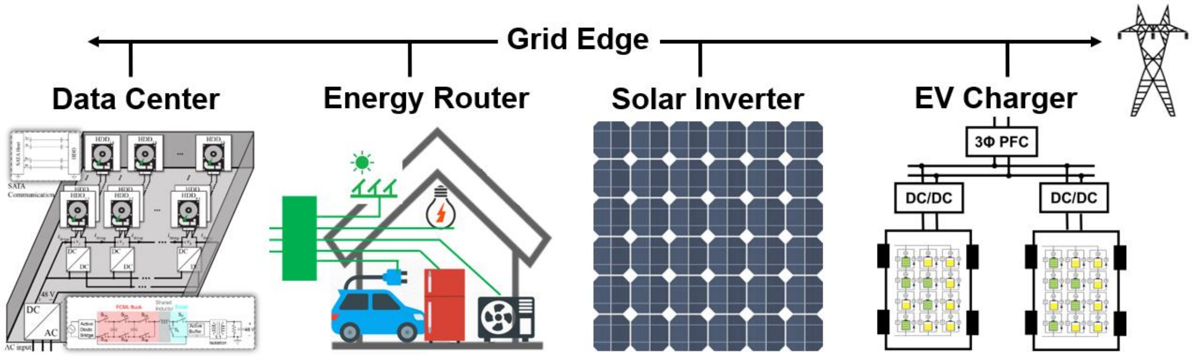

Fig. 1: New applications open new opportunities. Data centers, smart homes, solar farms, and electric vehicle charging stations all need advanced power electronics at the grid edge.

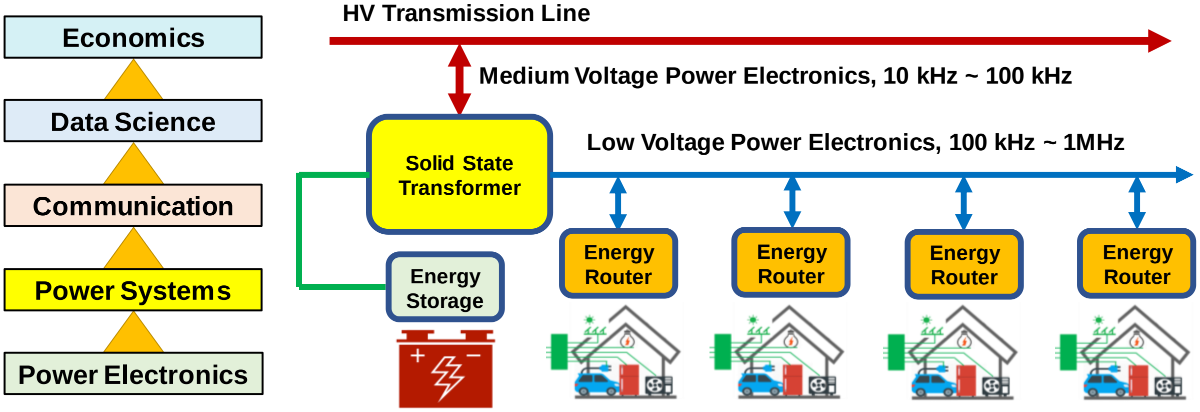

Fig. 2: The architecture of the future grid with pervasive power electronics at the edge. Innovations across disciplines, from power electronics, power systems, to data science and economics, are needed to enable the future smart grid [Further Reading: Divan 14].

conventional designs are simply considered as “grid followers” which passively extract energy from the grid. Grid interface and internal energy management are separately considered. More holistically integrated solutions are needed to connect distributed sources to loads and “form” the grid (Fig. 2).

Increasing the switching frequency and thus reducing the passive component size is a fundamental way to improve the performance of power electronics. Power semiconductor devices, control techniques, magnetics, packaging, and thermal management all pose difficulties in high frequency designs. Advancements are enabled by rapid developments in wide-bandgap materials, passive components, and supported by new architectures and fabrication techniques. Optimally designed high performance power electronics leveraging these state-of-the-art techniques promises significantly improved efficiency and power density. Both existing and emerging applications at the grid edge – ranging from power supplies for low power Internet-of-Things (IoT) devices, to kilowatt or higher power-level systems in electric vehicles, grid-scale energy storage, data centers, and

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renewable energy integration – require specialized power electronics to manage the sophisticated power flow.

High frequency power electronics are distributed “sensors” and “actuators” functioning at the grid edge. They replace the traditional centralized power plants and support the grid. By developing high performance high-frequency power electronics, the distribution grid's capability of hosting renewable energy resources and intermittent loads can be significantly enhanced, yielding a robust and resilient future grid with transformative societal impact and energy security benefits. High frequency power electronics will also improve the energy efficiency and power density of future energy systems. Research towards high frequency power electronics will enable the development of a new generation of energy systems that are intelligent and responsive while performing sophisticated functions, such as demand response, or peer-to-peer packetized energy trading. These new operation modes and cost allocation mechanisms will offset the steep high initial cost of high frequency, high performance power electronics, before the price is further driven down by large-scale commercial adoption.

High Frequency Power Electronics at the Grid Edge: Technical Barriers

The switching frequency of power electronics has continuously increased over the past few decades. The performance of a power electronics system is usually measured by its efficiency, power density, and functionality. Designing smaller, smarter, and more efficient power electronics is the goal. Higher switching frequency reduces the energy storage requirements and passive component sizes, which will benefit almost all power-electronics-enabled applications. The bulky nature of traditional power electronics means that miniaturization can often greatly reduce overall system size, weight, and cost as well as providing new system functionality. Miniaturization requires lower energy storage, smaller component size, tighter system integration, higher efficiency, and better thermal management. This is especially true in relatively high-voltage, low-power applications (e.g., voltages of up to a few hundred volts and power levels of up to tens of watts), such as offline power supplies, light-emitting diode (LED) drivers, converters, and inverters for photovoltaic panels and battery interface converters.

Energy efficiency, on the other hand, determines the life-time average cost of electricity. In applications like electric vehicles, improved energy efficiency in motor drives translates to extended drive ranges for electric vehicle. For solar inverters, improved energy efficiency leads to reduced average cost of electrical energy. Energy efficiency also sets a fundamental limit for the power density to be achieved due to thermal constraints. In a future smart grid, grid-forming power electronics are no longer simply designed for voltage conversion, but for routing the power among numerous distributed sources and loads. Multiway energy routers are needed to realize packetized energy management and peer-to-peer energy trading. Bottom-up innovations from materials, devices, packaging, modeling and control techniques drive improvements in switching frequency. Higher switching frequencies enable faster sensing and actuation at the grid edge. Wide-band-gap semiconductor devices facilitate high frequency operation with smaller footprints,

Fig. 3: Battery stacks, photovoltaic modules, and server racks all comprise a large number of modular units functioning together at the grid edge.

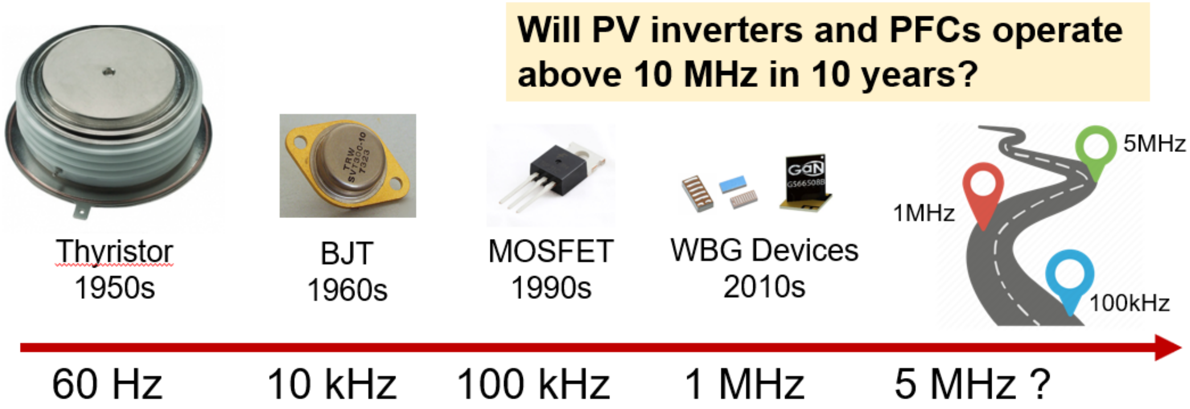

Fig. 4: Roadmap towards high frequency power electronics – will photovoltaic (PV) inverters and power factor correction (PFC) converters operate above 10 MHz in 10 years?

faster response times, and lower device losses. It is reasonable to expect that if appropriate system architectures, passive components and circuit designs are optimally combined, high frequency power electronics will achieve significant performance improvements over contemporary designs while offering unprecedented functions at the grid edge. The advanced functions and improved efficiency will justify the additional cost.

In addition to the needs of the electric grid, other technologies and markets for high frequency power electronics are beginning to emerge. The vision towards a future smart grid offers top-down motivations for high frequency power electronics. Power electronics are playing increasingly important roles in future energy systems, from supporting the future grid with more than 50% renewable energy, to powering data centers with millions of modular servers and microprocessors and managing thousands of battery cells in an electric vehicle (Fig. 3). Novel architectures open new challenges and enable application-driven innovation that cannot simply be achieved by increasing the switching frequency.

From the grid perspective, power converters become more “ideal” at higher frequencies. The gap between the switching frequency of the power converter and the 60 Hz grid

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frequency makes the inverters and power factor correction circuits look more like ideal voltage or current sources. As noted above, high frequency power converters are distributed sensors and actuators located at the grid edge – they probe the dynamic operating conditions of the grid and provide the needed response to contribute to grid stability and power quality. They will gradually replace bulky central power plants, and ultimately support the future grid as distributed generators.

Devices and Components

High frequency wide-band-gap semiconductor devices are ready to be adopted by grid interface power electronics. The voltage rating of GaN devices have reached 650 V or even higher, enabling them to be widely used in ac-dc adapters for consumer electronics, electric vehicle chargers and server power supplies, where miniaturization is the key. The switching frequency of commercial GaN based ac-dc adapter products have exceeded 1 MHz and are approaching 5 MHz. With their cost rapidly dropping, SiC devices are becoming commercially competitive in the medium voltage market. The switching frequencies of commercial SiC based inverter products are approaching MHz. The switching frequency of low power grid-interface power electronics (e.g., adapters, on-board chargers, roof-top inverters) is likely to approach 10 MHz in 10 years, and the switching frequency of medium voltage power grid-interface systems (e.g., PV inverters, fast chargers and data center uninterrupted power supply) is likely to exceed 1 MHz in 10 years (Fig. 4).

Magnetics components remain bulky and lossy (Fig. 5). They present an even greater

Fig. 5: The bottleneck of high frequency power electronics is in magnetics [Further reading: C. R. Sullivan 16, M. Chen 16].

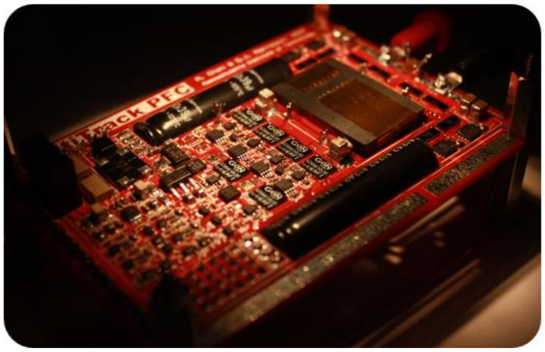

Fig. 6: A 1 MHz – 5 MHz power factor corrections circuit [Further Reading: M. Chen 19].

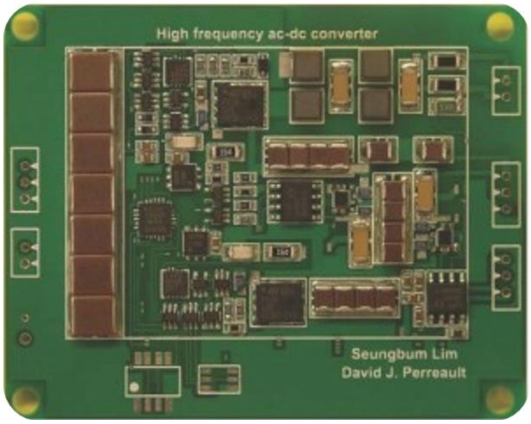

Fig. 7: A 5 MHz – 10 MHz LED driver [Further reading: M. Araghchini 13].

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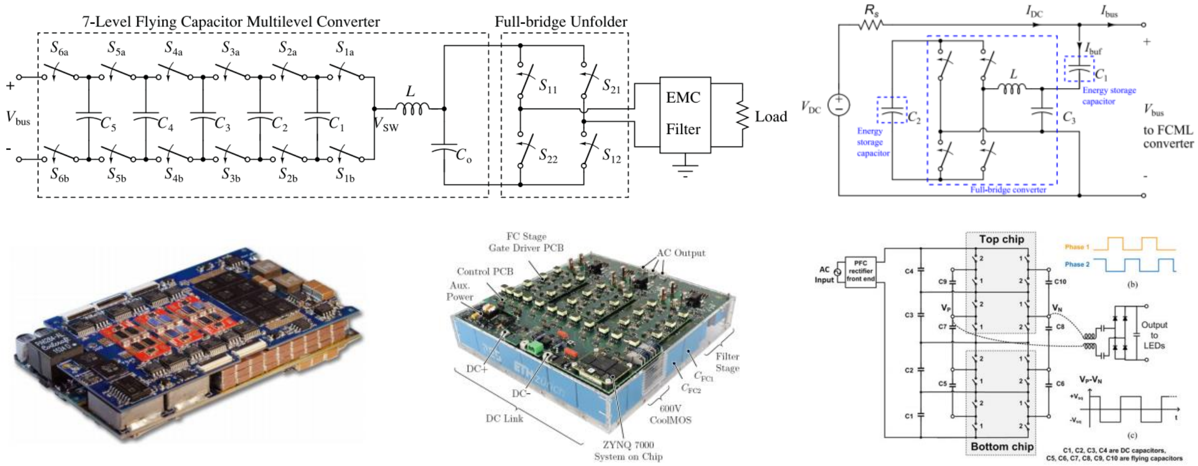

Fig. 8: Hybrid switched-capacitor converters leveraging the higher power density of capacitors over magnetics [Further Reading: Y. Lei 17, Van Tassell 16, Anderson 19, Chen 17].

bottleneck for high frequency power electronics than do semiconductor devices, especially at high power. It is not uncommon for sophisticated, modern power converter designs to have approximately half of their volume and power losses arising from inductors and transformers. While GaN and SiC devices offer superior performance at higher frequencies, the material performance and design techniques for magnetics are still limiting the path towards high frequency grid interface power electronics.

Despite the challenges, recent research has made significant advances in miniaturized power electronics operating in the HF and VHF ranges (3–300 MHz), well above typical modern designs operating from hundreds of kilohertz to a few megahertz (Fig. 6). Research shows that low permeability radio-frequency magnetic materials can offer higher performance factors than traditional ferrite materials in the MHz range (Fig. 7). While such advances have been substantial, the optimal design methods for using low-permeability magnetic materials are still unclear. Multidisciplinary efforts are still needed to model magnetic core losses and winding losses with holistic system integration.

Circuits and Topology

Single-phase power factor correction (PFC) converters in the hundreds of watts range typically need to meet harmonic current specifications, operate over a universal input voltage, provide hold-up energy for line transients, and create large voltage step down and isolation to the output. Meeting the harmonic specification requires precise control of the converter input current in order to provide a waveform with low harmonic content. Converters for many applications are often expected to deliver full load during a transient event in which the ac line is disconnected - a typical hold up time is one full line cycle or 20 ms for a 50 Hz ac input. The converter needs to have an energy storage element to provide said energy and this usually requires significant volume. Simultaneously meeting all these requirements while achieving high efficiency and power density is a challenge in miniaturized PFC converters. In order to function together with intermittent renewable energy sources, future PFC converters will likely include energy storage elements that can buffer energy for a longer duration.

The size of single-phase grid-interface converters cannot simply be reduced by increasing the switching frequency, as many of the challenges are determined by the line frequency (i.e., 50 Hz or 60 Hz), instead of the switching frequency. Innovations in advanced architectures are needed to 1) enable the converter to operate efficiently across a wide range; and 2) enable the converter to handle the line frequency pulsating power with enough energy storage. Active energy buffer technologies are critical in future grid edge power electronics. One emerging trend to enable the miniaturization of single-phase PFC converters is to leverage capacitor-based topologies. Recent progress in flying capacitor multilevel converters, switched capacitor circuits, high voltage monothetic integrated circuits, and multicell distributed architectures create opportunities for improving the system performance through circuit and topology innovations (Fig. 8).

Architecture and Control

Power electronics systems located at the grid edge are performing increasingly sophisticated energy management functions. The maximum power point tracking systems in solar farms manage power for thousands of solar panels. The energy routers in smart homes interface with energy sources (such as rooftop solar), batteries, electric vehicles, and the electric grid. The power delivery systems in data centers manage power for millions of servers and data communication devices. Power converters in electric vehicles interface with motors, on-board chargers, and dc fast chargers. These are emerging and important applications for society. There are opportunities to integrate the many functions in a grid-edge power electronics system and create mutual advantages. Modular, multicell, distributed, and reconfigurable power architectures will play important roles at the grid edge. Power electronics systems need to be “smarter” to form the grid and manage the sophisticated power flow. One way to improve the intelligence of power converters is to push towards granular power conversion with highly modular and distributed sensing and control.

Granular power conversion architectures comprise many modular building blocks that interface with multiple sources and loads and manage the multiway power flow. It fits particularly well to build energy routers at the grid edge. Switched-inductor, switched-capacitor, bridge-structures, and magnetic couplers (or in general, matching networks) can be considered as four basic building blocks. Fig. 9 shows four canonical energy conversion cells as building blocks of granular power electronics, including a bridge structure, a switched inductor cell, a switched-capacitor cell, and a magnetic coupler. A switched-inductor circuit creates multiple current paths; a switched-capacitor circuit creates multiple voltage domains; a bridge-structure can efficiently perform dc-ac conversion; and a magnetic coupler utilizes magnetic fields to transfer energy from one voltage/current domain to another and provides voltage and current scaling. These building blocks can be merged together to synthesize power electronics topologies that can maintain high performance across a wide operation range. Unlike designing and

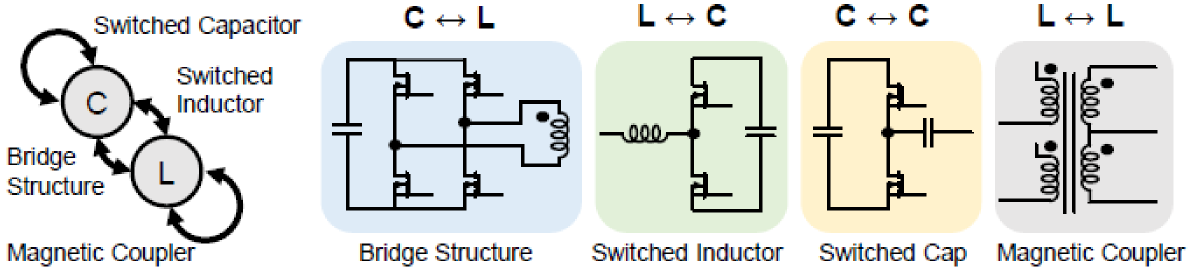

Fig. 9: Canonical cells for granular power conversion, including a bridge structure cell, a switched inductor cell, a switched capacitor cell, and a magnetic coupler cell.

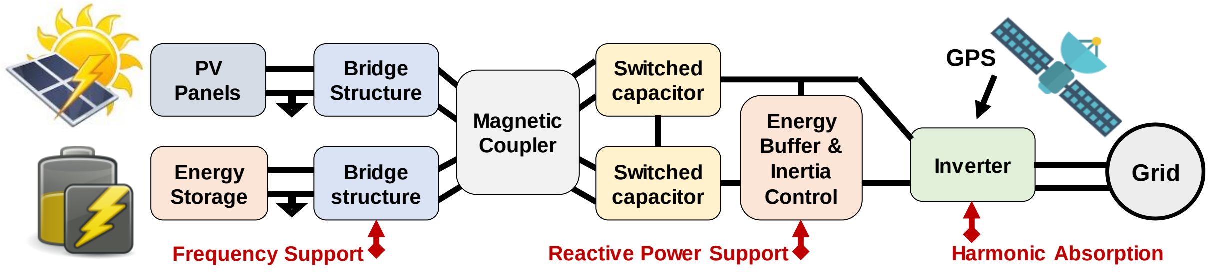

Fig. 10: An example multi-functional grid interface architecture with granular building blocks.

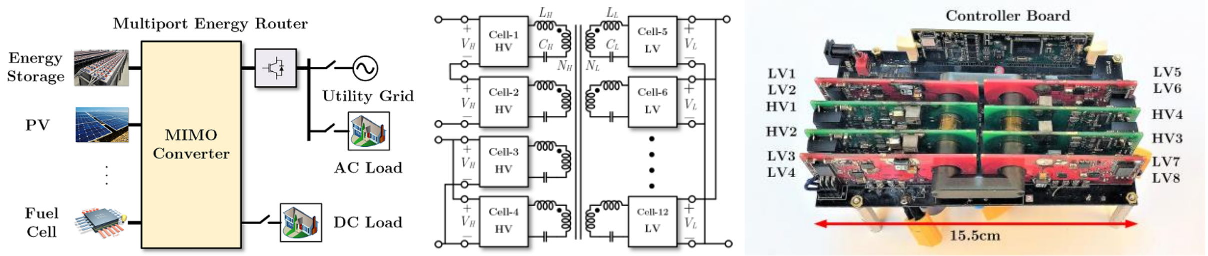

Fig. 11: Principle, schematic, and prototype of a multicell reconfigurable multi-input multi-output (MIMO) energy router [Further Reading: Y. Chen 20].

optimizing one specific power converter topology, granular power electronics need coordinated control of a large group of modular building blocks. Systematic approaches to designing and optimizing these building blocks are still unknown.

Many emerging energy systems at the grid edge comprise a large number of modular units – solar farms have thousands of solar panels, grid-scale energy storage comprise tens of thousands of batteries or fuel cells, and data centers comprise millions of servers. Novel power delivery architectures that can reliably manage the sophisticated power flow in these highly intricate systems are needed. Differential power processing, and partial power processing techniques fit particularly well to these applications. Fig. 10 shows an example multi-functional grid interface architecture with many granular building blocks that can be linearly extended to higher power levels. Fig. 11 shows the principle, schematic, and prototype of a multicell reconfigurable multi-input multi-output energy router architecture which can maintain high performance across a wide operation range.

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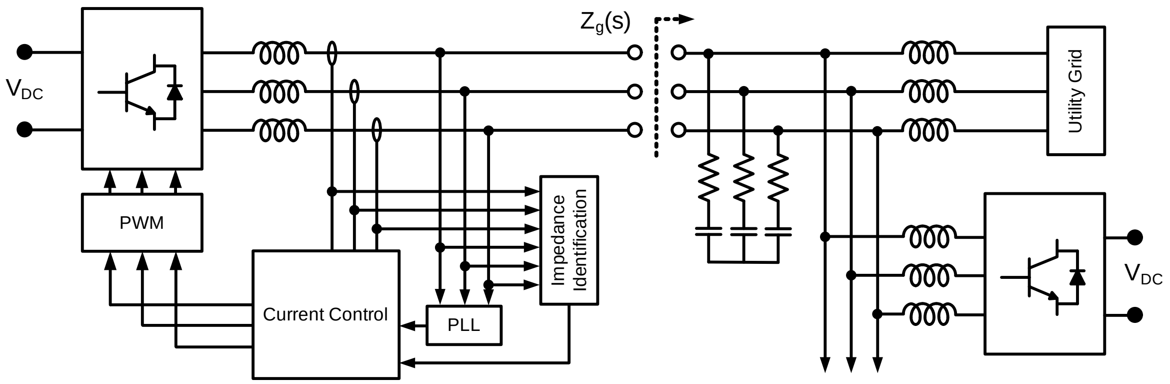

Fig. 12: An example grid impedance measurement setup. High frequency power electronics enable fast and broad-band impedance measurement [Further Reading: T. Roinila 14].

High Frequency Power Electronics at the Grid Edge: Advanced Functions

Grid Forming Power Electronics

With the increasing deployment of distributed energy resources, conventional “firm” grid interconnection requirements and static hosting capacity planning do not facilitate the integration of a high percentage of DERs. Efficient, compact, responsive, and intelligent grid-interface converters are required in future energy systems. Power electronics for data centers, solar farms, EV charging stations, and grid-scale energy storage can function as distributed inverters and loads at the grid edge, which may help to stabilize the grid voltage and frequency by contributing to volt-var control. Deploying smart power electronics at the grid edge can substantially improve the DER hosting capacity. Each smart inverter or smart rectifier is a multiport energy system with energy storage capacity. They can provide the needed “inertia” to stabilize the grid dynamics. They can autonomously cluster into nano-grids when facing cyber-attacks or natural hazards and provide black-start capability when the system restores from blackouts. They can actively sense the grid impedance and damp the inverter-grid oscillation. Innovations are sorely needed to enhance the capabilities of these grid forming inverters and rectifiers.

Recently, there has been important progress in impedance-based grid stability analysis, high frequency grid-interface power electronics, miniaturized phasor measurement unit (PMU), medium voltage modular multilevel converters (MMCs), and ultra-high-density ac-dc inverters. There are also very active discussions on the concept of “grid forming inverters”, including grid edge energy systems, virtual synchronous machines, virtual oscillators, virtual springs and smart loads. Grid interface power converters need to be able to function as current sources in a “stiff” grid, and function as voltage sources in a “weak” grid. Conventionally, innovations in the “smart inverter" domain often occur independently from the “topology” and “control” level. Innovations to address the challenges of coordinating a cluster of inverters and rectifiers at the grid edge securely and autonomously are needed.

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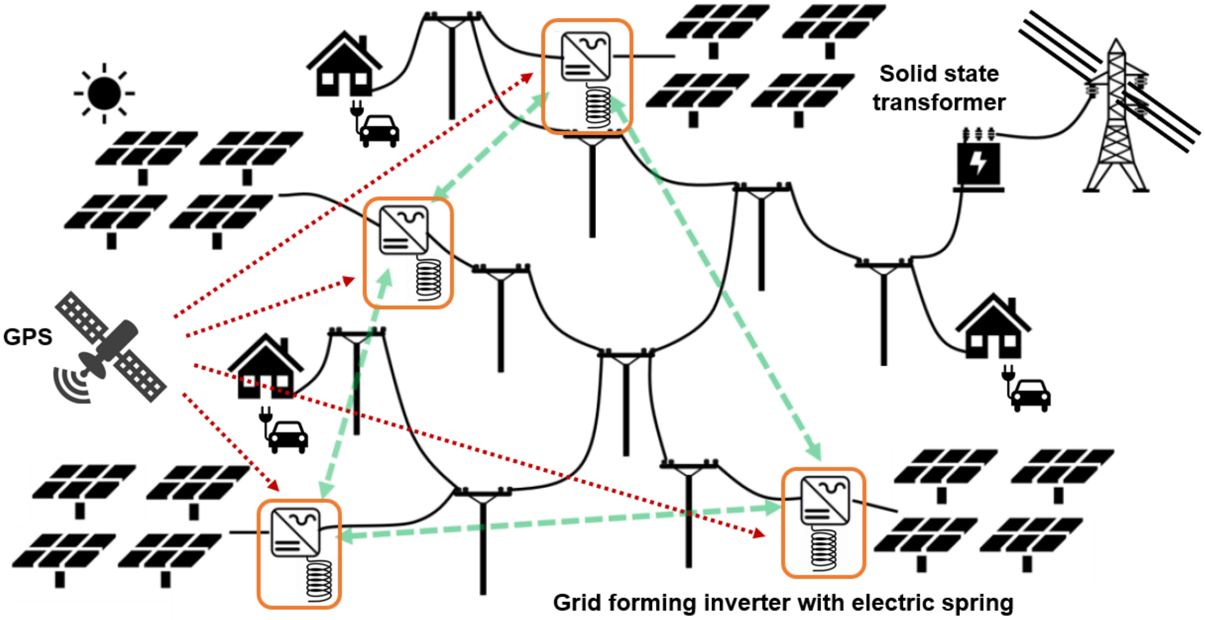

Fig. 13: Grid forming inverters and energy routers at the edge [Further Reading: S. Y. Hui 12].

The rapid development of microprocessors and digital control enables fast computation and quick response while performing complex tasks. The merging of the power grid and other existing and emerging large-scale information systems, such as 5G networks, optical communications, and global positioning systems open exciting opportunities.

Distributed Observability and Controllability

Grid impedance affects the stability and dynamic performance of grid-interfaced power electronic systems, such as inverters and rectifiers on the load side. Adaptive control of such inverters, to guarantee stability under rapidly changing grid conditions (including both the hardware status, and the power flow), requires rapid online estimation of the grid impedance performed in real time. Such online measurement can be performed by injecting a current perturbation from the inverter into the grid and by observing the grid voltage responses. To minimize the impact on grid operation, the injection must be kept as small as possible while producing enough voltage perturbation that can be reliably measured and processed to extract its relevant information. High frequency power electronics offer unprecedented capability of performing grid impedance spectroscopy with higher accuracy and shorter time intervals (Fig. 12).

The stable and efficient operation of the electric grid requires intricate control of the real and reactive power flow. Ideally, each inverter and rectifier should be controlled as pure resistors to maximize the efficiency and avoid other issues such as converter-to-converter oscillations. However, due to the existence of line impedances and non-resistive loads, as well as the reactance coming from the line-frequency filters in each power electronics device, the system may contain significant reactive power components at multiple harmonic frequencies and require active impedance compensation. High frequency

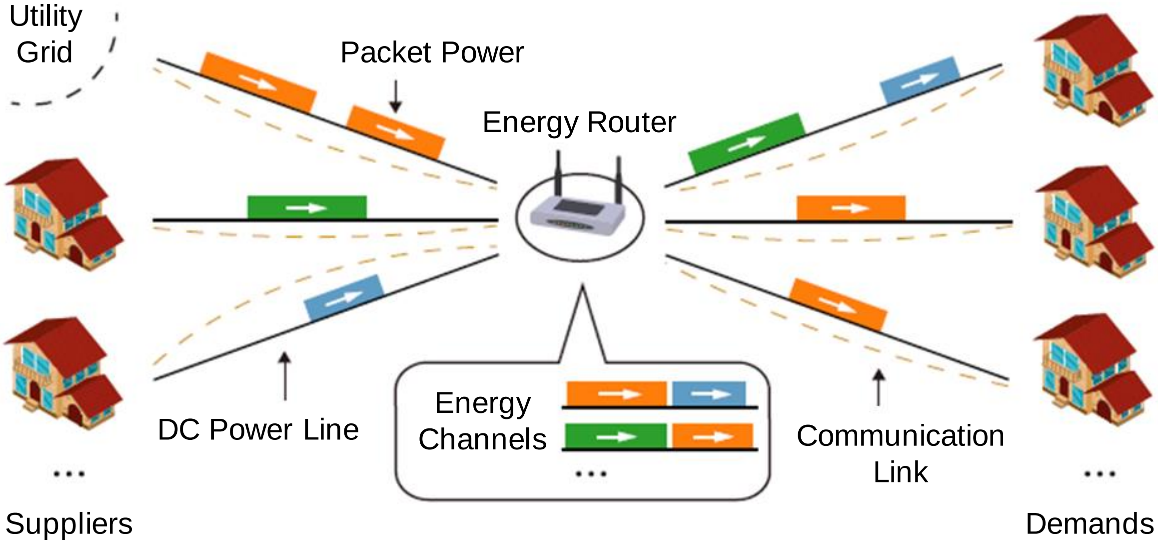

Fig. 14: Diagram of a DC packetized power microgrid [Further Reading: H. Zhang 20].

power electronics, if controlled appropriately, can inject or absorb the reactive power in these harmonic components and improve the stability of the future grid.

With granular observability and controllability at the edge, the recent advances in artificial intelligence and machine learning can enhance the supervisory control and data acquisition (SCADA) system at the distribution level. Machine learning algorithms can rapidly identify the grid status with reduced numbers of observations, and reinforcement learning can be used to explore optimal inverter control strategies.

Take the emerging “electric spring” concept as an example (Fig. 13). Analogous to a mechanical spring, an electric spring is a power electronics device that can: 1) provide electric voltage support; 2) store electric energy; and 3) damp low frequency oscillations. It can compensate for the voltage drop in the distribution network and stabilize the frequency. To achieve these goals, electric springs need to accurately infer the grid status and respond rapidly to power flow dynamics: both ultra-fast grid impedance estimation and ultra-fast control are needed. Increasing the switching frequency of the electric spring devices can improve the control bandwidth, reduce the EMI filter size, accelerate the overall control loop, and enable other grid response functions that have not been demonstrated before. Many similar active compensation devices have been proposed. Their performance and functionality can all benefit from higher switching frequency.

Power Quality, Low Frequency Osscilation, and High Frequency Harmonics

Power quality measures the electrical interaction between the power grid and the sources and the loads. Conventionally, power quality comprises two parts: 1) voltage quality - the way in which the supply voltage impacts equipment operation; 2) current quality - the way in which the equipment current impacts the system operation. With a large amount of power electronics at the grid edge, the voltage quality and current quality are cross-

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coupled and cannot be seperated. High frequency power electronics produces both low-frequency harmonics (below 1 kHz) and high-frequency harmonics (above 1 kHz). The low frequency harmonics can be mitigated by advanced control, but the high frequency harmonits appear in the distribution grid and cannot be easily eliminated, especially in the distributed grid without isolation transformers. Fixed frequency operation usually leads to groups of harmonics around the integer multiples of the switching frequencies. Hysteresis control, used in smaller converters, leads to a highly-distorted frequency spectrum. If the switching frequency is close to a system resonant frequency, it causes a large high-frequency ripple on the voltage. An increasing penetration of DER with power-electronic interfaces, will lead to an increasing level of high-frequency harmonics. The physical principles and system consequences of high frequency harmonics remain unclear. Standardized methods for measuring, islanding, and characterizing high frequency current and voltage harmonics are not yet available.

Packetized Energy and Peer-to-Peer Energy Exchange

As the deployment of distributed energy resources (DERs) expands, packetized power microgrids are emerging as promising solutions to effectively incorporate DERs (Fig. 14). The full benefits of a microgrid can only be realized when energy can be freely exchanged and traded between sources and loads with economic incentives. Dynamic peer-to-peer energy trading requires rapid and precise balance of the sources and loads within a distribution network (Fig. 15). To enable packetized power delivery in microgrids, the sources and loads interact with energy routers that manage multiway power flow. Fast, stable, and efficient power flow management is needed. Higher switching frequencies lead to faster control of the multiway power flow and will enable the hardware implementation of more advanced trading and packetizing functions with improved energy efficiency, faster control bandwidth, and higher power density. High switching frequencies enable Time-Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), and many other Multi-Input Multi-Output (MIMO) modulation schemes to be implemented in energy routers. With independent control of real and reactive power in each converter, and with much simplified and improved utility operation and control, it is possible to achieve peer-to-peer energy trading among neighboring communities (in the same secondary feeder) or even among neighbors with trading protocols across multiple time scales. With such peer-to-peer energy trading options, end users can sell their surplus energy either to the utility or directly to other end-users, and can provide the needed frequency support functions at the grid edge, making the best use of the distributed electricity generation and energy storage capability.

Peer-to-peer energy trading requires energy routing with system stability. High frequency power electronics are needed to perform fast state-estimation of the power flow (real and reactive), and ensure rapid and stable energy routing within the stability margin. High frequency power electronics enable high speed power-line-communication (PLC), which

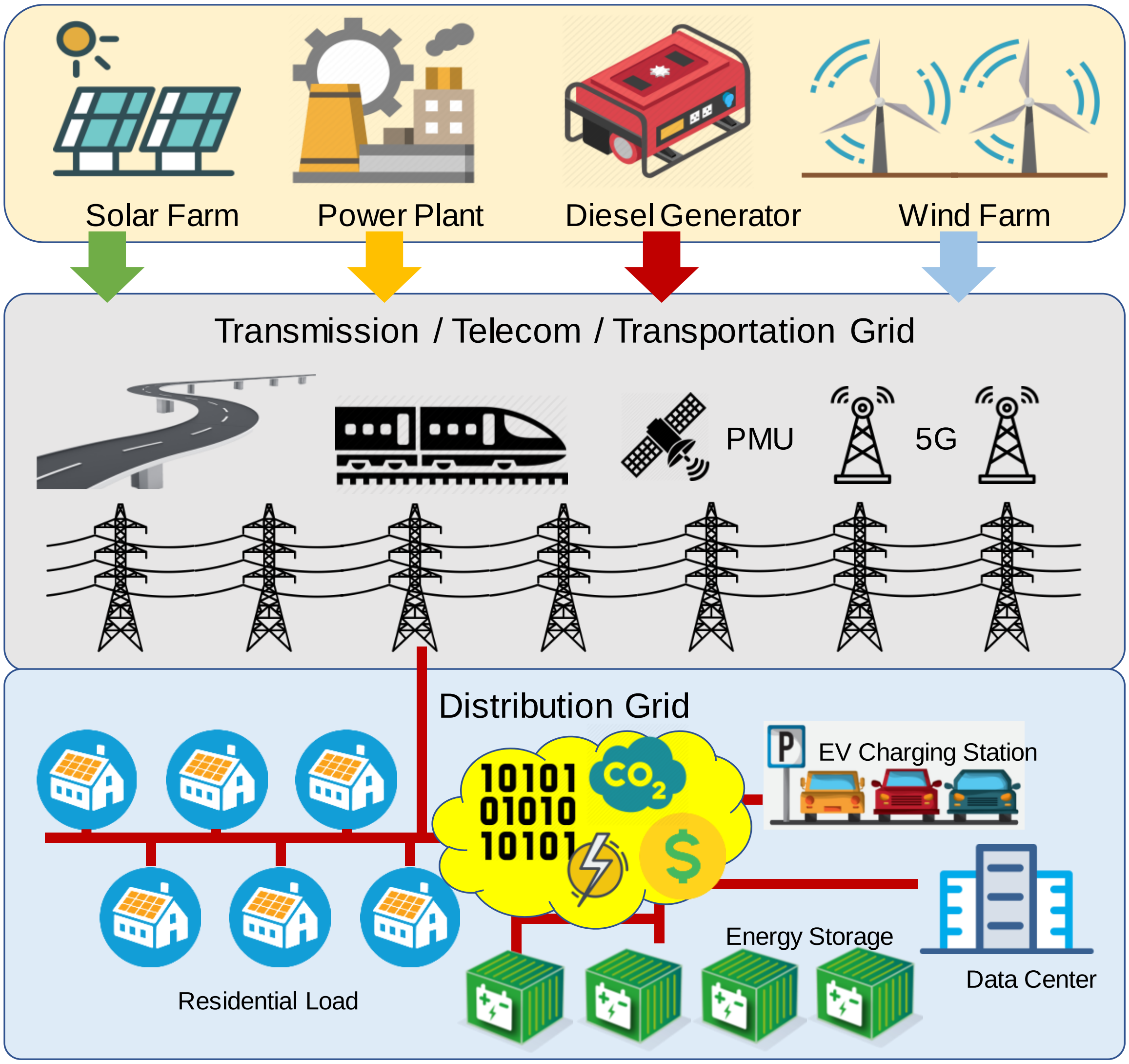

Fig. 15: Peer-to-Peer (P2P) energy trading at the grid edge [Further Reading: W. Tushar 20].

is an emerging data transfer mechanism that can ensure transaction privacy and enable point-to-point, inverter to inverter communication on the distribution level.

Summary: A Bottom Up Approach towards the Future Grid

The future grid needs to supply more than 50% renewable energy and support a massive number of intelligent loads. Transitioning towards such a future grid requires bottom-up technical innovations including new semiconductor devices, new circuits and topologies, new system architectures, and advanced control. These fundamental technologies will improve the performance of power electronics systems and will enable new functions that were not possible before. Continuous installation of intelligent electric vehicle chargers, solar inverters, and energy routers at the grid edge, as well as the deployment of high-speed communication networks, will make the future grid much more observable and controllable. The grid will be able to host intermittent renewable energy and become more

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robust against natural disasters and disturbances. Energy will be locally generated and consumed within a distribution grid, yielding significantly reduced stress on the transmission level. Innovations in grid operation and novel business models, such as demand response and peer-to-peer energy trading, will create value chains and foster an ecosystem to close the cycle for technical innovation.

With the electric grid delivering more than 50% of the societal energy consumption, the energy flow carried by the electric grid is mixing with the data flow on the information network, the pricing of electricity, and the geographical footprint of carbon emission. The security, privacy, and functionality of the electric grid, the transportation network, and the telecommunication network are coupling together. As more and more power electronics devices are installed at the grid edge, the one-way unidirectional power and information flow in the traditional electric grid will be replaced by the multi-way bidirectional power and information flow in the future grid, and the optimal way of operating such an electric grid is still unknown. A wide range of economic, societal, and technical challenges need solutions coming from multidisciplinary systems thinking.

To conclude, the opportunities of investigating high frequency power electronics at the grid edge are driven by fundamental technologies and motivated by high-impact applications. The performance benefits of high frequency power electronics will reduce the initial cost barrier for technical innovation. The new functions and capabilities of high frequency power electronics will make them attractive for large-scale adoption, further reducing the cost. The challenges for large-scale deployment of high frequency power electronics exist in the “transition” – how do we seamless switch from the current “grid-following” mode to the future “grid-forming” mode, without sacrificing the reliability, resiliency and low cost of providing electricity. Recent progress in other industries (e.g., transportation electrification, 5G communication, and IoT) are accelerating this transition. From small-scale solar powered data centers to “net-zero" distribution substations that support large numbers of MW-level EV charging stations, a “bottom up” approach, rooted in technologies and thriving in applications, can maximize the economic incentive of embedding distributed intelligence in power electronics, while mitigating the political, technical, economic, and societal barriers associated with the transition.

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