Envisioning the Future Renewable and Resilient Energy Grids—A Power Grid Revolution Enabled by Renewables, Energy Storage, and Energy Electronics

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***Abstract*—Today's power grids are facing tremendous challenges because of the ever-increasing power demand, system complexity, infrastructure cost, knowledge base, and policy and regulatory issues to achieve supply–demand power balance and resiliency with respect to more frequent extreme weather events and cyberattacks. It is particularly challenging when the transition toward 100% intermittent renewable energy sources is considered. Many countries are calling for building up more transmission and distribution lines to increase power delivery capacities. This article is an attempt to answer two urgent questions: Is more transmission and distribution infrastructure really needed to meet the increasing power demand? What kind of future grid infrastructure should we envision and build? This article attempts to answer these questions and proposes the concept of community-centric asynchronous renewable and resilient *energy* grids. By clearly differentiating the concepts of grid resilience and reliability, the importance of building resilient power electronics' devices and robust system-level control algorithms to achieve 100% renewable energy integrated resilient grids is presented. To identify the shortcomings and propose advancements, power electronics' technologies are categorized using the proposed concepts of natural source frequencies (NSf), energy storage, direct energy conversion/control and fault protection (DeCaFp), and high-efficiency energy consumption and buffering (heECaB) technology. The ability of networked microgrids to greatly reduce power outages and power system restoration time is demonstrated by leveraging robust decentralized and centralized control algorithms, identified through a comprehensive literature review. Future research areas are proposed to further enhance grid stability, controllability, cybersecurity, and protection against faults in the presence of 100% renewable sources by leveraging the advanced capabilities of NSf, DeCaFp, and heECaB devices and system-level control algorithms.**

***Index Terms*—Cyber security, distribution, energy grid, power electronics, power grid, renewable energy (RE), resiliency, transmission.**

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Nomenclature

NSf	Natural source frequencies.
DeCaFp	Direct energy conversion/control and fault protection.
heECaB	High-efficiency energy consumption and buffering.
GFL	Grid-following inverters.
GFM	Grid-forming inverters.
DERs	Distributed energy resources.
IBRs	Inverter-based resources.
HILF	High impact low frequency.
$H(\tau)$	H is a measure of system performance and is a function of τ, which represents grid states after a contingency event.
i_k	Current injection from any kth DeCaFp IBR.
v_k	Terminal voltage of any kth DeCaFp IBR.
f_k	Terminal frequency of any kth DeCaFp IBR.

I. Introduction

ELECTRICITY infrastructure (i.e., the power grid) is the greatest engineering achievement of the 20th century, according to a U.S. National Academy of Engineering report [1]. The traditional power grid has been constructed over more than a century, consisting of four basic parts: generation, transmission, distribution, and end-use consumption (or loads that play important roles but have been passive largely), from upstream power plants to downstream consumers. However, it is aging and needs an overhaul. It is timely that the power grids today are being transformed by an envisioned paradigm shift of this article and two positive forces—resiliency pull and decarbonization push—calling for a transformation/revolution.

A. Old Infrastructure and Resiliency Pull

Most generation is fossil fuel, hydropower, or nuclear-based large, centralized power plants, which have to be placed in remote areas away from population centers due to geographical constraints, pollution, and/or safety concerns. Therefore, electric power has to be delivered at a stepped-up voltage and long transmission lines have to be built to transmit bulk power to substations close to load centers (consumers) for distribution.

The power transmission network is massive, meshed, and interconnected for reliability and redundancy [2], [3]. Centralized generation facilities in the United States currently have the capacity to generate more than 1100 GW of electric power [4] and over 200 000 miles of transmission lines forming a meshed and interconnected infrastructure [5]. The estimated worth of the U.S. transmission assets is almost $1 trillion [6]. This meshed and interconnected approach requires that each bus voltage and its frequency be tightly maintained by limiting the load ability and reserving significant safety margins according to the worst-case peak-power demand. Therefore, there are calls to build up more transmission lines to meet the ever-increasing load demand, especially the peak demand.

To safely and reliably operate today's power grids as a whole, large generators have to be synchronized to the fixed frequency (50 or 60 Hz) and each bus voltage maintained within a tight range. The electrical frequency has an electromechanical link with the speed of the rotating synchronous machines [7], [8]. After an event, fast acting primary regulators stabilize the grid frequency to an off-nominal value, which is then brought back to the nominal value by the secondary automatic generation control within minutes to maintain grid stability [9].

While the transmission network is responsible for transporting bulk power from generating stations to the distribution substations, the distribution network is responsible for delivering power to consumers. As of 2010, there were an estimated 5 million miles of distribution lines in the U.S. power grid [5] and most of the network uses low-clearance overhead lines. With such an extensive network, the distribution network forms an extremely important part of the grid, which, however, has been neglected traditionally and largely. Moreover, in the U.S., over 90% of the power outages occur in distribution systems [10]. In a period from 2003 to 2012, over 80% of the overall power outages have been caused by severe weather conditions [11]. The 5 million miles of distribution lines, representing over $1 trillion infrastructure cost in the U.S. power grid, deliver power to over one billion electric loads that are worth over $3 trillion. These end-use electric loads, however, have been largely untapped resources for emerging opportunities in ancillary services, energy storage, and resiliency enhancement. The electric loads include heating, ventilation, and air-conditioning (HVA/C), water heater and boilers, refrigerators, ovens, manufacturing facilities, mining, construction, and agriculture machines, used in residential, commercial, and industrial consumers.

Unlike the transmission networks, the traditional distribution network for the most part uses a radial, ring, or interconnected architecture. In a radial architecture, an entire feeder is often cutoff in the event of weather-related faults/natural disasters [12]. This leads to a loss of power to all the consumers receiving power from the same feeder. In the case of multiple parallel feeders from a single source, voltage sags are observed by loads connected in a feeder due to faults in neighboring feeders [13]. In the so-called ring and interconnected structure that is mainly built for maintenance purposes, a real parallel or meshed operation is prohibited because a slight voltage difference could result in a huge circulating current and cause protection difficulties. Normally, different types of loads are connected to different feeders. They can create large voltage variations among feeders. The normally open-tie switch at the end of the feeders is primarily for feeder reconfiguration or service restoration. Although each voltage sag event typically lasts for less than 167 ms, repeated voltage sags have led to disruption to industries and consumers receiving power from the distribution system. Moreover, severe weather conditions together with electricity and other infrastructure damages (such as roadway, as shown in Fig. 1) have become a major barrier that prevents the grid from fast restoration.

Workers remove downed trees during cleanup operations in the aftermath of Hurricane Hermine in Tallahassee, Florida September 2, 2016. Photo by Phil Sears/REUTERS

Fig. 1. Hurricane aftermath picture shows the daunting task to restore service to the distribution network.

B. *Renewable Sources and Decarbonization Push*

In addition to the above-mentioned resiliency problem or resiliency pull force, power grids are experiencing an increasing share of renewable energy (RE) sources at the distribution level, thanks to their declining costs [14] and an increased focus on decarbonization of the electric grid (or the decarbonization push force). Countries, such as Norway (97%), Brazil (76%), and Canada (62%), have already achieved high renewable integration using transmission-connected hydropower energy [7]. However, hydropower and other forms of nonvariable RE sources, such as biomass and geothermal energy, are geographically constrained [15]. The path toward 100% RE grids will, thus, involve significant integration of IBRs, such as solar and wind.

As shown in Fig. 2, the future 100% RE-based grid will be characterized by a huge number of small IBRs distributed across the electric grid. Controlled current injections by IBRs can change the electrical frequency by modifying the phase angle of the bus voltage. IBRs will consequently be coupled with the 100% RE grid via control-based links instead of electromechanical links.

On the other end, smaller and islanded electric grids are already transitioning rapidly toward very high IBR penetration [16], [17]. Thus, unlike the larger transmission-connected power plants in current power grids, millions of IBRs will be connected to the distribution networks and expected to play a more important role to the end-users, which will further add to the system

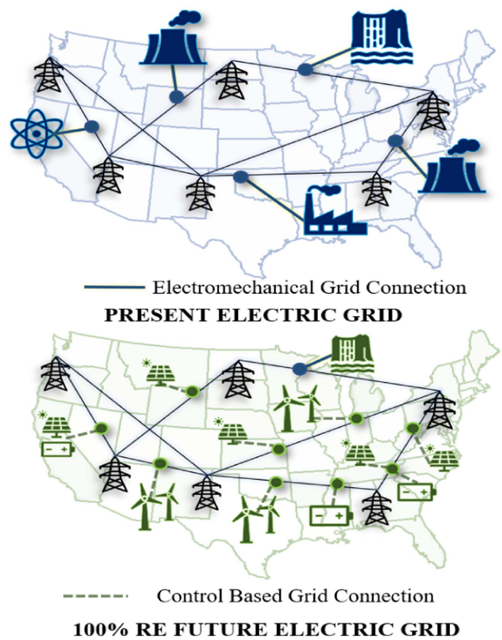


Fig. 2. 100% RE-based power grid of the future.

complexity and difficulty in terms of control, protection, and resiliency.

C. Grid Revolution by Resiliency and Decarbonization Calls

Improving grid resiliency is a critical aspect of the U.S. energy infrastructure [18]. It is not just natural disasters that the distribution systems need to be resilient against. The distribution systems should be able to withstand and recover from major unexpected events, such as cyber or physical attacks, pandemic events, and events due to system design or human errors [19]. Metrics are required to quantify resilience and enhancements in resilience achieved through intelligent control algorithms.

With little or no energy storage in today's grids, the generation has to meet the load demand instantly. The increasing penetration of RE sources with intermittent nature further exacerbates the supply–demand power balance problem. As a result, the power grid is vulnerable to extreme weather and natural disasters. The primary operation principle of today's power grids is to deliver instant power to consumers as much as possible while protecting the networks from damages/failures.

To summarize today's grids in one word, it is "power," from generation, transmission, distribution, to consumption. The focus on "power" has created major barriers and challenges.

1) System complexity (e.g., the U.S. power grid has a massive number of loads, millions of miles of distribution lines, hundreds of thousand miles of transmission lines, thousands of large power plants, photovoltaic (PV), and wind farms. A power grid is a synchronous complex machine.).
2) Costly infrastructure (over $6 trillion price tag for the generation, transmission, distribution, and load).
3) "Worst-case problem" (the power grid has to be designed and operated to withstand the worst-case scenario to achieve an instant balance of the power supply and demand).
4) Knowledge base (that is limited to power engineering; however, a paradigm shift to energy engineering is needed).
5) Policy, public awareness, and interest.

A grand challenge of the future electricity infrastructure is to overcome the above barriers and challenges, a grid revolution called for by the resiliency pull and decarbonization push, and a paradigm shift enabled by RE, energy storage, and power electronics. This article proposes the concept of renewable and resilient energy grids. The major research challenges that need to be overcome in order to achieve these grids are also highlighted through a comprehensive literature review. The rest of this article is organized as follows. Section II presents a discussion on the concept of grid resilience and how it differs from the more commonly studied concept of grid reliability. This section also highlights the importance of studying the interactions between power electronics and the power systems-level control schemes to enhance grid resilience. Section III proposes the concept of an "energy grid," which is fundamentally different from the traditional "power grid" concept. The renewable and resilient *energy* grids are featured with NSf, energy storage, DeCaFp, and heECaB. These technologies are transforming the existing *power* grid to an *energy* grid, and from a top-down power grid structure to a bottom-up community-centric energy approach. These concepts leverage asynchronous links where possible to minimize energy conversions and maximize the efficiency of the proposed renewable and resilient energy grids. In Section IV, the opportunities and challenges associated with controlling a 100% renewable resource integrated energy grid are explored. Through the concept of a resilience curve, the ability of networked microgrids to act as the building blocks of the future 100% renewable and resilient electric grids is demonstrated. Section V provides the authors' latest research results from device-level power electronics to a system-level case study to quantitatively compare and demonstrate the proposed versus the state-of-the-art approaches. Section VI discusses future research topics and perspectives to guide research needed for reliably managing the interactions between power electronics and grid-level control schemes to achieve 100% RE integrated resilient energy grids. Finally, Section VII concludes this article.

II. Concept of Grid Resilience

Understanding resilience from both device-level and power system's perspectives is important before the concept of renewable and resilient *energy* grids can be introduced. Severe weather events, such as hurricanes and floods, are the leading causes of equipment damages/power outages in North America [20]. It has been estimated that the cost of outages due to weather-related events ranges from 25 to 75 billion dollars annually [21]. With the distribution systems experiencing 90% of all outages [10], primarily because of their simplicity in design [19] and aging infrastructure, they make them a weak link toward achieving a resilient grid.

The reliability of distribution systems is measured based on the frequency (how often) and duration (how long) of outages experienced by the customers. The system average interruption frequency and the system average interruption duration indices are used widely by utilities to measure the impact of outages [22]. Resilience, on the other hand, is a relatively new concept that characterizes the ability of a distribution system to sustain the critical demand during extreme events when bulk generation sources become unavailable for an extended period and numerous transmission and distribution components are damaged [23]. Resilience as defined by the Federal Energy Regulatory Commission refers to, "*the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event*" [24]. The U.S. Department of Energy (DoE) and the North American Transmission Forum emphasize the ability to "withstand or minimize damage" and "rapidly recover" from HILF events as being key attributes of a resilient electric grid [19].

Grid hardening measures, such as deploying stronger poles and structures and undergrounding conductors, can enhance both the reliability and resilience of the distribution systems. It may, thus, seem that any step taken toward enhancing the distribution system's reliability will also enhance resilience. This may not always be the case, for instance, reclosing during a fault enhances reliability but also increases the risk of fires during dry weather. Resilience, thus, considers any event that may adversely impact the grid, including HILF, which may be excluded from reliability metrics. Resilience not only considers the final state of the grid but also the time it takes to transition between states, such as from the postdisturbance degraded state to the restorative state.

Thus, reliability metrics cannot be used to quantify resilience. IEEE and the U.S. DoE have recently proposed metrics to quantify resilience. IEEE power energy society (PESs) Distribution Resilience Working Group provides metrics that quantify the grid's ability to recover within the first 12 h of a severe weather event and its ability to withstand events in general [19]. The U.S. DoEs Grid Modernization Laboratory Consortium proposes performance-based metrics, such as "cumulative customer energy demand not served" and "critical customer energy demand not served" to quantify resilience [25]. These metrics can be used to determine the enhancement in resilience achieved by advanced distribution system management schemes, such as the deployment of microgrids.

As the frequency of weather-related events increases, high-impact events may happen more frequently. It has been shown that making distribution systems smarter and being able to respond effectively to extreme events is more beneficial in enhancing resilience from the device level than building redundant distribution infrastructure [26]. Thus, there is a strong need to develop advanced power electronics, such as hot-swap, hardened and unbreakable converter/inverter hardware, modular and redundant circuit topology, advanced control, and embedded fault protection—the DeCaFp technology.

The device-level resiliency technology [27] can go hand-to-hand with system-level control and management to greatly increase grid flexibility and robustness against weather-related events, as prioritized in [20]. For instance, the presence of intelligent DeCaFp converters, which can be programmed to work as relays, can significantly reduce the cost of deployment of differential protection schemes in microgrids. It is, thus, evident that the development of 100% RE integrated resilient grids will require intelligent device-level power electronics and robust system-level control algorithms. The proposed renewable and resilient energy grids and the device and system-level design considerations to achieve them are discussed in Section III.

III. Concept of Renewable and Resilient Energy Grids: Device-Level Considerations

Fig. 3 illustrates the proposed concept of renewable and resilient energy grids that are community-based, community-centered, and community-focused for community energy needs and security from the load-level up. In the proposed energy grid, each load is the center, from which a grid expands outward with "electrical distance" according to its energy demand over a period of T—from individual load's energy buffering within seconds ($T =$ seconds) to residential energy averaging (thermal and load shifting, $T =$ minutes), and community/utility-scale storage ($T =$ hours and days). The presence of energy buffering and storage at each level can help reduce peak-power demand dramatically and mitigate the traditional "worst-case problem," where the lowest power generation point due to DER intermittency has to meet the highest point of demand to satisfy the instant power balance. The power electronics' devices provide three main functionalities, namely NSf, DeCaFp, and heECaB, which will be discussed later. The presence of power electronics can enhance the grid resilience by:

1) interfacing the energy resources, storages, and loads in multiple flexible configurations and instant control of frequency, phase angle, energization of transformers, and grid synchronization;
2) providing enhanced control and stability among energy generation, conversion, and consumption stages;
3) integrating instant protection, isolation, and fast restoration features during and postextreme events.

A. *NSf, DeCaFp, and heECaB: State-of-the-Art*

The three revolutionary energy technologies enabled by power electronics are as follows:

1) adoption of NSf and asynchronous community-centric localized structure instead of the artificially fixed and synchronous 60-Hz ac power;
2) DeCaFp (its attributes and features are summarized in Fig. 4);
3) heECaB (as summarized in Fig. 5).

NSf for PV, battery, or fuel cell is dc (0 Hz) and, for many wind generators, it is low, variable frequency (10–20 Hz) ac. The dc power from PV is more suited for direct dc integration of battery energy storage rather than going through 50/60-Hz grid. The dc microgrids and dc and ac hybrid microgrids are the examples of NSf technologies [28], [29]. On the other hand,

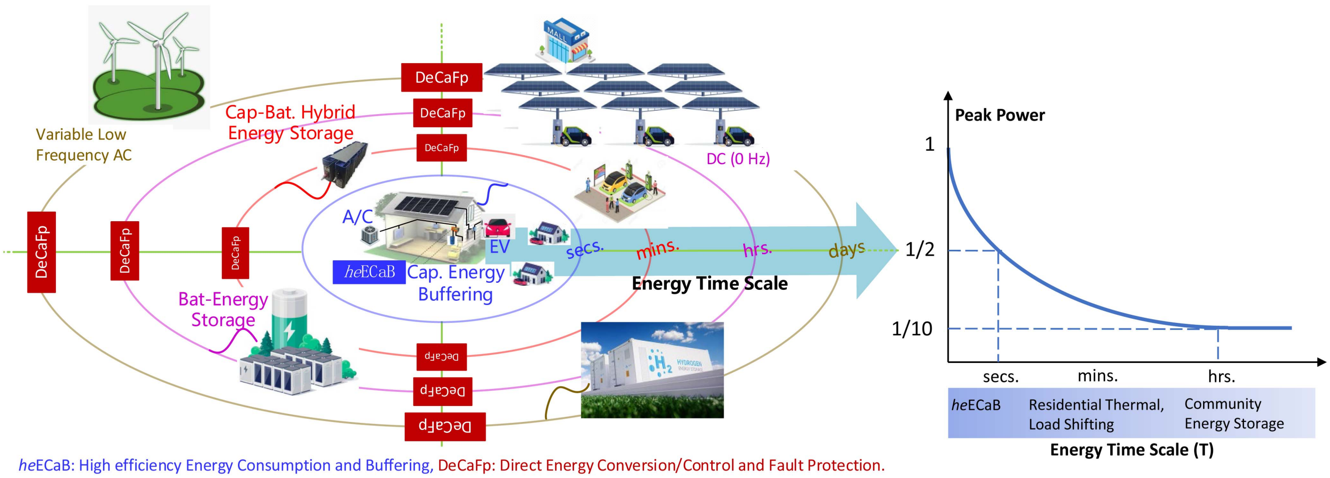


Fig. 3. Concept of resilient and RE grids.

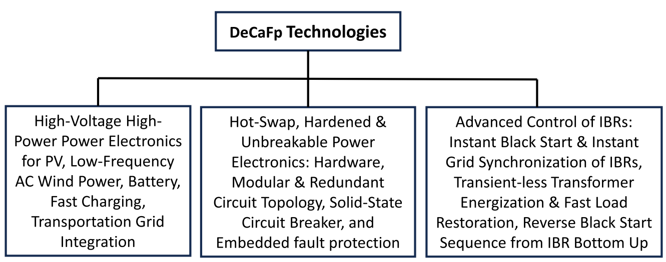


Fig. 4. DeCaFp technologies.

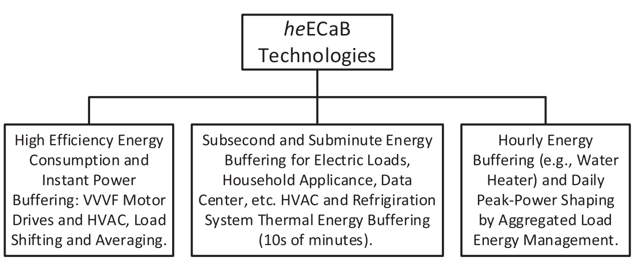


Fig. 5. Summary of heECaB technologies.

for long-distance power transmission, high-voltage dc transmission (HVdc) (0 Hz) technologies have been developed rapidly worldwide due to the controllability, economic, and environmental advancement [30], [31]. Alternatively, advanced flexible ac transmission systems and resilient ac distribution systems [27] enabled by DeCaFp technology have been developed to provide more economic solutions to increase the capacities and resiliency of the existing transmission and distribution systems. For the wind power transmission, increasing notices have been raised that fractional frequency or low-frequency high-voltage ac can multiply increase transmission capacity [32], [33], [34], [35], [36], [37].

Fig. 4 shows three major DeCaFp technologies: First, high-voltage high-power power electronics, including thyristor-based HVdc (line commuted converter—HVdc) [38], modular multilevel converter (MMC) [39], [40], [41], solid-state transformer [42], [43], dc circuit breaker [44], [45], [46], etc. Second, hardened power electronics hardware, including new development and application of semiconductor devices [47], [48], [49], gate-drive technologies [50], [51], [52], circuit or system integration and control [53], [54], [55], [56], [57], [58], [59], [56], etc. It should be pointed out that other than discrete dc circuit breakers, the integration of fault protection directly into power converters is an outstanding feature. An example is the thyristor-based HVdc converter that can prevent open-circuit voltage surge and short-circuit current. No additional dc circuit breakers nor dc voltage surge protectors are needed. Another example was shown in [60] where fault protection was integrated into the converters and programmed to act as relays for system protection. Third, advanced control of IBRs to implement instant black start and instant grid synchronization, transientless transformer energization and fast load restoration, and reverse black start sequence from IBR bottom up. These advanced controls pose a paradigm shift on how to control 100% RE grids.

The heECaB concept stands for energy consumption and buffering at all levels from individual loads to residential or end-users and to community and utility scale, with the purpose of reducing peak-power and transmission/distribution infrastructure demand. For power converters, novel circuit topologies are developed to buffer line frequency energy oscillations (120 Hz) [61], [62]. This concept can be extended to a broader consideration of energy buffering to mitigate peak-power demand through power converters. It should be noted that the size of the required energy buffering cannot be reduced simply through increases in switching frequency of an interface power converter; thus, the design approach will be significantly changed. In this sense, energy buffering with new topology/design, capacitors, and/or inductors for seconds/subsecond power averaging will help a wide range of grid-interface power electronic applications, including residential PV inverters, motor drives, power supplies, LED drivers, EVs, and data centers.

For minutes to hourly time scale, HVA/C represents over 40% of an average household's electricity consumption [63]. Induction motors used for compressors and fans in HVA/C systems run at full power for a short period of time to cool down the room. They are basically fixed-speed motors with the power grid frequency (50 or 60 Hz). They shut OFF when the temperature falls below the desired settings. This ON–OFF control creates two problems: First, a large inrush current (several times larger than the full power) every time when the HVA/C kicks in because the compressor has lost the pressure that had built up in the last run; and second, a large temperature swing to minimize the number of ON–OFF intervals. As a result, a very large peak-power demand (several times of the full power) happens at each kick-in operation. In the pieces of literature, control of large populations (ensembles) of small loads, such as residential HVA/Cs and heat pumps, is achieved using aggregated load models to shift the ON–OFF period of each HVA/C unit away from each other so that the total power demand will be averaged out. In addition, system-level approaches considering energy storage are found for optimal capacity design and operation, energy coordination modeling and analysis, frequency regulation from demand response, etc. [64], [65], [66].

On the other hand, variable-speed-drive inverter-based HVA/Cs provide more regulation resources to the grid because inverter devices can change their operating power continuously and flexibly, regulate room temperature to a constant temperature with no temperature swings, and produce much less audible noises. According to the North America Air Conditioning Systems Market, in 2022, the inverter-based HVA/C segment is dominating the market with the largest revenue share of 58.3% over the forecast period [67]. Nevertheless, targeted research on inverter-based HVA/Cs for participating in grid support and services is rare [68]. For emergency and ancillary services, inverter-based HVA/C systems can provide thermal energy storage functions to the grid when certain temperature swing is exploited, thus becoming an IBR to the grid. Fig. 5 shows a summary of heECaB technologies in subsecond/second, minute, and hourly time scales, respectively.

B. Proposed Advancements in NSf and DeCaFp Technologies

While the present NSf, DeCaFp, and heECaB technologies are transforming the current electric grid, challenges remain. Novel energy conversion topologies, design criteria, and control methods for DeCaFp from the energy source level to local community to distribution and transmission levels without grid information are needed for ultrafast (within milliseconds) automatic restoration of energy grids. One of the potential developments of DeCaFp technology could be series dc–dc converters as a direct charger/discharger between PV and battery or EVs, which only need to handle differential energy between two resources. Furthermore, a series device can be used as an ac–ac energy router to interface different NSf sources at individual connection points without the common medium of 50/60-Hz ac. These series devices (energy router and direct charger/discharger) are similar to unified power flow controller (UPFC) [41] and, thus, can reduce the number of power conversion stages. Fig. 6 summarizes future research examples regarding DeCaFp topologies. There is no one-size-fits-all topology. Each topology may find its niche according to different energy conversion needs between couple points 1 and 2, CP1 and CP2.

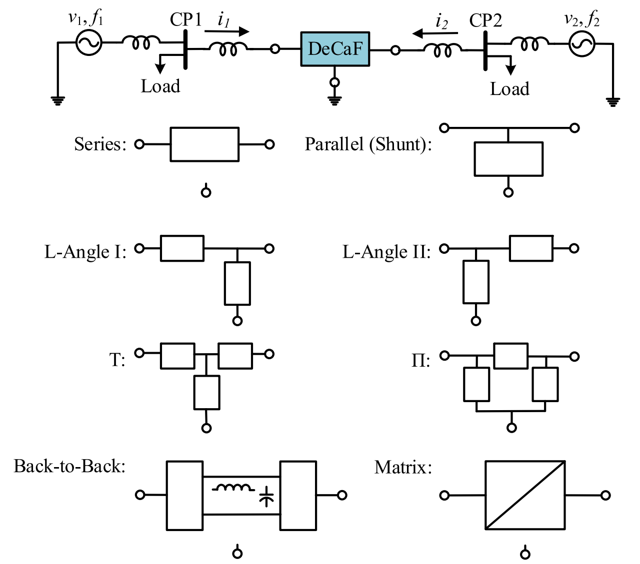


Fig. 6. Examples of DeCaFp topologies from series converters to modular multilevel matrix converters for future research.

For example, a series-type DeCaFp topology (i.e., the very first topology in Fig. 6) can serve as an energy router to transmit energy over a time period of T from CP1 to CP2 with only fractionally rated converters [69] for some cases. This series energy router works even when/where CP1 and CP2 have different voltages and frequencies. The operating principle can be summarized as the following governing equations: the energy router is controlled to force a current flow from CP1 to CP2

$$i_{12}(t) = i_1(t) = -i_2(t) \tag{1}$$

where $i_1(t)$ and $i_2(t)$ have a frequency, f_1 and f_2, respectively, so that the energy from CP1 to CP2 satisfying

$$\begin{aligned} E_{12}(t) &= \int_{t-T}^{t} v_1 i_{12} d\tau = \int_{t-T}^{t} v_1 i_1 d\tau \\ &= \int_{t-T}^{t} v_2 i_{12} d\tau = \int_{t-T}^{t} v_2 (-i_2)\, d\tau \end{aligned} \tag{2}$$

and

$$E_{\text{DeCaF}}(t) = \int_{t-T}^{t} (v_1 - v_2)\, i_{12} d\tau = 0. \tag{3}$$

Another very important aspect of DeCaFp technologies is to integrate fault protection into converters to achieve system resiliency. This is a key ingredient of the proposed DeCaFp-based technologies. The use of the full-bridge rather than the half-bridge as the basic submodule for modular multilevel converters (MMC) promoted in the early 1990s [70] was mainly because of its natural fault protection capability, as further discussed in [71]. The half-bridge MMC had some initial uses; however, the full-bridge submodule has become the dominant topology in recent MMC installations.

The third pillar of DeCaFp technologies is the advanced control of IBRs. Today, IBRs are mostly controlled to mimic the behavior of a synchronous machine with similar methods and procedures for startup, grid synchronization, and black start, thus having prolonged process and scarifying resiliency. However, an IBR or grid-tied inverter has an instant current control loop that the traditional synchronous machine does not. A paradigm shift can be made by utilizing the IBRs' instant current control to achieve instant black start and instant grid synchronization, transientless transformer energization, and fast load restoration. Also, black start local microgrids at any time instance and reverse black start sequence from IBR bottom up become possible. An inverter is essentially a function generator, capable of producing any magnitude with any frequency and any phase angle. Our most recent research shows that instant grid synchronization and phase jump are possible [72]. Therefore, the traditional stability issues, frequency control and grid synchronization, would not become an issue for 100% RE IBR-based grids.

C. Proposed Advancements in heECaB Technologies

The focal point of both DeCaFp and heECab is energy instead of power. This power-to-energy transformation and its benefits can be further explained by the following example. According to the U.S. Energy Information Agency, the average monthly electricity consumption for a U.S. residential utility customer is 900 kWh or 30 kWh per day, i.e., 1.3 kW daily average power with an instant peak power as high as 15 kW and average hourly power fluctuation of 1:2 over a typical day [73]. The daily average power is less than one-tenth of its instant peak power. Even after considering load diversity, the difference between a distribution feeder's peak and average demands can be significant. However, the entire delivery system, including transformers, cables, and protection devices, has to be sized up to handle its peak-power demand, resulting in an oversized infrastructure. It is very practical for today's battery technology to store such an amount of energy. A Tesla EV battery holds over 100 kWh of energy [74], thus being able to power an entire house for over three days without usage curtailment. A small EV can power a house for one full day. Electric transportation's integration into energy grids owes significant research opportunities, such as G2V and V2X [75], [76]. G2V smart charging has been tried out in many cities and some EV models have just been equipped with V2X functions to provide emergency power to loads and houses.

From HVA/C to water heaters and industrial boilers at the electric load level, power electronics as the enabling technology can improve efficiency, reduce instant peak-power demand, and enhance resiliency. Tremendous opportunities and R&D needs exist in this area. In summary, the existing power grids focus on power delivery requiring an instant power balance between supply and demand that must be supported by a massive power generation/transmission/distribution infrastructure, which is already unsustainable. The NSf energy grid enabled by RE, energy storage, and power electronics (i.e., DeCaFp and heECab technologies) will focus on energy from the local community level up. This grass-root bottom-up approach minimizes the energy infrastructure and maximizes resiliency.

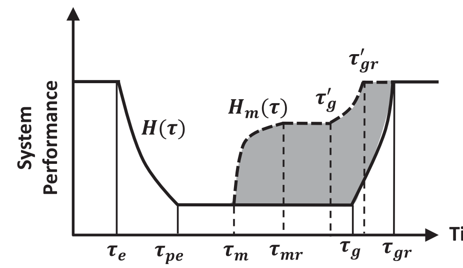


Fig. 7. Resiliency enhancement using microgrids (Adapted from [113]).

The simple goal of the proposed transformation from power to energy grids conceptually is to reduce power outages and power restoration time by an order of magnitude, achieve integration of electric transportation to energy grids, and increase RE plus energy storage capacity to 100%. Section IV will discuss on how to achieve the goal.

IV. Achieving Renewable and Resilient Energy Grids: System-Level Considerations

The proposed concept of renewable and resilient energy grids requires a bottom-up distribution system-focused approach. Increasing integration of IBR-based technologies in distribution systems provides opportunities to enhance their resilience. While device-level design focuses on the development of new NSf, DeCaFp, and heECaB power electronics' technologies, system-level design focuses on the stability enhancement of the grid by developing control schemes to better manage interaction among these power electronics' technologies. The presence of IBRs enables centralized and decentralized control to meet desired objectives and avoid costly network upgrades. Such community-centric renewable and resilient energy-based grids can be created by the formation of microgrids. This is because of their ability to enhance system resilience and stability in the presence of different types of DERs and IBRs, as discussed in this Section (IV). Multiple microgrids networked together can further reduce cost and further enhance resilience by leveraging fast acting decentralized control schemes.

A. Community-Centric Resilient Integration via Microgrids

A conceptual resilience curve during an extreme event has been proposed in [77], as shown in Fig. 7. In the absence of any local control capabilities, the system performance function $H(\tau)$, a measure of the load served, degrades after an event at τ_e and stays degraded until grid supply is restored at τ_g [78], [79]. Any additional demand met over this baseline during the event can quantify the enhancement in resilience. This may be achieved by the formation of a microgrid using locally available IBRs [80]. In Fig. 7, the microgrid picks up critical loads starting at τ_m. Once the microgrid has restored the critical loads at τ_{mr}, it can also help in reducing the outage duration by providing cranking power to the nonblack start generating units in the bulk grid. This helps in speeding up the recovery of the bulk grid from

τ_g to τ_g'. Also, since critical loads have already been restored by the microgrid, only the noncritical loads must be restored after the grid supply has been restored. This further reduces the overall grid-restoration duration from τ_{gr} to τ_{gr}'. The area under the dashed curve from τ_m to τ_{gr} is a quantitative measure of the enhancement of resilience. This approach of quantifying resilience is consistent with the metrics proposed by IEEE and the U.S. DoE, as described in Section II, as it helps in quantifying the additional critical customer energy demand served after an extreme event. Now that the ability of microgrids in creating resilient grids has been demonstrated, the next important system-level consideration is to ensure grid stability in the presence of different types of DERs.

Operation of microgrids requires control and dispatch capabilities to maintain voltage and frequency. Primary frequency response (PFR) of synchronous machines has traditionally been used for stabilizing the grid frequency after a disturbance. IBRs, on the other hand, can provide "synthetic inertia," or more appropriately fast frequency response (FFR). An inverter-based wind turbine can provide FFR at a rate of 10%/s of its rated capacity by rapid extraction of the kinetic energy of its rotating blades [81], [82] as against a 0.3%/s–2%/s PFR from synchronous machines [83]. Solar IBRs too can provide FFR by maintaining a real power headroom [7]. These then respond by rapidly increasing their real power injections within the headroom as commanded by the microgrid controller.

B. Stability of RE-Dominated Microgrids

Studies have shown that uncontrolled operation of DERs at high penetration levels can impact system stability, such as by worsening postcontingency voltage recovery or by reducing the damping of rotor oscillations [84], [85], [86]. On the other hand, controlled operation of IBRs [87] and power electronics interfaced loads [88] can improve transient system response and bring down operational costs by reducing headroom requirements for grid support. DERs, including IBRs, present in distribution systems can be controlled as a single controllable entity by the formation of microgrids [89]. To prevent stability issues in the bulk grid, microgrids should ensure the stability of DERs and loads during both grid-connected and islanded modes of operation. Stability in microgrids is broadly classified into "control system stability" and "power supply and balance stability" [90]. The focus is more on the equipment and controllers involved in the instability process rather than on the variables, frequency, or voltage, involved in instability. This is because there is a strong coupling between these variables, especially in the islanded mode of operation of microgrids, making it difficult to tie the instability process exclusively to either one of these variables.

Thus, it is important to design appropriate control schemes to ensure the stable operation of RE-dominated grids. IBRs are tied through control links with the grid that makes control algorithms a critical aspect of IBR design from a power systems perspective. Droop control based on the control of synchronous machines has been implemented in inverters. Studies have shown that fast response from GFM IBRs can bring the grid frequency to nominal values within seconds after an event, unlike the traditional control scheme where AGC may take minutes [9]. Thus, traditional frequency droop-based power-sharing techniques may not work in this constant frequency operational paradigm. Proportional resonant control [91] and model predictive control [92] techniques have been proposed. These, however, require significant computation and are sensitive to parameter variations [93]. Virtual synchronous machines, where an inverter behaves based on a synchronous machine's governing equations, have been evaluated. A decentralized control strategy, which does not force the inverter to work on the principles of a synchronous machine, is proposed in [9]. This technique determines power sharing among IBRs using deviations from the reference phase angle, which is determined by continuously tracking an IBR bus angle and freezing it when locally measured frequency deviation exceeds a tolerance. While this technique was found to maintain grid reliability, it puts a larger power-sharing burden on the IBRs located closer to the event.

Most inverters connected in distribution systems operate in the GFL mode [94]. Transient stability issues have, however, been reported in weak grids due to the phase-locked loops (PLLs) used in GFL inverters [95]. GFM inverters [96] are controlled as a voltage source using a frequency droop curve and can operate synchronously with the grid. GFM inverters appear to be a promising solution; however, the primary differences between GFL and GFM inverters are the control methodology and the way power is used from the DER. During a fault, a GFM inverter must limit its current either through a current loop or by saturating the voltage loop and, as a result, will cease to be a voltage source. Once this happens, the inverter will lock at a particular frequency unless it temporarily switches to a PLL, in which case it will start behaving as a GFL inverter [97]. To avoid such a scenario, GFM inverters would require expensive oversized switches and other components. It has been shown theoretically that GFL inverters can operate in an islanded mode just as GFM inverters and can even synchronize with other GFL inverters even in the absence of a voltage source [98]. GFL inverters have also been shown to be able to successfully ride through a bolted three-phase fault even without a stiff grid frequency in a 100% IBR grid [99]. This suggests that moving completely to GFL or GFM inverters may not be the answer. Research is needed to determine the required portions of GFL and GFM controls through large-scale stability studies with detailed models of all the DERs and microgrid components.

Centralized communication-based algorithms can provide more equitable power sharing and enhance "power supply and balance stability." Field tests conducted by the authors to operate a distribution system in the islanded mode revealed how minor voltage differences accompanied by low line impedance can cause instability [100]. Subsequent modeling and analysis highlighted how the proposed centralized communication-based algorithms can enhance transient stability even with synchronous generators (SGs) with droop coefficients [100]. Electric power grids are already experiencing high instantaneous IBR penetration. They may behave as IBR or synchronous machine dominated at different times of the year. Hence, control algorithms should be able to control any combination of DERs and manage interactions between IBRs and synchronous machines for the successful operation of a microgrid during an event. Even if synchronous machines are not used for generating power, they

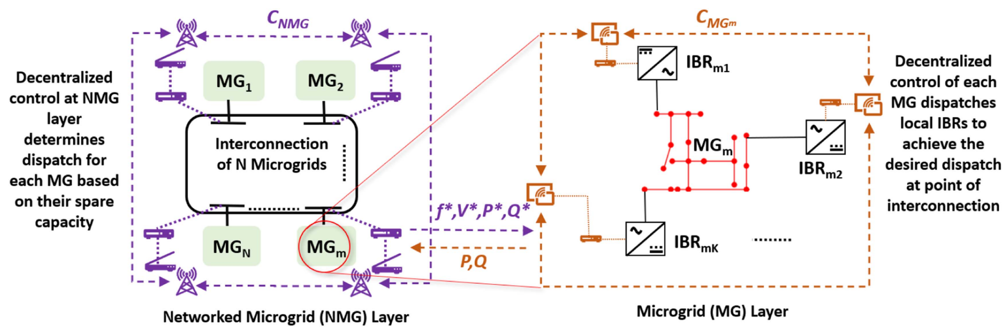


Fig. 8. Decentralized control in networked microgrids for resilience enhancement (Adapted from [109]).

may have been installed as synchronous condensers as has been done in ERCOT [101]. It has been shown that interactions between SGs and virtual synchronous generators (VSGs) can lead to transient instability, primarily due to the large difference in time-delay constants [102]. The difference in angular frequencies between SG and VSG is fed back to the VSG to stabilize the microgrid. This study was limited to a single SG and two VSGs. Studies considering small and large disturbances on realistic microgrid models with a high percentage of IBRs are required [103]. The communication latency should also be considered, especially as it can impact the effectiveness of the control algorithm. An analytical method for determining the critical reporting period of the data acquisition system and communication delay, beyond which a microgrid may become unstable, is provided in [104].

C. Networked RE-Dominated Microgrids

While a standalone microgrid can go a long way in enhancing resilience, it may have to take undesirable decisions, such as curtailing excess solar generation to balance the demand and supply, which is the “worst-case problem,” as discussed in Section III. This energy could be used in a neighboring microgrid by forming networked microgrids, which may, otherwise, have to resort to load shedding. Networked microgrids (see Fig. 8) can serve critical loads by an additional 25% during an event and reduce capital expenditure by more than 15% [105], [106]. Networked microgrids can, thus, enable bottom-up load restoration after an event [107]. However, controlling networked microgrids is significantly more complex than standalone microgrids due to the dynamics of operations [108] and the differences in capabilities of the microgrids being networked together.

A control architecture based on consensus-based distributed cooperative control for networked microgrids is presented in [109]. The networked microgrid layer has a communication network C_{NMG} and each microgrid has its own communication network C_{MG_m}. As shown in Fig. 8, a two-level decentralized control exists at the networked microgrid layer. This layer generates the dispatch commands for each microgrid to maintain a constant system frequency based on the spare capacity information received from each microgrid. The two-level decentralized controllers within each microgrid dispatch their local IBRs to achieve the required output at their point of interconnection. Other fast acting IBR control algorithms can also be evaluated using this architecture.

A two-layer optimization approach for designing networked microgrids is presented in [105] and [110]. It consists of an outer optimization layer, which aims at minimizing investment and maximizing revenue, and an inner layer, which ensures that resilience objectives are met under different extreme events. However, new tools are required to validate the full range of networked microgrid operations. These tools should have detailed dynamic models of networked microgrids and be able to accurately simulate the behavior of commercially available IBR controllers. Thus, networked microgrids supported by comprehensive and robust control algorithms can form the building blocks of the future community-centric 100% RE electric grid.

D. Cyber Security of Resilient 100% RE Distribution Systems

Resilient 100% RE networked microgrids will require centralized and decentralized controllers, intelligent grid-restoration algorithms, and fast communication-based protection algorithms. However, dependence on communication systems also adds vulnerabilities that may be exploited to gain unauthorized access to critical data and execute damaging cyberattacks [111]. There are many sources of cyber vulnerabilities in the electric power grid. Firewalls are used extensively to prevent unauthorized network access. However, configuring firewall rules requires having perfect knowledge of the cyber assets that utilities may not have, due to the use of proprietary software in intelligent electronic devices (IEDs) [112]. The distributed network protocol 3.0 (DNP3), widely used in supervisory control and data acquisition systems (SCADA), has been shown to be vulnerable to cyberattacks [111]. The use of standardized communication protocols and easy access to information about control systems further increases the vulnerability of distribution systems [113].

Once access to SCADA is gained; firmware of IEDs can be changed to cause severe disturbances as was done in the Stuxnet attack in 2010 [114], and more recently in the attacks against the Ukrainian power grid via spear phishing attacks [115]. It has been shown that the modification of the control command or minor modifications to the DER management system’s (DERMS) algorithm can cause severe overvoltages in microgrids [116]. Data privacy is also a major concern, especially in networked microgrids where different types of microgrids are interconnected. Control algorithms, such as the one proposed in [109], which

TABLE I
SUMMARY OF THE PROPOSED DEVICE-LEVEL AND SYSTEM-LEVEL DESIGN AND CONTROL APPROACHES FOR ACHIEVING 100% RE INTEGRATED RESILIENT GRIDS

Research area	Shortcomings with state-of-the-art approaches	Proposed approach based on literature review
• NSf	• Renewable sources, such as PV and BESS (NSf 0 Hz) and wind turbines (NSf 10–20 Hz), are integrated with the grid via individual inverters at an artificially fixed frequency (50/60 Hz) leading to unnecessary energy conversions and efficiency reduction.	• Development of series converters (energy router and direct charger/discharger) capable of working with DERs operating at different voltages and frequencies. These devices using a full-bridge module multilevel converter will have built-in fault protection.
• DeCaFp Technologies	• Using step-up transformers to achieve high voltage and high power • Fixed and inflexible power electronics hardware, separate protection • Mimic SG with the same or similar methods and procedures for startup, grid synchronization, and black start, thus having a prolonged process and scarifying resiliency	• Multilevel inverter technology, wide-bandgap devices • Hot-swap, modular structure, fault protection embedded to individual IBRs • Advanced control of each IBR for instant black start and instant grid synchronization of IBRs and adjacent microgrids, transient-less transformer energization and fast load restoration
• *he*ECaB technologies	• Traditional on–off control of loads • No energy buffering in individual loads • No energy buffering at load level and no storage at community level	• Aggregated load models to average out a large population of loads • Inverter-based VVVF HVA/C and other loads • Energy buffering and storage
• De centralized primary control of IBRs	• Frequency droop for power sharing may not work as fast acting IBRs that can bring grid frequency to nominal values within seconds. • Proportional resonant and model predictive control require significant computation and are sensitive to parameter variations.	• Power sharing among IBRs can be determined using deviations from the reference phase angle. This approach does not force the IBRs to work on the principles of synchronous machines such as in the virtual synchronous machine control mode.
• Centralized secondary control	• Low line impedance can cause instability during synchronized operation of IBRs with only primary autonomous controllers.	• Centralized secondary control can enhance transient stability in microgrids by feeding back differences in angular frequencies to IBRs. Analytical formulation to incorporate communication latency within feedback gain design has also been proposed [104].
• Networked microgrids	• Standalone microgrids are currently being deployed. Even though these enhance resilience, they may have to take sub-optimal decisions. For instance, in the islanded mode of operation, excess generation may need to be curtailed or load shedding may be needed due to demand and generation imbalance, which is the "worst-case problem," as discussed in Section III.	• Networked operation of microgrids can enable optimal power sharing which will minimize the need for energy curtailment or load shedding. Supported by consensus-based distributed control and centralized optimization-based dispatch algorithms, networked microgrids can form the building blocks of the proposed 100% renewable energy integrated resilient grids.

only shares available spare power capacity information amongst microgrids, are required to protect proprietary information. The necessity of restricting cyber–physical interactions to a minimum, while ensuring that resiliency criteria are met, has been suggested in [117], where the cyber vulnerabilities of grid-tied power converters have been discussed.

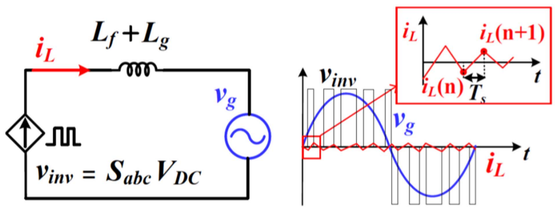
Cybersecurity of power electronics dominated electric grids is a critical area of research [118]. Detailed cyber–physical system (CPS) models of electric power grids are essential to identify and mitigate potential cyberattack paths [119]. A nonlinear autoregressive exogenous model neural-network-based IDS was shown to be able to successfully detect false data injection attacks in the cyber–physical models of dc microgrids [120]. The applicability of this IDS can be enhanced by using properties of data packets to detect cyberattacks instead of using historical voltage and current data. One such approach using a CPS model for DERMS is proposed in [116]. Here a two-tiered intrusion detection system (IDS) is proposed, which detects cyberattacks using message authentication codes, encryption, and time-delay tolerance. An online IDS, which uses chronological relations of abnormal behaviors to create possible attack paths on smart inverters, is proposed in [121]. It can then detect cyberattacks by comparing the similarities between any observed anomalies and the previously identified attack paths. A multiagent system-based approach for intrusion prevention is proposed in [122]. An IDS for use in IEC 61850 based substations to identify falsified measurements in a distributed manner before they are sent out via DNP3 communication is proposed in [123]. A multilayer resilient controller, which can detect compromised cyber links in distributed control algorithms, is proposed in [124].

More research is needed to securely communicate data packets after a cyberattack has been identified and mitigated. One such approach has been proposed in [125], where the focus is not only on cyberattack detection but also on providing an event-driven resilient signal constructed from identified genuine measurements to replace the malicious signal. Another approach could be to determine those points in a microgrid's control system that can cause the largest change in the control system's objective and secure them, as proposed in [126]. The use of network-based intrusion detection and prevention systems can automate the task of blocking malicious packets and re-establishing secure connections [113]. The IDS should not only aim at detecting attacks on smart meters or the SCADA system but also at preventing cascading events after the cyberattack [113]. There is also a need to make the IDSs of individual microgrids work together in a decentralized manner to identify and mitigate cyberattacks in networked microgrids. Table I provides a comparative summary of the shortcomings in the state-of-the-art approaches for device-level and system-level control techniques and the approaches proposed in Sections III and IV to improve them.

To more quantitatively compare the proposed versus the state-of-the-art approaches, the most recent research results by the authors from device-level power electronics to a system-level case study will be provided in Section V.

V. ADVANCED CONTROL AT DEVICE-LEVEL POWER ELECTRONICS AND A CASE STUDY AT SYSTEM-LEVEL CONTROL

A very challenging issue to enhance resiliency is SGs lack of controllability of current, slow process of synchronization due to large mechanical inertia, and long-transient transformer energization. IBRs, however, have an instant current control loop and no inertia, thus providing a great potential to enhance

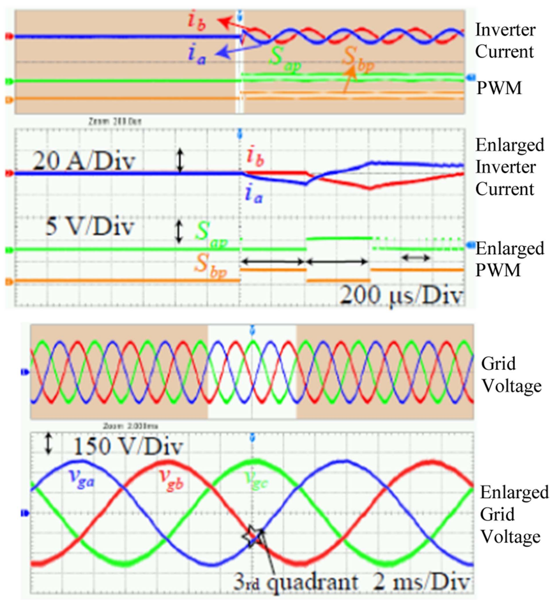


$$S_{abc}\cdot V_{DC} - v_g = (L_f+L_g)\frac{di_L}{dt}$$

$$\sin\theta_a(n+1) = \frac{2V_{DC}(1+K_a)}{3V_g(K_a-1)};\ \cos\theta_a(n+1) = -\frac{4\sqrt{3}V_{DC}}{9V_g}\left[\frac{K_a-K_b}{(1-K_b)(K_a-1)}\right].$$

where $K_a = \frac{i_{La}(n+1)-i_{La}(n)}{i_{La}(n+2)-i_{La}(n+1)}$; $K_b = \frac{i_{Lb}(n+1)-i_{Lb}(n)}{i_{Lb}(n+2)-i_{Lb}(n+1)}$.

(a)



(b)

Fig. 9. Instant synchronization of IBR to grid. (a) Simplified analytical model for IBR interfacing the grid. The derivation shows a grid phase angle that can be obtained by using current samples in two switching cycles. (b) Experimental waveforms of IBR startup and instant synchronization to grid. The IBR was able to provide regulated current (power) to grid after two switching cycles of pulsewidth modulation turned ON.

resiliency to an unprecedented level by advanced control to realize instant black start, instant synchronization, phase angle jumping or step change, and transientless instant transformer energization. For example, the traditional SG synchronization to the bulk grid takes tens of minutes. However, an advanced control of IBRs (a DeCaFp technology proposed in this article) showed that it is possible to synchronize with the grid instantly [72]. Fig. 9 shows that the control principal and mathematical theory to prove an instant synchronization of any IBR to grid is possible within a couple of switching cycles of the inverter. The grid phase angle information is within the current and an IBR has the instant current control, which the traditional SGs do not have.

Another feature of IBRs is instant phase angle jump or step change, which is very important for the fast and simultaneous black start of individual microgrids, bulk power generators, and individual sections of power grids, all independently. For example, after a total blackout due to an event, a local microgrid with local energy storage and IBRs, as shown in Fig. 3, can have an instant black start for itself without waiting for the bulk

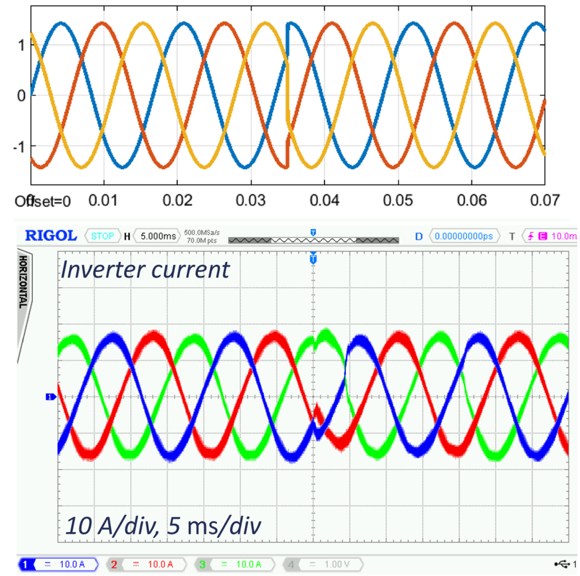


Fig. 10. Top: Grid voltage has a sudden artificial phase angle jump by 30°. Bottom: IBR output current is instantly resynchronized to grid and has good current regulation.

power and immediately restore local critical loads. Once the bulk power is back, IBRs capability for instant phase angle jump can synchronize a local microgrid to bulk power grid immediately. This phase angle jump capability can also be used to synchronize two adjacent microgrids that were initially and independently black started and operated. This reversed black start process (bottom-up approach) can greatly enhance the resiliency compared with the traditional top-down approach. The traditional SG can never have a phase angle jump due to its large mechanical inertia. As shown in Fig. 10, where a sudden phase angle jump is artificially introduced to the grid voltage, the IBR can follow the grid instantly and still regulate the current well in experimental validations.

Networked microgrids supported by advanced DeCaFp devices have been proposed to be essential for achieving community-centric renewable and resilient energy grids. The case study presented here illustrates this concept through theoretical analysis, simulations, and models created using real-time data. This study provides both analytical and quantitative comparisons of the three proposed system-level control approaches, as summarized in Table I. It shows how the proposed DeCaFp UPFC changes its terminal voltage's magnitude and phase angle to implement the optimal power dispatch determined by the secondary centralized control to ensure the stability of the networked Virginia Tech (VT) electric services (VTESs) microgrid and the bulk grid.

To achieve VTs goal of 100% renewable electricity as a part of its climate action plan, a resilience plan has been developed. This involved detailed modeling of the VTESs network and the creation of VTES network's digital twin in a real-time distribution simulator RTDS. Using this digital twin, the locations and ratings of IBRs, such as PV and battery energy storage systems (BESS), were determined. These IBRs can restore the critical loads within the VTES network after an outage and reduce its dependence on the bulk grid.

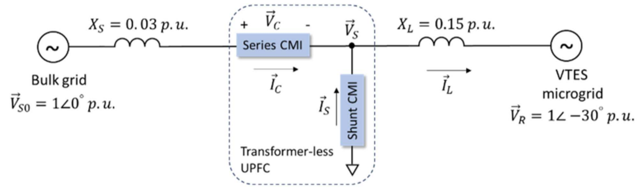


Fig. 11. Enhancing networked microgrids controllability and resilience using DeCaFp UPFC.

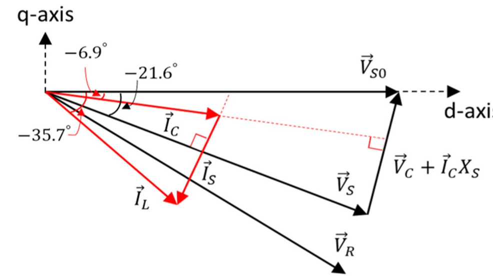


Fig. 12. Phasor diagram to achieve controlled power flow between networked microgrids using DeCaFp UPFC.

In this case study, an HILF event, such as a major hurricane or cyberattack, has been considered leading to widespread outages affecting both the VTES grid and the bulk grid, in more severe cases separating the VTES microgrid from the bulk grid. The VTES network supported by advanced control capabilities will be able to restore supply autonomously to its critical loads as a microgrid using the locally available IBRs, significantly reducing its power demand from or even feeding power to the bulk grid. This excess (or assisting) power enables faster restoration of the bulk grid, which itself is operating as a microgrid in the postoutage restorative state. As shown in Fig. 11, large angle differences may exist between the VTES microgrid and the bulk grid during the restorative state due to limited controllability and quick autonomous restorations [41]. This may lead to large power flows, line congestion, and even restoration failure. In the absence of any DeCaFp device, the uncontrolled power flow ($P_0 + jQ_0$) between these networked microgrids can be calculated using the following equation:

$$P_0 + jQ_0 = \vec{V}_R \left(\frac{\vec{V}_{S0} - \vec{V}_R}{j\left(X_L + X_S\right)} \right)^* = 2.78 - j0.74 \text{ p.u.} \quad (4)$$

This excess power flow can be controlled using a transformerless UPFC, a DeCaFp device, previously proposed by Peng et al. [41]. Unlike a conventional UPFC that must have coupling series transformers that require a very long energizing time during restoration and have a slow dynamic response, the proposed UPFC uses a series and a shunt-cascaded multilevel inverter (CMI) to eliminate the need for transformers completely, and thus provides high efficiency, high reliability, low cost, and most of all ultrafast restoration and dynamic response. As shown in Fig. 11, a UPFC can be added between VTES and the bulk grid to control the power flow between the networked microgrids to the desired value of $P^* + jQ^* = 1 + j0.1$, with the same bulk grid and VTES voltages. Compared with (4), it can be seen that in the absence of the DeCaFp UPFC, excess power would have flown between the networked microgrids potentially leading to instability and restoration failure. After deploying the UPFC, the value of the new sending end voltage $\vec{V}_S$ to obtain the desired power flow between the networked microgrids is obtained using the following equation:

$$P^* + jQ^* = \vec{V}_R \left(\frac{\vec{V}_S - \vec{V}_R}{jX_L} \right)^* \Rightarrow \vec{V}_S = 1.026\angle - 21.6^\circ \text{ p.u.} \quad (5)$$

This desired sending end voltage $\vec{V}_S$ is obtained by operating the series CMI as a controlled voltage source to generate a voltage $\vec{V}_C$, which controls the active and reactive power flows through the line. The shunt CMI injects a current $\vec{I}_S$, which ensures no active power exchange in either CMI, thereby eliminating the need for transformers. This is done by making the series ($\vec{I}_C$) and shunt ($\vec{I}_S$) CMI currents perpendicular to their respective voltages $\vec{V}_C$ and $\vec{V}_S$ [41], [69]. Thus, the values of the control commands for the series CMI ($\vec{V}_C = 0.35\angle 83.1^\circ$ p.u.) and the shunt CMI ($\vec{I}_S = 0.499\angle - 111.6^\circ$ p.u.) are obtained by solving (6)–(9), as shown in the phasor diagram in Fig. 12

$$\text{Re}\left(\vec{V}_C \vec{I}_C^*\right) = 0 \quad (6)$$

$$\text{Re}\left(\vec{V}_S \vec{I}_S^*\right) = 0 \quad (7)$$

$$\vec{I}_C + \vec{I}_S = \vec{I}_L \quad (8)$$

$$\vec{V}_{S0} - \vec{I}_C X_S - \vec{V}_C = \vec{V}_S. \quad (9)$$

The analysis above presented a detailed discussion of how the transformerless DeCaFp UPFC can provide power flow based on a particular set point between the networked bulk and VTES microgrids. This enables successful grid restoration and avoids congestion. This proposed DeCaFp UPFC provides independent control over both the magnitude and angle of $\vec{V}_C$, thereby allowing power flow control from light to heavy loading conditions even though the sending and receiving end voltages are fixed. Fig. 13 shows the waveforms for $\vec{I}_C, \vec{I}_S$, and $\vec{I}_L$ as the desired power flow set point is varied from light to heavy loading conditions. The uncontrolled power flow in the absence of UPFC is also plotted.

The above case study can be easily extended to cases to use the transformerless DeCaFp UPFC to link two adjacent microgrids that may have a large phase angle difference and are asynchronous with each other during their own restoration periods. Fig. 14 shows that a transformerless UPFC directly links two 13.8-kV/2-MW microgrids together, although the left and right microgrids have a large phase angle difference of almost 30°. The experimental setup demonstrated instantaneous power flow control between the two microgrids. The instantaneous phasor diagram and instantaneous current transfer from the left to the right microgrids are shown on the right-hand side of the figure. Without this DeCaFp device, the two adjacent microgrids cannot be restored quickly and autonomously. A direct linkage of

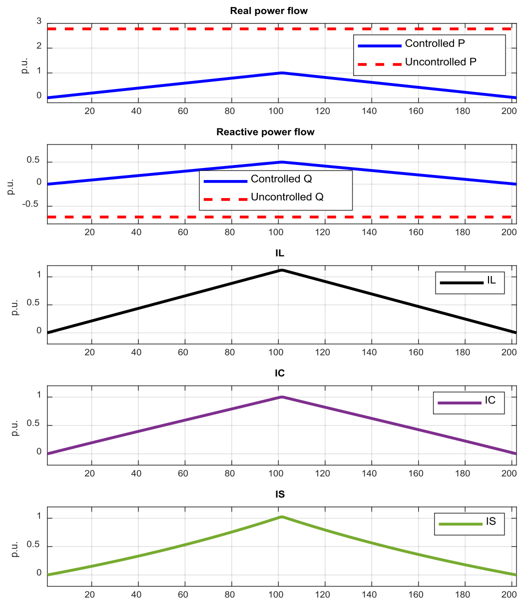


Fig. 13. Simulations results of light to heavy loading conditions.

two adjacent microgrids may result in instability and restoration failure.

VI. Future Research Topics

1) Resilient and RE grids start from the device level up. Resiliency at the device level includes hardening underground cable [127], [128], [129], [130], hot-swap and/or self-healing power electronics, redundant and modular circuit topologies, and plug-and-play features, which along with the following examples are among the top of the topic list.
2) The dc and instant ac circuit breakers.

With ever-increasing demand for reliability and resilience, dc and instant ac circuit breakers become indispensable to make it a reality for dynamic and reconfigurable energy grids. A typical ac circuit breaker takes a couple of fundamental cycles to interrupt fault current. Successful interruption of a fault in an ac system instantly, without waiting until its natural zero crossing moment, can reduce the cost of a single protection device by at least one-third, and the reduction of associated footprint for surrounding grids can also be significant. While an instant ac circuit breaker is technically achievable based on a similar principle as dc circuit breakers (i.e., to interrupt nonzero current anytime), novel circuits are needed to handle bipolar voltage and bidirectional current in ac systems.

3) Stability and controllability.

In a 100% RE grid, electromechanical links will be increasingly replaced with control-based links as IBR penetration increases in distribution systems. The use of intelligent power electronics based solutions has been shown to be more effective at increasing resilience than grid hardening measures [26]. Owing to the strong coupling between voltage and frequency in microgrids, stability is defined based on the interactions between equipment and controllers, rather than the variables impacted [90]. Resilient operation of 100% RE distribution grids would, thus, require fast and accurate control algorithms for the different NSf, DeCaFp, and heECaB technologies. Robust control algorithms for power electronics interfaced loads [88] and IBRs can improve dynamic system response during transients. Research is needed to develop such control algorithms. Control approaches, which make IBRs behave as SG, may lead to instability, as was shown in [102]. Centralized control algorithms can provide more equitable power sharing amongst IBRs and should be capable of controlling different combinations of DERs as the grid may be IBR dominated or SG dominated at different times.

Most current research evaluates the effectiveness of the proposed control algorithms using linearized state-space models of microgrids. Even if eigen values are found to be stable for these models, complete controllability of the microgrids under all operating scenarios is not guaranteed. Here, complete controllability refers to the ability of the microgrid to move from any state within a specified region of the state space to any other state in the same region [131]. This would require characterization of the complete controllability region of a nonlinear microgrid model for different types of controls using computationally feasible methods. Nevertheless, such a rigorous approach can provide better assurance about the ability of the control algorithms to steer the microgrid toward stable equilibrium points.

Studies have shown that the size, location, and numbers of GFM inverters can impact frequency response [9]. It has also been suggested that GFM inverters may start behaving as GFL inverters during a fault and cease to be a voltage source after limiting current. Theoretical algorithms should, thus, be developed for obtaining the optimum percentage of GFL and GFM IBRs required for the stable operation of microgrids. These should be validated using large-scale power system cases with nonlinear microgrid models and IBR controller models. IBR controller models should accurately mimic the behavior of commercially available IBR controllers.

4) Standardized microgrid DeCaFp building blocks.

Networked microgrids enhance resilience by allowing energy exchange between neighboring microgrids. However, microgrids may have different topologies and may be completely ac or dc or have a hybrid ac/dc configuration. Thus, to speed up the deployment of microgrids and simplify their networking process requires standardized control, power conversion (or DeCaFp), and communication capabilities. The concept of building blocks for microgrids as proposed in a white paper, which was produced as a part of the U.S. DoEs microgrid program, is a significant step in this direction [132]. Microgrids can then form the building blocks for the 100% RE electric grid [133].

This would require the development of distributed control algorithms supported by fast and reliable communication to enable the integration of fleet of IBRs providing services to the bulk grid. Analytical methods need to be developed to determine the critical latency of data acquisition systems to ensure networked microgrids remain stable. The interactions between cyber and physical systems of networked microgrids need to be managed to reduce vulnerabilities while ensuring that system reliability is maintained. The applicability of IDSs can be enhanced by using properties of data packets to detect

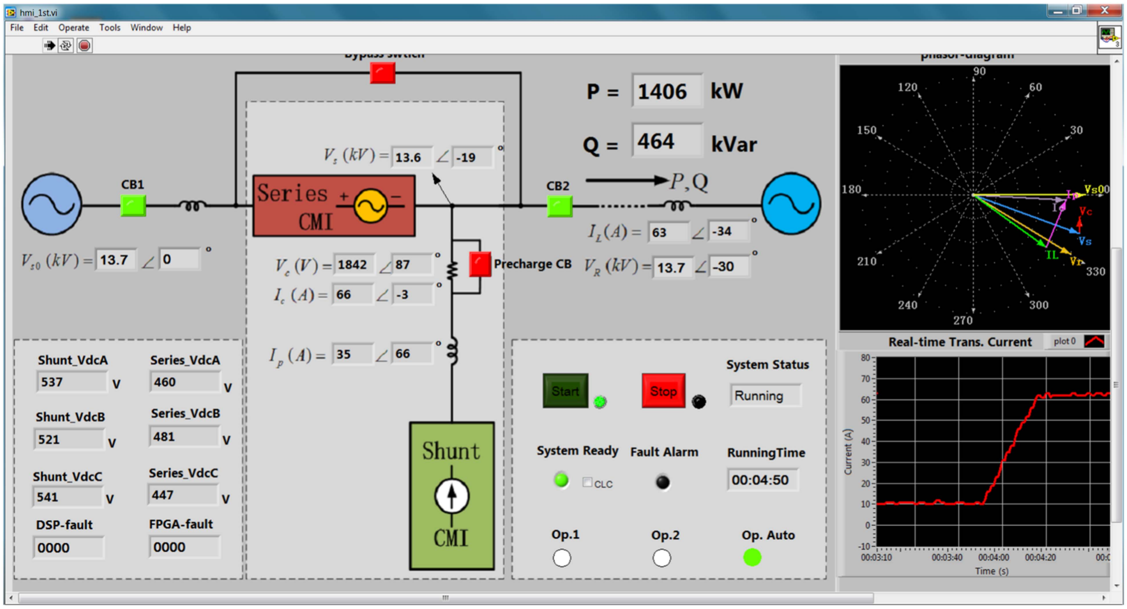


Fig. 14. Human machine interface showing networked microgrid operation enabled by the proposed DeCaFp UPFC.

cyberattacks instead of using historical data. Research is needed to not only detect cyberattacks but also to recover and securely communicate genuine control command data packets to ensure system stability.

5) Protection and coordination.

Faults may happen in microgrids, especially under extreme weather conditions. Traditional overcurrent protection schemes, which rely on the high subtransient fault currents from SGs, may not work satisfactorily in high IBR microgrids as inverter's fault current is limited to about 1.1–1.5 times of its rated current [134]. Distance protection suffers from over-reach and under-reach problems in microgrids with laterals, even in the absence of IBRs and cannot be used. Undervoltage protection can easily detect the presence of a fault in a microgrid with IBRs due to the very low voltages observed. However, due to the small fault currents from IBRs, the voltage drops within the microgrid are also small, which makes fault location identification challenging [134]. As IBRs may operate in either GFL or GFM mode based on whether the microgrid is in grid connected or islanded modes of operation, it is essential to have protection schemes capable of adapting relay settings under both configurations.

Differential protection has emerged as a promising solution that can be used effectively in high IBR penetration scenarios [135]. This scheme uses high-speed communication between digital relays to ensure that the vector sum of all current flowing in and out of the protected section is close to zero. This scheme, however, is expensive as it requires measurement devices to be installed at all locations where current enters or leaves the protected section. Solutions to reduce the cost of differential protection schemes, such as forming optimal protection zones instead of protecting each component individually [136], and low-cost measurement devices, such as DeCaFp devices programmed to act as differential relays, are required. More research is needed to develop protection schemes that do not rely on the

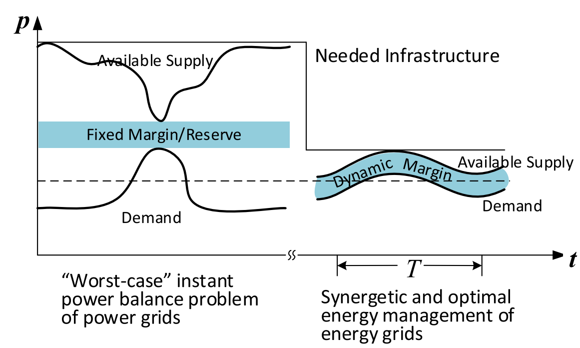


Fig. 15. From the power grid's "worst-case" instant power balance problem to the energy grid's synergetic and optimal management.

magnitude of fault current; examples are waveshape or time of arrival-based traveling wave techniques [137].

6) Artificial intelligence (AI) based energy management of energy forecasting, production, storage, and consumption.

Thanks to the advanced communication, data collection, and computer technologies, the management of the proposed energy grid can be enhanced by self-learning based on AI. By data fusion, the state-of-the-art production forecasting (one-day ahead) of a single renewable power plant is within an averaged 10% nominal mean absolute error over one year period (weather-scenario independent). Ongoing AI-based energy management research and development shows a reduction of the cost by means of increasing the forecast accuracy and reducing the system spinning reservation. An overall goal of managing energy production, storage, and consumption by forecasting and AI is illustrated in Fig. 15, where research topics include the following.

i) A holistic energy management approach to significantly maximize the values of utility assets, their energy delivery capacity with the existing infrastructure, and eliminate or

TABLE II
SUMMARY OF THE PROPOSED FUTURE RESEARCH TOPICS CRITICAL FOR ACHIEVING 100% RE INTEGRATED RESILIENT GRIDS

Research area	Shortcomings with state-of-the-art approaches	Proposed approach based on literature review
• Circuit Breakers	• AC circuit breakers wait until zero crossing and take several cycles to clear faults. • This increases grid-restoration time.	• AC circuit breakers using techniques similar to DC breakers to interrupt non-zero fault current and also capable of handling bipolar voltage and bidirectional current are required.
• Stability and Controllability	• Current research is limited to the use of small power system models with a few nodes to test the impact of inverter control algorithms. • Stability of power systems is analyzed using linearized state-space models.	• Algorithms to determine the optimal percentage of GFM and GFL inverters, validated using studies on detailed large-scale networked microgrid models, are required. • Controllability of nonlinear models of microgrids which is their ability to move from any state within a specified region of the state space to any other state in the same region, should be characterized.
• Microgrid DeCaFp building blocks	• Microgrid deployment currently requires significant customized engineering effort, which increases their time and cost of deployment.	• Standardized control, power conversion (or DeCaFp) and communication microgrid building blocks [97] are required to reduce the time and cost of deployment of networked microgrids
• System protection	• Traditional overcurrent and undervoltage protection schemes will not work effectively under high IBR penetration due to the low fault currents and low voltage drops. Distance protection too suffers from over and underreach problems in relatively smaller microgrids.	• Use of DeCaFp devices programmed to act as relays can reduce the cost of deployment of the most effective differential protection scheme. The scheme needs to be able to adapt to both GFM and GFL modes of operation.

delay the need to expand and/or upgrade infrastructure to meet ever-increasing load demands.

ii) Promising methods and algorithms to reduce energy storage requirements and use loads as a part of utility assets for energy buffering/peak-power shifting.

iii) AI and deep machine learning-based energy management methodologies and application examples to tackle the synergy, complexity, and optimization of energy production, storage, and consumption simultaneously.

iv) A transformation of the "worst-case problem" (i.e., the lowest point of power supply has to meet the highest load demand, the infrastructure has sized up according to, or the total energy delivery capacity of the existing infrastructure is severely limited by one single peak-power demand) to synergetic and optimal energy production, storage, and consumption.

7) Community energy grid planning.

The types and size of the energy storage are dependent on energy distance. Applications regarding energy distance from near to far can be reconsidered through the lens of energy rather than power in terms of voltage support, capacity firming (or grid firming), frequency regulation, curtailment reduction, load shifting, energy arbitrage, and so on. Small size (in watthours), fast response, and high-power density storages need to be integrated close to the end-user for energy delivery against short-term interruption. However, large size and high-energy-density storages are needed for longer energy distance (longer time scale) to the community, with the purpose to reshape the load curve for transmission demand reduction or economic operation. Table II provides a comparative summary of the shortcomings in the state-of-the-art approaches and proposed future research directions for the integration of DERs with power systems and how these can enhance system stability, controllability, and protection.

VII. REMARKS

Although we have focused on North American power grids to address the infrastructure challenges, similar situations can be found around the world, especially in large contiguous countries, such as India and China. Our proposed several fundamental and conceptual changes to today's power grids, as summarized in Table III, would have wider implications than just for North America alone.

TABLE III
FUNDAMENTAL AND CONCEPTUAL CHANGES

Power Electronics	Energy Electronics
Synchronous Power Grid	Asynchronous Energy Grid
Power generation, transmission, distribution, and load demand at each time instant	Energy production, transmission, distribution, and consumption over a period of time
Power supply and demand balancing (spinning reserves and demand response) at each time instant	Energy production, storage, and consumption management and coordination over a period of time from seconds to minutes, hours, and days
Fixed voltage and fixed 50/60-Hz AC power as the medium	Nsf and naturally variable voltage energy
IBR i.e., inversion to 50/60-Hz AC	Converter-Based resource CBR i.e., direct conversion w/o going through 50/60-Hz AC
Circuit breaker-based fault protection that is independent of power sources and loads	Integrated fault protection to energy sources, conversion devices, and consumption loads
Instantaneous control of reactive and active power, i.e., voltage and frequency	Energy management, including energy routing and storage
Dominantly inductive power sources and overhead lines	Dominantly capacitive energy sources and underground cables [127]-[130]

From the enabling technology's device level, one of the "fundamental and conceptual changes" summarized in Table III is from "power electronics" to "energy electronics." Traditionally, power electronics deals with the processing of high voltages and currents to deliver power that supports a variety of instant power conversion needs, acts as an interface between the electrical source and the electrical load, between two different sources, and so on. We define "energy electronics" as the integration—over both time or horizontal axis and functional or vertical axis—of power electronics with energy buffering functions, energy storage capabilities, and/or self-protection/circuit breaking, thus acting as an energy processing and delivery system. The proposed renewable and resilient energy grid can be built using a bottom-up approach starting from the community level and through the lens of energy instead of power to meet the need for both energy and resiliency with respect to natural and man-made disasters. Transforming today's power grids to energy grids can significantly increase the energy delivery capacity of the existing transmission and distribution grid infrastructure to meet community energy demand. The existing 50/60-Hz ac power grids with fixed voltage and fixed frequency pose significant challenges for large-scale RE integration and modernization to achieve resilient and secure energy generation and supply. The new energy grid will avoid multiple back-and-forth power conversion and the associated losses and vulnerability. The NSf energy grids use the natural frequencies of RE sources and optimal voltage levels in the generation, transmission, distribution, storage, and consumption with much higher efficiency. The controllability of energy systems involving numerous GFM, GFL, as well as traditional control resources will require comprehensive, in-depth studies based on large-scale system models. Networked microgrids supported by fast acting centralized and decentralized control algorithms can be the building blocks of these future grids. The development of suitable control and protection schemes will be essential to protect the proposed grids from cyber and physical threats. RE, energy storage, and power electronics together can and will revolutionize the existing power grids and transform them into energy grids.

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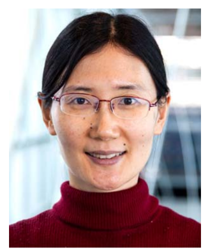

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