A Review of Current Research Trends in Power-Electronic Innovations in Cyber–Physical Systems

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***Abstract*—In this article, a broad overview of the current research trends in power-electronic innovations in cyber–physical systems (CPSs) is presented. The recent advances in semiconductor device technologies, control architectures, and communication methodologies have enabled researchers to develop integrated smart CPSs that can cater to the emerging requirements of smart grids, renewable energy, electric vehicles, trains, ships, the Internet of Things (IoT), and so on. The topics presented in this article include novel power-distribution architectures, protection techniques considering large renewable integration in smart grids, wireless charging in electric vehicles, simultaneous power and information transmission, multihop network-based coordination, power technologies for renewable energy and smart transformer, CPS reliability, transactive smart railway grid, and real-time simulation of shipboard power systems. It is anticipated that the research trends presented in this article will provide a timely and useful overview to the power-electronics researchers with broad applications in CPSs.**

***Index Terms*—Communication, control, cyber-physical systems (CPSs), microgrid, power electronics, protection, real, reliability, resilience, security, simulation, solar, storage, transformer, wind energy, wireless.**

I. Introduction

THE recent advancements in wide bandgap semiconductor devices, electric vehicles, and locomotives and a general push from the government agencies worldwide toward renewable energy integration have resulted in a number of advancements in power electronics research. These include, but are not limited to, high-efficiency power circuit topologies, sophisticated battery management and charging systems, intelligent power converters, wireless power transfer (WPT), and the Internet-of-Things (IoT) devices. A feature that distinguishes the current research from conventional power electronics is the attempt to seamlessly integrate the cyberlayer consisting

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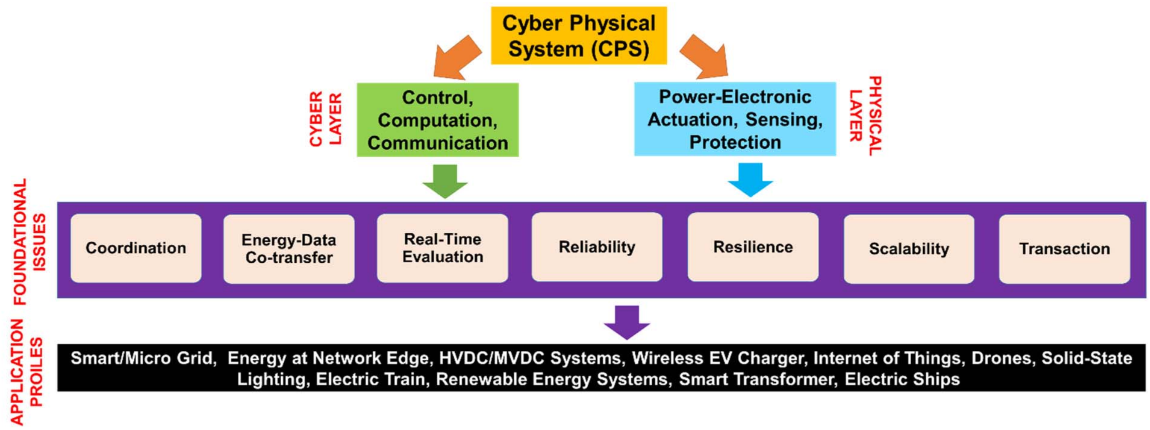


Fig. 1. Mapping of topics covered in this article to the components of CPSs.

of control, communication, and computing with the physical layer that includes the power semiconductor devices, passive, and active circuit components. It is this integration that helps in developing smart power solutions for applications, such as IoT, fast charging solutions for electric vehicles, and aircraft for urban air mobility.

In this article, a review of the current research trends in power electronics innovations in cyber–physical systems (CPSs) [1] is presented. This is described with reference to several broad application areas, such as smart/micro-/nano-grids, e-mobility, smart energy routing, IoT, and resilient energy systems. The topics include alternate power distribution architectures, topologies, protection schemes, communication technologies, smart power components, and reliability of CPS. Fig. 1 pictorially depicts all the sections presented in this article and maps them to the components of CPS.

It must be noted that such a broad collection of research topics that come under CPS has not been presented in the literature. This article is targeted at enabling the research community in the areas of power electronic hardware, control techniques, and communication technology (wired/wireless) to look for integrated CPS solutions that can help in developing smart and resilient power converter technologies with the ultimate goal of achieving energy sustainability.

The organization of this article is given as follows. Section II introduces a resilient energy CPS. Section III describes a power architecture and protection technology in modern and smart grids. Section IV discusses the recent trends and issues in e-mobility and power and information cotransmission. In Section V, promising methods for coordinated control of power-electronics-based networks are discussed. Section VI gives an overview of the reliability in CPSs, while Section VII describes power topology advances and smart transformer modules. In Section VIII, a transactive approach to cost of electricity reduction in a smart railway grid is outlined followed by a description of real-time (RT) simulation for shipboard power systems (SPSs) in Section IX. Conclusions are provided in Section X.

II. Cyber–Physical and Resilient Energy Systems

A power/energy system can be described as a CPS [1], where a network of heterogeneous energy-suppliers and

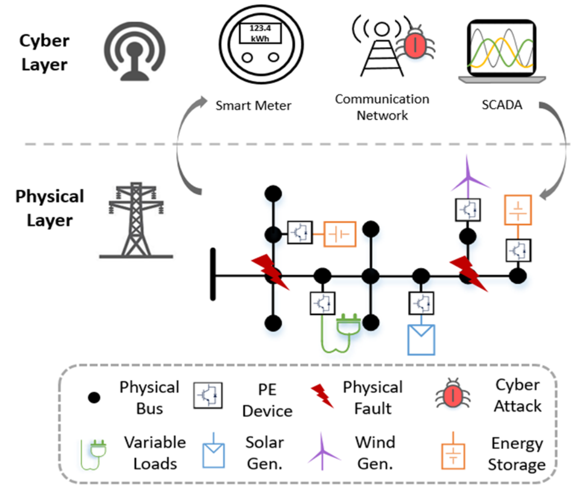


Fig. 2. Overview of an energy CPS.

end-users form the physical layer, and the sensors, communication networks, supervisory control and data acquisition (SCADA) systems, and control systems form the cyberlayer, as shown in Fig. 2. The proper operation of an energy system relies heavily on data collection, processing, and transmission, all conducted by the cyberlayer. For example, a variety of system measurements are synthesized at a SCADA to assist in system monitoring, protection, RT control, and economic dispatch [2]. Recently, the increasing deployment of advanced metering infrastructure, emerging communication networks, and powerful computing units have allowed for even more wide-ranging monitoring and remote-control capability for energy systems.

Although it is expected that the increasing investment in the cyberlayer will make an energy system more resilient to contingencies, many still are concerned that the increasing dependence of system operations on cybernetic technologies might introduce new challenges. First, a malfunction of a cyber-domain component could lead to high-impact physical-domain contingencies. For example, the cause of the costly Northeastern 2003 blackout was believed to be a software bug in the alarm system that hindered it from responding to a supposedly minor fault [3]. Second, adversaries might exploit or even plant loopholes in the cyberlayer to maliciously maneuver system operations or to steal private and security-related information. In the 2015 Ukraine power grid cyberattacks, the adversaries corrupted the information system to paralyze the power supply for tens of thousands of customers [1]. Third, when cyberevents are accompanied by physical contingencies, such as faults, as shown in Fig. 2, the harmful impacts might be even more severe. Fourth, many recent works have underlined the emerging challenges due to the rapid integration of distributed energy resources (DERs) [4]–[6], as their growing distributed capacity calls for the need for coordination to a certain extent; however, the sheer number creates difficulty for monitoring of cyber–physical threats. Fifth, the expanding data sets about an energy system may be eluding proprietary and security-related data; advanced data mining approaches can recover safety–critical information [7], [8]. For example, it is shown in [9] that using only publicly available data is enough to launch attacks to disrupt the operation of the power system of New York City. Sixth, many are concerned about the cybersecurity of new technologies, such as IoT and cloud computing [10], [11]. While the former promotes more communications, the latter requires the concentration of data, both of which could be vulnerable to cyberattacks [10]. To build a full-fledged energy CPS, the resilience issue with respect to all sorts of cyber–physical threats needs to be thoroughly addressed.

Resilience-related problems for an energy CPS have been studied recently with transdisciplinary approaches. For instance, functional analysis [12], data-driven approaches [13], and stochastic optimization techniques [14] have shown promising results in studying system analysis, attack detection, and system-hardening problems. Many cyberattack detection methods have been developed recently [15]–[19]. Both model-based and model-free methods have been developed [15]. For the former, attack detection techniques based on weighted least squares (WLSs) formulations are to be used in applications, such as state estimations [16], [17]; meanwhile, standard fault detection and isolation methods, such as observer-based fault detection methods, have been developed as well [18]. As for model-free methods, a variety of machine learning-based methods has been developed [7], [8], [19], ranging from supervised learning approaches [8], [19] and unsupervised counterparts [7].

III. Power Architectures and Protection Schemes in Modern Power Grids

A. Power Electronics Intelligence at the Network Edge Inverter Technology at the Grid Edge

DERs, such as solar, are expected to grow substantially in the near future due to the sharp drop in the cost of solar panels. More than half the total U.S. photovoltaic (PV) capacity comes from distributed PV connected to distribution systems [20]. High penetration of DERs typically has variable output; therefore, maintaining a good voltage profile becomes challenging due to the relatively low spatial and temporal resolution of voltage control devices [21]. In traditional residential systems, the house/load is directly connected to the grid, and the residential load is susceptible to grid voltage variations.

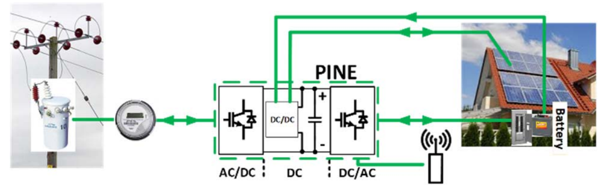


Fig. 3. Proposed power electronics at the grid edge—a self-organizing converter with control intelligence at the edge of the grid.

Furthermore, it is not possible to limit the amount of power delivered to each consumer in the case of limited availability, such as during disasters. Furthermore, nonlinear residential loads inject current harmonics into the grid.

A solution for fast volt-VAR control has been studied in [22], where an edge of network grid optimization (ENGO) device is used to inject reactive power at the secondary side of distribution transformers, correcting the voltage variations between 2 and 13 V at the edge of the grid. Such a device has been shown to work autonomously, with a subcycle response. Another option is the use of smart transformers to compensate for voltage variations at the grid edge [23], [24]. These transformers combine line and medium frequency transformers with partially rated power electronic modules.

In a recent study [25], a self-organizing power electronics converter (see Fig. 3) with control intelligence at the edge of the electric distribution network has been introduced. The proposed system, called Power Electronics Intelligence at the Network Edge (PINE), as shown in Fig. 3, consists of three main stages: a front-end PWM converter that reduces current harmonics and maintains constant dc-link voltage, rooftop solar PV/Battery system connected to the dc-link, and an output PWM converter that feeds the load. The proposed approach enables several advantages. The PINE converter processes all the power from/to the grid, adding the ability to manage and route the energy in all directions; this enables utility companies to limit the amount of energy delivered to each customer, particularly useful during power outages. Also, because PINE allows for the output voltage to be regulated, the voltage regulation needed from the utility company can be significantly reduced. Finally, the rectifier section of the topology can be controlled to exhibit a power factor close to unity, reducing the rms value of distribution line currents and, thereby, minimizing losses.

To study the behavior of multiple PINE converters connected in a distribution network (see Fig. 4), an average model for an individual converter is developed. The average model is exercised on a test feeder based on the IEEE-37 test-node feeder [26], as shown in Fig. 4. A detailed study of this concept is available in [25].

B. Coordinated Protection of HVDC and MVdc Systems in Microgrids

Voltage-source converter (VSC)-based high voltage direct-current (HVDC) systems have been well accepted as feasible solutions for grid interconnection and large-scale renewable energy integration over long distances [27]. Recently,

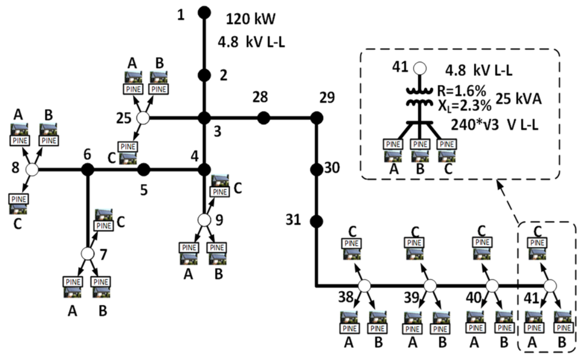


Fig. 4. Test feeder used to simulate high penetration levels of PINE in a distribution feeder, based on the IEEE-37 test node feeder.

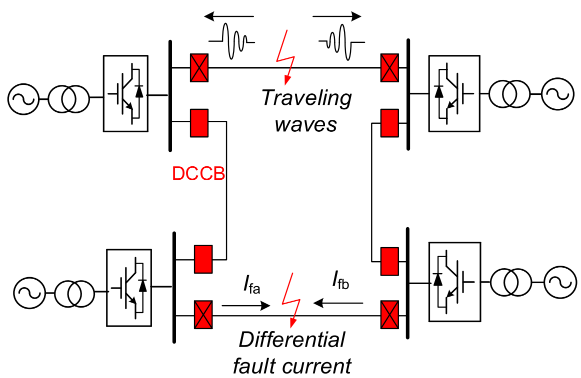


Fig. 5. Protection schemes of meshed dc grids.

the application of medium voltage direct-current (MVdc) systems has increased significantly due to their deployment in microgrids [28]. Protection of HVDC and MVdc systems is challenging since the dc circuit has a lower inductance, a higher rate of change of fault currents, and a faster fault propagation than an ac circuit with an identical rating. Therefore, the next-generation protection system for HVDC and MVdc systems is being developed using advanced cyber and physical techniques, such as digital relays, communication links, and dc circuit breakers (DCCBs), to enhance the security and resilience of hybrid ac/dc power systems.

Pilot protection schemes, such as those based on wavelet transform and differential current methods, require communication links between relays at both ends of a dc line to compare measured signals at two ends for fault detection [29], [30]. Specifically, the wavelet transform method is to detect the transient signals that travel along a dc line with multiple frequencies' waves moving away from the fault location toward both ends of the line, as shown in Fig. 5. The wavelet transform method can identify the time and frequency characteristics of a fault current traveling wave at two ends and extract their polarities to discriminate the internal faults located on a dc line. The differential method relies on the detection of the difference between fault currents (I_{fa} and I_{fb}) that feed into the fault location from two ends of a dc line. With the detection of dc faults, the relays on both ends of the dc line will trigger DCCBs to interrupt fault currents and isolate faults. These detection methods are reliable but rely

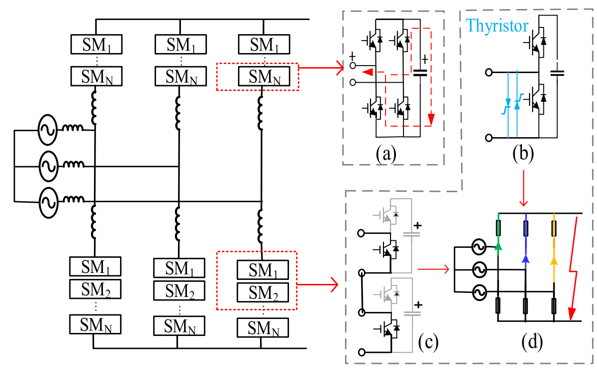


Fig. 6. Configuration of a MMC-HVDC protection strategy: (a) full-bridge MMC, (b) half-bridge MMC with a thyristor-based bypassing circuit, (c) bypassing circuit formed by control of IGBTs in a half-bridge MMC, and (d) balanced ac short circuit.

heavily on a communication link between the relays at two ends. The communication link can be costly for a long dc line and with a communication delay that cannot be neglected. Alternative protection schemes detect dc faults based on local signals, such as voltages, currents, and their derivations [31]. Although these methods cost less, they require a high sampling frequency and are less reliable since they are easily affected by signal noises and measurement errors.

There are protection schemes based on the coordination between converters and DCCBs. Currently, the existing DCCB techniques are limited by their response time, voltage rating, and cost. These protection schemes perform a flexible control of converters to limit dc fault currents to reduce the rating and cost of the DCCBs. The corresponding strategies include: 1) applying full-bridge modular multilevel converters (MMCs) to block the fault current flowing through IGBTs' diodes [see Fig. 6(a)] and 2) using half-bridge MMCs to form bypassing circuits using additional thyristors or controlling their own IGBTs [see Fig. 6(b) and (c)] [32], [33]. These bypass circuits can convert the dc fault circuit into a balanced ac circuit. As a result, the MMC capacitors stop discharging, and the dc fault current is reduced dramatically to enable successful tripping of the DCCBs with a lower rating.

The protection coordination between dc and ac systems is also significant for hybrid ac/dc power systems because the control and operation of dc systems have significant impacts on traditional protection systems of ac systems. The research work in [34]–[36] proposed a fast and reliable algorithm to identify miscoordinated relays in an ac system due to interconnection of the HVDC and determine their appropriate relay settings.

IV. E-Mobility and Wireless Information and Power Transfer

A. E-Mobility and Charging

Electric vehicles are here, and this time, they are here to stay. All-electric propulsion systems can be powered by a battery, a fuel cell, or a gasoline-powered alternator to form battery electric, fuel cell hybrid, and extended-range electric vehicles. The electric propulsion includes a traction inverter and an electric motor. In the fuel cell hybrid case, there is also a need for a voltage regulator to supply constant voltage to the inverter even when the fuel cell output voltage reduces at higher loads. The battery-electric vehicle includes either an onboard charger or an off-board charger. Typically, more than 100-kW power will be transferred through the inverters to move the vehicle. Cyber–physical security of these components is important to ensure that the right amount of power is produced at the right time. Hijacking the torque command or charging command can result in major damage to the vehicles and the people riding in them. In addition to these, the sensors on these vehicles must process the right data and output the correct results for the vehicle to function properly without posing danger to anyone. These vehicles will be carrying a lot of energy in the form of batteries, hydrogen, and gasoline, which could be volatile if not controlled properly using appropriate sensor data.

There are some semiautonomous vehicles on the road today with some navigation, at least on the highways. The future promises more connected and autonomous vehicles. These vehicles will have all the abovementioned power electronics along with many more sensors and computers requiring additional power [37]. In such vehicles, comprising communication, controls, and computing systems, including edge computing at the sensor level, there is the potential for more vulnerabilities. Eventually, with the humans out of the loop, for full Level-5 autonomy [38], these systems will be even more critical since there will not be a human driver to take control in the case of danger.

Charging systems connect vehicle electronics to the grid systems allowing critical communication between two important infrastructures. With an all-electric transportation system, there will be thousands and, eventually, millions of these vehicles connected to the grid at any time allowing people trying to gain access to the grid through the vehicle systems, or vice versa, which is why both systems should be designed in a secure manner and not necessarily independently but in coordination with each other preventing vulnerabilities [39], [40]. With charging power levels going beyond 350 kW for passenger vehicles and beyond 1 MW for commercial vehicles, an interruption could disable vehicles or reduce the charging power, which would take them out of service impacting large segments of society. These power levels also indicate much higher energy levels being transferred to the batteries, which makes it critical to have secure chargers and battery management systems to avoid any catastrophic failures.

Another charging technology that will allow autonomous vehicles is wireless charging [41]; after all, if someone must plug the vehicles in, they cannot be considered completely autonomous. There is also dynamic or in-motion wireless charging, which, together with autonomous static charging, potentially allows vehicles to have unlimited range eliminating the range anxiety of electric vehicles [42], [43]. For static charging, the vehicles are parked at home or at work. There is also dynamic or in-motion wireless charging, which, together with autonomous static charging, potentially allows the vehicle to have unlimited range eliminating the range anxiety associated with electric vehicles [42], [43]. Experimental evaluation of 120- [see Fig. 7(a)] and 20-kW [see Fig. 7(b)] static wireless charging systems demonstrated a dc-to-dc efficiency of 97% with a 150-mm gap between the transmitter [see Fig. 7(a)] and receiver coils. The feasibility of this system resulted in the team looking into 300-kW static wireless charging systems and 200-kW dynamic wireless charging systems.


(a) (b)

Fig. 7. (a) Double-D coil that was used by the Oak Ridge National Laboratory's (ORNL's) 120-kW static wireless charging demonstration. (b) Earlier 20-kW static wireless charging system demonstrated on a Rav4 EV at ORNL.

Static wireless charging at home or work brings the same concerns about the connection to the grid [41]. With vehicles being charged from the road dynamically, in addition to all the electronics mentioned earlier with respect to autonomous vehicles, to support high power, a medium voltage connected power electronics system will be a part of the traffic system connecting roads directly to the grid. This will open more ways for hackers to infiltrate vehicle and grid systems potentially causing havoc in traffic.

For these systems to be secure, not just cybersecurity of software but also cyber–physical security of power electronics is extremely important. While designing these systems, more consideration needs to be given regarding what part of controls and data processing needs to be software- or hardware-based.

B. Power and Information Cotransmission

Although radio waves can carry both energy and information simultaneously, the radio frequency transmission of these quantities has traditionally been treated separately. Some recent studies have provided experimental evidence for wireless information and power transmission (WIPT), in which information and energy flow together through the same signal. From a communication theory perspective, transmitting data and power over different spectra—such as using pulsewidth to overlay information on top of power transfer—or sending two signals over two time slots (not simultaneous) or using two antennas are conceptionally identical for wireless communication and not spectrum efficient. This is especially challenging in the case of massive-connected IoT devices that monitor, for instance, structural health, logistics, security, health care, and agriculture. The main open challenge here lies in the limited available frequency spectrum, shared by all devices to transmit data and receive power, combined with the requirement of maintenance-free and high-reliability data transmission, especially from the standpoint of energy sustainability. Most implementation of WIPT receivers did not operate using WPT and wireless information transmission (WIT) on the same received signal [44]–[48]. There are two facets to this restriction: first, the WPT operation on the WIT signal destroys the information content of the signal; second,

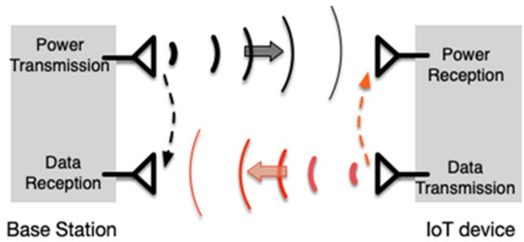


Fig. 8. Wireless cotransmission of power and information.

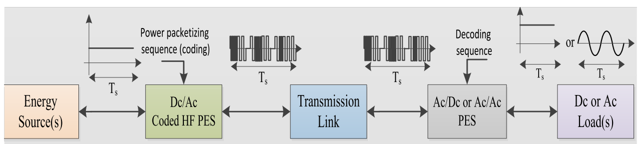


Fig. 9. Boolean power and data transfer mechanism.

the WIT and WPT have very different power sensitivity (e.g., −10 dBm for energy harvesters versus −60 dBm for information receivers) [44]. These limitations inspired several research efforts on splitting the received signal into two orthogonal parts. The common practical techniques include time switching, power splitting, and antenna switching [44]–[48]. All prior approaches have the disadvantage of interrupted information transmission and low-spectrum efficiency. This is logical since, up until recently, it was assumed that simultaneous reception and transmission on the same frequency, i.e., in-band full-duplex (FD) communication is impossible. Recent works have provided experimental methodologies for FD communication, in which a node can transmit and receive signals at the same time and on the same frequency band [49]–[51]. This research guarantees low-latency transmission as required by, among others, delay-sensitive sensor information. It also allows the use of wideband optimum waveforms for WPT to increase the dc power level at the receivers [52]–[56].

Motivated by the advances in RF-power transfer and FD communication, we believe that FD-WIPT (see Fig. 8) is a promising approach to sustainable-power low-latency data transmission IoT network. This is very relevant for low-power IoT devices with massive connections, such as communication in disaster scenarios. Within this framework, the IoT devices will harvest energy from incident RF signals and transmit a message to the base station at the same time and on the same frequency. The integration of wireless power and wireless communications receivers brings also new challenges related to self-interference cancellation and RF-power transfer enhancement.

While wireless power and information are typically transmitted using a common electromagnetic (continuous) mechanism, recently, Mazumder [57] and Mazumder and Gupta [58] have introduced a mechanism where power and data flow are no longer restricted to be continuous. In other words, and as shown in Fig. 9, the power/energy and data can be sent (with or without a waveguide) in discretized form. This yields added reliability and interestingly; just like data, energy packets can be coded. Furthermore, the signals can be modulated and do not need to be pulsating. Instead, the signals are Boolean in a generalized sense. Furthermore, the form of power transmission can be multiquadrant. Preliminary results have been provided in [59], and exciting research is ongoing with broad applications [60].

V. Coordinated Control

Systems, where converters are the interfaced between many of the main sources of energy and load centers, have the ability to direct the flow of energy if the control of the converters is appropriately coordinated. This allows for optimizing source operating points for a system cost function and directing load sharing and energy storage usage to meet operational requirements. Perhaps, the most common methods of coordination utilized in microgrids are droop-based. Droop coordination methods [61]–[64] are robust and are often adjusted via low-bandwidth communication links making them relatively insensitive to communication failures or delays. However, adjustments to sharing allocations are slow compared to fast communication-based methods, and bus voltage cannot be stiffly regulated. Higher bandwidth communication can form the basis of coordinating system control that allows for system-wide energy management strategies [65]–[67] as an alternative to droop-based methods when faster and tighter energy flow control is desirable.

A. Multihop Network-Based Coordination of Power Electronics

There has been a progress in the area of modular converter systems due to continued research and development of the power-electronics-building-block (PEBB) concept [68]. The PEBB concept has driven advancements in highly modularized converter systems with many identical subsystems, such as the MMC. In addition, recent developments in SiC power devices are yielding converters with far greater switching frequencies and resulting in an order of magnitude reduction of the time scales compared to converter systems utilizing conventional Si IGBTs. Faster time scales translate to a need for more capable control systems, which is usually being met using FPGA-based platforms. Communication and computational capabilities of new FPGA-based controllers provide opportunities beyond simply supporting SiC PEBB-based converters.

Modules that form the control system for single converters are traditionally colocated within the converter. In a PEBB-based power distribution system, control and measurement modules are spatially distributed. Thus, modules at the application level of each converter control can be networked and, furthermore, with sufficient communication speed, do not even have to be colocated with converter equipment. A study [69] was performed to determine the feasibility of distributing converter application control among the modules within converters and at control layers above individual converter control. The study determined that it is acceptable since application control for converter has a cycle time that is typically in the lower millisecond range [70].

The stability and performance of a system of PEBB modules are affected by the delay between when measurements are

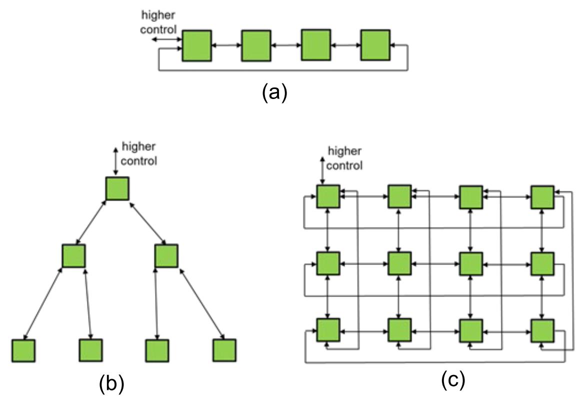


Fig. 10. PEBB control node communication network topologies. (a) Ring: latency=n, 2 channel/node. (b) Tree: latency=$\log_2$n, 3 channel/node. (c) 2-D Torus: latency=$\sqrt{n}$, 4 channel/node.

taken and when updated references are received from the controller. Since each level of the PEBB control hierarchy is connected in local network topology, transitioning packets between control levels will also contribute to the delay. Latency serves as a constraint for the overall control system design. As such, both the physical topology of the communication network and the routing algorithm are important considerations for the system design.

Several network topologies were evaluated [71], and some of the candidate topologies are shown in Fig. 10. Fig. 10(a) shows a simple 1-D bidirectional ring topology, where there is only one minimal-distance path between any two endpoints. The worst case round-trip path delay is n, where n is the number of nodes (where a message must traverse $n/2$ rings in both directions). In this topology, each module requires only two bidirectional channels. Fig. 10(c) shows a 2-D torus topology that offers more than one possible minimum-length paths between any two endpoints that are not horizontally or vertically aligned. The 2-D torus has a worst case round-trip latency of $n^{1/2}$ and requires four bidirectional channels per node. Extending further, a 3-D torus would require six-channel per node and have a worst case round-trip latency of $n^{1/3}$. The 2-D torus was selected as the best compromise of the number of communication links and performance.

The proposed multihop network topology is widely used for large-scale distributed computing systems to smaller scale networks-on-chip [72]–[75]. However, while these networks seek to minimize average-case latency for varying dynamic traffic, a PEBB controller network must guarantee a worst case latency for regular static traffic. Power electronic control systems consist of multiple control loops and levels or layers of control within a hierarchy.

Single-hop communication latency in the 0.7-μs range has been achieved [69], which includes all necessary subsystems to implement application-level control functions. An additional advantage of mesh networks is multiple reroute paths in the event of a network or control node failure. In the event of a node failure, the network can reroute by adding two additional hops resulting in a worst case additional latency of 1.4 μs. This is acceptable since application control for converter control systems has a cycle time that is typically in the >100-μs range [70]. With worst case hop timing needing less than 1% of the application control cycle time, several tens of converters can be coordinated via the 2-D torus PEBB control network.

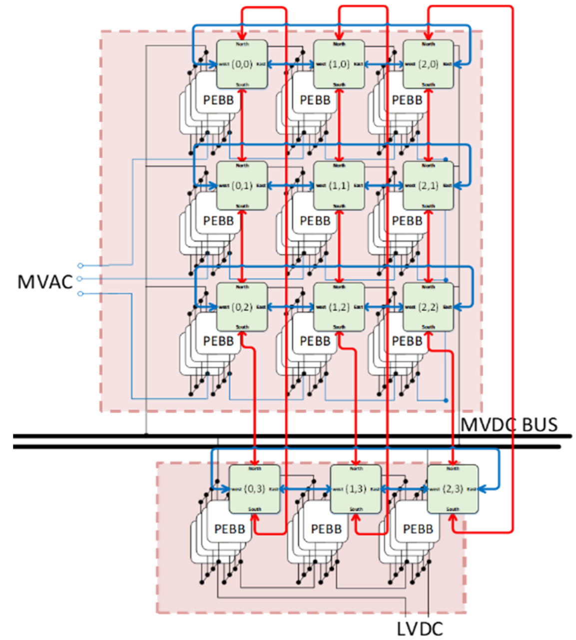


Fig. 11. Cluster of PEBBs coordinated over 2-D torus multihop network.

Increasing communication and computational capabilities of new FPGA-based controllers provide a new paradigm where, as opposed to two distinct converters outlined in the pink boxes of Fig. 11, this can be viewed as a single cluster of PEBBs. The cluster with tight synchronization and coordination across the multihop network reduces the need for energy-storage-based decoupling at buses and other points in the electrical network. Capacitive storage, for example, provides sufficient energy to maintain the voltage at a bus within an acceptable range when converters that are attached to the bus interact. The capacitive storage must buffer response lags between converter control subsystems. Low latency and tight synchronization of control subsystems enabled by the network reduce response times of systems interacting on a bus, and thus, the required storage is reduced for the same bus transient limit.

B. Event-Triggered and Encoding-Based Control of Distributed Power-Electronic Systems

An important question is how the communication-based coordination workload, with the increasing penetration of power electronics in networked power systems (e.g., micro-grid, VPP, naval integrated power systems, and more-electric aircraft), is ensured notwithstanding the advantages of coordination of such CPSs. Conventional approaches often use periodic data transmission, which typically incurs progressively higher latency as the number of power-electronic nodes increase. As such, there is ongoing exploration if a need-based and/or control-centric communication (guided by the event- or self-triggering) would be more beneficial [66]–[69], [76]. Preliminary work, as illustrated in Fig. 12 [66], seems to suggest promise by reducing the data rate for communication.

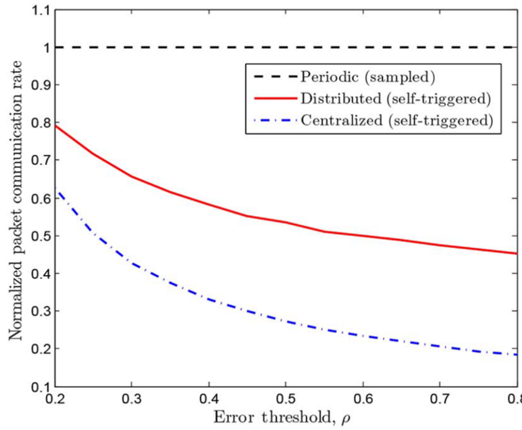


Fig. 12. Comparison of rate of data packet transmission using conventional periodic data transmission and that obtained using self-triggering (need)-based data transmission for a centralized or a distributed coordination framework in a power network. The efficacy of local event-triggered (need)-based communication is evident.

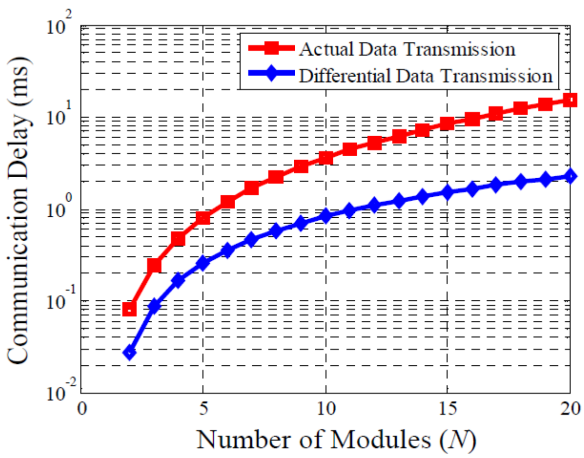


Fig. 13. Illustration of the ability of a coding approach to reduce the computation delay involved in the coordination of a plurality of inverters.

While event-triggering and control-centric communication reduces data rate by carrying out need-based packet exchange, a coding-based approach essentially focuses on the information content of the data. For instance, such an approach may reduce the rate of communication by transmitting a data packet between control nodes when there is new information content or sending only the new information content. Fig. 13 [72] illustrates the result of one such case study. The latter pertains to coordinated control of multiple parallel inverters. The figure shows that, if a differential data transmission is adopted, then the number of inverters that can be coordinated for the same delay is significantly higher, thereby boosting the scalability of the coordinated inverter control. As power-electronics penetrates networks at a larger scale, such coding approaches become increasingly relevant.

VI. Reliability in Power-Electronic-Based Cyber–Physical Power Systems

CPS for power has facilitated the integration of physical power networks with embedded computing processes,

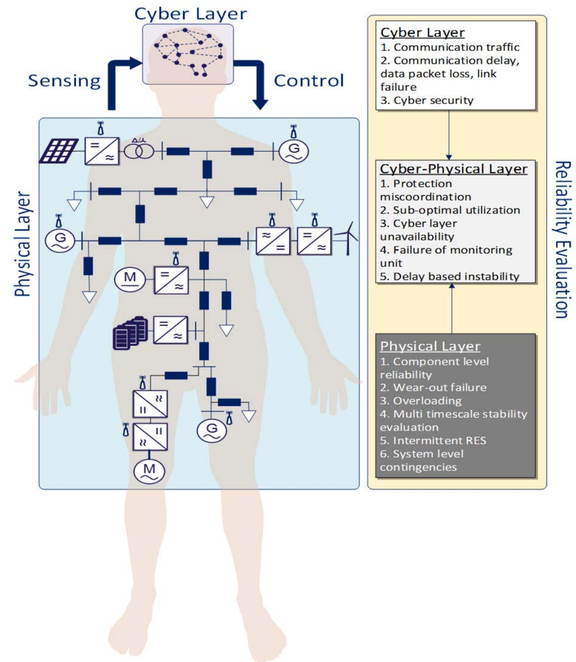


Fig. 14. Reliability evaluation and situational awareness of power-electronics-based power CPSs.

thereby adding new capabilities. Furthermore, with the aim to decarbonize the energy production process, power electronics is dominating in modern power systems acting as the key enabler in the energy conversion unit to extract "green" energy from renewable energy sources. By virtue of these increasing demands, the cyberlayer was brought in to become the "brain" in handling and coordinating the operation and control of modern power systems, which acts as the "body" (as shown in Fig. 14).

The addition of more sensing, communication, variable power sources, and storage under the renewable energy thrust and smart grid initiative will add even higher orders of dimensionality and complexity. This order of complexity, intended to achieve higher levels of efficiency, flexibility, and fault tolerance, can also be a source of higher failures of complex nature that can degrade reliability. Since most of the literature is focused on reliability indices emerging only from the physical layer [78], it is crucial to assess the failure modes resulting from the cyber–physical interactions in power-electronics-based power CPSs.

As the cyber interdependence keeps growing, new reliability indices from the power systems operation perspective need to be developed to account for issues in the cyberlayer, such as communication traffic, delay, data packet loss, link failure, and cybersecurity (as shown in Fig. 14). With a higher degree of cyber–physical interoperability, cyber failure modes may indirectly trigger events in the physical layer, such as power electronics component level reliability, stability concerns, and overloading of converters, finally leading to emergency contingencies. An account of the power CPS has been shown in Fig. 15, where a large communication delay affects the system performance. In the long run, these high-frequency

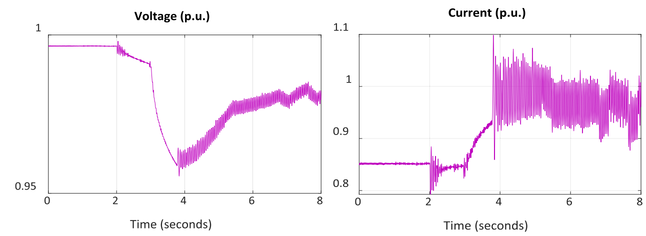


Fig. 15. Impact of large communication delay on the operation of power CPS.

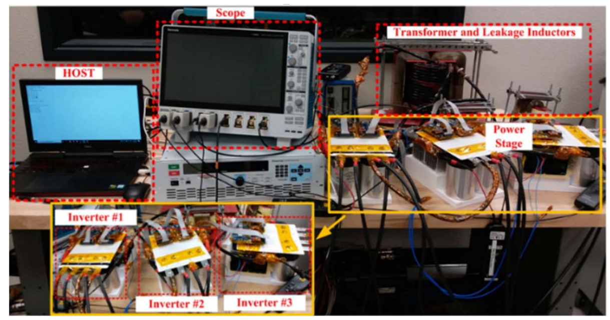


Fig. 16. Test setup of a 150-kW TAB converter for solar plus storage systems.

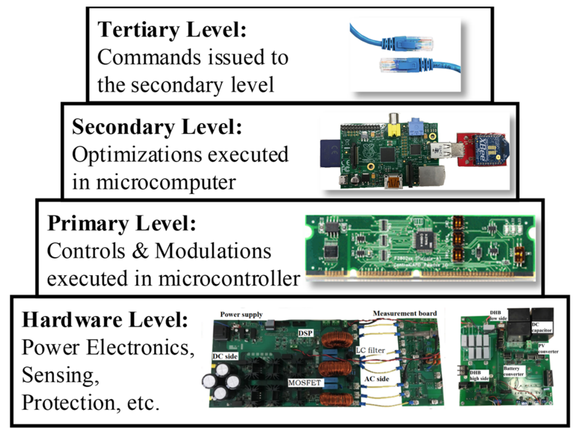


Fig. 17. EMS for the solar plus storage-based RPR.

oscillations will not only degrade the component's lifetime but will also alter system stability.

Finally, new reliability metrics need to be defined for power-electronic-based power CPSs to account cyber–physical disturbances and evaluate the failure, availability, and lifetime of cyber–physical components [79], specifically for applications such as protection against faults where the omnipresence of both cyber and physical layers is inevitable. Moreover, further research can be carried out to recommend the degree of cyber–physical interoperability to ensure the reliability of power electronics-based cyber–physical power systems.

VII. Advances in Hardware and Power-Converter Topologies

A. Power Electronic Converters for Solar Plus Storage Systems

The solar-plus-storage system is a typical configuration for a DER generation system, where a battery energy storage system (BESS) can be integrated with a solar PV system to mitigate the irregularities of the PV system and improve system reliability [80]. In a dc-coupled solar plus storage system, both the PV and BESS are connected to a common dc bus to supply energy to a grid-tied inverter or directly to the loads in a microgrid. A bidirectional multiport dc–dc converter is desirable to achieve power transfer among the PV arrays, BESS, and the common dc bus. Among various solid-state transformer (SST) topologies, the triple-active-bridge (TAB) converter [81], [82], where three dc–ac converters are coupled through a three-port transformer [83], can enable galvanic isolation and transfer power among three dc ports with fewer components. Moreover, similar to its two-port counterpart, i.e., the dual-active-bridge (DAB) converter [84], the TAB converter can operate at the zero-voltage-switching mode to reduce switching losses. Thus, the TAB converter inherently satisfies the needs of the solar plus storage system.

Compared to the conventional system configuration, the TAB converter-based solar plus storage configuration enables integration at the converter level, which will provide a faster dynamic response and improve system robustness, as a centralized controller can adjust the power distribution between the PV port and BESS port rather than controlling power through communication between different dc–dc converters [85]. To increase system efficiency and power density, SiC devices have been adopted in the TAB design. Fig. 16 shows the test setup of a 150-kW TAB system developed by the University of Arkansas [83] using 1.7-kV SiC power modules.

For residential applications, various power router designs are proposed to provide solar plus storage solutions. For instance, a power router is proposed in [86], which has a PV terminal, a BESS terminal, an isolated dual-half-bridge (DHB) converter, and a split-phase inverter for load connection. The residential power router (RPR) is controlled by a hierarchical energy management system (EMS) shown in Fig. 17. The secondary control of the EMS can minimize and a lifetime of cyber–physical components [79], specifically expenses on residential electrical utilities when grid-connected and maximize the power supply duration when off-grid. To prevent the overgeneration at the PV terminal in the islanded mode, the RPR system can operate with limited power point tracking. In addition, the RPR can provide grid support, e.g., compensate reactive power and phase imbalance.

In addition to the enhanced electrical performance reliability described above, the RPR described has been further enhanced with advanced cybersecurity features that provide enhanced resiliency and availability [87]. This follows a defense-in-depth strategy to enhance the overall cybersecurity of the device and system but addressing communications, controls, and hardware aspects of the design in Fig. 17. This includes encryption, authentication, and protections that span both hardware and firmware in addition to communications that provide added assurance that solar plus storage systems can

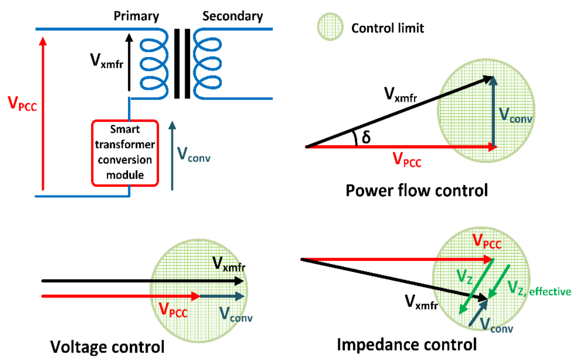


Fig. 18. Enhancement of substation transformer to perform advanced system support.

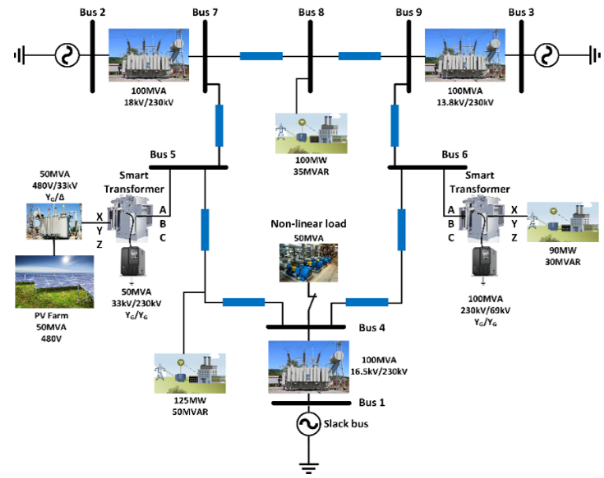


Fig. 19. IEEE nine-bus system depicting hybrid smart transformers with high penetration of intermitted resources and active loads [97].

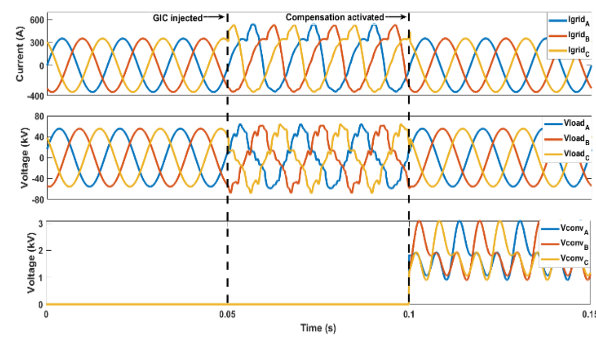


Fig. 20. Mitigation of transformer saturation due to unwanted dc injection using hybrid smart transformers [97].

remain safely in operation—even in the event of a cyberattack. These measures address detection and mitigation methods against the attack surface of the power electronics device as a whole—preventing compromise and physical damage. These cyber-hard-by-design approaches cost relatively little in terms of additional hardware components but provide great benefits for the RPR and grid.

B. Smart Transformer Conversion Module

The current U.S. power network is undergoing revolutionary structural and functional changes with the proliferation of renewable, converter-based DERs, and increased use of active loads. Advancements in digital sensor networks, data analytics, and communication technologies add new challenges to power system control, grid visualization, operation, communication bandwidth, and physical and cyber securities, with a resulting threat to grid resilience and reliability [88]–[91].

One of the most strategic power equipment, in the legacy power network, is the substation transformer. It is important to transition traditional transformers into smart transformers that can perform a variety of advanced grid support functions [85], [92]–[94]. While the concept of smart SSTs is being widely recognized, their respective lifetime and reliability raise serious concerns with power utilities, thus hampering the replacement of traditional transformers with fully electronic SSTs. It is, therefore, proposed to introduce smart features in conventional transformers utilizing simple, cost-effective, and easy to install modules, which is highly desirable [91], [93], [94]. These include voltage regulation, voltage and impedance balancing, harmonics isolation, voltage ride through (VRT), blocking dc in ac networks, and the prevention of the critical grid assets from natural or man-made disturbances, as shown in Fig. 18.

Adding more controllability in a traditional power transformer does provide greater flexibility and mitigation features in power network operation, microgrid forming, and mitigation, but it also provides challenges in terms of vulnerabilities in terms of system protection, unintending islanding, reliability, and cybersecurity. Additional requirements in terms of localized self-healing and controllability from local system parameters are essential in moving forward with more advanced power system control and mitigation using AI [88], [95], [96].

This power electronic-enhanced hybrid transformer concept [91] was evaluated for several applications of these grid support and mitigation functions on a nine-bus power system with [97], as shown in Fig. 19. The HIL simulation results of some of these functions are plotted in Fig. 20.

C. Applications of CPSs in Wind Energy Systems

More interest needs to be directed toward the generation stage, especially the renewable energy sources, such as wind energy, which has developed rapidly on a worldwide scale [98]. Global advancement of wind energy has encompassed deployments on a large scale, such as offshore, floating, and airborne wind turbines. Apart from facilitating monitoring and control of wind energy conversion systems (WECSs), SCADA systems are also prominently being used for operation and maintenance. Specifically, at the wind turbine level, SCADA systems are used for control system interface and diagnostics [99] along with data collection facilities. These data can further be used for troubleshooting applications, reducing downtime and improving the reliability and availability of a wind turbine. On the other hand, at the wind farm level, SCADA is typically used for robust security model, verification of grid codes, and for configured displays to monitor the generation [100].

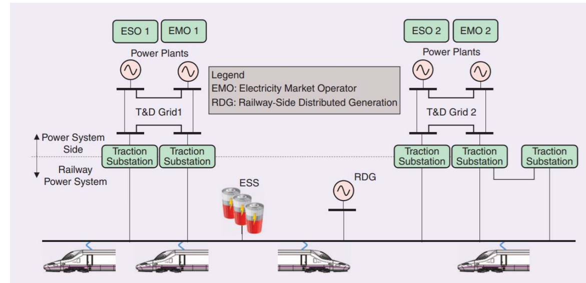
Apart from these basic tasks, SCADA is primarily used for condition monitoring (CM) using fault identification techniques to alleviate the operation and maintenance in WECS [101]. CM systems usually deploy high sampling rate sensors, thereby imposing challenges on data communication, computation, and storage within a reasonable cost margin. Nevertheless, it has been shown in [102] that SCADA using a cyber–physical mechanism has managed to improve the fault diagnosis over conventional physical methods. A general trend of reducing the cost and computational and communication burdens can be to extract the features during critical events using event-triggering methods [103].

Modeling also becomes a major challenge by integrating heterogeneous wind turbine models into the cyberlayer. Hence, different aspects need to be considered for a detailed compositional CPS modeling hierarchy [104]. It is also crucial to assemble the abstract CPS models and information flow graphs from the sensor networks into the physical models of mechanical and electrical parts inside wind turbines. Recent innovations in the sensor network, such as the IoT, have facilitated interactive sensing, communication, and control, which could serve as an upgradation to the next-generation WECS. However, the abovementioned advancements also limit its operation as it increases the security concerns [105], thereby mandating a security framework for cyber–physical WECS. Hence, further research efforts need to consider these aspects for a cost-effective, reliable, and resilient WECS.

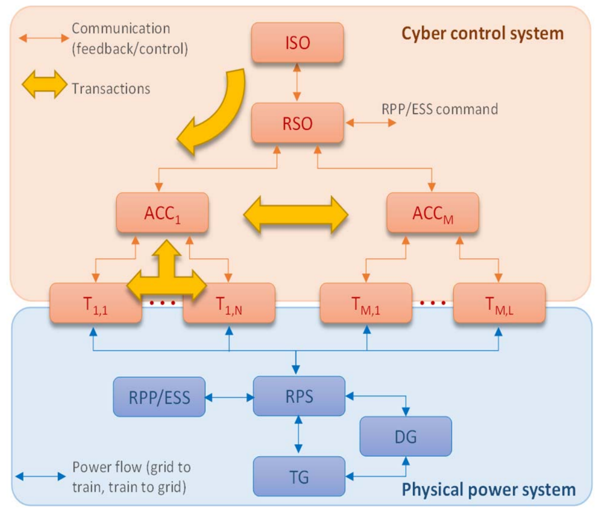
VIII. Transactive Smart High-Speed Railway Grid

One of the application areas where power electronics has made a tangible societal impact worldwide is high-speed electric trains. With the burgeoning population, the need for electrical trains and their faster travel is increasing. This also translates to increased energy requirements. However, as the demand for such locomotive power increases, so arises the challenges associated with operating such infrastructures with a manageable cost. This is especially important since an electrical train is a unique spatiotemporal load [106], [107], as captured in Fig. 21 for the overall energy CPS.

Currently, the cost of electricity usage for a high-speed electrical train is typically determined by solving an energy-minimization-based optimization problem. However, recently, guided by de la Fuente *et al.* [107], new approaches [108], [109] based on transactive optimization have been explored, which have the potential to appreciably reduce the cost of electricity consumption in such high-speed trains. The transaction is essentially between the electrical train and the grid. In one such approach, instead of minimizing only the energy consumption, the focus, instead, is on minimizing the weighted product of the unit cost of electricity and energy demand (while satisfying the time-scheduling constraints) recognizing the spatiotemporal navigation of a high-speed electrical train via the plurality of geographical regions at different instances of time. As illustrated in Fig. 22, the new approach leverages the instantaneous velocity profile of the train to vary power



(a)



(b)

Fig. 21. (a) Illustration of emerging high-speed smart railway grid. (ESO: electrical system operator and ESS: energy storage systems) of the cyber–physical electric railway system. (b) Illustration of the smart railway grid CPS transactive control architecture: the independent system operator (ISO) controls the transmission grid (TG). The TG feeds the trains (T) via the railway power system (RPS) after voltage step-down or through a distribution grid (DG). RPS is controlled by the railway system operator (RSO), which also coordinates with the ISO and commands any dedicated distributed railway power plant (RPP)/ESS that can also support part of the train's load demand. ACC or area control center supervises the train control and coordinates with RSO and coordinates with other ACCs.

consumption while ensuring that the average velocity satisfies the scheduling constraint. In another approach, the transaction stretches beyond the electrical train and the grid to include other RT loads and outlines an innovative concept of demand-shifting-based transactive optimization to further reduce the cost of electricity usage.

These preliminary works have been conducted using primarily a centralized approach. With the advancements of power electronics and intelligent microelectronics, such transactive control can be explored at the power-converter level using a coordinated CPS approach by further incorporating dispatchable and nondispatchable energy sources and extending control objectives to achieve spatiotemporal multiscale optimization.

IX. Real-Time Simulation of Shipboard Power Systems

A. Overview

There is a pressing need for frameworks that provide the ability to analyze and evaluate cyber–physical SPS in RT

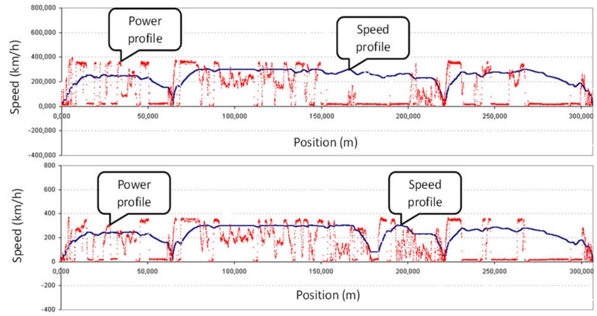


Fig. 22. Two power and speed curves measured in a high-speed train with identical trains and time schedules yielding different instantaneous power profiles and potentially different cost of electricity consumption. This forms the basis for transactions based on weight cost-energy minimization.

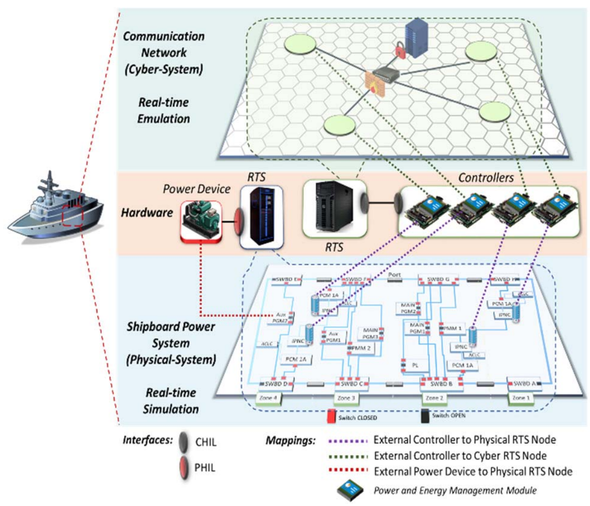


Fig. 23. Top-level diagram of cyber–physical SPS in an RT simulation environment.

environments. These RT environments are intended to provide system relevant characteristics that capture the physical-level (electrical, mechanical, and thermal-fluid) and the cyberlevels (computer network and computational resources). Fig. 23 illustrates some requirements in terms of hardware and software simulation solutions. The simulation capability in Fig. 23 is based on developments of the control evaluation framework (CEF) [110]–[112]. For the physical system, the electrical and mechanical components are simulated using hardware and application-specific tools and support interfacing controls and power devices in hardware-in-the-loop (HIL) implementations. The HIL implementations are mainly realized using interfaces that support control HIL (CHIL) and power HIL (PHIL). Similarly, the cybersystem is modeled using specialized hardware and software tools that support the representation of complex communication network characteristics that exist in deployed communication networks. Such characteristics include packet delays, packet drops, and bandwidth limitations. In addition, the RT simulation environment is designed to support the integration of external devices, which can be proprietary external controllers or generic physical network devices, such as wired/wireless routers, switches, or hubs.

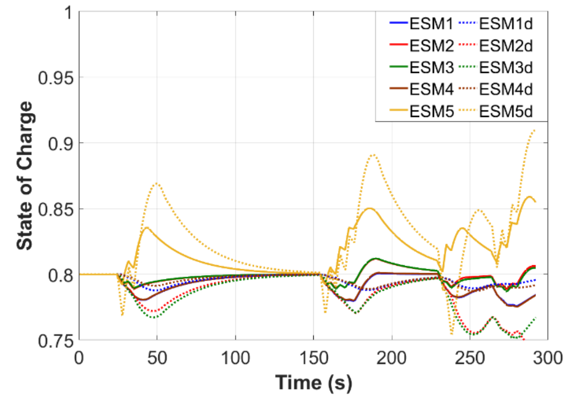


Fig. 24. SoC graphs of distributed controllers during the case study. (a) (ESM1-ESM1) are these scenarios where no delays are introduced. (b) (ESM1d-ESM5d) are the scenarios where 100-ms delays are introduced into the emulated communication network.

The modeling, simulation, and interfacing of SPS components, as shown in the framework, can then be used to define performance metrics. These performance metrics are determined by the application being evaluated and would depend on the tests being conducted. In the past, the CEF has been primarily used to evaluate power and energy management algorithms specifically tailored for naval applications; various metrics, such as power quality, ability to serve load, and controllers' response (based on communication degradation), have been used as for evaluating the IPES operation. Overall, multidomain simulations are valuable for helping ensure evaluation coverage of naval power systems and their operation. The multidomain simulation provides system-relevant scenarios. In Section IX-B, an example case study is given to help describe an SPS RT simulation.

B. Case Study

In this section, a case study is described as a notional cyber–physical SPS. In this case study, a distributed power and EMS is deployed in a four-zone MVdc ship power system (see Fig. 23) [112]. The physical system, i.e., the electrical and mechanical properties of the SPS, are modeled and simulated on an RT Simulator (RTS), while sensor data coming from the devices modeled inside the RTS are sent, through fiber optic and an FPGA, to the communication infrastructure connected to the respective external controllers. The power system modeled is a notional 12-kV/100-MW class MVdc distribution system with multiple energy storage modules (ESMs) with maximum capacities of 1 GJ and a charging/discharging rated power of 5 MW and 10 MW, respectively. The power system also has multiple loads modeled as motors and pulse loads that try to replicate the operation of an SPS under different scenarios.

Eventually, the communication network infrastructure of the SPS will be modeled in a high-performance server running the Common Open Research Emulator (CORE) to achieve RT performance [113]. To explore this approach, an Ethernet switch was modeled in CORE for the example shown here. Controllers, running the distributed management system, are connected through Network Interface Cards (NICs) and mapped to virtual nodes inside the emulated environment. The controllers communicate through a virtual Ethernet switch using DDS and TCP/IP communication protocols.

Fig. 24 shows the results of two scenarios wherein each scenario five ESMs are controlled in a distributed fashion and are designed to maintain an 80% state-of-charge (SoC) consensus value but diverge during operation of pulse loads at $t = 50$ s. The differences in the controllers' responses are shown when 100-ms packet delays are introduced into the communication network links connecting the ESM controllers. The consensus of the distributed algorithm is heavily affected since multiple SoC measurements present higher oscillations before reaching consensus.

X. Conclusion

This review covers a broad range of topics involving the confluence of power electronics and CPSs encompassing a plurality of emerging applications. It provides an overview of multiple research issues and challenges in these application areas and the solutions that are being pursued.

To begin with, the issue of vulnerability of CPSs based on power-electronic converters to cybernetic technologies and the evolving need for resilience to such vulnerabilities has been introduced. On a similar note, the reliability of power-electronic systems that form the backbone of energy CPSs needs careful consideration and incorporation of emerging data-centric methodologies, as have been captured in this article.

Subsequently, a discussion on a self-organizing power-electronic converter with control intelligence at the edge of the grid is presented, which can improve the system performance for large-scale renewable energy integration. Following this, the protection of MVdc/HVDC systems is discussed with practical considerations on the power-circuit topologies, such as MMCs.

Challenges and implementation approaches in e-mobility, such as fast charging wireless, are highlighted next. On a related note, cotransmission of power and information in wireless (and waveguided) medium are outlined, which may have a significant impact on mobile and stationary IoT technologies.

Coordinated control is an important feature in modularized-converter-based CPSs. In this context, a multihop-network-based coordination scheme for distributed and fast-switching converters using a 2-D torus topology is discussed with an eye on latency reduction. Regarding the latter, two complementary methodologies, based on coordinated control guided by event triggering (i.e., need-based communication) and encoding (information- and not data-centric communications) are outlined next.

The other important aspect of energy CPS is the topological advances that form the physical layer. TAB converter topology and smart transformers for systems, such as solar plus storage, are outlined.

Finally, energy CPS involving smart spatiotemporal high-speed railway grid (with a focus on transactive optimization for the cost of electricity usage reduction) and control for novel and next-generation electrical ships with a focus on RT simulation of complex SPSs are outlined.

The wide range of research topics presented in this review article is expected to provide an overview of ongoing research in power-electronics-based energy/power CPSs and help the researchers working in this area with the eventual aim of energy sustainability and smart power solutions.

Acknowledgment

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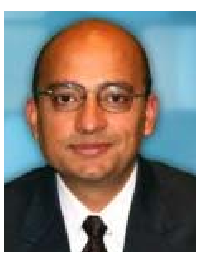

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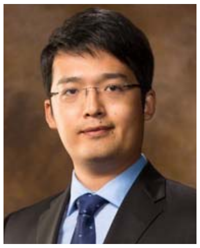
Dr. Balda is the Chair of the IEEE Power Electronics Society (PELS) TC5 Committee and a Faculty Advisor of the local chapter of the PELS.



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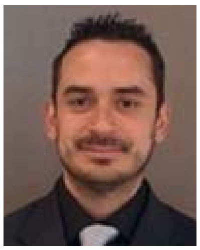

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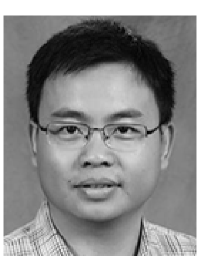

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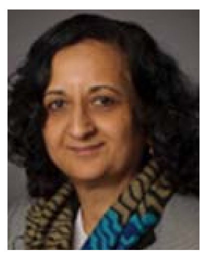

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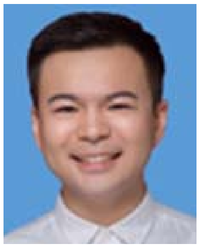

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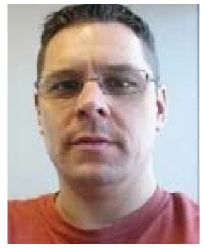

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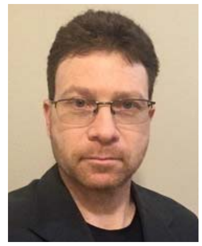

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