Innocent Kamwa

taming wind and solar resources

smart inverters are key

THE U.S. ENERGY INFORMATION Administration (EIA) predicted that the U.S. power grid will host more than 56.1 GW of new utility-scale electric-generating capacity during 2023, the largest amount of added capacity since 2002. However, behind this headline, the real news is that in 2023 more than half (52%) of the capacity additions will be solar, followed by battery storage at 17%. The case of storage is interesting. In 2023, the U.S. battery capacity more than doubled in sized compared to 2022. Yet, the EIA has forecasted that it will likely be doubled in size in 2024, to reach about 30 GW in capacity.

Recently, discussions have focused on distributed energy resources (DERs), after Federal Energy Regulation Council Order 2222 was enacted in 2020. However, when excluding demand response programs, the immediate impact of DERs, connected in distribution systems, is rather limited in many jurisdictions. The Dunsky study for the Independent Electricity System Operator of Ontario projected less than a 10% reduction in system capacity needs from nondemand response DERs in 2032, under the business-as-usual scenario. Over the next decade, while significant, DERs in the form of rooftop solar photovoltaic systems and batteries will not be the main capacity driver in the DER business. Dunsky's study found that DERs will represent only 25% of the capacity supply in Ontario under the business-as-usual scenario, leaving a full 75% capacity to grid-scale resources in the form of nuclear, solar, wind, and battery plants.

We need batteries to capture the full value of weather-driven generation resources since the latter often produce electricity when transmission is congested and/or the load is sufficiently large to fully consume it. Electricity then needs to be stored for later consumption to prevent the unavoidable loss of useful green energy. In 2022, the California Independent System Operator's (CAISO's) curtailment of utility-scale solar and wind was 2.4 million MWh, a 63% increase compared with 2021, with about three quarters of curtailments resulting from transmission congestion. In this context, inverter-connected batteries can provide resource adequacy by charging during low-cost, low-consumption hours and being available to discharge when needed, for system reliability. Lithium-ion and especially lithium iron phosphate (LiFePO) batteries also have the flexibility to quickly ramp up and down in real time to balance the grid, although they have some round-trip losses that must be accounted for. It's not surprising that the world's largest lithium-ion battery energy storage system, the Moss Landing Energy Storage Facility (rated at 750 MW/3,000 MWh), is located in California to combat the bad trend observed in the "duck" curve (Figure 1).

After analyzing these trends, we quickly realize that the top news currently must be about integrating utility-scale variable renewable resources in the electric grid while also maintaining its reliability (see the article referenced in Figure 1). This is where the inverter-based resource (IBR) concept comes to play a critical role. An inverter is a power electronic device that converts dc electricity to ac [the definition from the North American Electric Reliability Corporation (NERC) website (https://www.nerc.com/pa/Documents/2023NERC_Guide_Inverter-Based-Resources.pdf)]. There is no practical means for tapping into solar and wind and merging into the existing ac-dominated grid without inverters.

Three types of inverter-interfaced resources are illustrated in Figure 2,

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including wind turbines, solar photovoltaic systems, and battery energy storage. The picture (which is amazingly animated on *The New York Times* website) draws no difference between IBRs at the transmission level and IBRs located in distribution systems. In the NERC terminology, the former are called *utility-scale IBRs* (referring to connecting onshore and offshore wind farms, photovoltaic and concentrated solar plants, battery plants, etc.), while the latter are termed *inverter-based converter-connected DERs* (referring to electric vehicle charging plugs and

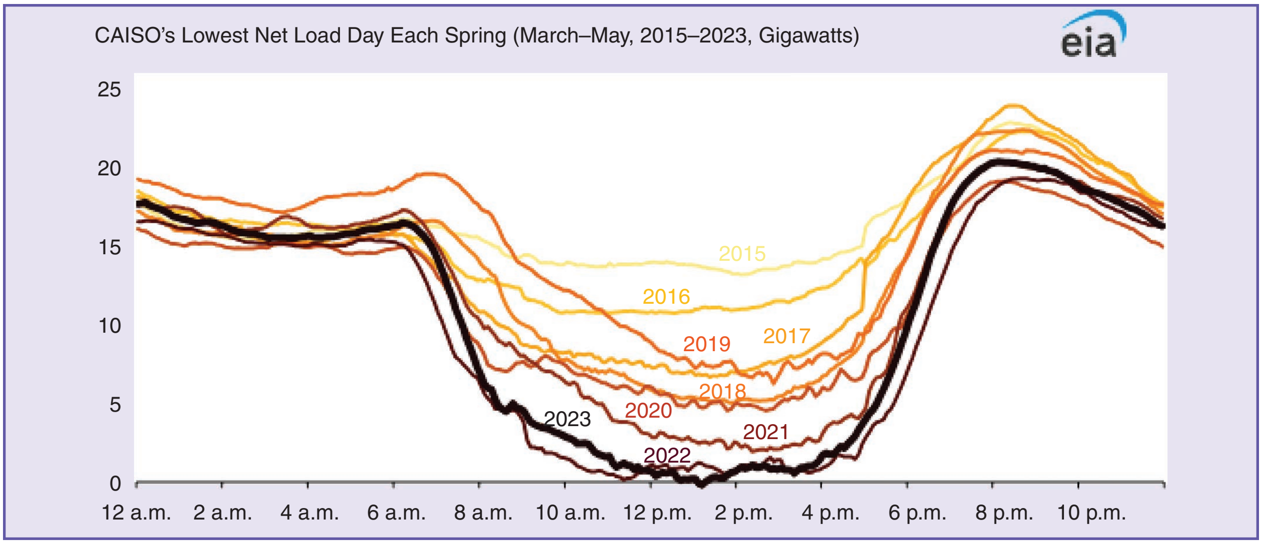

figure 1. California's duck curve is getting deeper (https://www.eia.gov/todayinenergy/detail.php?id=61103). (Data source: CAISO, https://www.caiso.com/; graphics: EIA.)

stations, rooftop solar photovoltaic facilities, behind-the-meter batteries for backup energy, etc.).

The combined wind and solar share of total power generation in the United States increased from 12% in 2021 to 14% in 2022. These numbers show that the consistent energy output from variable renewable energy resources to the bulk electricity grid remains moderate. But instantaneous penetrations of IBRs are reaching very high levels (70+%) across multiple areas in North America, according to the latest NERC Long-Term Reliability Assessment, published in December 2023. In the Australian grid, the growth rate of IBRs is just as fast, and in 2022, they reached an incredible 5.3 GW of new solar capacity. This is a 20% increase in just one year, and a similar rate of increase is expected for 2023.

What to make of this IBR invasion of the electric grid? It is posing huge challenges to reliability entities. IBRs differ from conventional synchronous generation in many ways. They 1) are driven by power electronics and software, instead of physical properties of the generating device; 2) have no inertia, when compared to large rotating inertia of conventional generation; 3) have very low fault current versus high fault current; 4) have sensitive power electronic switches that are subject to quick aging, when compared to the typical rugged equipment that is tolerant of extremes and built to last more than 50 years; and 5) are dispatchable based on available power (headroom) versus the full dispatchability of conventional resources. However, there are areas where IBRs come close to conventional generation or perform even better: 1) they offer very fast, flexible ramping to follow fast load changes or intermittent generation; 2) there is minimal plant auxiliary equipment prone to tripping; and 3) they have the capability to provide essential reliability services, including very fast frequency control. In other words, IBRs are a mixed bag, with both challenges and opportunities.

Compared to the grid-scale IBR, the inverter-connected DER (Figure 3) is still in its infancy. A May 2023 Brattle study found that it is developing

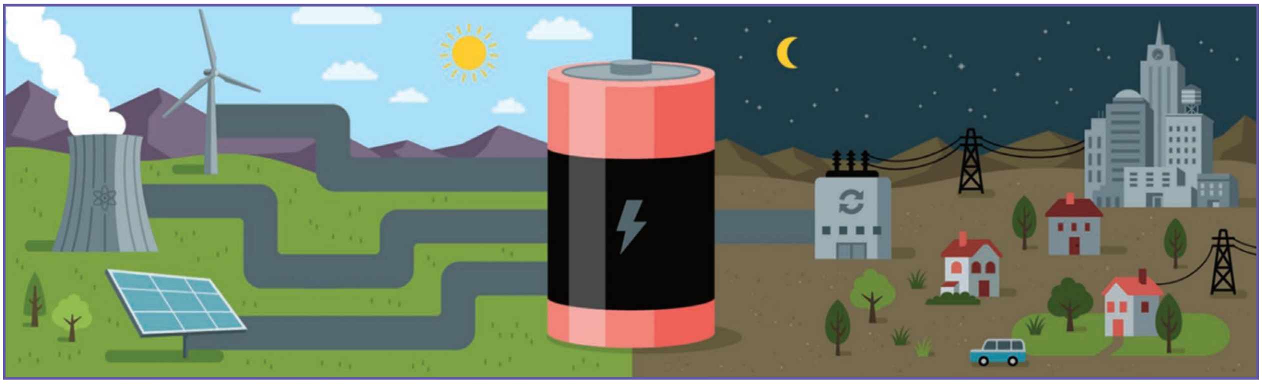

figure 2. The symbiosis of inverter-based batteries and inverter-based renewable energy sources. [Source: The New York Times (https://static01.nyt.com/images/2017/03/21/business/batteries-cover/batteries-cover-superJumbo.gif).]

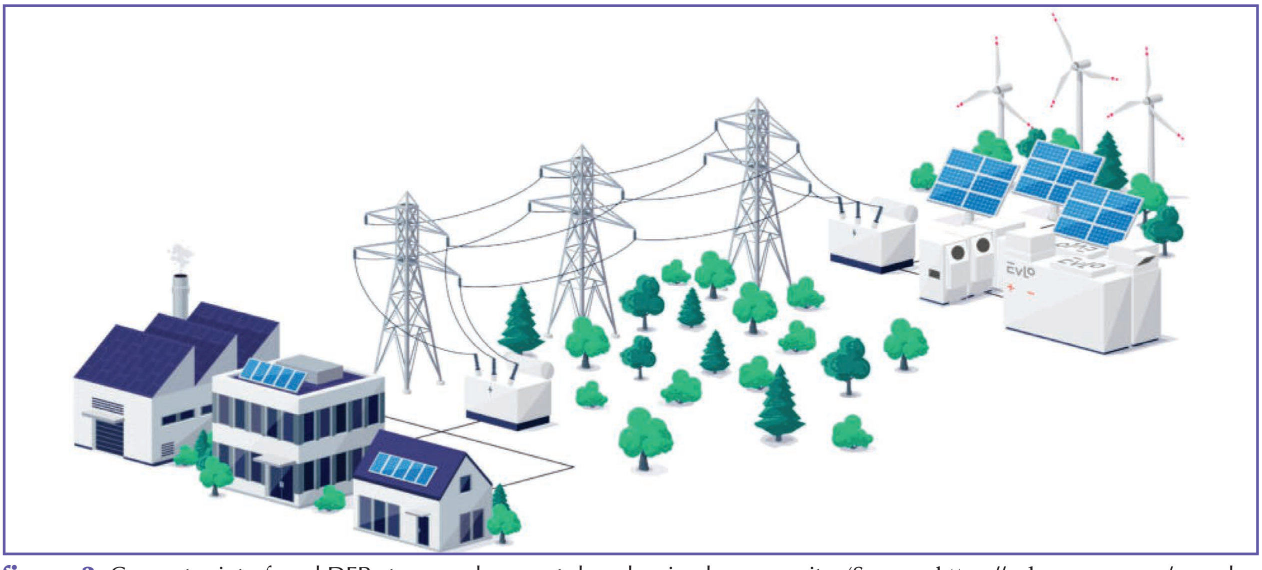

figure 3. Converter-interfaced DERs to propel a smart decarbonized community. (Source: https://evloenergy.com/; used with permission.)

quickly in the United States. Rooftop solar installed capacity will likely increase from 27 W today to 83 GW in 2030, while behind-the-meter battery capacity will increase from 2 GW to 27 GW in 2030. These changes in generation mix will undoubtedly further raise the profile of the IBR as a key enabler of deep decarbonization through electrification. As IBRs gradually penetrate the power grid and displace synchronous generators, addressing issues such as the behavior of low-inertia IBR-dominated grids, local needs for voltage support, and frequency/voltage ride-though requirements under fault conditions will become more important.

Fortunately, modern inverters (often called *smart inverters*) are now up to the task as they comply with IEEE Standard 1547-2018 at the distribution level and IEEE Standard 2800-2022 at the transmission level, at least in North America. These standards contain more stringent clauses as the IBR penetration increases in the concerned electric power network, leading to smart inverters with advanced functionalities, enabling IBRs to more closely mimic the physical properties of synchronous generators through various available controls. Additionally, the use of aggregated DERs/IBRs for grid services is specified in IEEE Standard 2030.11-2021. Currently, most applications of inverters are as grid-following (GFL) inverters, which work well in power grids dominated by synchronous generators. The evolution toward advanced IBRs based on grid-forming (GFM) converters [i.e., converters that can work independently of a synchronous grid or when the latter is weak (with a low short circuit current)] is necessary to achieve an accelerated growth of IBR applications in electric power networks with 70+% of IBR penetration. We need to consider the increased risk when grid reliability stands on the shoulders of "controls and software" instead of the rugged "copper and iron" assets in conventional generation resources. IBRs further raise significant modeling and simulation issues, which are properly addressed under NERC auspices.

This brief overview is aimed at highlighting the timeliness and relevance of IBRs in understanding the transformations happening now on the grid (transmission) and the grid edge (distribution). Let us now look at the value proposition of the current issue. The guest editors have attracted a remarkable team of authors from all regions of the world. The breadth and depth of coverage of the challenges and opportunities facing highly IBR-penetrated power grids is exceptional. One article [A1] addresses the topic from the system operator viewpoint. In doing so, the focus is not set on a single region; rather the article provides a collective view of several system operators, such as the Australian Energy Market Operator, EirGrid, Hawaiian

Electric, National Grid Electricity System Operator, and Fingrid. I am sure that the reader will appreciate the diversity of viewpoints, challenges, and means to address them through grid codes and new technologies. For those with an engineering mindset, who understandably trust only what they see, there is an article [A2] on current and recent demonstrations and pilot projects for GFM converters worldwide. Examples of actual implementation include both small- and large-scale projects in Australia, France, Switzerland, Germany, Great Britain, and the United States.

At a more conceptual level, we feature an article [A3] that discusses the control functionalities necessary for supporting pervasive IBRs in electric networks, while also clarifying the differences between GFL and GFM controls for IBRs. The article concludes with research directions on GFM control strategies, models, and performance validation. As discussed previously, IBR interconnection standards are key to avoid IBRs adversely impacting the power grid reliability, according to NERC reports. Our next article [A4] focuses on the standards landscape promoted by the IEEE Power & Energy Society (PES), including IEEE Standard 1547-2018, IEEE Standard 2800-2022, and the relevant standard numbers within the 2030 IEEE standards

In This Issue

Over the last 10 or so years, continued growth in the capacity of wind, solar, and battery energy storage systems in power systems around the world has resulted in multiple points in time where the power system industry largely agreed that major changes or technological advancements were needed. For instance, the variable nature of wind and solar generation caused power markets and operators little concern until such resources became large enough that their inherent weather-dependent nature required careful consideration. We are now at one of those points in time where the nature of the installed generation fleet, or future fleet, requires careful consideration. Inverter-based resources (IBRs) are fundamentally different from traditional synchronous generation sources. They offer considerable flexibility but also, seemingly, some fragility as well. The six articles in this issue provide a broad set of perspectives on the current state and future of IBRs as the dominant resource in future grids.

- Grid-forming (GFM) inverters [A3] are a potential control-based avenue for IBRs to interoperate with each other and with other grid elements, such as conventional generation, in a manner conducive to a stable and reliable grid. The landscape of various GFM methods, the development of GFM functionality requirements, and grid services provided by GFM capability are presented by a diverse set of international experts.
- Not all power systems have the same level of IBRs currently integrated, and the perspective of operators already operating at significant IBR levels is invaluable [A1]. The challenges of high IBR operation and modeling IBRs is discussed in detail as well as the initial steps taken to mitigate these challenges.
- As power systems transition to higher IBR operation, the level, criticality, and even necessity of current grid services will change [A5]. Experts working at the forefront of systems operation for high-IBR scenarios provide a comprehensive view of how the intertwined grid needs and services have already changed and how they may continue to change.
- Modeling IBRs is difficult enough because of their inherent fast-dynamic qualities, but validating IBR models is just as difficult as it is important for getting an accurate model of power system operation [A6]. The current best practices for IBR models across all modeling time domains are presented as well as guidance on appropriate model usage and a framework for generalized model validation.
- Standards clearly play a critical role within the power system industry, particularly for interconnected equipment that is expected to interoperate in a predictable and reliable manner, such as how fleets of IBRs would in high-IBR systems [A4]. The current state of interconnection and interoperability standards, conformance verification, equipment manufacturer readiness, and identified gaps in the grid interconnection space are detailed by a diverse set of experts from a cross section of the industry.
- Globally, there are already a number of ongoing GFM IBR demonstrations that are helping to define how GFM IBR technology can be effectively used. Both large- and small-scale GFM demonstrations and pilots are described, including key findings from Europe, Australia, and the United States [A2].

Last but not least, the "In My View" column [A7] rounds out the issue with an expert perspective on how the IBR transition in Australia has proceeded from concern about IBR adoption to using them as an active flexible asset to maintain a stable and reliable grid.

—Barry Mather

suite. The contrasting approaches to grid codes and IBR standardization in Australia and some European countries are also discussed and compared to Federal Energy Regulation Council- and NERC-inspired approaches in North America. Another article [A5] develops a road map of emerging grid services and system needs as the grid is progressing from moderate levels of IBRs to being IBR dominated and all of the way through to 100% IBR. The last article [A6] touches on a subject that cannot be avoided when planning and operating a reliable power grid: accurate simulation tools based on validated models that represent both existing GFL IBRs and advanced GFM IBRs. The discussion accounts for the validation of IBR unit and plant simulation models across multiple simulation models and domains (i.e., electromagnetic simulation versus positive sequence or root-mean-square simulation). Here again, the authors trace the needed research direction and development activities toward IBR models and simulation tools as well as screening methods to identify the need for the use of each type of simulation domain. Closing the issue is a statement by the CEO of the Australian Energy Market Operator. One of his four pillars of energy transition is, unsurprisingly, "power systems capable of running, at times, with 100% IBR."

Looking back on the issue casting, we have perhaps only one regret: inverter-based-DERs and related virtual power plants are not addressed. This issue focuses on bulk power systems, which is appropriate, given the low contribution of existing DERs to system capacity and energy needs. Converter-interfaced DERs and their applications represent, in our view, a good follow-up to this issue, to be considered in planning future magazine topics in 2025.

Leader's Corner

It is time to say goodbye to our vice president of publications for the last five years, Dr. Bikash Pal, of Imperial College in London. As the guest leader in this issue, Bikash put pencil to paper to look over the past years and provide a summary of the achievements of PES in the Publications Department during his term. His farewell message to the PES members addresses comprehensively the various facets and impacts of his role, from sustaining top-quality journals with both high impact factors and high usage in *Xplore* to enhancing the due process in article reviews, while ensuring equity, diversity, and inclusion on various editorial boards. The "Leader's Corner" column [A8] contains many informative facts in which you may be interested. Over his tenure, Bikash launched the new *IEEE Transactions on Energy Markets, Policy and Regulation*. He also promoted open access publications through a new PES section in *IEEE Access* and launching of the *IEEE Open Access Journal of Power and Energy* in 2020. This was an amazing period for PES journals indeed, with an increase of 33% in total usage of our transactions (i.e., revenue) and the moving of *IEEE Power & Energy Magazine* from its archaic e-mail-based processing of submissions to the standard IEEE ScholarOne platform.

Bikash has tirelessly given his time, often behind the scenes, to the role of vice president of publications—at times, sacrificing some of his more personal aspirations. Please join me in giving Dr. Pal a well-deserved accolade for a successful tenure as vice president of publications, by all measures. Let us also welcome the new vice president of publications, Prof. Jovica Milanovic from Manchester University, who began in this position in January 2024. We heartily congratulate him. Jovica is also the outgoing editor-in-chief (EIC) of *IEEE Transactions on Power Systems*. We have recently seen enormous growth in the number, quality, and total usage of articles published by these transactions in addition to a more transparent editorial process and a deeper respect for the authors, who are the key stakeholders of any publication. Jovica, we wish you all the best during your tenure as PES vice president of publications over the next five years.

Society News and Awards

This year, the IEEE Fellow Committee ranked 983 nominations for elevation to the status of Fellow across IEEE. Based on the famous rule stating that "The total number of IEEE senior members elevated to Fellow in any one year may not exceed one tenth of 1% of the total IEEE voting membership on record as of 31 December of the preceding year," only 323 nominees were elevated to form the 2024 class of fellows. Among this elite group, we counted 40 new Fellows who are members of PES [A9]. Please join me in extending to them our heartiest congratulations for their outstanding contributions to the advancement of science and technology in the technical fields of PES.

On another topic, Aaron Ledger reflects on the last 2023 PES General Meeting, which was held in Orlando, FL, USA, on 16–20 July 2023 (https://pes-gm.org/gm-2023/) [A10]. The meeting was a huge success with a 22% growth in registrants. To prepare yourself for the next meeting, check the website of the 2024 PES General Meeting, to be held on 21–25 July 2024 in Seattle, WA, USA: https://pes-gm.org/.

At the time of this writing in early January, we are closing on a special issue of *IEEE Power & Energy Magazine* for the 2024 IEEE PES T&D Conference and Exposition (ieeet-d.org). We hope that you will read this information in time to register for this amazing event, to be held on 6–9 May 2024 in Anaheim, CA, USA. This year, editorial board member Marianna Vaiman acted as chief editor to deftly manage the issue with steadfast support from the EIC and assistant editor. Marianna is also a newly elected IEEE Fellow in the 2024 class. Congratulations! Sincere appreciation goes to Marianna for accepting the assignment and developing a quality supplement to the conference with the contributions from a fine set of authors. All of this was accomplished over a very time-constrained schedule, coinciding with the holiday break. The special issue of the magazine will feature five original articles that address the theme of this year's conference, "Accelerate the Grid of Tomorrow." It will be distributed as part of the registration package, another benefit you will receive for registering for the T&D conference.

In Memoriam

On the topic of sad news, we are reporting with a heavy heart that Prof. Dagmar Niebur passed away on 10 July 2023 [A11]. Together, Joydeep Mitra, Damir Novosel, and Marianna pay a well-deserved tribute to the memory of this great lady, who spent most of her career as a professor at Drexel University after obtaining her Ph.D. degree at the Swiss Federal Institute of Technology, Lausanne. She will be remembered for her excellence in teaching and her leadership in bridging the gaps between academia and industry.

News From the Magazine Desktop

In this issue, our sincere thanks to outgoing board member Barry Mather. Barry was also an early *IEEE Power & Energy Magazine* associate editor. He pioneered this role and contributed, together with my predecessor, Steve Widergren, to enhancing the review processes and hence the quality of the articles published by the magazine. A world of thanks to Barry for the numerous hours given to the magazine since 2017. To replace Barry, with the concurrence of the vice president of publications, Prof. Géza Joos of McGill University, Montréal, Canada, has been appointed as an associate editor and editorial member, responsible for special issues related to transmission and distribution. We are grateful that Dr. Joos, as a leader with his stature and reputation, is willing to serve as a volunteer on the magazine's editorial board. His expertise in power electronics and standards expands significantly the breadth and depth of coverage of PES technical fields by *IEEE Power & Energy Magazine*.

I am pleased to report that the editorial board has finalized the schedule of the magazine from January 2024 to June 2025 during its fall meeting, held on 14 December 2023. We are pursuing a policy of continuous planning and updating of magazine topics to respond to PES leadership priorities in addition to community-driven interests. As an example, we are working on an issue on "Energy Justice" for July/August 2024, which was not included in the original 2024 schedule. Such changes can happen again. The magazine agenda (as published on the PEM website [*IEEE Power & Energy Magazine*–PES (ieee-pes.org)] is a prospective tool that shall not limit PES's agility in addressing timely topics or fast-rising policy matters.

I conclude my introduction to this issue by asking all of you to join me in giving a well-deserved accolade to guest editors Julia Matevosyan and Hannele Holttinen, who are also editorial board members. Working with these outstanding guest editors was easy for me. The articles were on time in ScholarOne, thanks to the dedication of the authors—not only at the first submission but also during revisions and up until submission of the final files to production. The great team of authors they assembled to suit this daunting task warrants, as well, a round of applause. Last but not least, I want to stress the extraordinary dedication of associate editor Barry Mather, who accepted to oversee this issue even as his term as editorial board member was over.

As a last notice, we encourage unsolicited article submissions, which may or may not be aligned with the future topics posted on the magazine website. Reserving a page budget in each issue for unsolicited articles is our way of keeping the magazine adaptive to new trends not foreseen at the time of planning, 12 months ahead. Feel free to write to us with inquiries regarding the magazine policies and activities at powerandenergymagazine@gmail.com. This is also the e-mail box for sending letters to the EIC, which we are eager to read and publish as you see fit, with only minor edits.

For Further Reading

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Appendix: Related Articles

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[A2] B. Badrzadeh et al., "Grid-forming inverters: Project demonstrations and pilots," *IEEE Power Energy Mag.*, vol. 22, no. 2, pp. 66–77, Mar./Apr. 2024, doi: 10.1109/MPE.2023.3342766.

[A3] B. Bahrani et al., "Grid forming inverter-based resource research landscape: Understanding the key assets for renewable-rich power systems," *IEEE Power Energy Mag.*, vol. 22, no. 2, pp. 18–29, Mar./Apr. 2024, doi: 10.1109/MPE.2023.3343338.

[A4] A. Hoke et al., "Foundations for the future power system: Inverter-based resource interconnection standards," *IEEE Power Energy Mag.*, vol. 22, no. 2, pp. 42–54, Mar./Apr. 2024, doi: 10.1109/MPE.2023.3341795.

[A5] B. Chaudhuri et al., "Rebalancing needs and services for future grids: System needs and service provisions with increasing shares of inverter-based resources," *IEEE Power Energy Mag.*, vol. 22, no. 2, pp. 30–41, Mar./Apr. 2024, doi: 10.1109/MPE.2023.3342113.

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