unifi consortium

universal interoperability for grid-forming inverters

Annual Newsletter 2024

A look back at key developments in the Universal Interoperability of Grid-forming Inverters (UNIFI) Consortium in 2024

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Front page: UNIFI group at the NREL South Table Mountain campus. (Image credit: Gregory Cooper @ NREL.)

Foreword

The Universal Interoperability for Grid-forming Inverters (UNIFI) Consortium is a US Department of Energy (DOE) funded effort to advance research and development of grid-forming (GFM) inverter based resources (IBRs). UNIFI brings together leading researchers, industry stakeholders, utilities, and system operators to develop technologies that guarantee interoperability of GFM IBRs deployed on the grid. The ultimate goal is to ensure reliability, security, and affordability of the future US grid. We have 43 members including 5+ national & industry-research labs and non-profits, 10+ universities, and 20+ industry partners. (See back page.) There are several benefits to membership spanning participation in research and development working groups, education and workforce development activities, and a wide range of outreach and training efforts across academic institutions and industry. This newsletter recaps key accomplishments across the consortium in 2024, the third year of the UNIFI consortium operation. Particularly exciting ones attributable to consortium-wide efforts include

- UNIFI published Version 2 of the *Specifications for Grid-Forming Inverter-Based Resources*. This has been used as the basis for ERCOT's and MISO's draft requirements for GFM. It is also being used around the world (most recently, in Chile).

> We are currently drafting Version 3 of the *Specifications for Grid-Forming Inverter-Based Resources*, and we plan to move that forward as an IEEE Standard. Standardizing requirements will make it easier for both vendors and system operators to agree on expected performance of GFM technologies.

- UNIFI has worked with its members to develop generic models of GFM IBRs that are now approved by WECC and available for use in popular modeling and simulation packages. This allows utilities to rapidly model GFM IBRs in interconnection studies.

- UNIFI continues the execution of a multi-vendor GFM experiment at the Energy Systems Integration Facility (ESIF) at the National Renewable Energy Laboratory (NREL). The experiment involves seven GFM inverters from five different vendors rated at a total 1 MW.

- UNIFI has released a draft *Large Scale Field Demonstration Evaluation Plan*. This document is being developed to guide the commissioning and evaluation of GFM plants.

Reading on, you will learn more about the 1 MW multi-vendor demonstration at ESIF, our experiences in working with system operators in Kaua'i (the only system in the world with multiple closely coupled GFM IBRs from different vendors), recaps from our annual meetings, a technical deep-dive into the hot-topic issue of current limiting with GFM IBRs, and some individual accomplishments of members.

Benefits of UNIFI membership. We offer three tiers of membership; see here for details.

Multi-vendor 1MW Demo

A one-of-a-kind experiment at 1 MW featuring GFM products from five vendors is currently undergoing within ESIF at NREL. Now in its third year, we have learned quite a bit about whether GFM technology is ready to be operated out of the box and on the field. The short answer: it depends on conditions and context; the long answer: we are still learning as discussed ahead.

Our experiments have revealed that all GFM inverters offer some common functionality including dispatchability, steady-state voltage control, dynamic reactive-power support, active-power frequency control, disturbance ride-through performance, and fault-current and negative-sequence current contribution per the *NERC GFM Functional Specifications* published in June 2023. We have also observed that GFM inverters all exhibit similar output impedance characteristics. These common attributes across products attest to the ability of vendors in keeping up with good design practices and recognizing common desirable functionality despite the nascency of the industry at large.

While the commonalities and interoperability noted above are noteworthy, there continue to be several challenges that require additional research and development. For instance, droop is the key control strategy upon which we can ensure GFM inverters output the target power and achieve power sharing goal. Active power is easy to handle, however, reactive power is problematic and requires regulation via secondary control across a variety of operating conditions (presence / absence of a stiff grid at the point of interconnection). Droop coefficients need to be tuned in case of stability issues and to have smaller frequency and voltage deviations from nominal values. A more challenging aspect that has come to light is that other control parameters corresponding to internal loops need tuning to optimize performance as do current/power ramp rates to ensure minimal transients during disturbances. We have also observed that GFM IBRs can easily trip due to disturbances. (As expected, with less GFM IBRs in the system, GFL IBRs tend to trip rather easily with smaller disturbances.) Under disturbance events, GFM often trip off with DC under voltage due to the insufficient energy in DC side. Furthermore, the anti-islanding function of GFL IBRs needs to be disabled with systems with high IBRs for better system stability and robustness.

These experiences suggest several opportunities to advance GFM IBRs. While interoperability appears solidly enforced with appropriately tuned droop characteristics at the autonomous primary-control layer, much work needs to be done to ensure interoperable operation across layers in the control hierarchy.

Real-time dashboard of 1 MW demo at ESIF. (Image credit: Xinyang Zhou @ NREL.)

UNIFI Meetings & UNIFI at Meetings

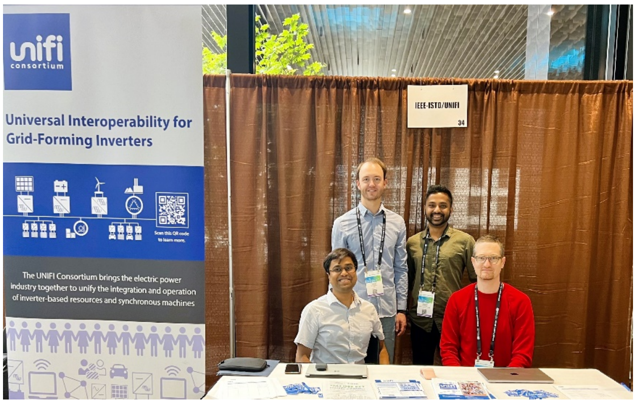
One of the key benefits of UNIFI membership is attending our in-person meetings twice a year. In the Spring, we organize our *Annual Meeting*: an opportunity to game plan work efforts in close coordination with industry; and in the Summer, we organize our *General Meeting*: a longer and decidedly more elaborate affair that includes several technical sessions and learning opportunities. In all, these meetings offer the opportunity to get together with researchers, engineers, students, and regulators to discuss latest GFM technologies, listen to presentations from industry leaders, tour lab facilities engaged in cutting-edge GFM research, and roadmap next steps for GFM technologies across UNIFI work streams.

For the 2024 *Annual Meeting*, UNIFI team members were hosted by Brian Johnson at the University of Texas Austin on February 6-7. This gathering featured in-depth technical presentations from consortium members, big-picture viewpoints from invited speakers across academia and industry, and posters from our student researchers. Early results from the 1 MW multi-vendor experiment drew a lot of discussion, as did UNIFI's latest endeavor to set up agile teams focusing on cross-cut topics relevant across the wide spectrum of the consortium's activities including: control under constraints, stability limitations/interactions of GFM technology with multiple devices, scalability in simulation and control architectures, and certification. Our Annual Meeting includes a poster competition for students, and Ashwin Venkataramanan from Virginia Tech (advised by Ali Mehrizi-Sani) won the award for his work: "Black and Model-Free Transient Response Shaping for IBRs."

Our 2024 *General Meeting* was termed "GFM Week" and it was organized over 5 days in July at NREL. This meeting brought together UNIFI consortium members, members of our external advisory board, and DOE technical program managers. This event featured a series of tutorials, an overview of the second version of UNIFI specifications for GFM IBRs, and updates from consortium areas and cross-cut teams. Key discussions included the system-level impacts of GFM current limiters, particularly on stability and protection, OEMs' and system operators' perspectives on GFM specifications and the latest standards, WECC-approved GFM models, recent advancements in generic models, the necessity of EMT studies, and insights from Kaua'i Island Utility Cooperative's (KIUC's) experience with operating an IBR-dominant grid.

The UNIFI General Meeting was followed by the IEEE Power & Energy Society General Meeting (PESGM) in Seattle, where UNIFI set up an exhibitor booth for the first time. UNIFI researchers were active throughout this gathering of power-systems experts from around the world and participated in several technical sessions and panels.

In addition to the 2024 IEEE PESGM, UNIFI researchers participated in several other meetings throughout the year including ERCOT's Innovation Summit, CIGRE (Conseil International des Grands Réseaux Electriques) 2024 in Paris, and the GE Electrification Symposium in Niskayuna.



UNIFI booth at the 2024 IEEE PESGM.

Dispatches from Kaua'i

The Kaua'i Island, nicknamed "The Garden Isle" due to its dramatic natural beauty, is Hawaii's fourth largest island. This island's power system is operated by Kaua'i Island Utility Cooperative (KIUC), and it is unique due to its high penetration rate of IBRs. Recent studies by UNIFI on this IBR-dominant power system have greatly enhanced our understanding of the impacts of IBRs on power system dynamics.

A team of researchers from NREL and Purdue university, together with KIUC, has developed a streamlined real-world oscillation event analysis framework under a US DOE SETO-funded project called SAPPHIRE. The proposed framework allows one to readily identify which IBRs cause oscillations, what the root cause of the oscillation event is, and how to effectively mitigate oscillations. Leveraging this framework, the team uncovered the root cause of a real-world 18-20 Hz oscillation event in Kaua'i to be suboptimal GFL tuning. This event can be effectively mitigated by GFM technology, because the GFM inverter can improve the grid strength and provide positive damping to the 18-20 Hz oscillations.

Building on this success, under UNIFI, the team has performed further work uncovering how well-designed GFM IBRs and well-tuned parameters can offer grid-stabilizing effects. For example, in another small-magnitude 1 Hz oscillation event in Kaua'i, the team traced back the source of the oscillation to a particular block in the GFM IBR, and further demonstrated that GFL IBRs were providing positive damping to this oscillation mode.[1]

The Kaua'i system study provides a systematic real-world oscillation event analysis framework for the evolving power systems with increasing share of IBRs. This framework aims to improve the efficiency of tackling other oscillation events worldwide by streamlining the whole analysis process. Following the proposed framework, the 18-20 Hz oscillation event investigation provides a concrete example that demonstrates the grid-stabilizing effects of well-designed and well-tuned GFMs. Moreover, the Kaua'i system study has been crucial to show how power grids can operate at extremely high levels of IBRs and provide stable, reliable, and affordable power. This highlights the importance

[1] See: S. Dong et al., "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems With Case Study for Kaua'i System," in *IEEE Trans. Circuits & Systems I: Regular Papers*, 2025.

of the ongoing GFM specification development work under UNIFI and is a shining example of how UNIFI members continue to work with system operators and vendors to evaluate the impacts of GFM technologies on power system dynamics around the world.

KIUC operates a meshed network with high numbers of IBRs and multiple GFMs from different vendors. (Photo credit: KIUC.)

Technical Note: Current Limiters

A key research question that has dominated attention across the industry is current limiters. GFM IBRs, unlike traditional synchronous generators, tend to struggle with over-current events during disturbances. Without proper current limiting, excessive currents can damage inverters and disrupt grid stability. A deep dive into current limiting and GFM IBRs follows.

How Current Limiters Work

Without proper safeguards, excessive currents during disturbances can damage the inverter's power stage, leading to system failures and jeopardizing grid stability. Addressing this challenge is where current limiters come into play. Current limiters are the first line of defense during grid disturbances. These controls regulate the flow of electrical current, ensuring it remains within safe operational limits. There are three main approaches to current limiting in GFM inverters: direct, indirect, and hybrid methods.

Direct current limiting caps the inverter's output current using techniques like current-reference saturation, which dynamically scales down current commands to prevent excessive output, offering an immediate response to fault-current surges. Indirect methods regulate current flow by adjusting control variables such as voltage or power references; e.g., virtual impedance introduces a simulated resistance or reactance to limit fault current while preserving the inverter's voltage-source characteristics. Hybrid approaches combine both strategies, using direct limiting for rapid fault-current control and indirect methods to stabilize voltage and frequency, ensuring both hardware protection and system stability during disturbances.

System-Level Impacts

Current limiters do more than just protect the inverter; they also shape the way these devices interact with the grid during and after disturbances. The design and implementation of current limiters have far-reaching implications for grid stability and reliability, specifically on transient stability, voltage and reactive power support, post-fault recovery, and grid resynchronization.

The *Equal Area Criterion*, developed in the early 20th century, provided a graphical method for assessing transient stability in power systems before numerical simulations became widespread. While initially applied to synchronous machines, where the power-angle curve is shaped by mechanical and electrical power exchange, GFM IBRs introduce new dynamics due to their reliance on current limiters. Direct limiters truncate the power-angle curve, reducing the system's ability to recover from disturbances, whereas indirect limiters, like virtual impedance, preserve its continuity, aiding stability. As grids transition to inverter-dominated networks, researchers are refining the power-angle framework to incorporate current limiting effects, ensuring accurate stability assessments in modern power systems.

Impact on Power System Protection

Power system protection with IBRs is challenged by the limited fault currents of inverters, disrupting traditional overcurrent, distance, and directional protection schemes. Conventional overcurrent protection struggles with fault detection, but GFM IBRs can improve reliability by providing maximum available current during faults. Distance protection faces issues as current limiters alter fault current phase angles, but designs like highly inductive virtual impedances help GFM inverters emulate synchronous generators, restoring efficacy. Line-differential protection remains reliable as it compares currents at both ends of a line, though adjustments in communication and relay settings may be required.

Striking the Right Balance

Designing current limiters requires balancing hardware protection with grid stability and post-fault recovery. Direct methods rapidly curb fault currents but may disrupt the voltage-source nature of GFM IBRs, while indirect methods, like virtual impedance, support stability but may under-utilize the IBR's over-current capacity. Hybrid limiters combine these strengths, offering rapid protection with improved synchronization. Advances such as anti-windup feedback and adaptive designs further enhance performance. However, no single design fits all scenarios, making flexible, customizable solutions essential. Collaboration among researchers, system operators, and manufacturers is key to refining these technologies for evolving grid demands.

The Road Ahead

Robust current-limiting strategies for GFM IBRs are crucial for grid stability. Future research must focus on adapting power system protection to account for GFM inverter behavior and ensuring compatibility with legacy protection schemes. With thousands of GFM inverters expected to operate alongside other generation assets, understanding their interactions and impact on system stability remains a key challenge. Additionally, revising grid codes to define GFM performance during faults will streamline integration.

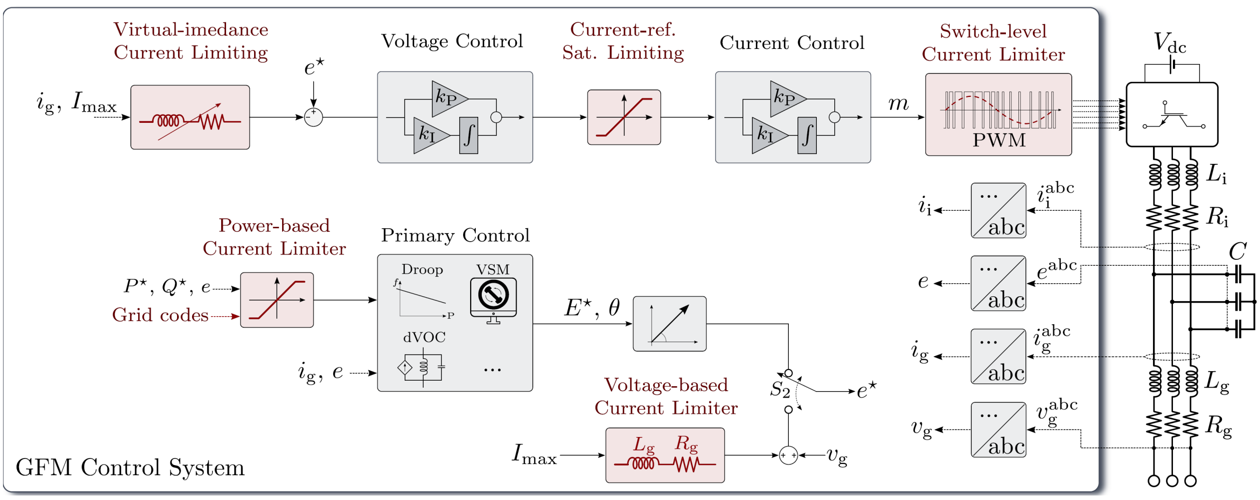
Further Reading

A number of papers on the topic of current limiting and GFM operation under constraints have been published by UNIFI researchers:

- N. Baeckeland, D. Chatterjee, M. Lu, B. Johnson, and G.-S. Seo, "Overcurrent Limiting in Grid-Forming Inverters: A Comprehensive Review and Discussion," in *IEEE Transactions on Power Electronics*, 2024.
- M. A. Awal, S. Cen, D. Michaud, and I. Husain, "Capacity Optimized Grid-Forming Control: A Framework for AC Grid-Forming under Hardware and Source Constraints," in *Proc. IEEE Energy Conversion Congress and Exposition*, 2024.
- N. Baeckeland, G.-S. Seo, A. Domínguez-García, D. Ramasubramanian, D. Groß, and S. Dhople, "Equivalent-circuit Models for Grid-forming Inverters under Unbalanced Steady-State Operating Conditions," in *Proc. 58th Hawaii International Conference on System Sciences*, 2025.
- X. Lyu, W. Du, S. M. Mohiuddin, S. P. Nandanoori, and M. Elizondo, "Criteria for Grid-Forming Inverters Transitioning Between Current Limiting Mode and Normal Operation," in *IEEE Transactions on Power Systems*, 2024.
- A. Acharya and R. Ayyanar, "Enhancing Stability of dVOC Controlled Grid-Forming Inverters Under Large Grid Transients A Power Angle Based Approach," in *Proc. IEEE Energy Conversion Congress and Exposition*, 2023.

Points of Pride

All in all, it has been a busy year for UNIFI team members! Our efforts in advancing R&D in power systems and power electronics continue to be recognized broadly across industry, professional societies, funding agencies, and regulatory bodies. Some notable points of pride from 2024 are:



Overview of direct and indirect current-limiting methods for GFM IBRs. (Image credit: Nathan Baeckeland @ NREL.)

- Ali Mehrizi-Sani (Virginia Tech) was promoted to Professor and appointed as Director of the Power and Energy Center at Virginia Tech.

- Deepak Ramasubramanian (EPRI) was secretary of the taskforce that received the 2024 IEEE PES Technical Committee Working group award for outstanding technical report "TR113: Simulation methods, models, and analysis techniques to represent the behavior of bulk power system connected inverter-based resources."

- Xiaonan Lu (Purdue) has been selected as the co-Editor-in-Chief of the IEEE Transactions on Power Electronics (2025-2026). He has also received the 2024 Outstanding Engineer Award for the Joint PES/PELS/IAS Central Indiana Chapter.

- Wei Du (PNNL) led the UNIFI Modeling and Simulation team in the development of a standard library grid-forming inverter model $\mathrm{REGFM}_{\mathrm{C1}}$ and plant controller model $\mathrm{REPCGFM}_{\mathrm{C1}}$ in collaboration with WECC, Tesla Energy, and commercial power system simulation software vendors. The model specifications have been approved by WECC in late January in 2025, and the models are expected to be finally approved by WECC and released in commercial simulation tools later this year.

- Charles Hanley (Sandia) served as General Chair of the IEEE eGRID 2024 Workshop sponsored by the IEEE Power Electronics (PELS) and Power and Energy Societies (PES) organized in Santa Fe, NM.

- Nathan Baeckeland (NREL) presented the paper, "Equivalent-circuit Models of Grid-forming IBRs for Electromagnetic-transient Simulations," at the Best Paper Session at the 2024 IEEE PES General Meeting. He also won the NREL Science-in-3 (Sci3) competition, an event where postdocs are challenged to present their research to an audience in less than 3 minutes; he advanced to the national-level competition as a result.

- Deepak Divan (Georgia Tech) was awarded the 2024 IEEE Medal in Power Engineering "For contributions to advanced power conversion technologies for modern electric power grid." His book, Energy 2040 was selected by Forbes to be in the top-10 list for 2025. Also, he was appointed to the US DOE's Electricity Advisory Committee.

- Dominic Groß (UW-Madison) appointed as Dugald C. Jackson Assistant Professor at the University of Wisconsin-Madison.

- The University of Puerto Rico at Mayaguez team, advised by Eduardo I Ortiz Rivera, has emerged victorious, claiming first place in the 2023-2024 US Department of Energy Solar District Cup.

- Ben Kroposki (NREL) selected as co-chair of the US DOE Grid Modernization Laboratory Consortium (GMLC).

- Iqbal Husain (NCSU) delivered plenary talk at the 2024 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES).

- A brave group of UNIFI members scaled the 14,265 ft. Blue Sky Mountain in CO during the 2024 UNIFI General Meeting organized in NREL in July 2024.

UNIFI scales the 14,265 ft. Blue Sky Mountain.

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