A Guide to Current Limiting and Stability With Grid-Forming Inverters

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Background

The electric power grid is changing. For many decades, the synchronous generator—an electromechanical device invented in 1887—has been the workhorse and backbone of power grids across the globe. Our entire infrastructure is built around it. But times change, and so does the power grid. Since the early 21st century, we have seen a gradual shift in modern power grids away from synchronous generators to ones dominated by power electronic inverter-based resources (IBRs). Sources such as photovoltaics, wind turbines, battery storage, fuel cells, and other technologies like high-voltage DC transmission interconnections all rely on an inverter to connect and interface with the grid. They are increasingly being installed on the grid to augment, or even replace, traditional energy sources (see Figure 1). This change is a fundamental shift that brings tremendous technical challenges and questions: Can a power grid remain stable with many more IBRs? How do we avoid more blackouts on the grid? How do we keep the grid secure and resilient during disturbances? After all, power electronic inverters are nothing like the big, rotating, iron-and-copper machines that the grid heavily relies on. Many of these questions can be answered by using grid-forming (GFM) inverters, yet many research challenges remain. This document explores GFM inverters and how they can help stabilize the future grid, especially during disturbances and contingencies. It summarizes a two-year research and development fellowship program at NREL. We point interested readers to more detailed works developed during the project along the way. Let's dive in.

What Are GFM Inverters and

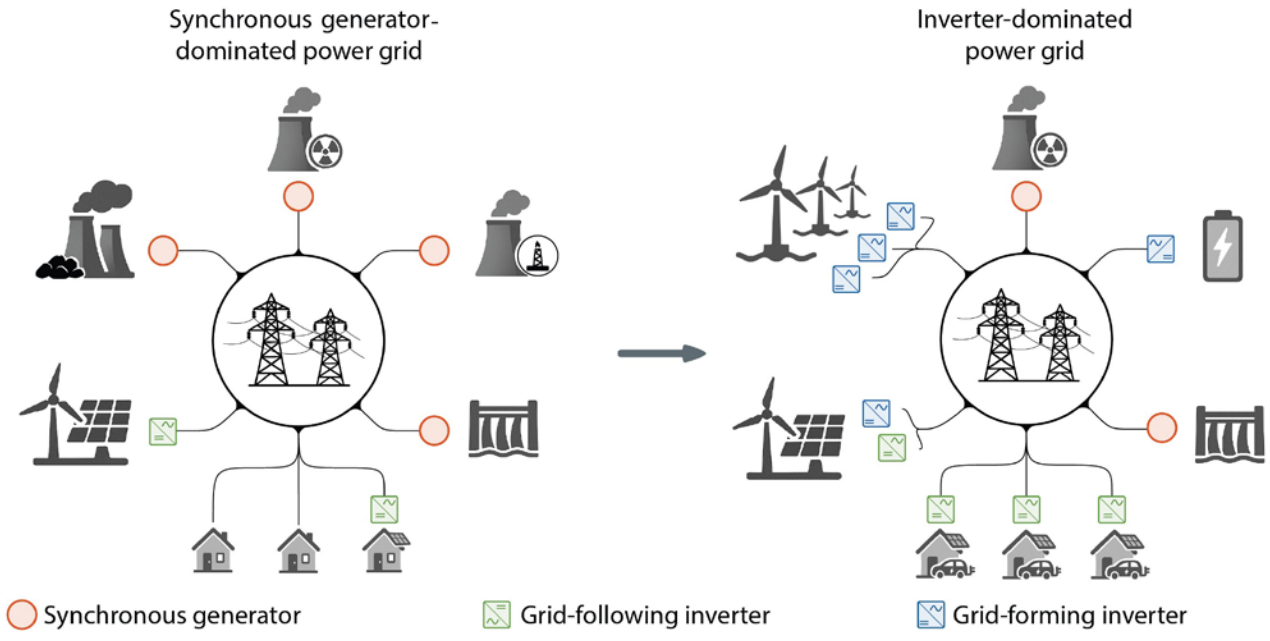

Figure 1. The transition from a synchronous generator-dominated power grid to an inverter-dominated power grid. *Graphic courtesy of NREL*

Why Do We Need Them?

An inverter consists of a physical layer (the hardware) and a control layer (the software) that operates on the microprocessor of the inverter (see Figure 2). The control layer takes in measurements of currents and voltages, and it generates a set of reference values to fire the semiconductor switches, constructing an appropriate AC voltage waveform. The control system can be implemented in many ways, but, in general, we can classify them as grid-following (GFL) or GFM control concepts. What is the difference, and why do we need GFM controls in inverter-dominated power grids?

Imagine a normal bicycle (Kenyon et al. 2020), as illustrated in Figure 3 (left). The rider can set the pace and the direction of the bicycle. Similarly, GFM inverters can autonomously regulate or "form" the frequency and voltage of the grid while also synchronizing and sharing power with the grid. Next, imagine a tagalong bike that simply latches onto and follows the pace and direction of the normal bicycle (Figure 3, middle). This is analogous to GFL inverters on the grid, which track the voltage and latch onto an existing voltage waveform. Adding too many tagalong bikes to the normal bike will make the system unstable. Only having tagalong bikes does not work because the bikes would fall over (Figure 3, right). In a similar way, a power grid becomes unstable or could even collapse entirely when there are too many GFL IBRs on the grid. So, if the grid becomes inverter dominated, some of the inverters will need to operate in GFM mode.

The Challenges of GFM Inverters in Practical Grids

How should a GFM inverter behave during disturbances and during off-nominal conditions that fall outside the normal operating boundaries of the device? In other words, how can we design a GFM control system that can ride through any

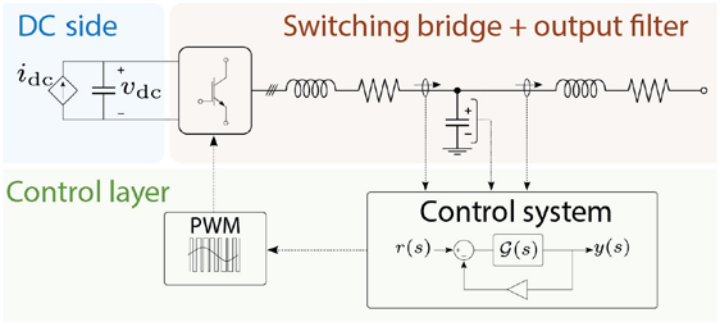

Figure 2. The physical and control layers of a generic grid-connected inverter. The control system can be either GFL or GFM. *Graphic courtesy of NREL*

type of disturbance (e.g., line faults, phase shifts, and black starts) while continuing to operate stably and support the power grid? It is one aspect of GFM technology that is still a topic of discussion, and it is precisely the topic that this NREL fellowship aimed to investigate. Why is this such a challenging topic? Synchronous generators have a large mechanical and thermal inertia because of their distinct physical design and characteristics. This enables them to withstand prolonged and severe overloading and overcurrent—for example, during disturbances on the power grid. In comparison, inverters that are built of semiconductor switches and components do not have such high thermal inertia. That makes inverters vulnerable to damage inflicted by even slight overloading. We can avoid damaging the inverter's hardware by limiting the current flowing out of the inverter so that it never breaches a critical and irreversible state. Say hello to the current limiter.

A current limiter lives in the controls of the inverter. It manipulates control signals so that the output current remains within certain bounds. The current limiter's primary job is to curtail overcurrent; however, once the current limiter engages, it manipulates the control system of the inverter, which induces an entirely different dynamic output behavior of the inverter. So, the current limiter should not only facilitate quick and accurate limiting but also restrain from causing excessive

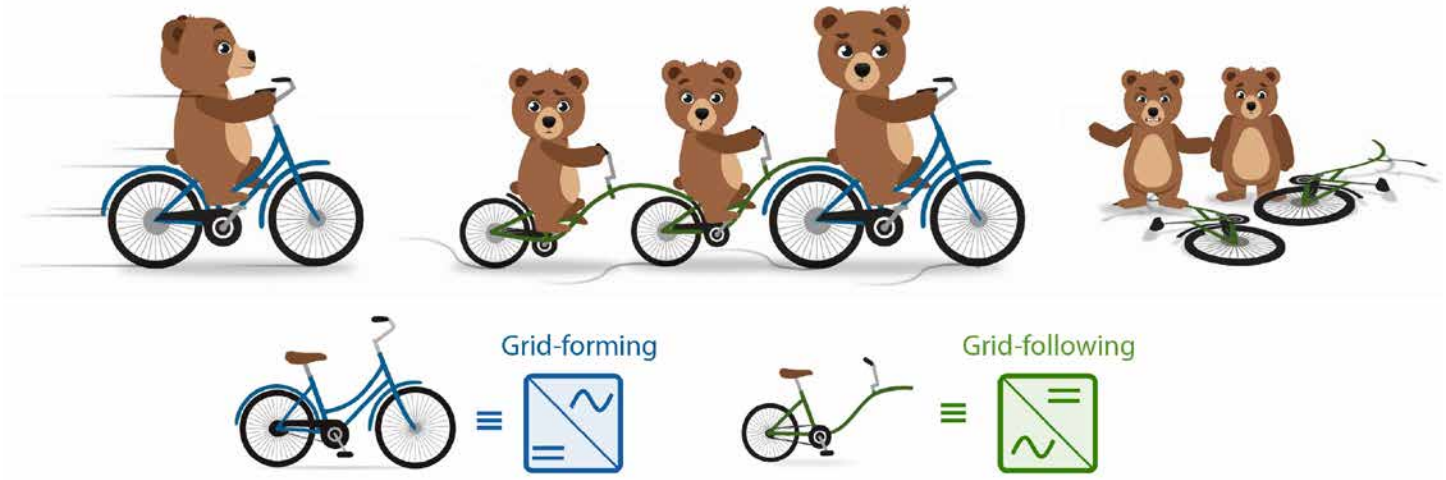

Figure 3. The concept of GFL and GFM inverter controls explained through a bike analogy. *Graphic courtesy of NREL*

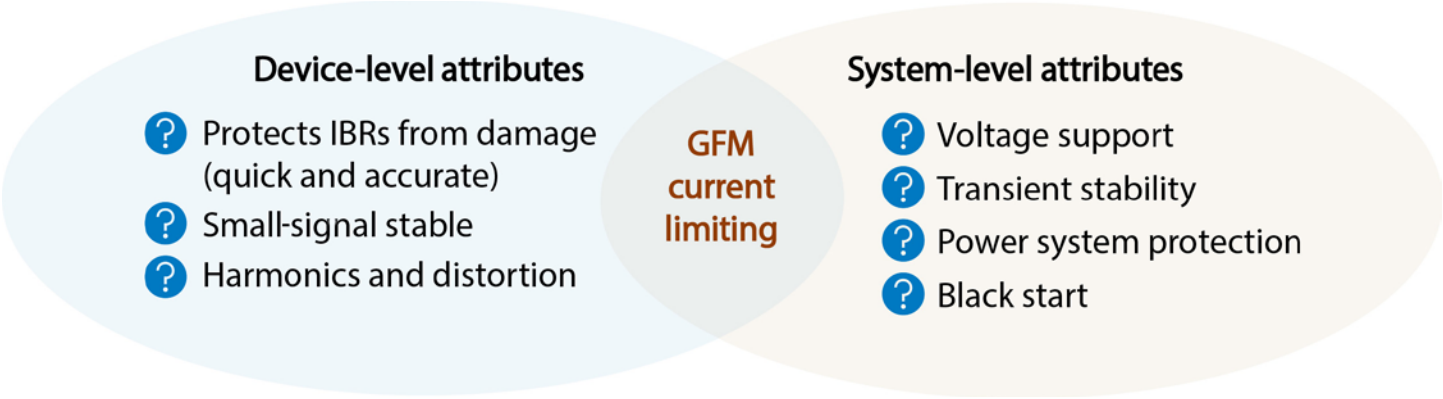

Figure 4. GFM current limiting has numerous ramifications on device-level and system-level attributes *(Baeckeland et al. 2024)*

harmonics in the inverter output voltage and currents or compromising the small-signal stability. And it does not end here. The altered dynamic behavior of the inverter during current limiting also affects the entire power system to which it is connected. A change in the output voltage and currents affects the output impedance of the inverter, which has implications for many different network-wide attributes and systems, such as power system protection, transient stability, voltage support, and grid synchronization (Baeckeland et al. 2024). This fine balancing act between device-level and system-level impacts of the current limiter in the inverter is captured in Figure 4.

Research and Development

There are many ways to achieve current curtailment in GFM controls. The performance and characteristics of each current-limiting method strongly depend on its location in the GFM controls (see Figure 5). Current-reference saturation limiting, virtual impedance current limiting, and switch-level current limiting are some examples of methods that aim to curtail the current output of the inverter during grid disturbances. During this fellowship program, we developed a hybrid current limiter solution that combines concepts of current-reference saturation and virtual impedance limiting (Baeckeland and Seo 2023). The results illustrated greater controllability over voltage and current phasor outputs than the classical current-limiting methods. Nonetheless, each limiter design has merits and drawbacks. Designing a current limiter that performs optimally, both at the device level and at the system level, remains extremely challenging and requires a deep understanding of the current-limiting mechanisms as well as how the current limiter impacts the system's stability, voltage, and protection mechanisms. For that reason, we authored a review paper that summarizes the most common current-limiting types (Baeckeland et al. 2024). In that work, we present a thorough discussion on their merits and drawbacks, and we investigate their impacts on system-level attributes like transient stability and protection. From there, this research fellowship program primarily focused on the impact of current limiting in GFM inverters on the transient stability of the connected electric system. But what is transient stability? Why does the current limiter influence transient stability? And what can we do to improve this?

In classical power systems, many individual synchronous generators collectively provide power to the grid by all rotating at the same frequency (typically 60 Hz or 50 Hz). To compare this with the bike analogy, they are all riding in one group at the same speed. When a disturbance happens on the grid (e.g., a generator trip or a short-circuit fault on power lines), the generators can lose synchronization with each other—i.e., the bicycles become separated and are no longer riding together in one group. This causes large and unwanted fluctuations in the grid voltage and frequency. We call this transient or large-signal instability. The same issue can occur with GFM inverters. In a GFM inverter, a similar power-to-frequency relationship as in a synchronous generator is programmatically implemented in the primary controller. This allows the inverter to share power and synchronize with the

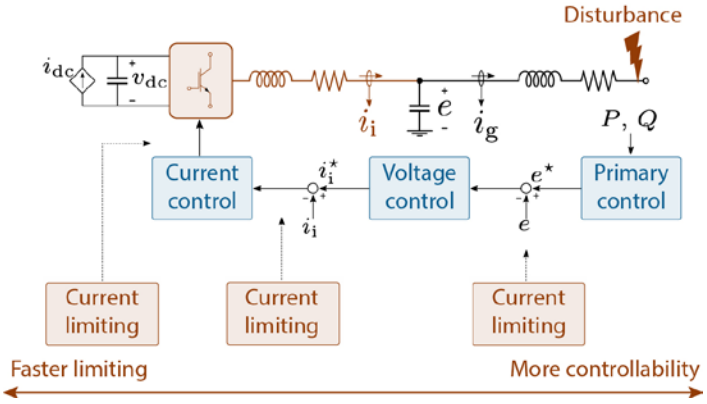

Figure 5. There are many ways to implement current-limiting controls in a GFM inverter control system. Depending on the limiter's location in a control system, the limiter is faster or has more controllability. *Graphic courtesy of NREL*

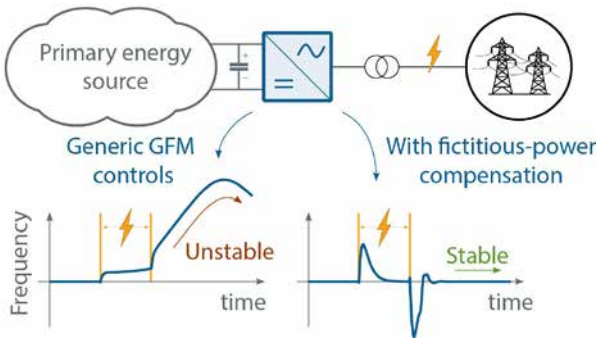

Figure 6. We developed a control method based on fictitious power to keep the GFM inverter stable in the face of faults on the grid.
Graphic courtesy of NREL

grid, just like a synchronous generator. So, even though GFM inverters do not have a rotating mass that spins at the grid frequency, the internally generated frequency reference can lose track and deviate, resulting in transient instability. And here's the problem: Because the current limiter curtails the output power of the GFM inverters during grid disturbances, the inverter is even more vulnerable to losing synchronization and causing instability.

As part of this research fellowship program, we investigated this current-limiter-induced instability phenomena in GFM inverters. In Baeckeland et al. (2025), we translate the inverter controls into equivalent analog circuitry, from which it is possible to intuitively compute the energy stored in the system. This novel approach allows for energy function-based stability analysis while incorporating all the details of the inverter controls. In Baeckeland, Yang, and Seo (2025a), we dig into the root causes of GFM instability and aim to give intuitive insights.

Second, we developed a control method to make the GFM inverter more robust against instability (Baeckeland, Yang, and Seo 2025b). As explained, the current limiter curtailing the inverter output power during disturbances is detrimental to the inverter's ability to remain stable and synchronized. So, what if we can offset the effect of the current limiter on the output power and frequency? In doing so, can we make the inverter controls more robust and stable? To do that, we introduced the concept of fictitious power: the power that the inverter cannot inject into the grid because the current limiter is curtailing the output. We then feed back this fictitious power to the primary controller, which, in turn, adjusts the frequency accordingly. This is illustrated in Figure 6. Essentially, we make the primary controller "think" that the inverter is not constrained and can withstand overloading. After all, the frequency of the GFM inverter is a control signal that can be manipulated. Extensive simulation and hardware experiments have illustrated the efficacy of this control method. A U.S. nonprovisional patent, U.S. 2025/0007294 A1, has been published for this technology.

Contact

For questions about this research project, or if you are interested in incorporating these technologies into your commercial products, contact Nathan.Baeckeland@nrel.gov or Gabsu.Seo@nrel.gov.

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NREL is a national laboratory of the U.S. Department of Energy
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Operated under Contract No. DE-AC36-08GO28308

NREL/FS-5D00-95957 • September 2025