WECC

Grid-forming Inverters

November 2023

OVERVIEW

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Executive Summary

The resource transition occurring in the West is replacing synchronous generators with inverter-based resources (IBR), which results in a decrease in inertia. Inertia is the total kinetic energy stored in synchronously connected machines and provides a fast injection of active power to the system when large changes occur, such as the sudden loss of generation.

In 2021, WECC conducted the Changes in System Inertia (CSI) study, which found that a large generator outage during spring conditions with low system inertia could pose a risk for the Western Interconnection in activating the underfrequency load shedding program due to the frequency hitting 59.5 Hz. WECC concluded that operating the system with reduced inertia and without frequency support from IBRs could create a reliability risk. This grid-forming (GFM) inverter study builds on the CSI study and analyzes similar conditions to evaluate how recent changes in IBR technology may affect frequency response.

Most IBRs currently deployed in the Western Interconnection use grid-following (GFL) technology, meaning they react to or follow changes and then try to inject real and reactive power to "follow" the voltage. New GFM technology provides immediate response to changes in the external system and maintain IBR control stability during underfrequency and low voltage conditions during a large disturbance. This study aims to better understand the potential of GFM technology to aid in maintaining system frequency under a range of stressed conditions. The study looks at two hours, both of them light load spring hours, one in 2020 and one in 2024. It simulates two system disturbances: a double Palo Verde Generating Station outage (2PV) and a 20% imbalance, where 20% of online generation is tripped.

Observations and Recommendations

Observation 1: Based on our assumptions, GFM IBR technology shows advantages over GFL technology in maintaining system frequency. With the expected increase in the IBR fleet, ensuring that the Western Interconnection has adequate frequency response from IBRs is critical.

> **Recommendation 1**: Planning Coordinators should strongly consider using GFM technology when replacing synchronous generators with IBRs. With increasing penetration of IBRs, WECC anticipates that the Western Interconnection will need increased and more robust frequency response from IBRs. If the IBR is a battery energy storage system (BESS), it should be designed to provide reliable and robust performance that supports high IBR penetration in the Western Interconnection.[1]

[1] Grid Forming Functional Specifications for BPS-connected Battery Energy Storage Systems. NERC. Sept. 2023

Observation 2: Imbalance simulations show that up to an additional 10% of the original amount of generation is tripped offline due to protection settings or lost synchronization with the grid. This increase resulted in more load shedding than planned in the simulations with just the 20% imbalance.

> **Recommendation 2**: The Underfrequency Load Shedding Work Group (UFLSWG) should look at the Underfrequency Load Shedding (UFLS) methodology considering the results of the imbalance simulations in this study and determine how to evaluate the additional generation tripped by the protection relays in the imbalance simulations.

Observation 3: Rate of Change of Frequency (ROCOF) is one measure of the health of a power system and is very sensitive to the amount of inertia. With the increasing number of IBRs replacing traditional synchronous generators, the subsequent reduction in system inertia is likely to increase ROCOF, and the faster that frequency declines after the loss of generation, the more load is at risk of being shed due to underfrequency conditions. It was also observed that when the amount of generation lost far exceeds the frequency responsive generation, ROCOF remains relatively unchanged. However, the initial frequency response within 0.1 seconds of disturbance does improve when there is significant penetration of frequency-responsive GFM inverter technology in the system.

WECC conducts its study work in partnership with stakeholders. WECC would like to thank all the stakeholders who participated in this study.

Technical Summary

In 2021, WECC conducted the Changes in System Inertia (CSI) study that replaced several synchronous generators with IBRs without frequency response capability. The study found that a large generator outage during spring conditions with low system inertia could pose a risk for the Western Interconnection in activating the underfrequency load shedding program due to the frequency hitting 59.5 Hz. WECC concluded that operating the system with reduced inertia and without frequency support from IBRs could create a reliability risk. A lack of adequate, fast injection of active power could cause a frequency excursion during a generation outage.

This study builds on the CSI study and analyzes similar conditions to evaluate how recent changes in GFM technology may affect frequency response. Most IBRs currently deployed in the Western Interconnection use Grid Following (GFL) technology, meaning they react to or follow changes and then try to inject real and reactive power to “follow” the voltage. Approximately two-thirds of the IBRs in the West are not set to provide frequency response or voltage control. IBRs have, in recent years, experienced a major advancement with the advent of a new GFM technology. Preliminary simulations show GFM functions include extremely fast power injection in the sub-transient to transient time frame in response to frequency events, islanded operation capability without synchronous generation, blackstart capability, and operation in parallel with existing resources. Preliminary studies have shown that when enabled and implemented, GFM technology can arrest the frequency decline more effectively than GFL technology in responding to a frequency event. This study evaluates this new technology under stressed system conditions to better understand its potential to aid in maintaining system frequency.

The assessment included two cases: the 2020 Light Spring (3:00 AM) case, which was studied in the CSI study; and the 2024 Light Spring (1:00 PM), a typical light spring case produced by WECC. The 2024 case was modified to represent a low load (90GW) and low inertia scenario (163,744 MW-seconds (MW*s). These cases were examined under two disturbance scenarios: a double Palo Verde (2PV) outage scenario and a 20% Imbalance scenario, where 20% of online generation is tripped.

2020 Light Spring 3:00 AM Case

For the 3:00 AM case, the study team replaced GFL technology-based IBR resources with IBR resources with GFM technology. WECC simulated a “double Palo Verde generating unit outage” (2PV) to benchmark the modeled differences between GFL and GFM technology. In this comparison of the CSI study, Phase 2 was used because in Phase 1, the GFL did not have the frequency response active, whereas in the simulation for Phase 2, the GFL frequency response was active. In Phase 2, the frequency nadir at Malin was 59.573 Hz. However, when GFL (10% headroom and 4% droop) resources were replaced with the GFM models using a 10% headroom with a 1% droop the frequency nadir increased to 59.85 Hz. This was largely due to how much generation was replaced with the GFM models; 33,368 MW of generation responded to the frequency deviation.

2024 Light Spring 1:00 PM Case

In the 1:00 PM case, WECC replaced 36,570 MW of synchronous generation with GFL IBRs with inactive frequency controls. WECC then simulated the 2PV outage. This caused the frequency nadir to drop below the 59.5 Hz threshold,[2] and load shedding occurred. WECC then replaced 25% of the 36,570 MW GFL IBR resources with GFM IBR resources and ran two sensitivity studies with various levels of headroom (the difference between the unit's maximum capacity and output):

- GFM with a 10% headroom with 1% droop, and 6% headroom with a 1% and 3% droop.
- GFL with a 10% headroom with 4% droop and 6% headroom with a 4% droop.

In the simulated 2PV generation loss (approximately 2,700 MW), the GFL and GFM IBRs performed differently. In the GFL IBR simulation, half of the 36,570 MW of replaced generation was required to keep the frequency in the Western Interconnection above the 59.5 Hz threshold. The amount of generation needed to stay above 59.5 Hz depends on parameters governing how fast the unit can respond. By comparison, 12% of the 36,570 MW of installed GFM was sufficient to keep the frequency above the 59.5 Hz threshold.

During the 20% imbalance scenario 21,733 MW of generation was tripped offline in the 1:00 PM case to create a generation to load imbalance for the following scenarios:

- 25% (of 36,753 MW) of resource capacity with either GFL or GFM with 6% headroom
- 12.5% of GFM with 6% headroom.

It was noticed that in this imbalance simulation that the GFM technology was responding faster than the GFL during the first 0.1 seconds; however, due to the significant magnitude of this disturbance they were unable to provide enough frequency response because they were using the headroom to respond to the disturbance and could no longer provide any additional frequency response. We also observed that due to protection relays triggering and loss of synchronization additional generation was lost; this imbalance simulation resulted in approximately 30% imbalance scenario after additional 7,905 to 10,069 MW of generation tripped. Each simulation resulted in different generation being tripped due to system conditions in each scenario. In losing 29,638 to 31,805 MW of the generation, the frequency fell below the 59.5 Hz UFLS threshold and load shedding occurred. However, due to the activation of UFLS plan the Western Interconnection remains stable and the frequency returned to 60 Hz or above. It was noticed that the GFL technology frequency nadir was lower than the GFM, which would result in more load shedding.

Highlighted Results

[2] The 59.5 Hz is the threshold at which load shedding occurs per the WECC Off-Nominal Frequency Load Shedding Plan. This plan is a safety net in the Western Interconnection if the frequency drops below 59.5 Hz to prevent the system from collapsing.

- If a GFM is electrically near the tripped generator, it responds to the disturbance almost instantaneously by increasing the active power. The further the GFM IBR is from the disturbance, the longer its response time.
- In the 3:00 AM case, frequency response improved as GFM IBRs replaced GFL IBRs.
- In the 1:00 PM case, when 36,570 MW of synchronous generation was replaced with GFL IBRs frequency dropped below the UFLS threshold of 59.5 Hz under a double Palo Verde Outage (2PV) event. When 25% of these IBRs (9,100 MW) were changed to GFM technology in the simulation, frequency remained well above the UFLS threshold.
- Only 4,500 MW of GFM IBRs were necessary to keep frequency from dropping below the UFLS threshold under simulated conditions with the 2PV outage.
- Simulations showed no voltage issues with the GFM or GFL IBRs.
- Under a simulated loss of 20% of online generation, nearly 22 GW of generation tripped offline.
    - Protection relays, or loss of synchronization to the grid, caused an additional 10 GW of generation to trip. This resulted in a simulated load loss of approximately 30 GW.
- In the 20% imbalanced study, it was noticed that the GFL technology frequency nadir was lower than the GFM, which would result in more load shedding.

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Background and Purpose

In 2021, WECC conducted the *Changes in System Inertia (CSI) Study*, which concluded that a large generator outage during spring conditions with low system inertia could pose a risk for the Western Interconnection in activating the underfrequency load shedding program due to the frequency hitting 59.5 Hz. WECC concluded that operating the system with reduced inertia and without frequency support from IBRs could create reliability risk. A lack of adequate fast injection of active power could cause a frequency excursion during a generation outage.

As the replacement of synchronous generation resources with IBRs continues to increase, this issue will grow. As such, WECC decided to conduct an additional analysis of the issue. This study builds on the CSI study and analyzes similar conditions to evaluate how recent changes in grid-forming (GFM) technology may affect frequency response. Most IBRs currently deployed in the Western Interconnection use grid-following (GFL) technology. Two-thirds of the IBRs in the Western Interconnection do not provide frequency response. In recent years, IBRs have experienced notable advancements with the advent of new GFM technology. Preliminary simulations show that GFM functions include high-speed power injection in the sub-transient to transient time frame in response to frequency events, islanded operation capability without synchronous generation, blackstart capability, and operations parallel with existing resources. Preliminary studies have shown that GFM technology can arrest the frequency decline more effectively than GFL technology in responding to a frequency event. This study investigates modeling this new technology and recommends considering some minimum levels of installation that generation developers and transmission planners should consider.

With this new GFM technology, IBRs can potentially reduce the need to initiate the [WECC Off-Nominal Frequency Load Shedding Plan] (the Underfrequency Load Shedding (UFLS) Plan) during system disturbances involving large amounts of tripped generation. In 2021, WECC performed the CSI study with GFL technology and identified potential underfrequency risks to the Western Interconnection during spring conditions (approximately 72 GW of demand). This study will expand on this work using the GFM technology and determine whether these IBRs can provide enough frequency response in the Western Interconnection to keep the frequency above 59.5 Hz during a significant generation loss. 59.5 Hz is the threshold at which load shedding starts to occur, as per the UFLS plan.

This study answers these questions:

1. How do GFM inverters respond during a major loss of generation?
2. What percentage of total generation is needed from GFM and GFL inverters to keep the frequency in the Western Interconnection from hitting the 59.5 Hz UFLS threshold?

GFL and GFM technology function and respond differently to frequency events. In the case of GFL technology, inverters measure the grid voltages and frequency and then try to inject real and reactive power to *follow* the voltage. In other words, GFLs are reactive and only respond after the frequency or voltage event occurs. On the other hand, GFM technology measures active and reactive power output and subsequently determines the inverter output voltage and frequency.

Grid-forming Inverters

GFM inverters are a new technology within IBRs. The primary objective of the GFM technology is to maintain an internal voltage phasor that is constant or nearly constant in the sub-transient to transient time frame. The GFM technology allows the IBR to immediately respond to changes in the external system and maintain IBR control stability during underfrequency and low voltage conditions. The voltage phasor must be controlled to maintain synchronism with other devices in the grid and must also regulate active and reactive power appropriately to support the grid.[3]

There are many benefits to the interconnection from using this GFM technology. According to NERC's white paper, Grid Forming Functional Specifications for BPS-connected Battery Energy Storage Systems, GFM IBRs "provide grid[-]stabilizing characteristics that support reliable operation of the BPS under increasing penetration of IBRs. Enabling GFM in BPS-connected BESS allows for system-wide enhancement of stability margins as these resources are interconnected." The paper goes on to explain that, because of this, system stability enhancements can happen at a much lower cost than by adding transmission assets. With some limitations, any IBR can use GFM controls, including new solar photovoltaic and wind plants. However, GFM controls in BESS provide an easily implemented BPS reliability mechanism since they already have the needed energy buffer on the DC side, which makes the enhancement purely software-based (minimizing much more costly hardware-based improvements or the moderate level of curtailment that may be needed for other IBR technologies).[4]

Study Assumptions

This study highlights two cases: the 2020 Light Spring (3:00 AM) scenario case (used in the 2021 CSI study) and the 2024 Light Spring 2 (1:00 PM) scenario case. (See Table 1 for a comparison of assumptions for the two cases.)

[3] Grid Forming Technology—Bulk Power System Reliability Considerations. NERC. Dec. 2021

[4] Grid Forming Functional Specifications for BPS-connected Battery Energy Storage Systems. NERC. Sept. 2023

Table 1: Case Assumptions

Case	Assumptions
2020 Light Spring 3:00 a.m. (2020 LS11 or 3:00 AM)	High Wind generation, Light load (approximately 72 GW) Inertia (397,840 MW*s)
2024 Light Spring 2 1:00 p.m. (2024 LSP2S or 1:00 PM)	High IBR (wind and solar) Medium load (approximately 90 GW) Inertia (163,744 MW*s)

2020 Light Spring—3:00 a.m. Case (3:00 AM)

WECC used the 3:00 AM case in the 2021 CSI study, and, for the current study, it used this case to benchmark the GFM models. WECC made no changes to this case other than replacing GFL IBRs with GFM IBRs. Further details can be found in the CSI report.

The synchronous generation dynamics data was replaced in four phases based on the inertia constant "H" found in the dynamics models. The base inertia for the 3:00 AM case is 397,840 MW, and, after replacing all the synchronous generators in Phase 1 through 4, the inertia is 173,769 MW*s. The inertia changes are as follows:

- Phase 1—For units where H is greater than 5 seconds, the inertia is 310,015 MW*s;
- Phase 2—For units where H is greater than 3 seconds and less than or equal to 5 seconds, the inertia is 218,692 MW*s;
- Phase 3—For units where H is greater than 1.5 seconds and less than or equal to 3 seconds, the inertia is 177,018 MW*s; and
- Phase 4—For units where H is less than or equal to 1.5 seconds, the inertia is 173,769 MW*s.

The generator models for hydro synchronous condensers and renewable units already identified in the case were not replaced.

2024 Light Spring 2—1:00 p.m. Case (1:00 PM)

The 1:00 PM case, which is part of WECC's Base Case Compilation Schedule, was used as a starting point and modified to achieve the desired case assumptions. This case started with approximately 128 GW of load. WECC scaled this down to simulate medium load and low inertia conditions with approximately 98 GW of load, of which approximately 8 GW was distributed generation. WECC also scaled down the generation profile by either reducing generation unit output or turning units off. (See Appendix 1 for generation and load changes for each area.) Next, WECC determined which synchronous generation to replace with GFM or GFL technology. WECC categorized all generators by turbine type code from the planning case. The replaced units in this study have synchronous generation turbine codes. (See Table 2.) WECC replaced the synchronous generation units with an IBR model, except for the nuclear and geothermal units.

Table 2: Turbine Type Codes

Generation	Turbine Type Code[5]
Wind	20–25
Solar	31–33
Hydro	5
Synchronous	1-4, 6, 7, 11, 12, 13, 14, 19, 29
Other	0, 40, 41, 42, 47, 54, 60, 99

Models and Input Data

With the 3:00 AM and 1:00 PM cases adjusted, WECC then identified the models to simulate GFM and GFL IBRs and replaced its existing synchronous generator models with the GFM and GFL models.

WECC used the REGFM_A1 model to represent the GFM units, and the Pacific Northwest National Laboratory (PNNL) supplied the parameters used for this study. A unit must have *headroom*—or the difference between maximum capacity and present output—to provide the desired frequency response. One model parameter—*Pmax*—was modified to simulate headroom depending on how much response was required from a frequency event. WECC used only two headroom values for its simulations: X = 1.06 for 6% headroom and X = 1.1 for 10% headroom. The following equation was used for the modifications: *Pmax* = [(PGEN in MW) *X] / (MVA Base).

WECC used generic GFL data from the General Electric (GE) Positive Sequence Load Flow (PSLF) manual. The following models were used to model the dynamics of GFL IBRs:

- REGC_A—generator/converter model
- REEC_A—renewable energy electrical control model
- REPC_A—power plant controller model
    - To activate the frequency response in the REPC_A model, the parameters listed below were adjusted. The *Pmax* value was adjusted the same way as in the GFM model depending on the desired percentage of headroom:
        - Frequency Flag: *frqflg* = 1
        - Maximum Power: *Pmax* = [(PGEN in MW) *X] / (MVA Base of REPC_A)
        - Droop was set to 4% *ddn*=*dup* = 25

[5] WECC 2023 Data Preparation Manual

- Deadband was set to 36 mHz *dbd1* = -0.0006, *fdb2* = 0.0006
- Time constants were to reflect battery configuration

In some power networks around the world, where 80–90% instantaneous penetration of IBRs exists, IBR fleets can offer high-speed frequency response as a service to the grid. If offered, this high-speed frequency response is expected to be delivered in full and in a stable manner within one second of the occurrence of a load-generation mismatch. Further, the IEEE Std 2800TM-2022 expects IBRs to have high-speed frequency response capabilities. However, IBRs previously deployed in the Western Interconnection do not have high-speed frequency response requirements at the same capacity. This study did not investigate the impact of this capability in other global regions.

Study Approach

To perform an extensive evaluation of the potential effects of GFMs, WECC studied the system under different levels of generation loss in two scenarios:

1. **Double Palo Verde Outage Scenario**: WECC simulated the "double Palo Verde" (2PV) outage, which is a loss of two nuclear units at the Palo Verde Generating Station totaling between 2,600 and 2,700 MW of generation. WECC then evaluated the 2020 Light Summer 3:00 AM case and the 2024 Light Summer 2 1:00 PM case to compare the effects on frequency from the 2PV outage.
2. **20% Generation Imbalance Scenario**: WECC simulated the loss of approximately 20% of online generation to understand how IBRs affect the WECC Off-Nominal Frequency Load Shedding Plan (ONFLSP) or UFLS. WECC wanted to understand whether the ONFLSP shed load quickly enough under the various simulations in this scenario.

Double Palo Verde Outage Scenario

During the 2PV outage simulation, WECC monitored system frequency at the Malin substation in the Pacific Northwest at various levels of GFM penetration and settings. WECC also monitored the output from hydro plants, gas turbines, GFL with frequency response active (GFL FR), and GFM IBRs to understand the effect of the 2PV outage on these resources. Both resources close to and far from the Palo Verde Generating Station were monitored to identify how proximity to the disturbance may affect generator response. To make performance comparisons between the various generators, WECC normalized the results by using the same generating unit with varying dynamics data to represent different generation types.

3:00 AM Case

In the 2021 CSI study, the 3:00 AM case had 71 GW of load in the Western Interconnection. In this study, WECC re-ran the CSI study simulations but replaced the GFL IBRs with equivalent GFM IBRs before applying the 2PV outage. In the CSI study, the GFLs were modeled with 10% headroom, so WECC used 10% headroom in the GFM model.

1:00 PM Case

The 1:00 PM case represents a spring afternoon with approximately 90 GW of load, a typical load level for the Western Interconnection. WECC determined which synchronous generators would be replaced by IBRs. All nuclear, hydro, and geothermal generators retained their online or offline status as represented in the 1:00 PM case. Ultimately, 582 synchronous generating units producing 36,570 MW of power were replaced with nonresponsive GFL IBRs. Next, GFM IBRs replaced 25% of the 36,570 MW capacity. WECC randomly selected the replaced units and ensured they were distributed throughout the Western Interconnection. It was important for the study to distribute the GFM units throughout the Western Interconnection and not have them all located in one area, to distribute the frequency response of these GFMs.

WECC evaluated six simulations in this scenario, each with different GFL or GFM IBR levels, headroom, and droop settings:

Table 3: Simulations

Simulation 1	Baseline test (Base)
Simulation 2	100% GFL IBRs and 4% droop setting (GFL_100NFR)
Simulation 3	75% GFL IBRs, 25% GFM IBRs, 10% headroom, 1% droop setting (GFM_25_10)
Simulation 4	75% GFL IBRs, 25% GFM IBRs, 6% headroom, 1% droop setting (GFM_25_6)
Simulation 5	75% GFL IBRs, 25% GFM IBRs, 6% headroom, 3% droop setting (GFM_25_6_3)
Simulation 6	87.5% GFL IBRs, 12.5% GFM IBRs, 6% headroom, 1% droop setting (GFM_12.5_6)

Results

Proximity Analysis

WECC monitored the response of two generators at different electrical distances from the Palo Verde Generating Station. The results highlighted differences in how units close to the disturbance respond as opposed to units electrically far from the disturbance.

Figure 1 shows the generation response of GFM, hydro, gas, and GFL with frequency response after the 2PV outage. A GFM inverter responds like a synchronous machine when there is an initial spike due to the change in phase angle from a generation outage. The GFM model maintains the internal voltage phasor approximately constant in the sub-transient to transient time frame. Therefore, a GFM's initial response to a disturbance depends on the electrical distance between the disturbance and the GFM resource. If a GFM is electrically near the tripped generator, it responds to the disturbance almost instantaneously by increasing the active power. (See the GFM line in Figure 1.) The power frequency (P-f) droop control and active power limiting control (*Pmax* control) adjust the internal voltage phase angle and limit its output power at *Pmax* in a steady state. In inspecting Figure 1 below, the GFM technology responds similarly to gas and hydro.

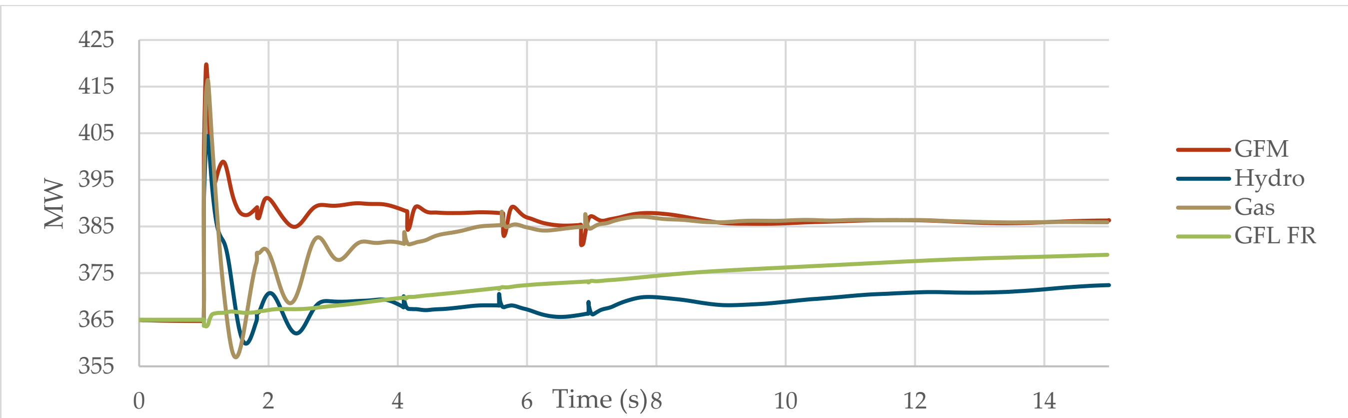

Figure 1: Response of Generators Near Outage

In contrast, if a GFM is electrically far from the generator outage, it does not increase the active power instantaneously. (See Figure 2.) However, the P-f droop control makes the GFM respond within one second to participate in frequency regulation. (See the GFM line in Figure 2.) The output power of the GFM is also limited at *Pmax* by the active power limiting control being in a steady state.

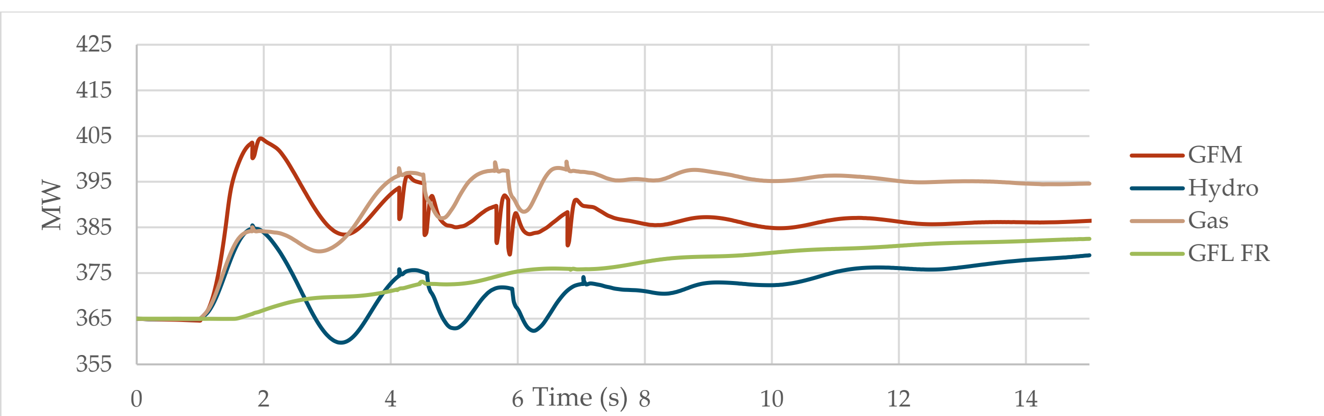

Figure 2: Response of Generators Far from Outage

3:00 AM Case

In the CSI study, the frequency nadir at the Malin substation for Phase 1 was 59.507 Hz—just above the UFLS threshold (Phase 1). In this study with GFM, the frequency nadir was 59.77 Hz (GFM P1_10). This result is due to the GFM inverters' ability to respond to the frequency event, whereas, in the CSI study, the GFL for Phase 1[6] did not have the frequency response controls active. In Phase 2[7], the GFL units responded to the frequency event because the frequency response controls were active. The frequency nadir for Phase 2 (p2_10%) in the CSI study was 59.573 Hz, and after replacing these units with the GFM technology (GFM P2_10), the frequency nadir increased to 59.85 Hz. (See Figure 3.)

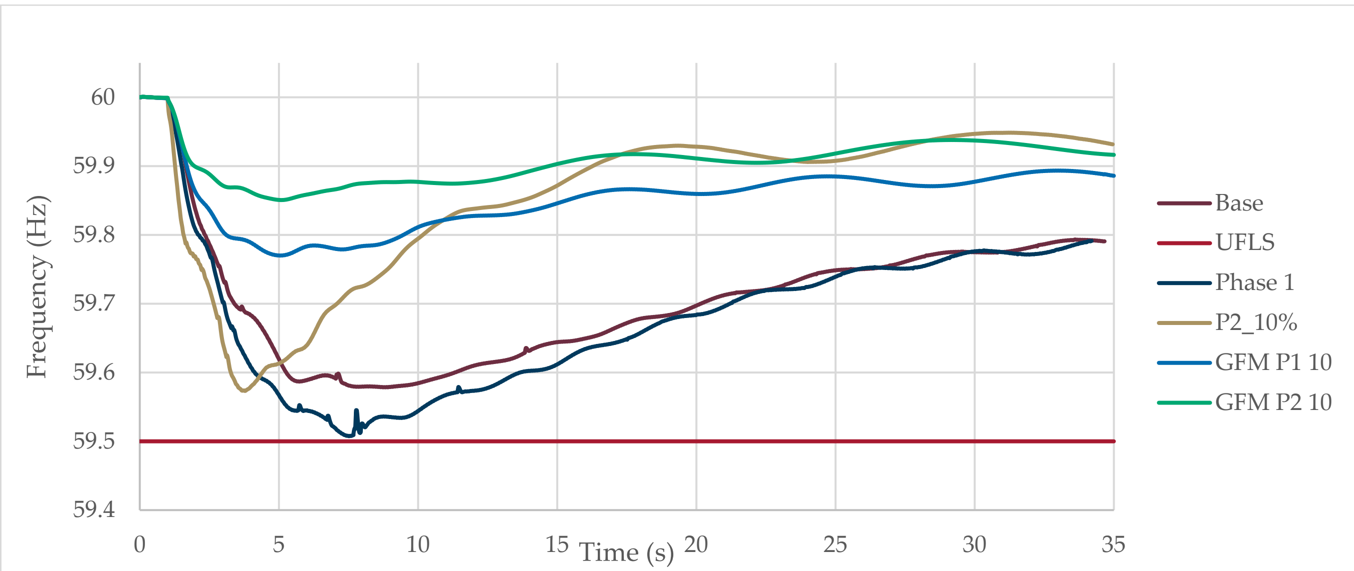

Figure 3: GFM vs. GFL in 3:00 AM case for Phase 1 and 2

Phase 3 (P3_10%) and Phase 4 (P4_10%) continue to improve as more frequency response is added through the GFM IBRs. (See Figure 4.) The frequency nadir in Phase 3 was 59.55 Hz in the CSI study, and when the GFM technology replaces these units, the frequency response increases to 59.92 Hz in Phase 4. In this simulation, the GFM technology replaced 53,165 MW of generation, almost half of the 109,806 MW of generation in this scenario. Of the total generation, 33,328 MW was hydro generation, and 23,313 MW was IBR generation without frequency response active.

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[6] For information on each Phase, see page 10.

[7] 33,368 MW of generation were replaced with GFM IBRs in the model.

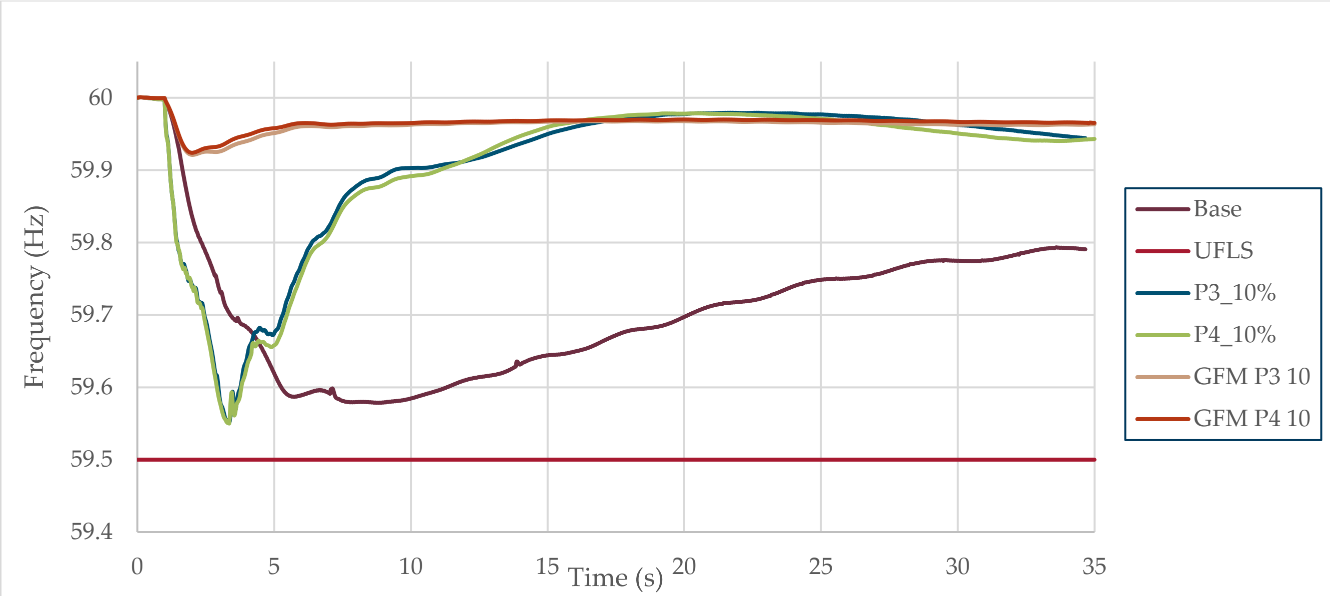

Figure 4: GFM vs. GFL in 3:00 AM case for Phases 3 and 4

1:00 PM Case Frequency

The first simulation (Base) was the baseline test showing the frequency response after the 2PV outage without replacing any synchronous generators with IBRs. (See the "Base" line in the Figure 5.) The frequency nadir for the base line simulation is 59.7 Hz.

The second simulation (GFL_100NFR) shows the frequency response for the worst-case scenario in which all synchronous generators are replaced by GFL IBRs. In this simulation, WECC replaced 582 synchronous generators with nonresponsive GFL IBRs. The resulting frequency nadir is 59.45 Hz. Since the frequency dropped below the UFLS 59.5 Hz, the UFLS plan activated, triggering load shedding (See the GFL_100NFR line in Figure 5.)

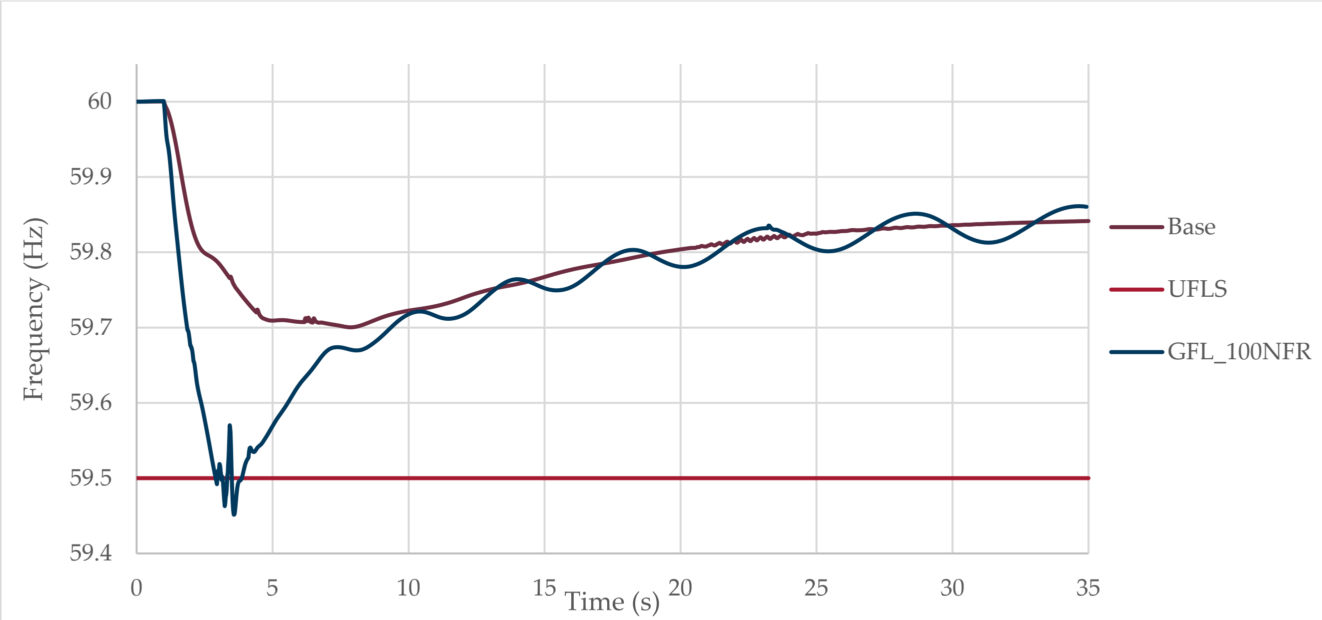

Figure 5: Frequency Response for GFL in 1:00 PM Case

In the third simulation (GFM_25_10), WECC replaced 25% (approximately 9,100 MW) of the 36,507 MW of nonresponsive IBRs with GFM IBRs, leaving approximately 27,000 MW of generation as nonresponsive IBRs. The response from the GFM units was limited to providing up to 10% headroom in generation. WECC changed the *Pmax* value in the REGFM_A1 model, and the frequency response from the GFM performed like the baseline test with a frequency nadir of 59.64 Hz compared to the baseline test of 59.7 Hz. (See the GFM_25_10 line in Figure 6.)

In the fourth simulation (GFM_25_6), the headroom was changed from 10% to 6% to reflect the current reserve requirements on generation specified in BAL-002-WECC-3 (3% of generation and 3% of load responsibility). To do this, WECC changed the *Pmax* value in the REGFM_A1 model. The reduction to 6% headroom dropped the frequency nadir to 59.584 Hz, but the frequency response of the GFM IBRs kept the system frequency above the 59.5 Hz threshold. (See the GFM_25_6 line in Figure 6.)

The fifth simulation (GFM_25_6_3) evaluated how changing the droop setting from 1% (as seen in the previous simulations) to 3% affected the frequency response from GFM IBRs.[8] To do this, WECC changed the droop parameter "*mp*" from 0.01 to 0.03. In this 3% droop simulation, the frequency responded slightly slower than in the prior two simulations with the 1% droop. (See the GFM_25_6_3 line in Figure 6.)

[8] Droop setting controls how much a unit responds to changes in frequency. A smaller droop setting will make a unit provide a full response for smaller frequency deviations.

In the final simulation (GFM_12.5_6), WECC estimated how much GFM IBR generation is required to maintain a frequency above the 59.5 Hz threshold during a generation loss event. To study this element, the GFM IBRs were reduced by half, from 25% (approximately 9,100 MW) to 12.5% (approximately 4,550 MW), with 6% headroom and a 1% droop setting. In this simulation, the frequency dropped to 59.506 Hz, just above the 59.5 Hz UFLS threshold. (See the GFM_12.5_6 line in Figure 6.) See Table 3 for the frequency nadir summary.

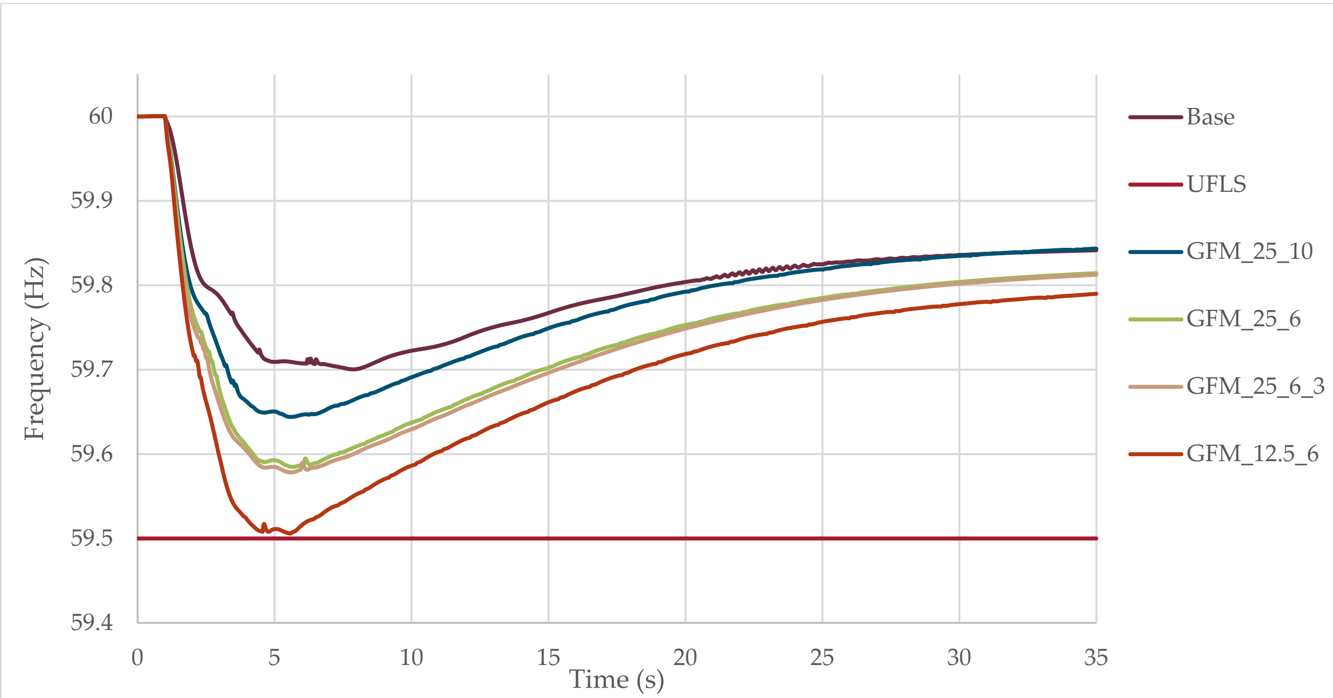

Figure 6: Frequency Response for GFM in 1 PM Case

Table 4: Frequency Nadir for all Simulations

Simulation	Frequency Nadir (Hz)
Base	59.700
100% GLF, 4% droop	59.451
25% GFM, 10% headroom, 1% droop	59.644
25% GFM, 6% headroom, 1% droop	59.584
25% GFM, 6% headroom, 3% droop	59.578
12.5% GFM, 6% headroom, 1% droop	59.506

To compare GFL and GFM IBR technology in the 1:00 PM case, WECC simulated the same conditions as the simulations described above but used the GFL technology (referenced in the 2021 CSI study) instead of GFM (GFL_25_6). Twenty-five percent of the 36,507 MW (approximately 9,100 MW) was replaced with the GFL using 6% and 10% headroom. The remaining approximately 27,000 MW of generation remained nonresponsive IBRs. By changing the IBR technology to GFL inverters, the Western Interconnection hits the UFLS 59.5 Hz threshold. The frequency recorded at Malin for both the 6% (GFL_25_6) and 10% (GFL_25_10) was 59.508 Hz, above the UFLS threshold (See Figure 7.) However, the southern portion of the system had a frequency drop below that threshold to 59.493 Hz at the Moenkopi substation, resulting in load loss. (See the GFL_25_6 line in Figure 8.) Based on the results of the GFL_25_6 run, WECC ran another simulation, replacing 50% of the generation (18,000 MW) with GFL IBRs. In this simulation (GFL_50_6), the frequency nadir at Malin drops to 59.532 Hz. (See the GFL_50_6 line in Figure 7.) In the southern part of the system at Moenkopi, the frequency dropped to 59.516 Hz. (See Figure 8.)

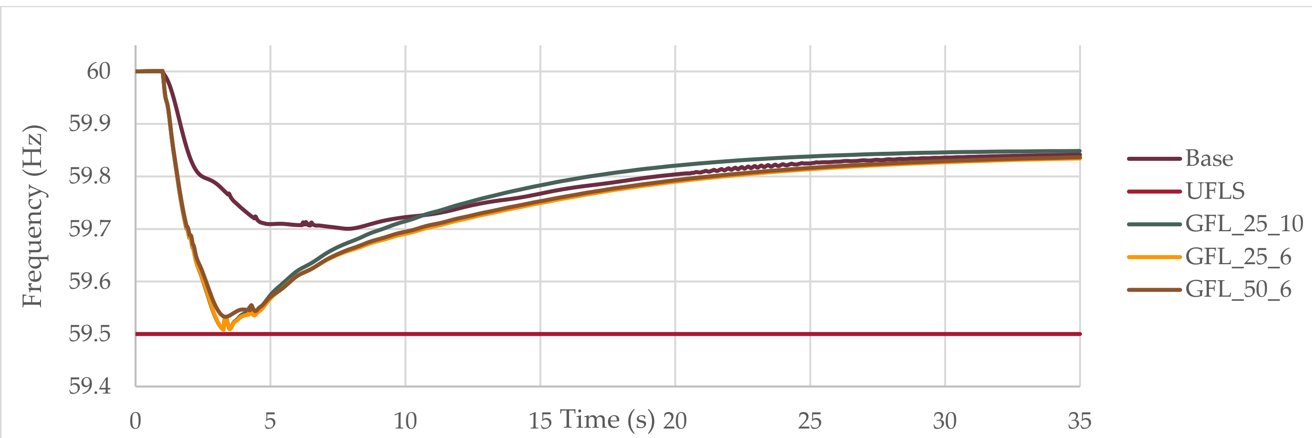

Figure 7: GFL Frequency Response for 1:00 PM Case in the Northern Portion of the System

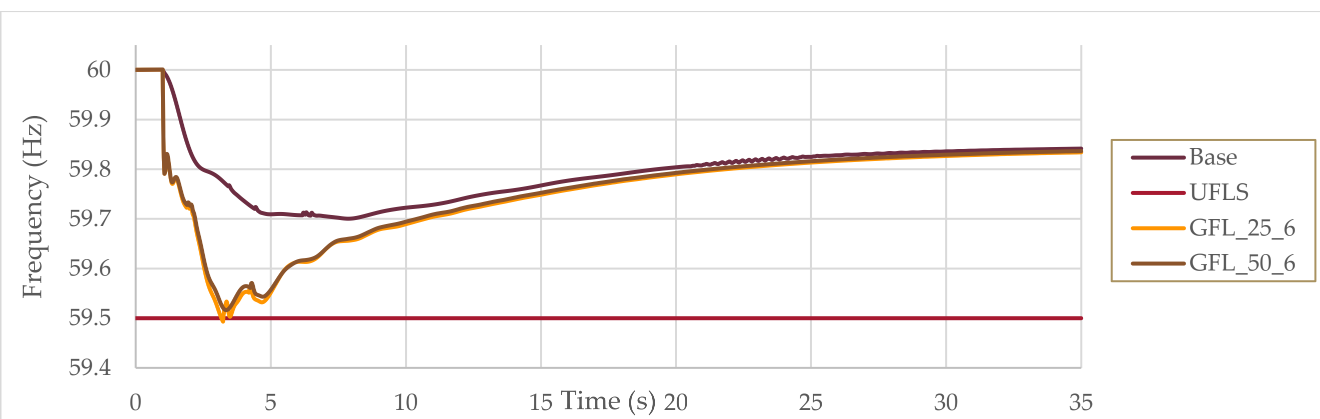

Figure 8: GFL Frequency Response for 1:00 PM Case in the Southern Portion of the System

1:00 PM Voltage

WECC also monitored voltages in each simulation at several 500-kV substations across the system. The simulations showed no voltage issues with the GFM or the GFL models. It is important to note that there were few voltage issues in the 2021 CSI study. After further evaluation, however, it was determined that the models used in the 2021 CSI study were on a coordinated Q/V control. The REEC_A model was set to control the voltage at the point of interconnection. However, in the 3:00 AM power flow model, these IBRs did not precisely model the low kV collector system (detailed model of the plant representation). After the disturbance, these IBRs attempted to return to their Q set point due to the outer Q loop. This, in turn, provided minimum reactive power support when the Western Interconnection needed this reactive power support to keep the voltage at desired levels and prevent unexpected load tripping caused by low voltage. In the current study, this issue was corrected by setting the *vflag* parameter to 1 and the *qflag* parameter to 0 in the REEC_A. (See Figures 9, 10, and 11 below for the resulting plots. Only the 6% headroom runs are included in the figures, as the results of the 6% and 10% headroom scenarios were almost identical.)

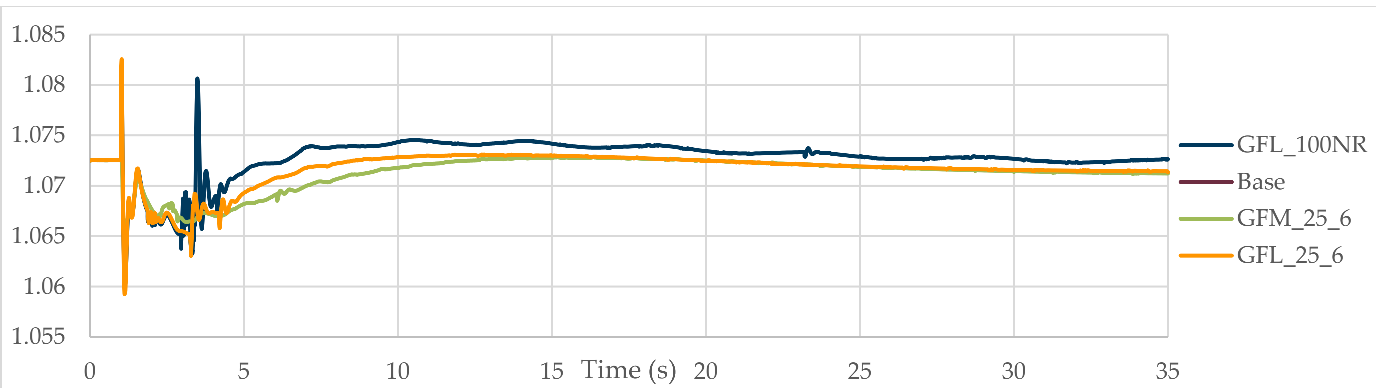

Figure 9: Voltage at a 500-kV Substation in AZ

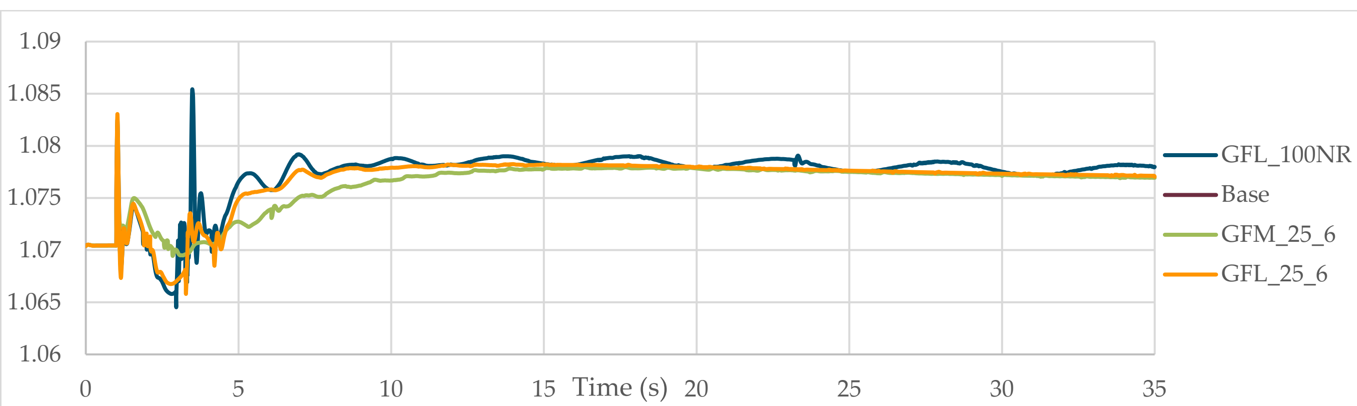

Figure 10: Voltage at a 500-kV Substation in CA

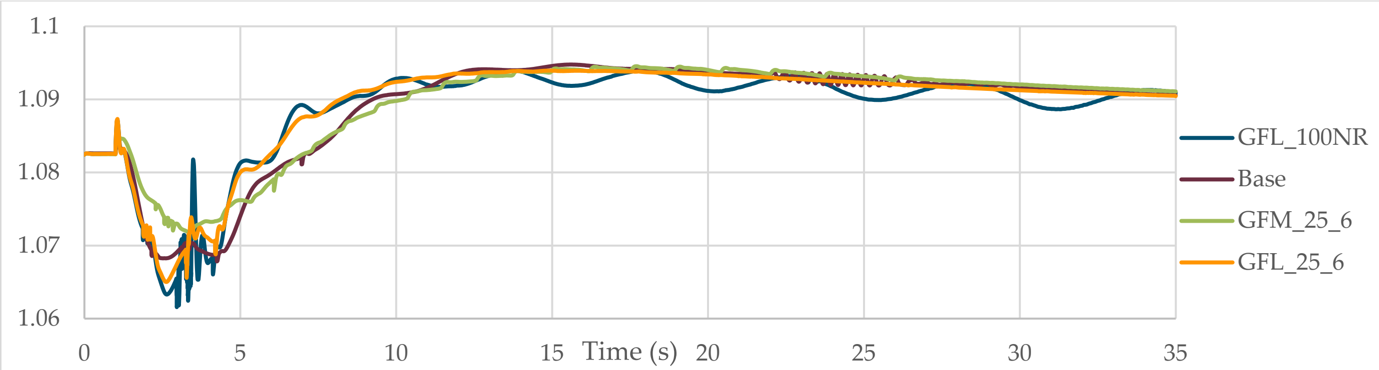

Figure 11: Voltage at a 500-kV Substation in the Northwest

20% Imbalance Scenario

As more IBRs replace synchronous generators, an additional concern is how the IBRs affect the WECC ONFLSP or UFLS. WECC wanted to understand whether the ONFLSP shed load quickly enough under a generation imbalance scenario in which 20% of online generation is lost.

WECC monitors the Rate of Change of Frequency (ROCOF) metric when studying generation loss events because it quantifies how fast the frequency drops during a disturbance. The faster the frequency drops, the faster loads must trip offline to stabilize the frequency. ROCOF is calculated using the following formula:

$$ROCOF_{0.5} = \frac{f_{0.5} - f_0}{0.5\ sec}$$

The WECC ONFLSP is considered a safety net that begins to shed load if the system frequency drops below 59.5 Hz. After a loss of generation, the following factors contribute to determining how much load will need to be shed during the outage to maintain stability:

- The speed at which the frequency drops,
- How low frequency drops, and
- The length of time that it remains lower than desired levels.

Improvement of any of these factors could result in a corresponding reduction in the amount of load lost during a generation outage.

For the 20% Imbalance Scenario, WECC used the 1:00 PM case because it represents a low system inertia of 163,744 MW*s. At low system inertia during a generation loss event, the frequency will drop faster and to lower nadir levels than in a high inertia scenario. WECC evaluated three simulations in this scenario, each with different GFL or GFM IBR levels and headroom to determine whether the ONFLSP can activate and arrest the frequency decline during low inertia and high penetration of IBRs:

- GFM_25_6: 75% of the IBR generation is nonresponsive GFL, 25% is GFM, headroom is 6%.

- GFM_12.5_6: 87.5% of the IBR generation is nonresponsive GFL, 12.5% is GFM, headroom is 6%.
- CSI_25_6: 25% of the IBR generation is frequency responsive GFL, 75% is nonresponsive, there is no GFM generation, headroom is 6%.

Results

All simulations represent the system frequency when there was an imbalance between generation and load.

During the simulation, 222 generating units tripped off, totaling 21,733 MW. (See Figure 12 for frequency response at the Malin substation.) An additional 7,390 to 10,069 MW of generation tripped during the simulation due to loss of synchronization with the grid or protection relays from either voltage violation or frequency deviations. In all three simulations, the system recovered to 60 Hz or higher by tripping load to rebalance the system.

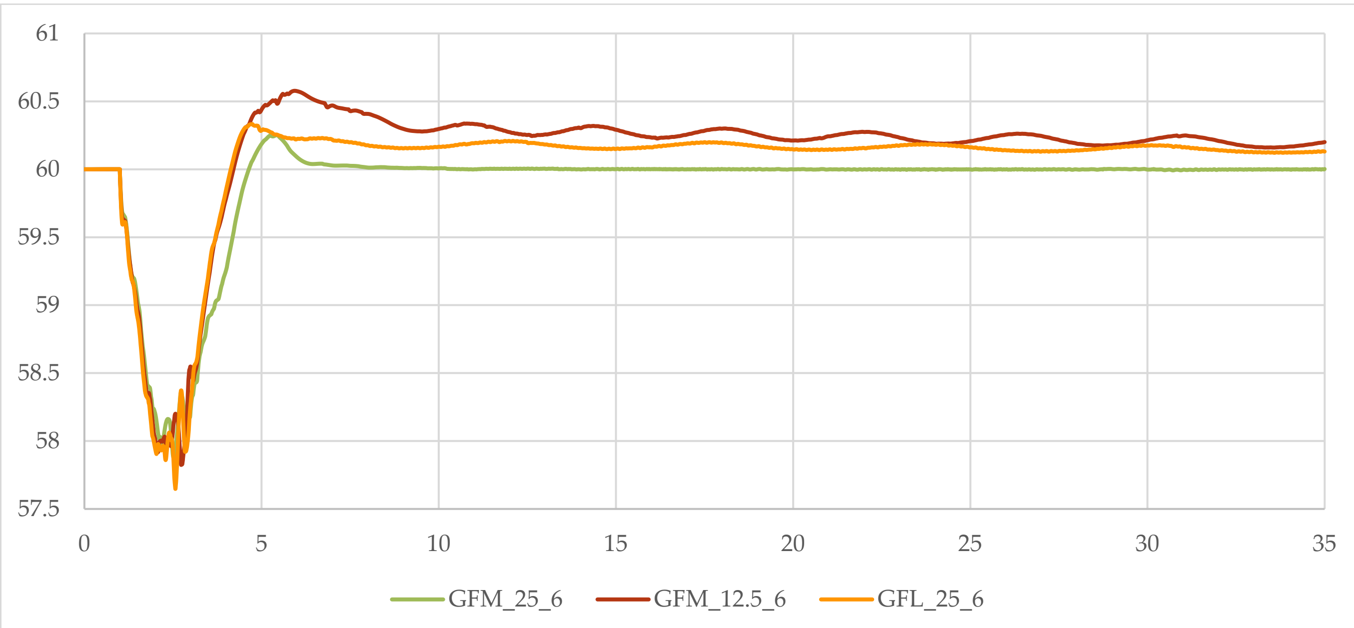

Figure 12: Frequency Response of the Imbalance Simulations

Table 4 summarizes the three simulations to better understand and compare each scenario. The difference in ROCOF between the 25% GFM and 25% GFL is 0.27 Hz/s which is a slight difference between the two technologies, as seen in Figure 13 below. The ROCOF declines faster with the GFL technology, because the GFM technology is better at arresting the frequency decline initially. In Figure 13, between 1 and 1.2 seconds, you can see the frequency response from the GFM is slightly better than GFL. However, due to the significant size of this disturbance, the GFM units were unable to provide enough frequency response to prevent UFLS from triggering because these GFM units were using the headroom to respond to the disturbance and could no longer provide any additional frequency response. The system still had to rely on load shedding to bring the frequency back to 60 Hz.

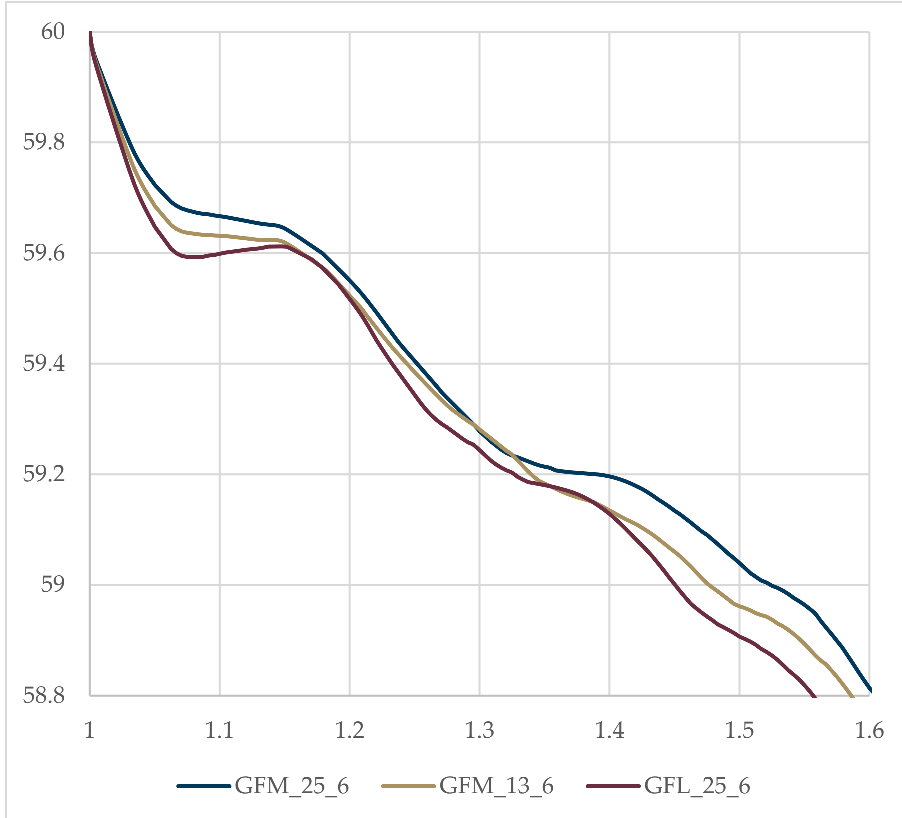

Figure 13: ROCOF of the Imbalance Simulations

Table 5: Summary of Imbalance Simulation

Case name	Initial # Generating units tripped	Generation units lost	Generation loss (MW)	Load loss (MW)	ROCOF(Hz/s)	Frequency Nadir (Hz)
GFM_25_6	222	456	29,638	29,123	-1.92	57.87
GFM_13_6	222	448	31,802	30,475	-2.08	57.82
GFL_25_6	224	439	30,855	30,023	-2.19	57.64

Findings and Conclusions

The change from GFL to GFM technology results in a significant improvement in interconnection-wide frequency response. In the 1:00 PM case when the interconnection lost approximately 2700 MW of generation, while it had approximately 4,500 MW of generation with at least 6% headroom provided by GFM, system frequency remained above the 59.5 Hz threshold. However, using the GFL technology would require approximately 18,000 MW of frequency responsive GFLs to keep the frequency above this threshold. With the expected increase in IBRs throughout the interconnection, it will be increasingly important to ensure there is adequate frequency response. As expected, the ROCOF declines faster with the GFL technology, while the GFM technology does better at arresting the frequency decline.

In the 20% Imbalance Scenario, in Figure 13, between 1 and 1.2 seconds, you can see the slightly better frequency response from GFM as compared to GFL technology. However, due to the significance of this disturbance, they are unable to provide enough frequency response to prevent UFLS from triggering because these units were already using all their headroom and no longer provide any additional response. In comparing the two technologies, the GFM has a slightly faster recovery between 1 and 1.2 seconds. It was noticed that in this scenario it did not matter what technology is being used due to the significant size of the disturbance and the system would have to rely on the activation of the UFSL plan to arrest the frequency decline. It was also noted that 7,905 to 10,069 MW of additional generation tripped offline in all three simulations due to loss of synchronization with the grid or relay and protection devices. It is important to note that this additional generation loss increased the total generation outages in the simulation from 20% (as planned) to close to 30%, which resulted in more load loss. With the loss of 29,638 MW of generation, the UFLS plan activated, tripping loads offline. The activation of the UFLS plan maintained stability in the Western Interconnection, returning the frequency to 60 Hz or above. (See Figure 12 above.)

Recommendations

Observation 1: Based on our assumptions, GFM IBR technology shows advantages over GFL technology in maintaining system frequency. With the expected increase in the IBR fleet, ensuring that the Western Interconnection has adequate frequency response from IBRs is critical.

> **Recommendation 1**: Planning Coordinators should strongly consider using GFM technology when replacing synchronous generators with IBRs. With increasing penetration of IBRs, WECC anticipates that the Western Interconnection will need increased and more robust frequency response from IBRs. If the IBR is a Battery Energy Storage System (BESS), it should be designed

to provide reliable and robust performance that supports high IBR penetration in the Western Interconnection[9].

Observation 2: Imbalance simulations show that up to an additional 10% of the original amount of generation is tripped offline due to protection settings, or lost synchronization with the grid. This increase resulted in more load shedding than planned in the simulations with just the 20% imbalance.

Recommendation 2: The Under Frequency Load Shedding Work Group (UFLSWG) should look at the Under Frequency Load Shedding (UFLS) methodology considering the results of the imbalance simulations in this study and determine how to evaluate the additional generation tripped by the protection relays in the imbalance simulations.

Observation 3: Rate of Change of Frequency (ROCOF) is one measure of the health of a power system and is very sensitive to the amount of inertia. With the increasing number of IBRs replacing traditional synchronous generators, the subsequent reduction in system inertia is likely to increase ROCOF, and the faster that frequency declines after the loss of generation, the more load is at risk of being shed due to underfrequency conditions. It was also observed that when the amount of generation lost far exceeds the frequency responsive generation, ROCOF remains relatively unchanged. However, the initial frequency response within 0.1 seconds of disturbance does improve when there is significant penetration of frequency-responsive GFM inverter technology in the system.

WECC conducts its study work in partnership with stakeholders. WECC would like to thank all the stakeholders who participated in this study.

[9] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Functional_Specification.pdf

Contributors

WECC thanks the following individuals and organizations for their valuable input and contributions to this project:

Name	Organization
Dmitry Kosterev	BPA
Deepak Ramasubramanian	EPRI
Yilu Liu	University of Tennessee
David Le	CAISO
Wei Du	PNNL
Song Wang	PGE
Dhurian Vitoldas	Siemens
Fred Heutte	NW Energy
Spencer Tacke	Auriga Corp.
Bharat Vyakaranam	PNNL
Hari Singh	PSCo
Xiaoyu Wang	ENEL North America
Robert Pan	BCHydro
Malati Chaudhary	PNM
David Glennon	BPA
Marcos Ayala	BPA
Eric Baran	WIRAB
Peter Mackin	GridBright
Quan Nguyen	PNNL
Qian Zhang	EPRI

Appendices

The table below shows the starting case generation and load in the 24 Light Spring Case (24lsp) and the new values used in the 1:00 PM case.

Area	Wind		Solar		Hydro		Synchronous		DER		Other		Generation		Load	
	24lsp	1PM	24lsp	1PM	24lsp	1PM	24lsp	1PM	24lsp	1PM	24lsp	1PM	24lsp	1PM	24lsp	1PM
10	736	260	942	778			554	312			-404		1829	1292	1904	1386
11			152	152			1093	382			50	50	1295	584	1673	977
14	236	236	1033	593			3660	3583	992	644	519	516	6441	5573	4356	3495
15							1677	1253					1677	1253	2773	2362
16	119	50	401	401			1661	1146					2182	1598	1968	1392
17			16	16	5		484	305					505	321	829	651
18			3035	2790			1833	744					4869	3534	5114	3824
19	200	200	180	180	1972	1736	585	585					2937	2701	950	720
20	8	8	41	41			2640	1421					2689	1471	2633	1444
21			852	831	49	35	895	704			-5	-5	1792	1565	592	374
22	190	165	1022	1022	2	2	654	546	725	311			2503	2047	2576	2136
24	3096	2796	6009	5636	1198	915	6418	5237	2935	1878	-1111	-1111	18547	15352	18325	15229
26	105	105	951	951	-164	-247	1748	1224			160	160	2800	2193	2682	2087
30	1197	1183	3273	3213	4695	4303	7009	6781	7285	5095	-664	-664	22797	19913	22103	19277
40	2092	1628	722	692	13717	7166	4215	2742			-50	-50	20697	12179	22552	14300

50	187	180			4336	3164	319	318			-6.8	-7.7	4837	3655	6423	5298
52					841	624	-2	-2			-22	-22	817	600	798	587
54	1144	912	451	399	210	260	7895	7434			-296	-296	9405	8710	8758	8121
60	131	62	432	399	1619	591	153	144			5.2	5.2	2342	1203	2653	1543
62	532	532	278	278	681	681	1678	1270					3171	2763	1459	1063
63					64	38							64	38	144	119
64	40	40	678	505			1162	585					1880	1130	2139	1403
65	2264	2221	1029	1002	162	162	2010	1089			16	16	5482	4491	5184	4214
70	1081	1049	913	676			3569	2381	12	12	-320	-320	5256	3799	6087	4107
73	214	214	49	49	1003	615	3949	1981	11	11	-80		5148	2873	3474	1816
total	13578	11846	22466	20611	30395	20050	55776	42174	11962	7954	-2209	-1788	131970	100849	128187	97936

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