

Frequency Stability of Different GFM-GFL Ratios in Zero-Inertia Grids

Capstone Research Project

Joshua | December 2023

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Introduction



Introduction

- More renewables into the grid
 - Grid becomes weak due to lack of inertia
- GFL: inject power, follow the grid
 - prone to instabilities
- GFM: form voltage at its PCC
 - less prone to instabilities, more like a synchronous machine vs GFL
- GFMs: solution to fully renewable based grid?

Introduction

- SCR - measure of grid strength (voltage stiffness)
 - The higher the better.
- However,

Grid Strength Impedance Metric: An Alternative to SCR for Evaluating System Strength in Converter Dominated Systems

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“grid characteristics **change** at high penetration”

Introduction

- GFM known to be better than GFLs
- However,

Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory

Yitong Li , Member, IEEE, Yunjie Gu , Senior Member, IEEE, and Timothy C. Green , Fellow, IEEE

“GFMs are **unstable** at voltage stiff grids”

“GFLs are unstable at *current* stiff grids”

“GFMs and GFLs are dual”

“rethink grid strength at high penetration”

Introduction

- GFM and GFL control modes **BOTH** used in Isolated power grids

A Grid Forming/Following Sequence Switching Control Strategy for Supporting Frequency Stability of Isolated Power Grids

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Motivation

- At high penetration - GFMs and GFLs might be both useful.
 - Grid strength changed, GFMs and GFLs are dual...

Can we investigate how GFM and GFL ratios affect frequency stability during disturbances?

Background Study



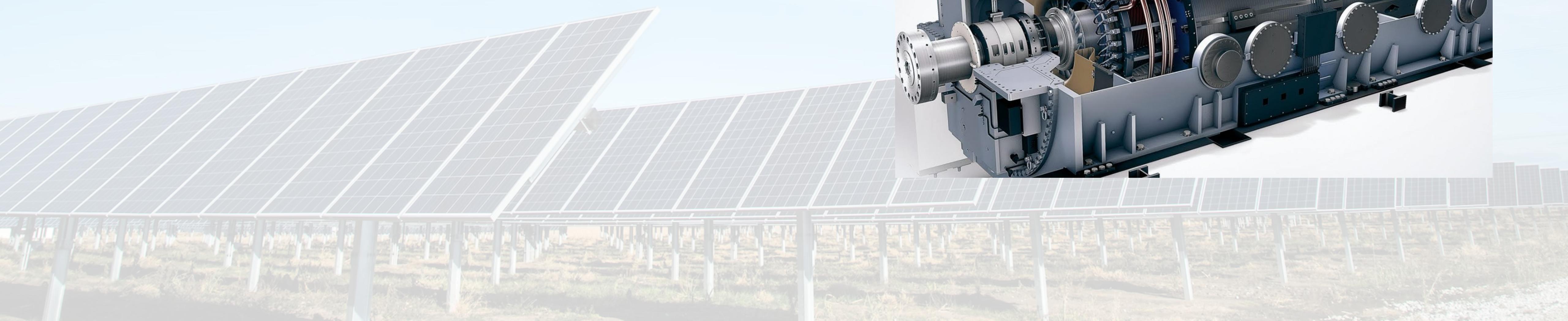
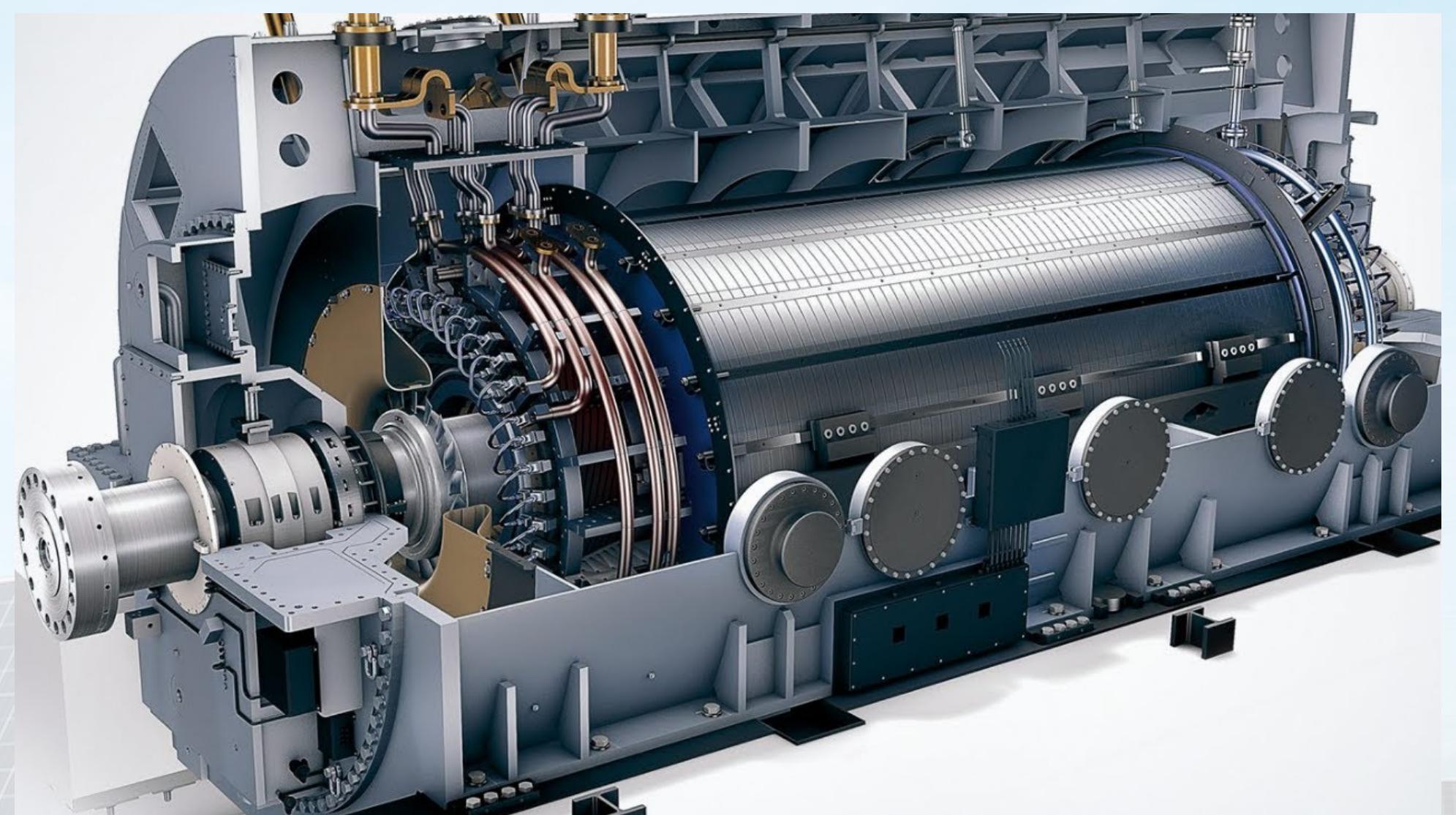
1. Grid Frequency and Inertia

- Analogy: a bicycle running...



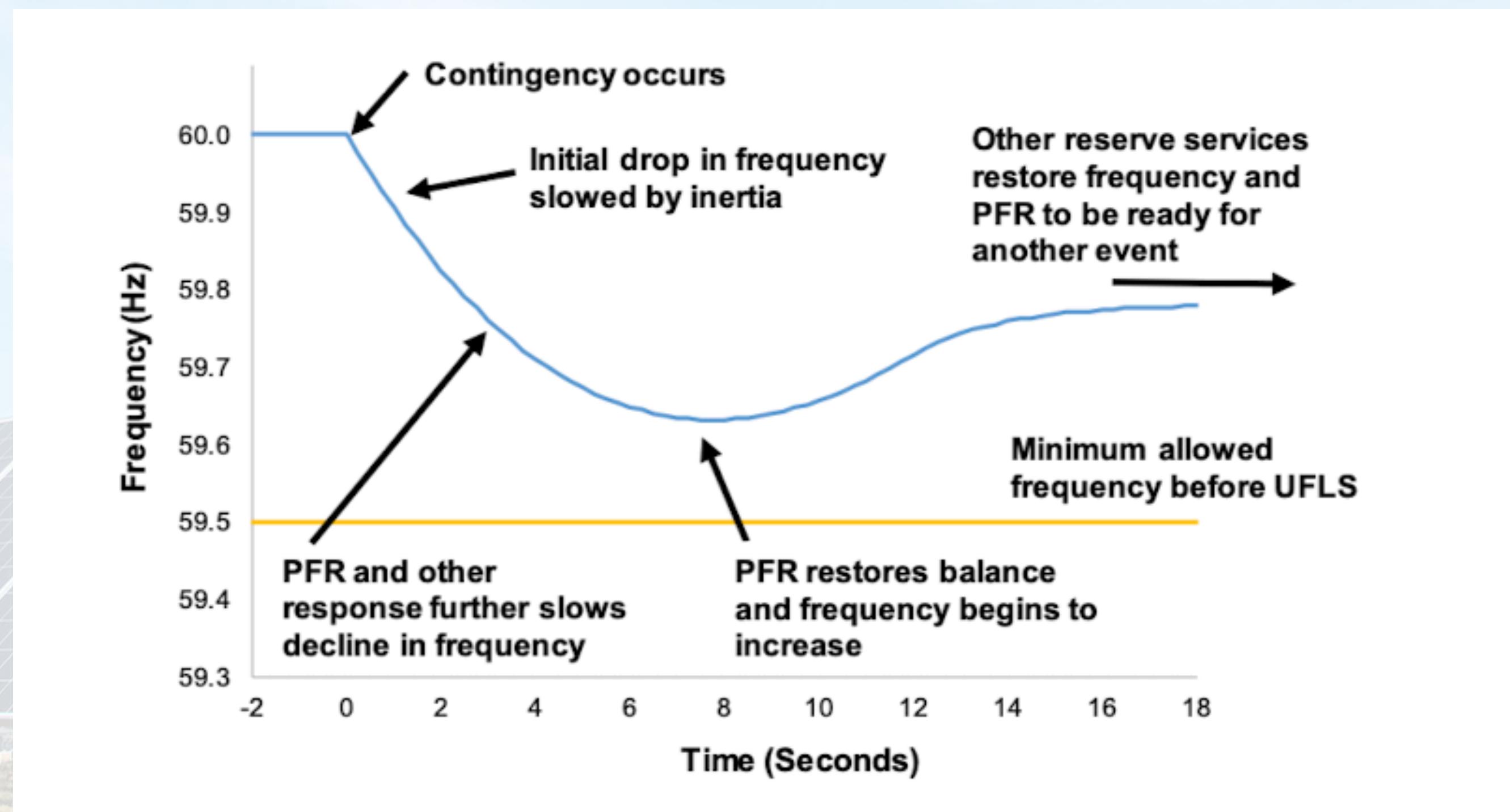
1. Grid Frequency and Inertia

- Inertia stored in rotating masses of generators
- Temporary energy during events
- Keeps frequency stability
- Allows time to react
- Becomes an **issue with renewables**



1. Grid Frequency and Inertia

- Frequency stability: measure of grid strength
 - Generators operate in lock-step
 - Failure to keep frequency: disaster



2. Voltage Sourced Converters

- Core element in building inverters
- Converts DC to AC
- Uses PWM

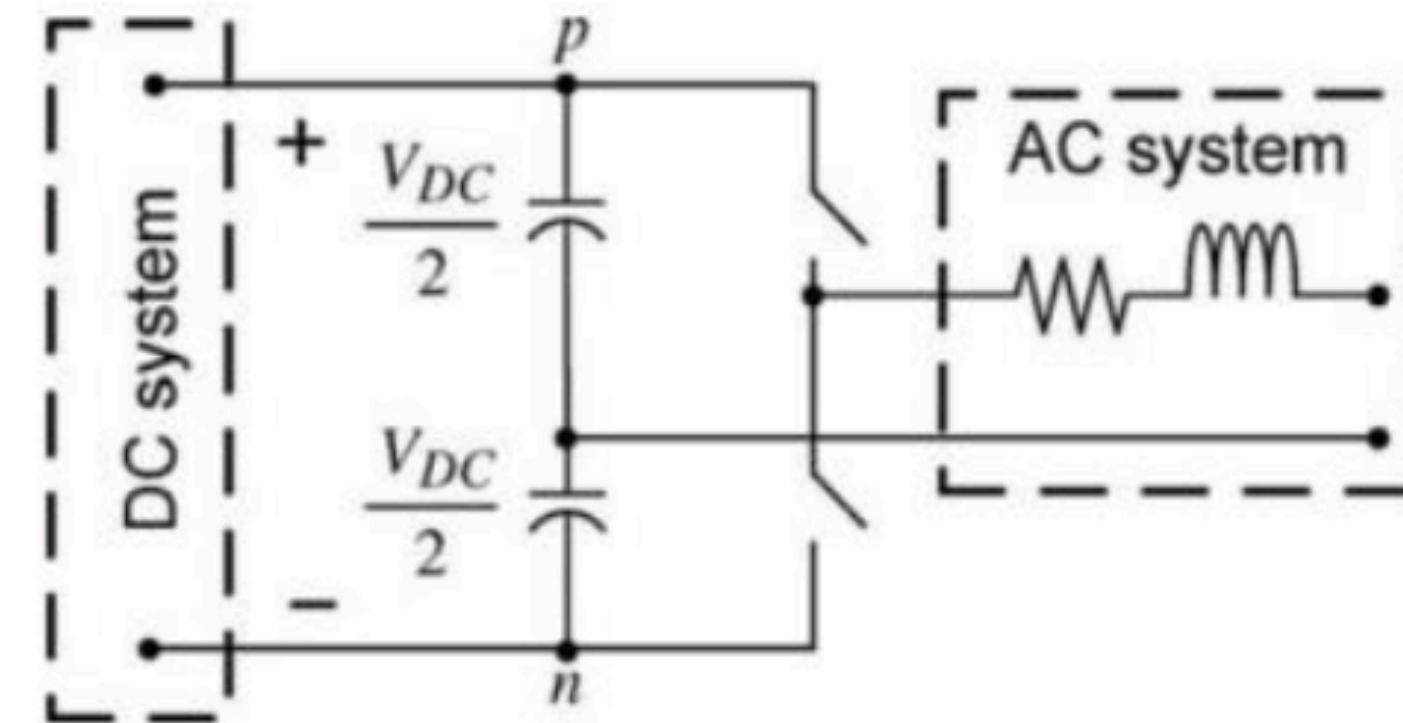


Figure 1: Single Phase Half-Bridge Converter [7]

2. Voltage Sourced Converters

- Controller design
 - Sinusoid input: difficult
 - Vector: not in Cartesian
 - $\alpha\beta$ -frame: vector in Cartesian, still sinusoidal
- Use dq -frame for designing controller
 - AC signal viewed in DC

2. Voltage Sourced Converters

- *dq-frame* rotates the *$\alpha\beta$ -frame* axes based on frequency of rotation

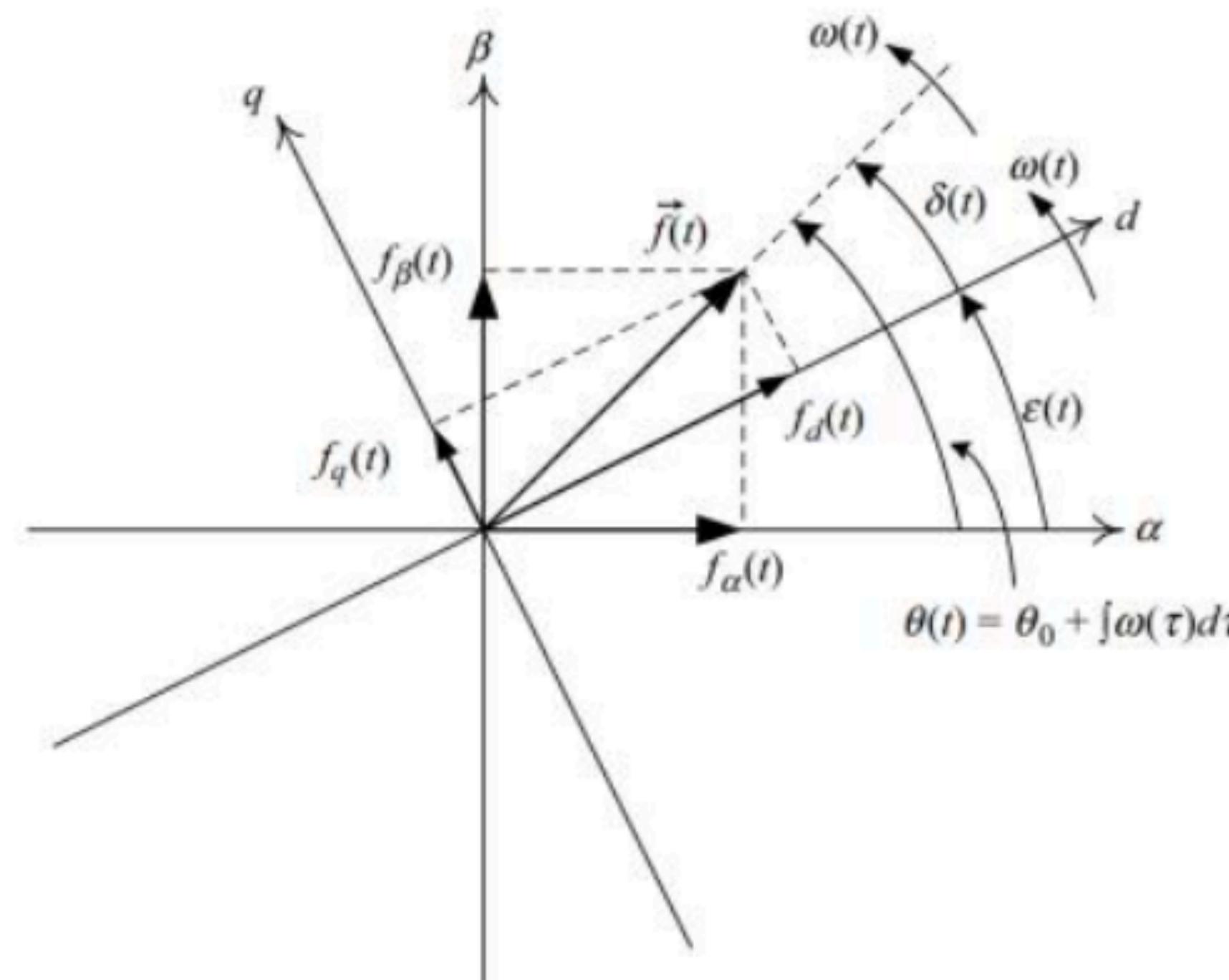


Figure 2: Difference Between $\alpha\beta$ - and dq - frames

2. Voltage Sourced Converters

- PLL used to *follow* the frequency

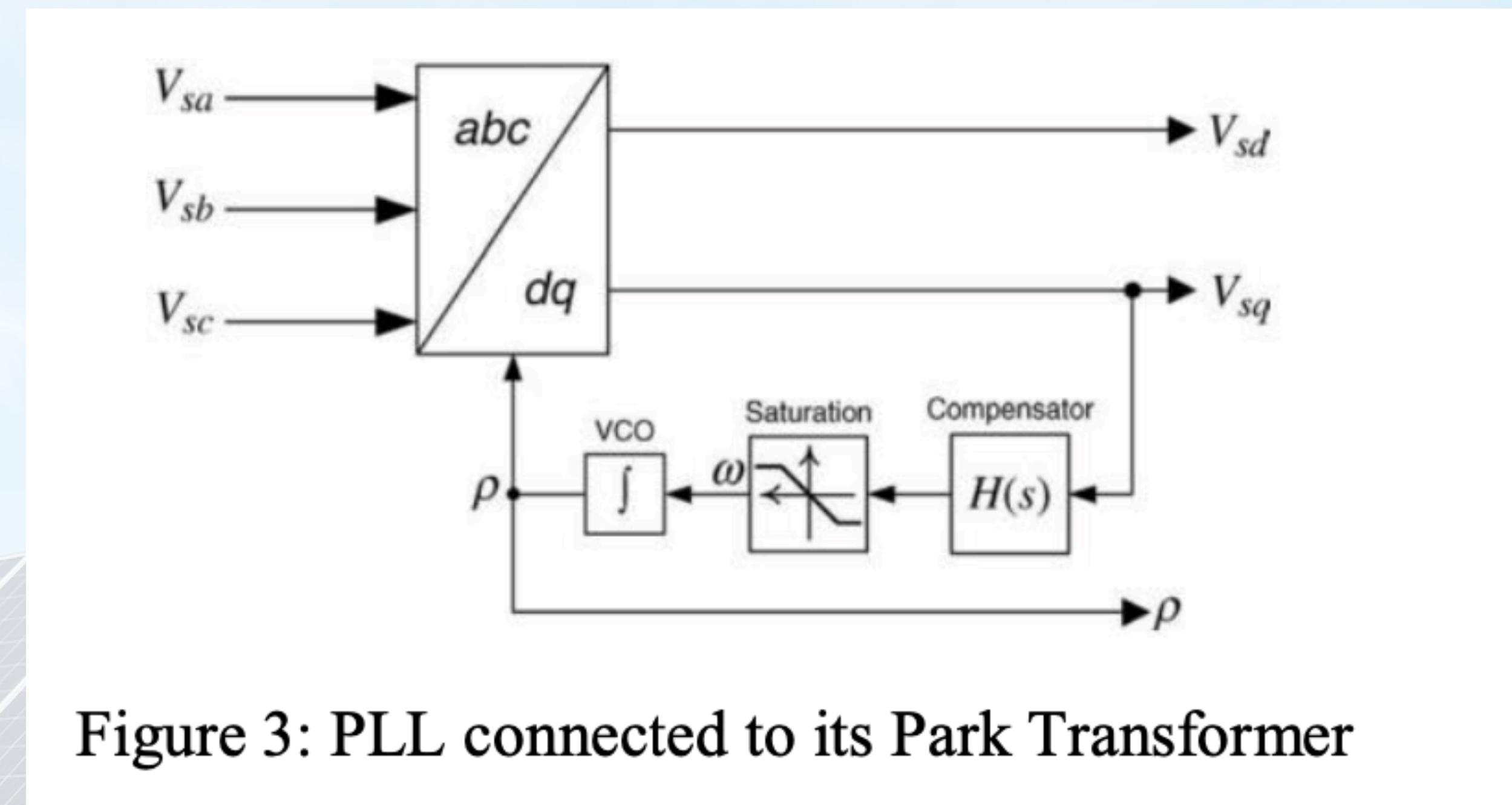


Figure 3: PLL connected to its Park Transformer

3. Grid Following Inverters (GFL)

- Basically, follow the grid using PLL
- Main goal: inject power via MPPT
- Modeled as **current source**

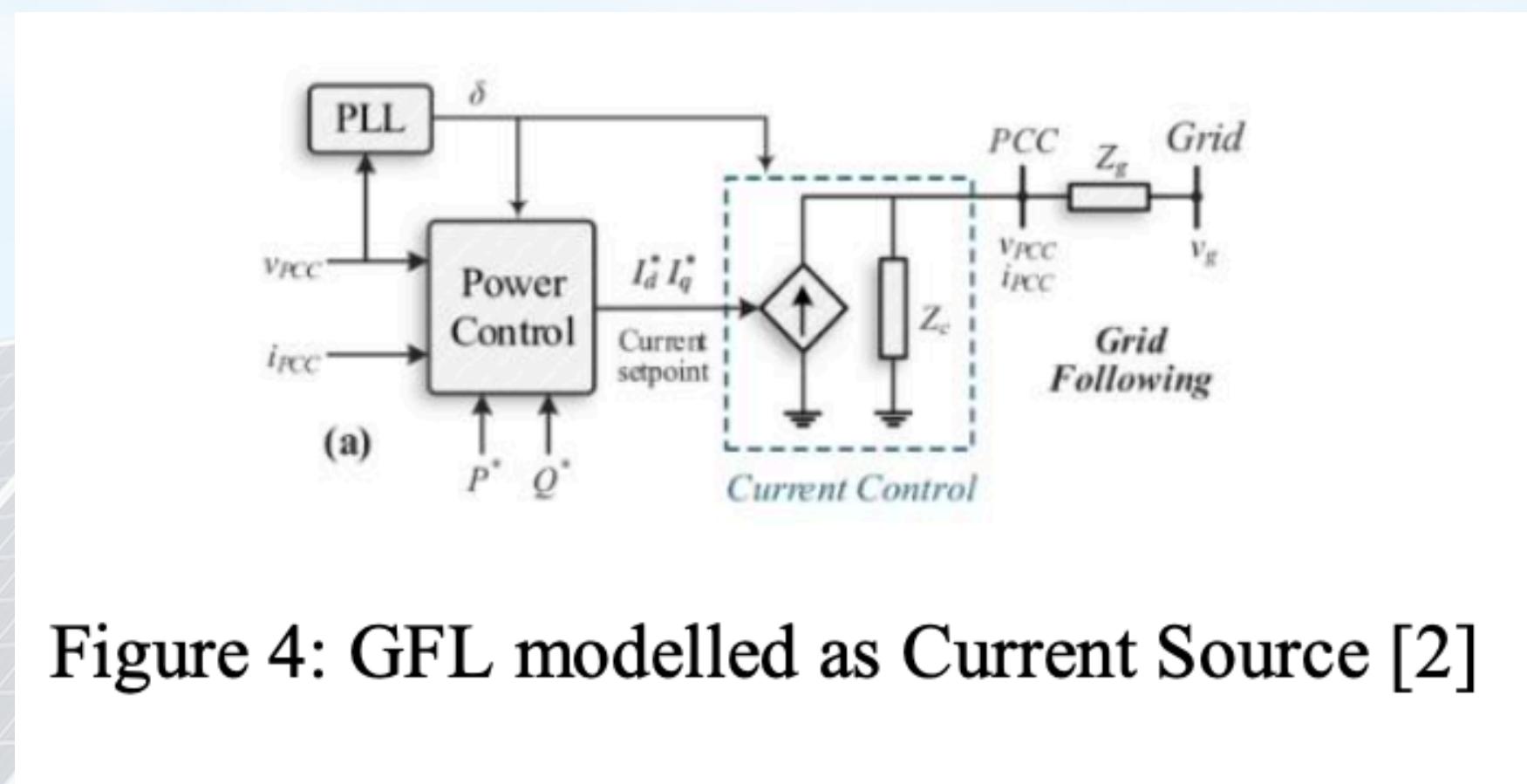


Figure 4: GFL modelled as Current Source [2]

3. Grid Following Inverters (GFL)

- During contingencies, GFL is **unstable** mainly due to PLL
 - main goal: inject power
 - **follows the grid, follows the disturbance**

4. Grid Forming Inverters (GFM)

- Do not follow the grid for reference, **form the reference**
- Modeled as **voltage sources**, closer to synchronous generators than GFLs
 - *emulate* inertial response, frequency response
- “*better*” than GFLs

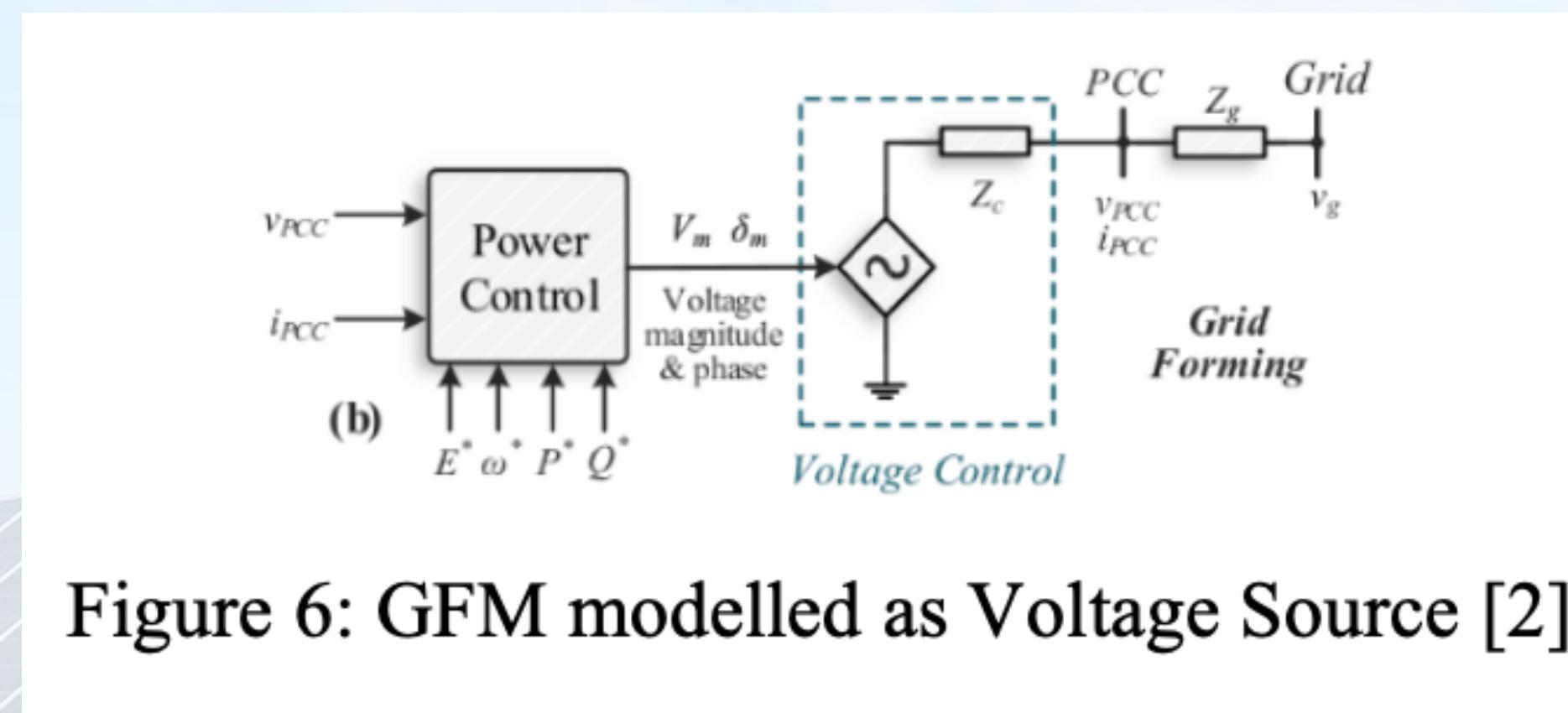


Figure 6: GFM modelled as Voltage Source [2]

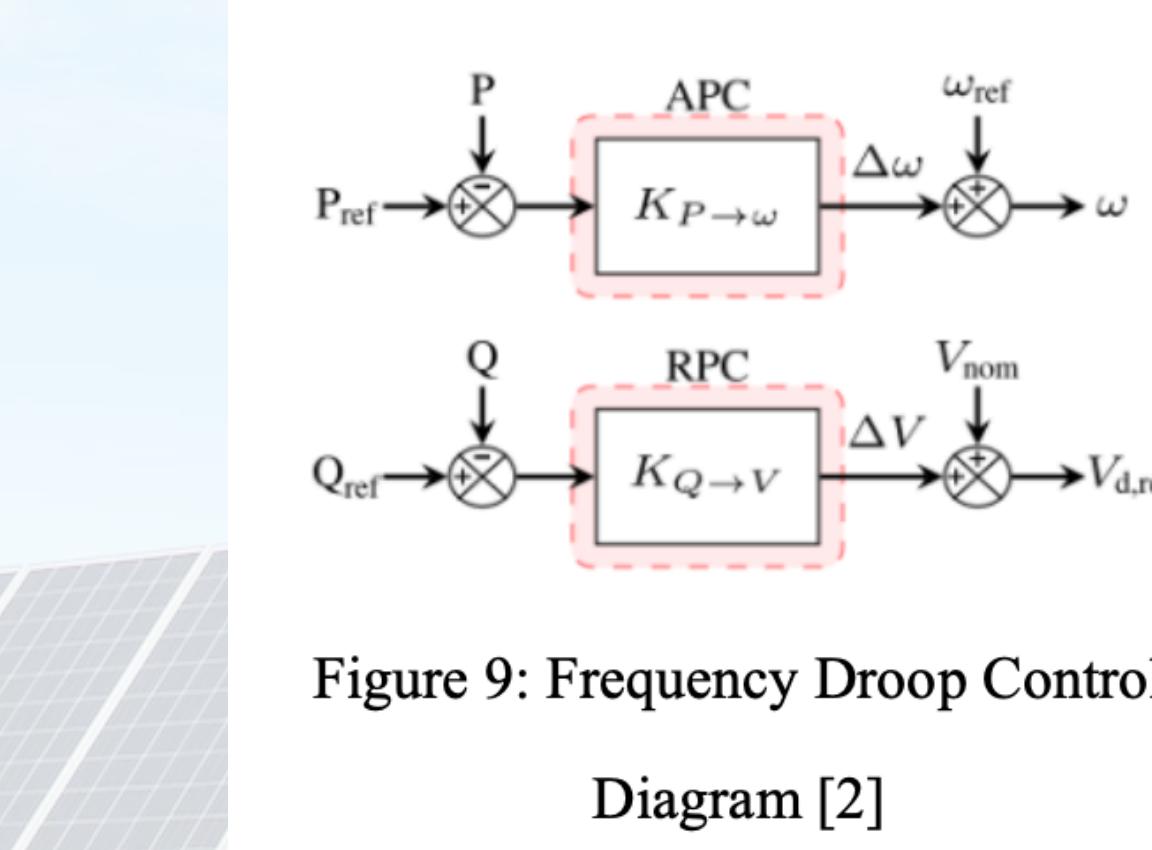


Figure 9: Frequency Droop Control Diagram [2]

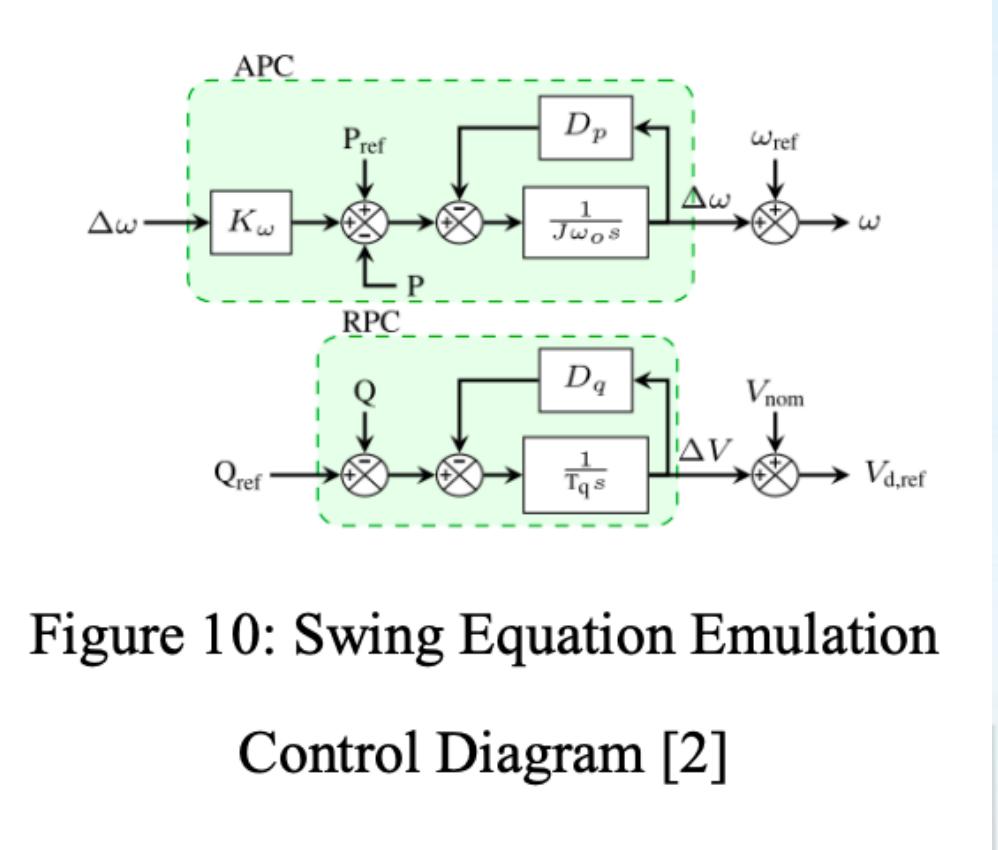


Figure 10: Swing Equation Emulation Control Diagram [2]

5. Grid Strength and Duality

- So, disregard GFLs entirely?



5. Grid Strength and Duality

- So, disregard GFLs entirely?

A Grid Forming/Following Sequence Switching Control Strategy for Supporting Frequency Stability of Isolated Power Grids

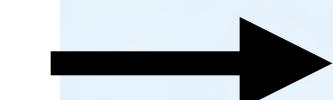
Grid Strength Impedance Metric: An Alternative to SCR for Evaluating System Strength in Converter Dominated Systems

Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory

5. Grid Strength and Duality

- So, disregard GFLs entirely?

A Grid Forming/Following Sequence Switching Control Strategy for Supporting Frequency Stability of Isolated Power Grids



Use **GFM** mode to reduce frequency deviation, **GFL** mode to quickly settle to a new stable point

At high penetration, SRC **might not be applicable anymore** as a metric for grid stability



Grid Strength Impedance Metric: An Alternative to SCR for Evaluating System Strength in Converter Dominated Systems

Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory



GFMs are **unstable** in a grid we thought to be **strong** but GFL is

Methodology



Methodology

- PSCAD Simulation with different ratios of GFMs and GFLs
- Kenyon Model for Zero Inertia Grids
 - Droop Control for GFM
- IEEE 14-Bus Grid
- Considering:
 - Load Changes
 - Faults

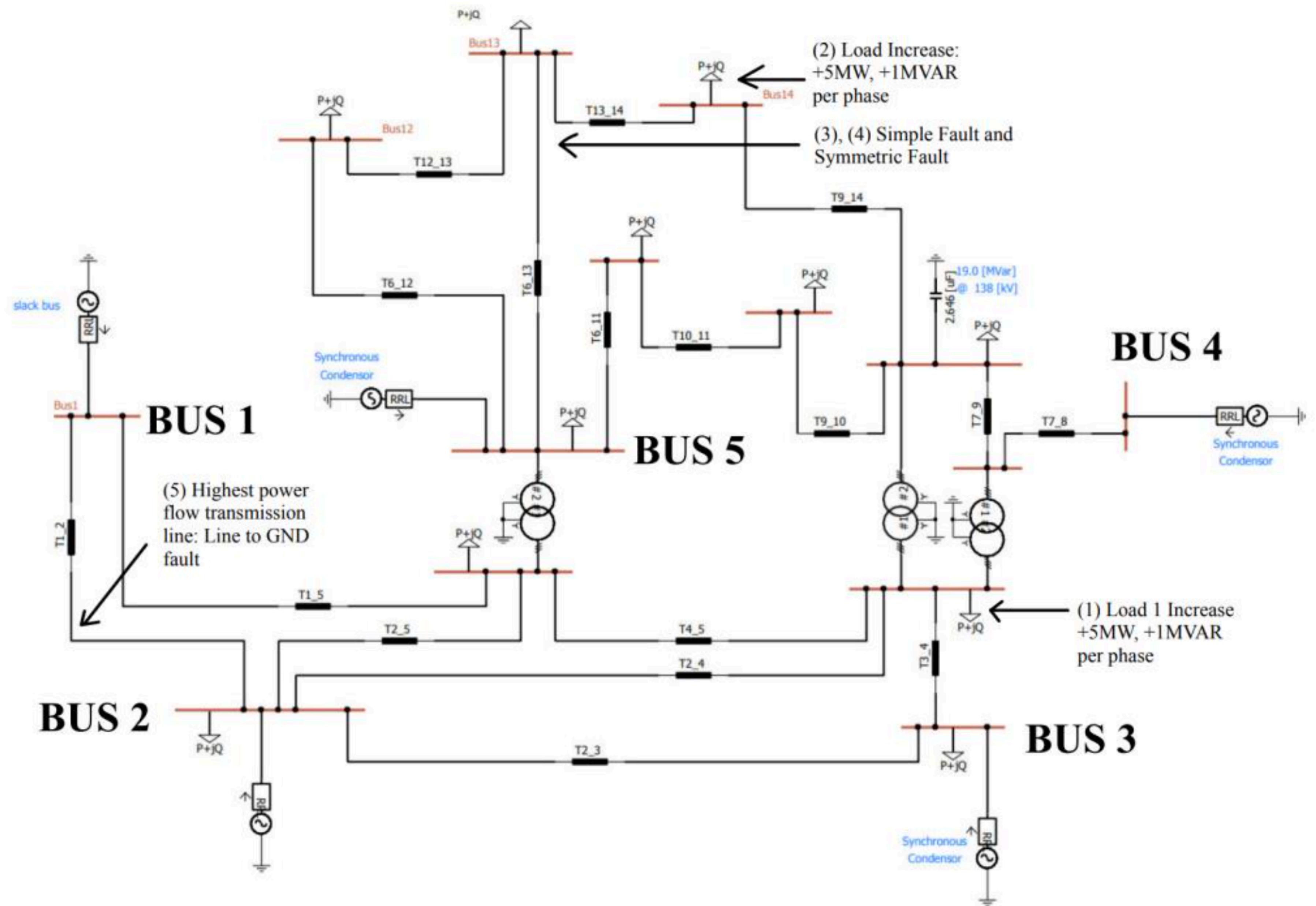


Figure 11: IEEE 14 Bus System in PSCAD

Bus	V [kV]	Angle [deg]	P [pu]	Q [pu]
1	146.28	0.0000	2.3239	-0.1655
2	144.21	-4.9826	0.4000	0.4356
3	138.38	-12.7250	0.0000	0.2508
6	147.66	-14.2209	0.0000	0.1273
8	150.42	-13.3596	0.0000	0.1762

Table 1: IEEE 14 Bus Set Points

	Simulation Cases for Load Increase (+5MW, +1MVAR / phase) and Faults							Additional Cases for Faults		
Generator	Base	5:0	4:1	3:2	2:3	1:4	N-2:3	N-3:2	N-4:1	
Bus 1	IDEAL	GFM	GFM	GFM	GFM	GFM	GFM	GFM	GFM	
Bus 2	IDEAL	GFM	GFL	GFL	GFL	GFL	GFL	GFL	GFM	
Bus 3	IDEAL	GFM	GFM	GFM	GFL	GFL	GFM	GFM	GFM	
Bus 8	IDEAL	GFM	GFM	GFL	GFL	GFL	GFL	GFM	GFM	
Bus 5	IDEAL	GFM	GFM	GFM	GFM	GFL	GFL	GFL	GFL	

Table 2: GFM-GFL Configurations per Simulation

Simulation Sets

1. Load Change at highest power consumption bus
2. Load Change at a different bus
3. Single Phase to Ground Fault at a random location
4. Symmetric Fault at a random location
5. Fault at the highest power flow transmission line

Load Change: +5MW, +1MVAR per phase

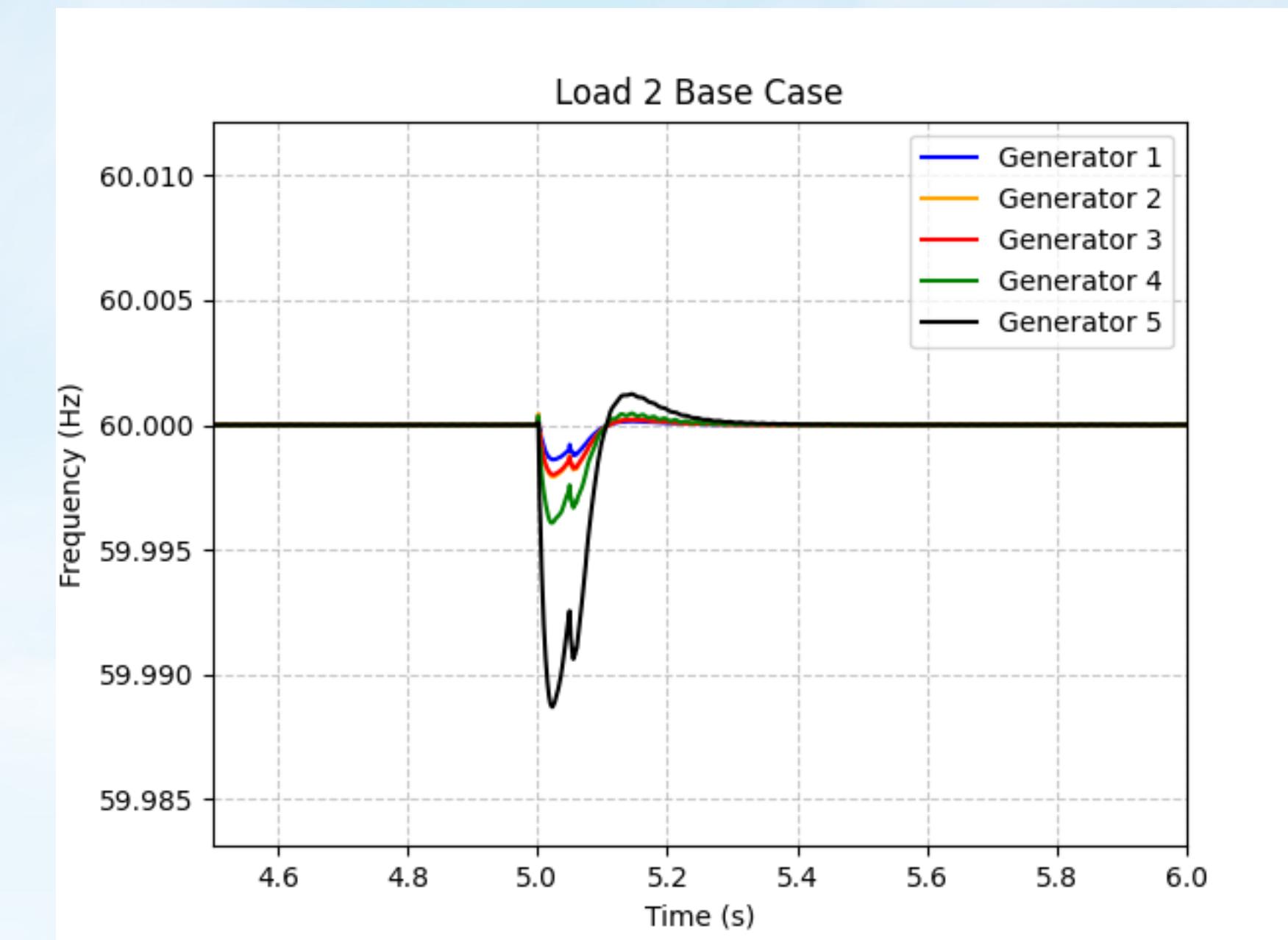
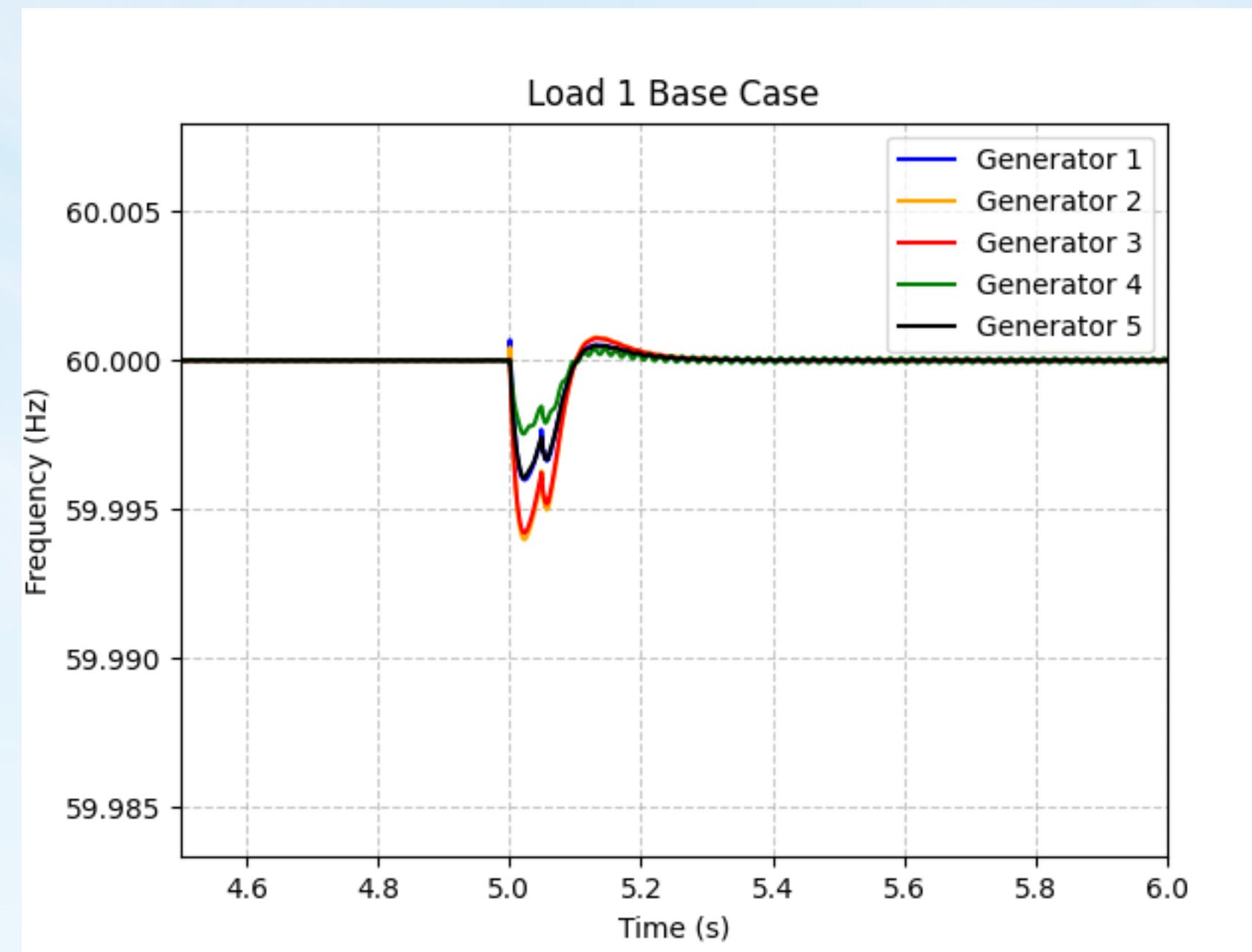
Line with fault is tripped after 100 ms.

Results



Load 1

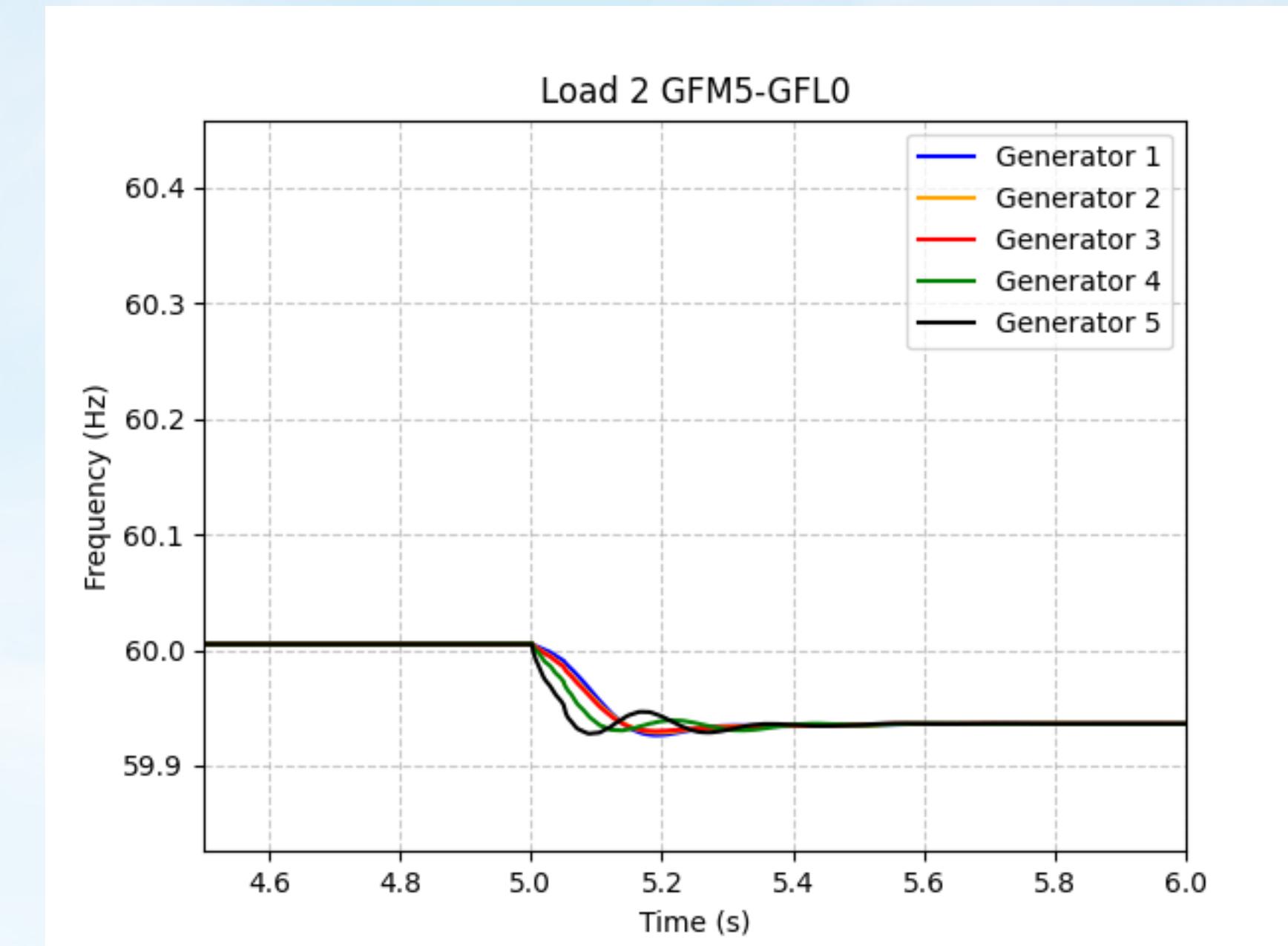
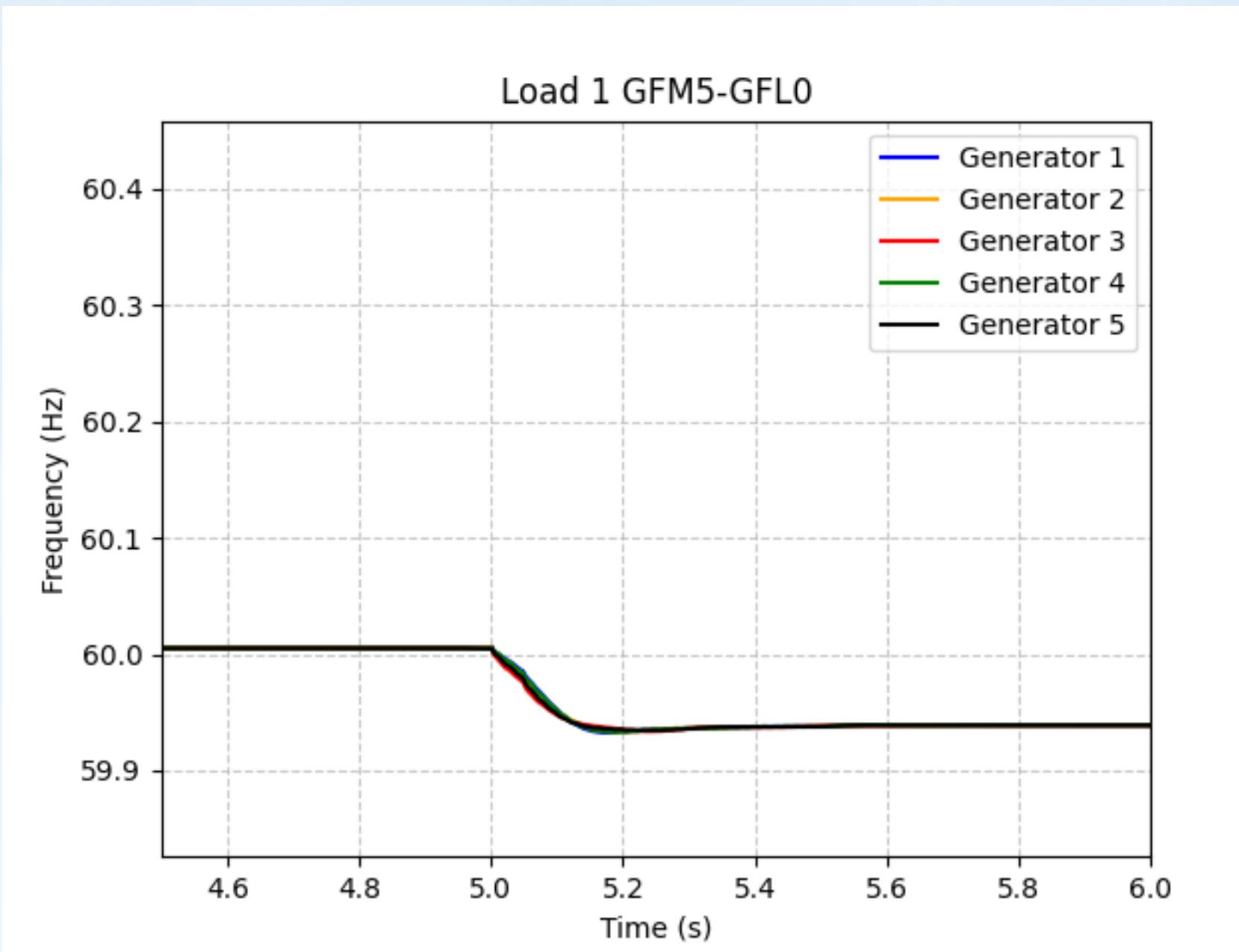
Load 2



Base Case

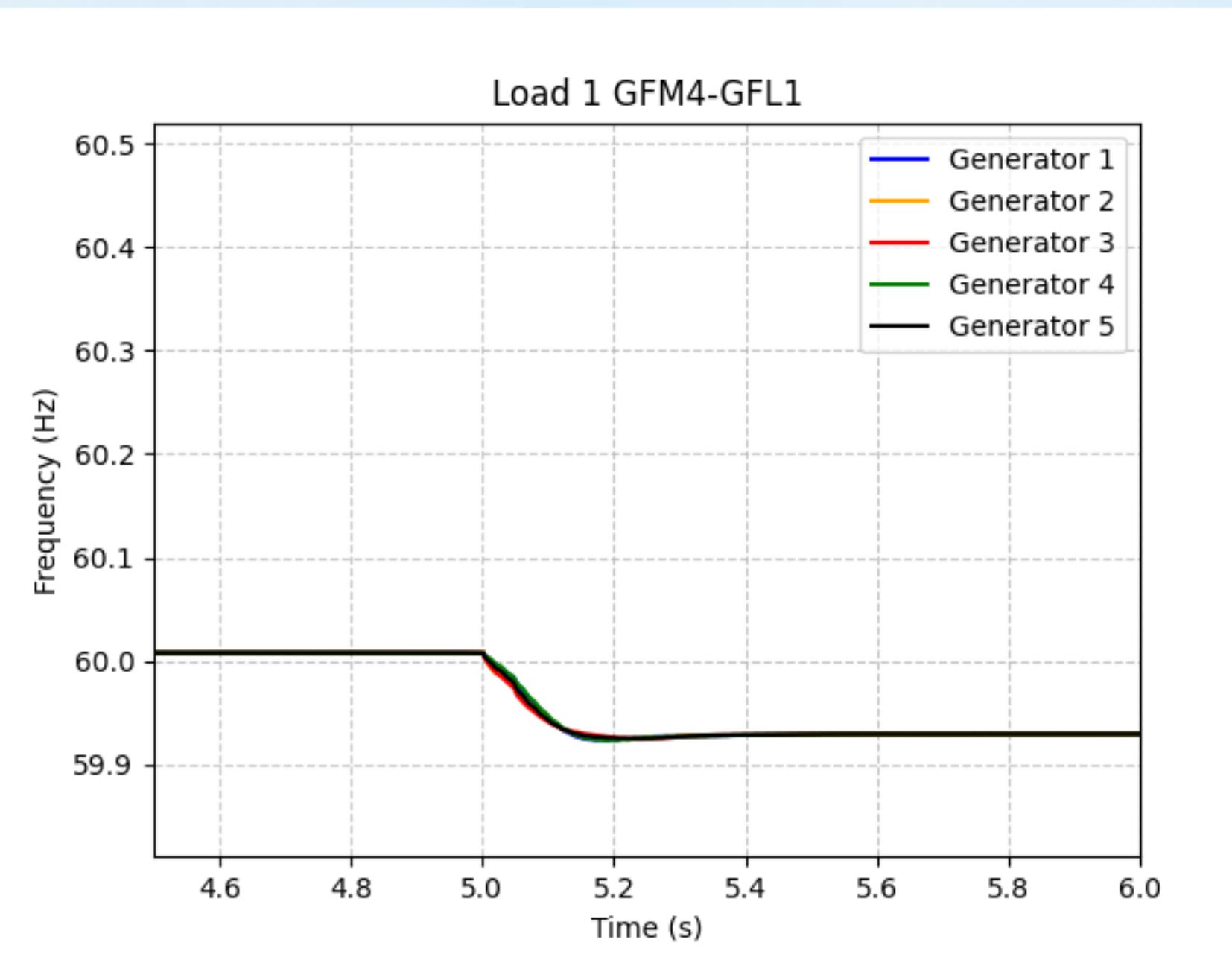
Load 1

Load 2

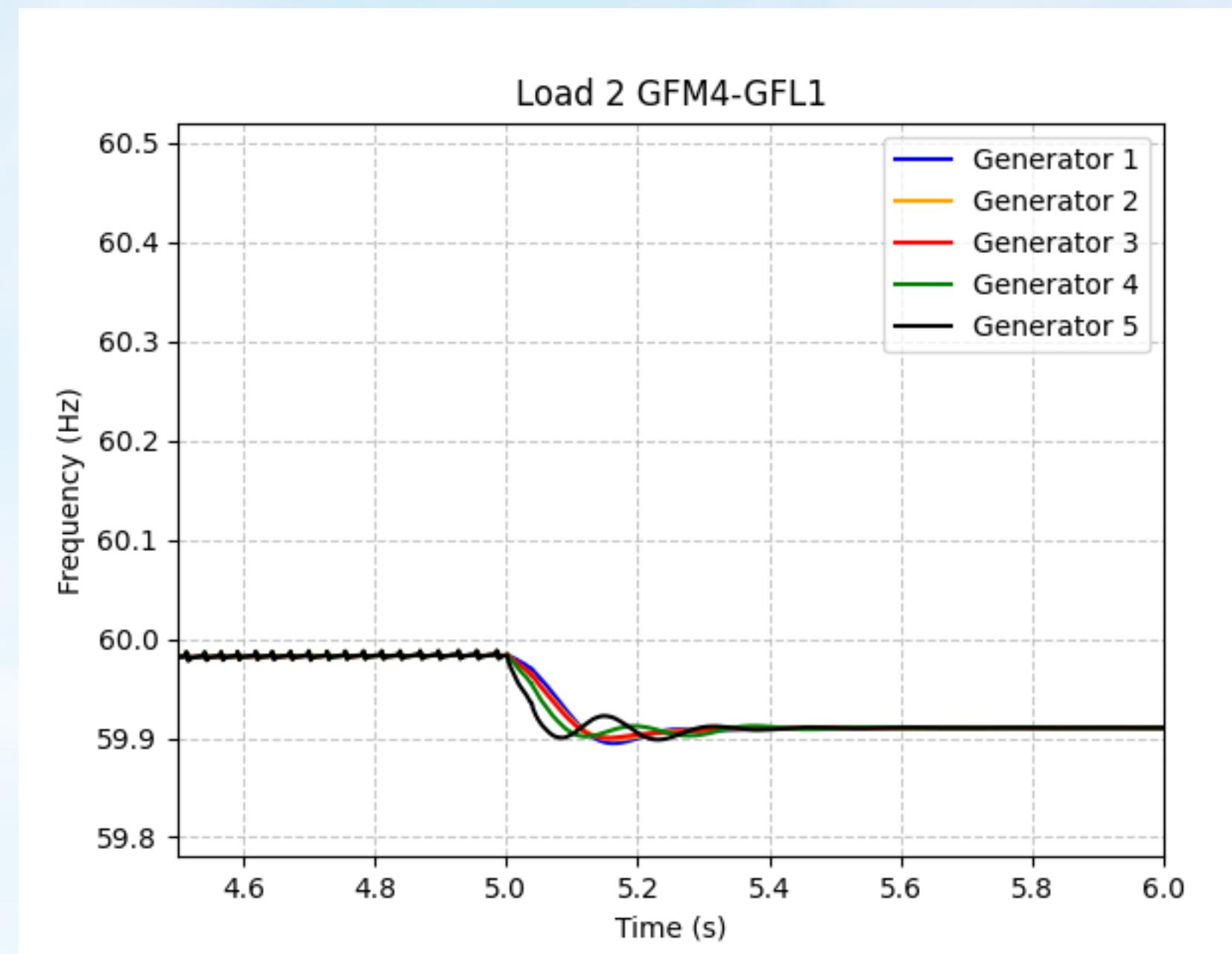


GFM5:GFL0

Load 1

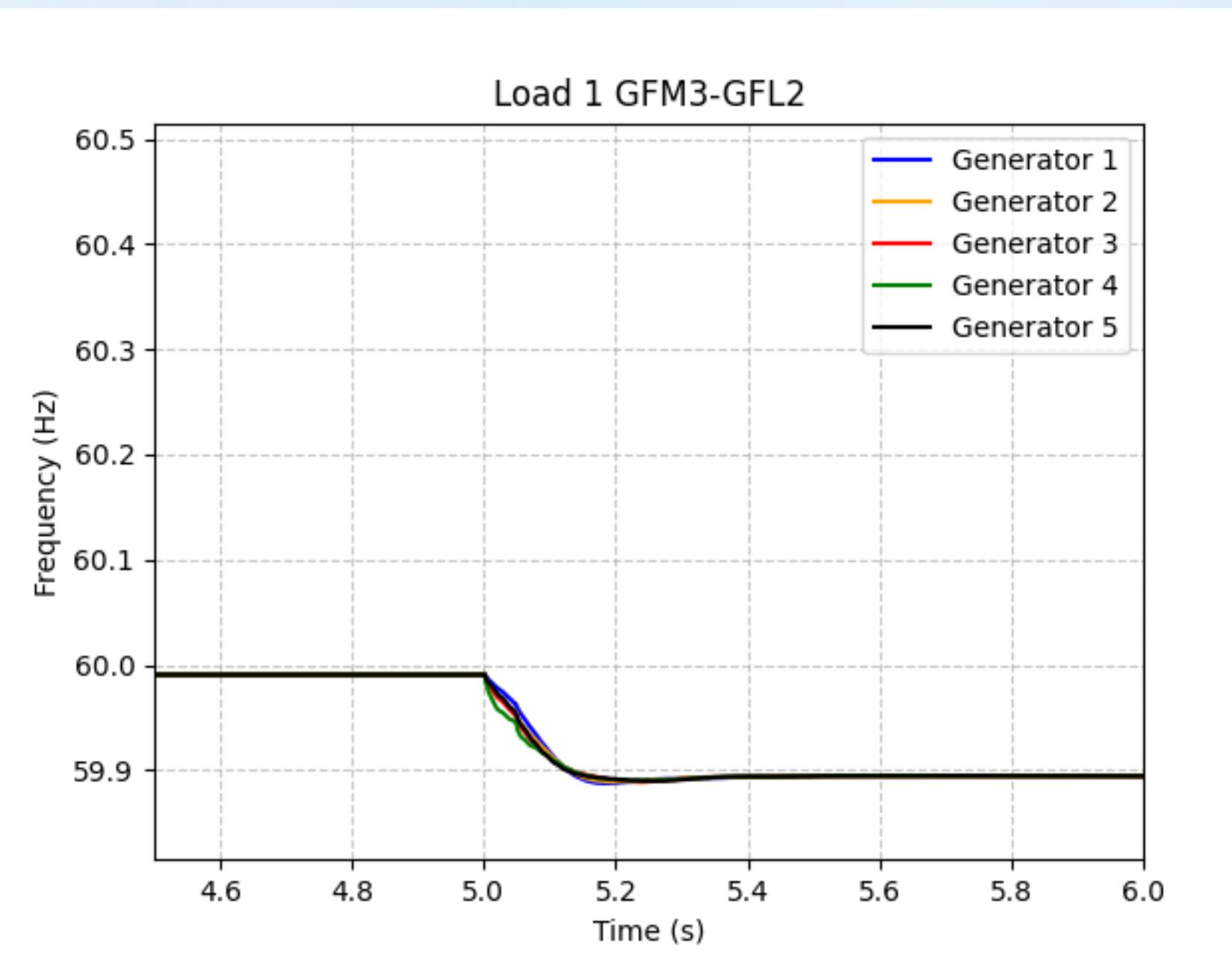


Load 2

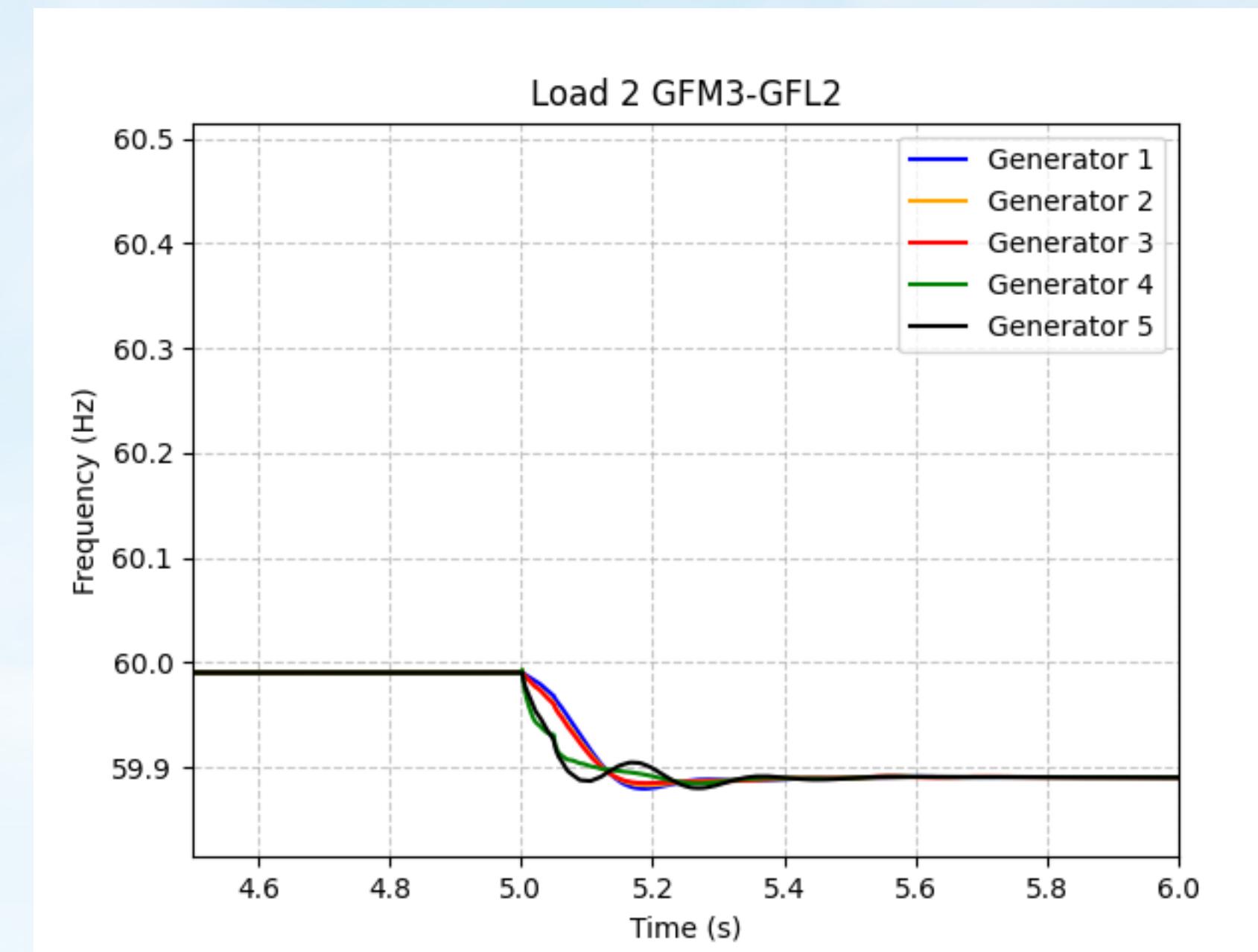


GFM4:GFL1

Load 1

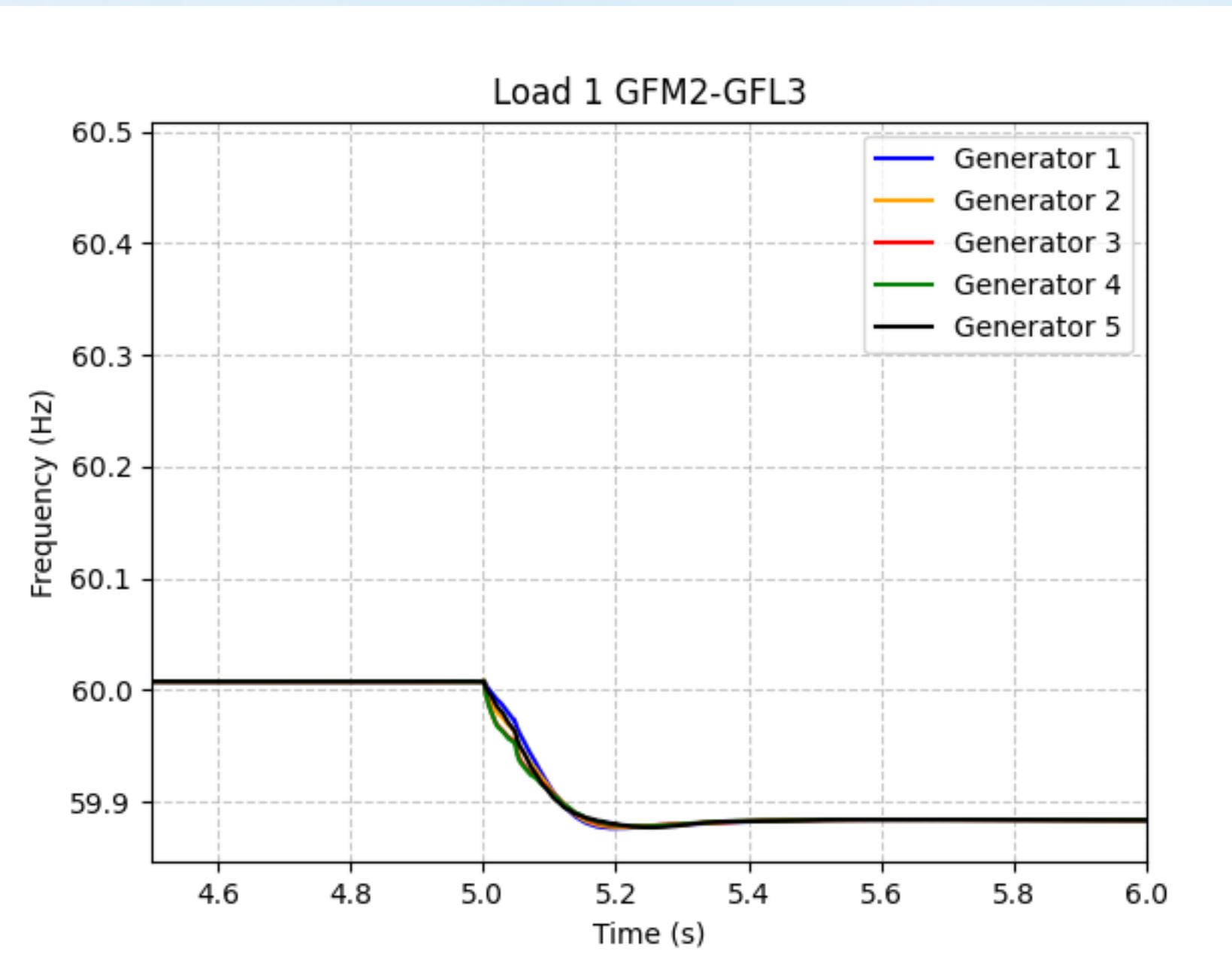


Load 2

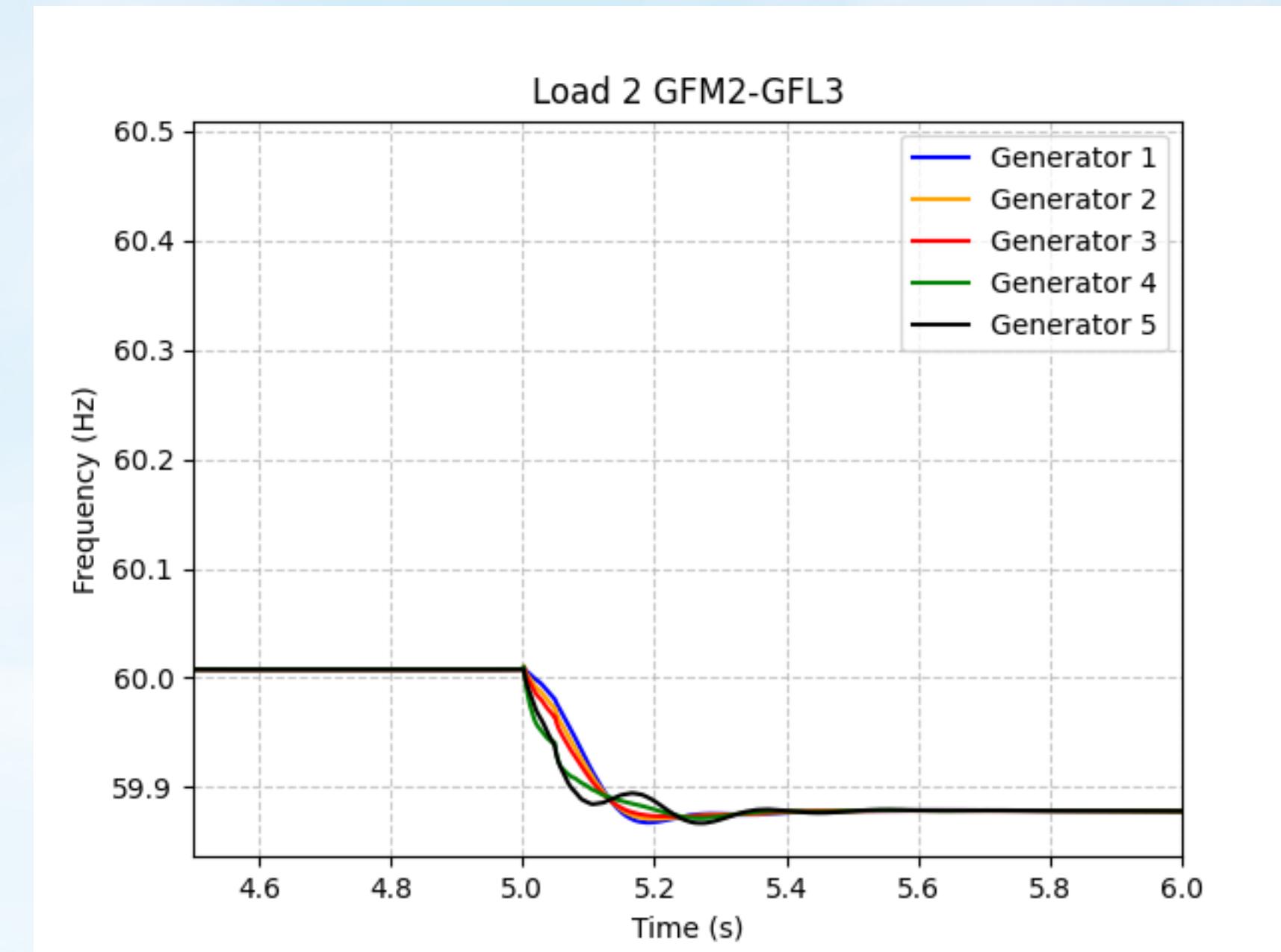


GFM3:GFM2

Load 1



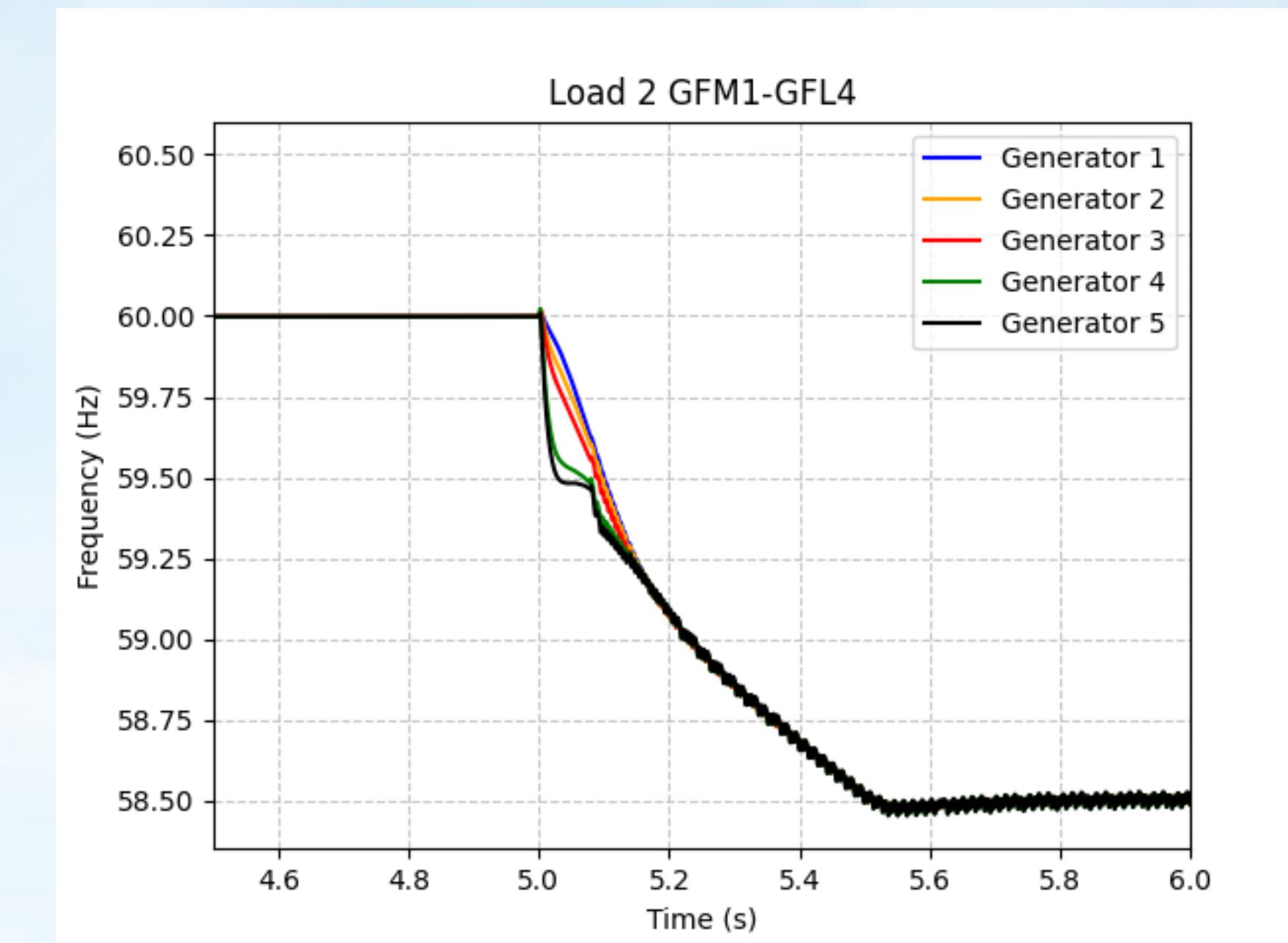
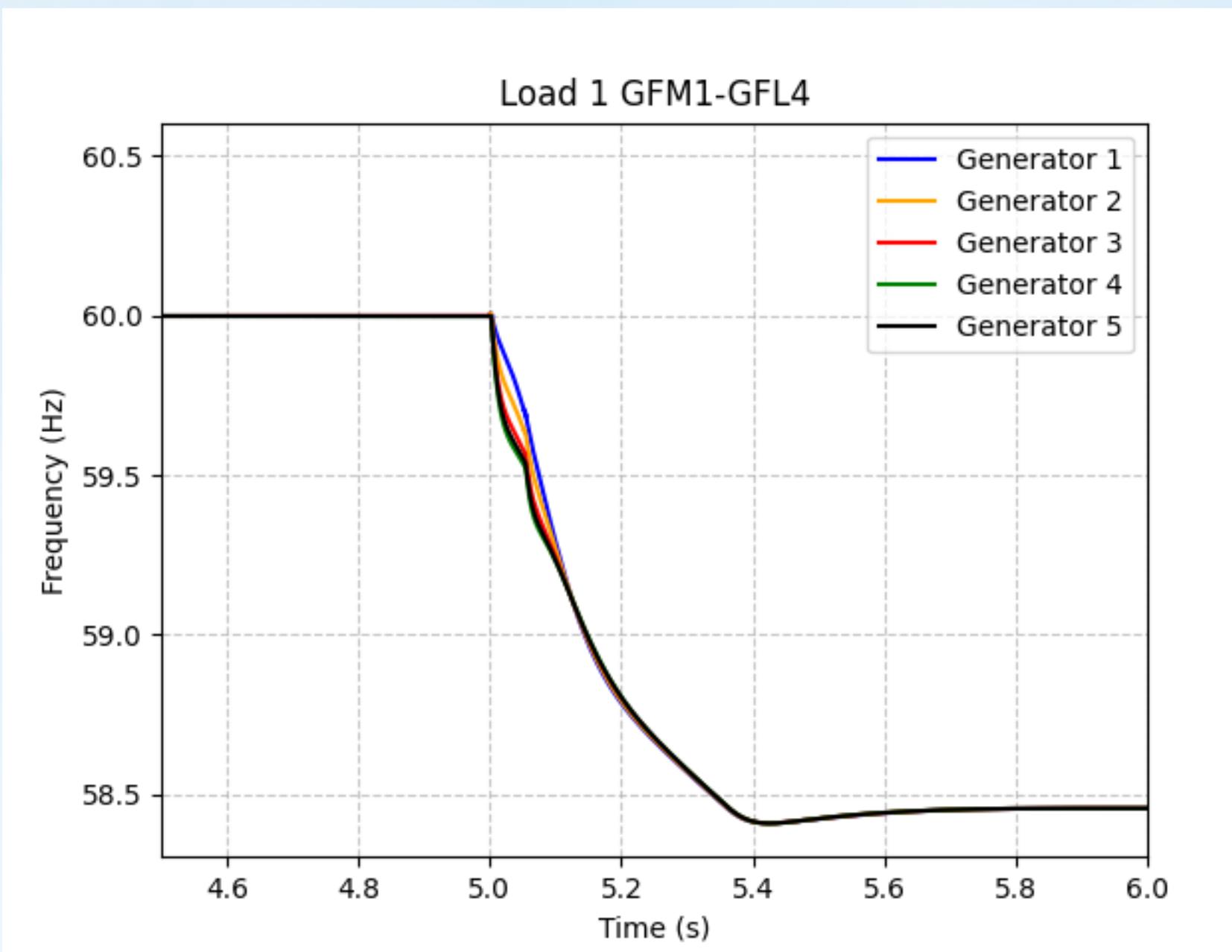
Load 2



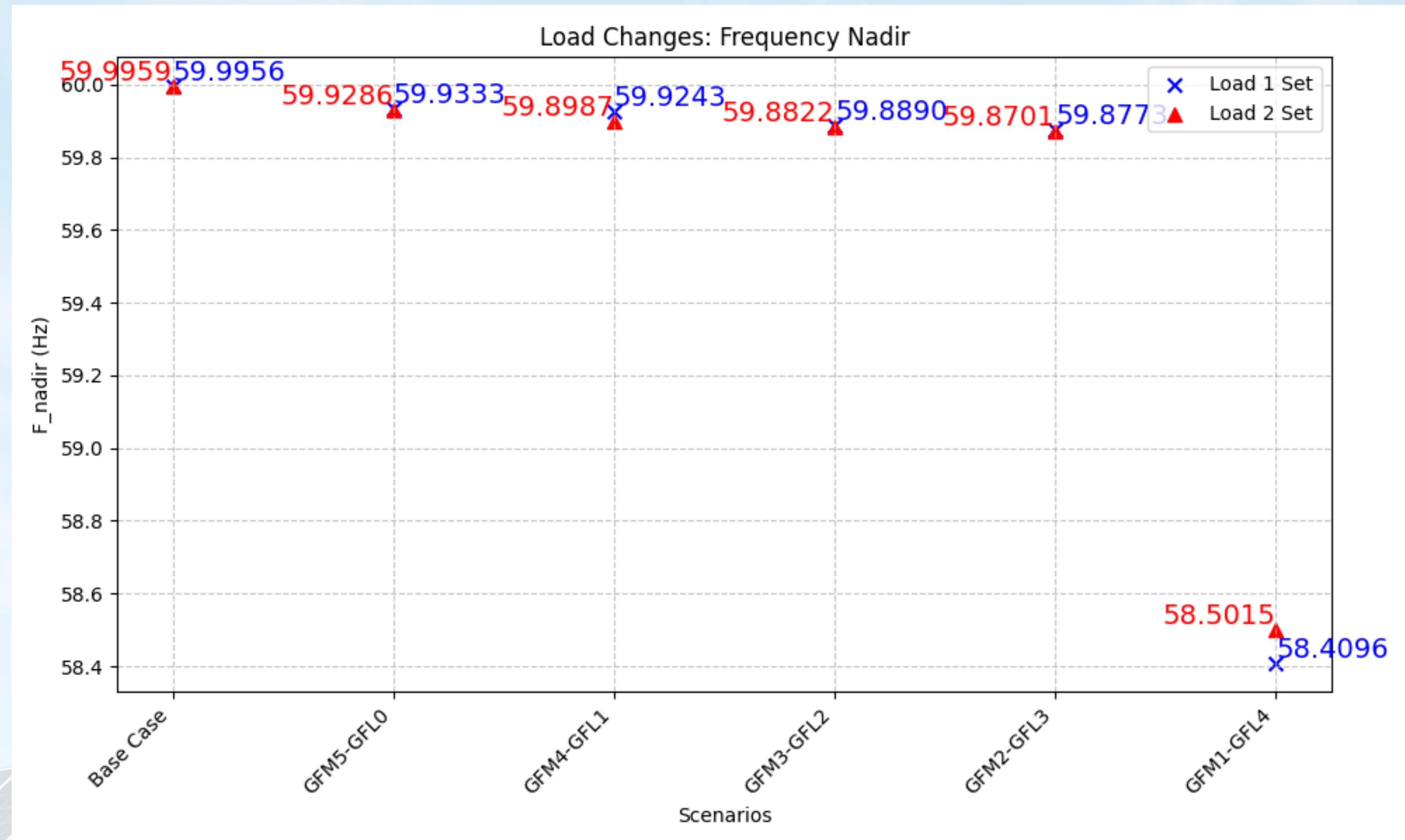
GFM2:GFL3

Load 1

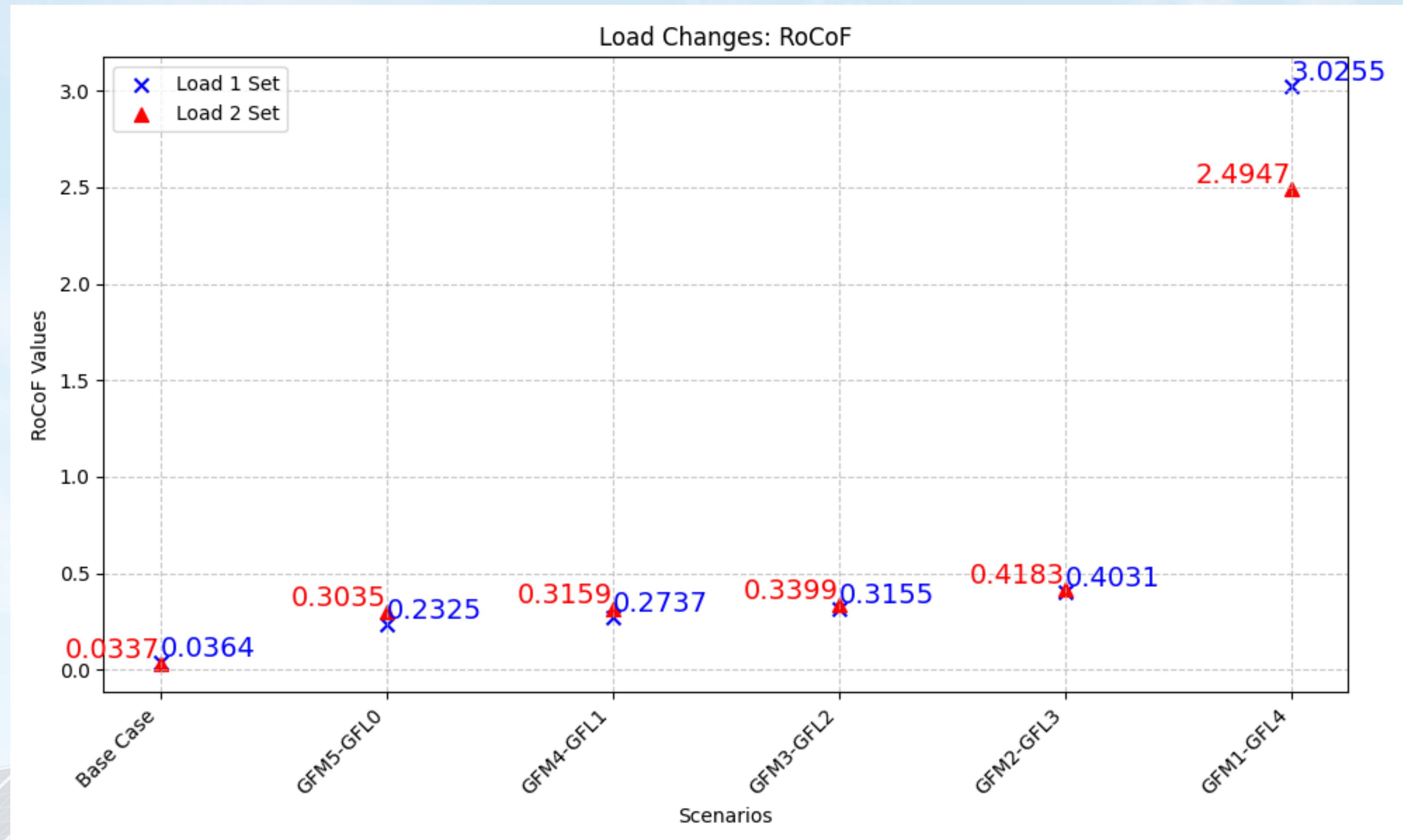
Load 2



GFM1:GFM4



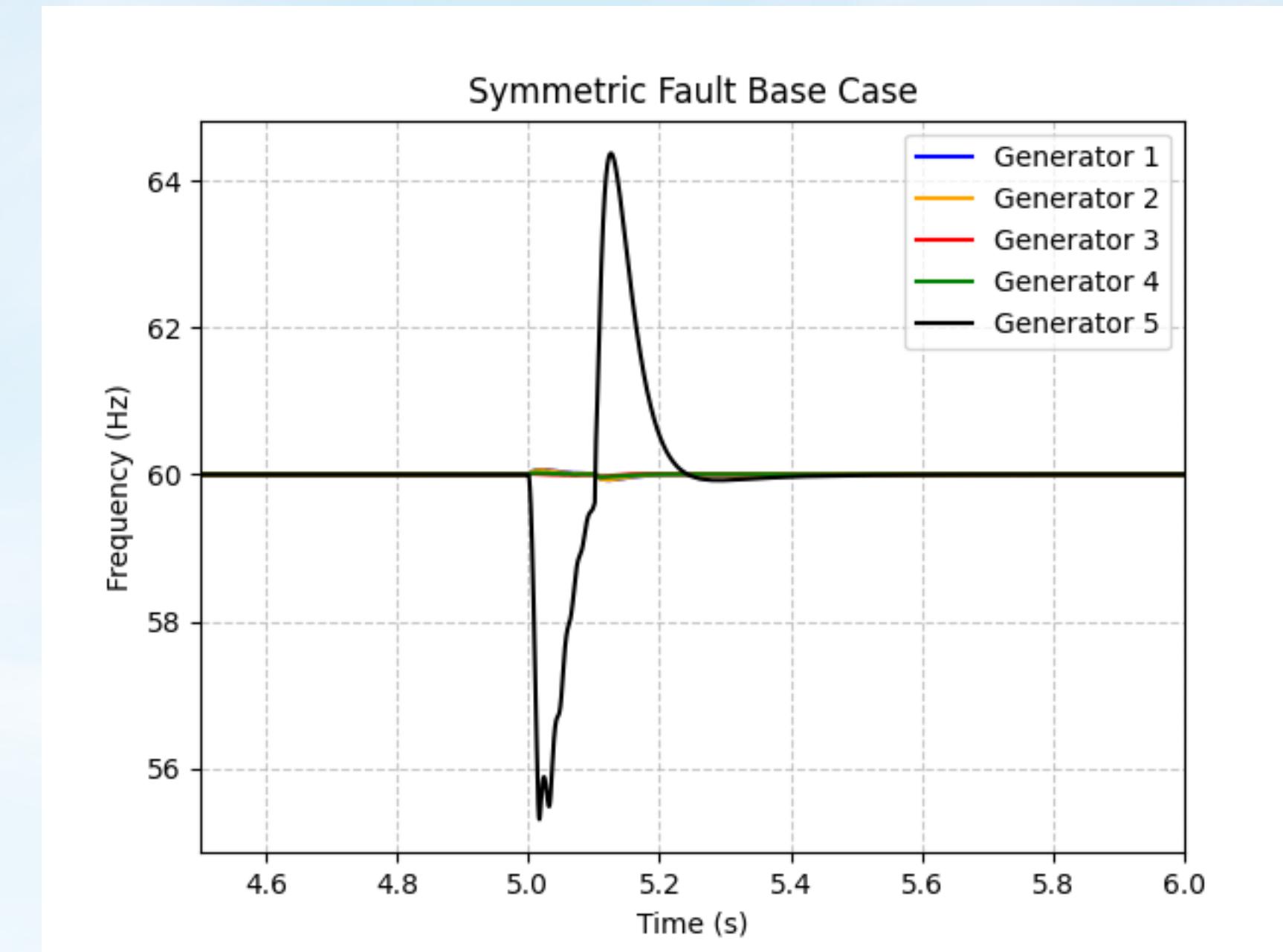
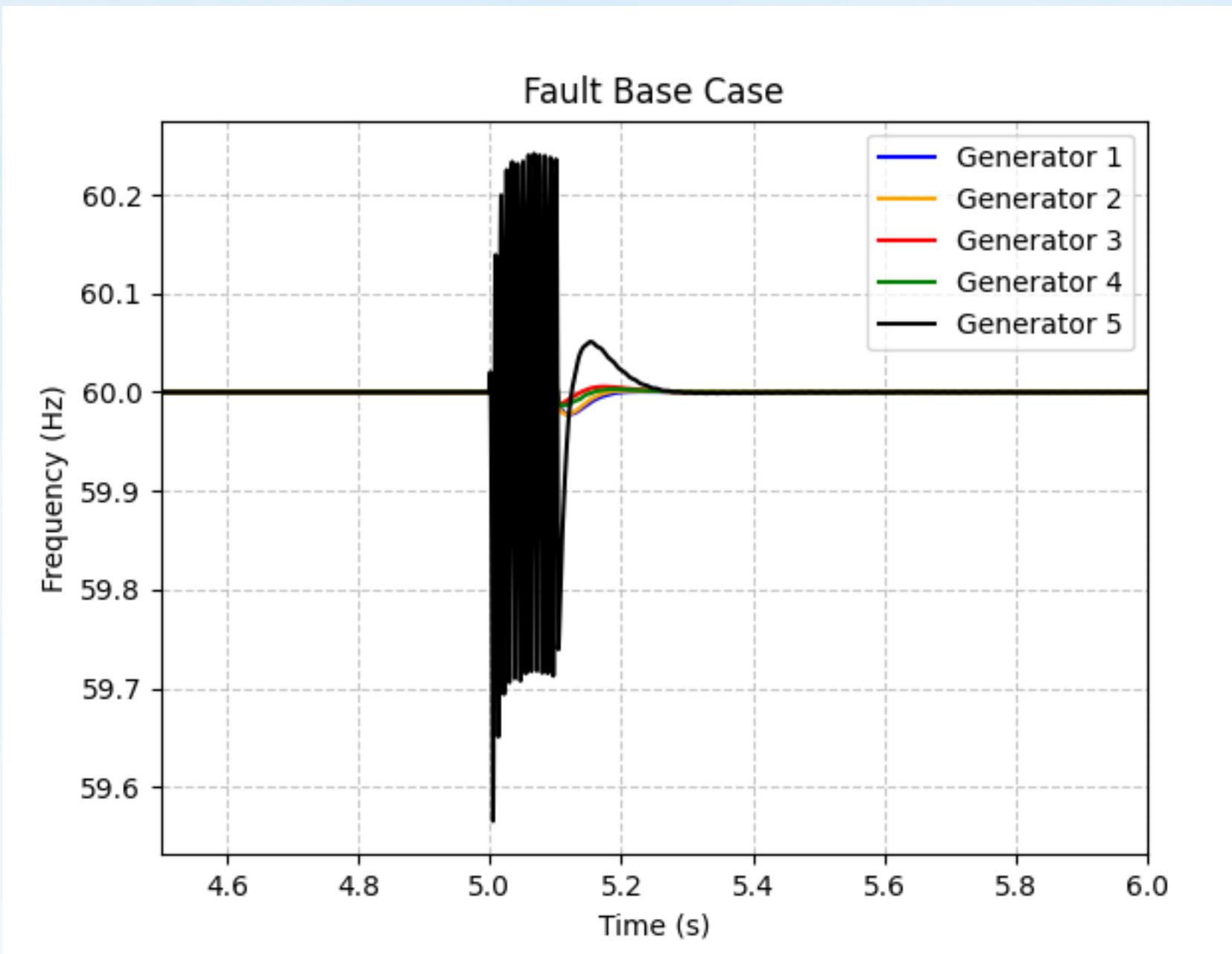
Load Changes Frequency Nadir



Load Changes *RoCoF**

Single Phase to GND Fault

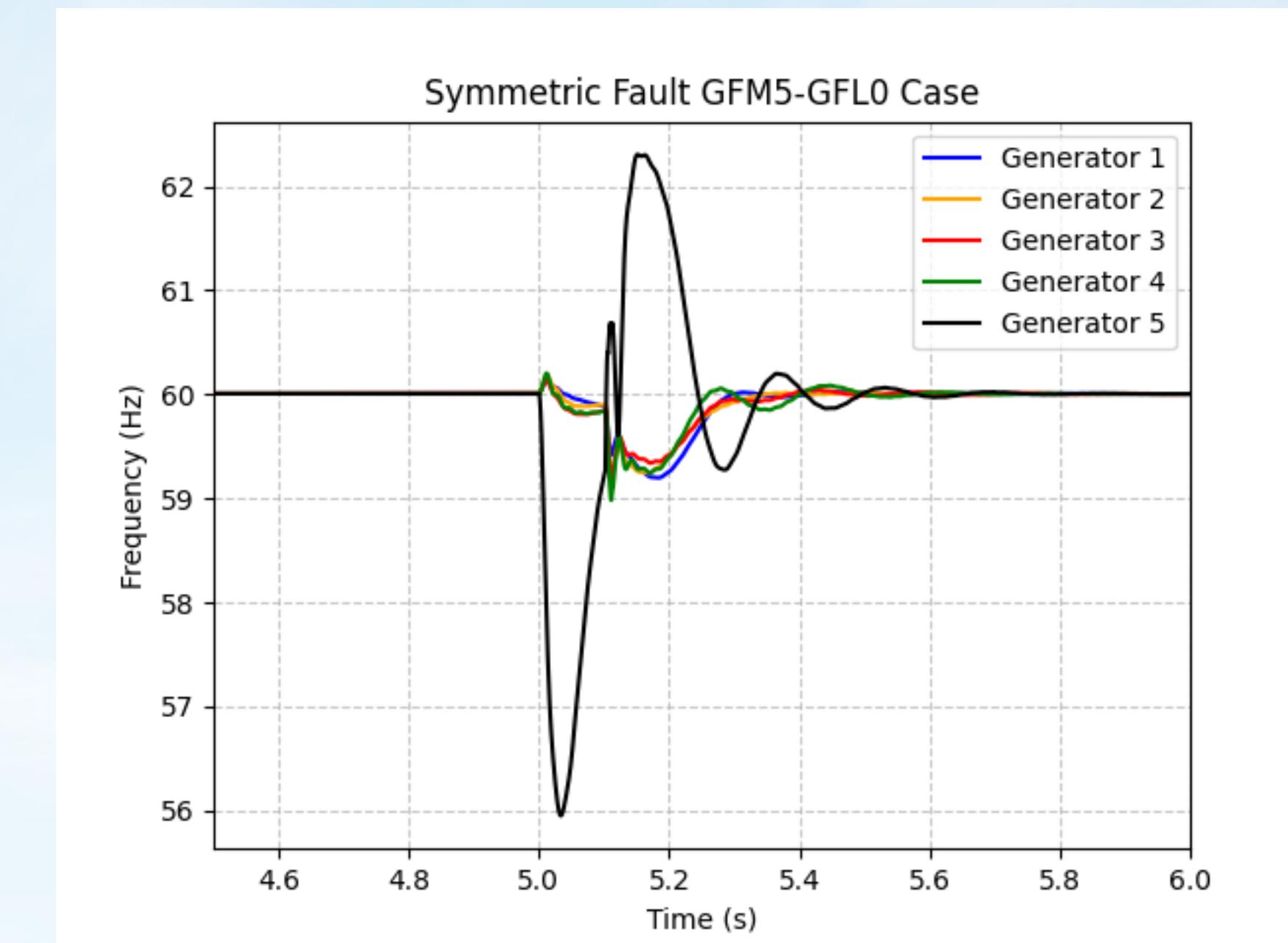
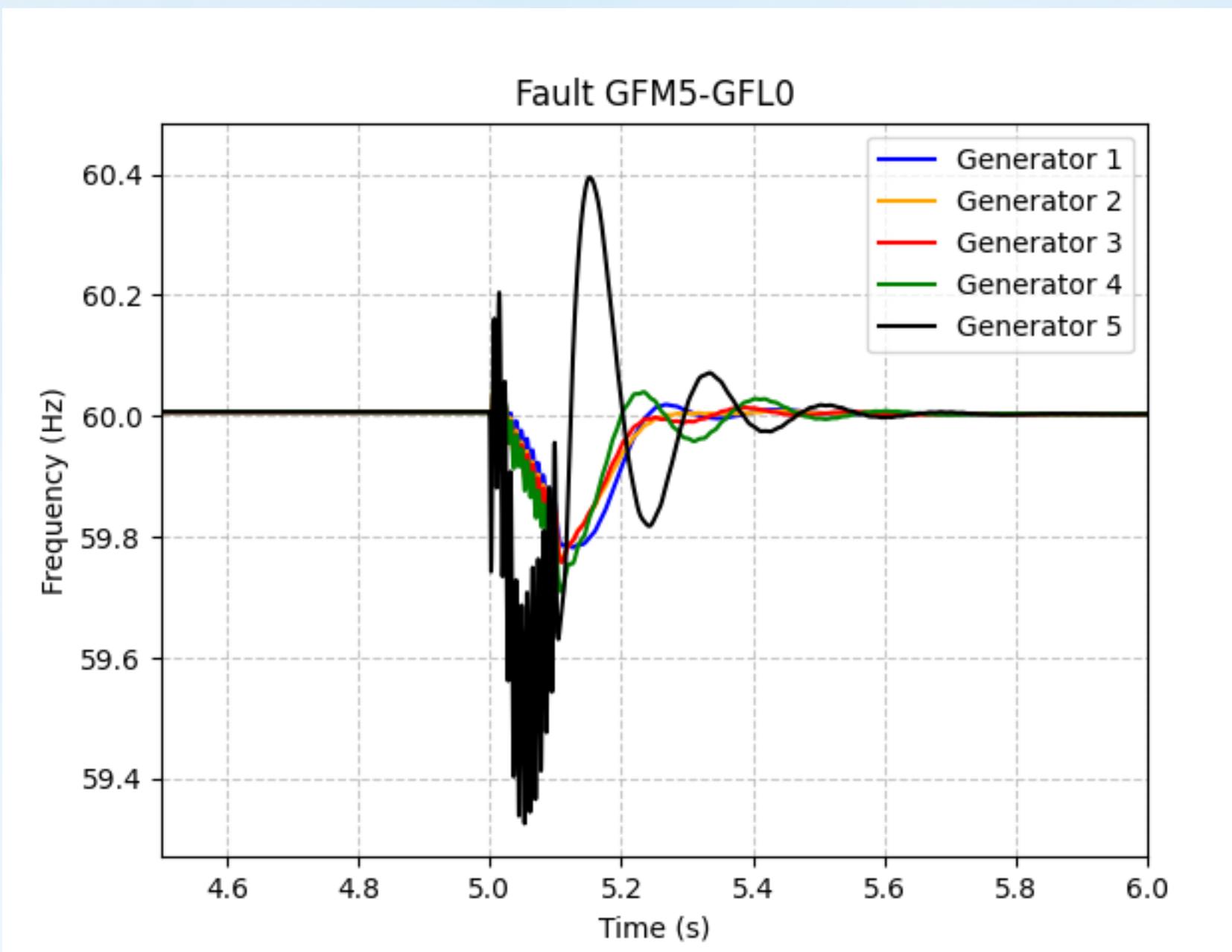
Symmetric to GND Fault



Base Case

Single Phase to GND Fault

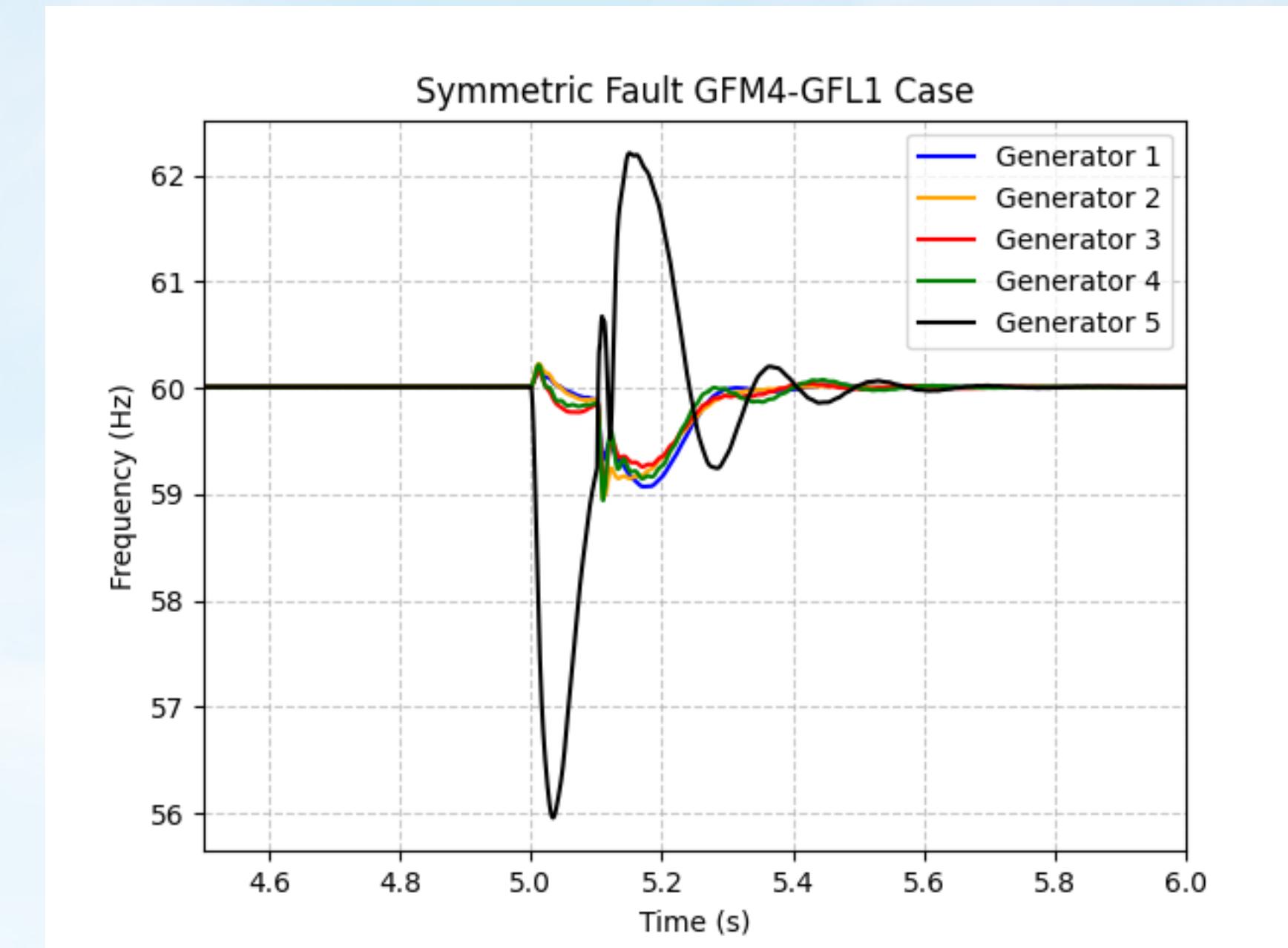
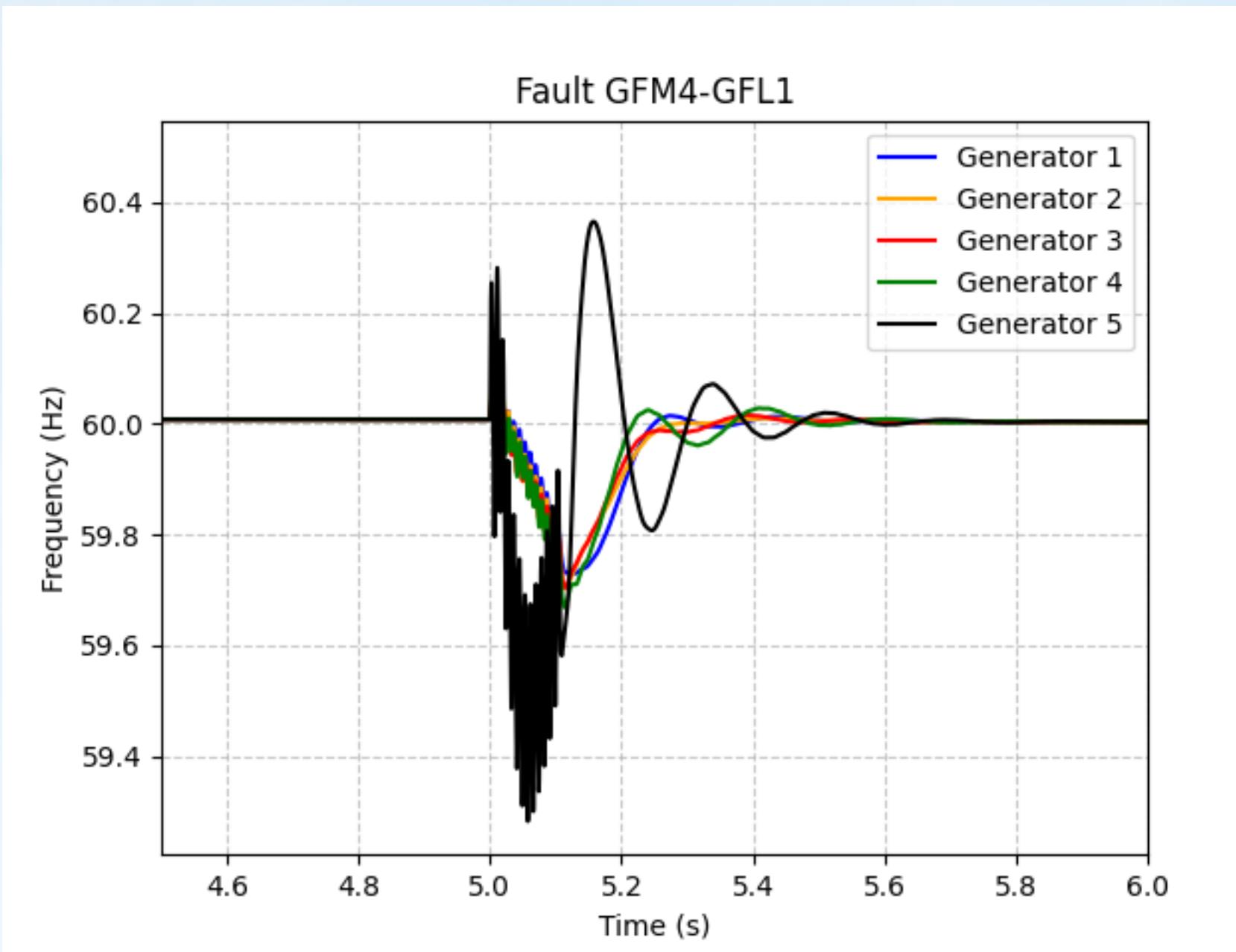
Symmetric to GND Fault



GFM5:GFL0

Single Phase to GND Fault

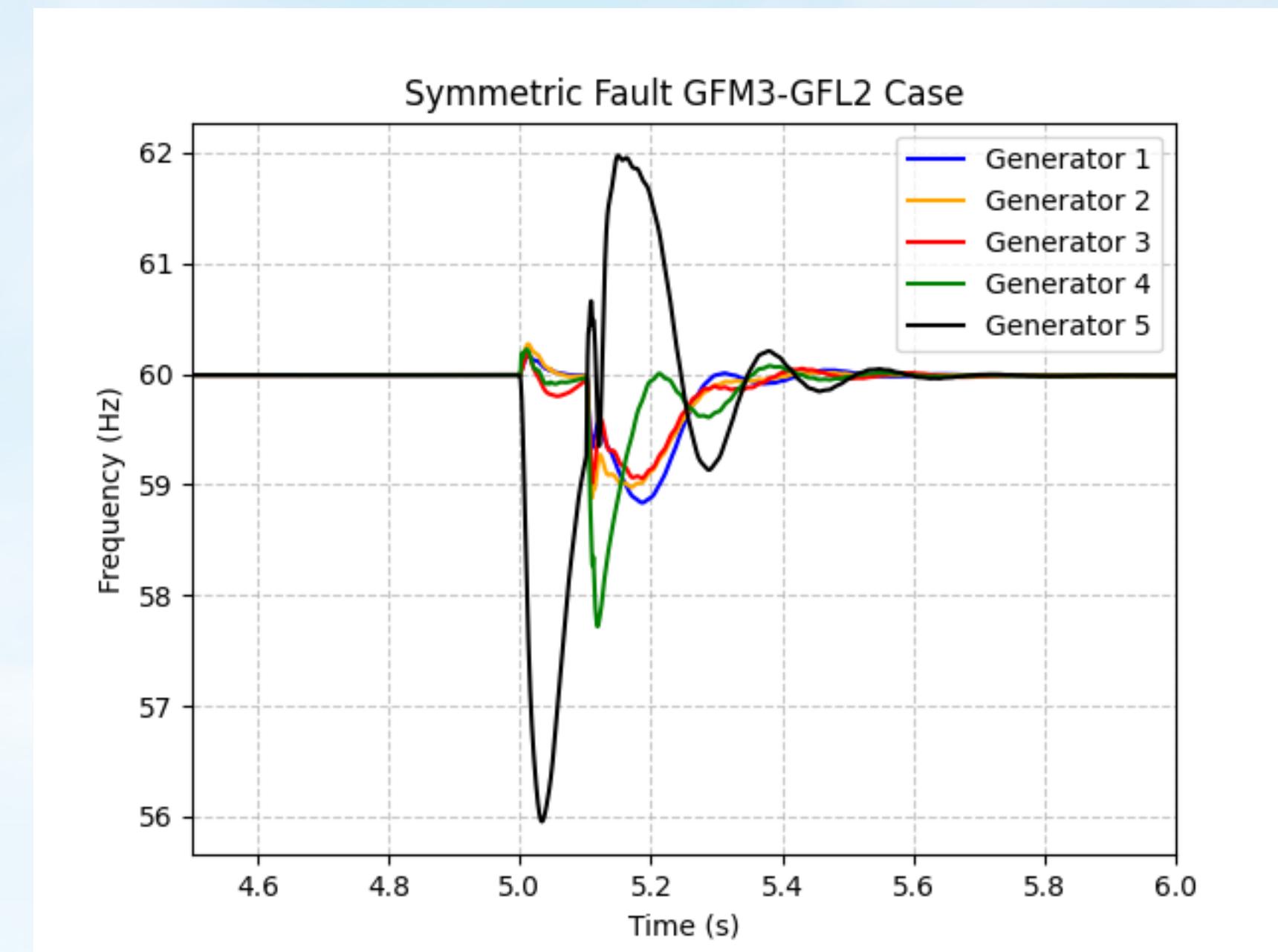
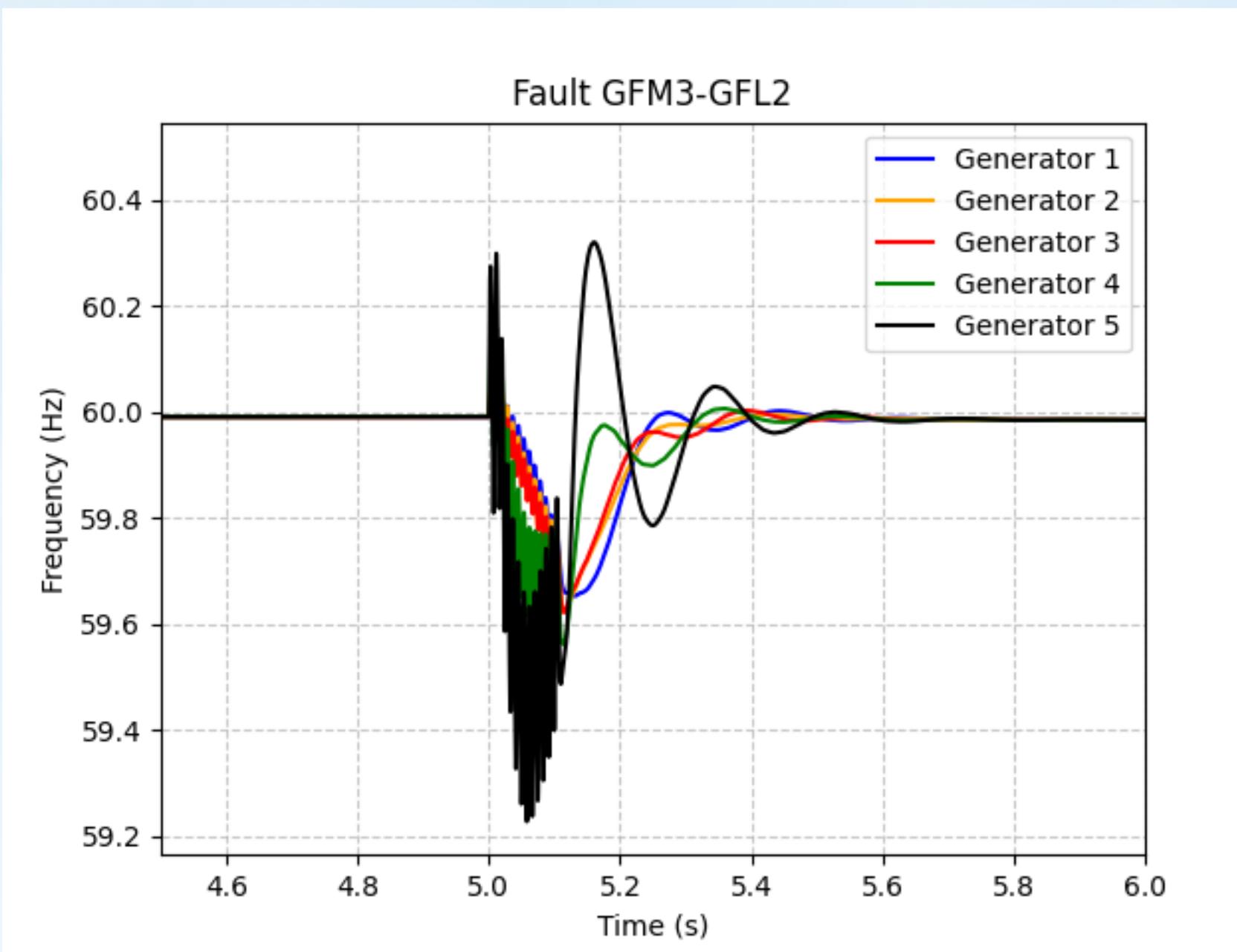
Symmetric to GND Fault



GFM4:GFL1

Single Phase to GND Fault

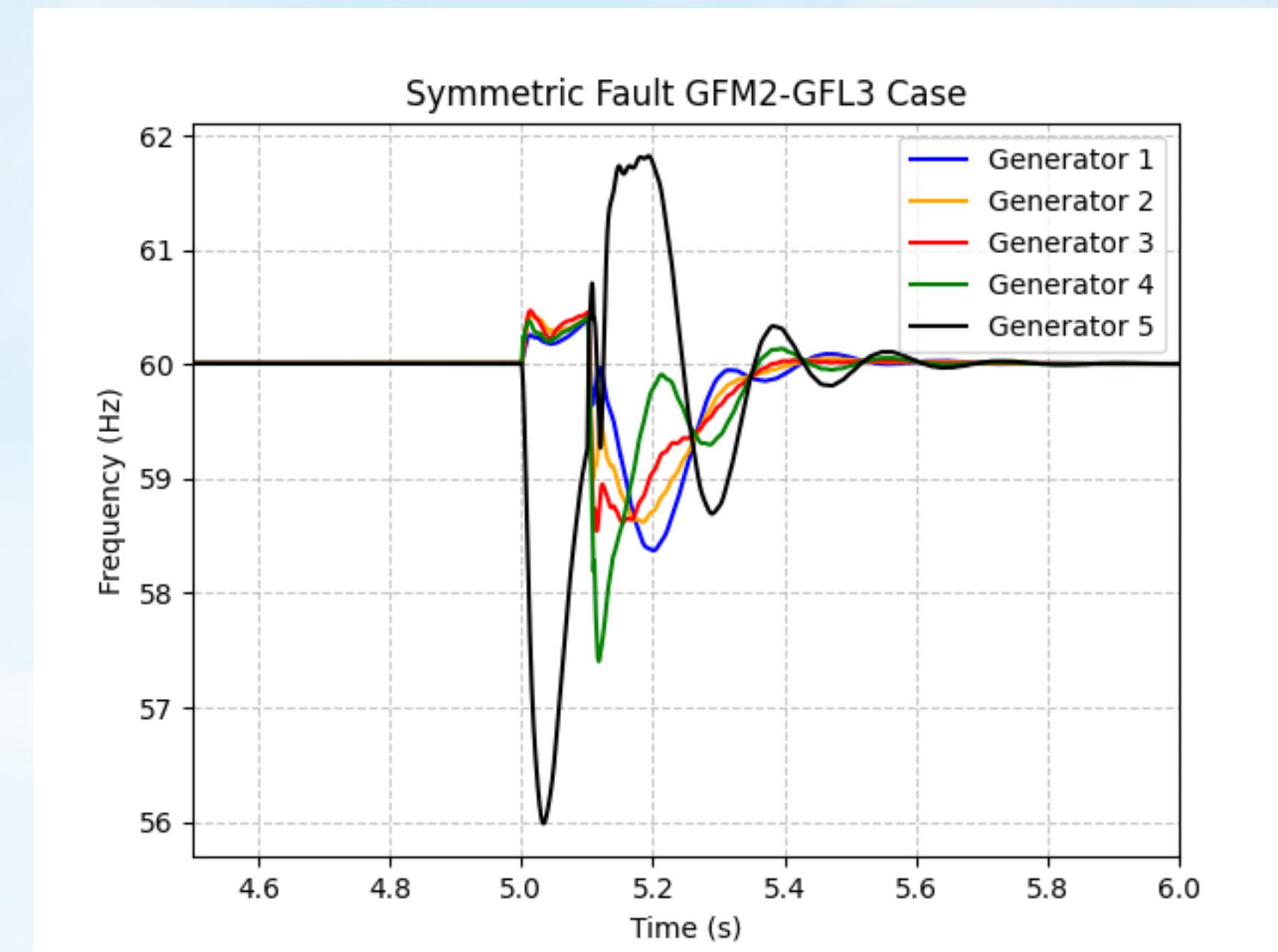
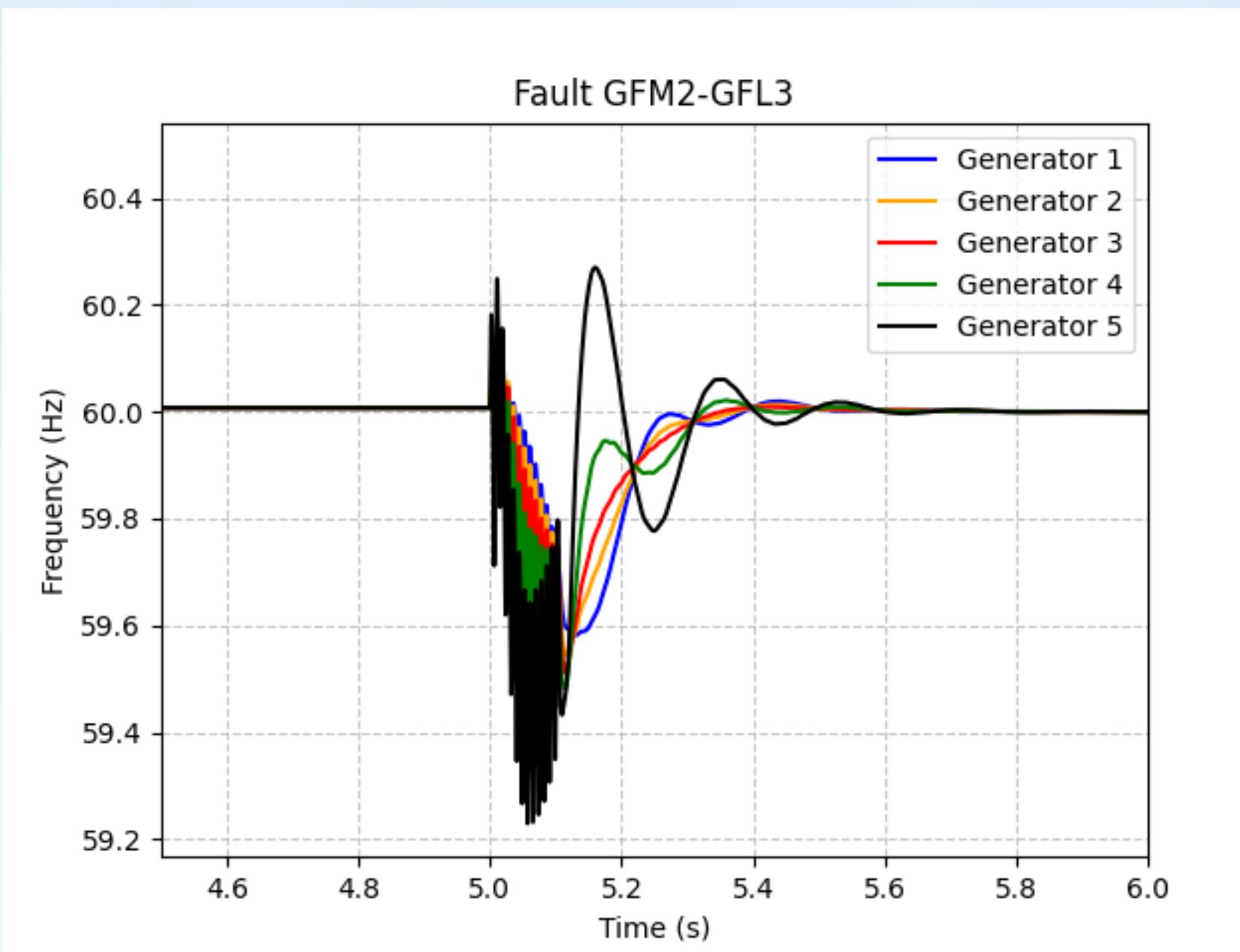
Symmetric to GND Fault



GFM3:GFL2

Single Phase to GND Fault

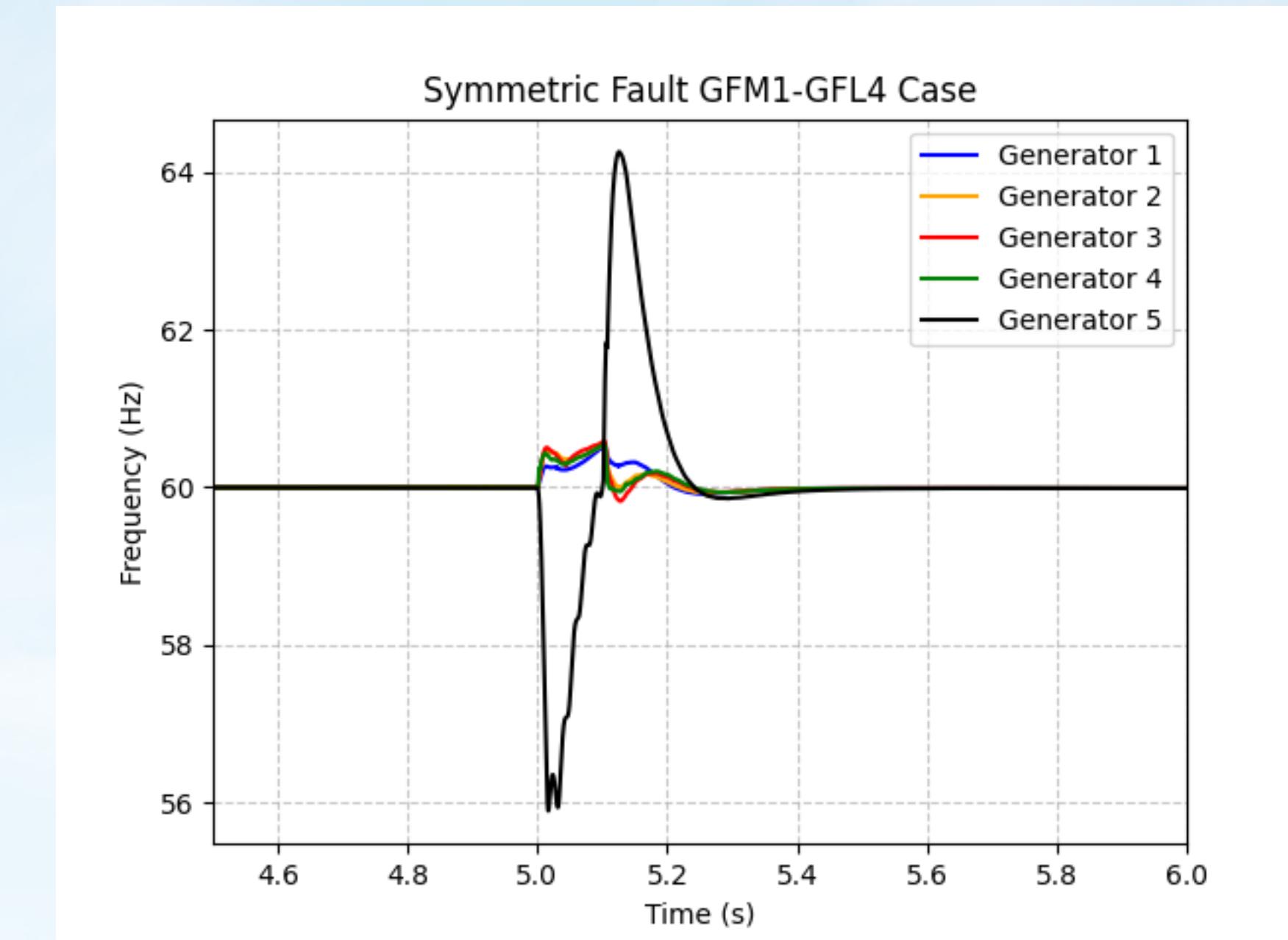
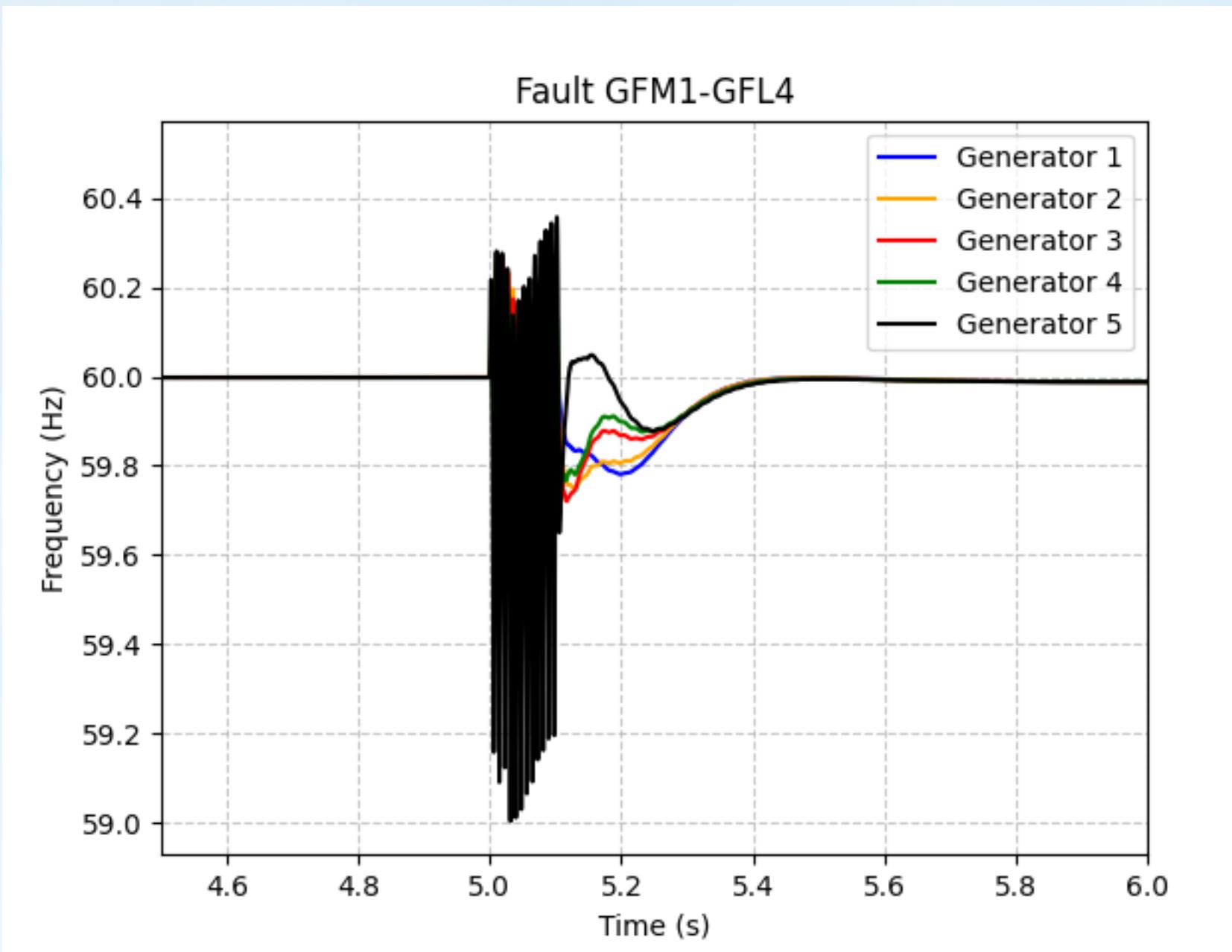
Symmetric to GND Fault



GFM2:GFL3

Single Phase to GND Fault

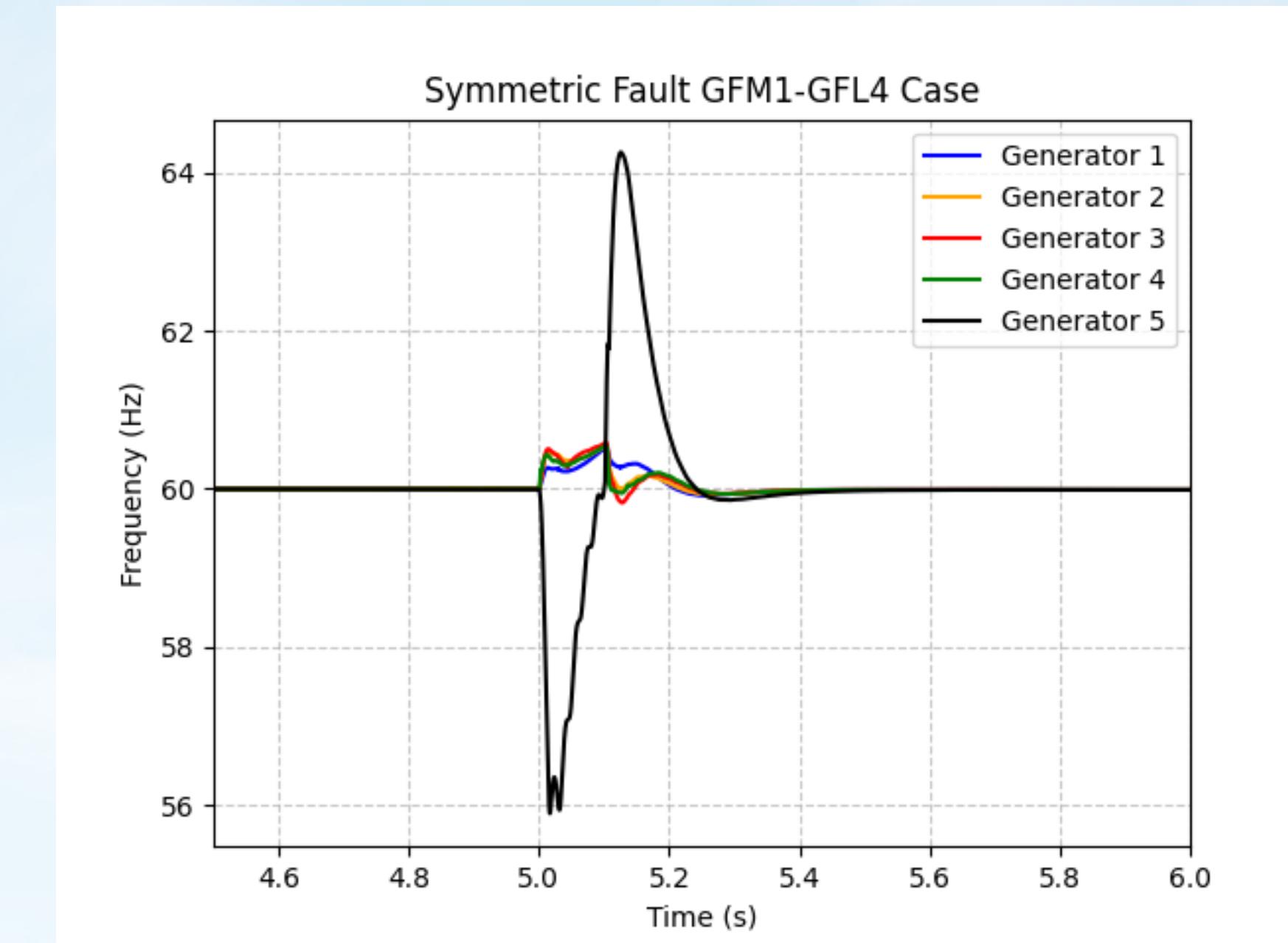
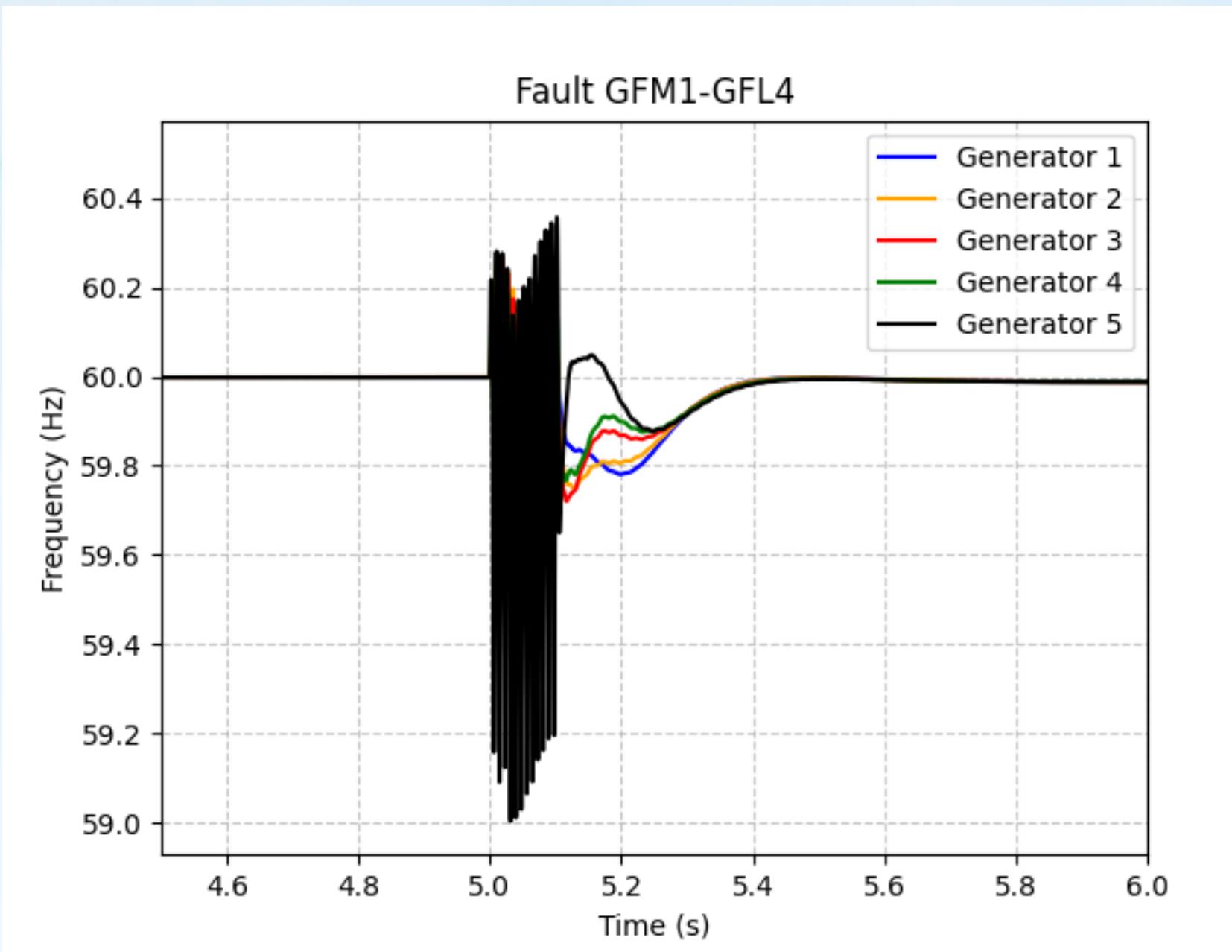
Symmetric to GND Fault



GFM1:GFL4

Single Phase to GND Fault

Symmetric to GND Fault

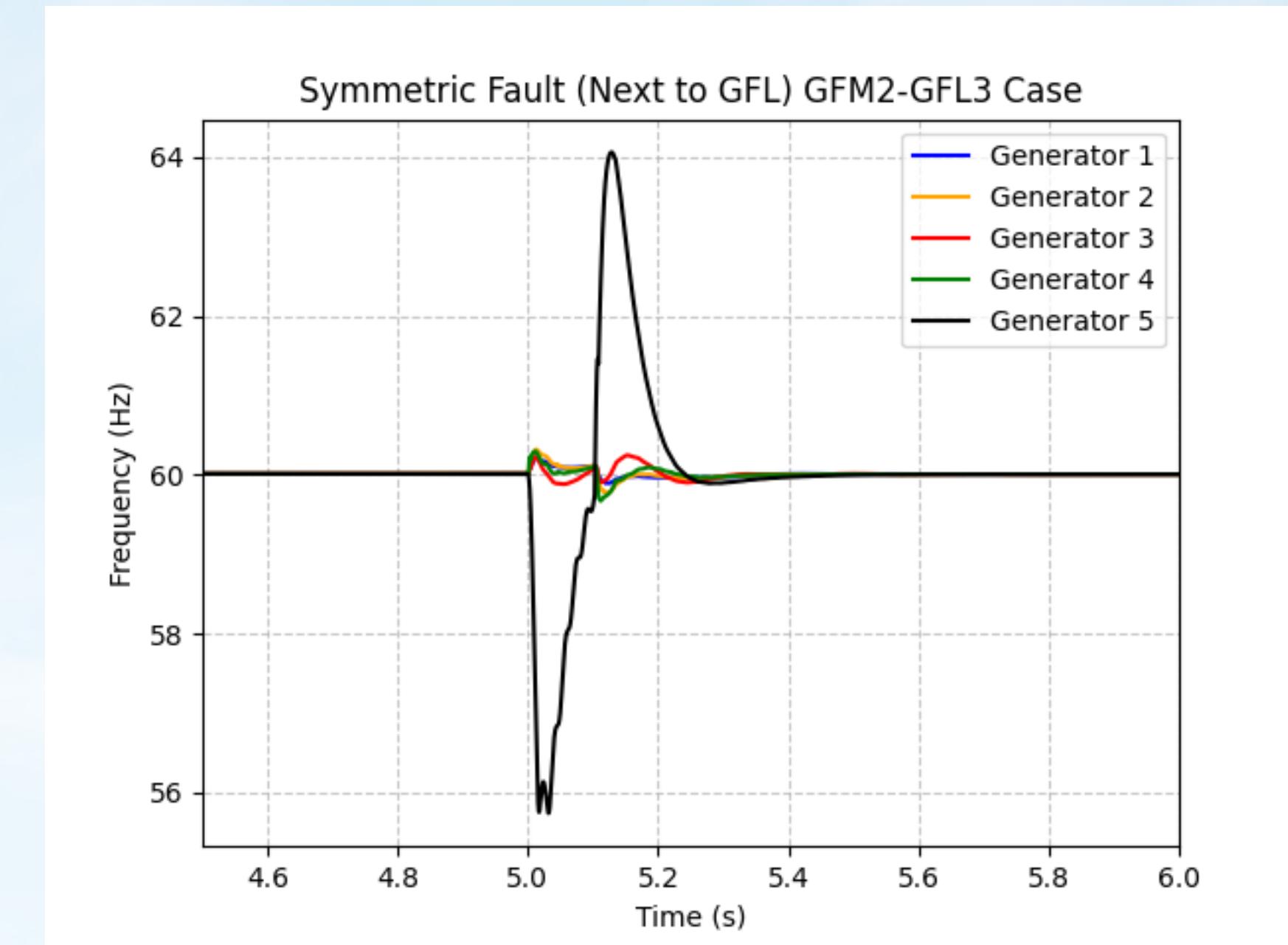
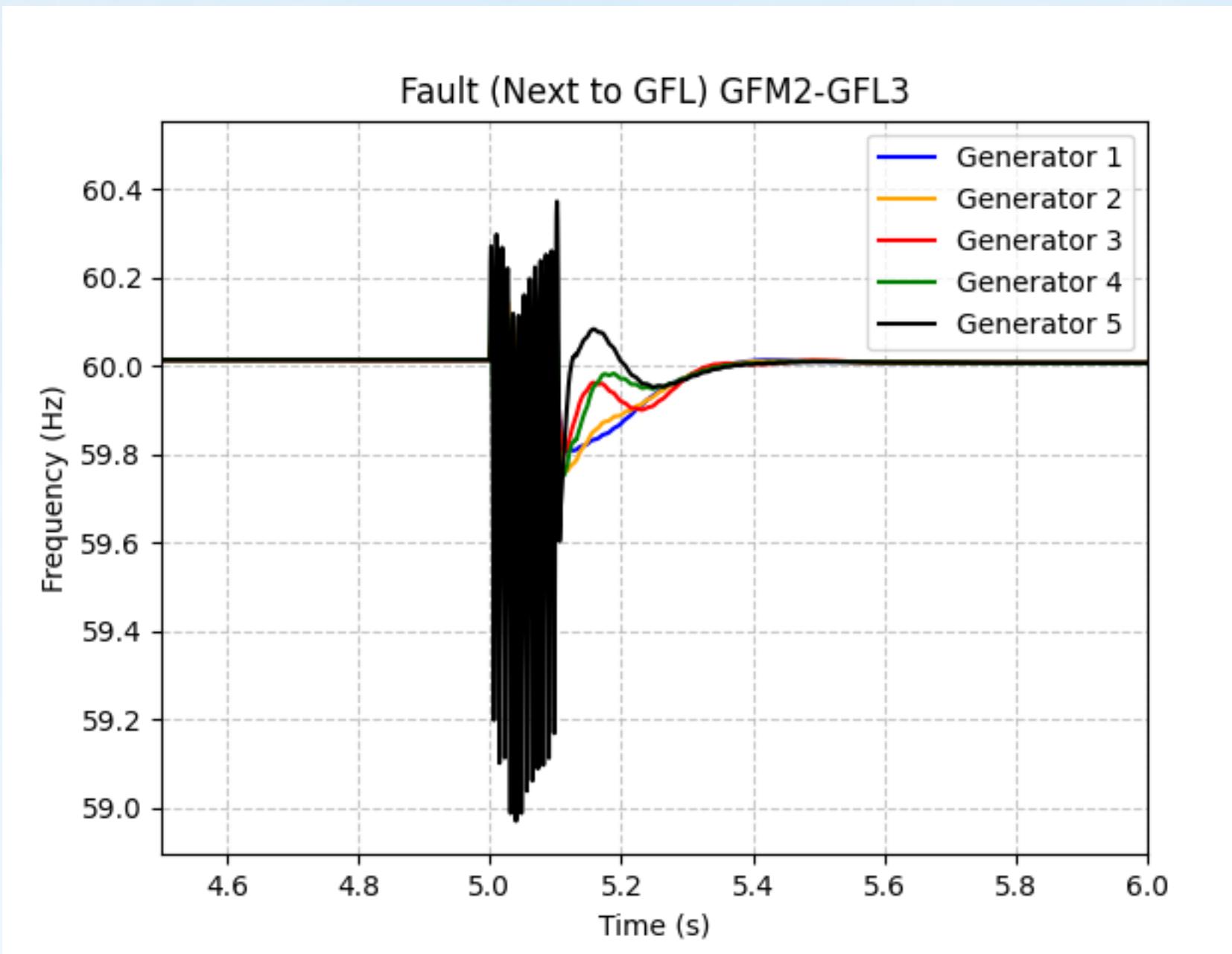


This looks so similar to Base Case when next a GFL...

GFM1:GFL4

Single Phase to GND Fault

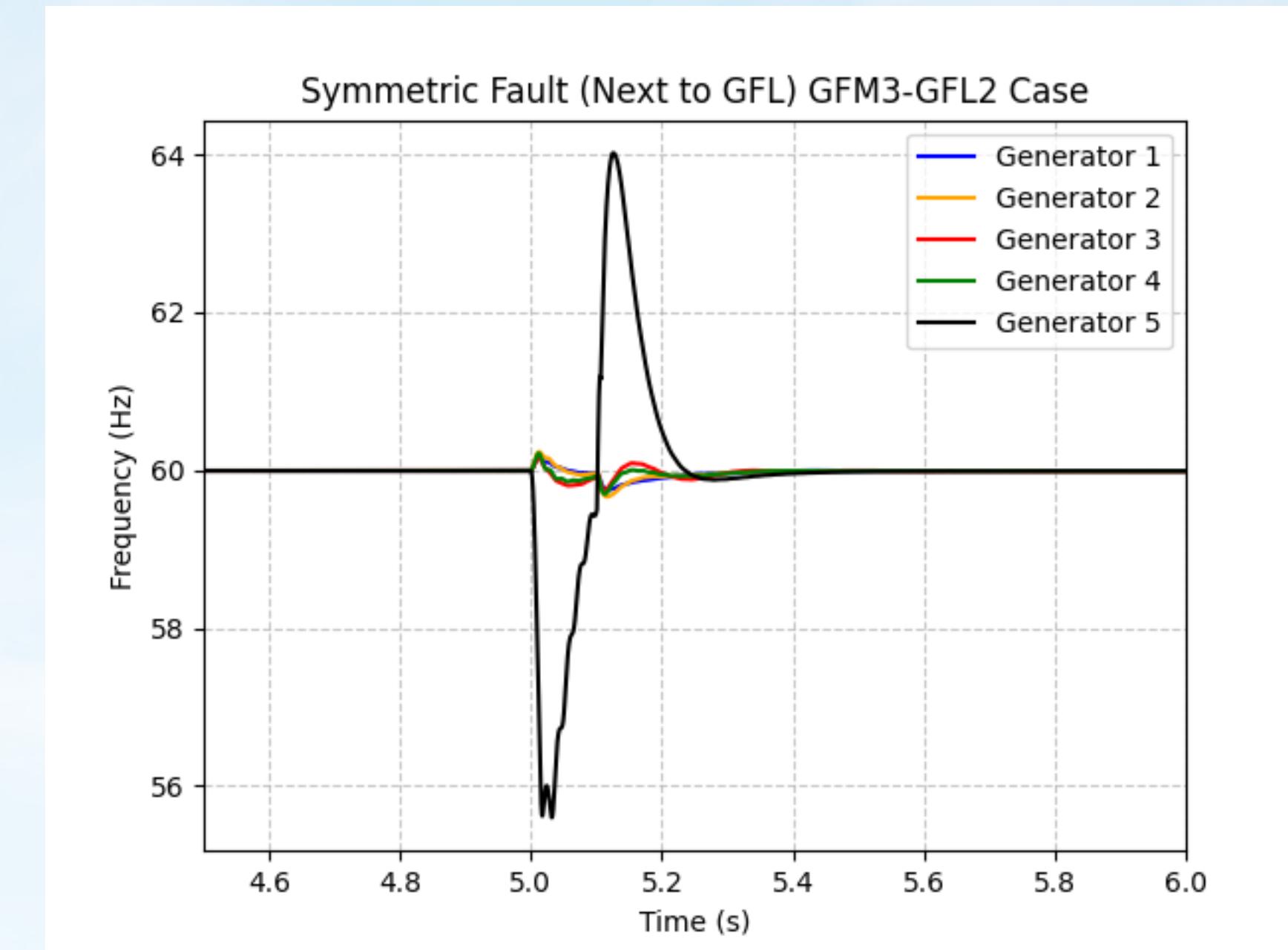
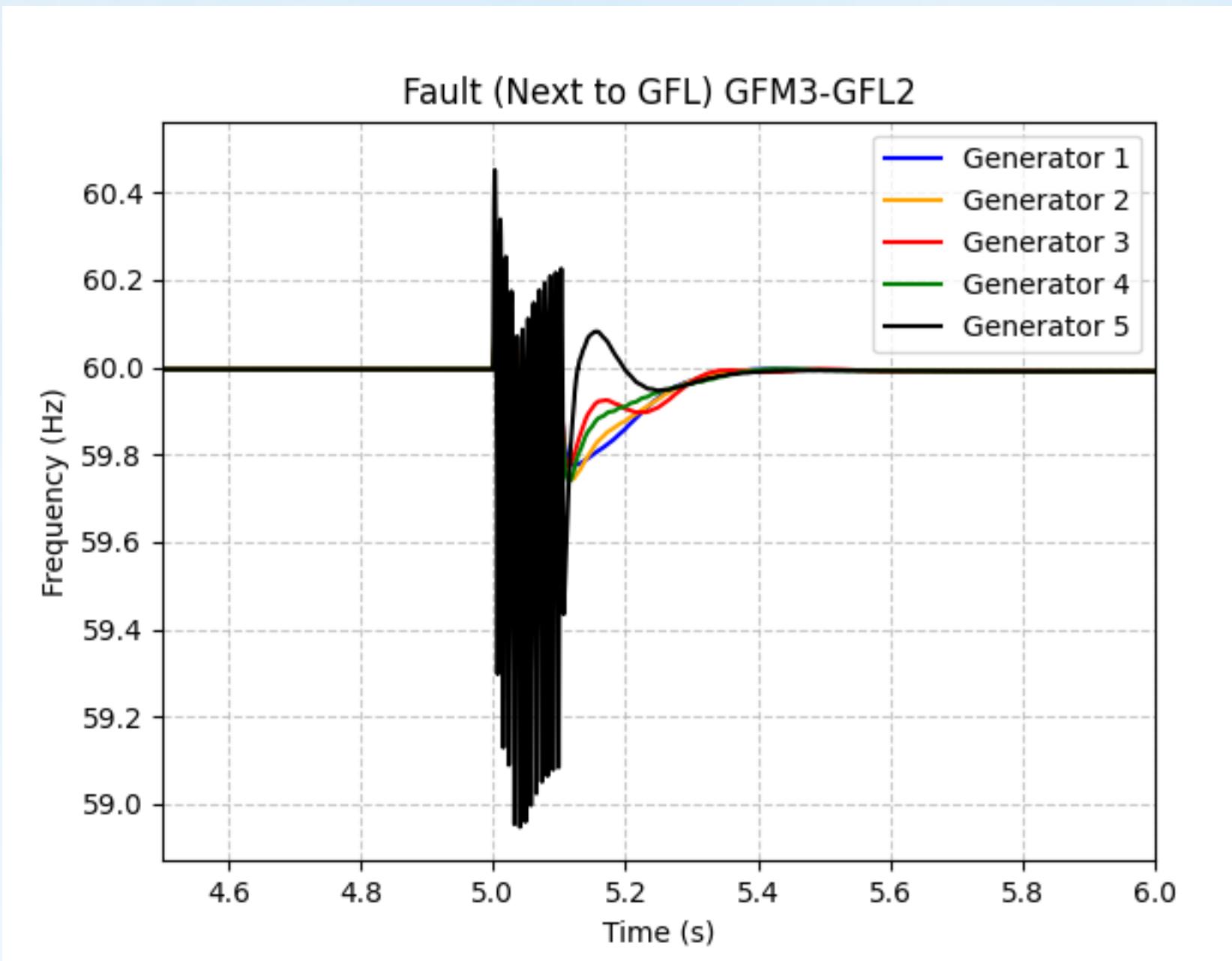
Symmetric to GND Fault



N-GFM2:GFL3

Single Phase to GND Fault

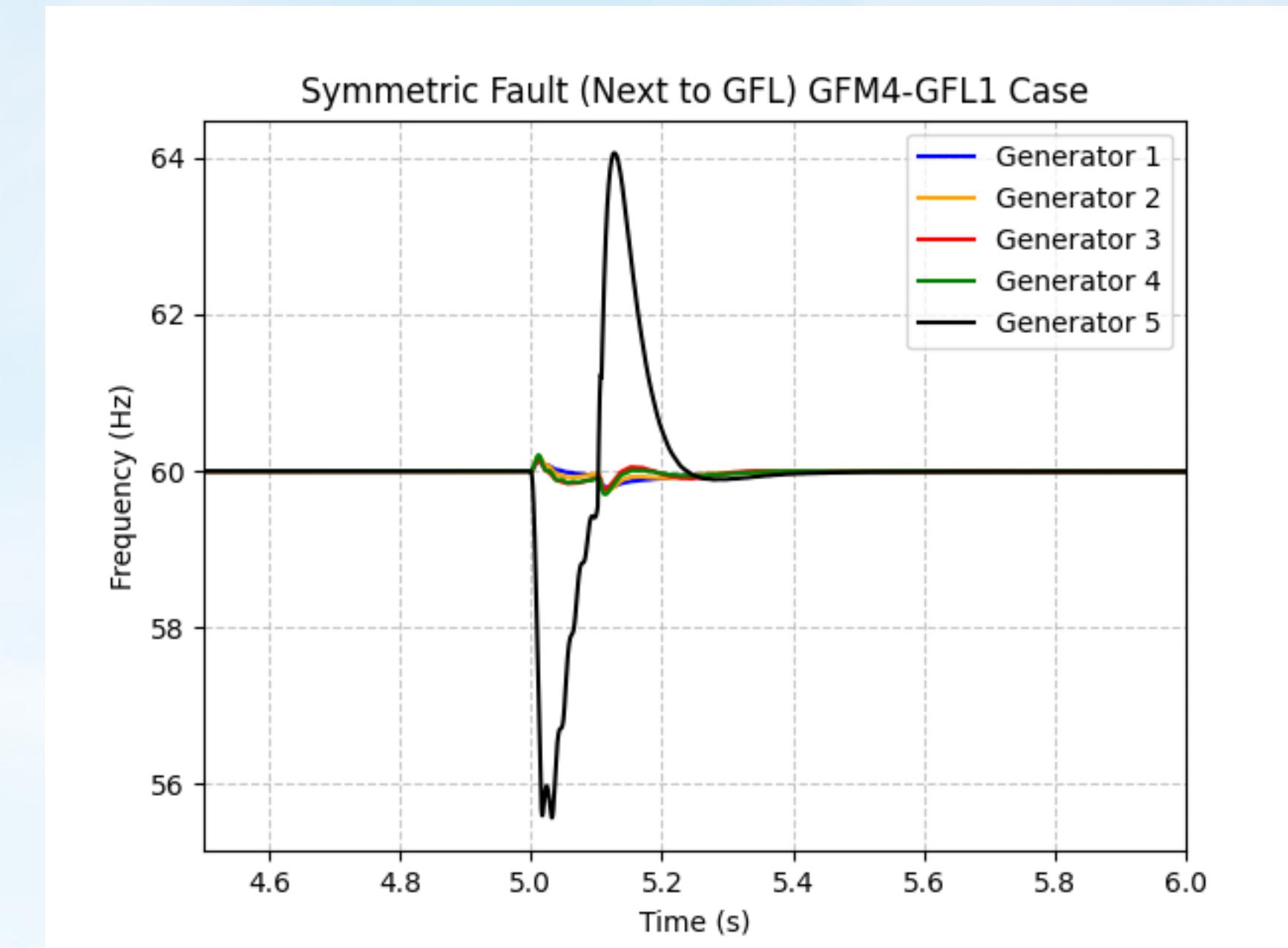
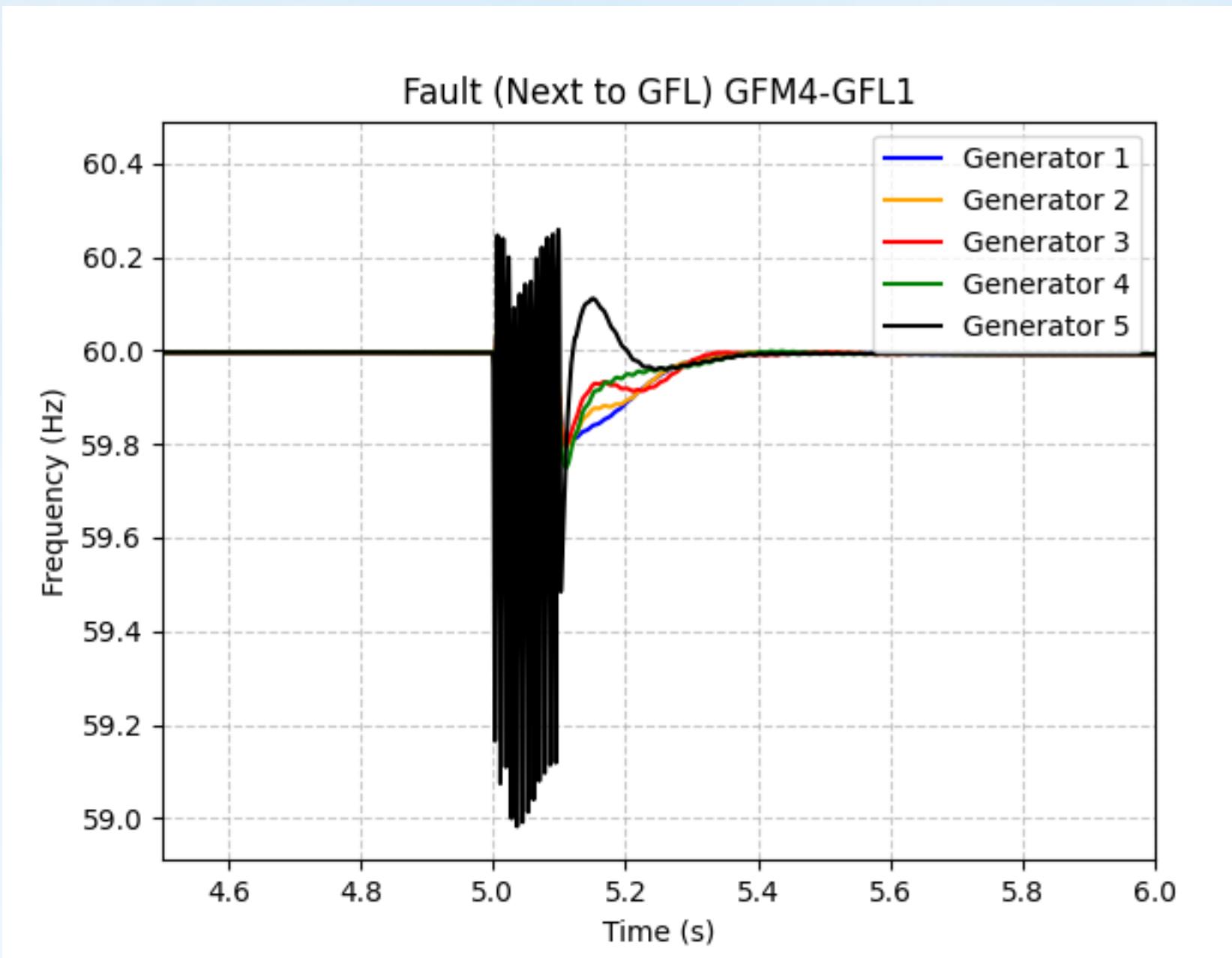
Symmetric to GND Fault



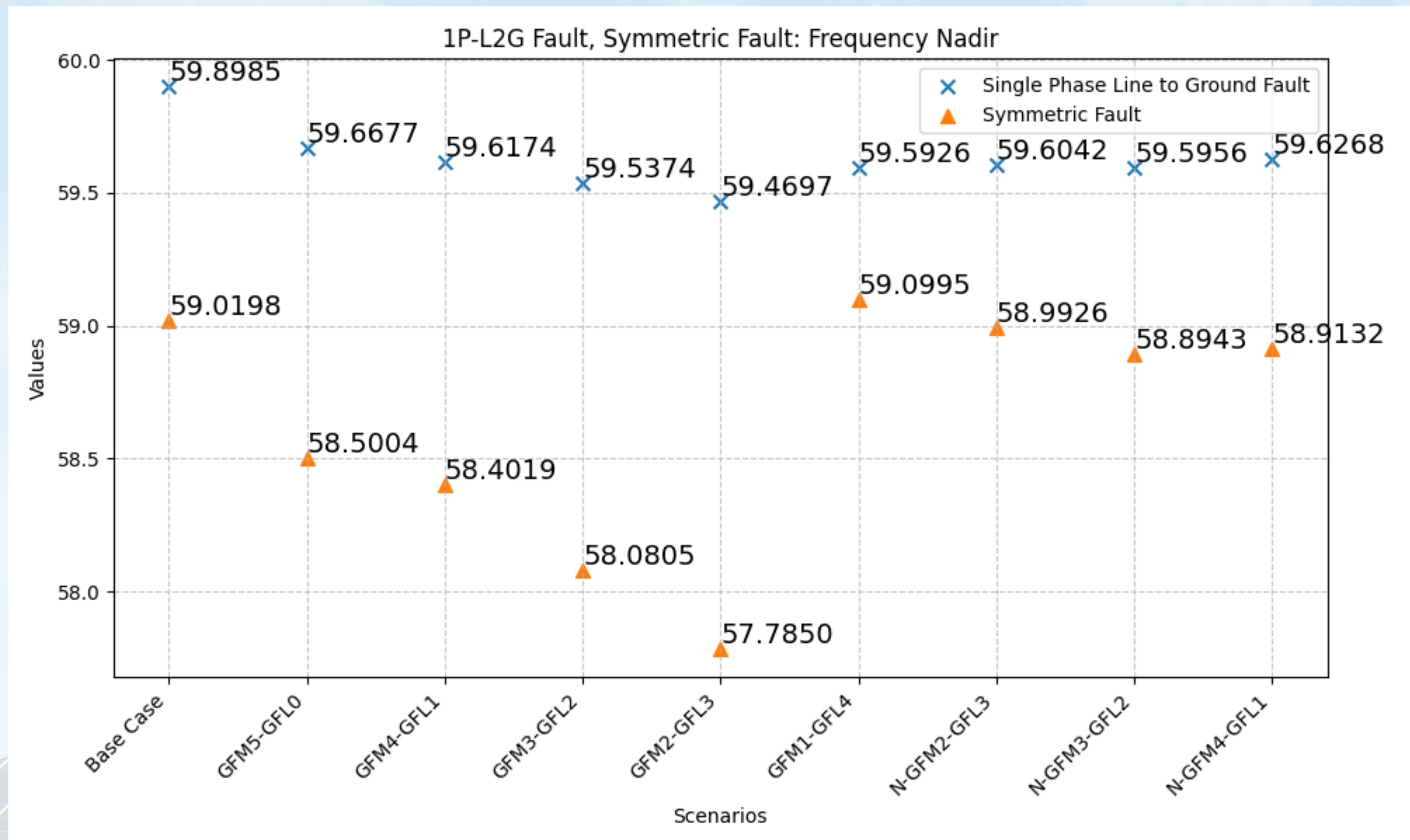
N-GFM3:GFL2

Single Phase to GND Fault

Symmetric to GND Fault

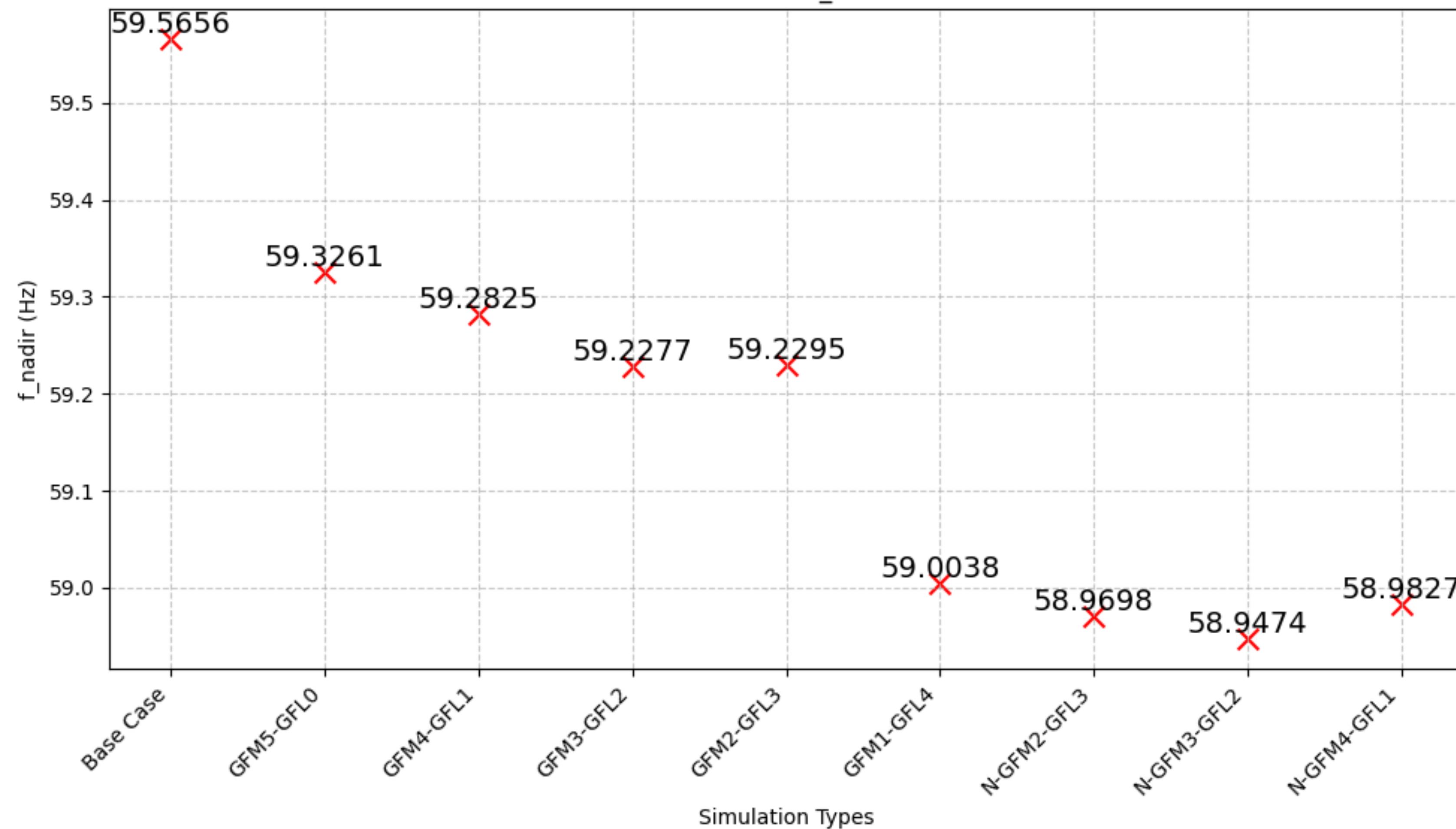


N-GFM4:GFL1

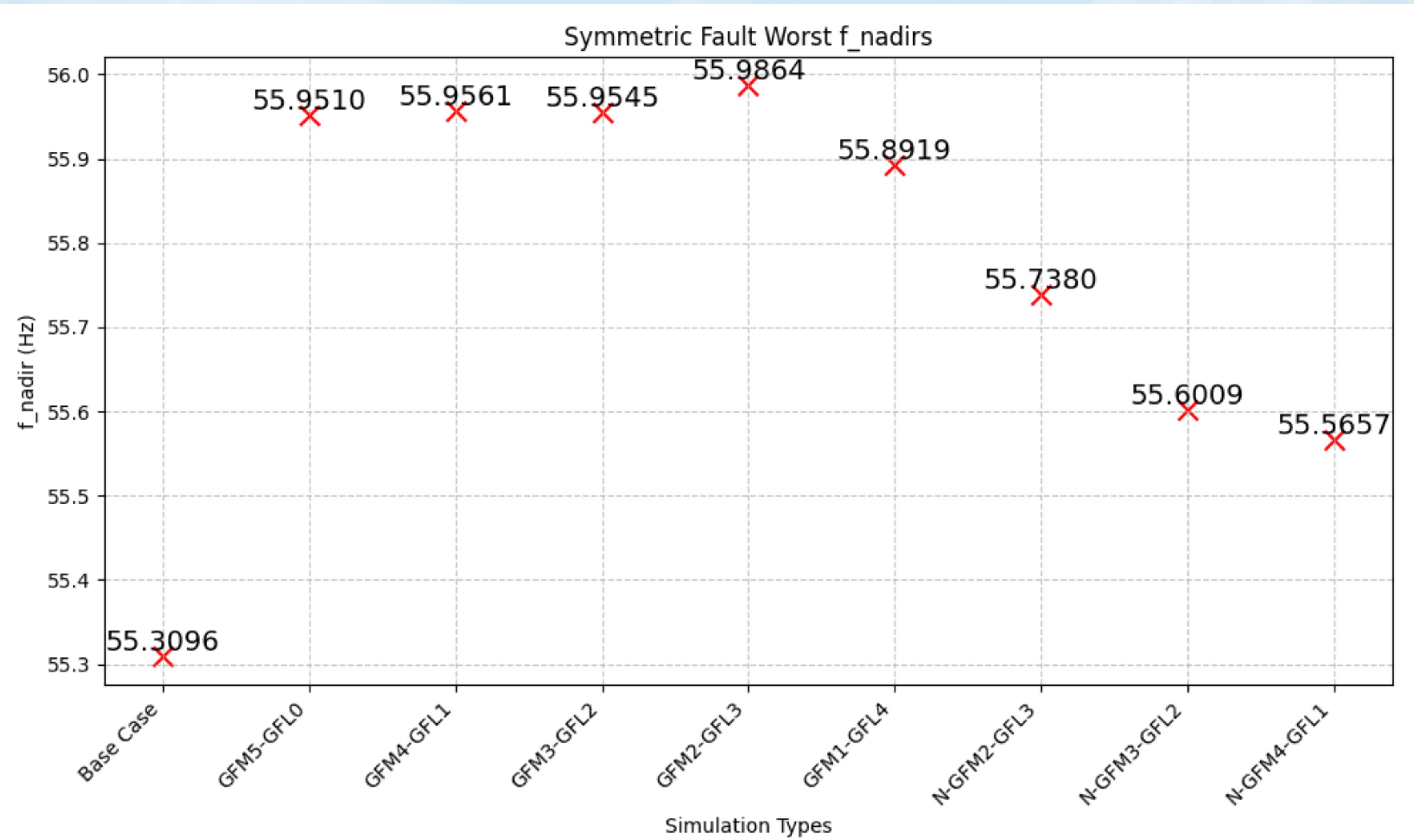


Fault and Symmetric Fault Changes Frequency Nadir

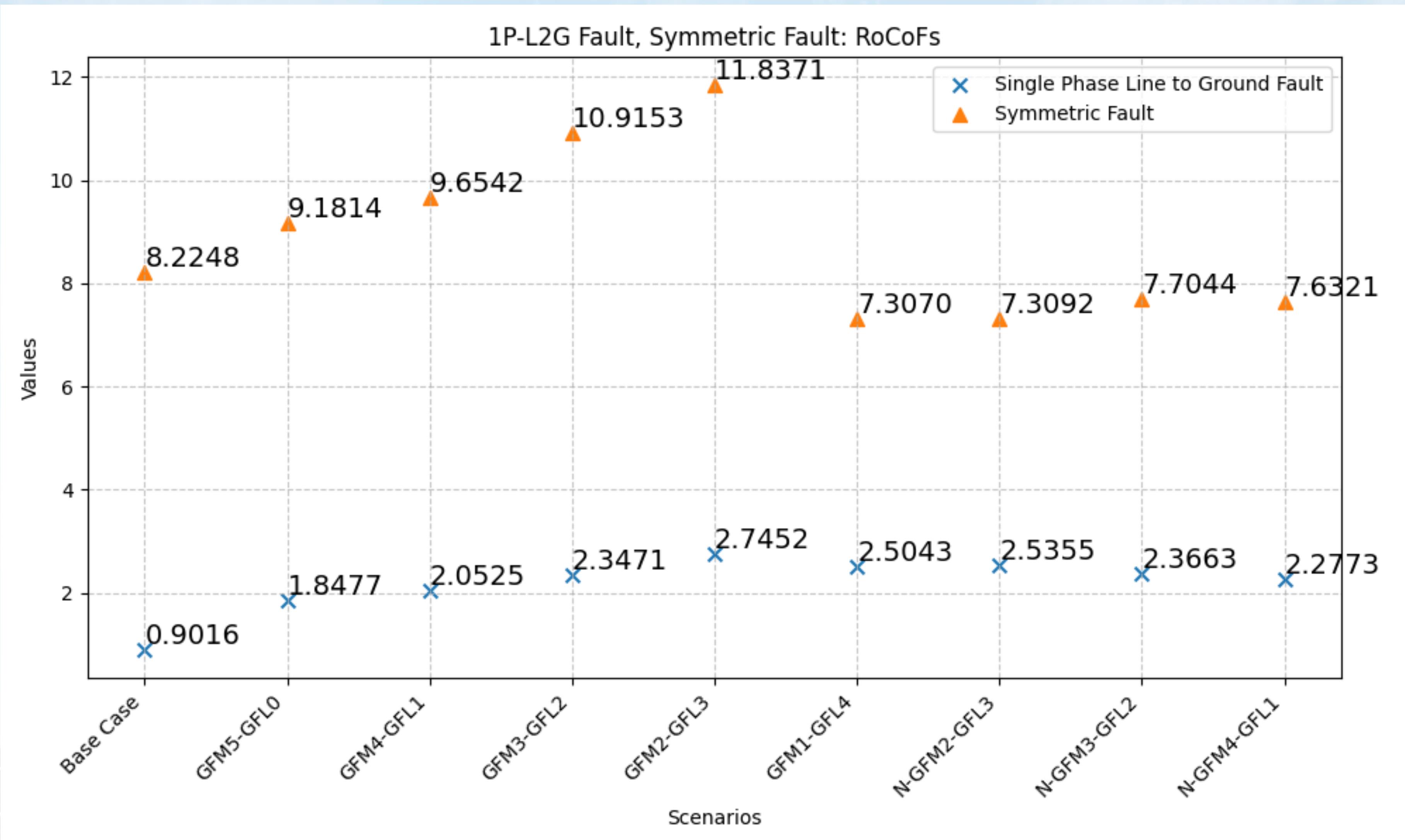
Fault Worst f_nadirs



Fault: Worst Frequency Nadirs

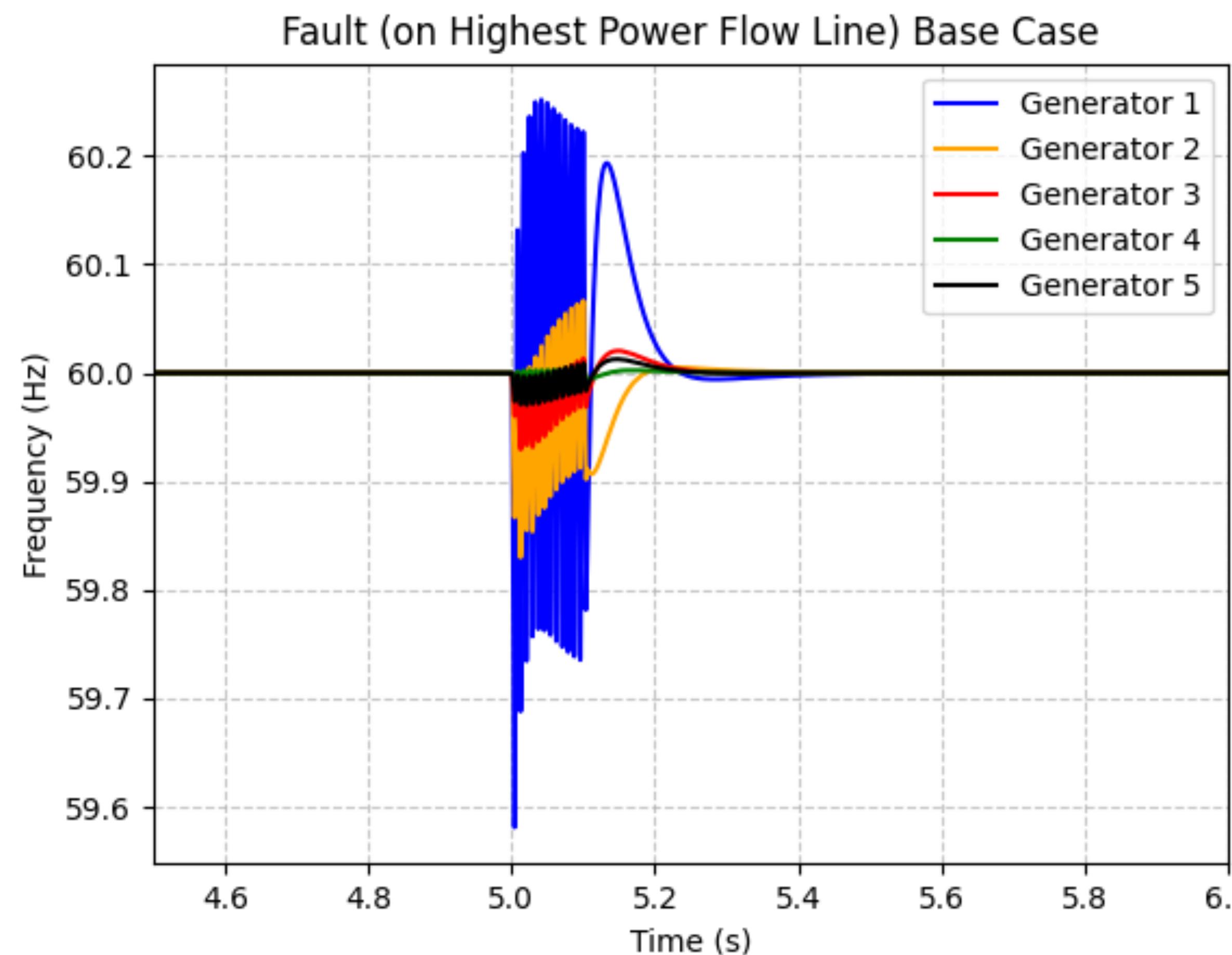


Symmetric Fault: Worst Frequency Nadirs



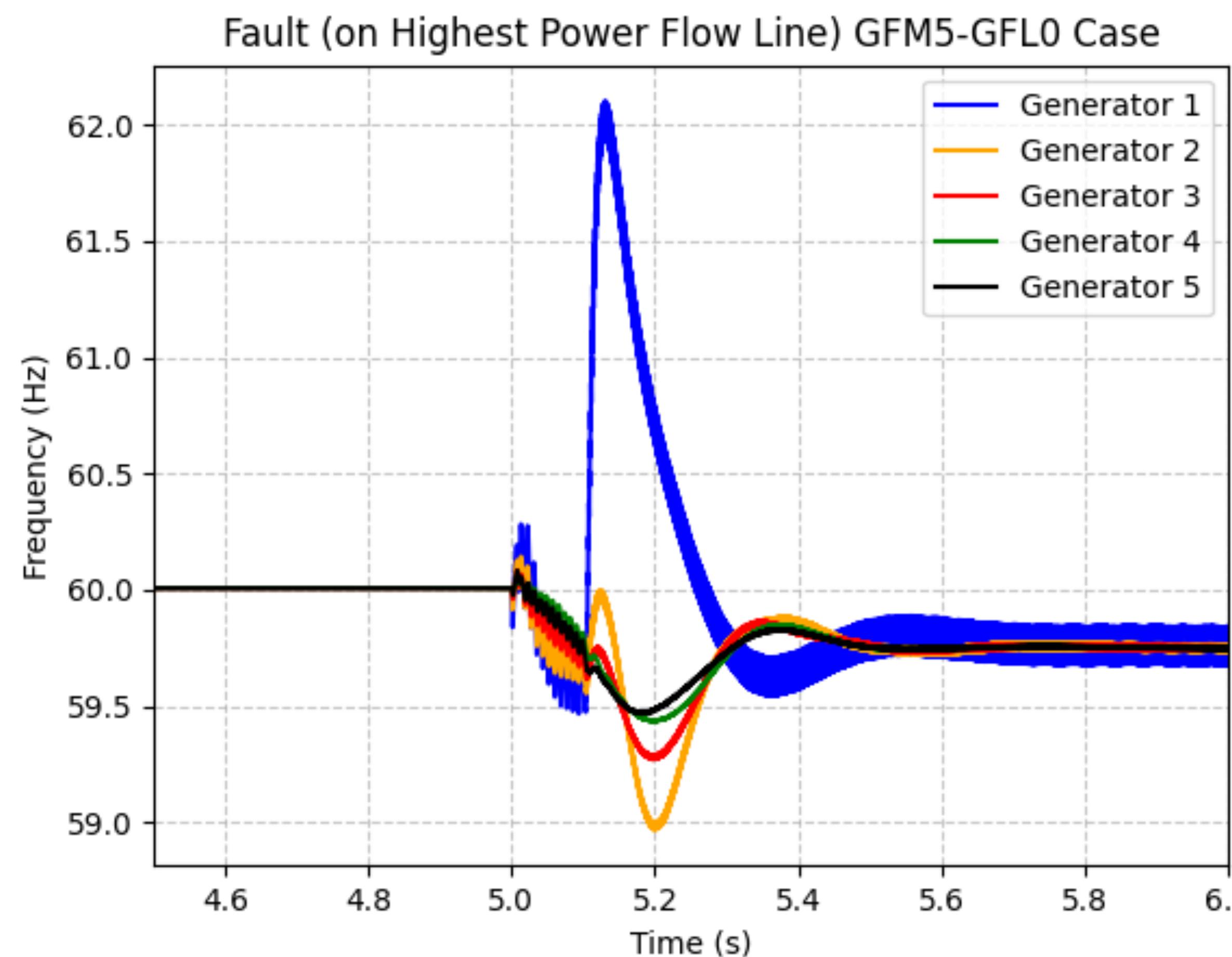
Faults and Symmetric Faults RoCoF

Single Phase to GND Fault on Highest Power Flow Transmission Line



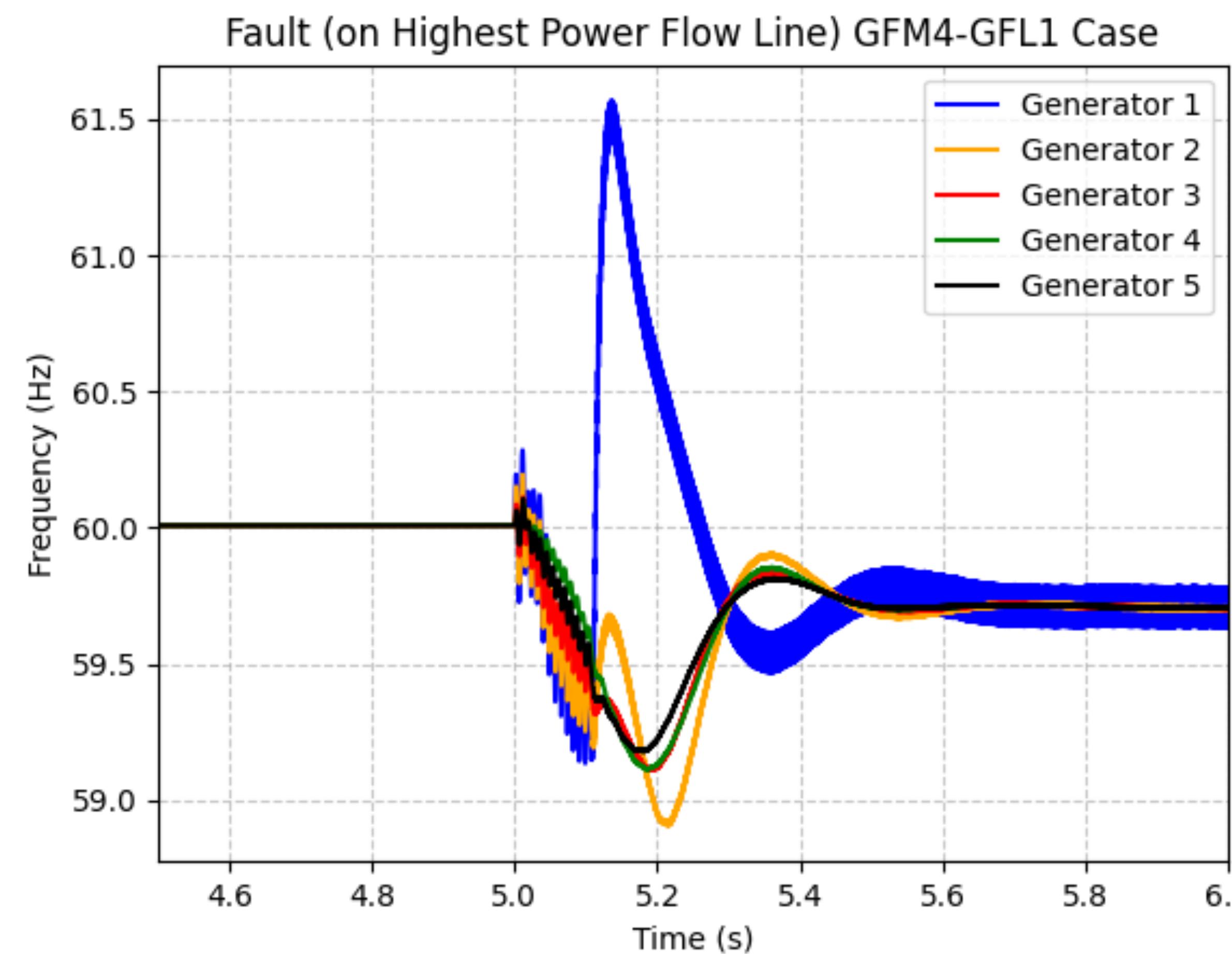
Base Case

Single Phase to GND Fault on Highest Power Flow Transmission Line



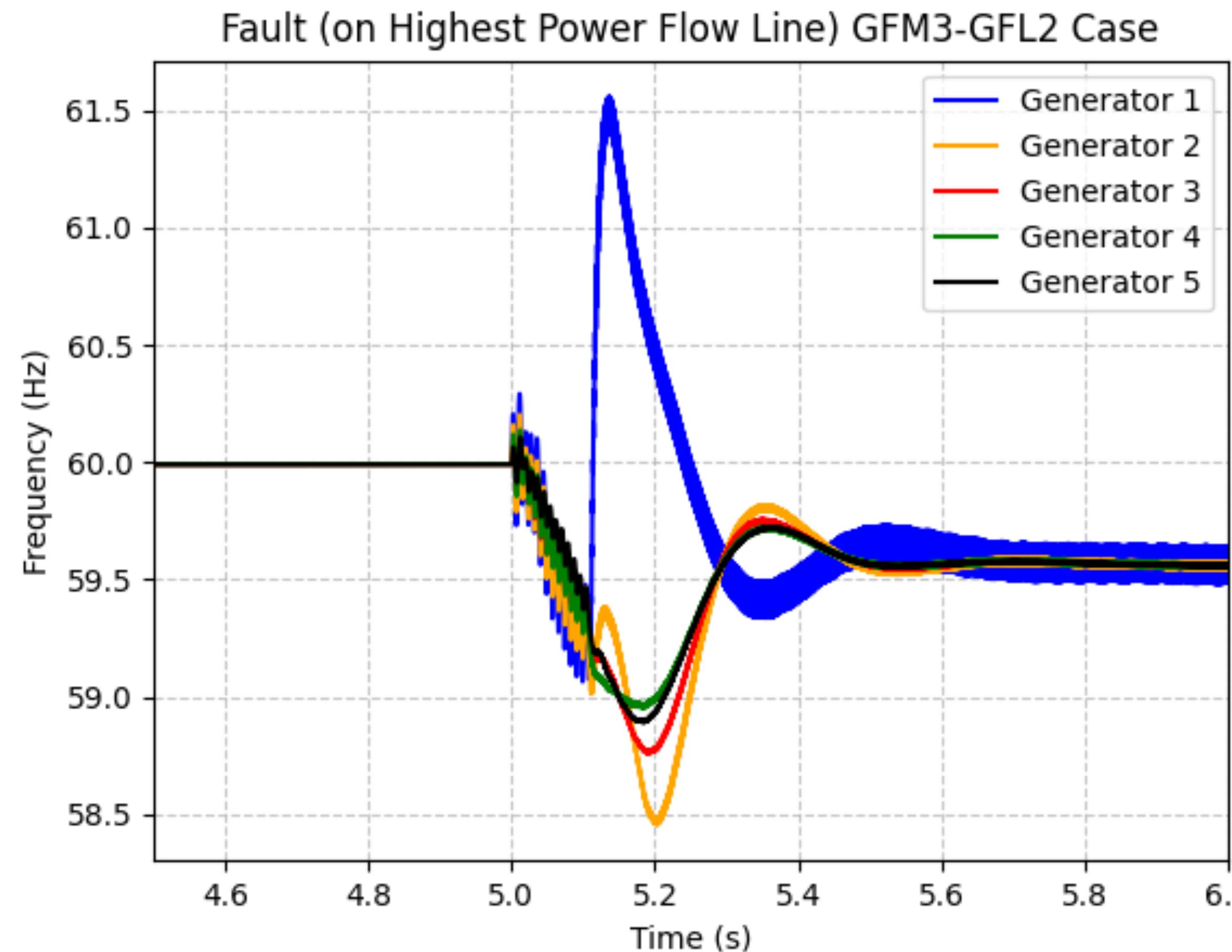
GFM5:GFL0

Single Phase to GND Fault on Highest Power Flow Transmission Line



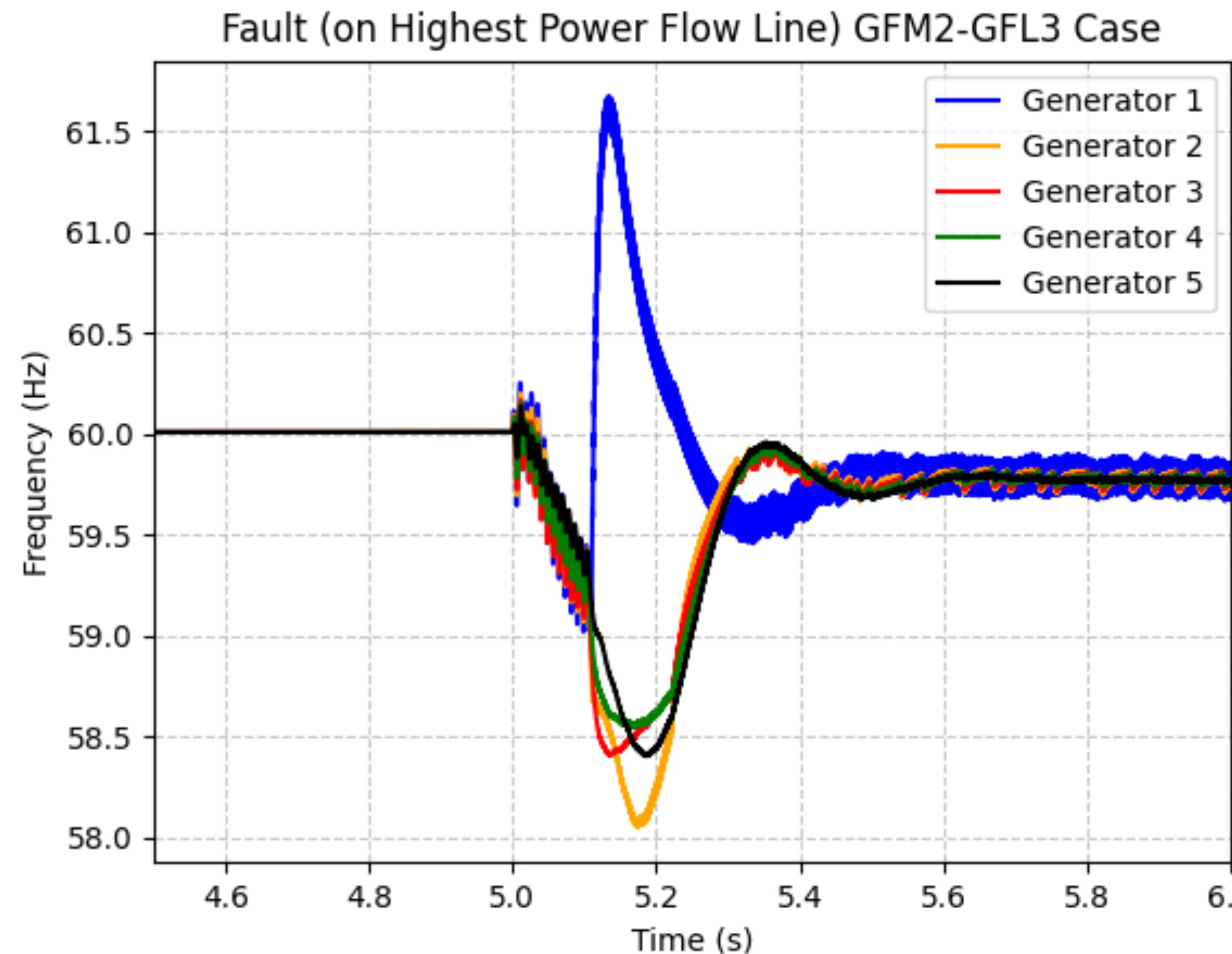
GFM4:GFL1

Single Phase to GND Fault on Highest Power Flow Transmission Line



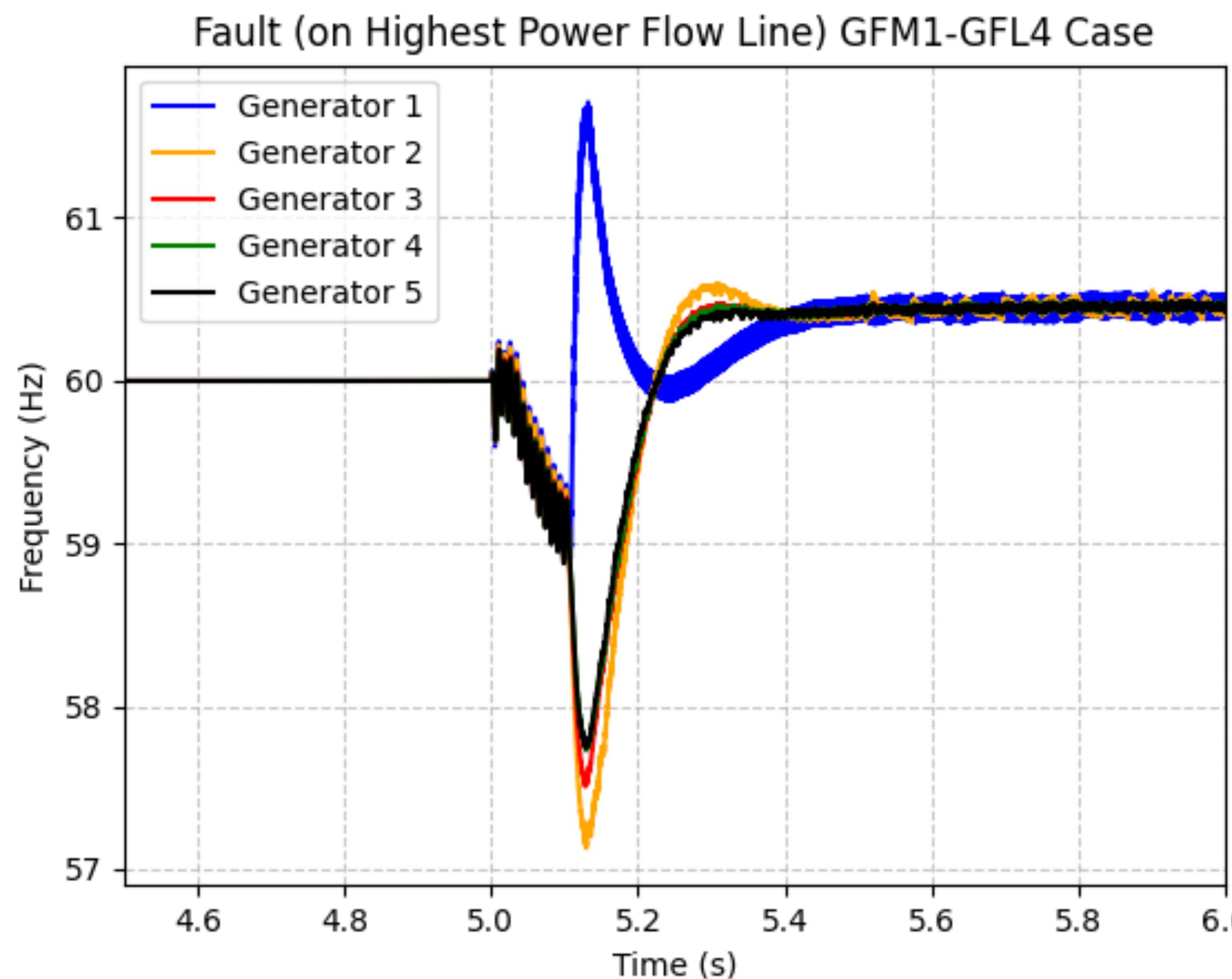
GFM3:GFL2

Single Phase to GND Fault on Highest Power Flow Transmission Line



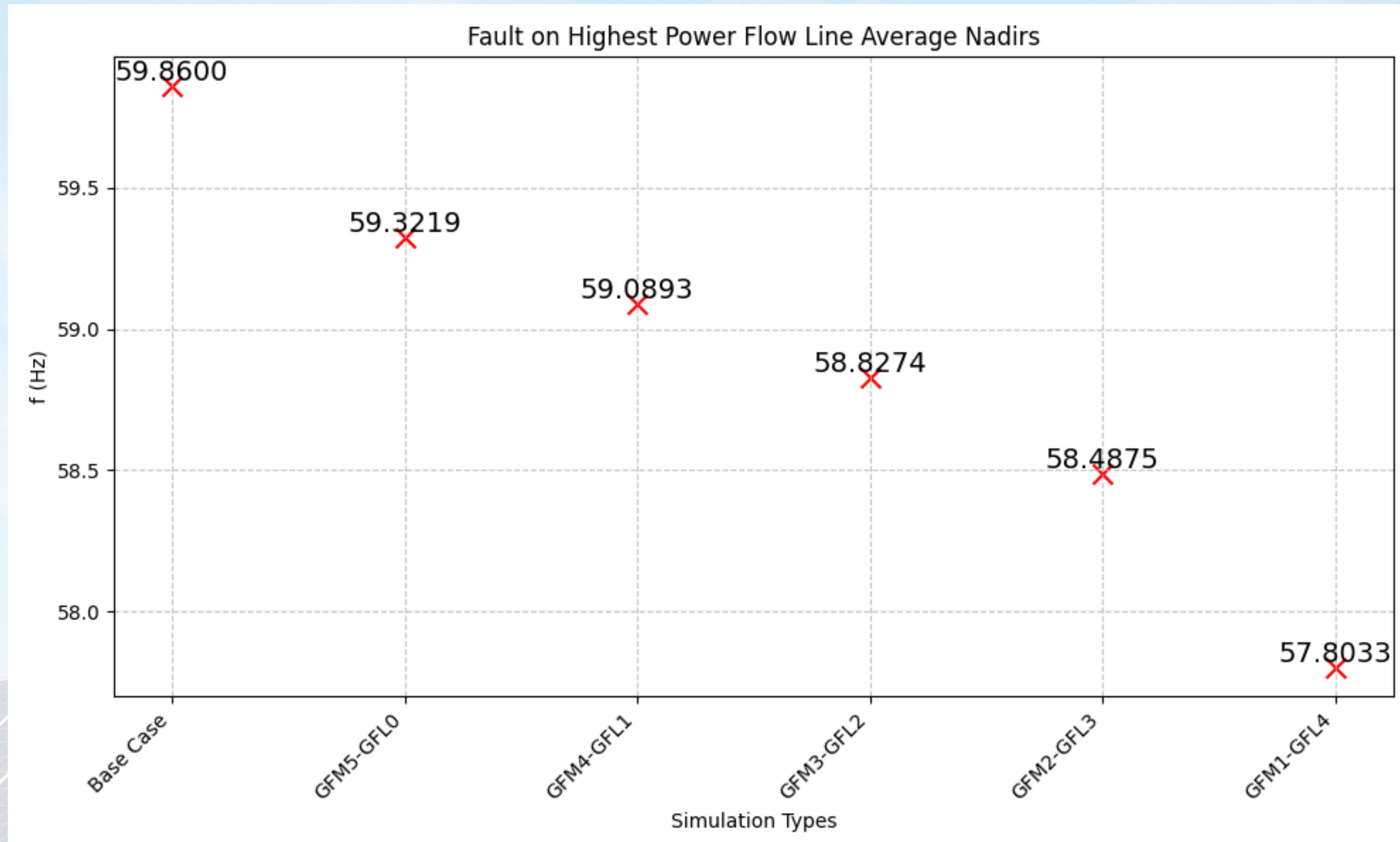
GFM2:GFL3

Single Phase to GND Fault on Highest Power Flow Transmission Line



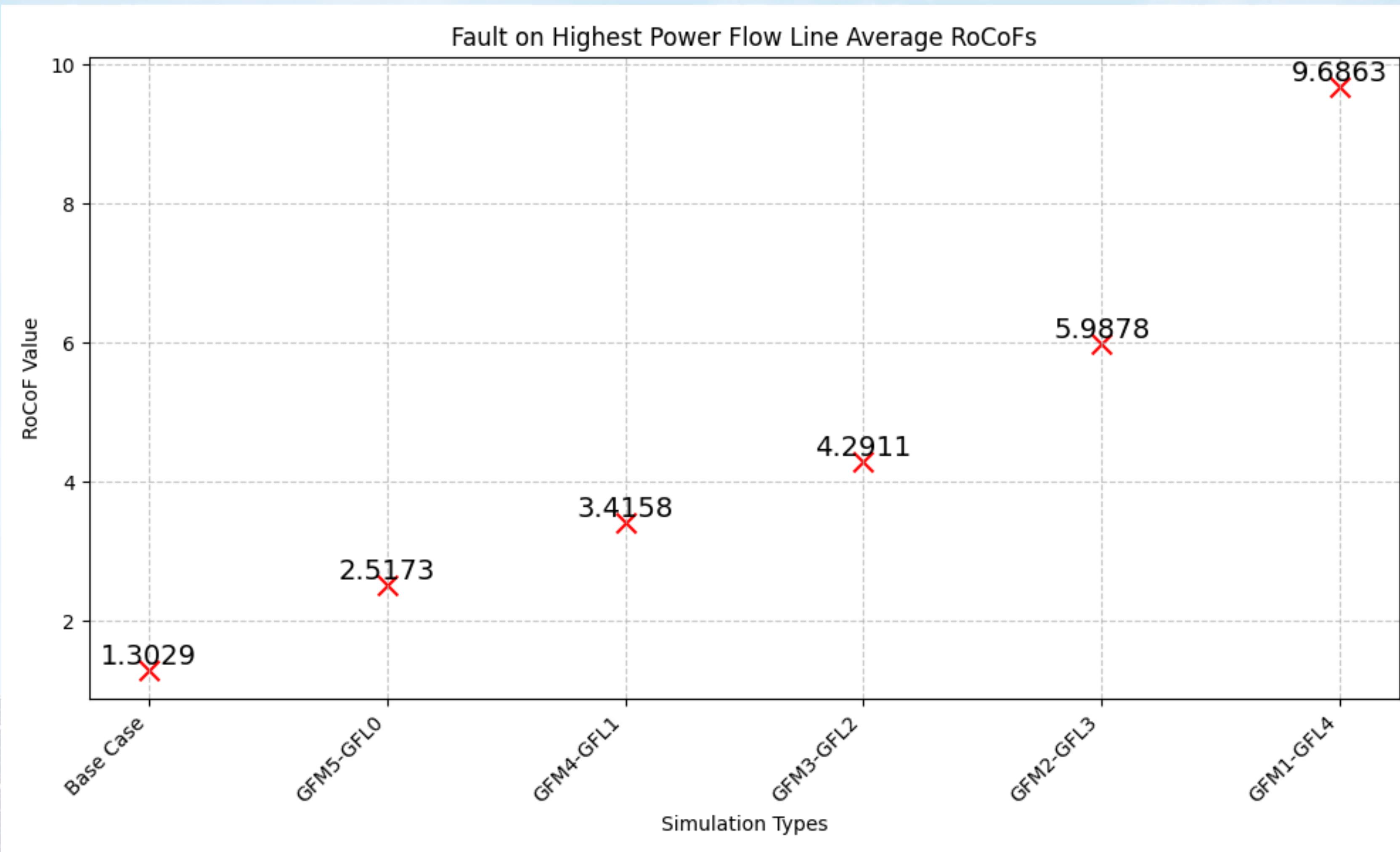
GFM1:GFL4

Single Phase to GND Fault on Highest Power Flow Transmission Line



Fault on Highest Power Flow Average Frequency Nadir

Single Phase to GND Fault on Highest Power Flow Transmission Line



Fault on Highest Power Flow Average RoCoF

Discussion



Frequency Stability for Load Changes

- As expected: more GFMs the better.
 - Less burden on GFMs to do **load sharing**
 - At GFM1:GFL4, only one GFM handles load sharing
- Observation: **avoid below 1:4 ratio**
 - All other cases remain relatively similar frequency response



Frequency Stability for Faults

- Initially: the more GFMs the better
- However:
 - Next to a GFL, **similar to base case**
 - Agrees with duality? Maybe. Needs more study.
 - P and Q set points are too low to conclude duality.
- Overall:
 - **Next to GFL = 4:1 ratio frequency response**
 - Also true for highest power flow transmission line fault.

Conclusion



Conclusions

- More GFM indeed the better.
- If a number is required:
 - **4:1 Ratio for consistent frequency response**
- Implication:
 - Started with GFLs, no need to remove all
 - Just keep 4:1 ratio and all will be fine.

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