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

Capstone Research Project

Joshua | December 2023

Table of Contents

Introduction

Introduction

- More renewables into the grid (IBRs)
  - Grid becomes weak due to lack of inertia, which keeps frequency stable
  - SGs: provide inertia using rotating masses, IBRs do not have rotating masses
- 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
  - *Voltage source*
- 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

Callum Henderson[1], Agusti Egea-Alvarez[1], Thyge Kneuppel[2], Guangya Yang[3], Lie Xu[1]
1 EEE. Dept, PEDEC Group, University of Strathclyde
2 Siemens Gamesa Renewable Energy
3 DTU Wind, PWR Group, Technical University of Denmark
callum.henderson.100@strath.ac.uk

"this metric is **outdated**"

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

Weijie Qiu
Anshun Power Supply Bureau
Guizhou Power Grid Co., LTD
Anshun, China
qiuwj@gzas.csg.cn

Qiang Yang
Anshun Power Supply Bureau
Guizhou Power Grid Co., LTD
Anshun, China
yangq@gzas.csg.cn

Tingbang Yang
Anshun Power Supply Bureau
Guizhou Power Grid Co., LTD
Anshun, China
yangtb@gzas.csg.cn

Xin Ma
Anshun Power Supply Bureau
Guizhou Power Grid Co., LTD
Anshun, China
max@gzas.csg.cn

Xiaobing Xiao
Guizhou Electric Power Research Institute
Guizhou Power Grid Co., LTD
Anshun, China
xiaoxb@gz.csg.cn

Hujun Shi
Anshun Power Supply Bureau
Guizhou Power Grid Co., LTD
Anshun, China
shihj@gzas.csg.cn

Yuanliang Zhao
Anshun Power Supply Bureau
Guizhou Power Grid Co., LTD
Anshun, China
zhaoyl@gz.csg.cn

Shuai Liang*
School of Electrical Engineering and Automation
Wuhan University
Wuhan, China
liangshuai93@163.com

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 in high penetration grids?

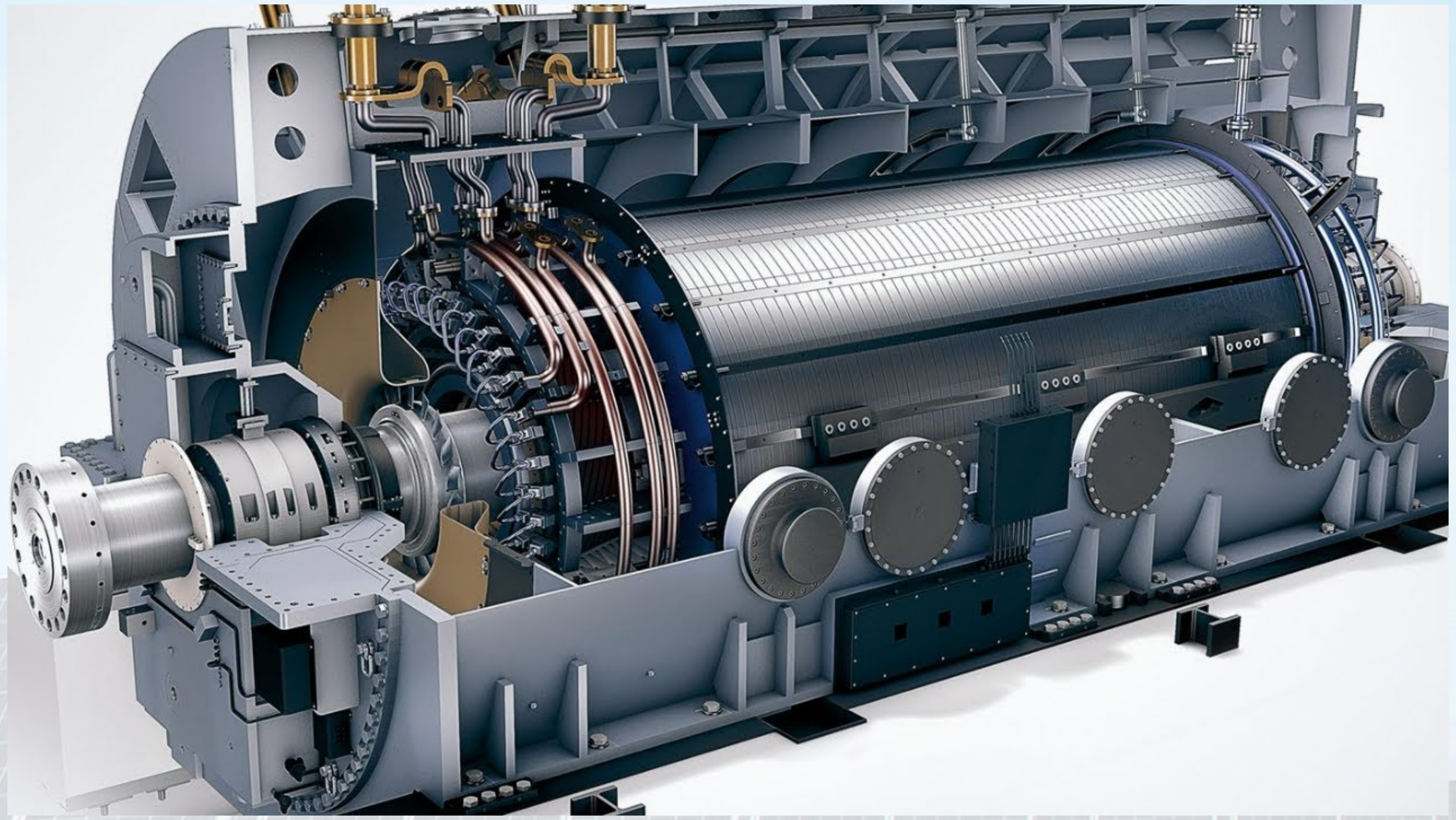
Background Study

1. Grid Frequency and Inertia

- Analogy: a bicycle running…

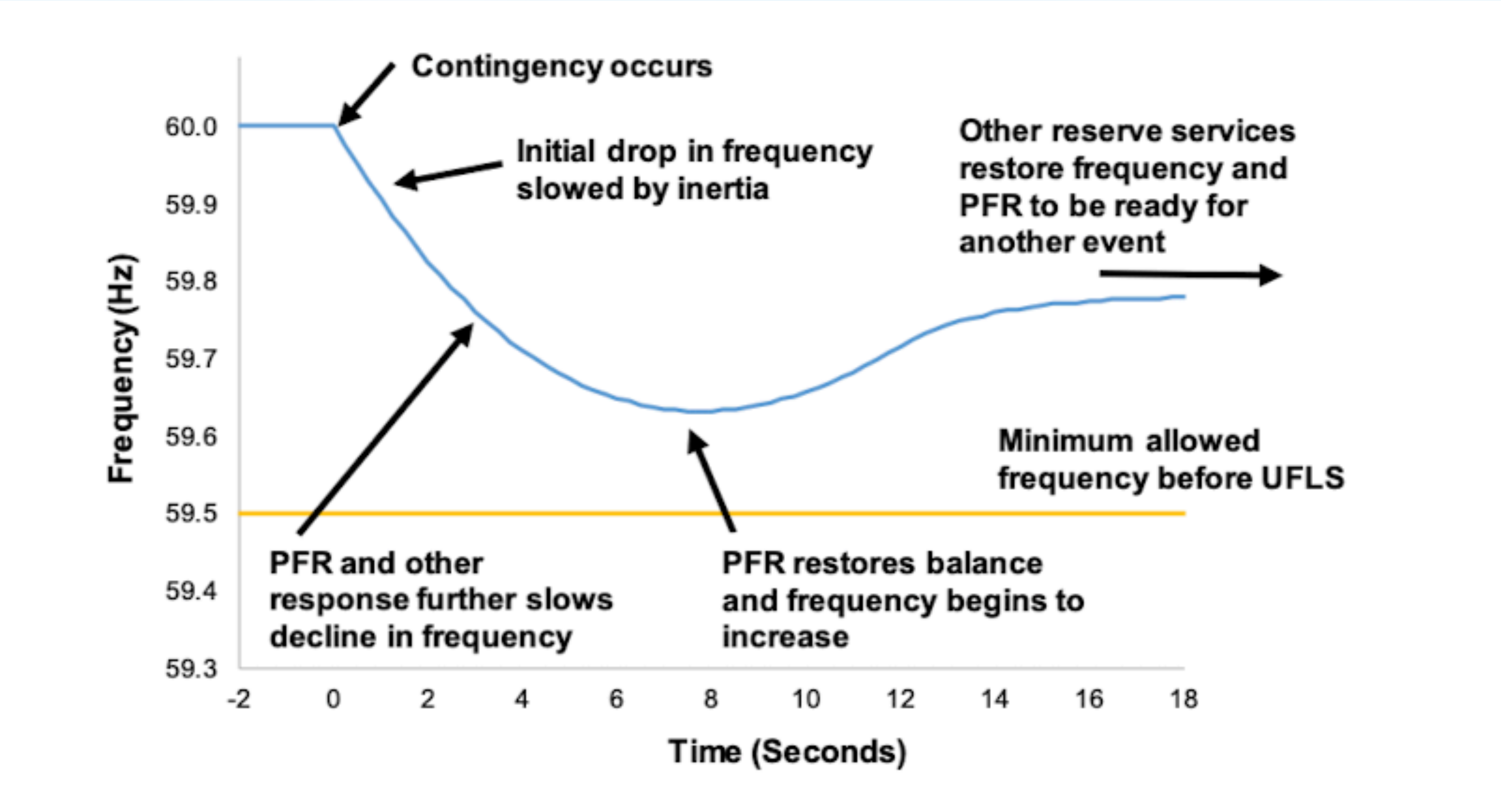
1. Grid Frequency and Inertia

- 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

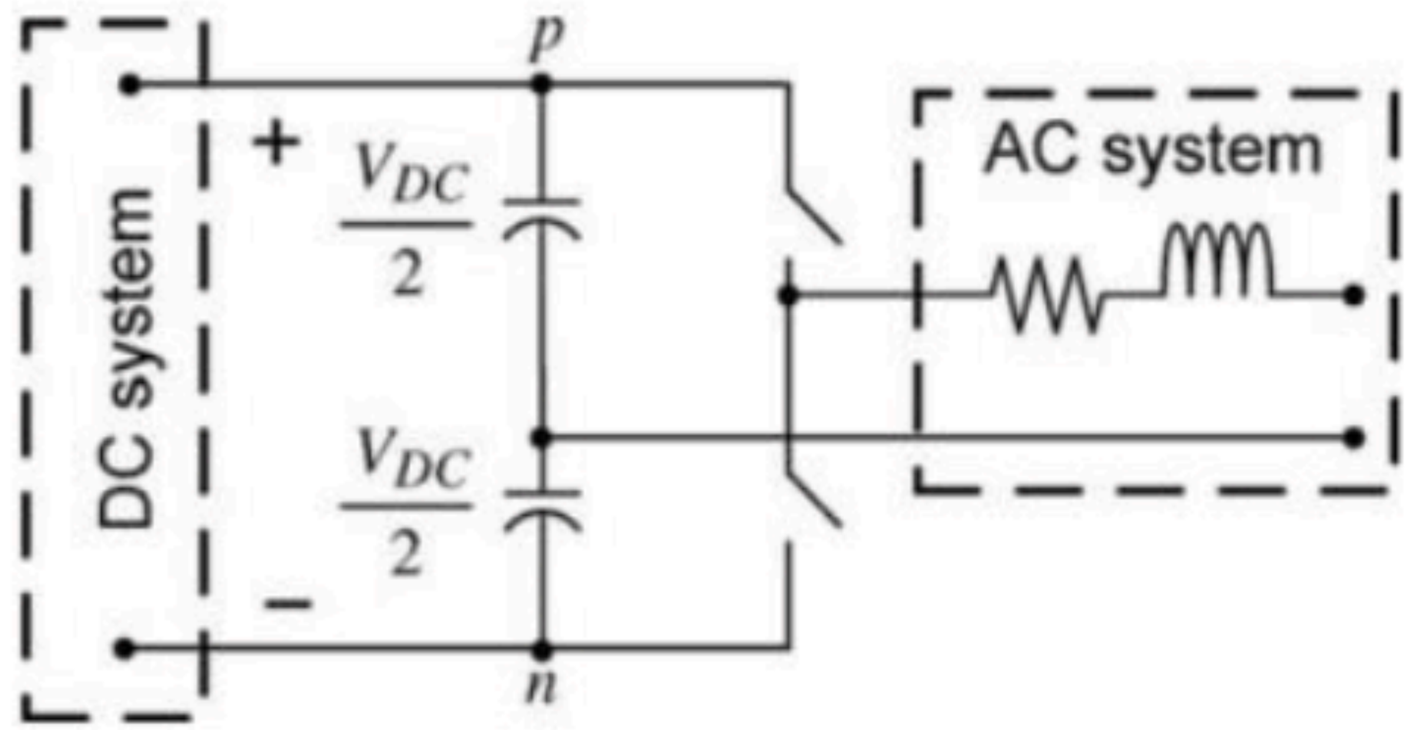


Figure 1: Single Phase Half-Bridge Converter [7]

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

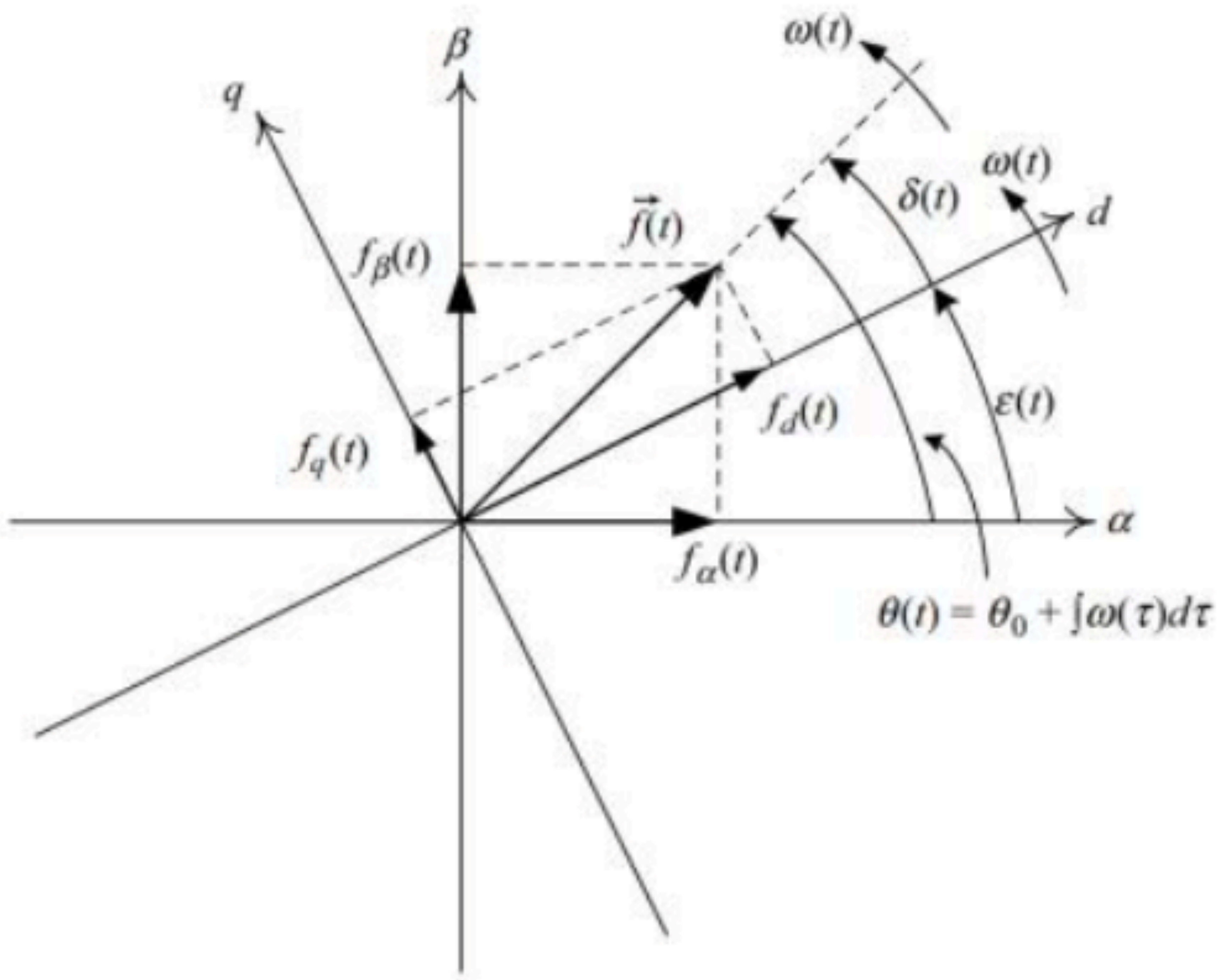


Figure 2: Difference Between $\alpha\beta$- and dq- frames

2. Voltage Sourced Converters

- PLL used to *follow* the frequency

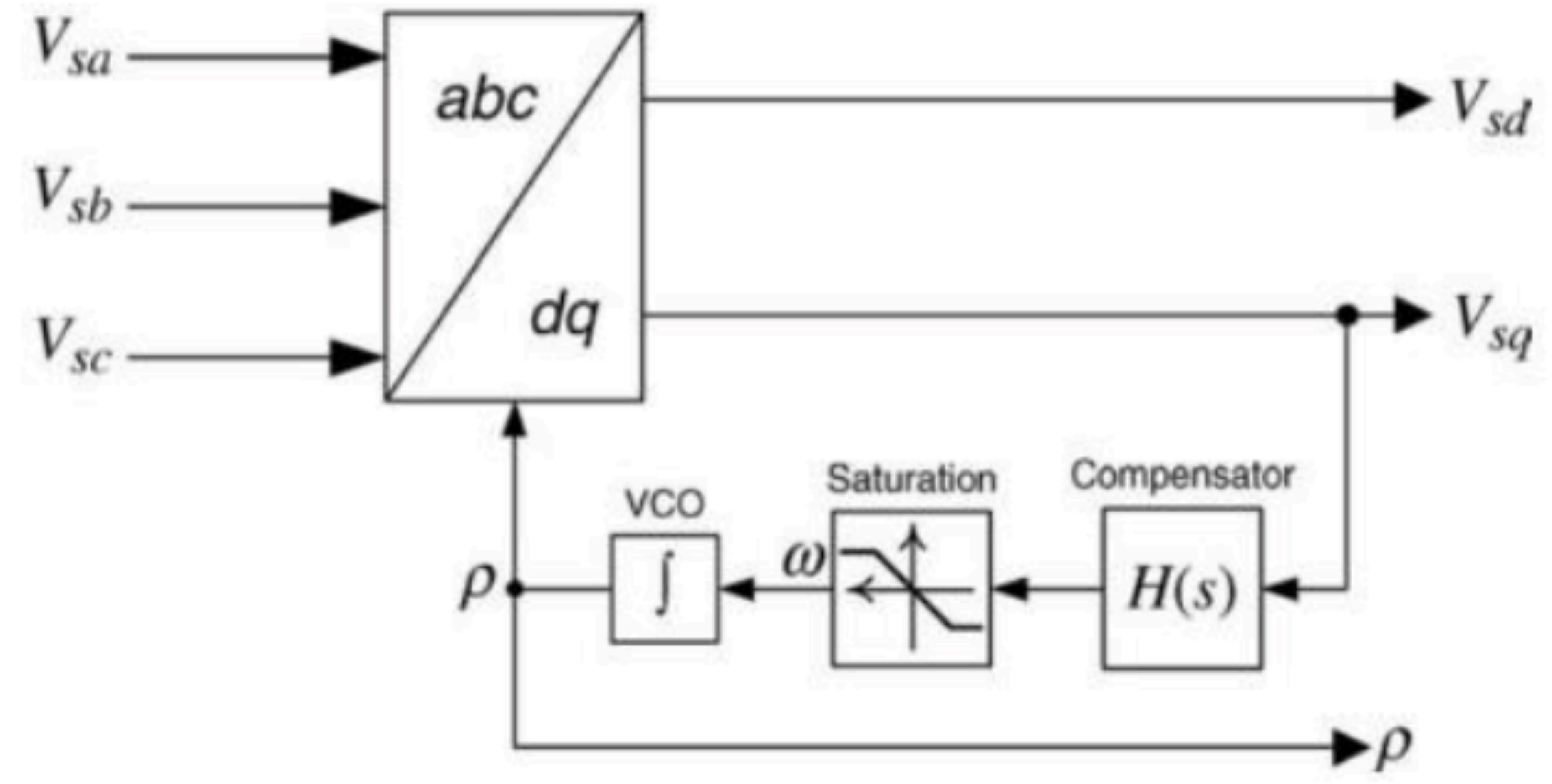


Figure 3: PLL connected to its Park Transformer

3. Grid Following Inverters (GFL)

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

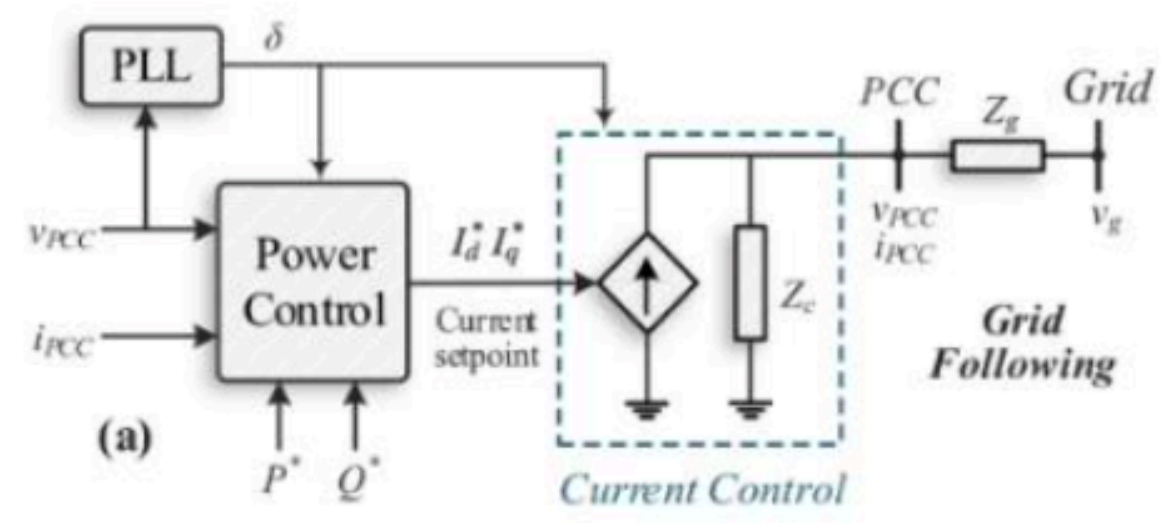


Figure 4: GFL modelled as Current Source [2]

3. Grid Following Inverters (GFL)

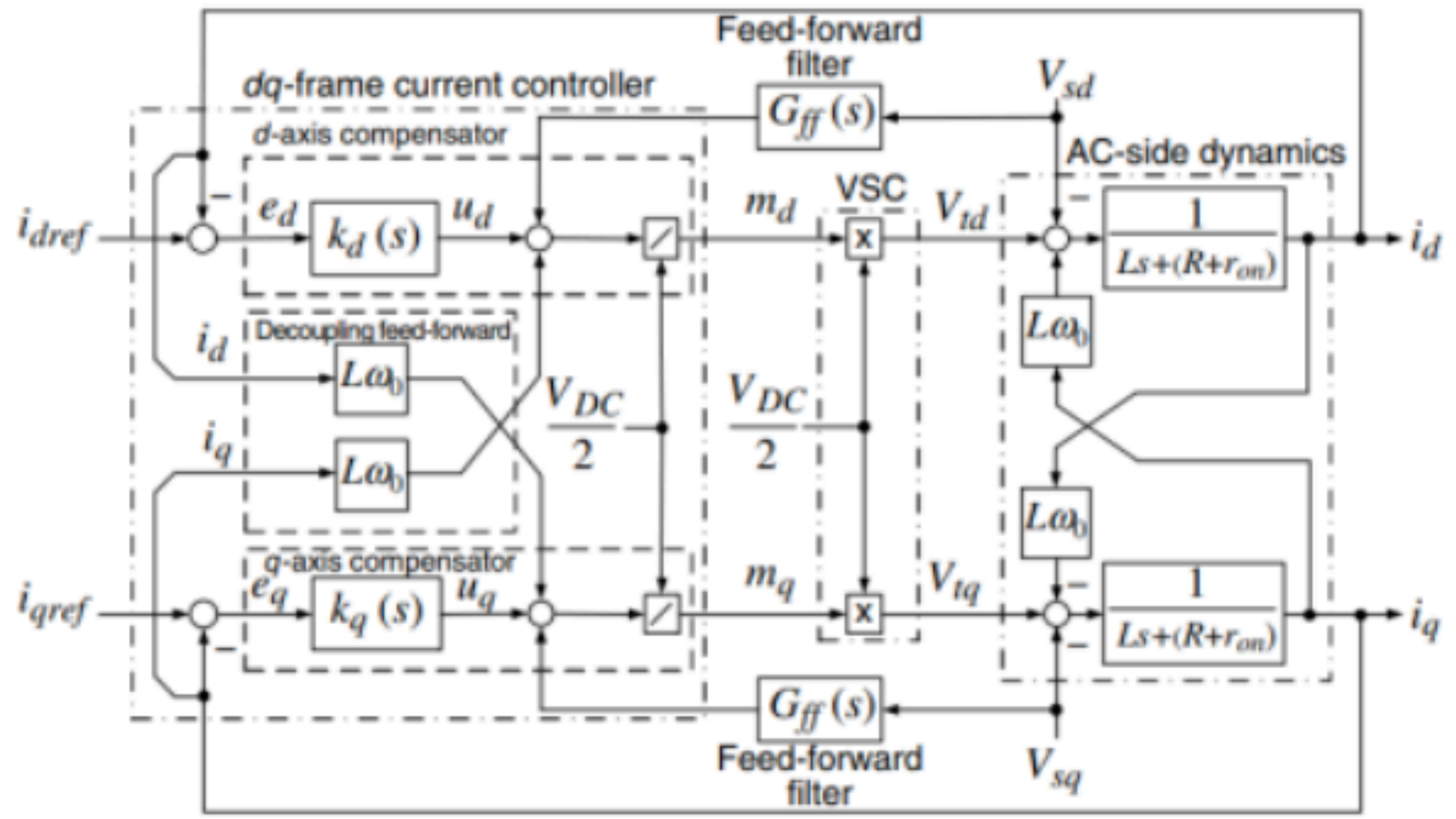


Figure 5: GFL control block: a current controller

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*

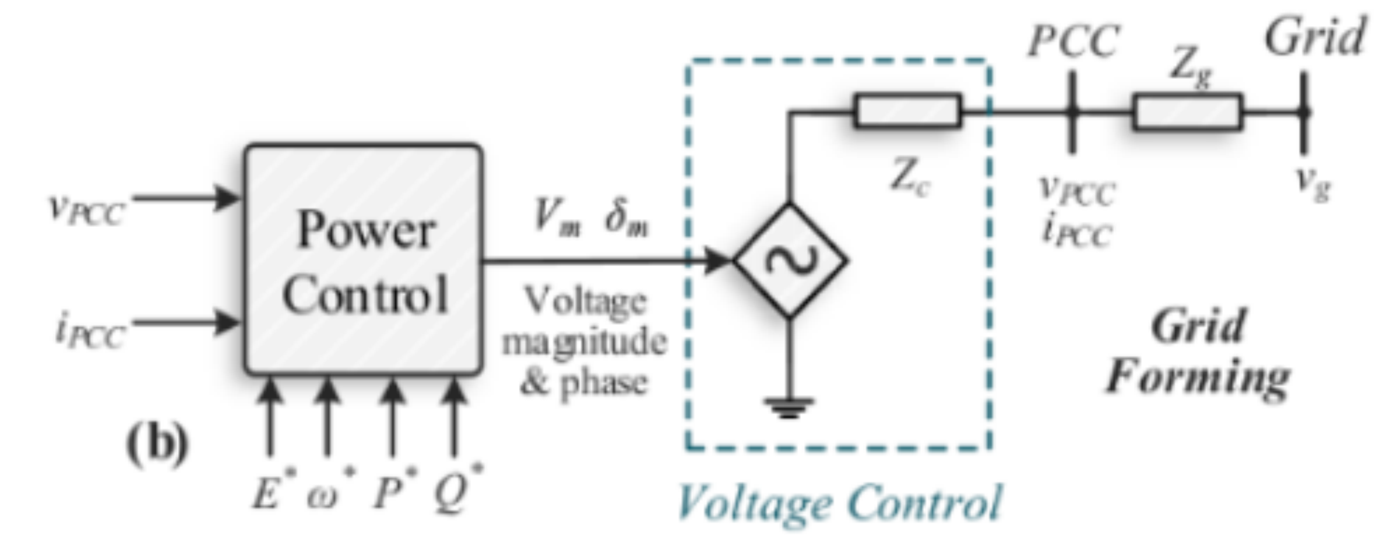


Figure 6: GFM modelled as Voltage Source [2]

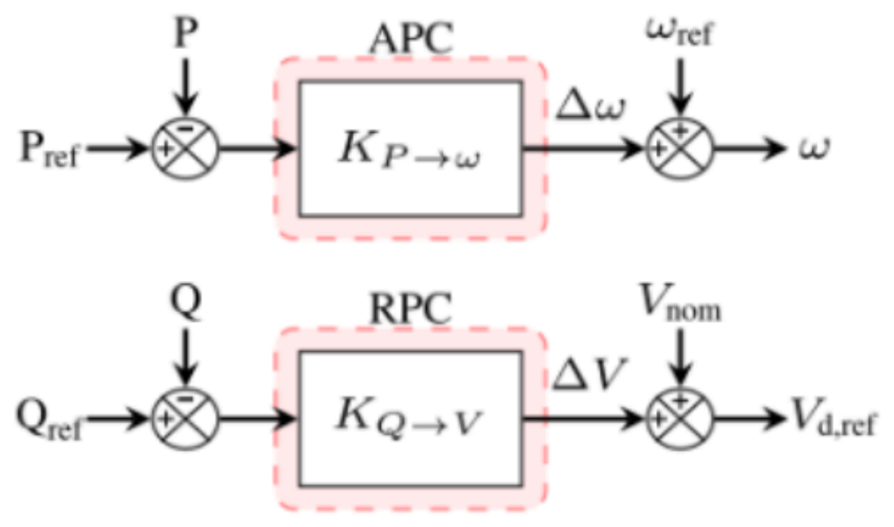


Figure 9: Frequency Droop Control Diagram [2]

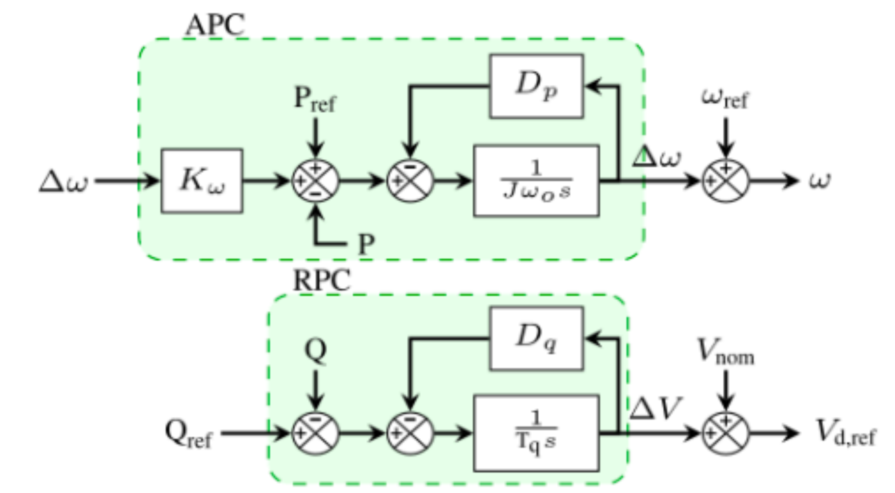


Figure 10: Swing Equation Emulation Control Diagram [2]

4. Grid Forming Inverters (GFM)

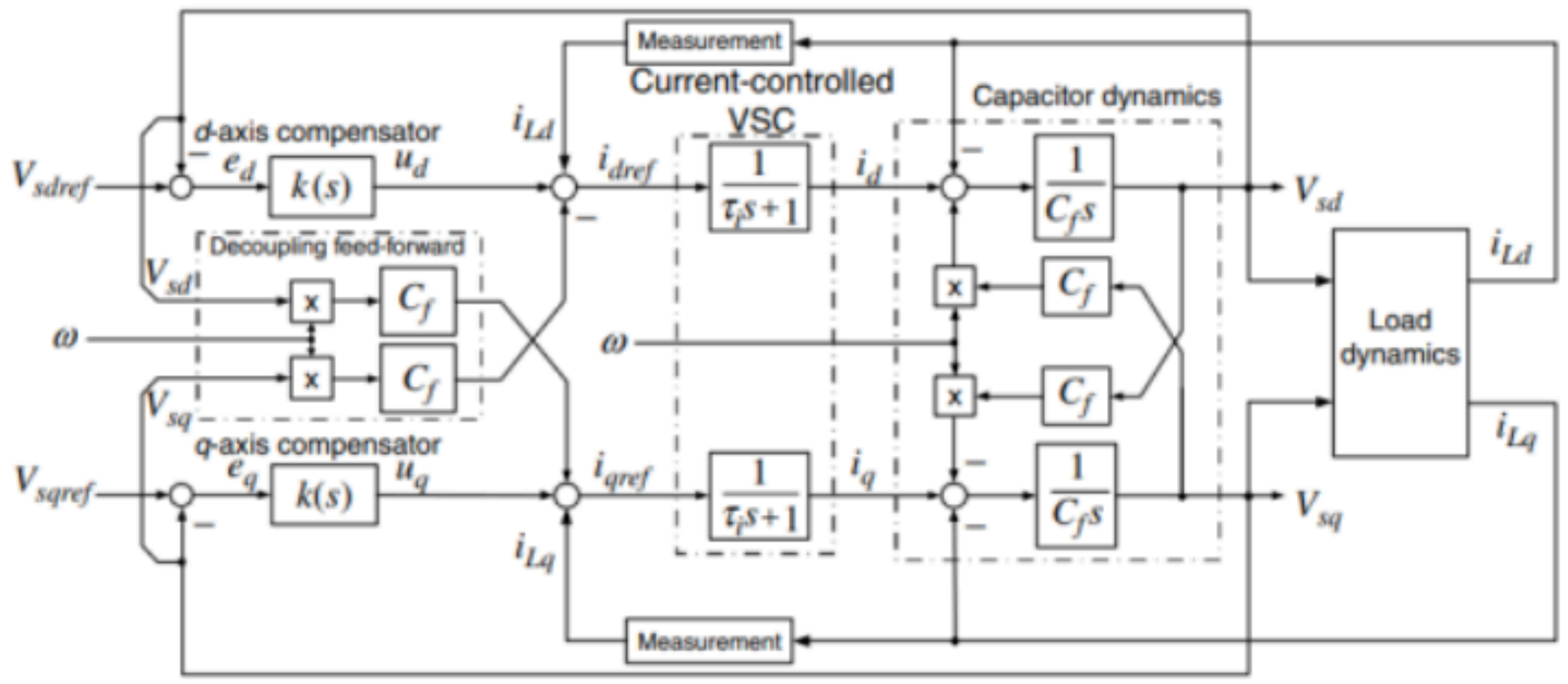


Figure 7: GFM Control Block Diagram [7]

4. Grid Forming Inverters (GFM)

- Frequency-Based Droop Control
  - Allow the frequency to decrease linearly with increasing P
  - Usually with a LPF
  - Allow Grid Connected and Islanding mode
  - Power Sharing Capability

$$K_{droop} = \frac{\Delta\omega}{\Delta P}$$

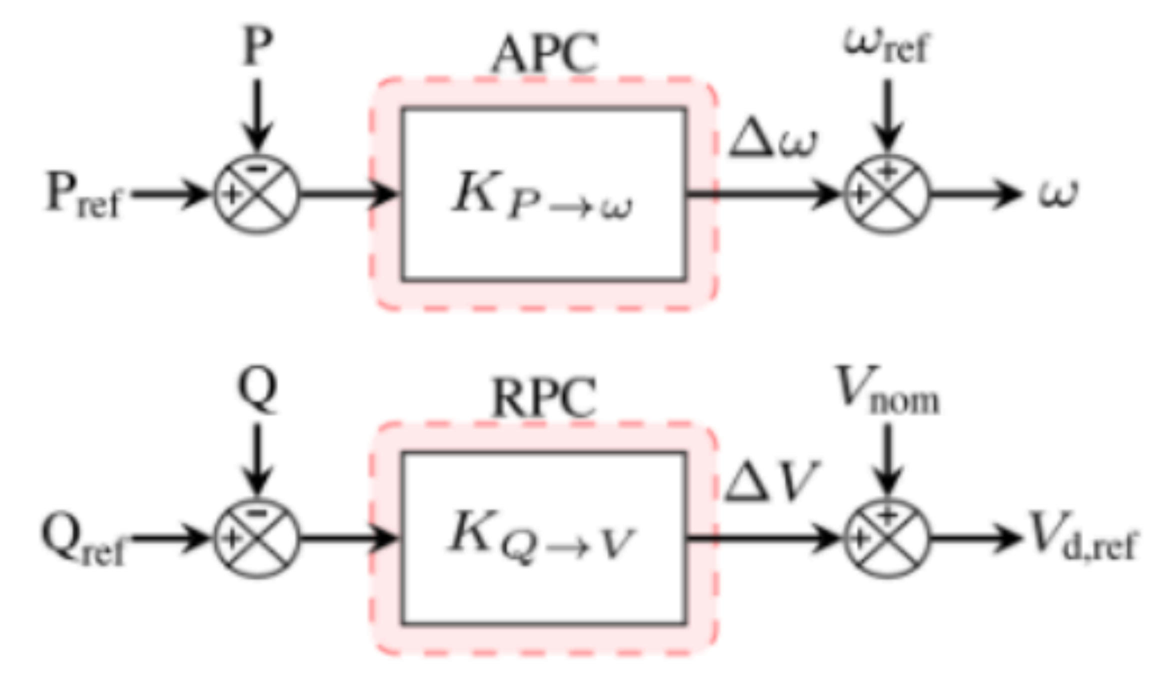


Figure 9: Frequency Droop Control Diagram [2]

4. Grid Forming Inverters (GFM)

- Swing Equation Control
  - Emulate the behavior of a synchronous generator
  - Stabilize the frequency fluctuations
  - Provide short-term inertia

$$J\omega_0 \frac{d\omega_r}{dt} + D_p\omega_r = P_m - P_e$$

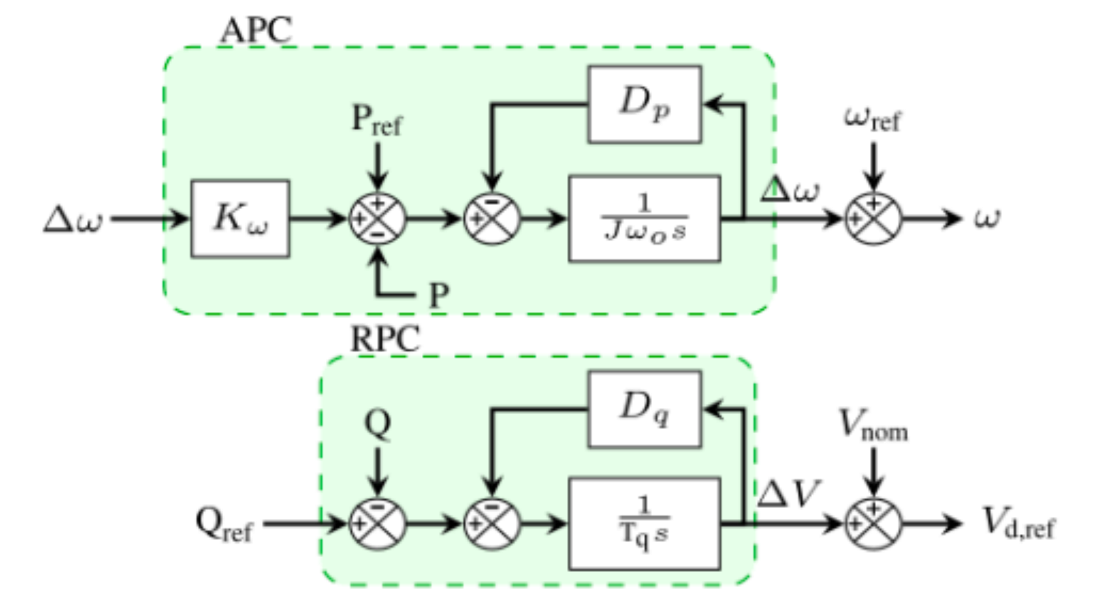


Figure 10: Swing Equation Emulation Control Diagram [2]

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

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

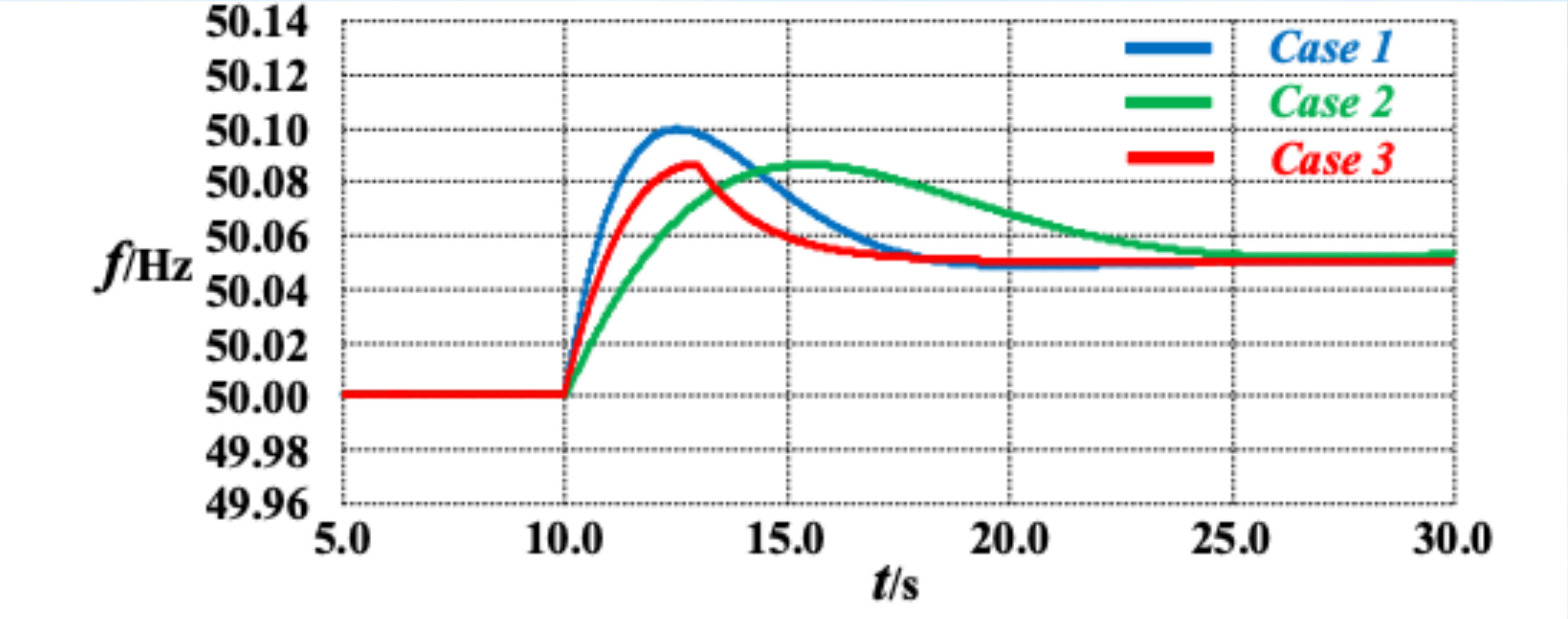
← At high penetration, SRC **might not be applicable anymore** as a metric for grid stability

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

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

5. Grid Strength and Duality

- **Grid Forming/Following Switching Control Strategy**
  - Case I: GFL
  - Case II: GFM
  - Case III: Both



  - GFM: Reduce Deviation
  - GFL: Fast response

5. Grid Strength and Duality

- **Grid Strength Impedance Metric**
  - SCL - increased current during 3-phase faults, also expressed as SCR
  - SCR - ratio between the current provided during a three phase fault to the nominal current
  - SG: 2-4 pu, IBRs: 1.1-1.2 pu
  - With IBRs, the fault current is now determined by inverter current limit, traditional definitions of SCR now INVALID
  - They propose: separate SCL with grid strength, build using SCR
- Change in grid characteristic with IBRs

5. Grid Strength and Duality

- **Duality of GFMs and GFLs**

Duality of Gird-Forming and Grid-Following Inverters

		Frequency Droop Grid-Forming Inverter	**PLL Grid-Following Inverter**
Synchronization Control		P-ω droop control with droop gain G_{FD}. (i_d-ω droop control with droop gain G_{FD}.) (i_d-PLL with phase-locking controller G_{FD}.)	v_q-PLL with phase-locking controller G_{PLL}. (v_q-ω droop control with droop gain G_{PLL}.) (Q-ω droop control with droop gain G_{PLL}.)
Grid-Interfacing Characteristics		Grid current-following voltage-forming.	Grid voltage-following current-forming.
Swing Characteristics		I-θ swing or P-θ swing.	V-θ swing or Q-θ swing.
Extreme Operation		Stable when open-circuit with $Z_g \to \infty$, or connected to an ideal current source. Unstable when short-circuit with $Z_g = 0$, or connected to an ideal voltage source.	Stable when short-circuit with $Y_g \to \infty$, or connected to an ideal voltage source. Unstable when open-circuit with $Y_g = 0$, or connected to an ideal current source.
Interaction	Grid Strength	Unstable when grid is strong with small Z_g. (Weak-grid-current-strength instability; Strong-grid-voltage-strength instability.)	Unstable when grid is weak with small Y_g. (Weak-grid-voltage-strength instability; Strong-grid-current-strength instability.)
	Synchronization Controller	Unstable when G_{FD} (e.g., droop gain m) is large, i.e., Z_{FD} is large.	Unstable when G_{PLL} (e.g., PLL bandwidth) is large, i.e., Y_{PLL} is large.
	Inner Loop Controller	Unstable when voltage control bandwidth is low, i.e., Z_c is large.	Unstable when current control bandwidth is low, i.e., Y_c is large.

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

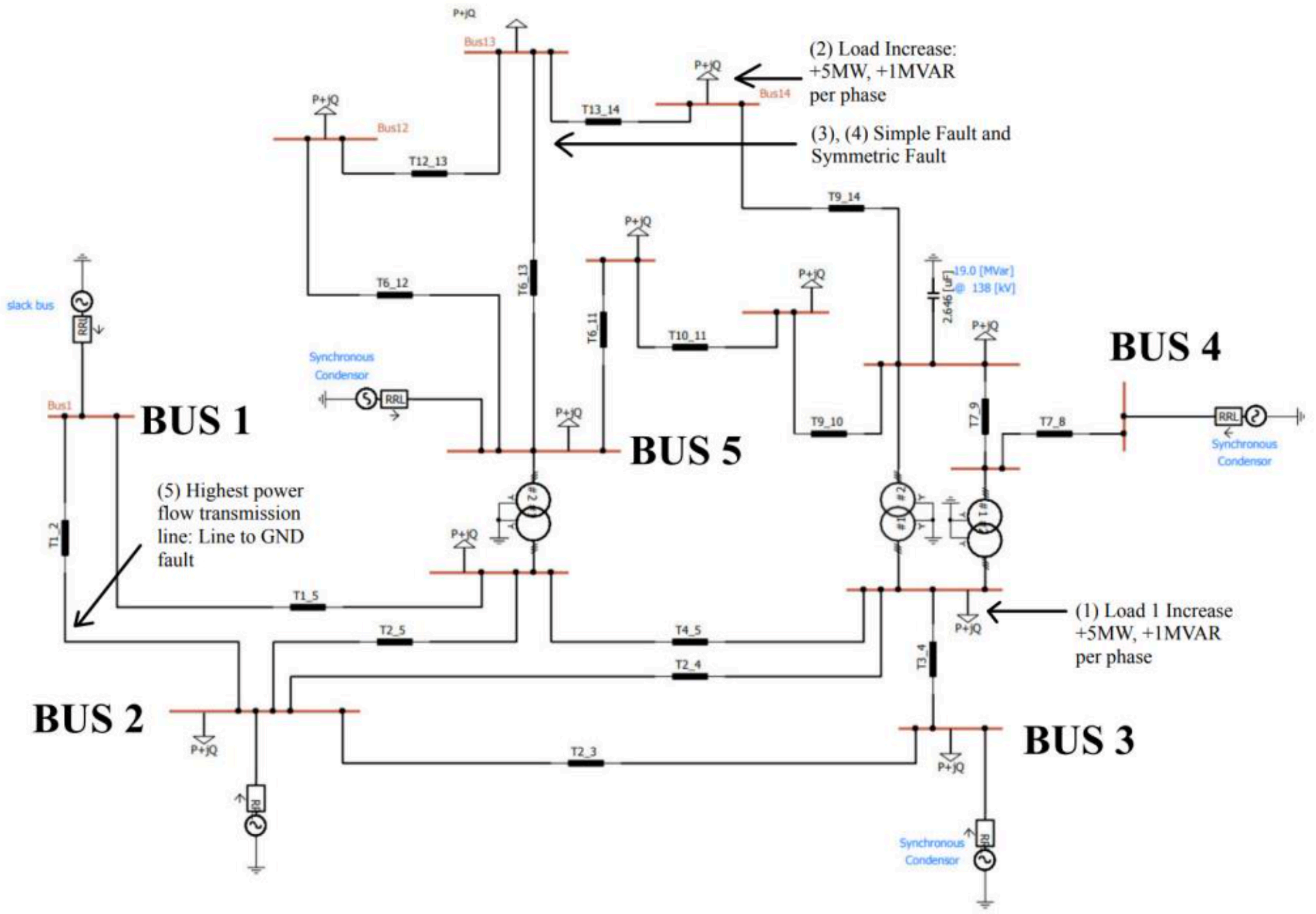


Figure 11: IEEE 14 Bus System in PSCAD

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

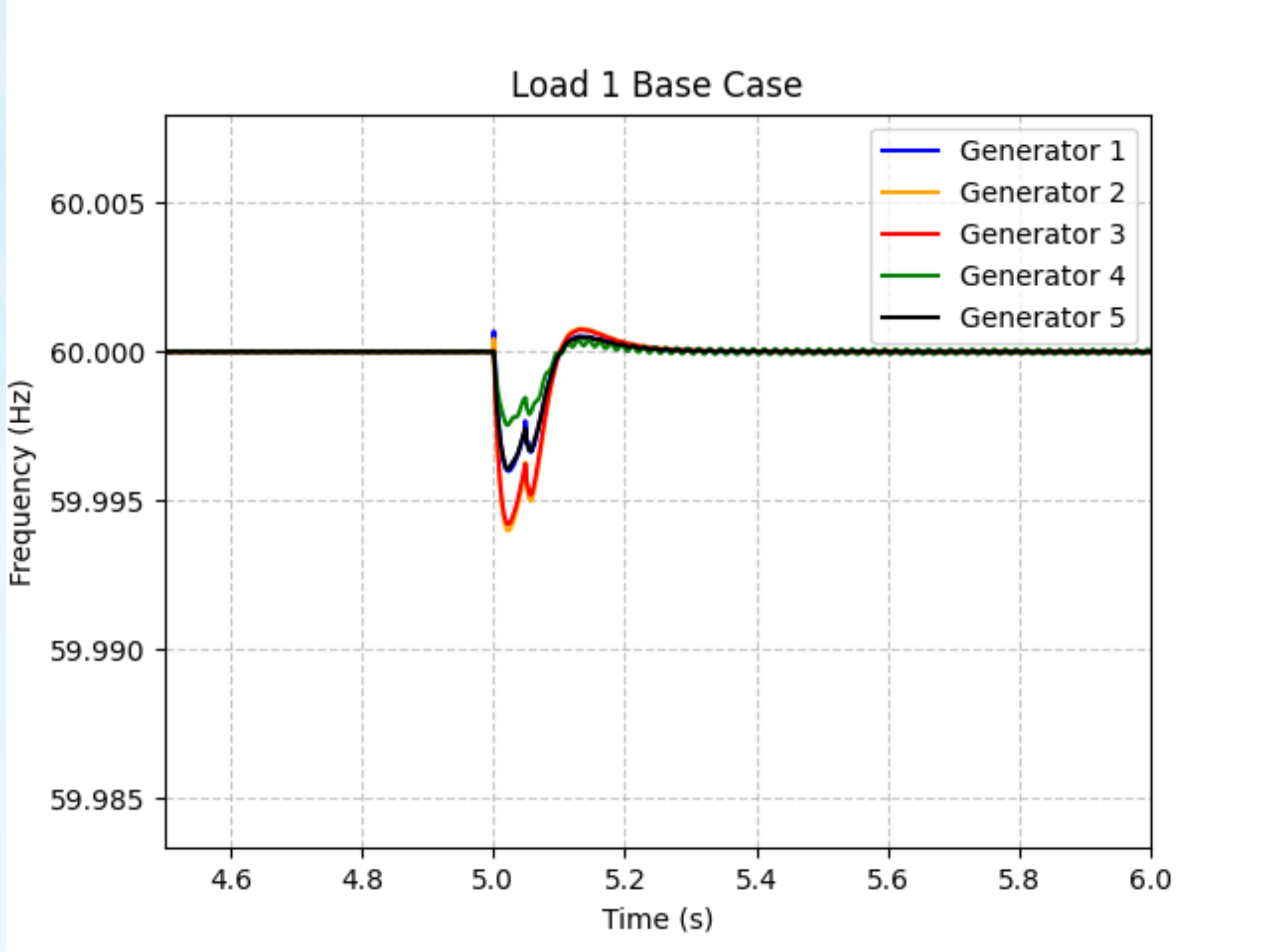
Load Change: +5MW, +1MVAR per phase

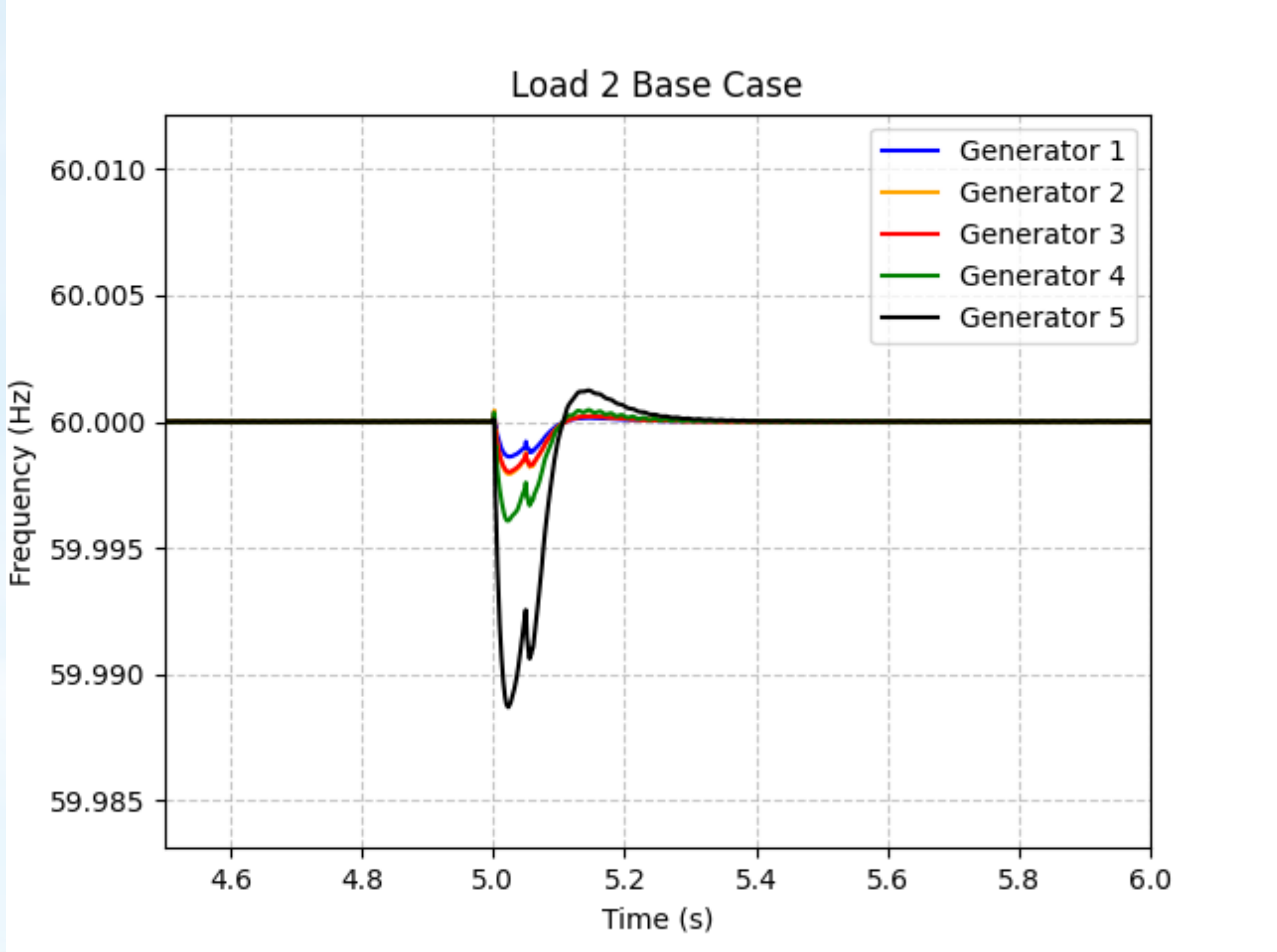
Line with fault is tripped after 100 ms.

Results

Load 1

Load 2

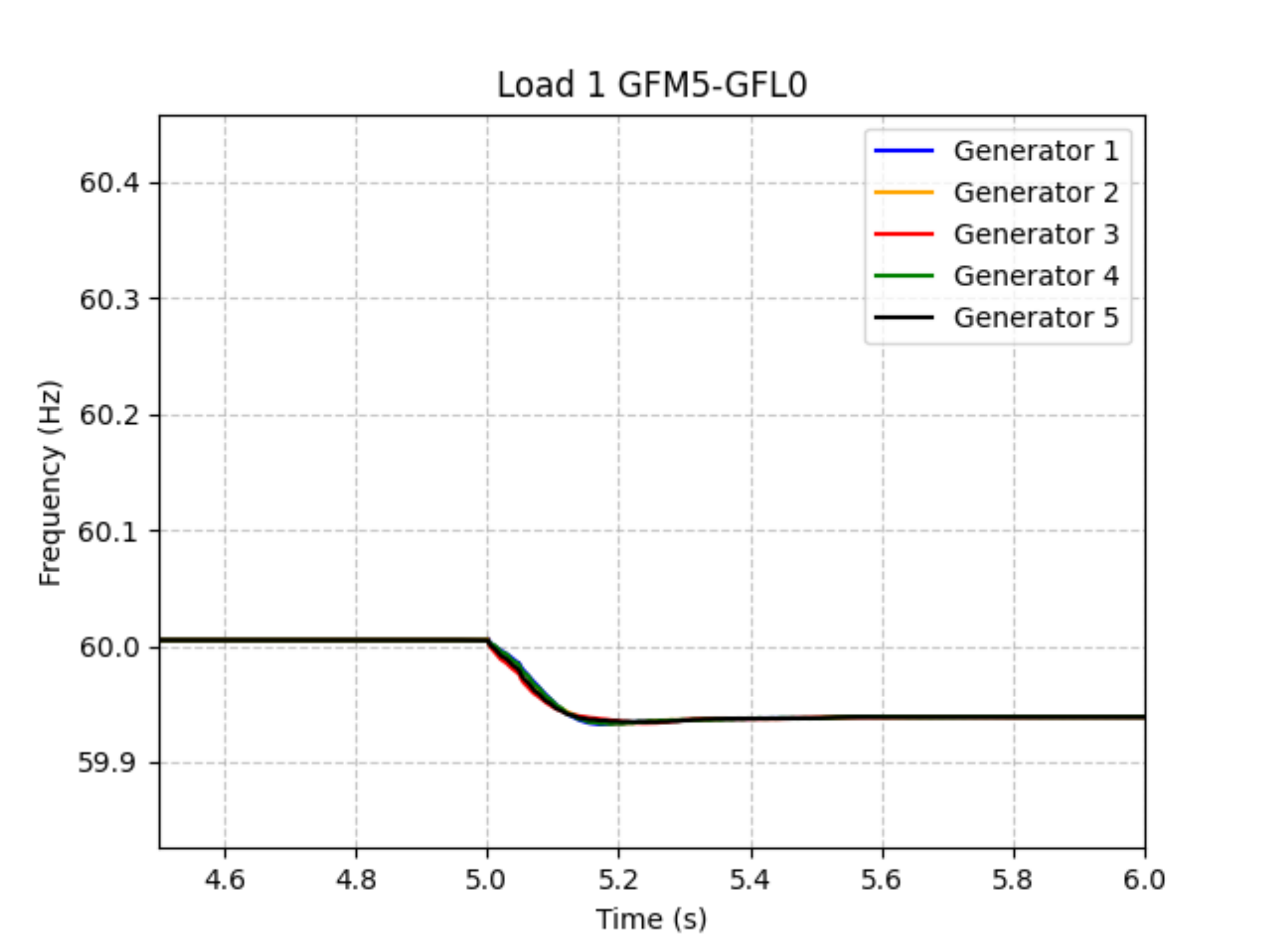


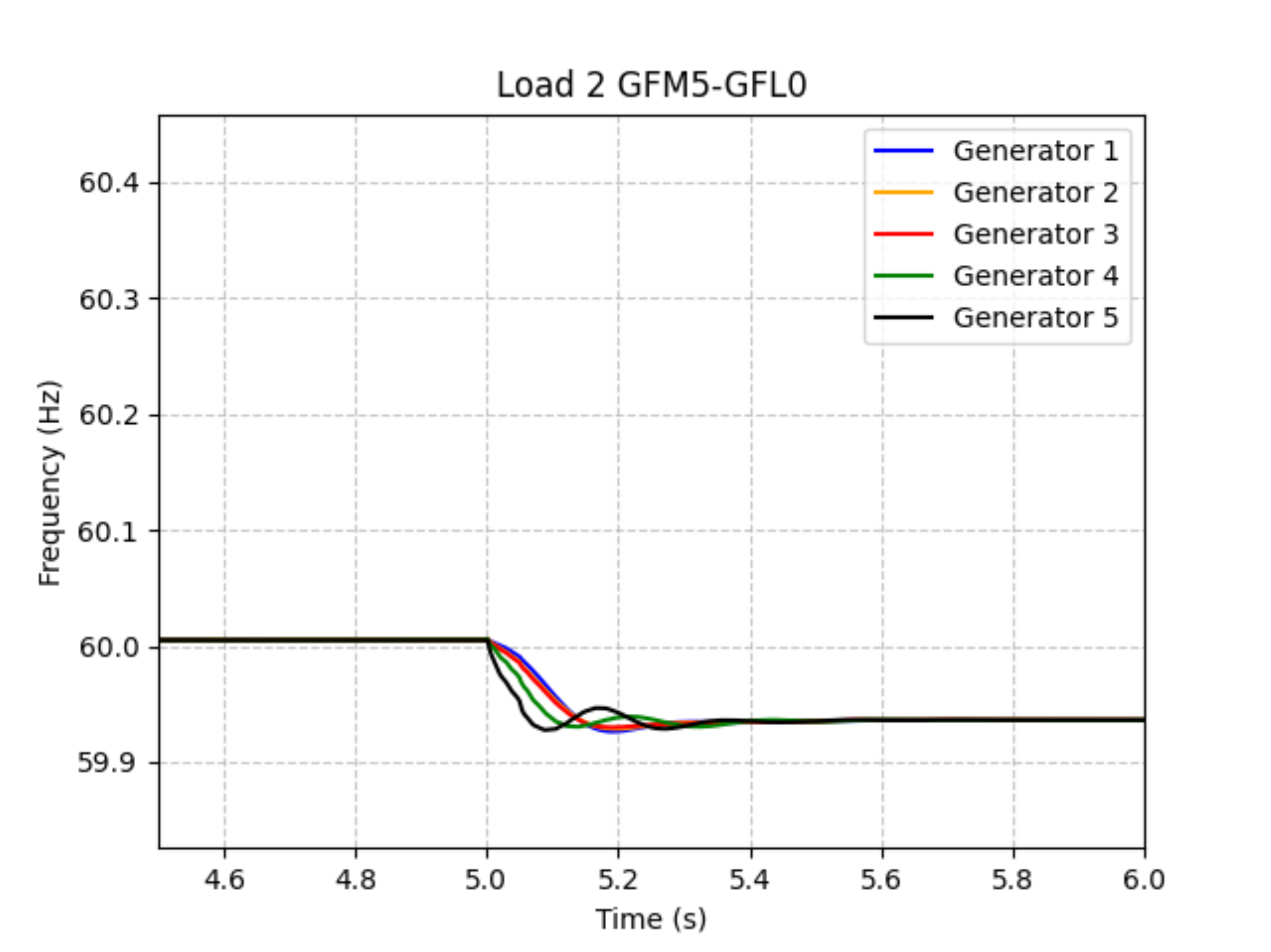


Base Case

Load 1

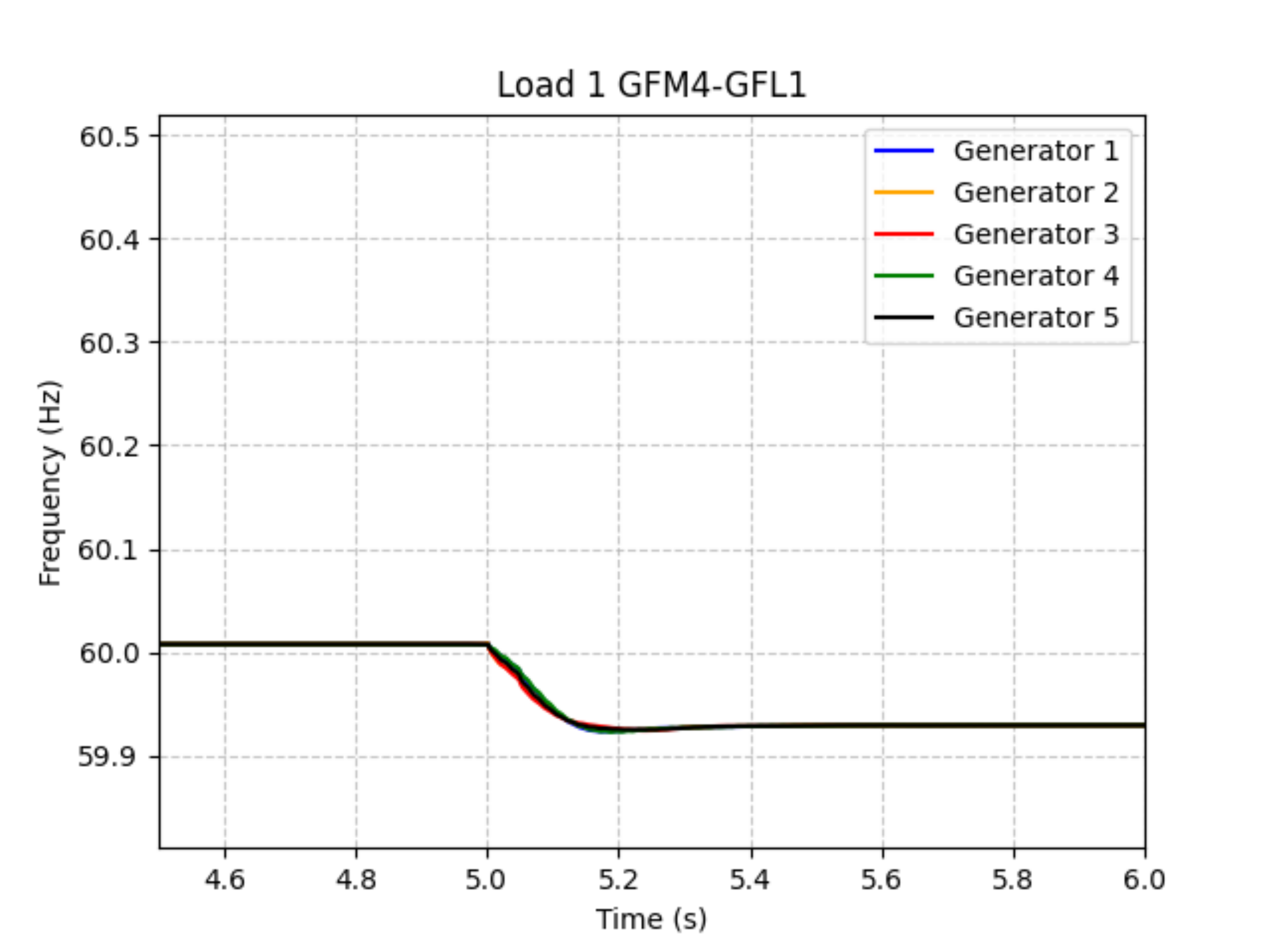
Load 2



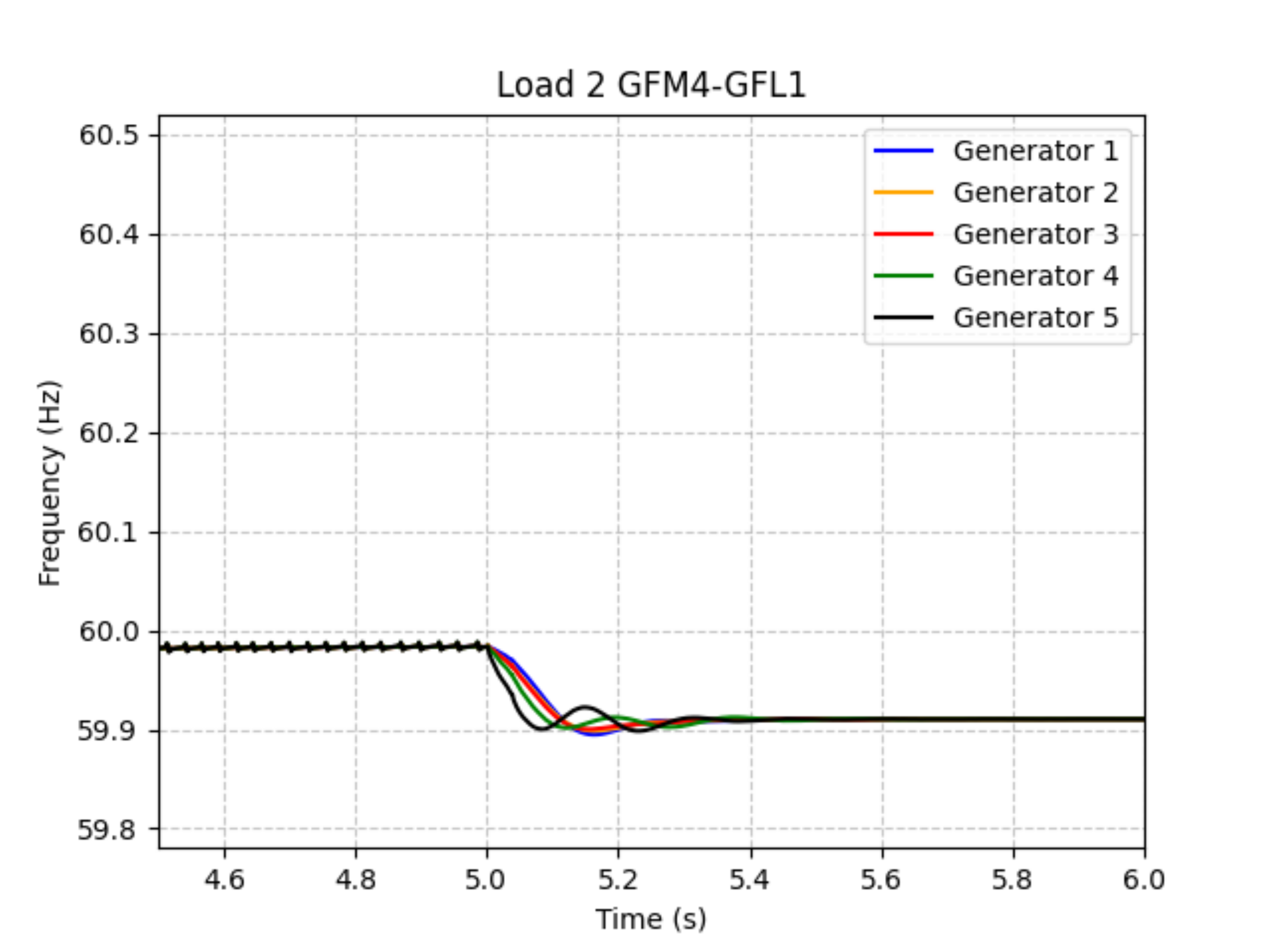


GFM5:GFL0

Load 1



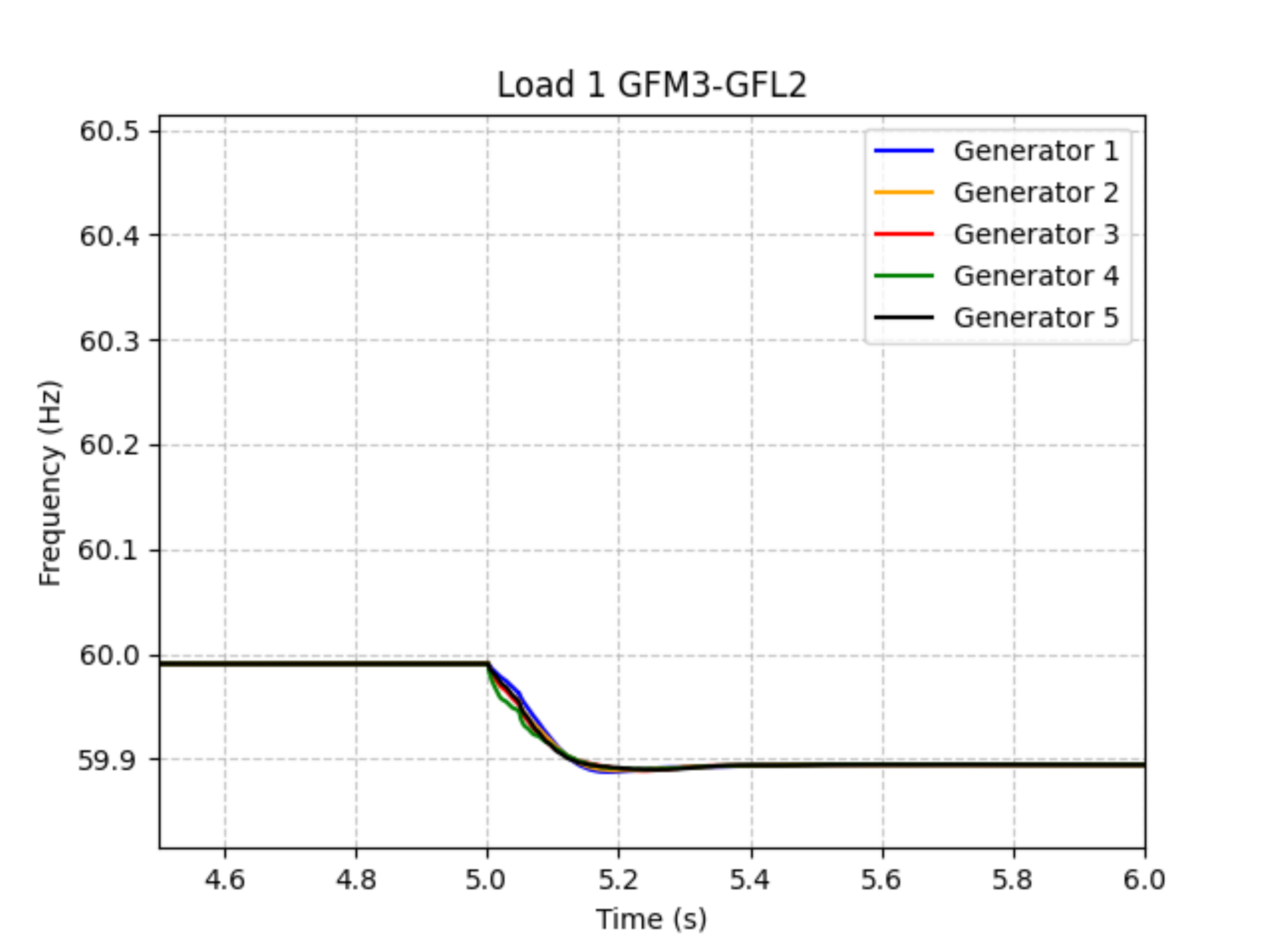
Load 2

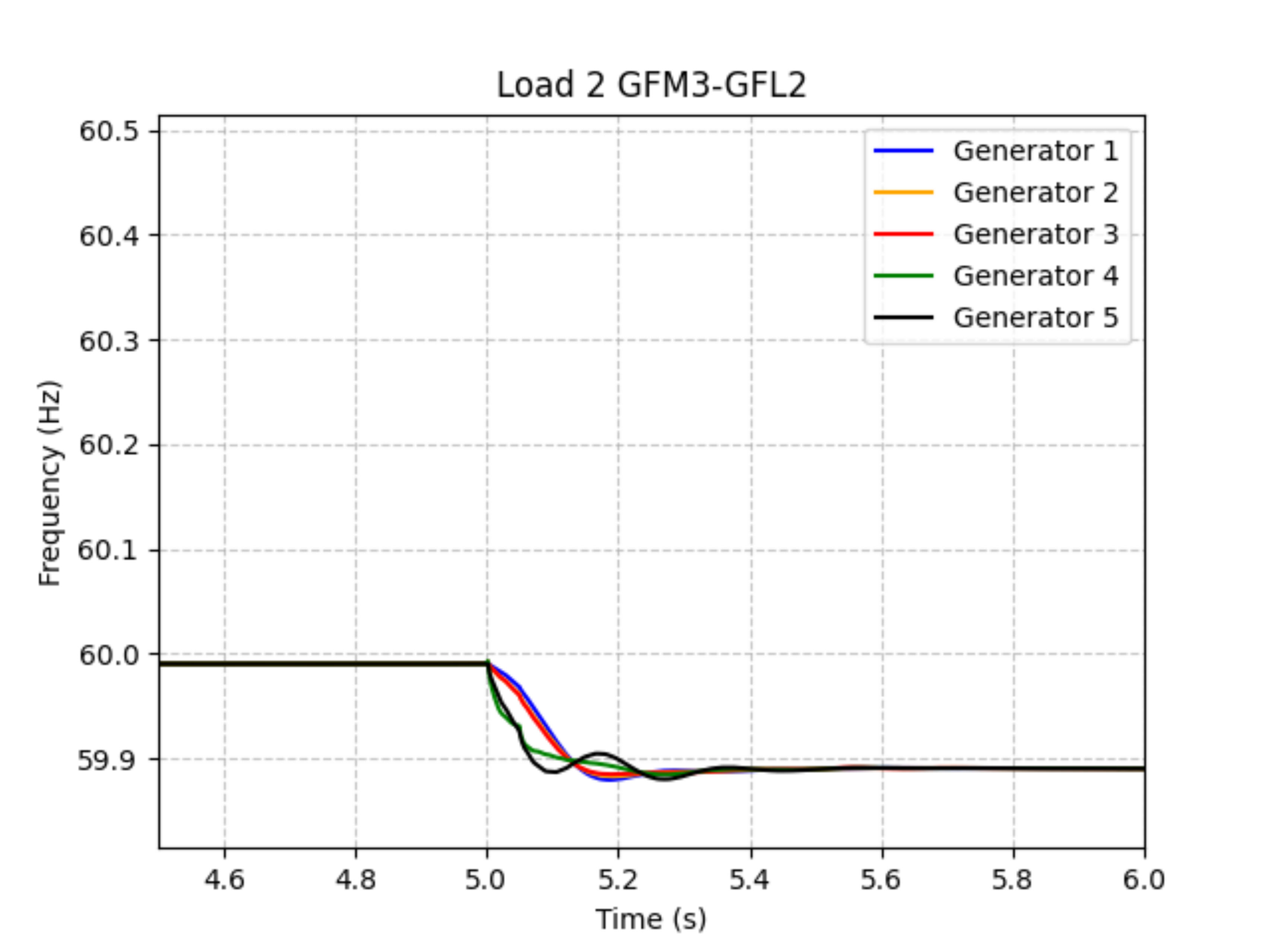


GFM4:GFL1

Load 1

Load 2

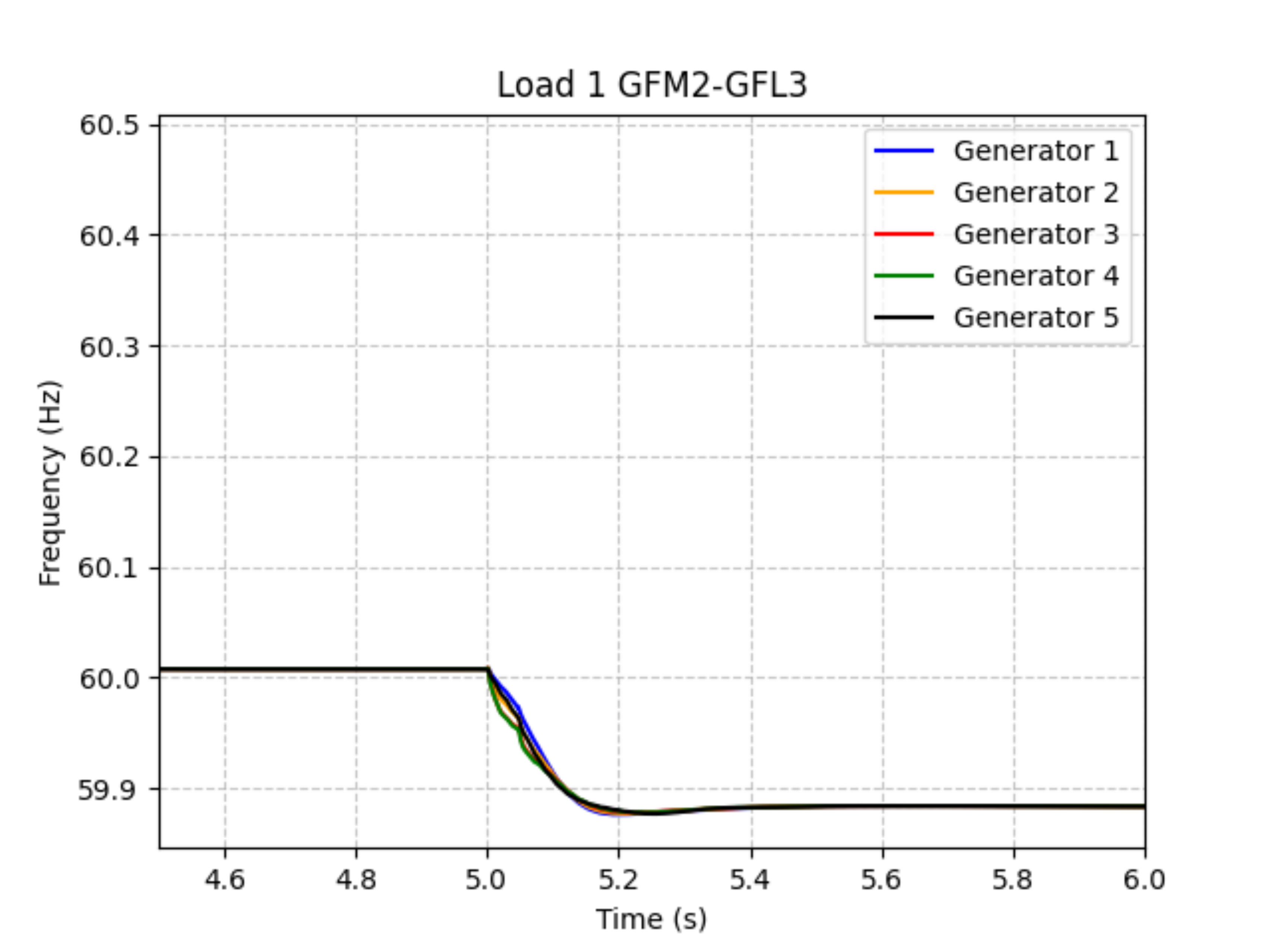


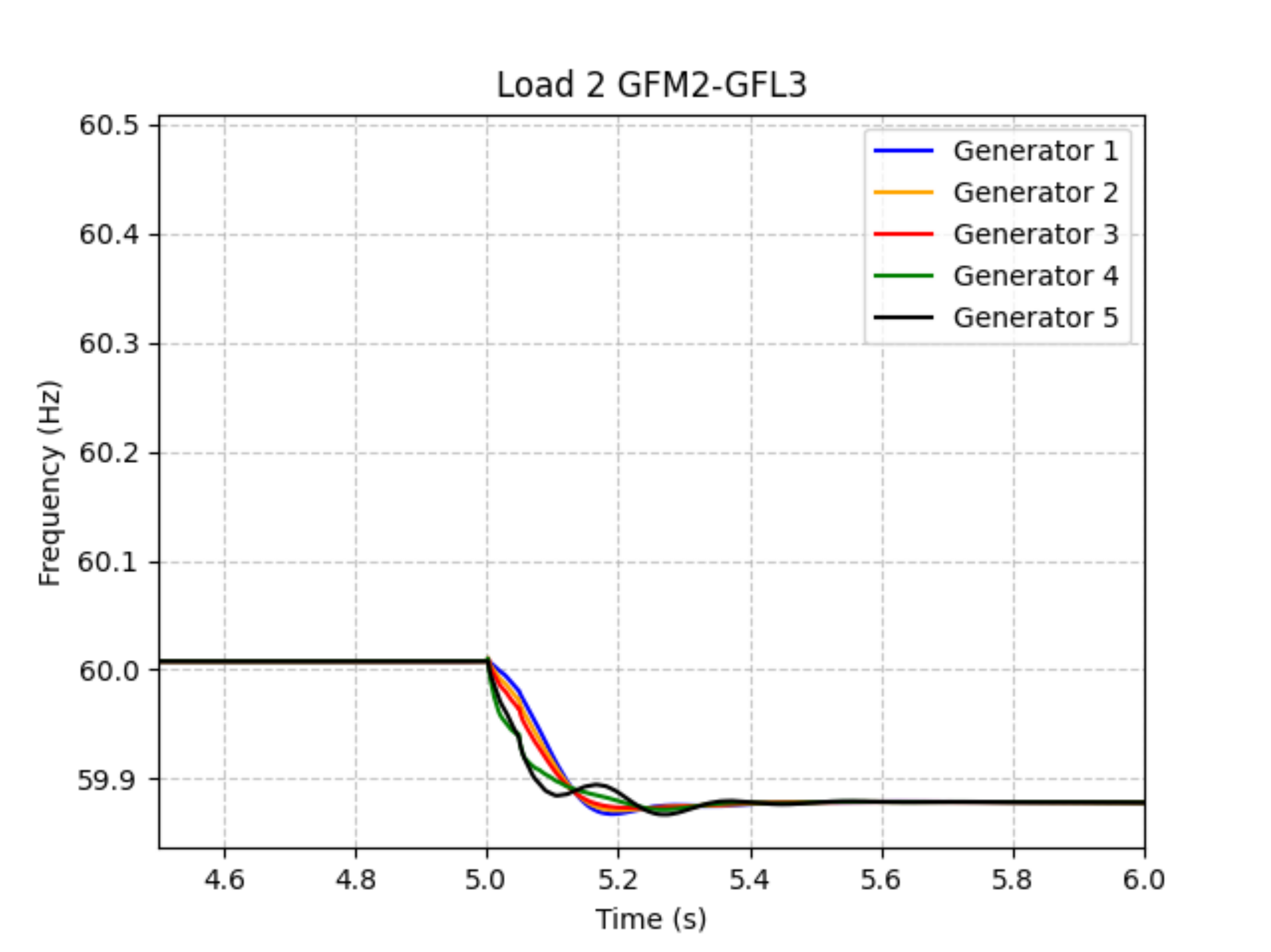


GFM3:GFM2

Load 1

Load 2

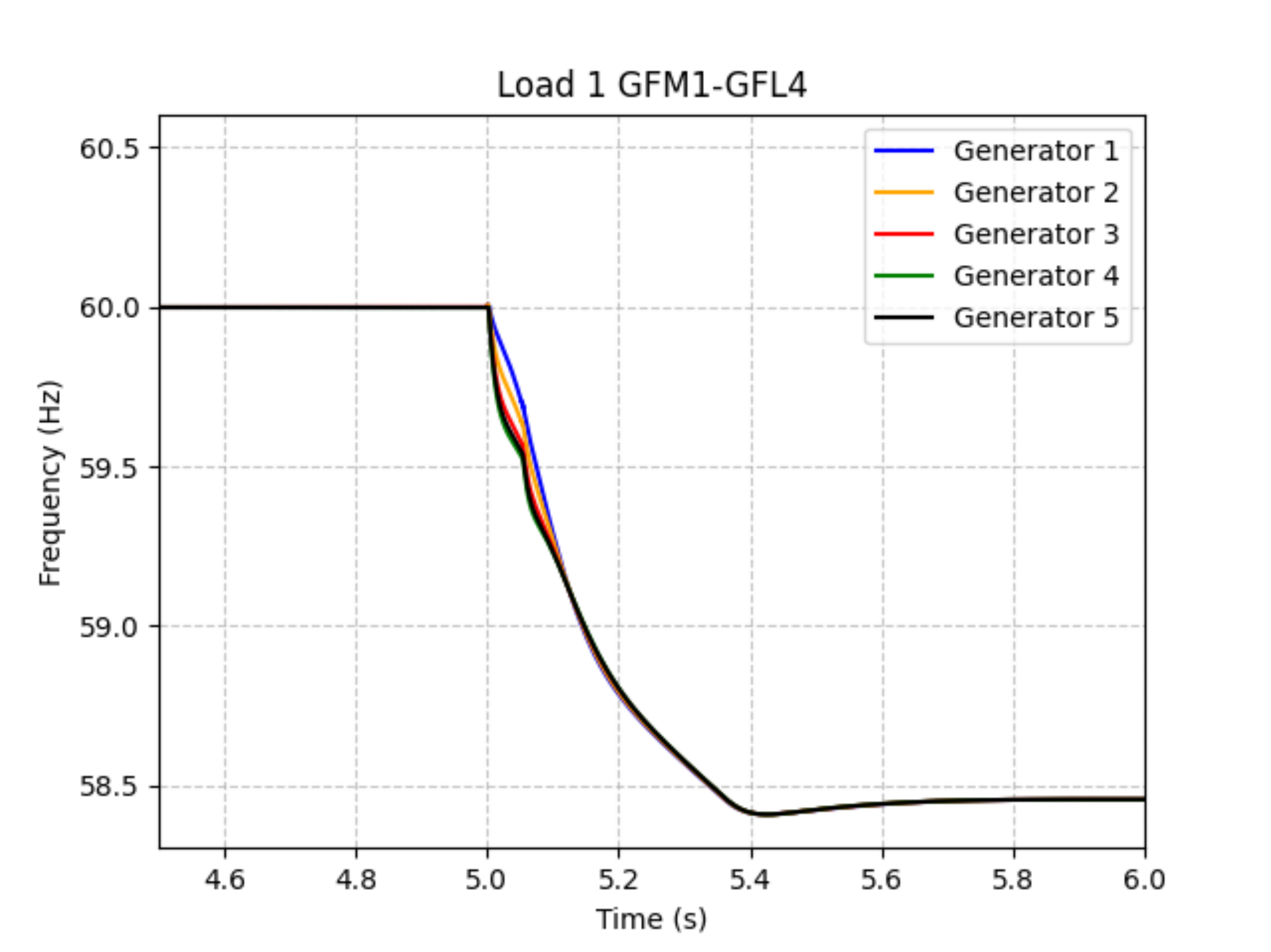


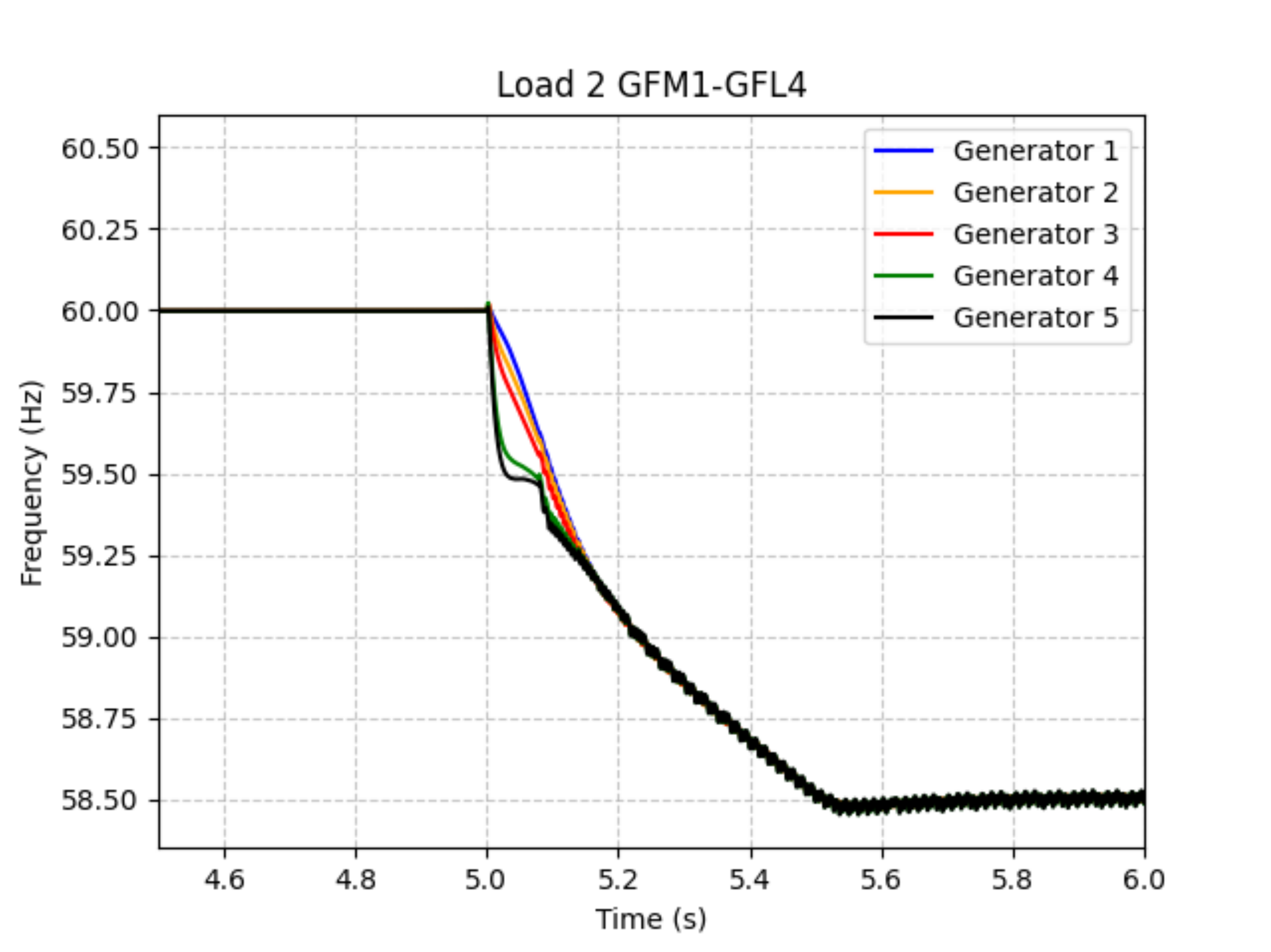


GFM2:GFL3

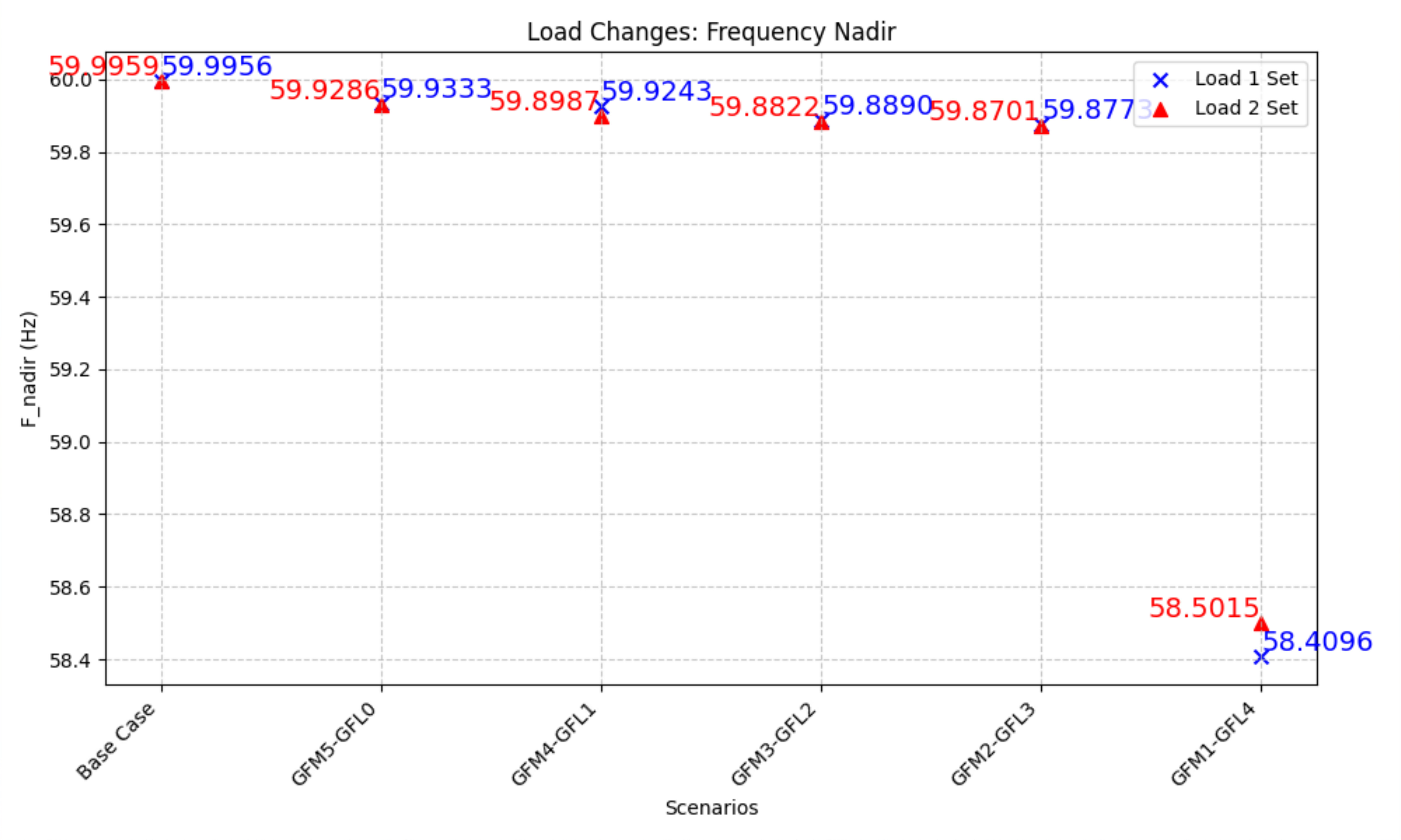
Load 1

Load 2

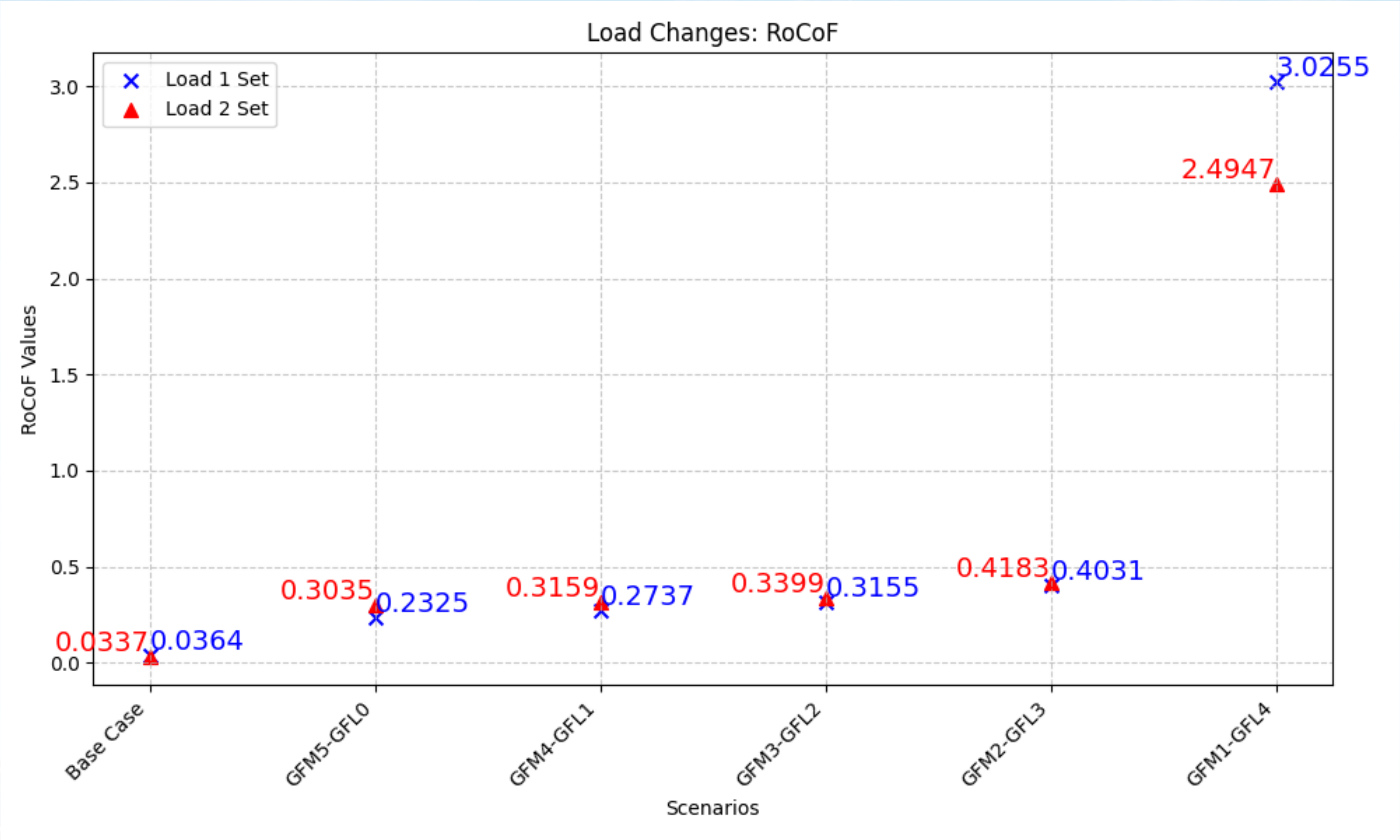




GFM1:GFM4

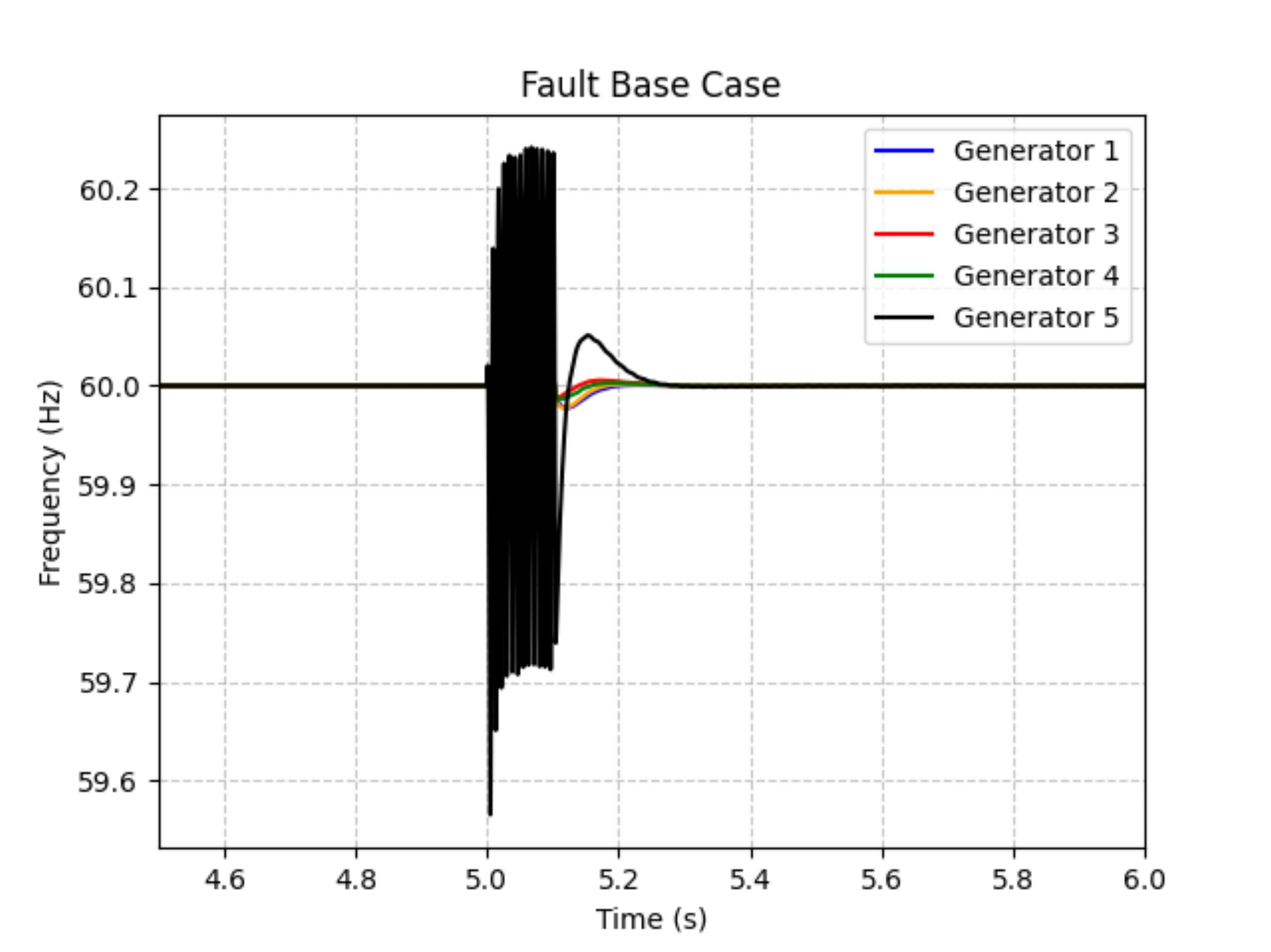


Load Changes Frequency Nadir

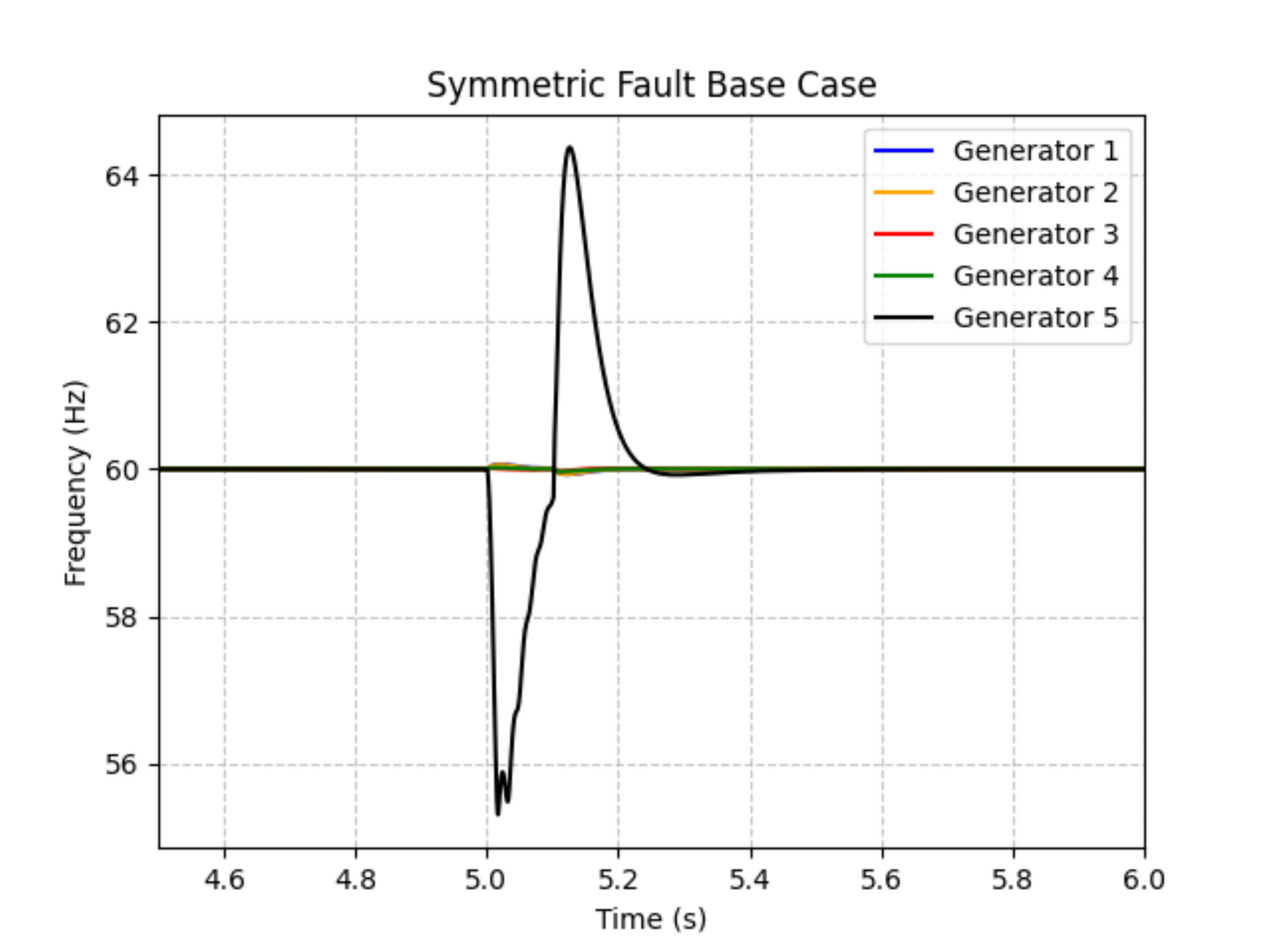


Load Changes *RoCoF**

Single Phase to GND Fault

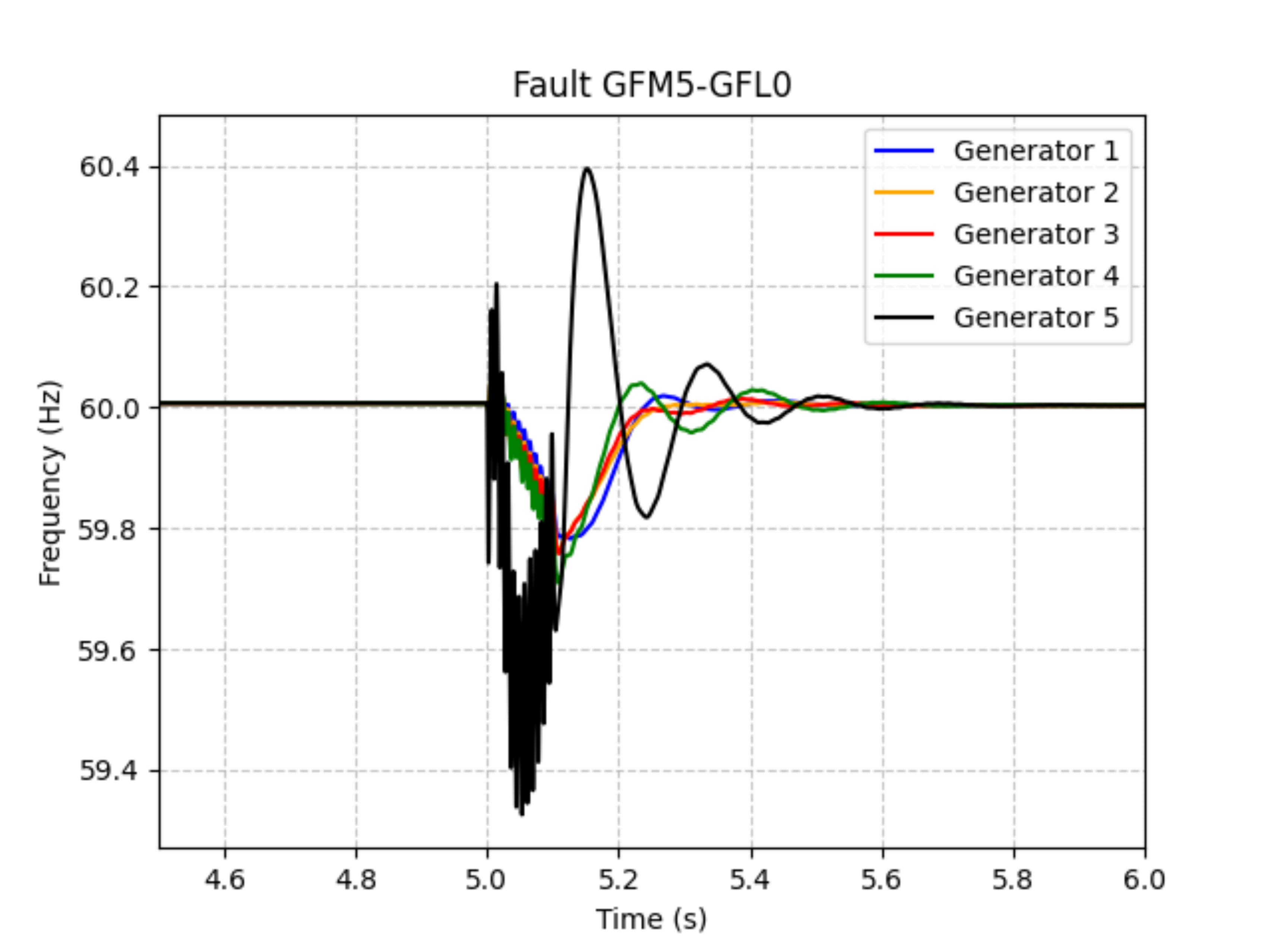


Symmetric to GND Fault

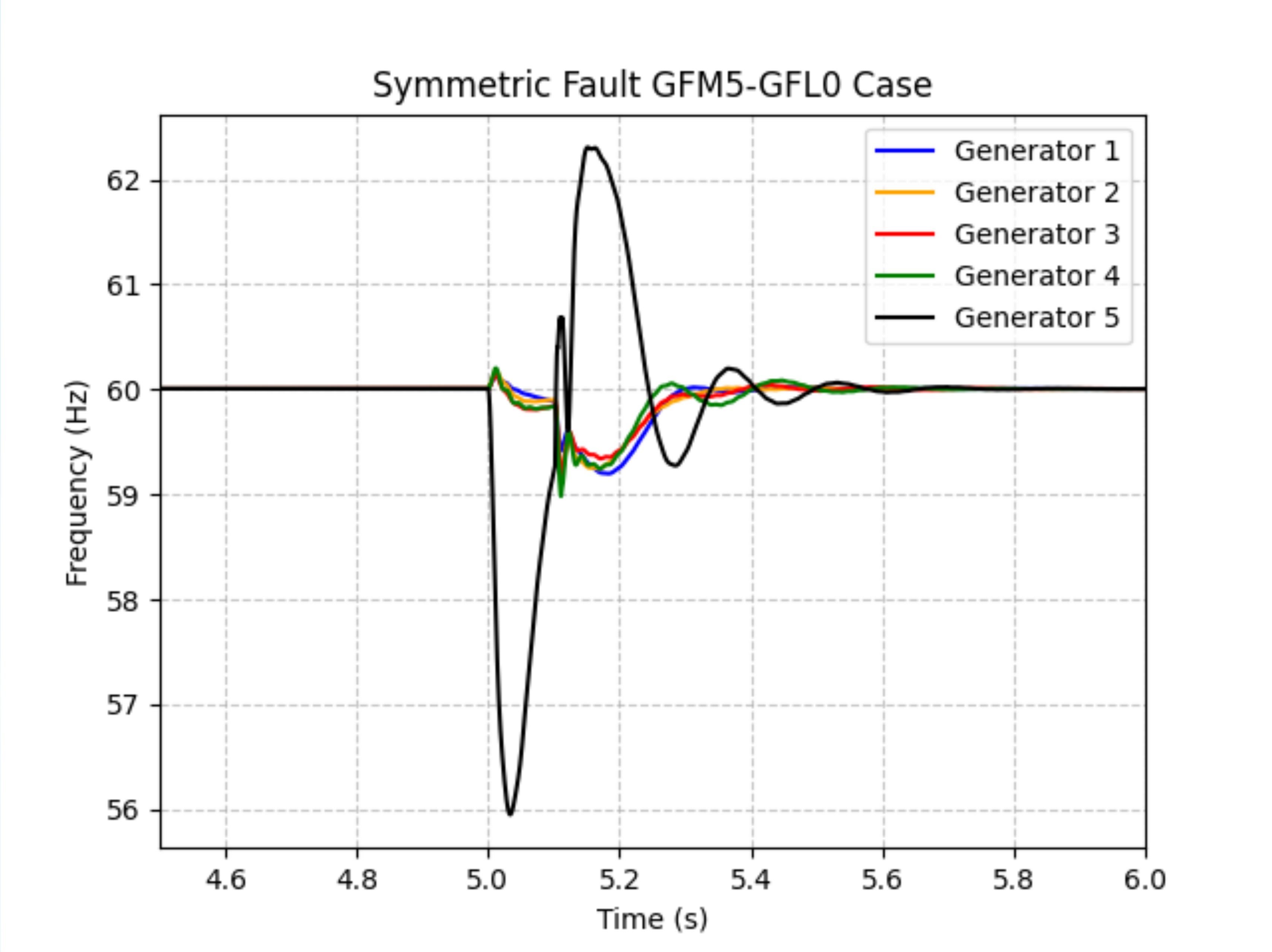


Base Case

Single Phase to GND Fault



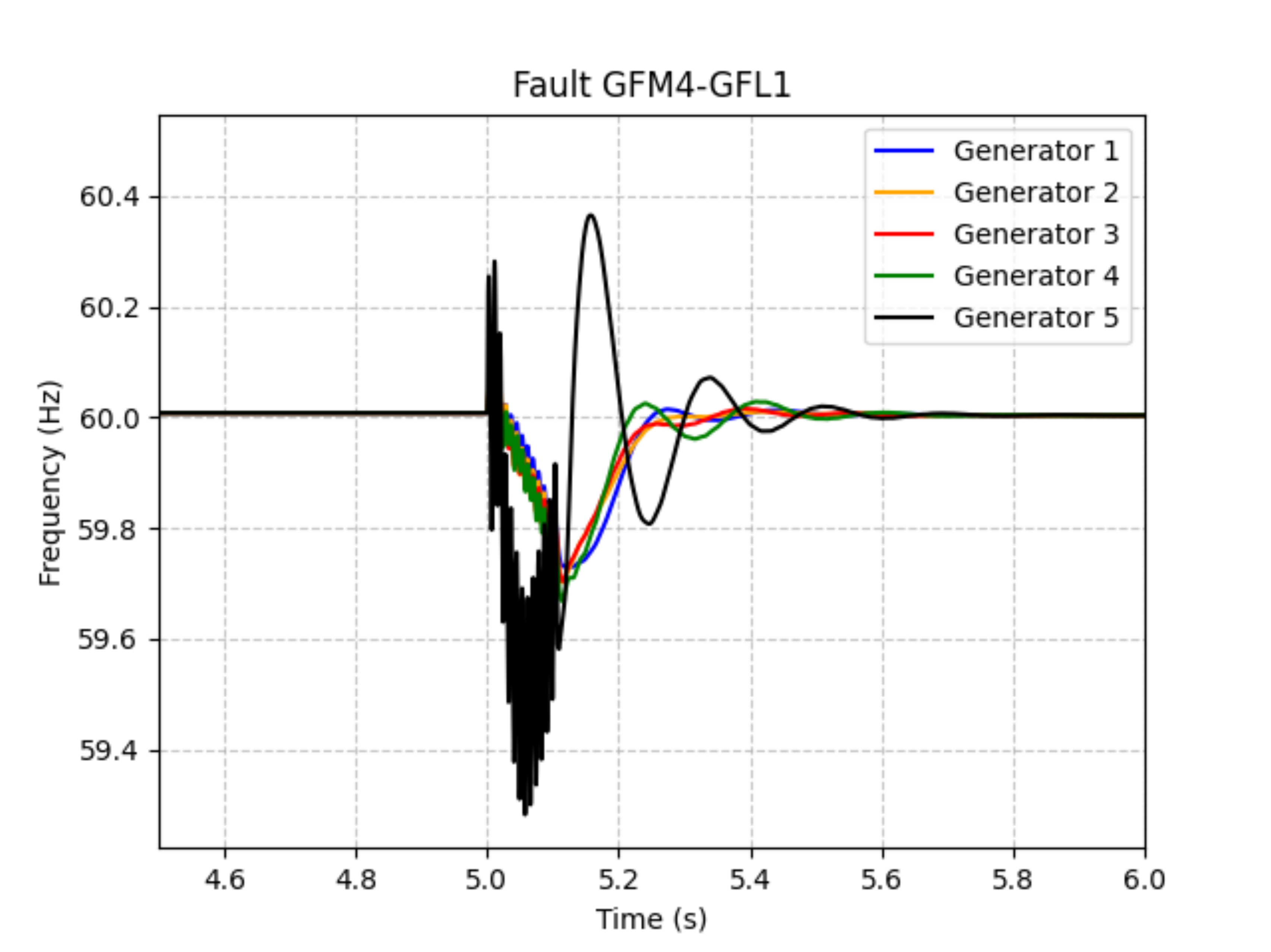
Symmetric to GND Fault

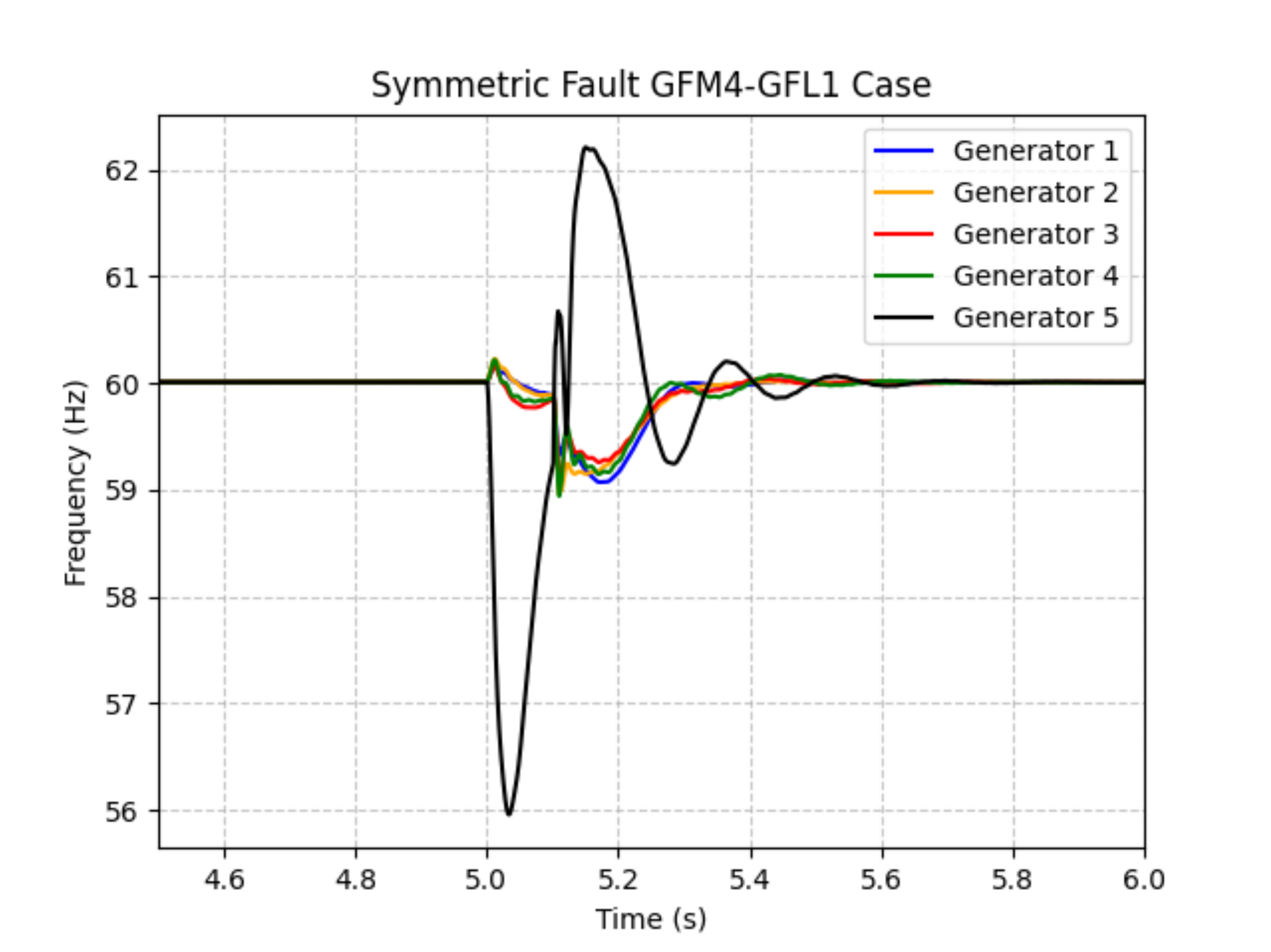


GFM5:GFL0

Single Phase to GND Fault

Symmetric to GND Fault

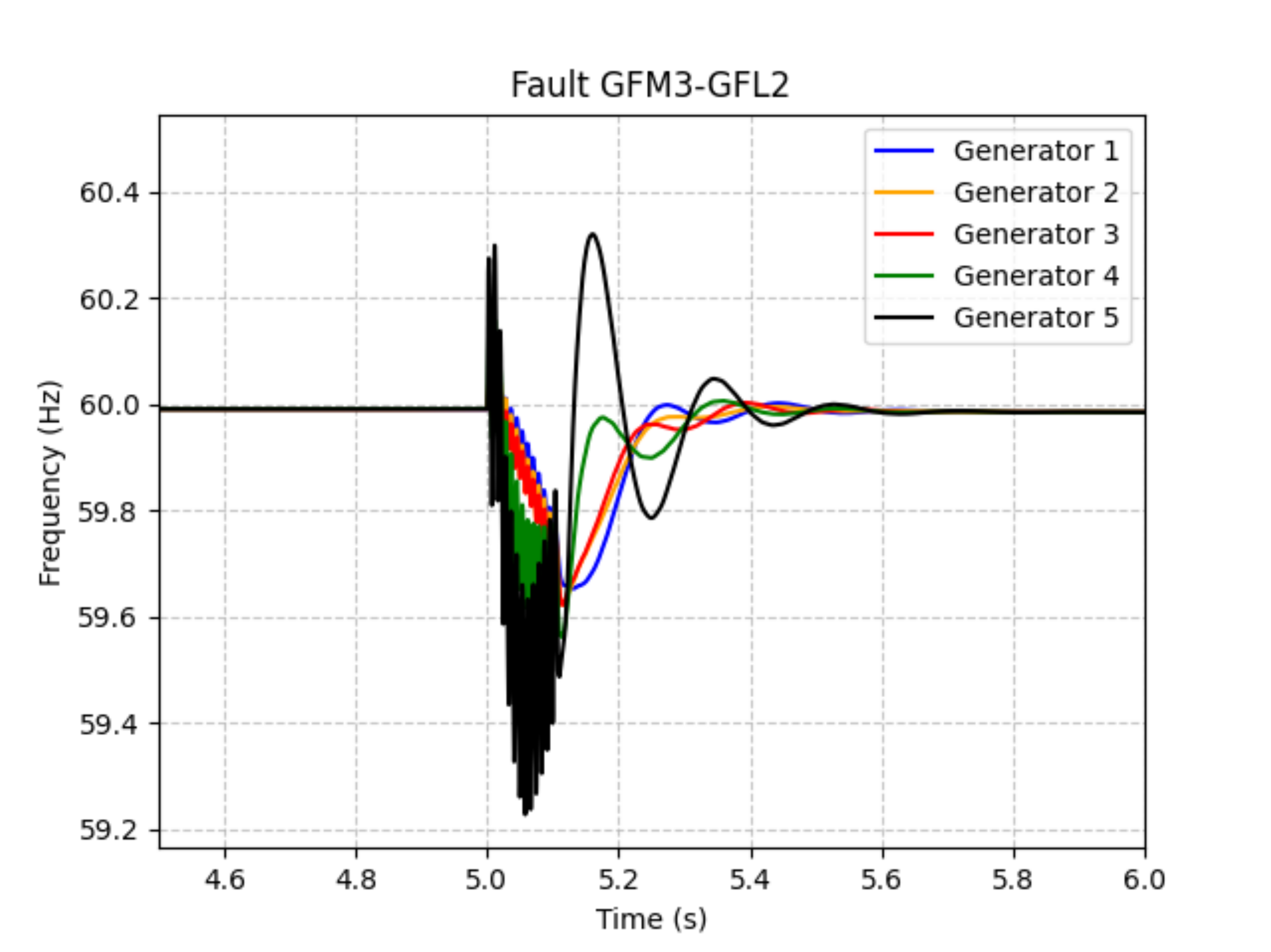


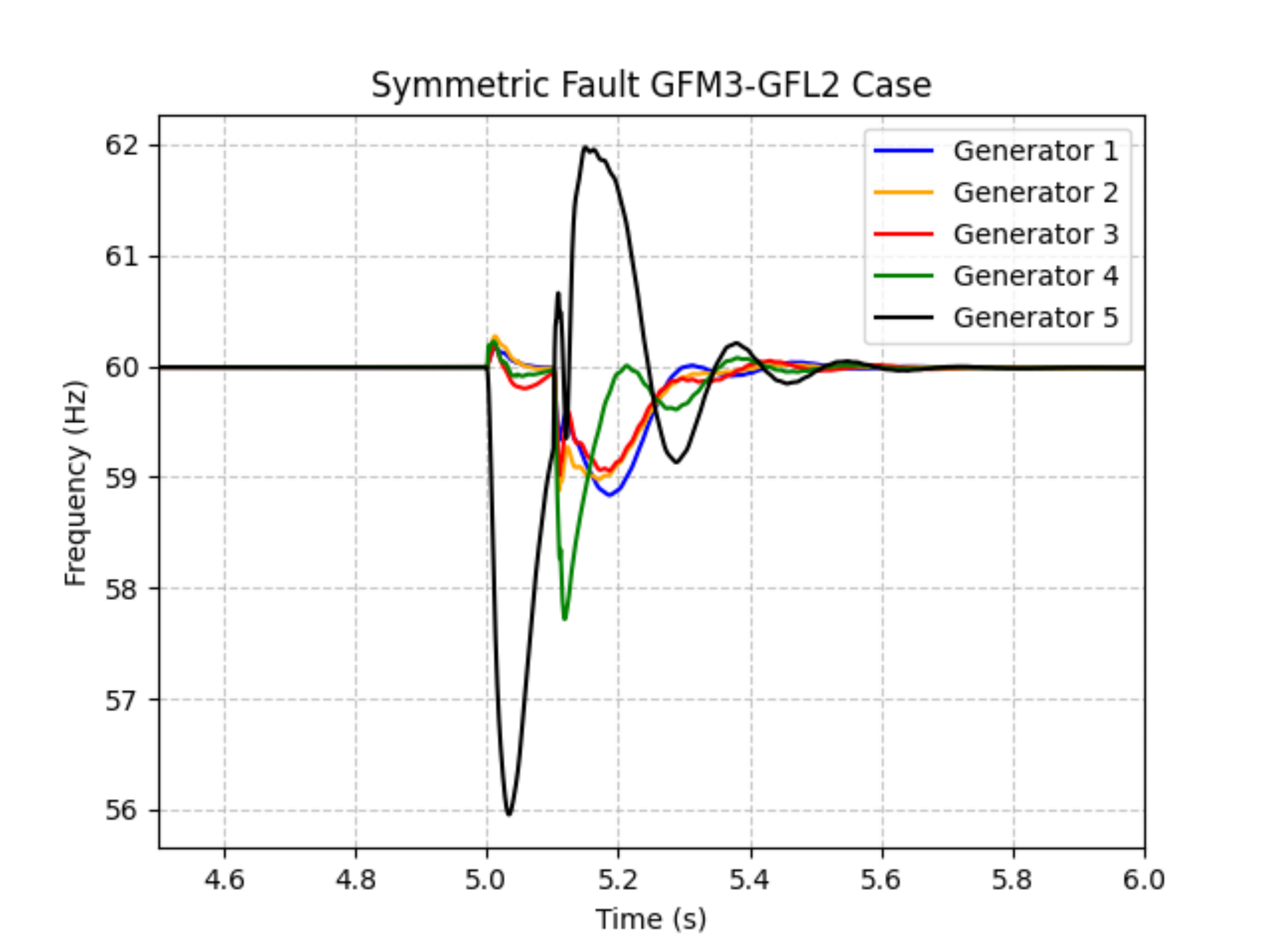


GFM4:GFL1

Single Phase to GND Fault

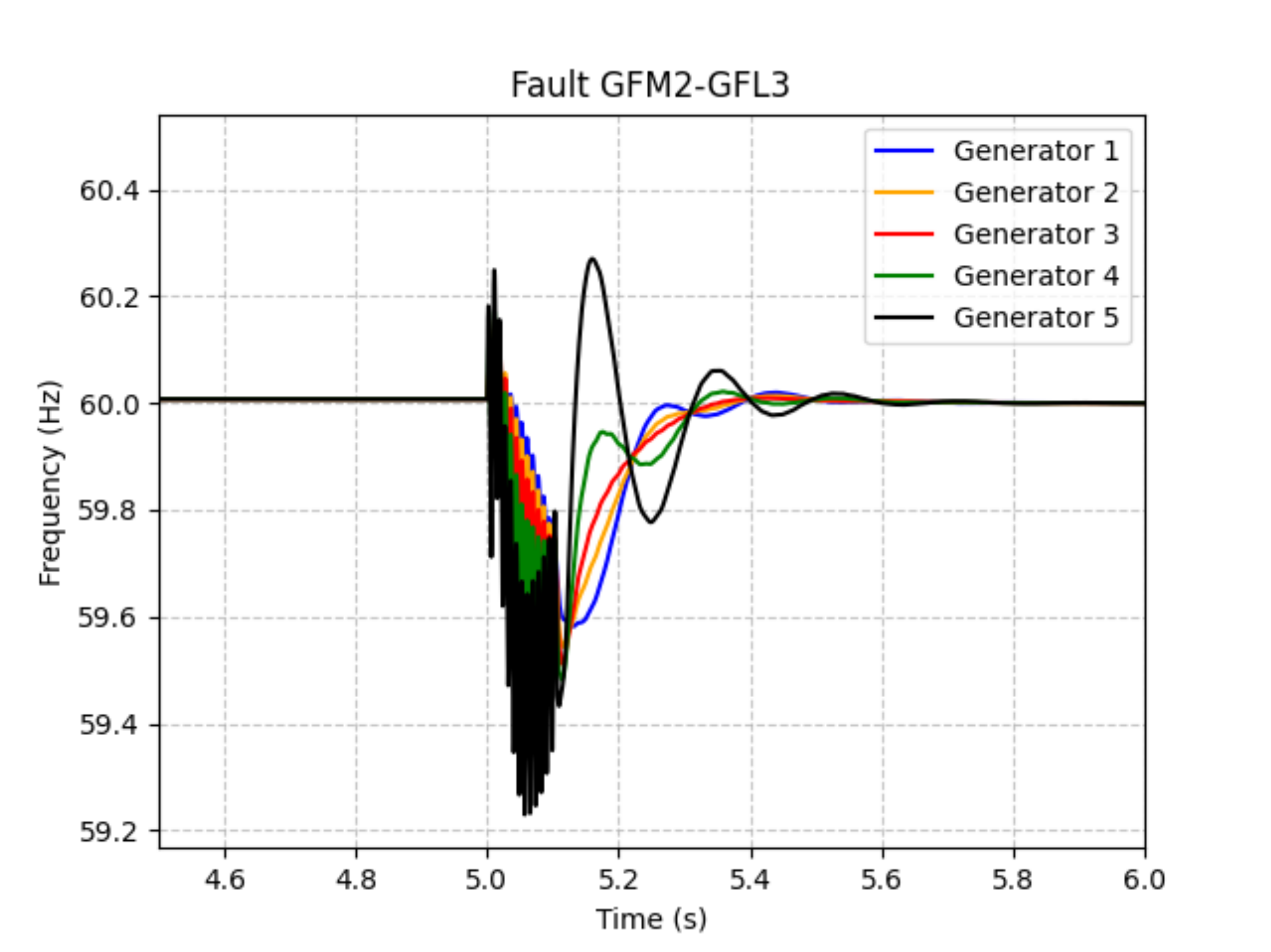
Symmetric to GND Fault



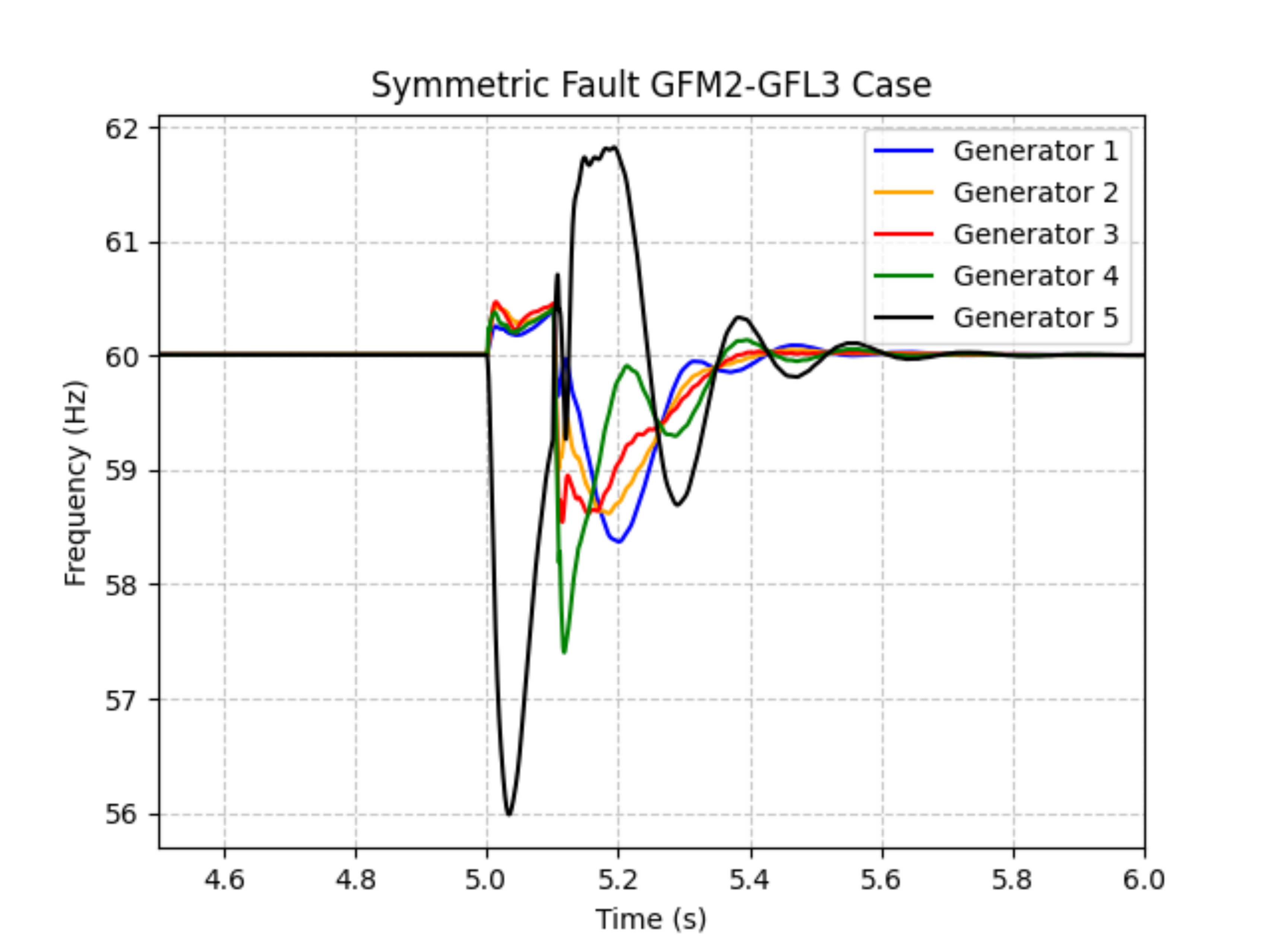


GFM3:GFL2

Single Phase to GND Fault



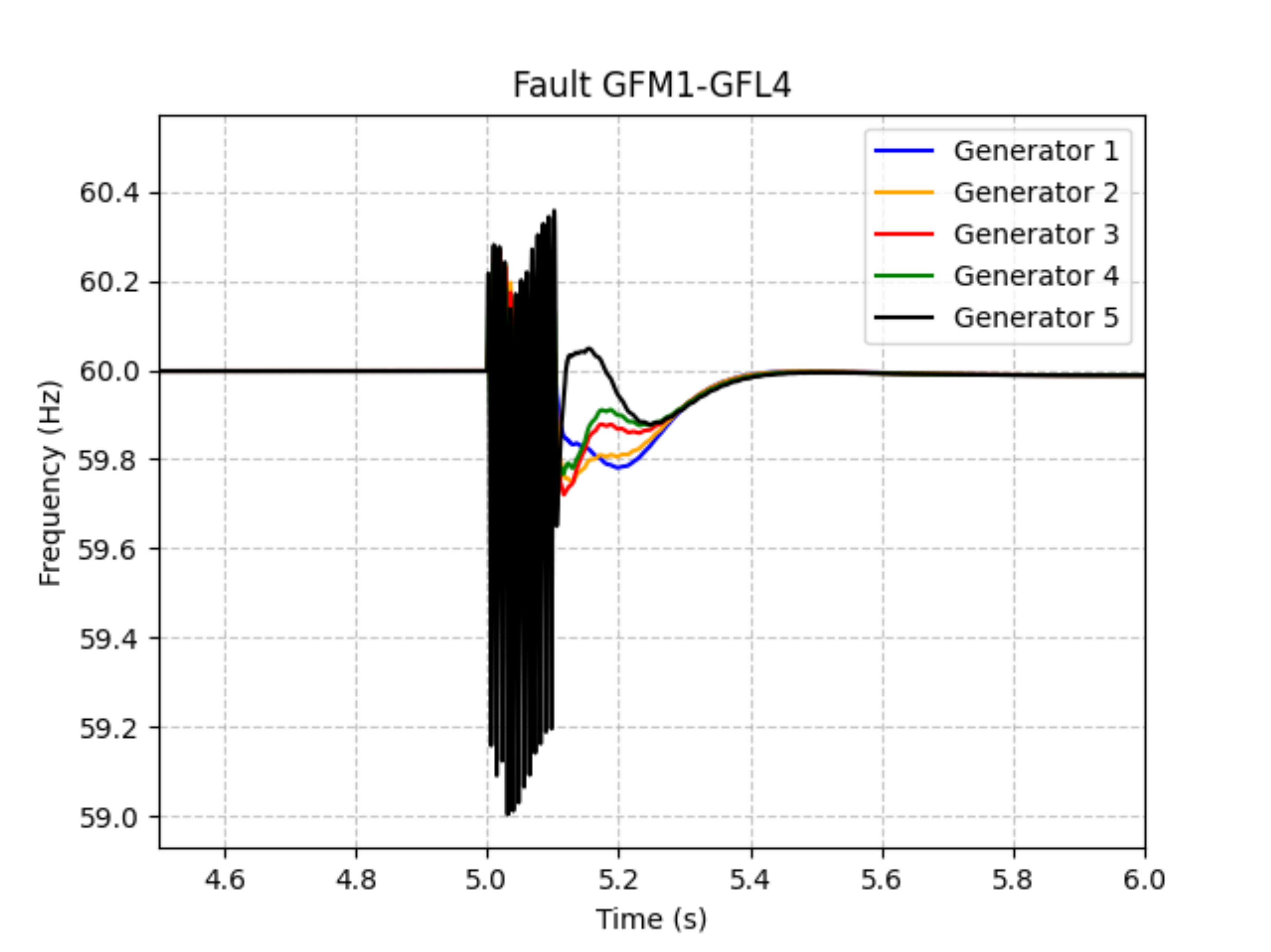
Symmetric to GND Fault

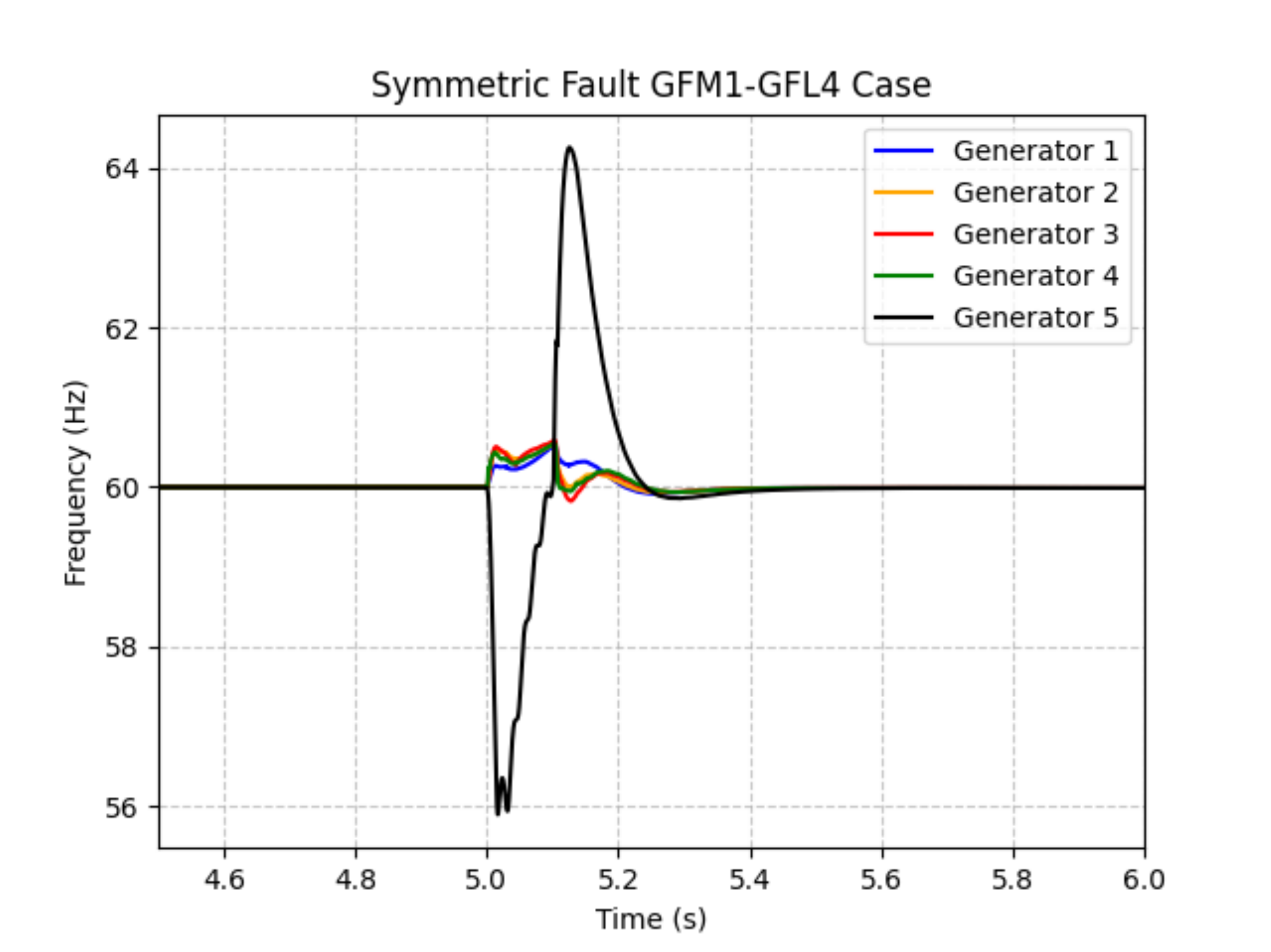


GFM2:GFL3

Single Phase to GND Fault

Symmetric to GND Fault

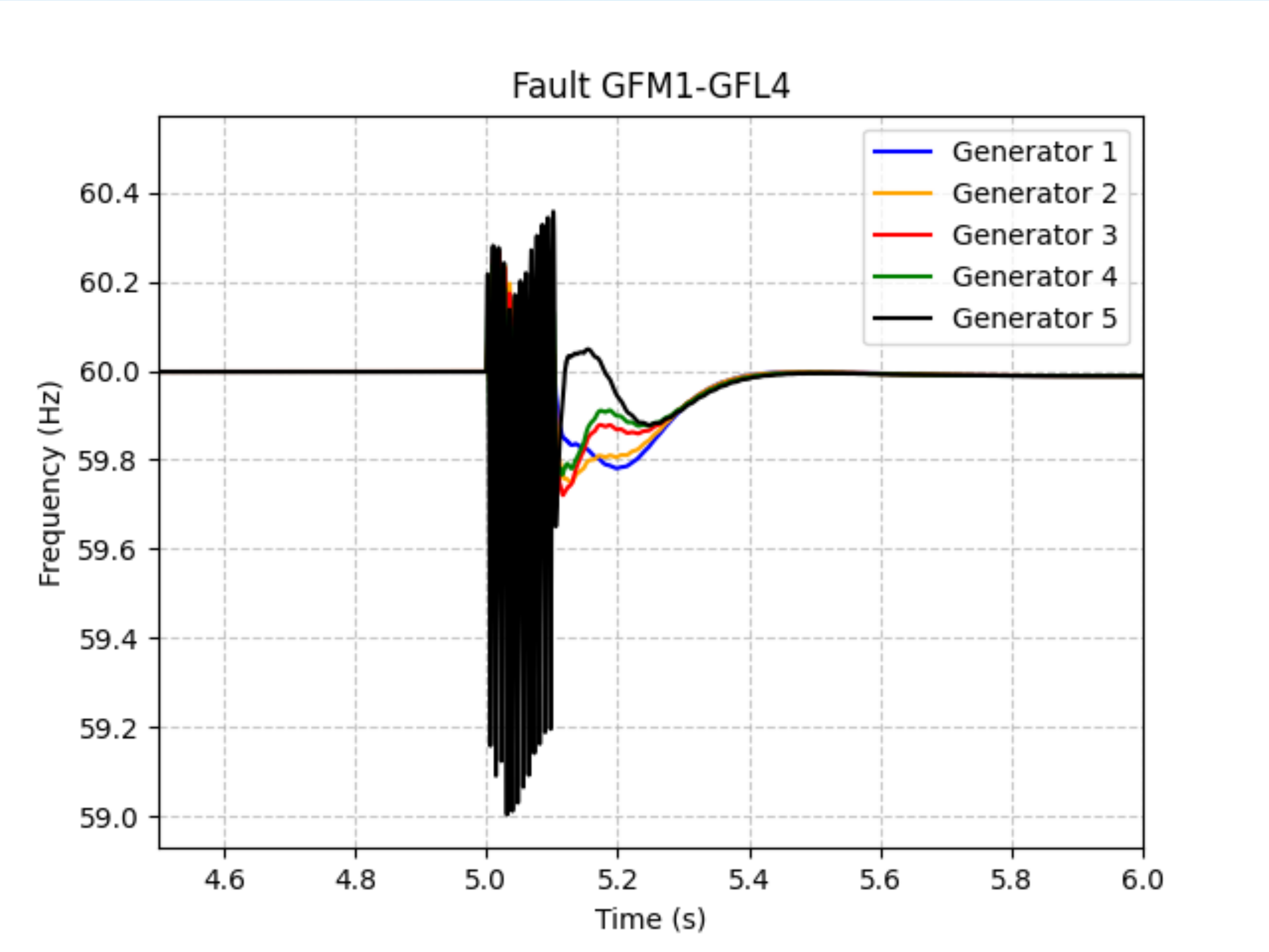


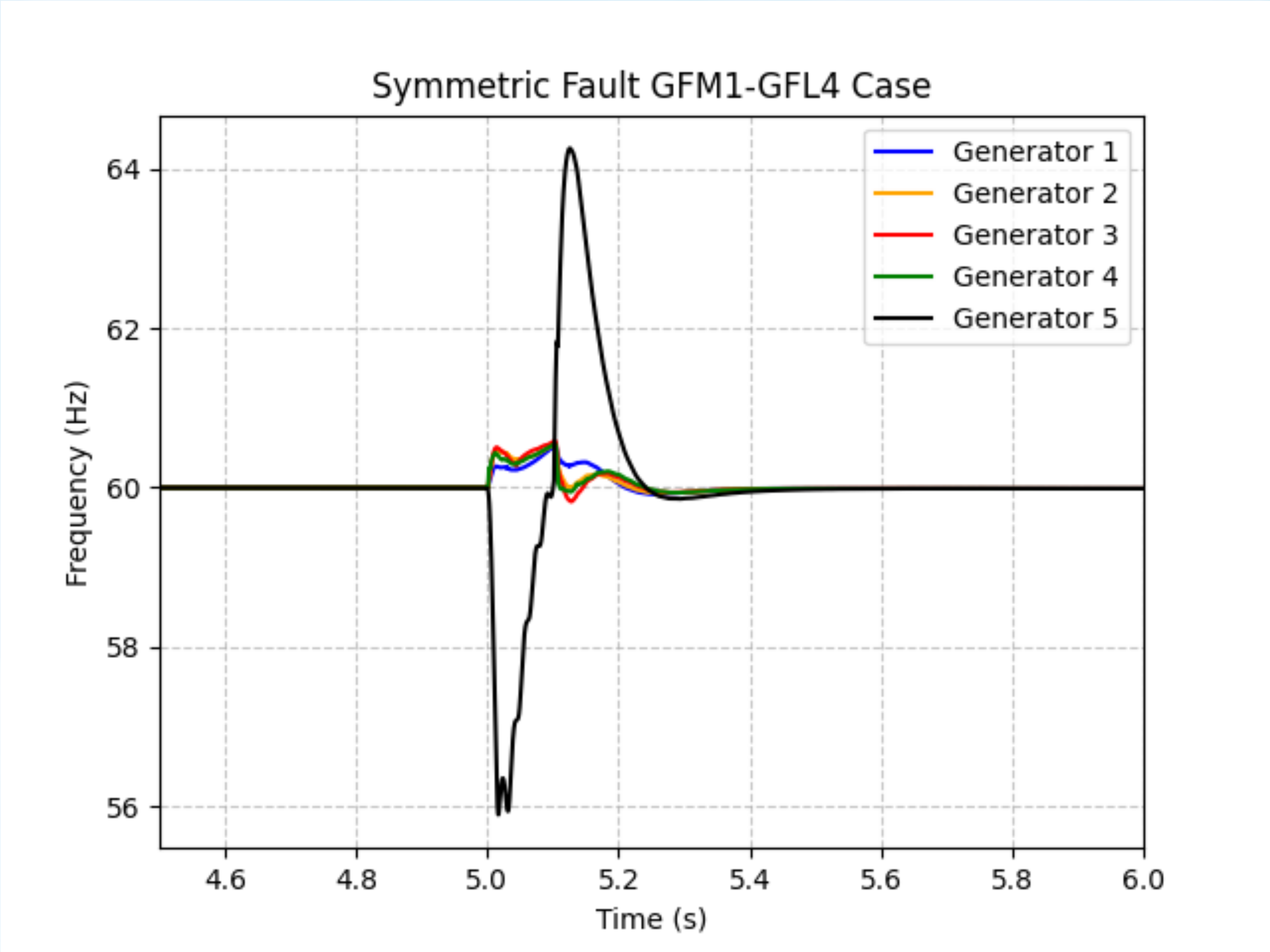


GFM1:GFL4

Single Phase to GND Fault

Symmetric to GND Fault

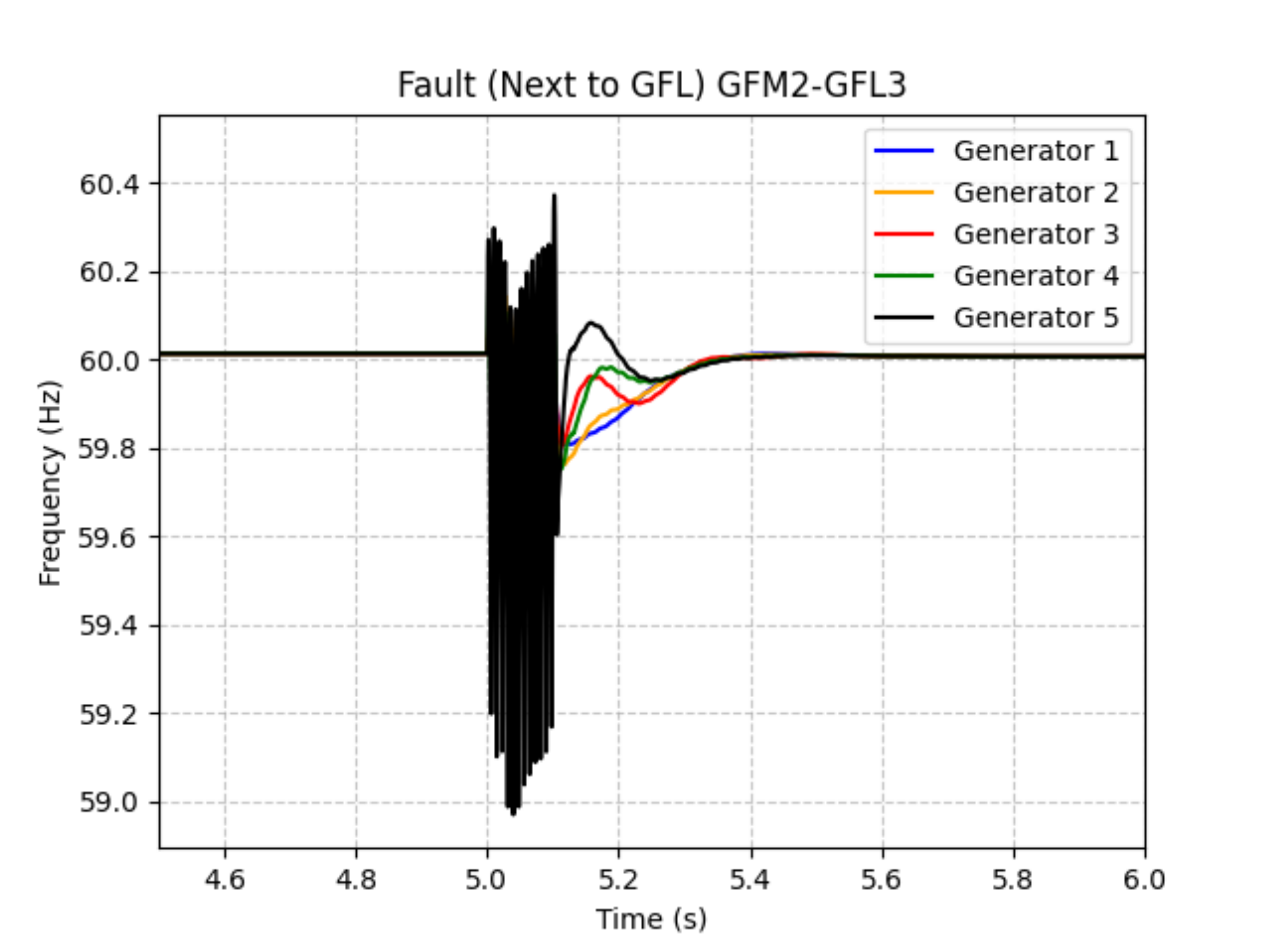




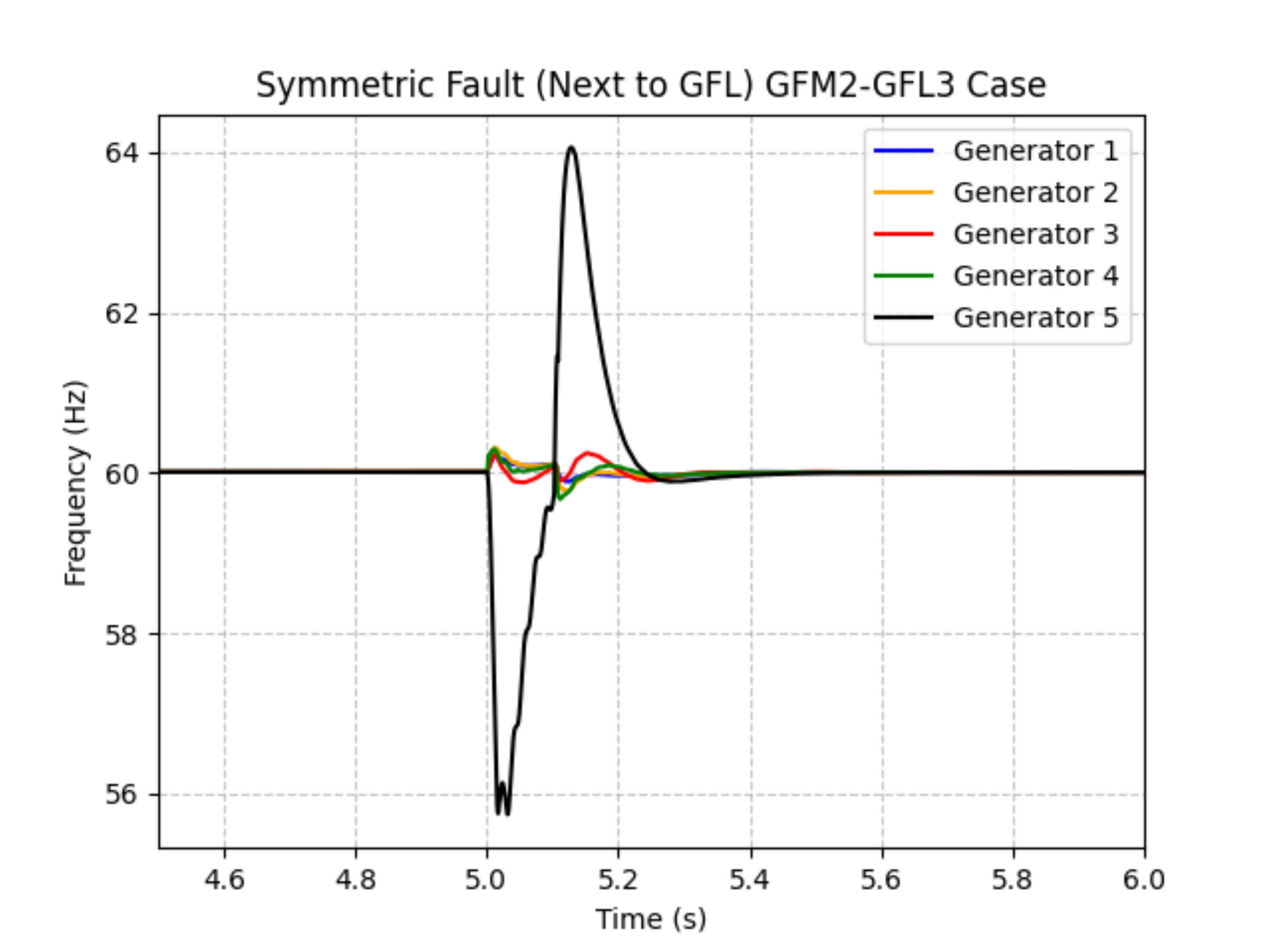
This looks so similar to Base Case when next a GFL…

GFM1:GFL4

Single Phase to GND Fault



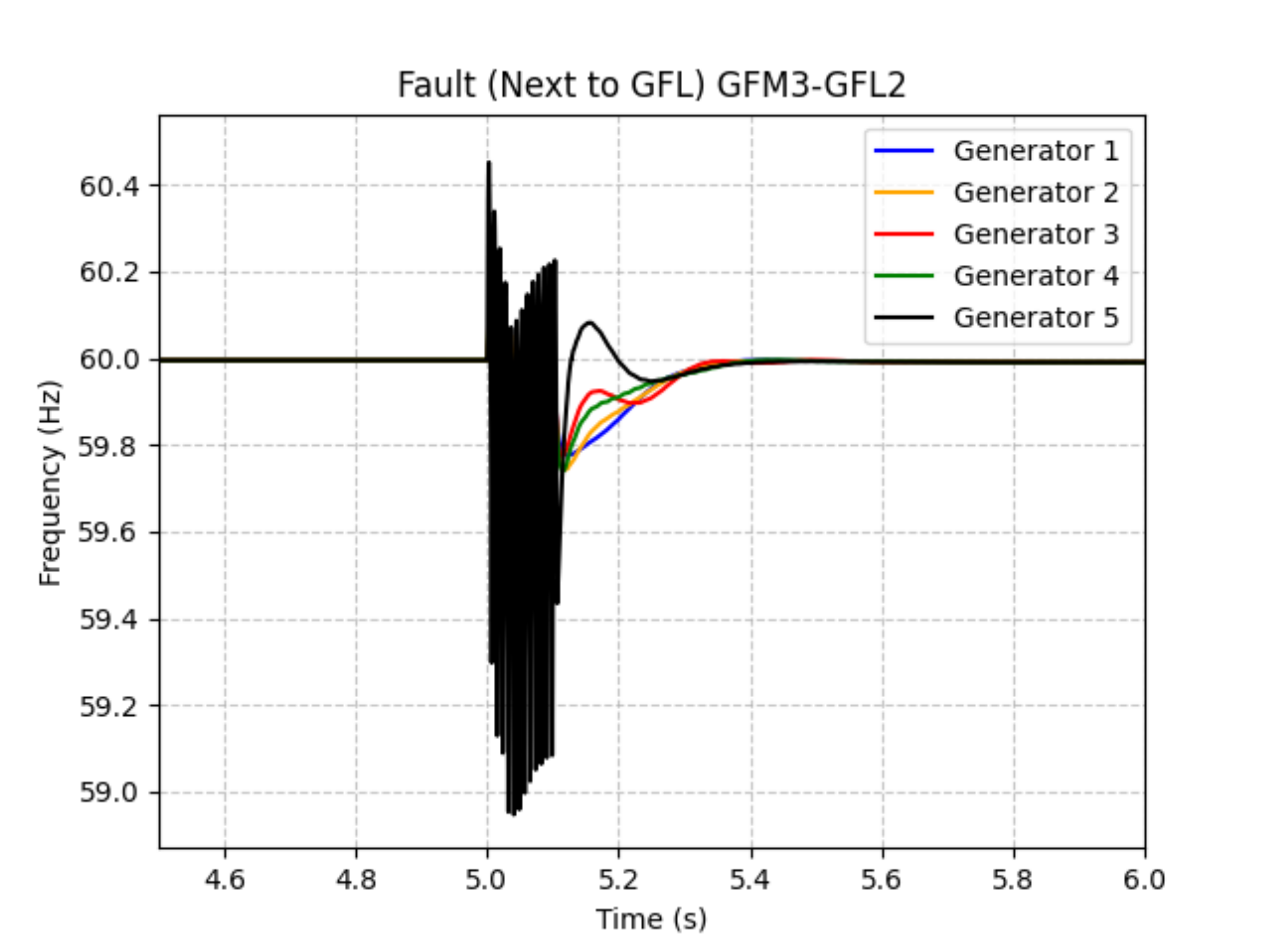
Symmetric to GND Fault

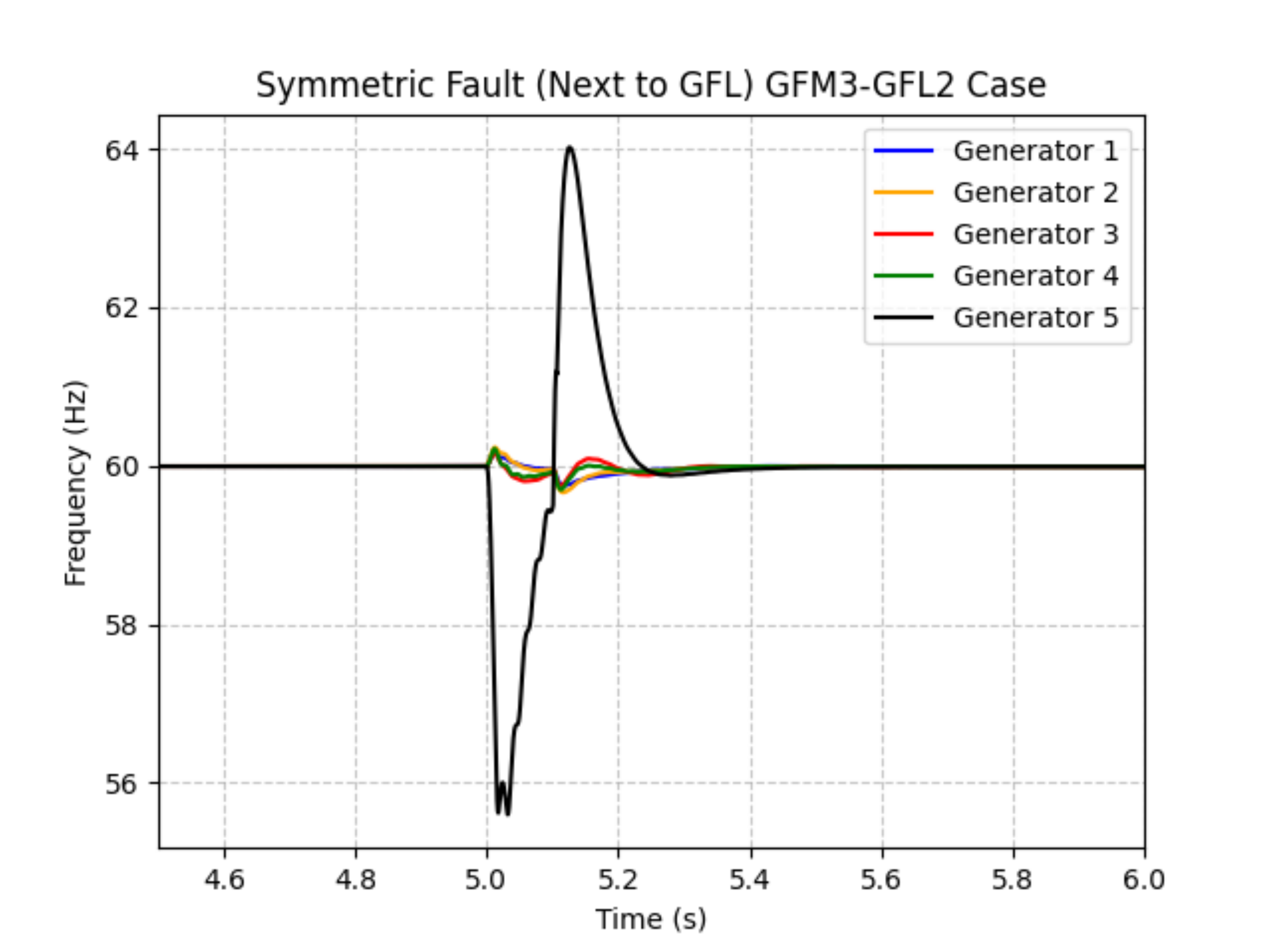


N-GFM2:GFL3

Single Phase to GND Fault

Symmetric to GND Fault

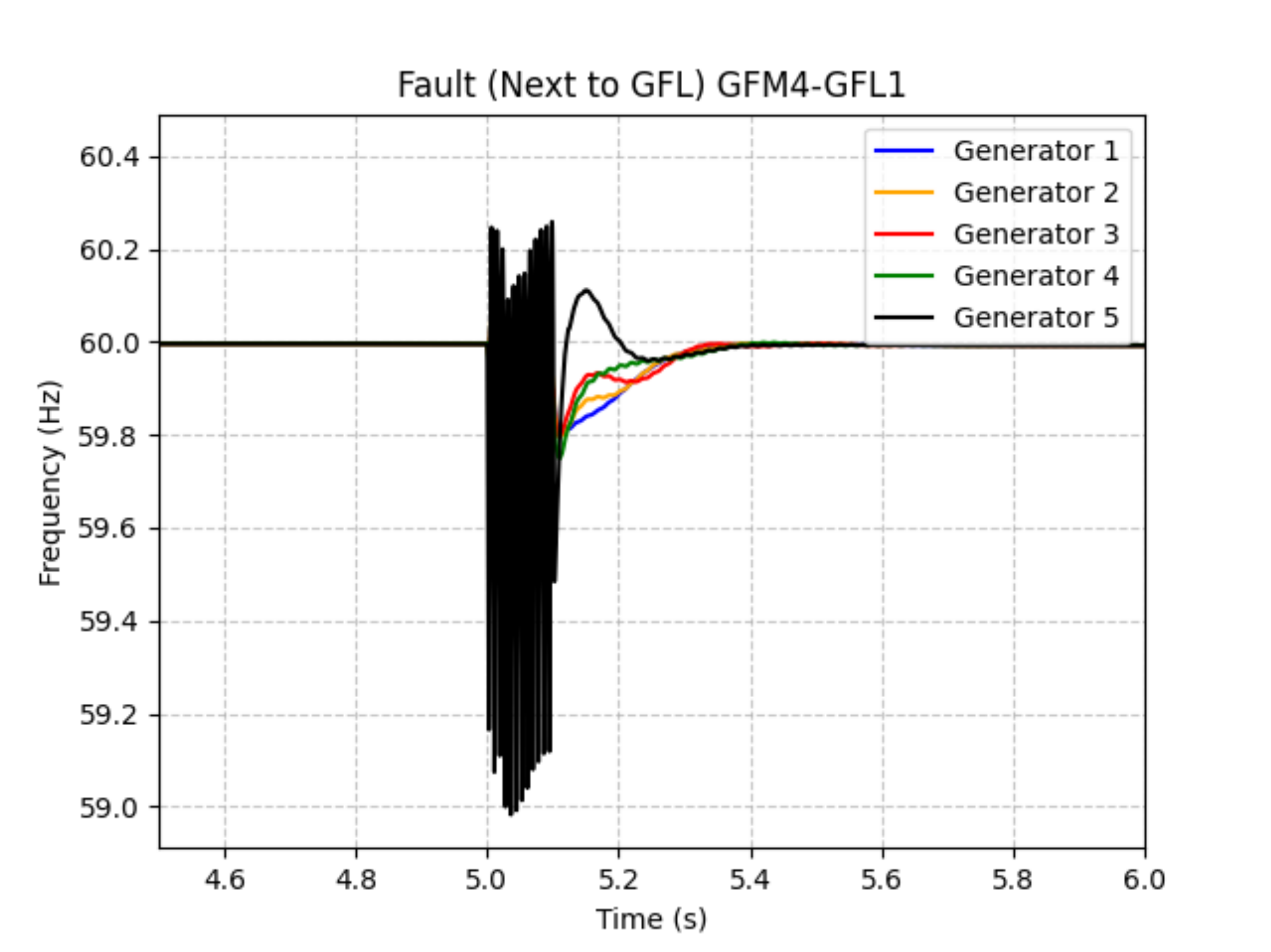


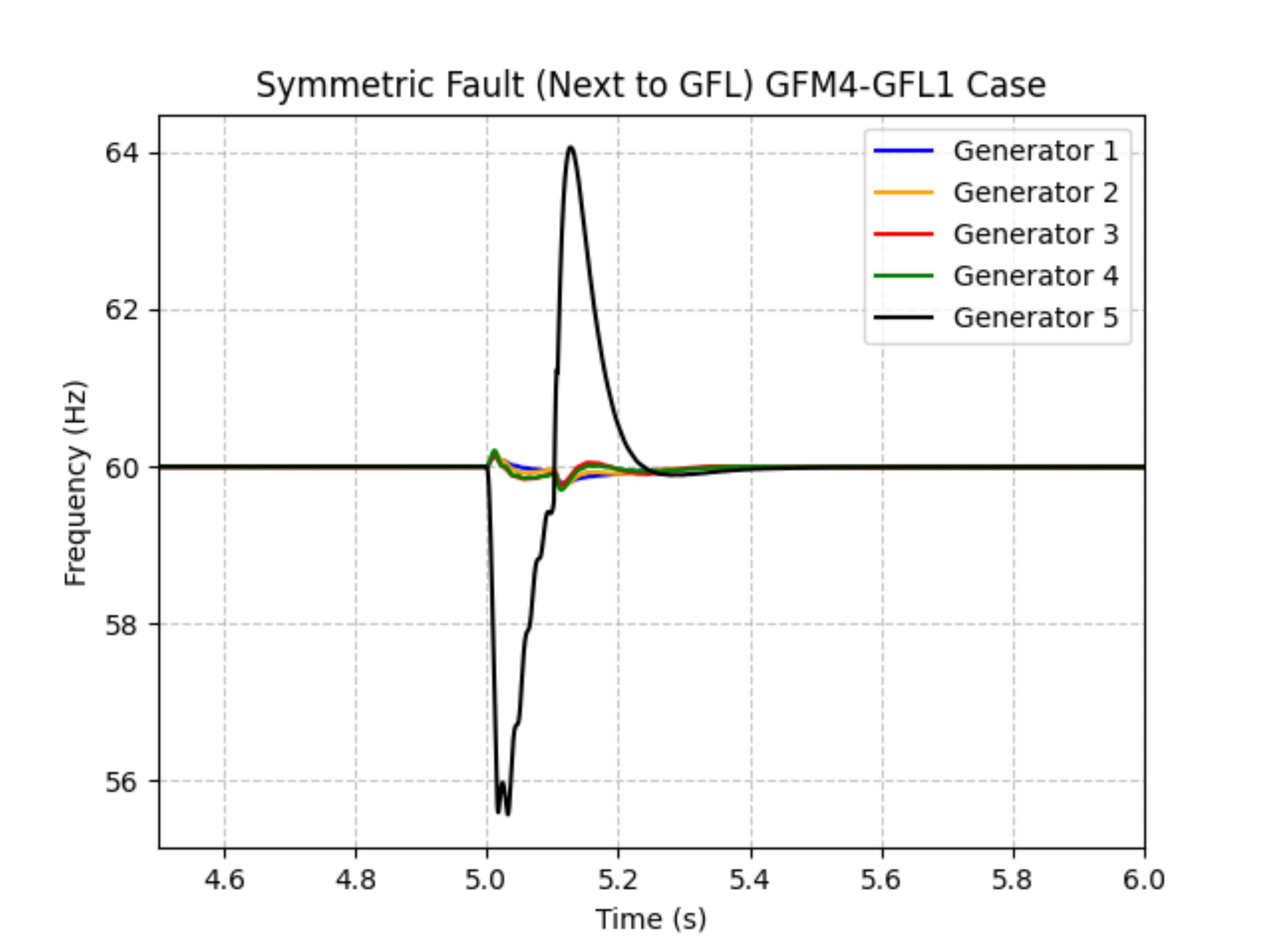


N-GFM3:GFL2

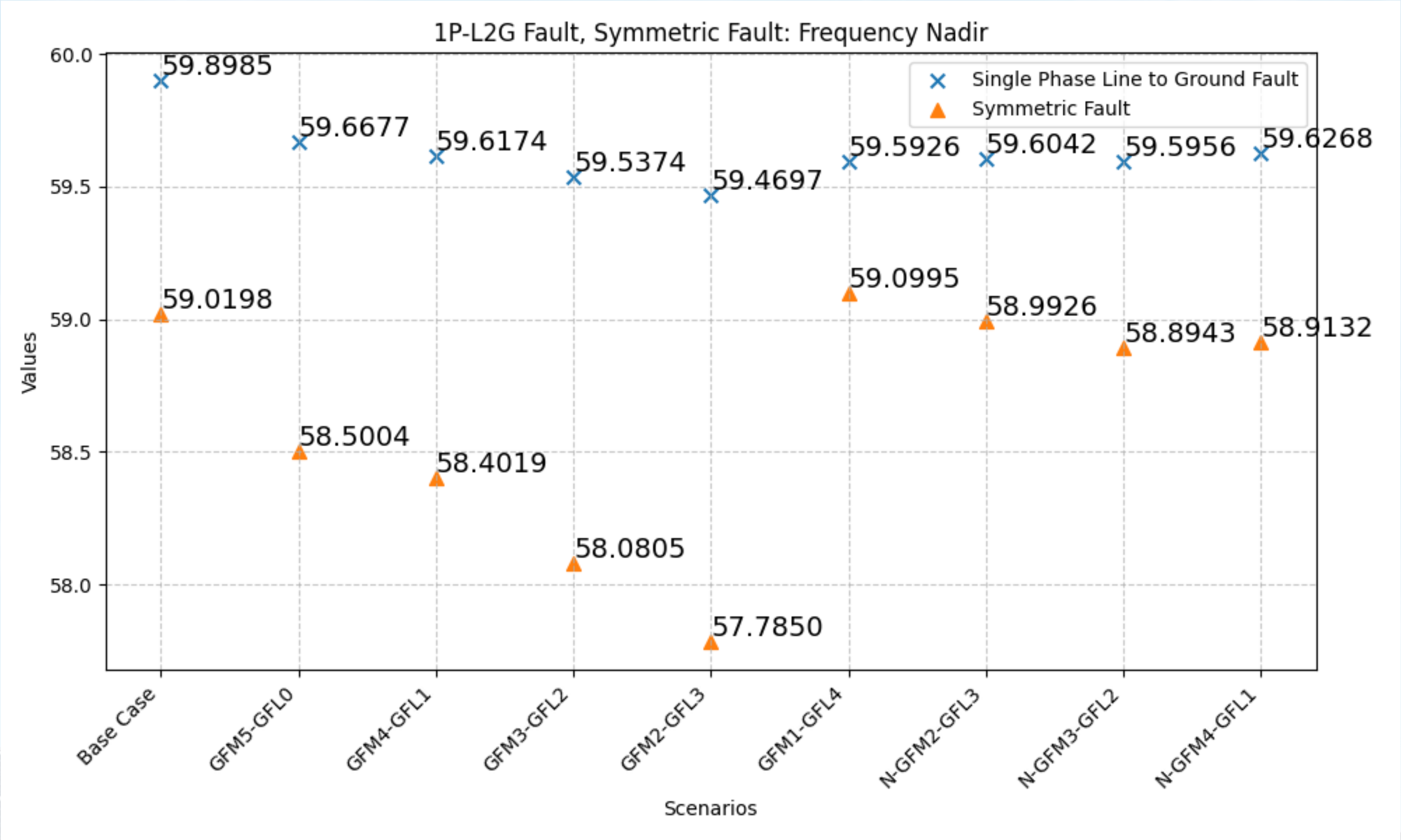
Single Phase to GND Fault

Symmetric to GND Fault

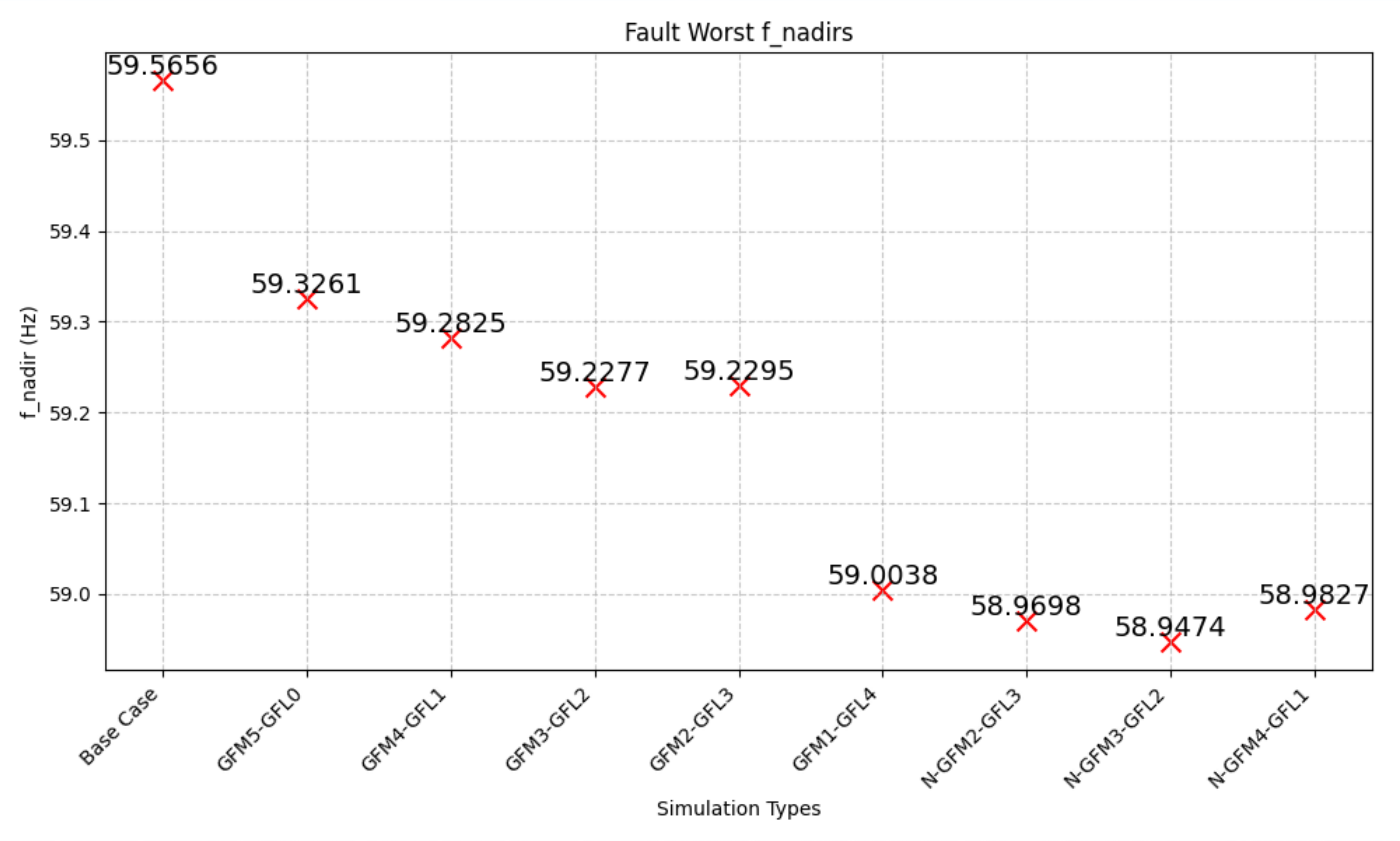




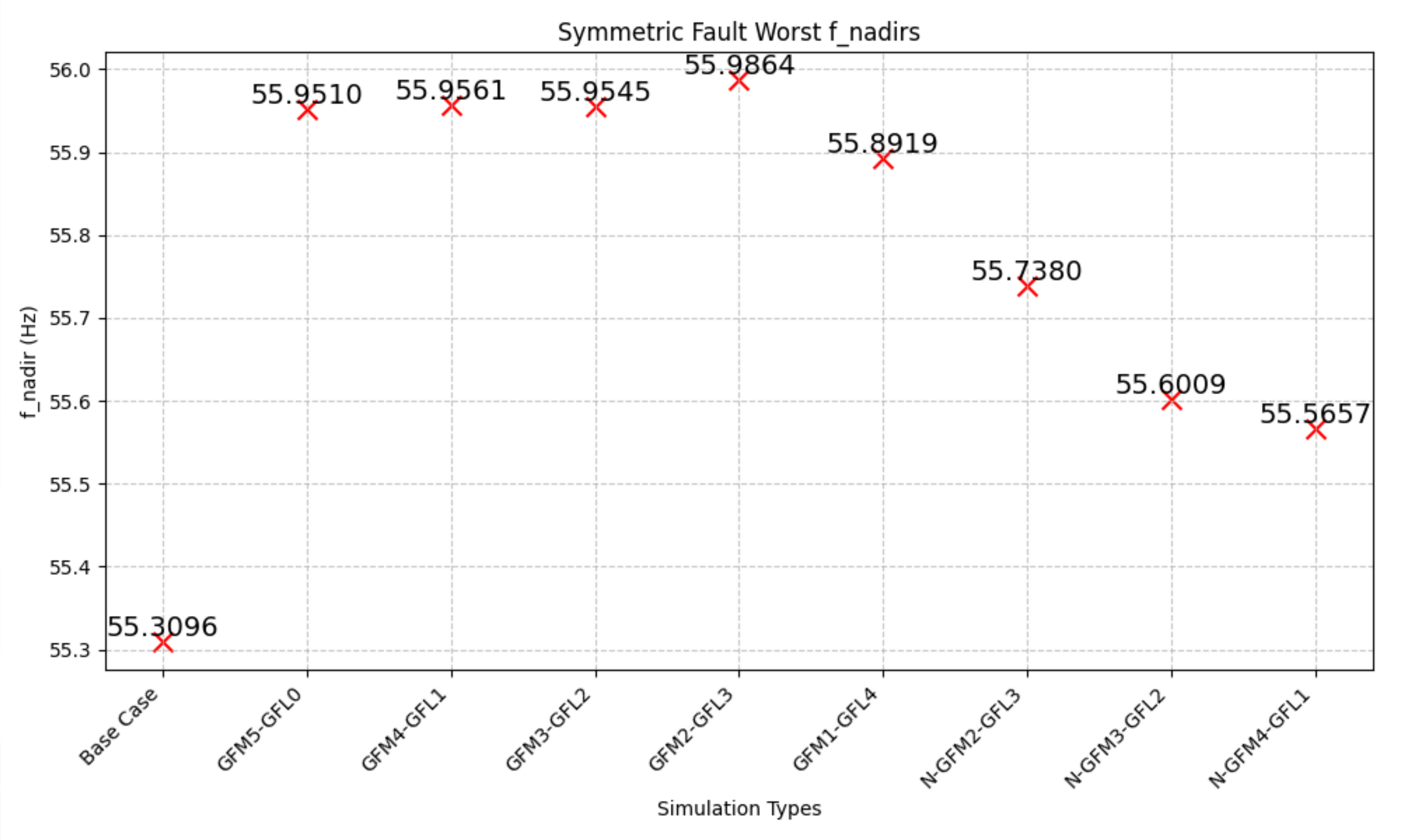
N-GFM4:GFL1



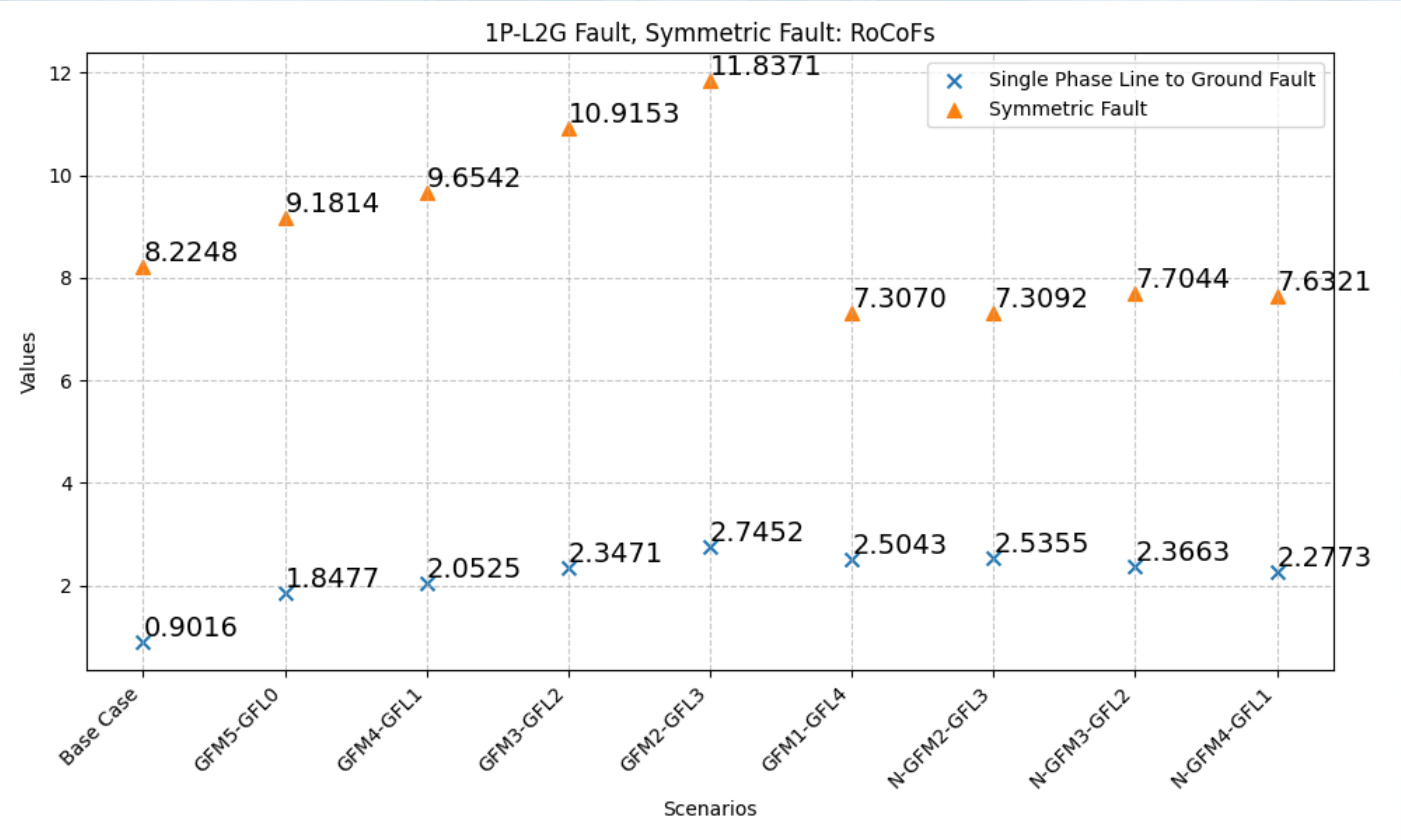
Fault and Symmetric Fault Changes Frequency Nadir



Fault: Worst Frequency Nadirs

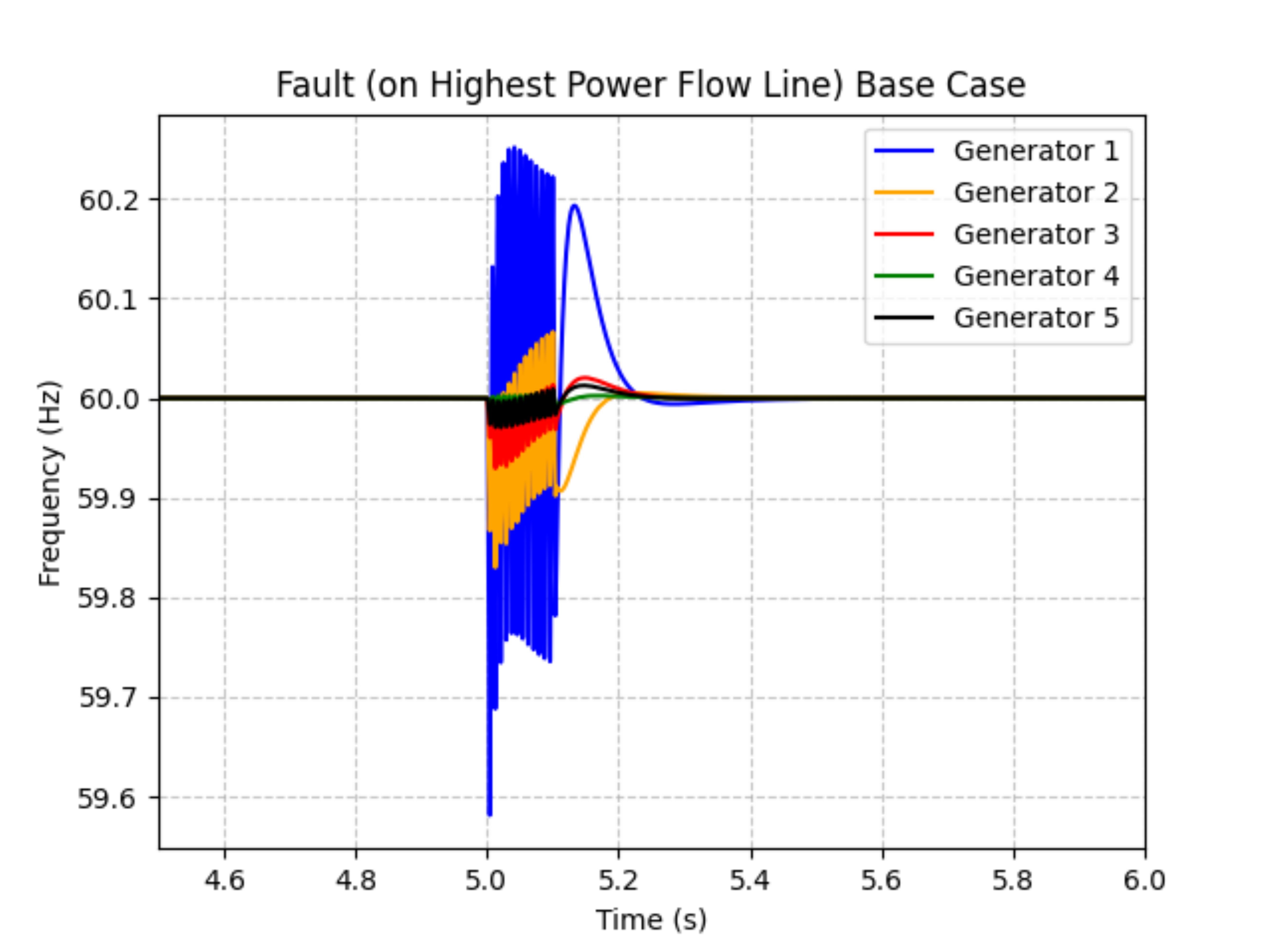


Symmetric Fault: Worst Frequency Nadirs



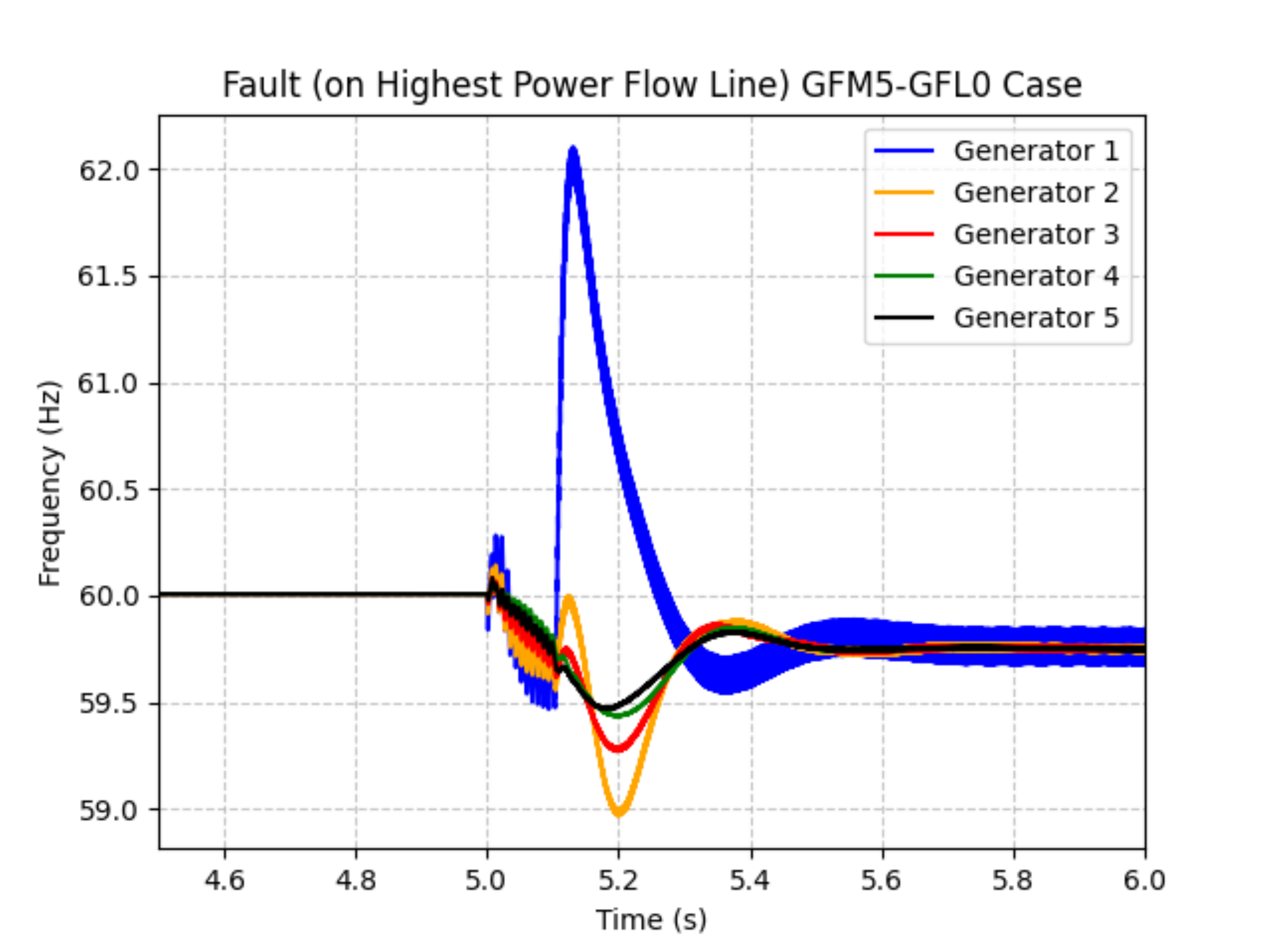
Faults and Symmetric Faults RoCoF

Single Phase to GND Fault on Highest Power Flow Transmission Line



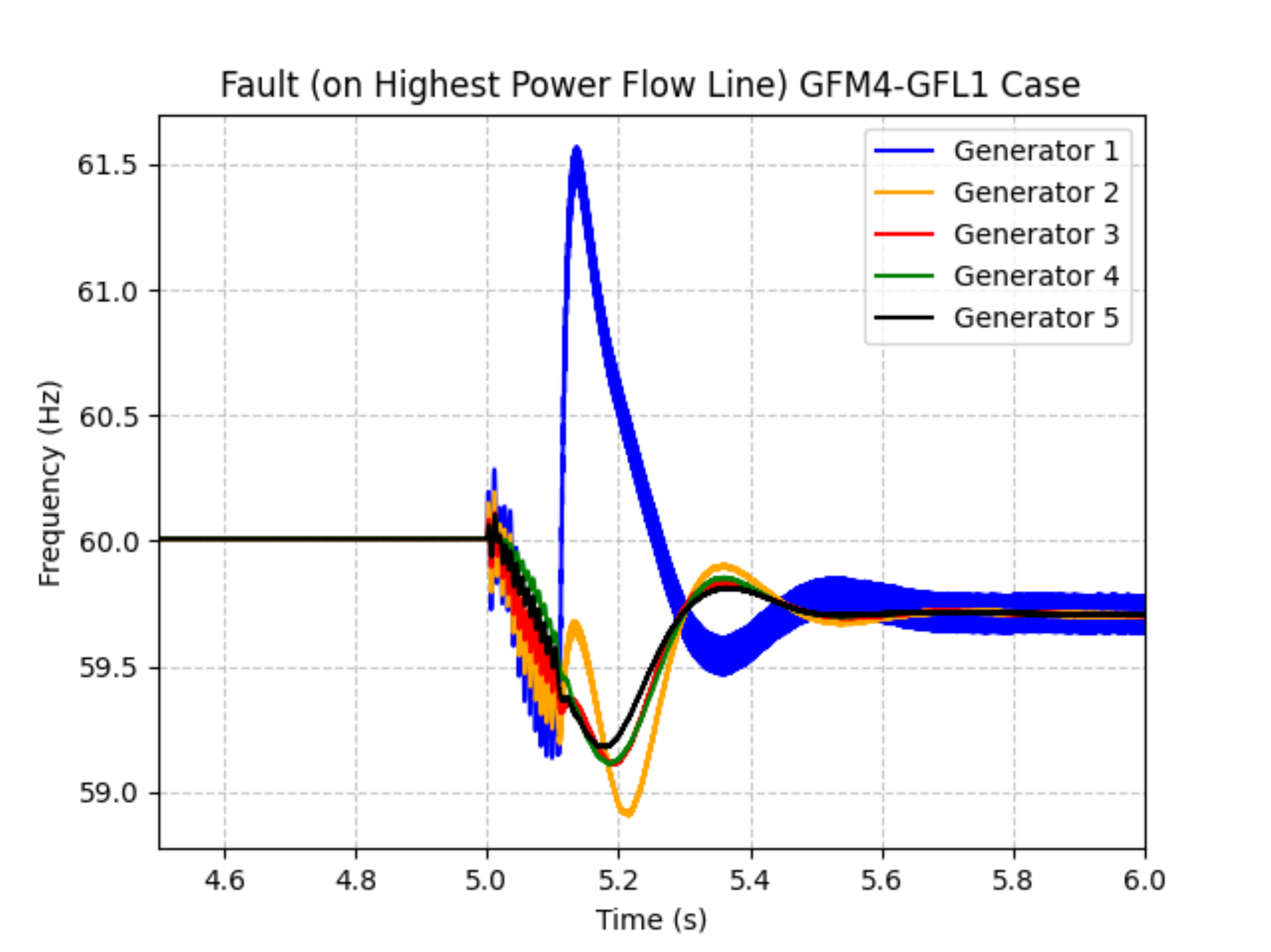
Base Case

Single Phase to GND Fault on Highest Power Flow Transmission Line



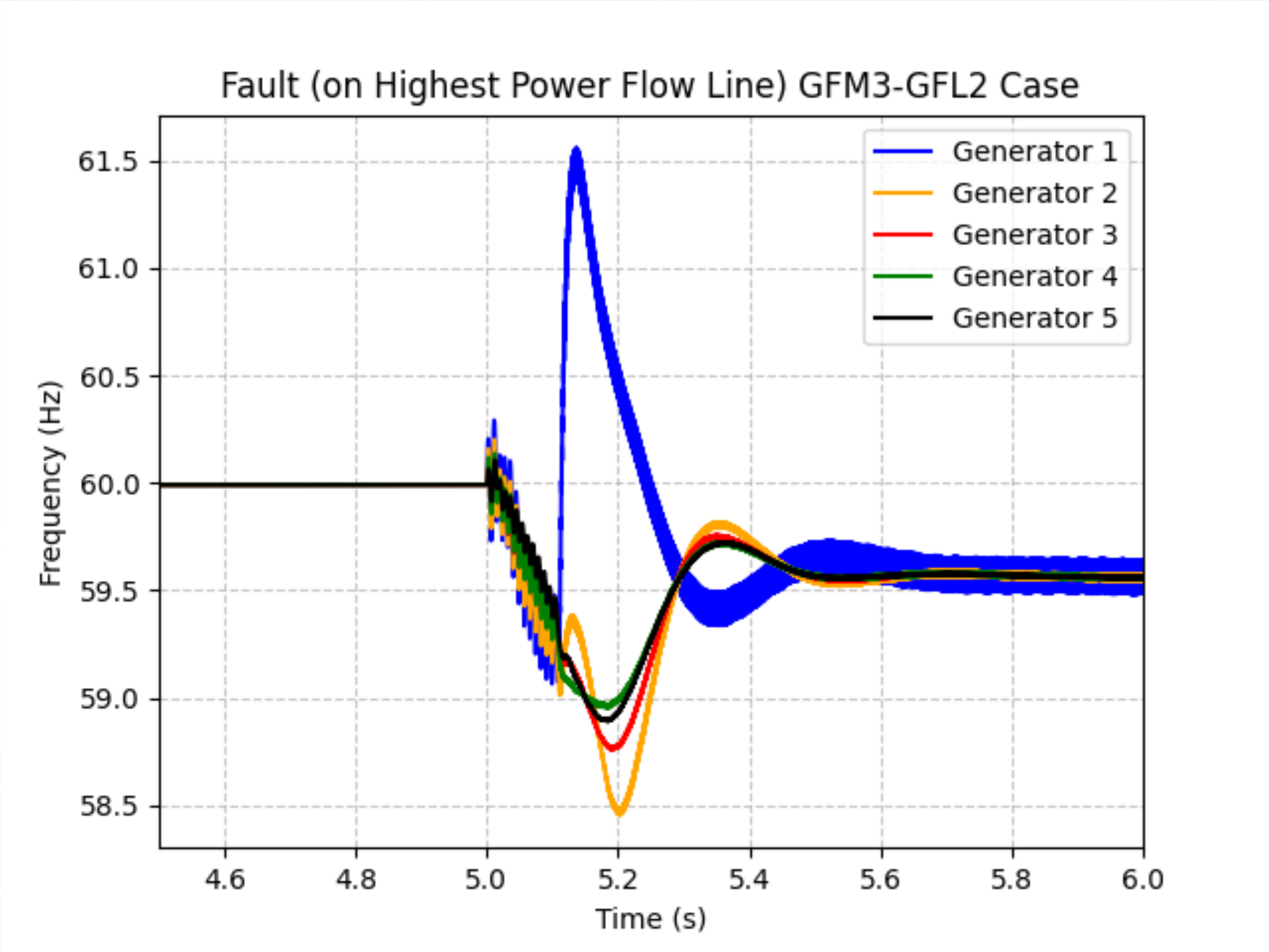
GFM5:GFL0

Single Phase to GND Fault on Highest Power Flow Transmission Line



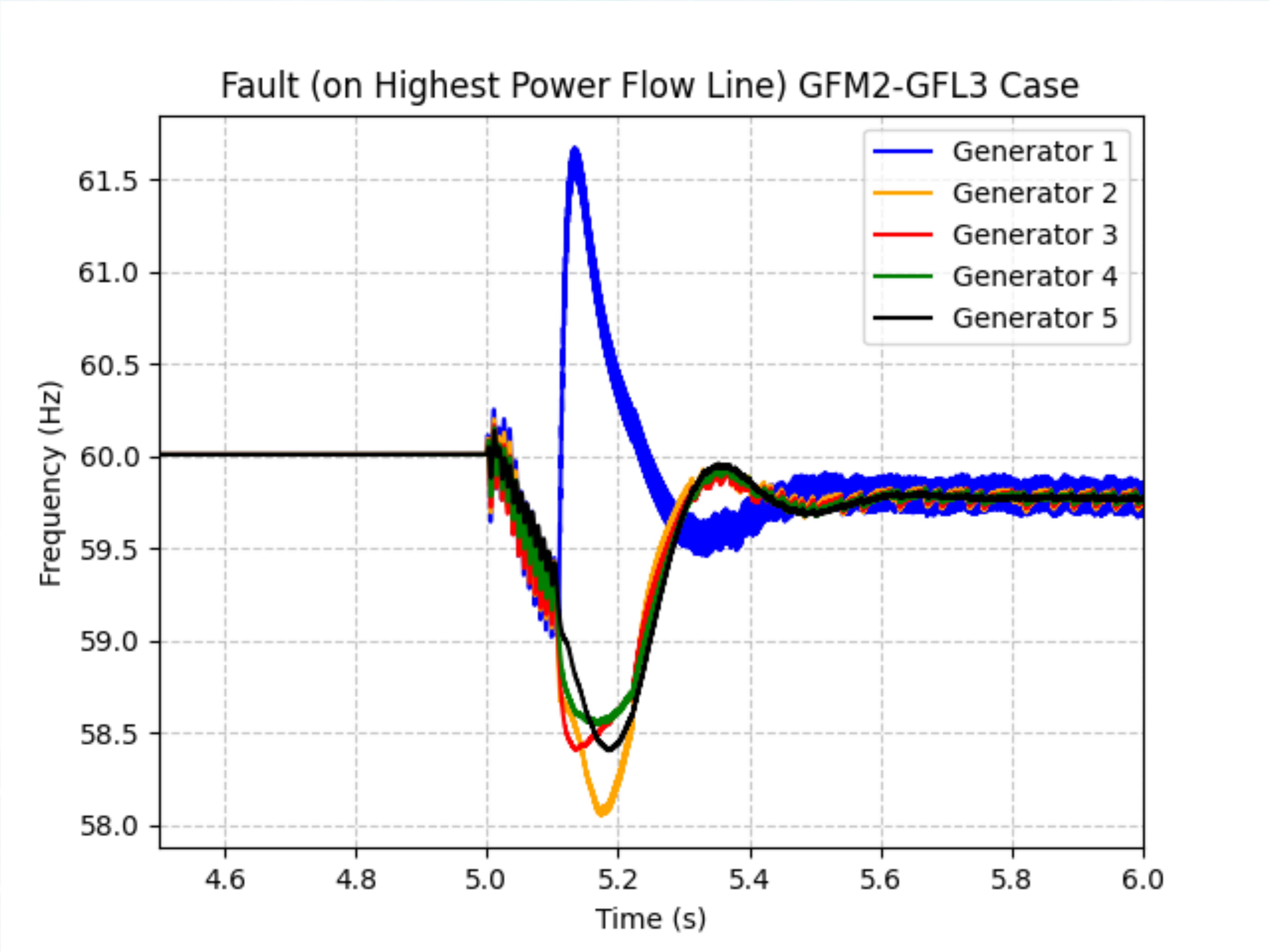
GFM4:GFL1

Single Phase to GND Fault on Highest Power Flow Transmission Line



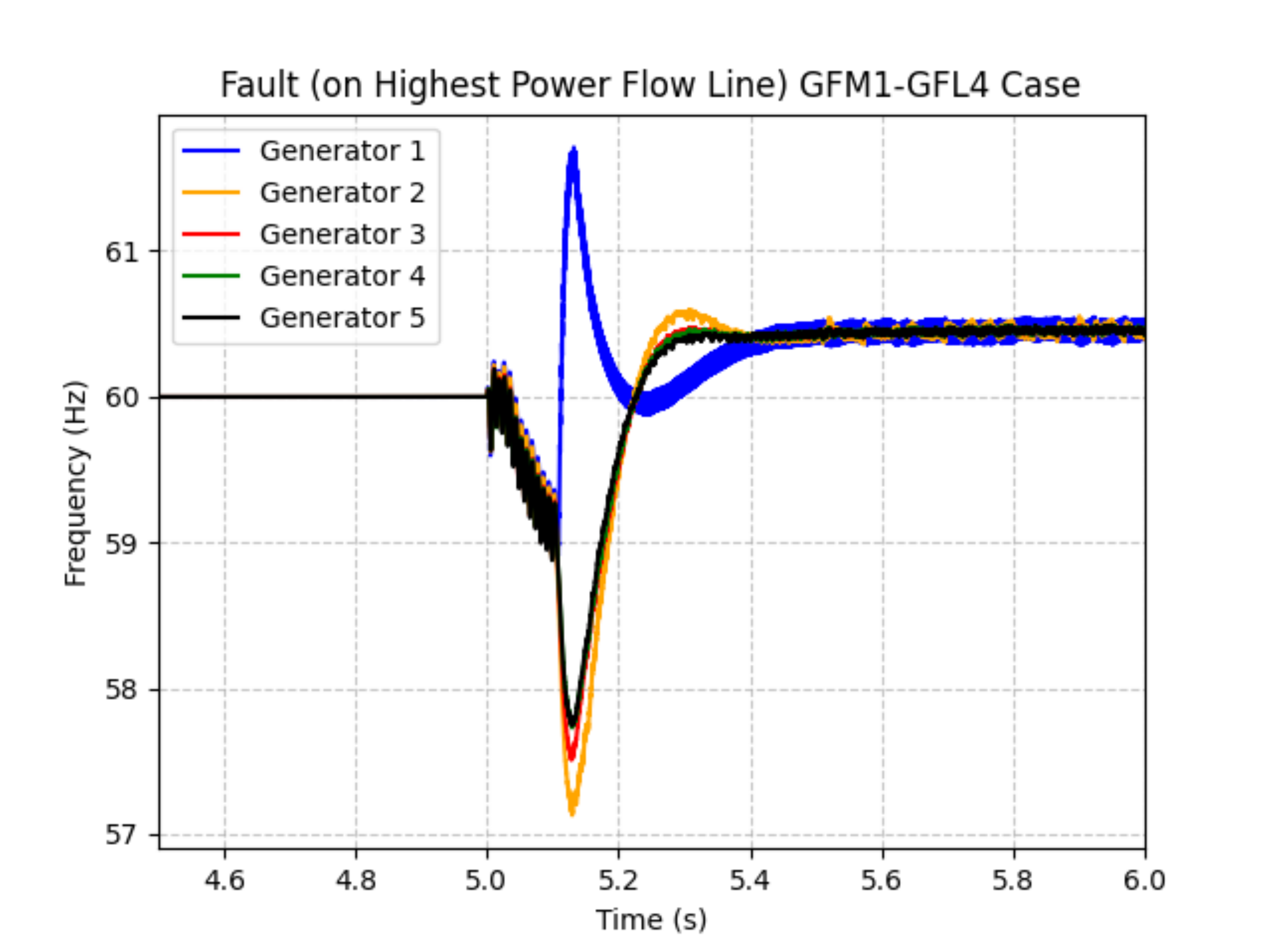
GFM3:GFL2

Single Phase to GND Fault on Highest Power Flow Transmission Line



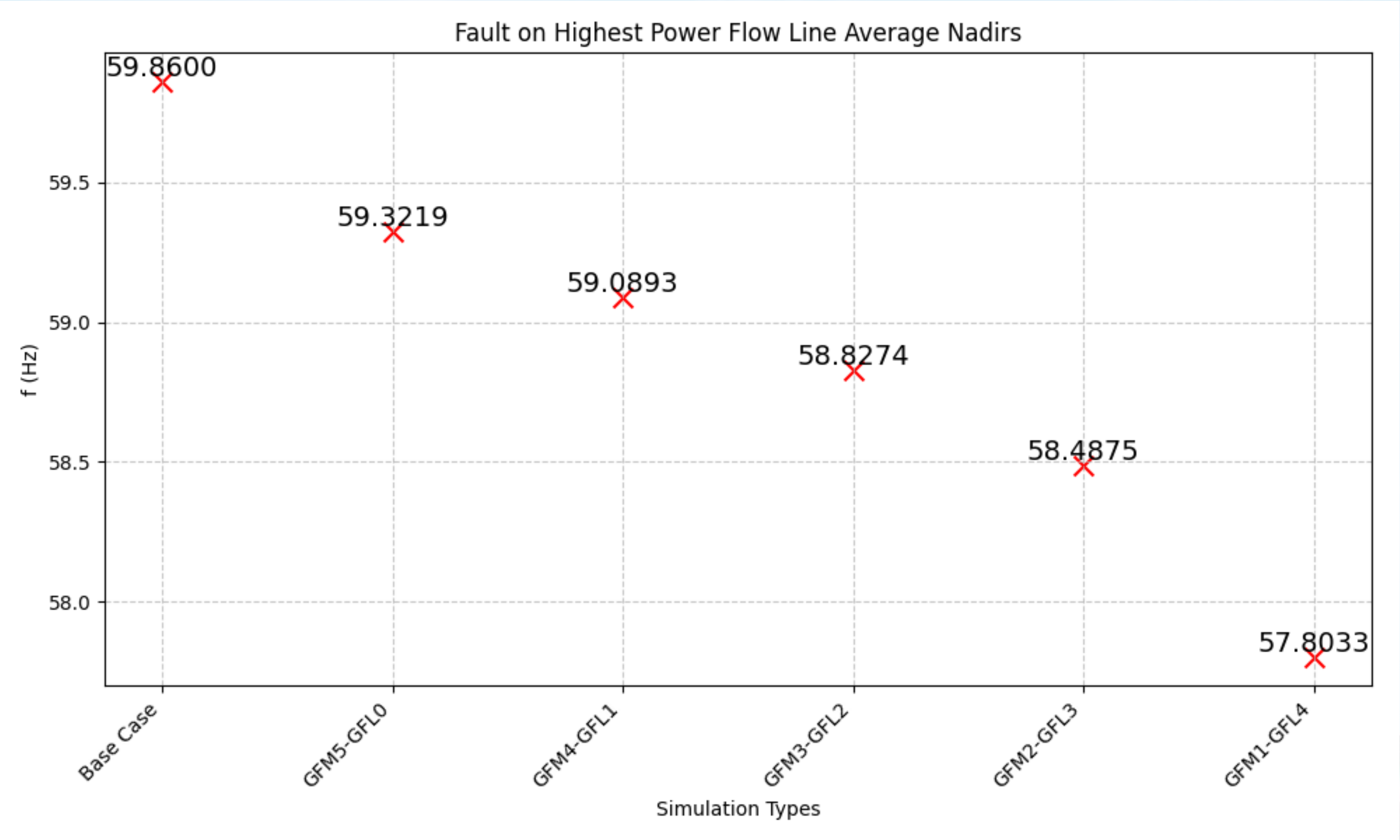
GFM2:GFL3

Single Phase to GND Fault on Highest Power Flow Transmission Line



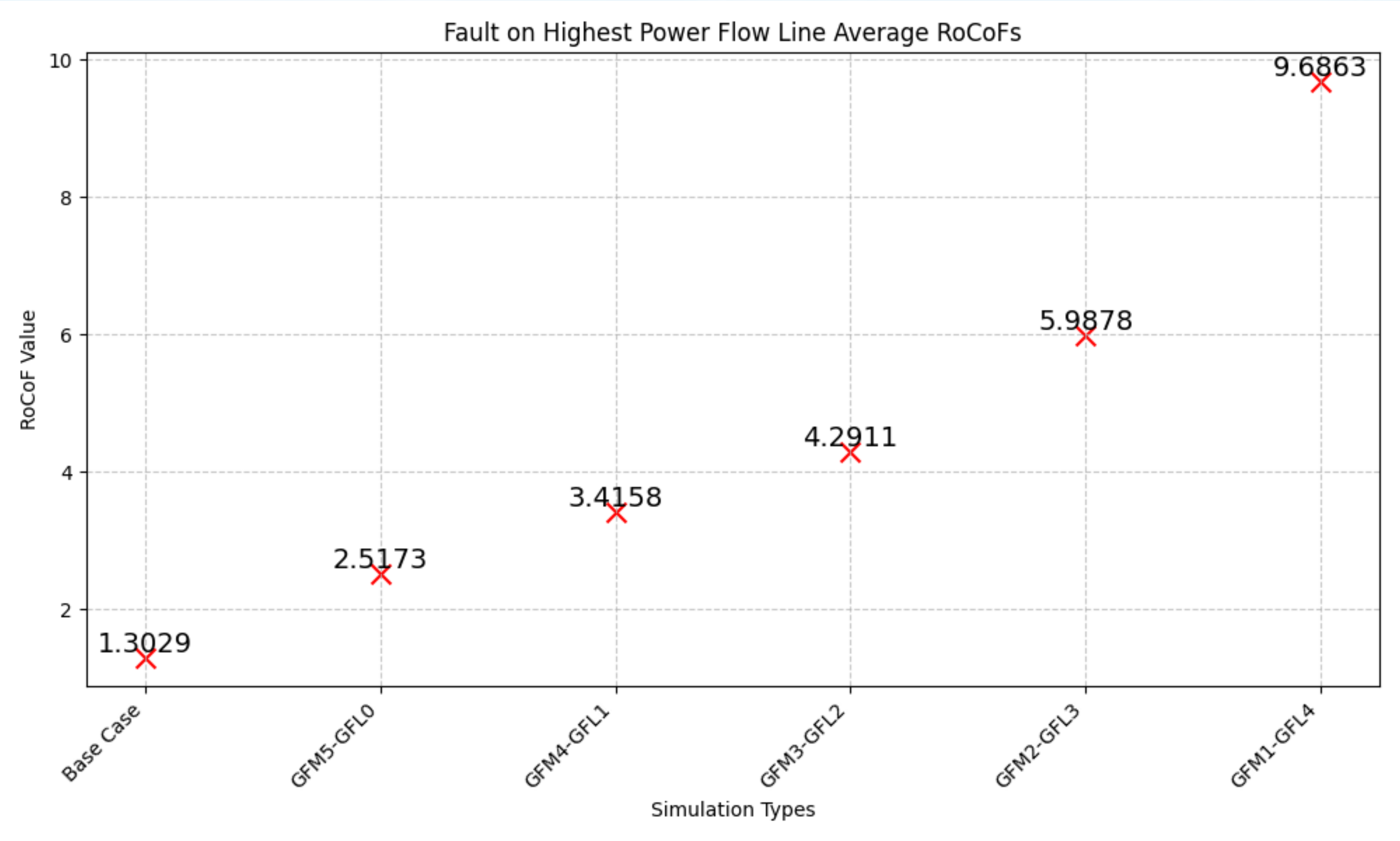
GFM1:GFL4

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.
  - Better start putting GFMs early into the grid.

References

[1] P. Denholm et. al. “Inertia and the Power Grid: A Guide without the Spin”, National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NLEL/TP-6A20-73856

[2] D. B. Rathnayake et al., "Grid Forming Inverter Modeling, Control, and Applications," in IEEE Access, vol. 9, pp. 114781-114807, 2021, doi: 10.1109/ACCESS.2021.3104617.

[3] C. Henderson, A. Egea-Alvarez, T. Kneuppel, G. Yang and L. Xu, "Grid Strength Impedance Metric: An Alternative to SCR for Evaluating System Strength in Converter Dominated Systems," in IEEE Transactions on Power Delivery, doi: 10.1109/TPWRD.2022.3233455.

[4] Y. Li, Y. Gu and T. C. Green, "Revisiting Grid-Forming and Grid-Following Inverters: A Duality Theory," in IEEE Transactions on Power Systems, vol. 37, no. 6, pp. 4541-4554, Nov. 2022, doi: 10.1109/TPWRS.2022.3151851.

[5] W. Qiu et al., "A Grid Forming/Following Sequence Switching Control Strategy for Supporting Frequency Stability of Isolated Power Grids," 2023 5th Asia Energy and Electrical Engineering Symposium (AEEES), Chengdu, China, 2023, pp. 212-217, doi: 10.1109/AEEES56888.2023.10114155.

[6] R. W. Kenyon, A. Sajadi, A. Hoke and B. -M. Hodge, "Open-Source PSCAD Grid-Following and Grid-Forming Inverters and A Benchmark for Zero-Inertia Power System Simulations," 2021 IEEE Kansas Power and Energy Conference (KPEC), Manhattan, KS, USA, 2021, pp. 1-6, doi: 10.1109/KPEC51835.2021.9446243.

[7] A. Yazdani, R. Iravani. “Voltage-Sourced Converters in Power Systems: Modelling, Control, and Applications”, Toronto: IEEE. Press, 2010.