Case Studies of the Stability Benefit of Grid Forming Inverters on Energy Storage Facilities

CIGRE US National Committee 2023 Grid of the Future Symposium (Accepted)

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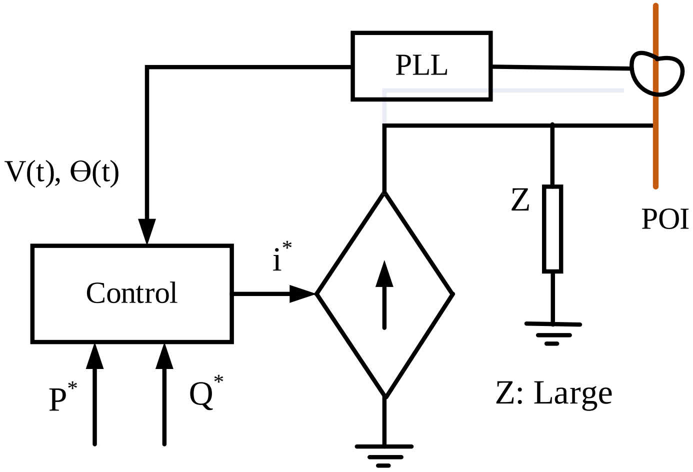
Outline

- Overview of Grid-Forming (GFM) vs Grid-Following (GFL)
- Summary of EPRI positive sequence generic GFM model
- Available control modes in EPRI GFM model
- Positive sequence simulation case studies:
  - Case 1: 230 kV station in Oklahoma
  - Case 2: 345/138 kV station in ERCOT
  - Case 3: 138 kV GTC area in ERCOT
- Conclusion and future directions

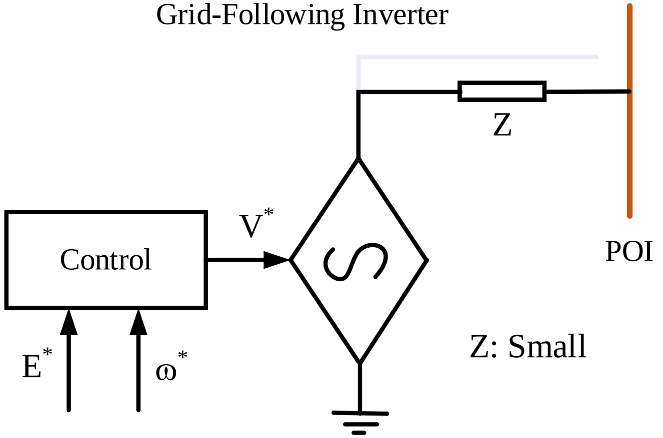
Control Comparison: GFL vs GFM

Grid Following: Adjust output to track external voltage reference synchronizing to grid voltage via PLL.

Grid Forming: Set internal voltage reference while synchronizing to grid independent of grid voltage angle and without PLL.



Grid-Following Inverter



Grid-Forming Inverter

Source: https://www.nerc.com/comm/Documents/NERC_IBR_Strategy.pdf

GFL Summary

- All inverters in ERCOT power grid are grid following (GFL).
- GFL behaves like a controlled current source.
- Inverters with GFL control do not contribute to system inertia and very little to short circuit capacity.
- GFL requires a reasonably stable grid voltage reference.
- Offer fast frequency response (FFR) in a short time delay, for frequency measurement and control response.
- Do not serve as an initial black-start source.

GFM Summary

- Grid-Forming (GFM) can improve stability in weak grid areas.
- GFM behaves as a controlled voltage source.
- GFM does not depend on stable external grid voltage for its own stable operation.
- Can operate in isolated grids without synchronous generators.
- May serve as an initial black-start source if it designed for that purpose.

Examples of GFM activities

GFM BESS Projects Deployed or under construction			
Project Name	**Location**	**Size (MW)**	**Time**
Project #1	Kuai, USA	13	2018
Kuai PMRF	Kuai, USA	14	2022
Kapolei Energy Storage	Hawaii, USA	185	2023
Hornsdale Power reserve	Australia	150	2022
Wallgrove	Australia	50	2022
Broken Hill BESS	Australia	50	2023
Riverina and Darlington point	Australia	150	2023
New England BESS	Australia	50	2023
Dalrymple	Australia	30	2018
Blackhillock	Great Britain	300	2024
Bordesholm	Germany	15	2019

https://www.nerc.com/comm/RSTC_Reliability_Guidelines/White_Paper_GFM_Spec_BESS.pdf

EPRI Positive Sequence GFM Model

- The positive sequence generic GFM model should not be used for black start studies. However, it can be used for system separation studies.
- Positive sequence models are not suitable for study of unbalanced events.
- The default values of control gains shown in the reference documents and associated example files are meant to be treated as a starting point. Their values may need to be changed depending on, and not limited to,

  a. Different ratings or operating conditions.

  b. Different network topologies.

  c. Different load dynamic characteristics.

  d. Different number of varied source device characteristics.

Source: https://www.wecc.org/Administrative/Ramasubramanian_Proposal%20for%20Generic%20Grid%20Forming%20(GFM)%20Model.pdf

https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Memo%20on%20Proposal%20for%20Generic%20GFM%20Model_v2.pdf&action=default&DefaultItemOpen=1

Control Modes in EPRI GFM

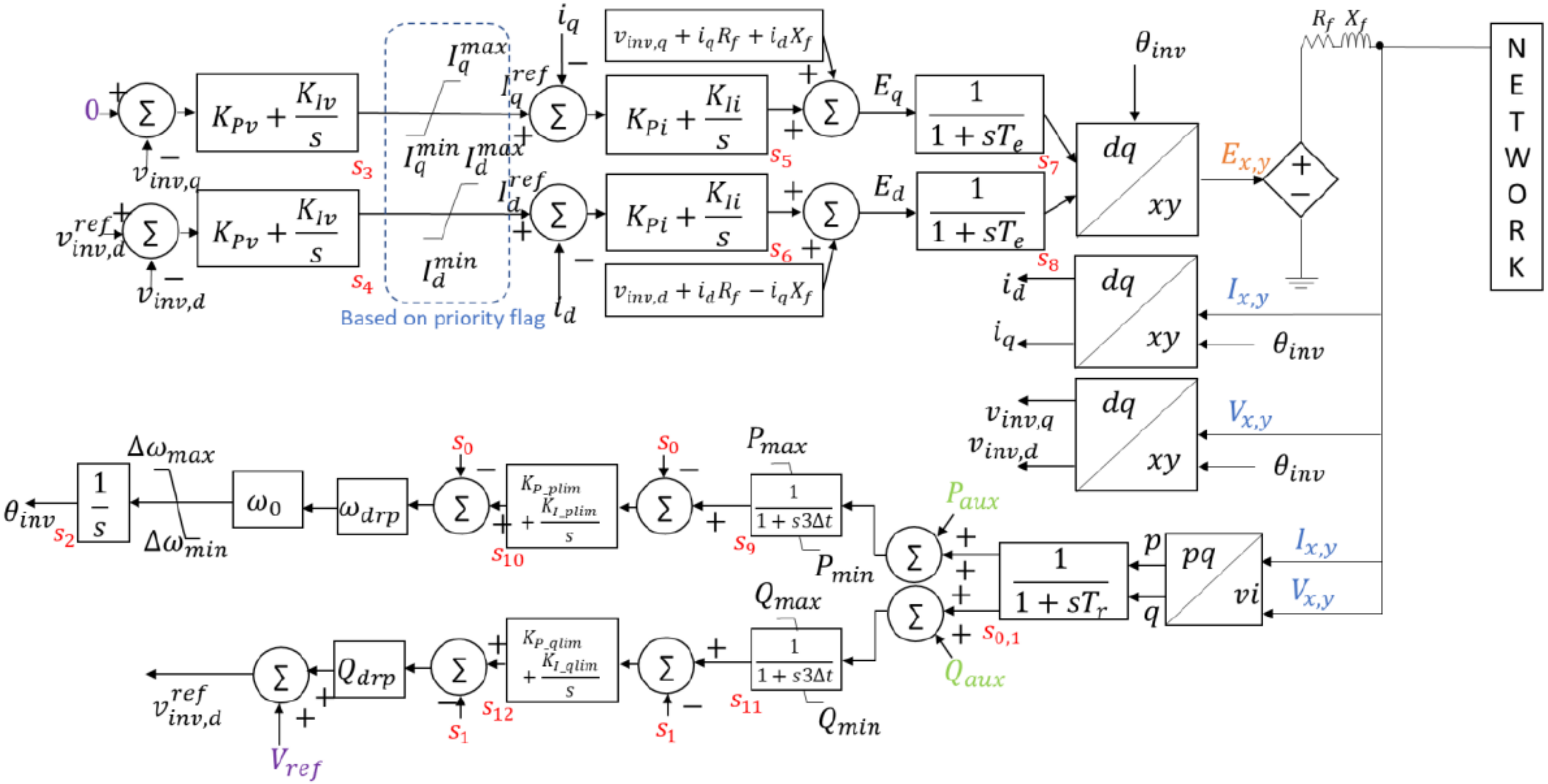
The suite of generic GFM models can represent, in a general way, three different types of GFM control methods that have been proposed in the literature. These methods are:

1. Droop based GFM
2. Virtual Synchronous Machine (VSM) based GFM
3. Dispatchable Virtual Oscillator (dVOC) based GFM

The more details and control block diagrams are provided in EPRI reference document :

https://www.wecc.org/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/Memo%20on%20Proposal%20for%20Generic%20GFM%20Model_v2.pdf&action=default&DefaultItemOpen=1

Generic model of droop-based GFM



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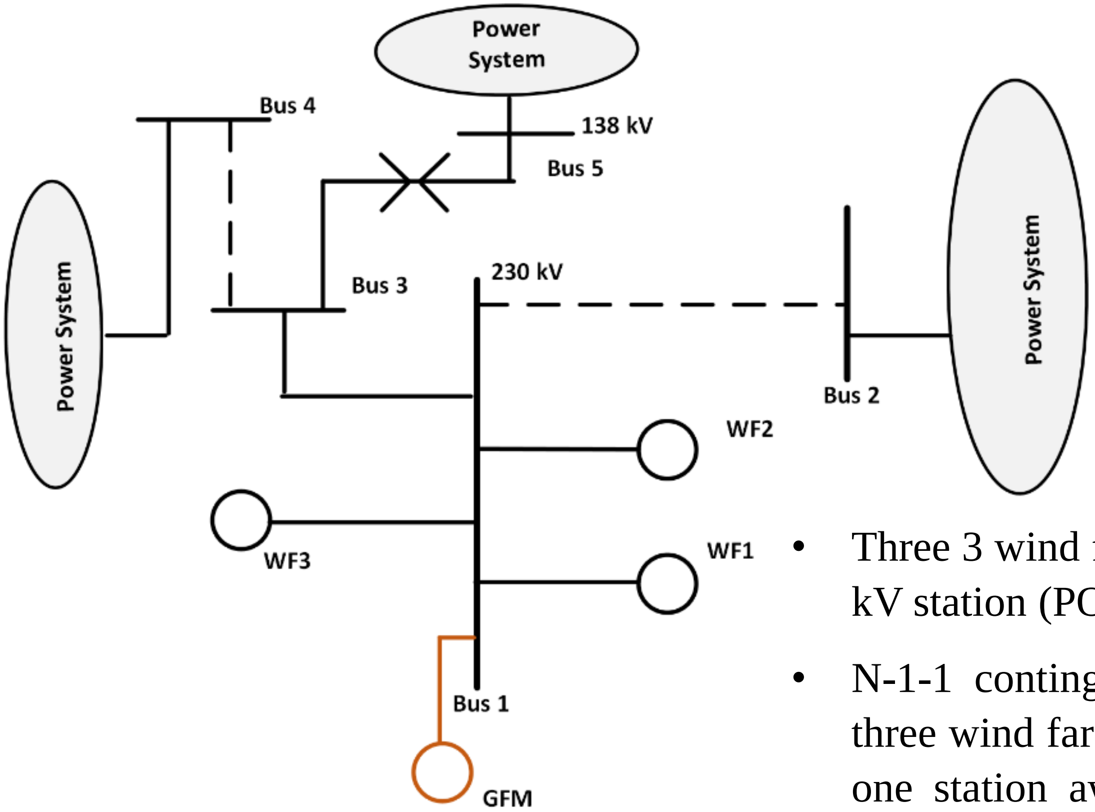
Case 1: 230 kV Station

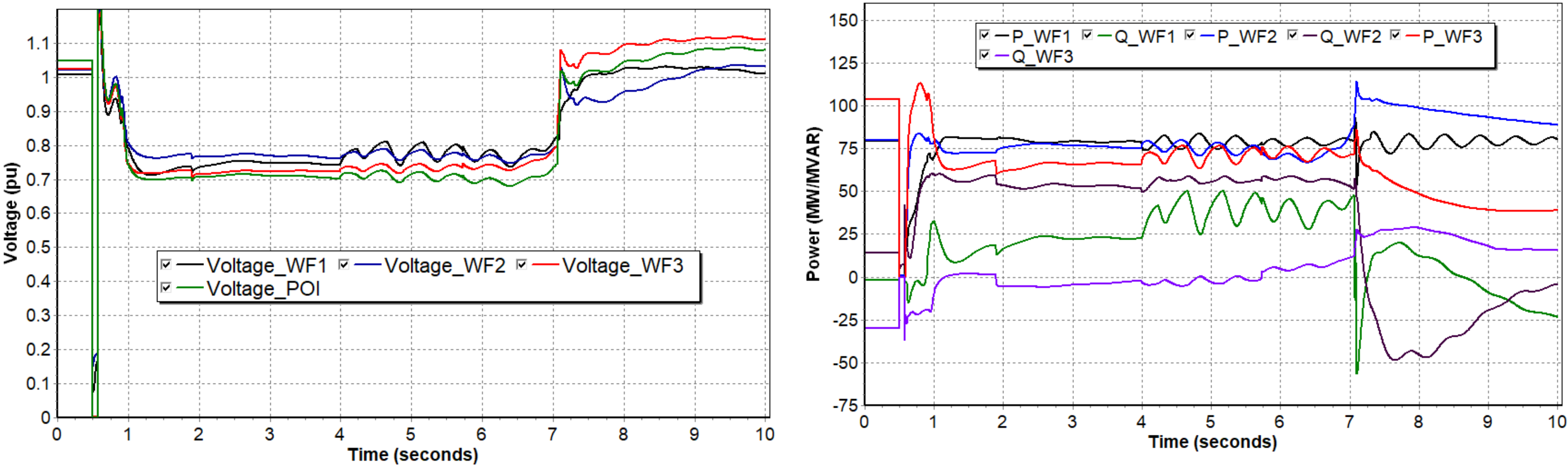


Case Study #1 system configuration

Wind Plant	**Stable limit MW**	**Pmax MW**
Plant 1	74.5	99
Plant 2	74.5	99
Plant 3	99	132

- Three 3 wind farms are interconnected at a common 230 kV station (POI) with two exit paths.
- N-1-1 contingency (marked by dashed lines) puts all three wind farms radially into a 230/138 kV transformer one station away, causing low voltage instability and collapse.
- The maximum generation capacity of the wind farms is 330 MW. Without GFM, this system is unstable after the N-1-1 contingency when total wind plant loading is above ~250 MW.

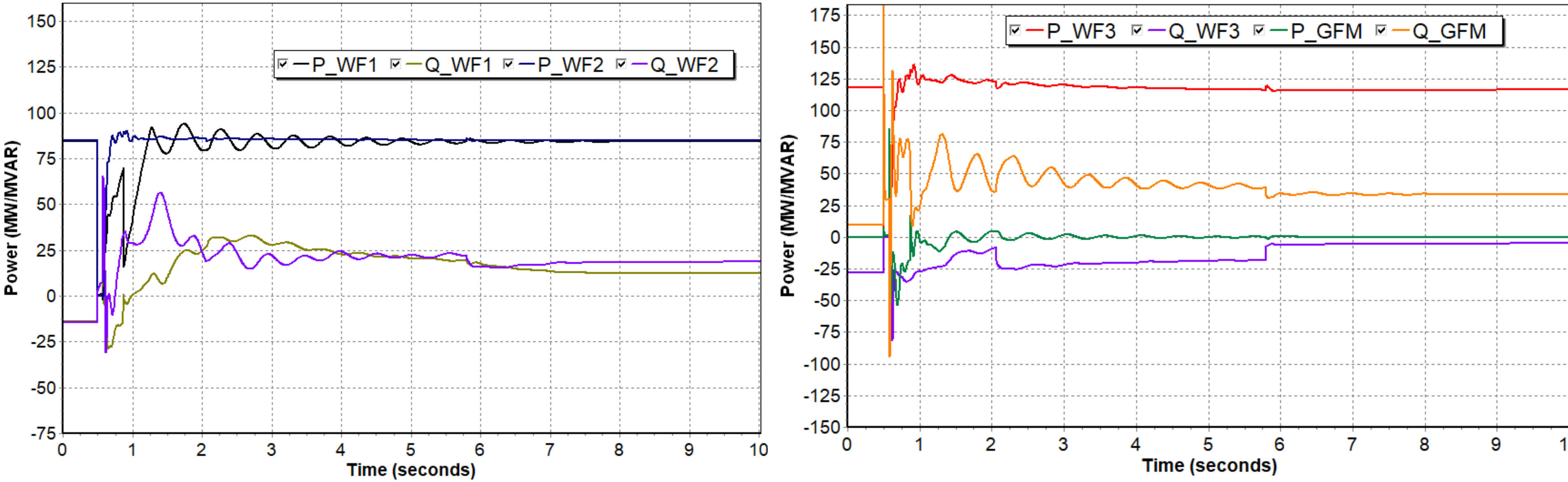
Case 1: Results without GFM



Voltage (left) and power (right) of WF 1, WF 2, and WF 3 at 80 MW, 80 MW, and 105 MW generation without GFM

- In this first simulation, the wind total generation level is set at 265 MW (above the stable level of 250 MW).
- Partial voltage collapse observed before sufficient reactive power can be mustered by the wind farms to bring voltage back to the normal range.

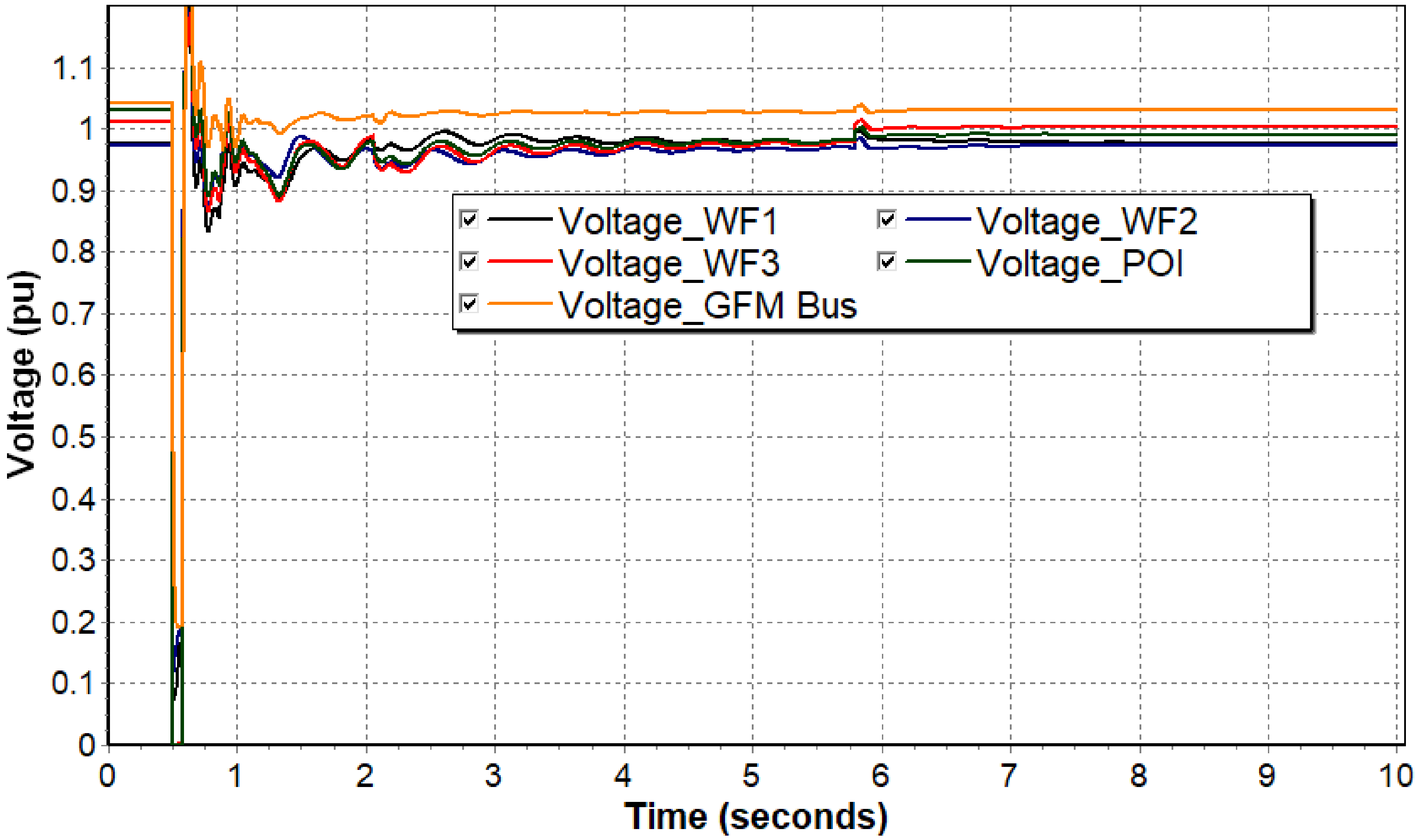
Case 1: Results with GFM



WF 1 and WF 2 power (left) and WF 3 and GFM (right) at 85 MW, 85 MW, and 120 MW wind generation with GFM

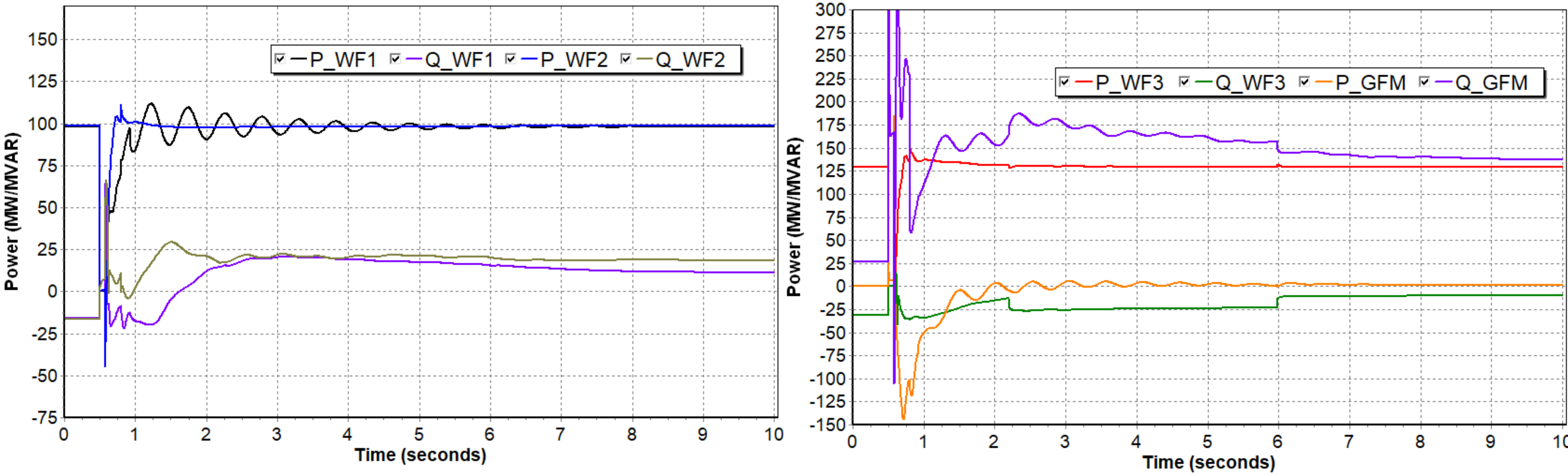
- GFM battery connected to bus 1 at 0 MW
- Wind farms stabilized at initial power and voltage levels after fault / line outage disturbance
- GFM injects zero active power and non-zero reactive power at the end

Case 1: Results with GFM (cont.)



Same simulation: Voltage of WF 1, WF 2, and WF 3 at 85 MW, 85 MW and 120 MW wind generation with GFM

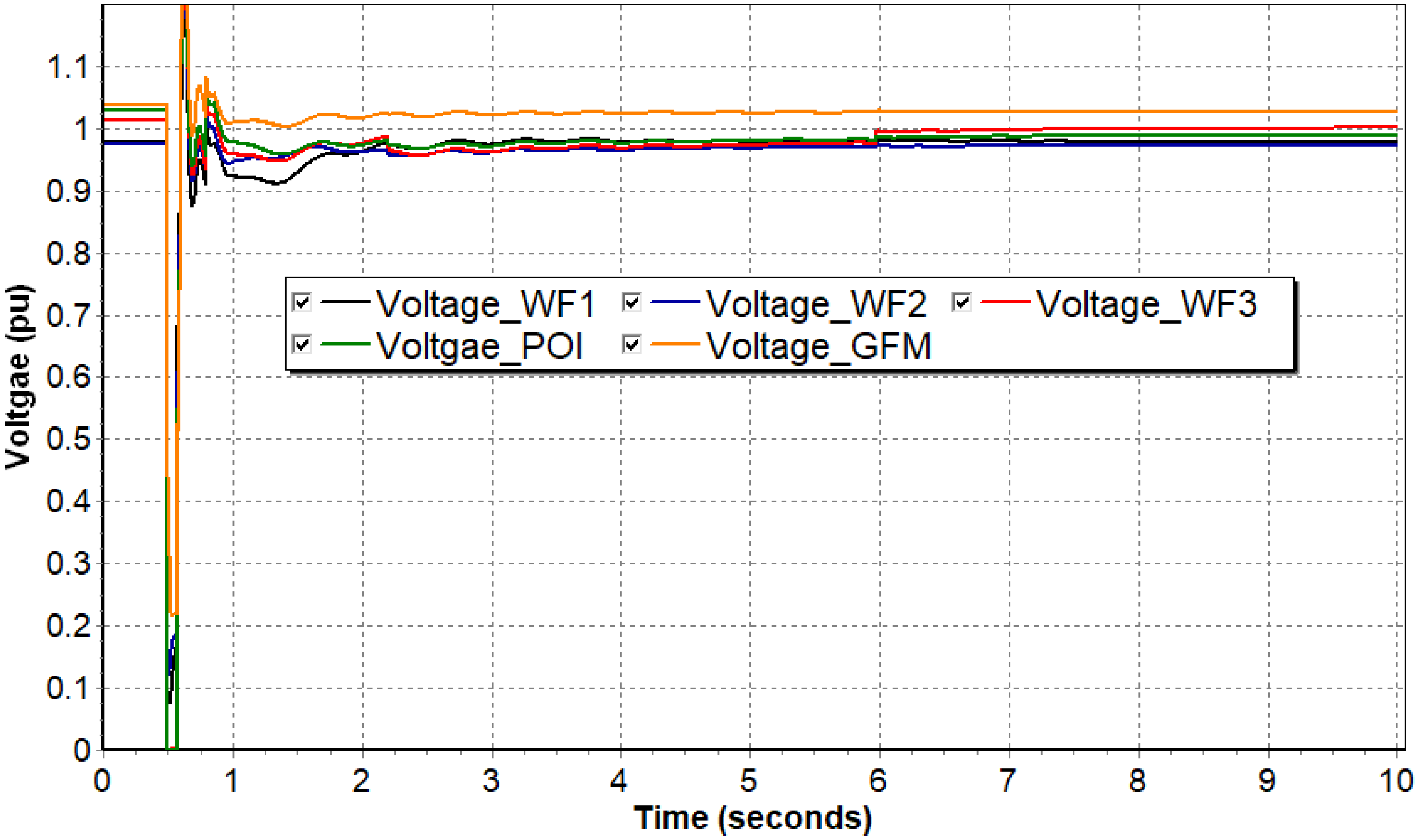
Case 1: Results at maximum generation with GFM



WF 1 and WF 2 power (left) and WF 3 and GFM (right) at 99 MW, 99 MW and 132 MW wind generation with GFM

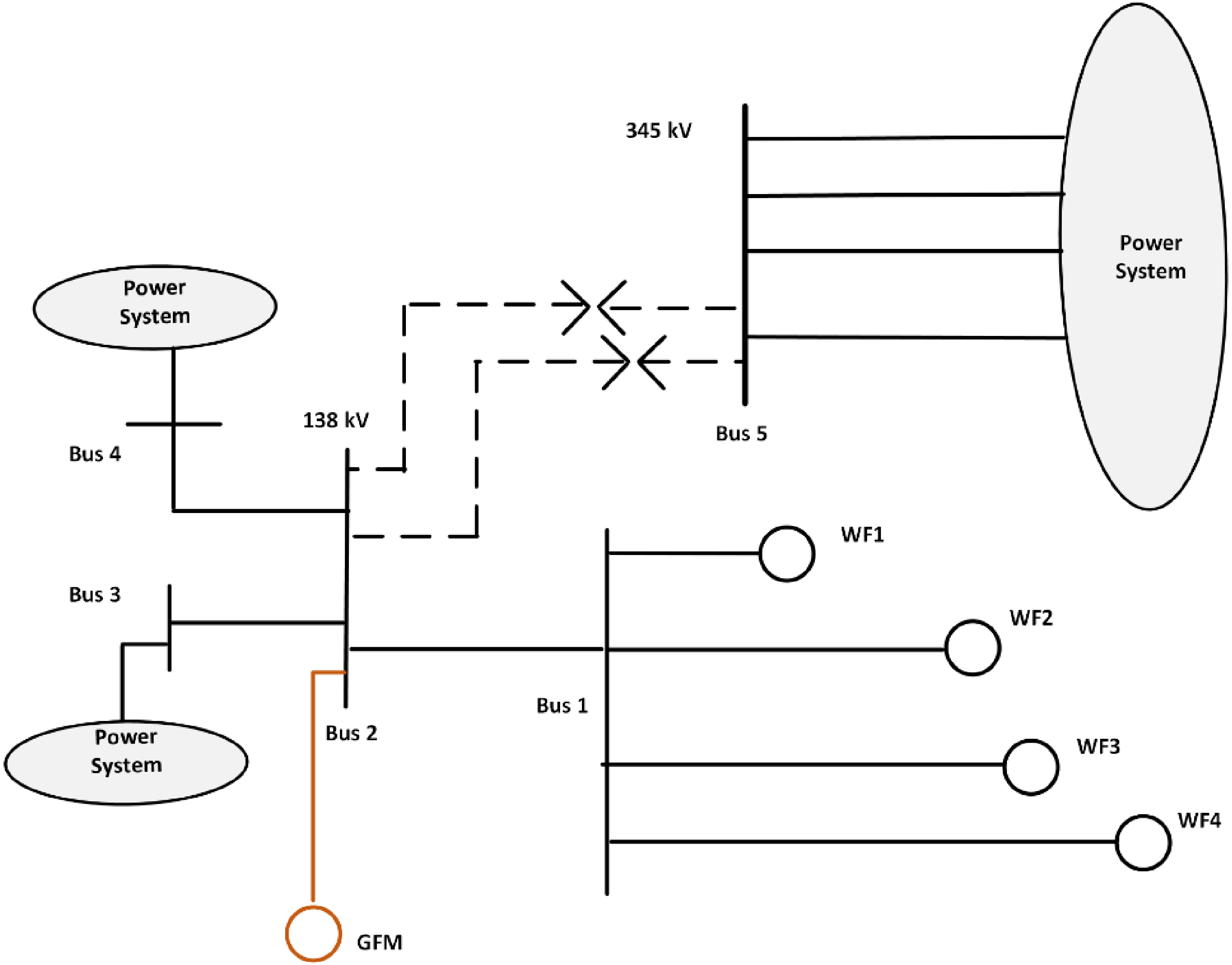
- GFM battery is connected to bus 1 at 0 MW
- Wind farms again stabilized after same fault / line outage disturbance

Case 1: Results at maximum generation with GFM (cont.)

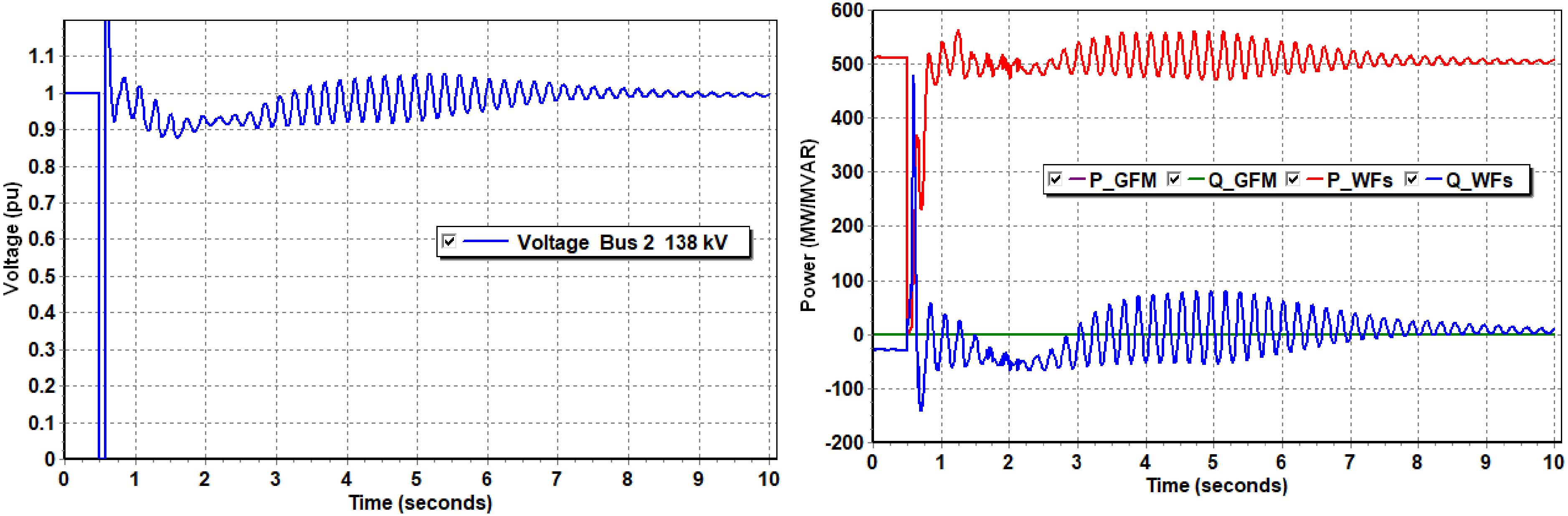


Voltage of WF 1, WF 2, and WF 3 at 99 MW, 99 MW and 132 MW wind generation with GFM

Case 2: 345/138 kV Station



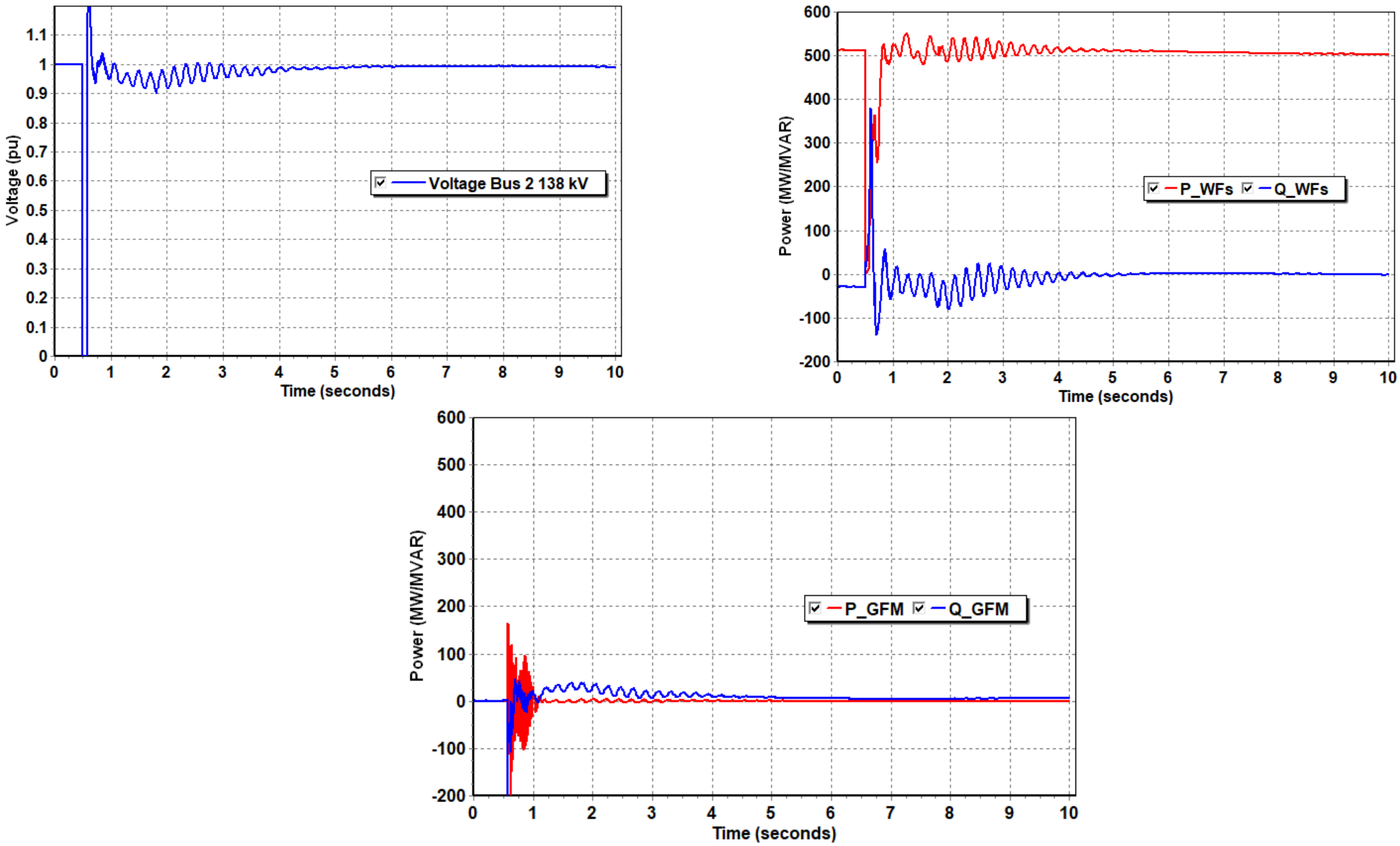
Case 2: Results without GFM



POI voltage (left) and sum of wind generation MW/MVAR (right) without GFM battery

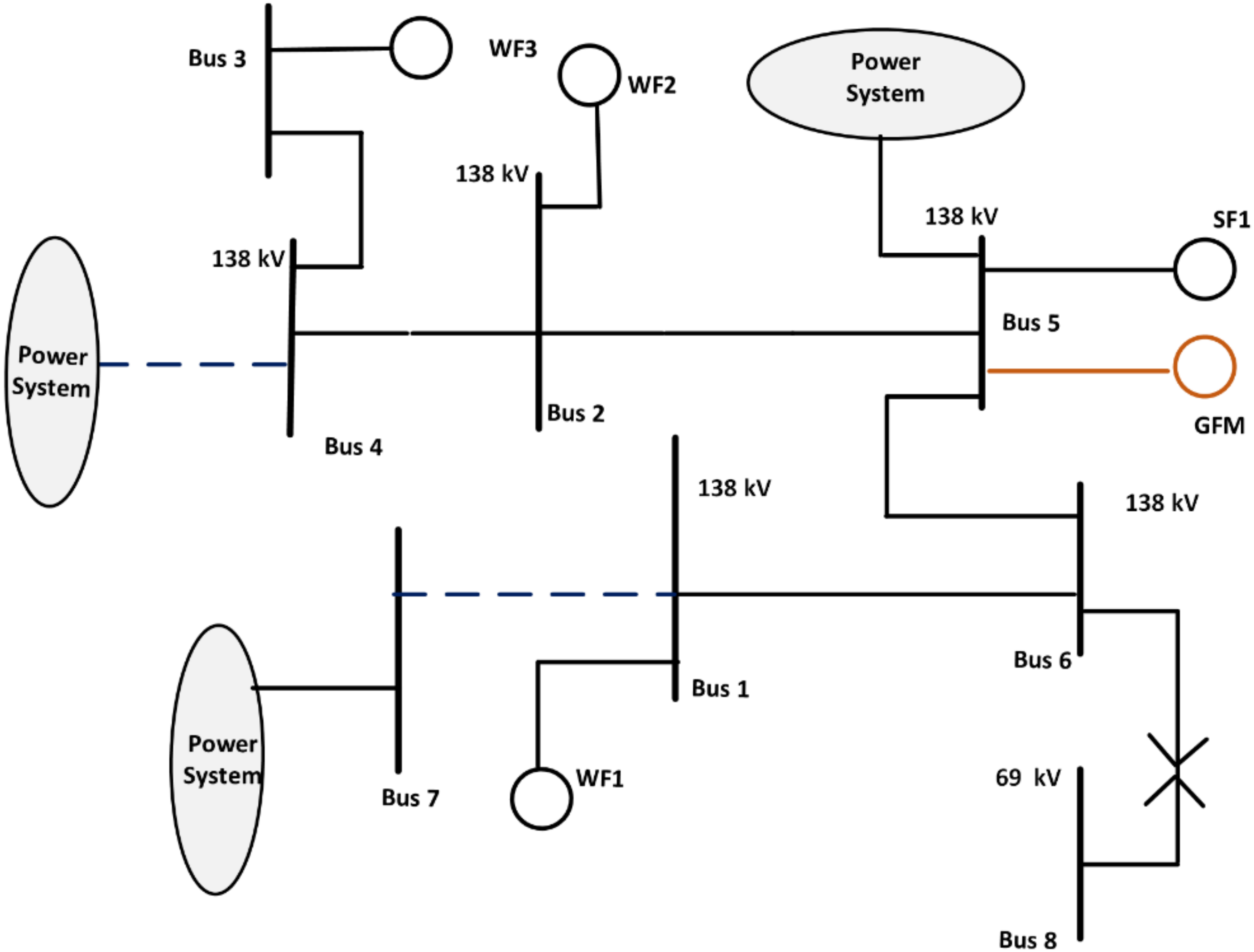
- Four wind plants are connected at bus 1
- Low post-contingency short circuit ratio (SCR) results in undamped oscillations
- Significant damping improvement observed after adding GFM at bus 2

Case 2: Results with GFM

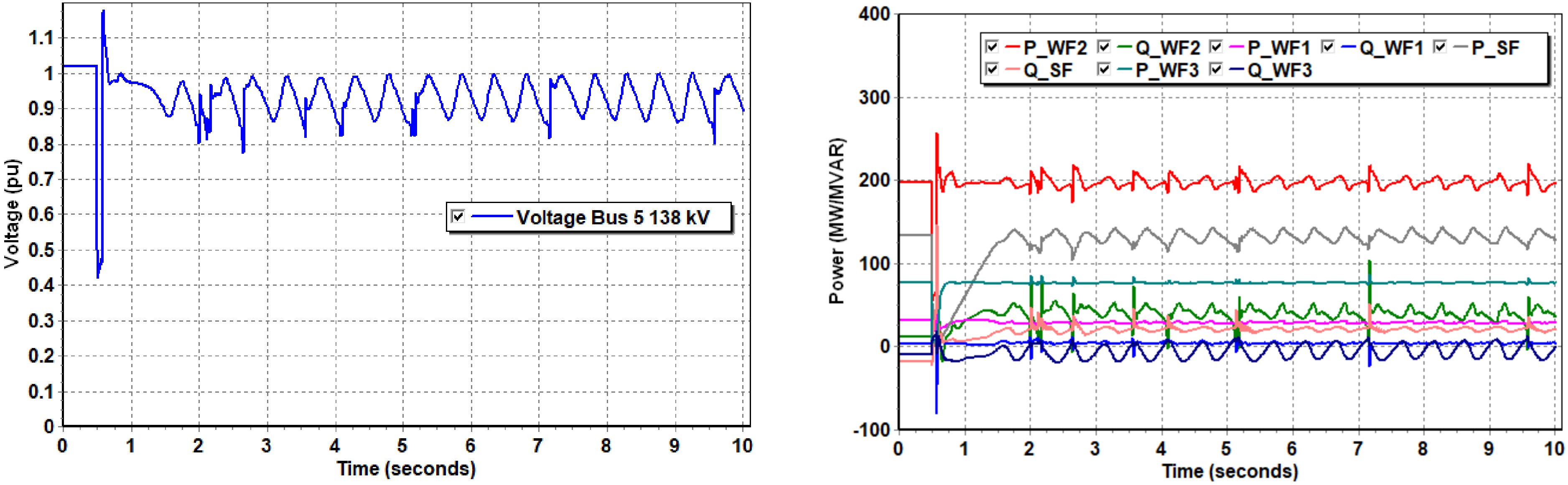


POI voltage (left), sum of wind generation MW/MVAR (right), and GFM MW/MVAR (bottom) with GFM battery

Case 3: 138 kV GTC Area



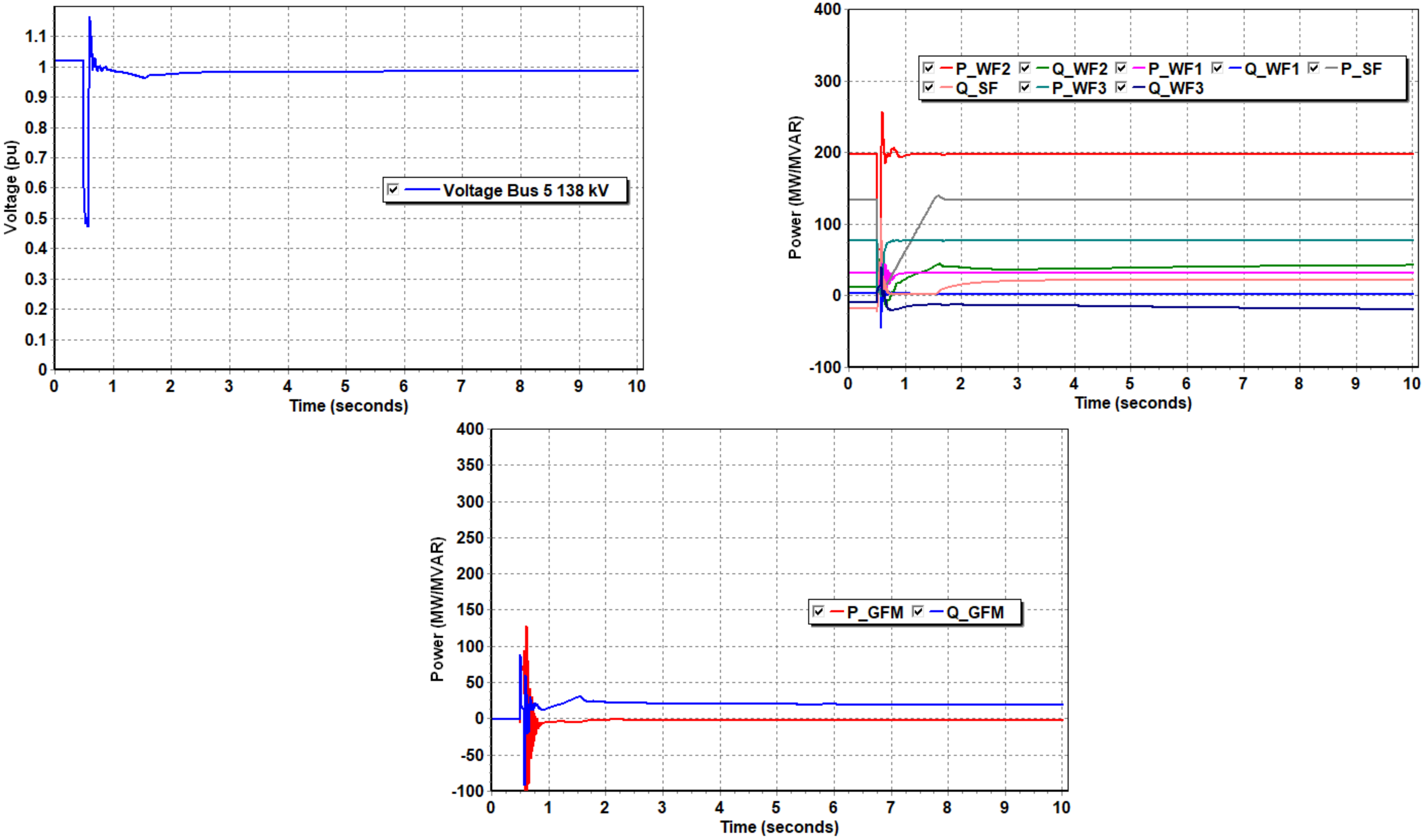
Case 3: Results without GFM



Solar farm POI voltage (left) and wind/solar generation MW/MVAR (right) without GFM battery

- Three wind farms and a solar farm in the local study area
- System has stability constrained IBR export power transfer limitations
- GFM added to bus 5 added for stability improvement
- System stabilized with small permanent reactive injection after adding GFM

Case 3: Results with GFM



POI voltage (left), wind/solar generation MW/MVAR (right), and GFM MW/MVAR (bottom)

Conclusions / future directions

- A battery inverter equipped with GFM control is effective in stabilizing GFL wind and solar IBRs under various post-contingency “weak” grid conditions.
- Different forms of instability: partial voltage collapse, poorly damped oscillations, and rapid unstable GFL IBR mode shifting can all be resolved.
- GFM battery drives systems to stable operating points by short-term dynamic active and reactive power injection (either without continuing power injection or with minimal continuing reactive contribution).

Conclusions / future directions

- The results are limited to the droop-based GFM control mode.
- Application of other control modes (dVOC and VSM) to the above discussed unstable cases, and study of GFM behavior in other unstable events are directions of possible continuing work.
- Determination of optimal GFM sizing as well as the appropriate number and placement of GFMs are some other possible future directions.
- GFM device control tuning is also important and one shouldn't expect a particular GFM inverter control tuning to always function effectively in all scenarios.

Key references and Acknowledgements

Acknowledgements:

Special Thanks to EPRI P173 for proving the positive sequence grid forming model

References

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QUESTIONS/COMMENTS