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Improved Control Strategy of Grid-Forming Inverters for Fault Ride-Through in a Microgrid System

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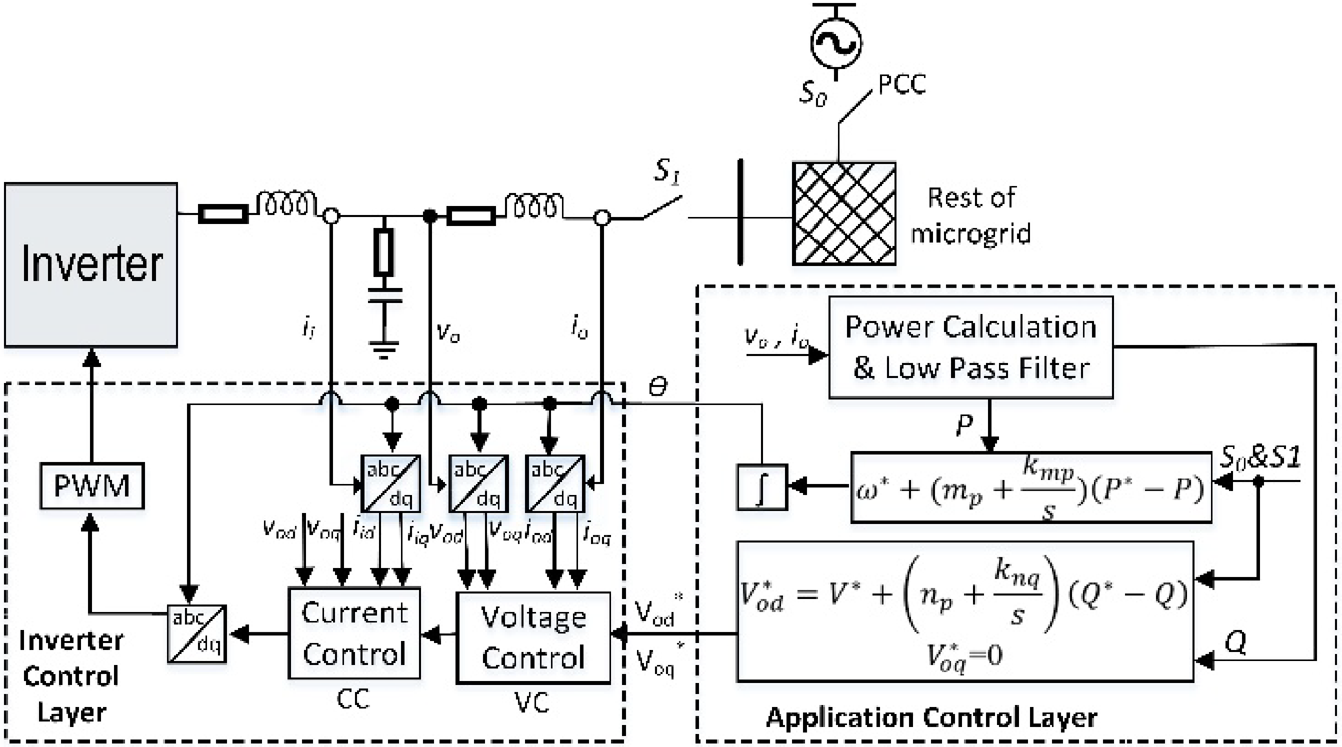
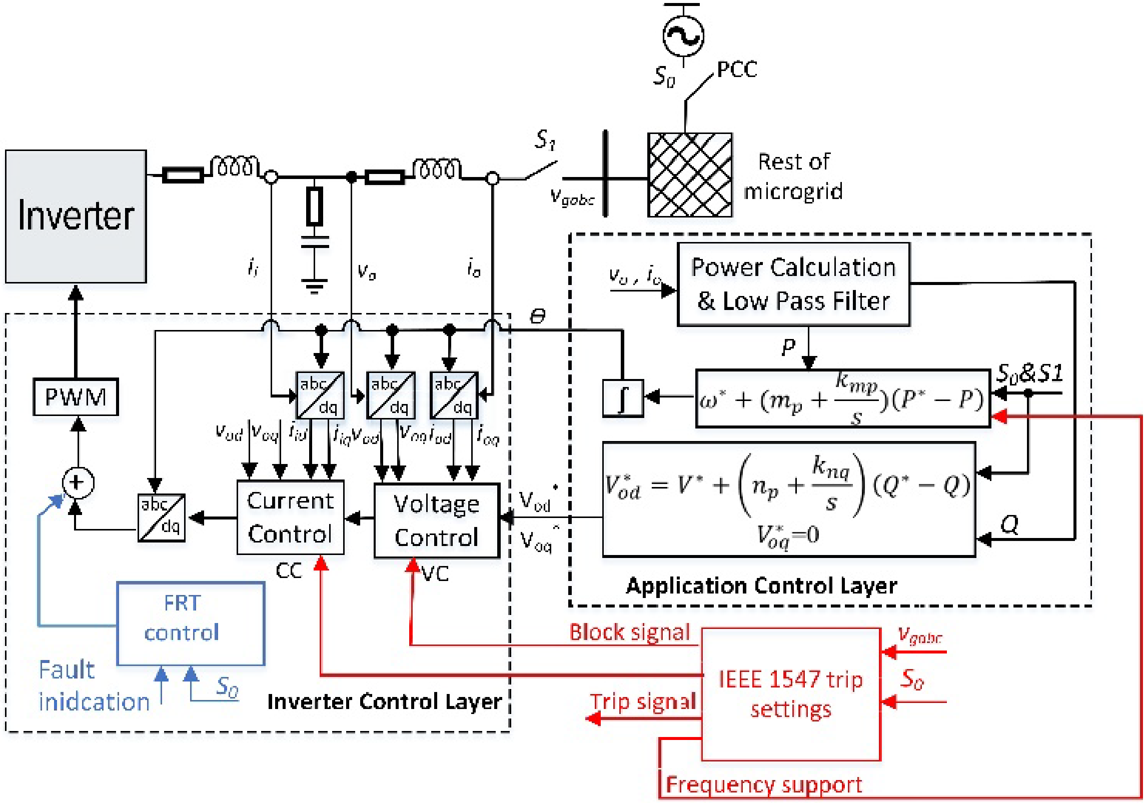
OVERVIEW

- Grid-forming (GFM) inverter fault ride-through (FRT) control is not yet fully studied.
  - Affects system stability, especially in islanded microgrids
  - Mostly study balanced faults or switch to current control for FRT capability
  - No unified control structure for GFM inverters with GFM capabilities in grid-connected and islanded mode.
- GFM inverter FRT control needs to be differentiated between grid-connected and islanded mode in microgrids:
  - Grid-connected: Complies with IEEE 1547-2018
  - Islanded: No standard yet.

CONTROL STRUCTURE OF GFM INVERTERS

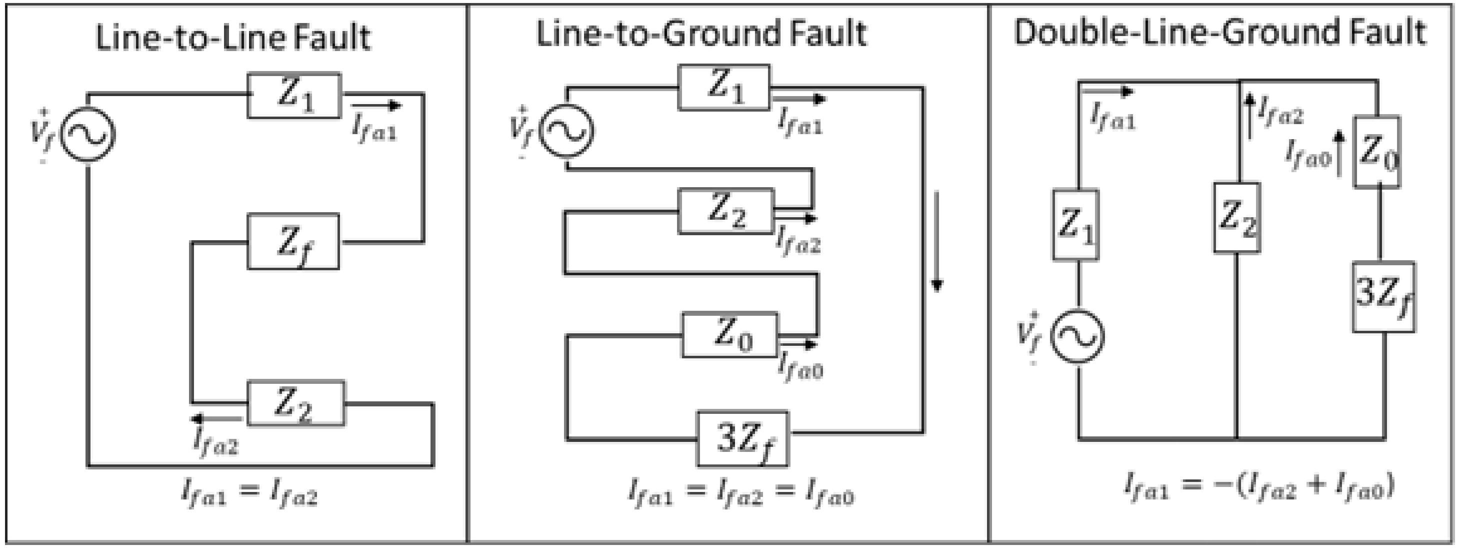
- The same control structure is used for both grid-connected and islanded mode. (An integrator is enabled if it is in grid-connected mode for power tracking.)
- Separate FRT strategy: IEEE 1547-2018 compliant in grid-connected mode and designated FRT control in islanded mode.





GFM Inverter's Behavior Under Fault Conditions

- Thevenin equivalent circuit of asymmetrical faults

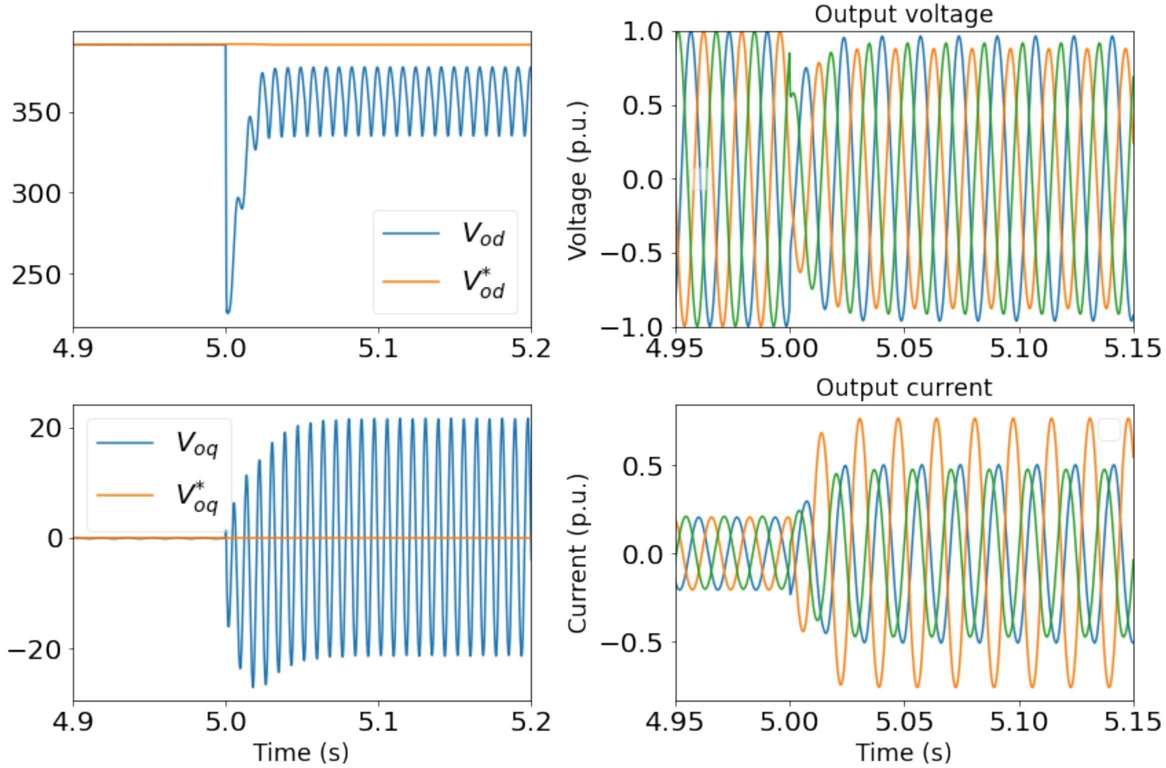


- Inverter behavior with asymmetrical faults

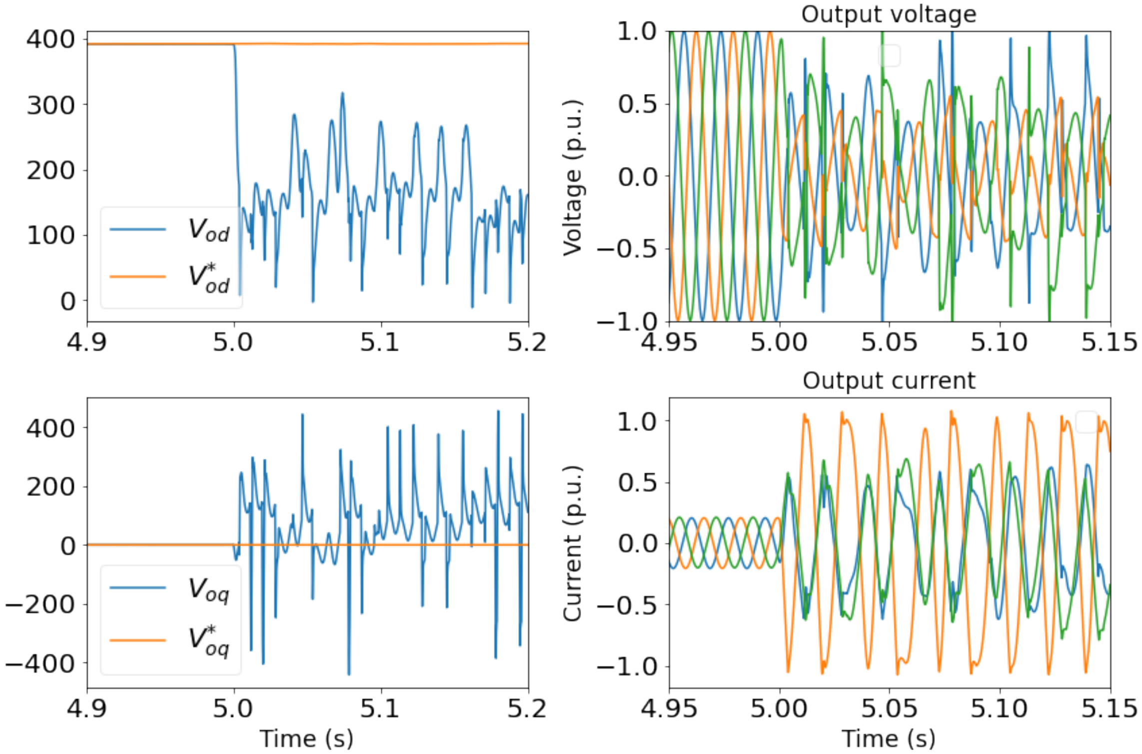
Element	Positive Sequence	Negative Sequence	Zero Sequence
V_d	V_1	$V_2\cos(2\omega t)$	0
V_q	0	$V_2\sin(2\omega t)$	0
V_o	0	0	$V_0\sin(\omega t)$

GFM Inverter's Behavior Under Fault Conditions

- Initial study of GFM inverters under asymmetrical faults with different fault impedances:
  - With high impedance, the system is stable, but the tracking performance is very poor because the d-q components contain the negative-sequence components.
  - With low impedance, the system is unstable.



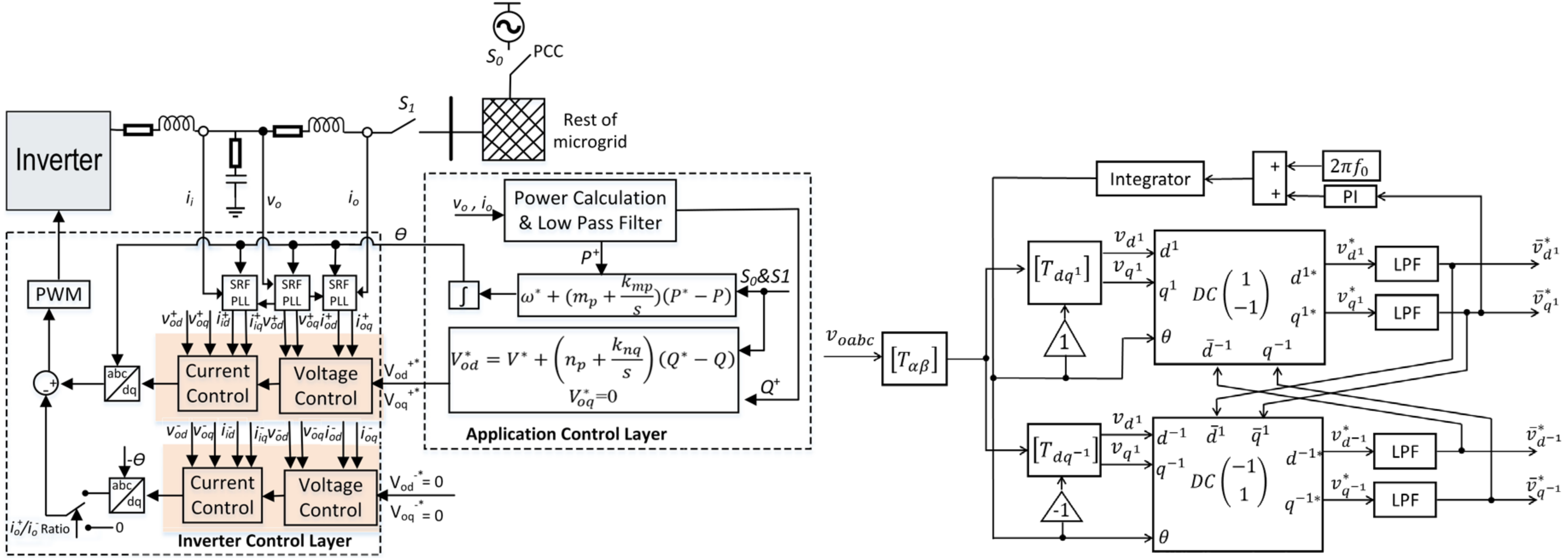
2LG fault with 600-Ω fault impedance



2LG fault with 50-Ω fault impedance

Improved Control Strategy of GFM Inverter for FRT

- Dual control structure of the improved control strategy of GFM inverters:
  - Control objective: Achieve balanced and stable three-phase voltages under asymmetrical faults.
  - Extract the positive- and negative-sequence accurately and control them separately.



Improved Control Strategy of GFM Inverter for FRT

- Virtual impedance control:
  - Need virtual impedance control to reduce the voltage reference because the fault generates a large fault current and causes the voltage to drop.
  - Only the d-component of the positive sequence is needed.

$$V_{od}^{+*} = V_{od}^{+*} - (Ri_{od}^{+} - Xi_{oq}^{+}), V_{oq}^{+*} = 0, V_{od}^{-*} = 0, V_{oq}^{-*} = 0$$

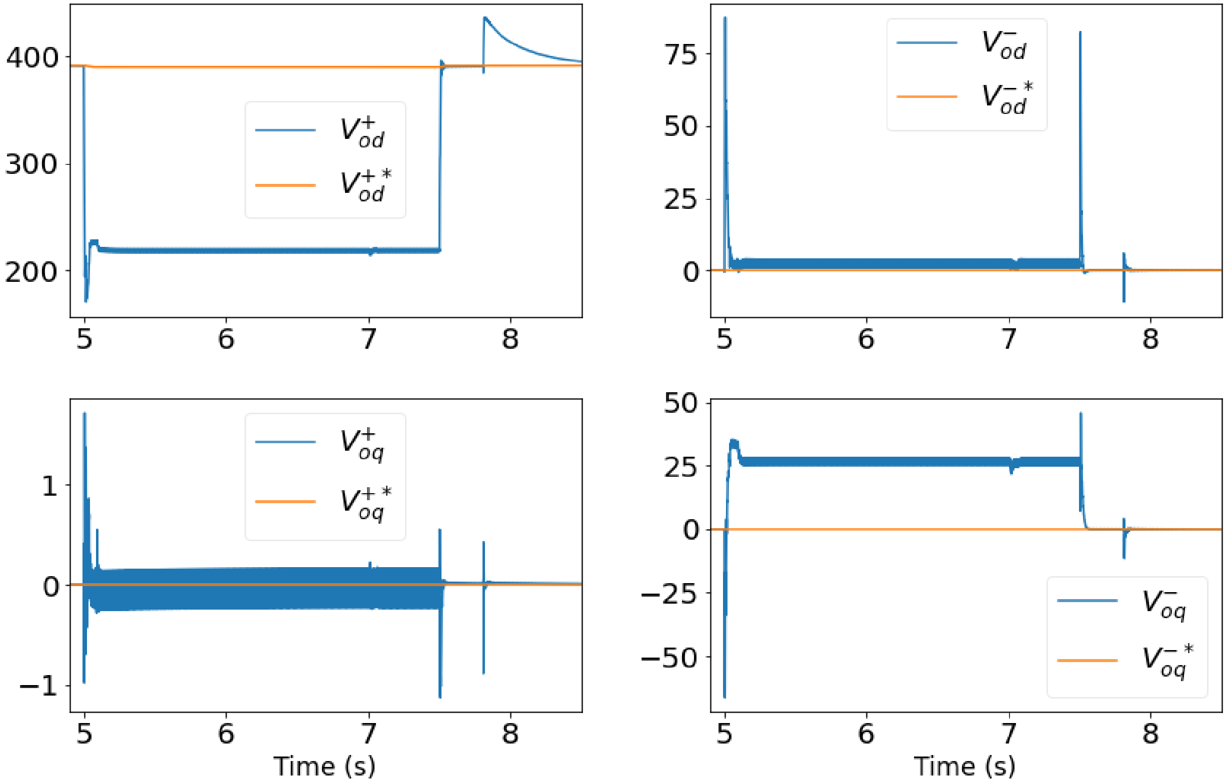
Even though this is a small change, its improvement to the stability of GFM inverters is significant.

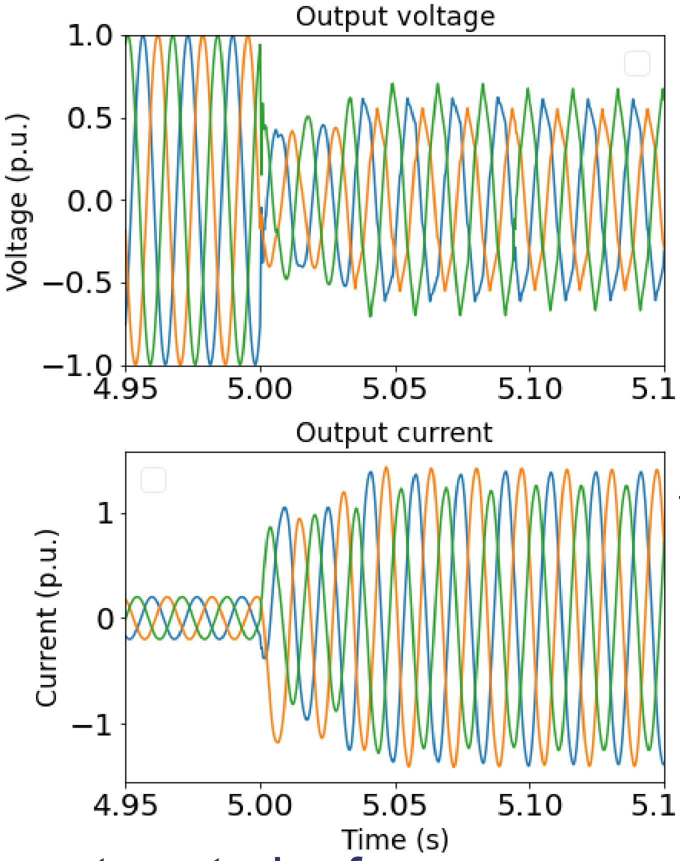
- Adaptive virtual impedance control

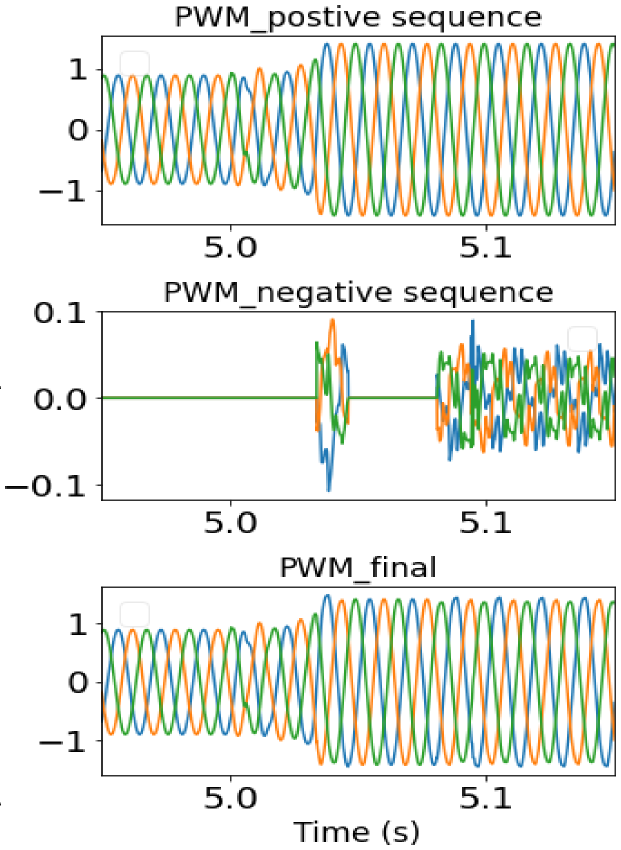
Tracking error ($e = V_{od}^{+*} - V_{od}^{+}$)	V_{od}^{+*}	R	X
$> 5\ V$	Be reduced.	If i_{od}^{+} is positive, increase R by $\frac{0.8e}{i_{od}^{+}}$, otherwise reduce R by $\frac{0.8e}{i_{od}^{+}}$.	If i_{oq}^{+} is positive, reduce X by $\frac{0.2e}{i_{oq}^{+}}$, otherwise increase X by $\frac{0.2e}{i_{oq}^{+}}$.
$< -5\ V$	Be increased.	If i_{od}^{+} is positive, reduce R by $\frac{0.8e}{i_{od}^{+}}$, otherwise increase R by $\frac{0.8e}{i_{od}^{+}}$.	If i_{oq}^{+} is positive, increase X by $\frac{0.2e}{i_{oq}^{+}}$, otherwise reduce X by $\frac{0.2e}{i_{oq}^{+}}$.

Simulation Results

- Islanded microgrid with 2LG fault with 50-ohm fault impedance (with only negative-sequence control)



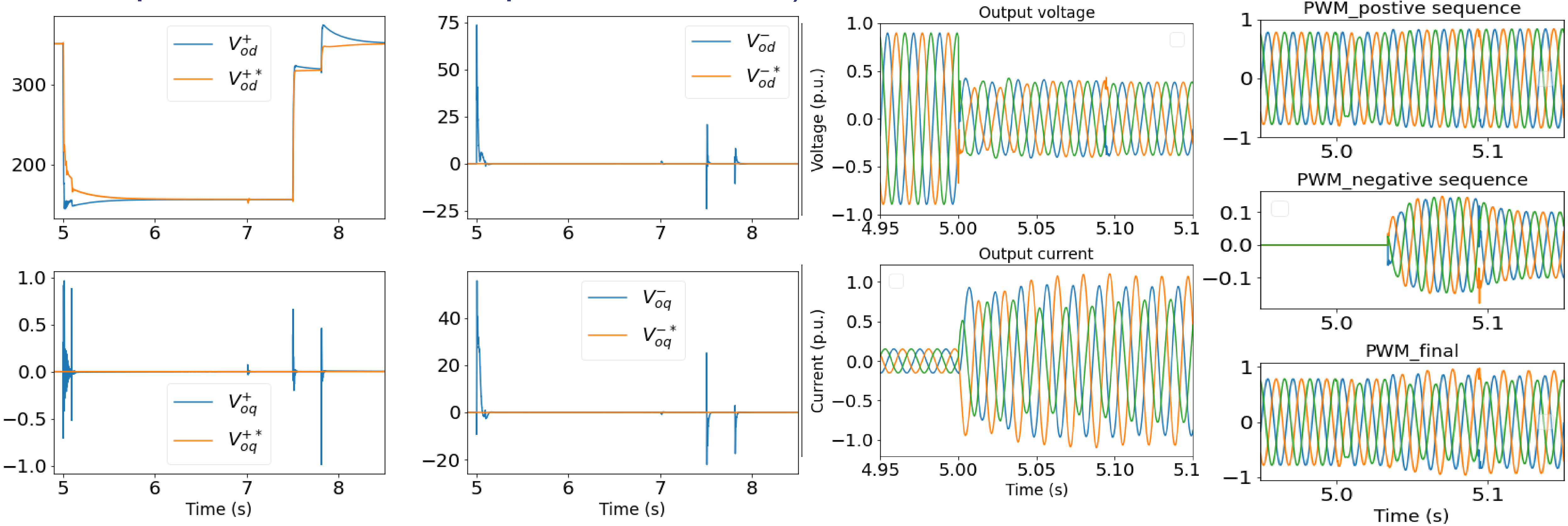




- The GFM inverter has a problem to track the target control references.
- Without virtual impedance control, the GFM inverter is unstable with the studied fault.

SIMULATION RESULTS

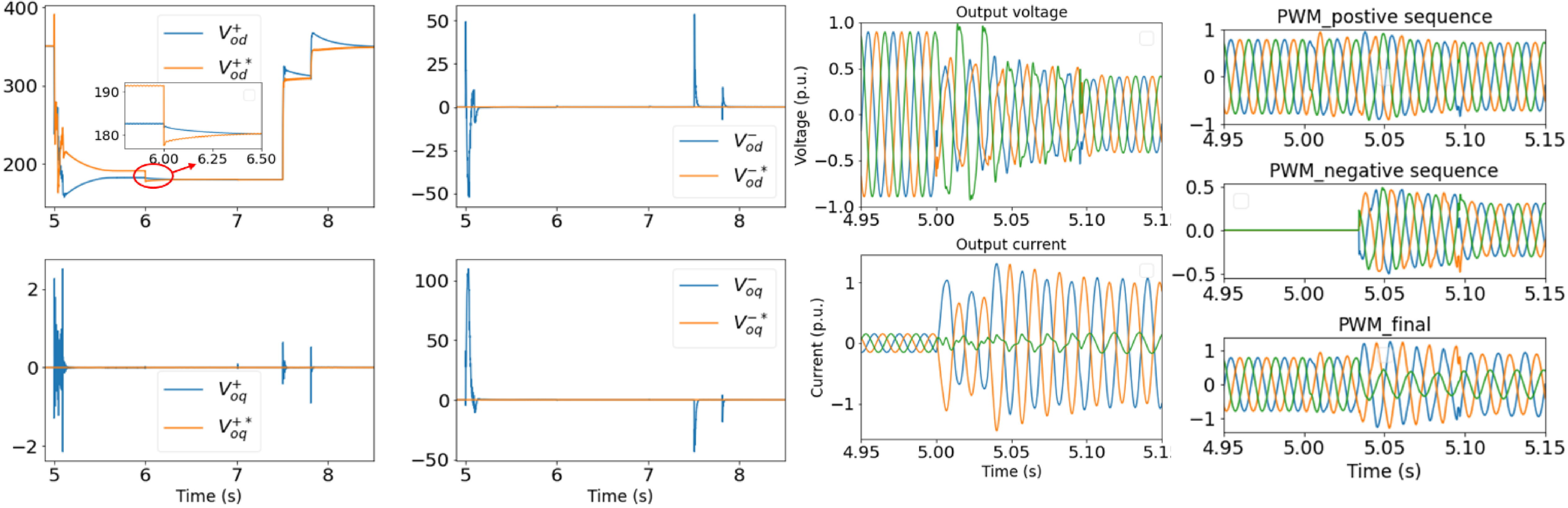
- Islanded microgrid with 2LG fault with 50-ohm fault impedance (with negative-sequence and virtual impedance control)



- Virtual impedance control can effectively generate the correct and reachable voltage reference.
- The tracking performance of the GFM inverter significantly improves and so does the stability.

Simulation Results

- Islanded microgrid with LG fault with 0.1-ohm fault impedance



- Adaptive virtual impedance control functions well to further reduce the tracking error.
- The stability of the GFM inverter is further improved.

Simulation Results

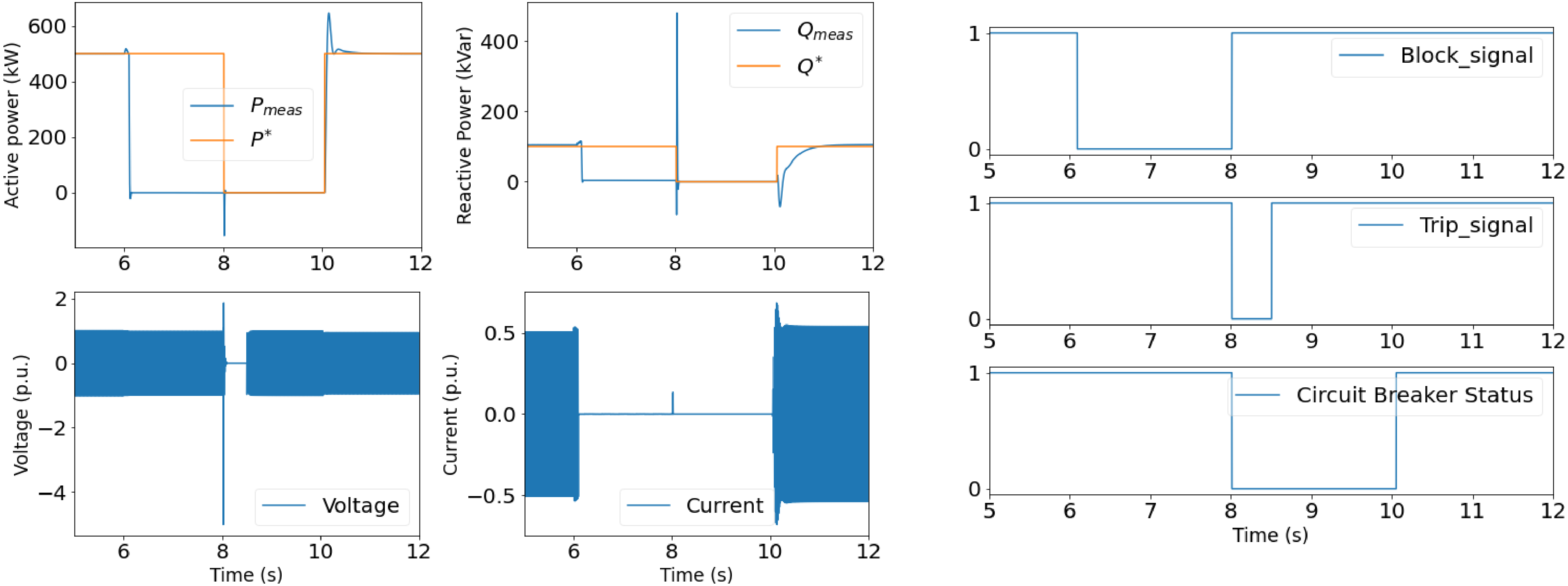
- Islanded microgrid with high- and low-impedance faults

Fault	Virtual Impedance
LG, 0.1 ohm	R_VI=0.065; L_VI=1.4e-3
LG, 100 ohms	R_VI=0.065; L_VI=1.4e-3
LLG, 0.1 ohm	R_VI=0.025; L_VI=1.43e-3
LLG, 50 ohms	R_VI=0.025; L_VI=1.4e-3
LL, 0.1 ohm	R_VI=0.025; L_VI=1.4e-3
LL, 100 ohms	R_VI=0.025; L_VI=1.4e-3
3LG, 1 ohm	R_VI=0.025; L_VI=1.4e-3
3LG, 100 ohms	R_VI=0.0138; L_VI=0.77e-3

The proposed control for FRT capability works well for all the high- and low-impedance faults, balanced and unbalanced faults.

Simulation Results

➢ Grid-connected microgrid with LG fault with 0.1-ohm fault impedance



- Inverter trips after 2 seconds because the PCC voltage stays lower than 0.5 p.u. for 2 seconds (momentary cessation)
- Only generates power for the first five cycles and then goes to zero injection.

CONCLUSION

- Negative-sequence control with virtual impedance control is essential to make the GFM inverter with FRT capability for islanded microgrids.
- Virtual impedance control can be very simple and effective with only the d-component of the positive-sequence control.
- Virtual impedance control needs to be adaptive to cope with different voltage drops caused by various unbalanced faults.
- The GFM inverter can be IEEE 1547-2018 compliant in grid-connected mode and designed with FRT capability in islanded mode.

Thank You

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