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Design Power Control Strategies of Grid-Forming Inverters for Microgrid Application

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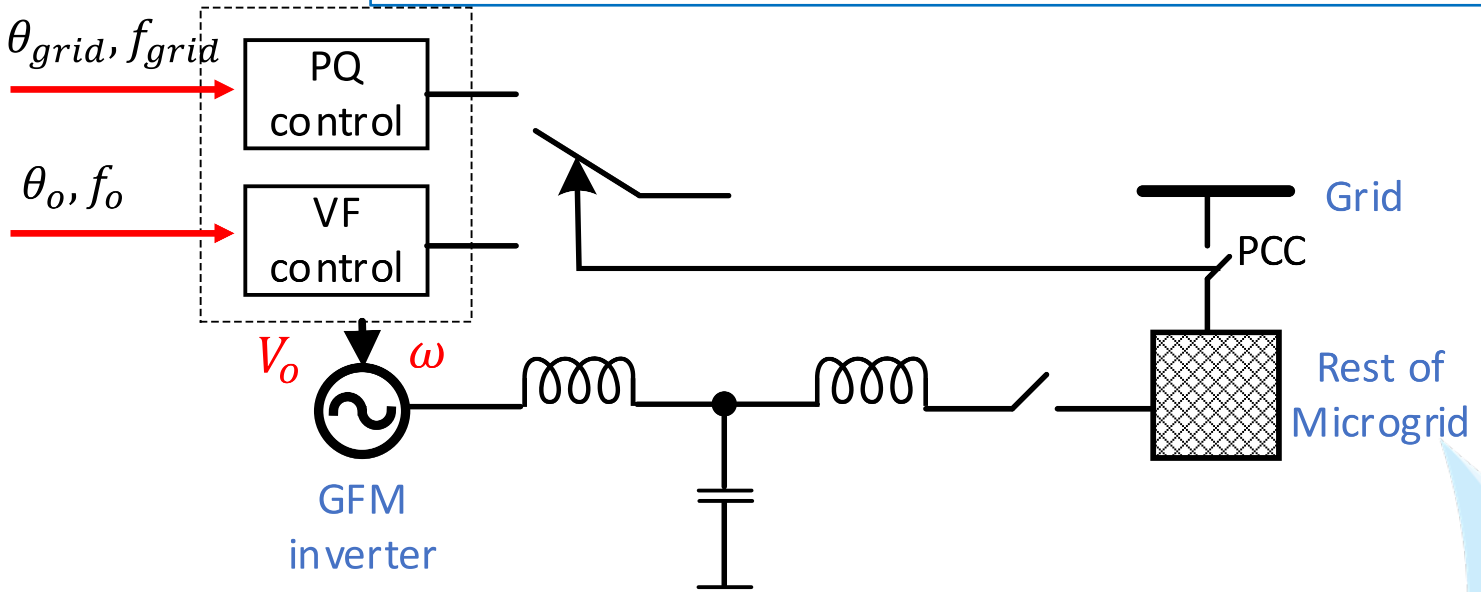
Background

- State-of-the-art grid-forming inverter control: PQ in grid-connected (current source) and VF in islanded mode (voltage source) ✗
- Problem: phase jump during microgrid transition operation
- Solution: use grid-forming control in both grid-connected and islanded mode
- Problem: grid-forming control controls system voltage rather than power.
- Objective: design power control strategy of grid-forming inverters for microgrid applications

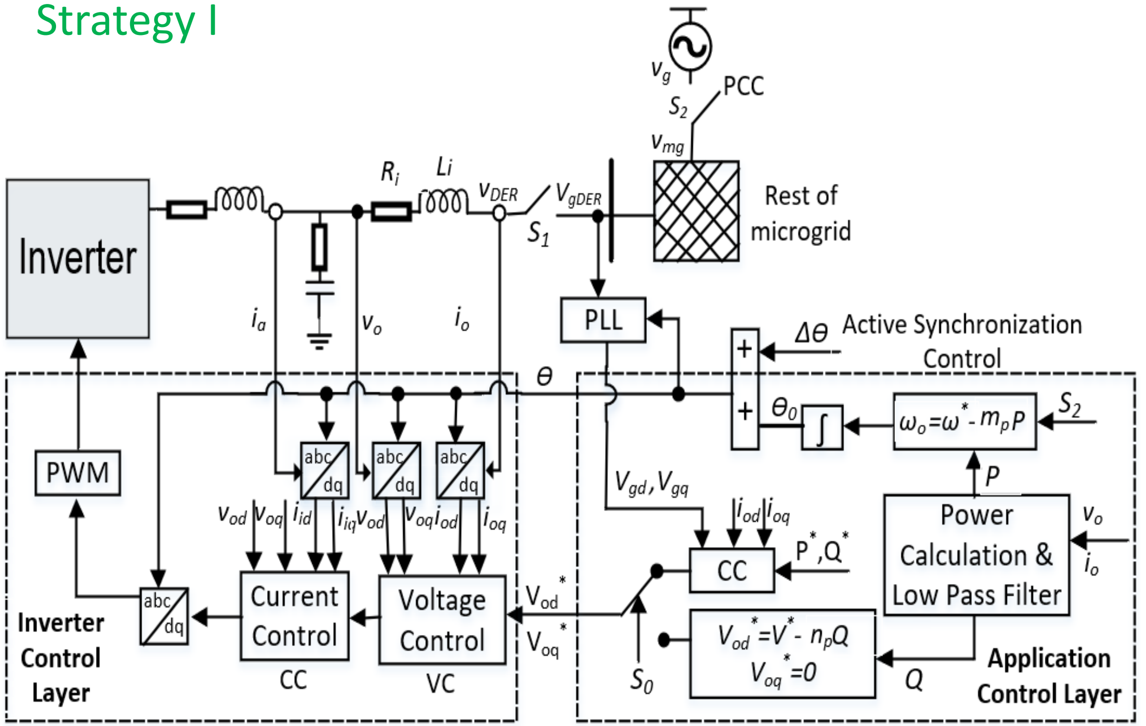
How to control PQ via grid-forming control in grid-connected mode



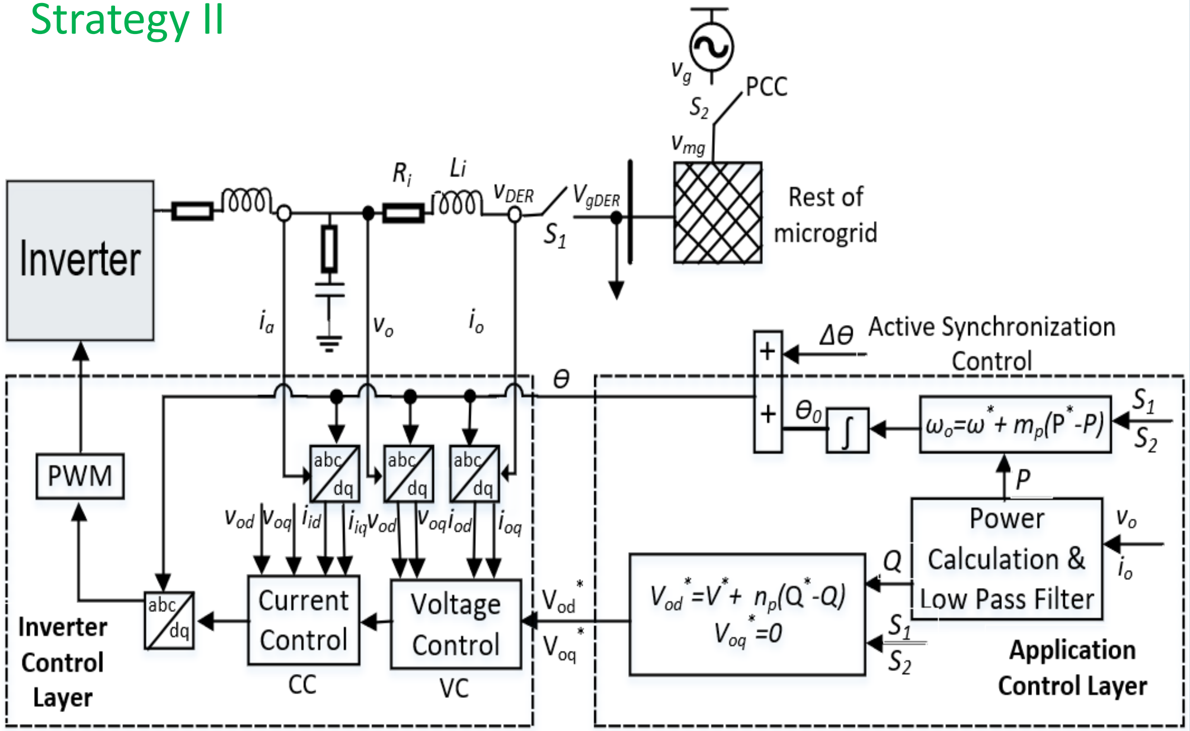
Solution

- Strategy I: Current controller outer loop in grid-connected, and droop control in islanded mode
- Strategy II: Droop control in both grid-connected and islanded mode

Strategy I



Strategy II



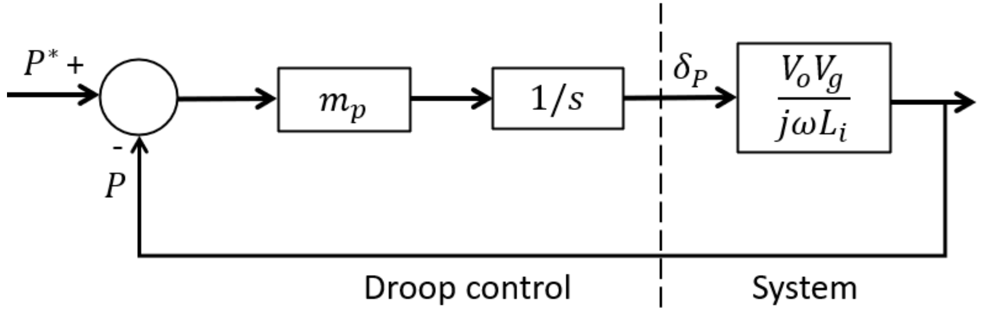
Comparison of These Two Strategies

Control Strategy	Startup	Grid-Connected	Islanded
Strategy I	$\omega_o = \omega^*$ $V_{od}^* = V^*$ $V_{oq}^* = 0$	$\omega_o = \omega^*$ $V_{od}^* = V_{gd} + R_i i_{od}^* + K_{po}(i_{od}^* - i_{od}) - \omega_o L_i i_{oq},\ i_{od}^* = \frac{2}{3}\frac{P^*}{V_{gd}}$ $V_{oq}^* = V_{gq} + R_i i_{oq}^* + K_{po}(i_{oq}^* - i_{oq}) + \omega_o L_i i_{od}, i_{oq}^* = -\frac{2}{3}\frac{Q^*}{V_{gd}}$	$\omega_o = \omega^* - m_p P$ $V_{od}^* = V^* - n_p Q$ $V_{oq}^* = 0$
Strategy II	$\omega_o = \omega^*$ $V_{od}^* = V^*$ $V_{oq}^* = 0$	$\omega_o = \omega^* + m_p(P^* - P) \rightarrow \omega_o = \omega^*, P^* = P$ $V_{od}^* = V^* + n_p(Q^* - Q) \rightarrow V_{od}^* = V^* + (n_p + \frac{k_{np}}{s})(Q^* - Q)$ $V_{oq}^* = 0$	$\omega_o = \omega^* - m_p P$ $V_{od}^* = V^* - n_p Q$ $V_{oq}^* = 0$

J Wang, B. Lundstrom, A. Bernstein, "Design of a non-pll grid-forming inverter for smooth microgrid transition operation," IEEE PESGM 2020.

$$i_{od} = \frac{1}{sL_i + R_i}(V_{od} - V_{gd} + \omega_o L_i i_{oq}),\ P = \frac{3}{2} V_{gd} i_{od}$$

$$i_{oq} = \frac{1}{sL_i + R_i}(V_{oq} - V_{gq} - \omega_o L_i i_{od}),\ Q = -\frac{3}{2} V_{og} i_{oq}$$



Strategy I: decouple the intrinsic power-angle characteristics

Strategy II: follow the power-angle characteristics

Different power-angle stability

Comparison of These Two Strategies

Control Strategy	Startup	Grid-Connected	Islanded
Strategy I	$\omega_o = \omega^*$ $V_{od}^* = V^*$ $V_{oq}^* = 0$	$\omega_o = \omega^*$ $V_{od}^* = V_{gd} + R_i i_{od}^* + K_{po}(i_{od}^* - i_{od}) - \omega_o L_i i_{oq},\ i_{od}^* = \frac{2}{3}\frac{P^*}{V_{gd}}$ $V_{oq}^* = V_{gq} + R_i i_{oq}^* + K_{po}\left(i_{oq}^* - i_{oq}\right) + \omega_o L_i i_{od}, i_{oq}^* = -\frac{2}{3}\frac{Q^*}{V_{gd}}$	$\omega_o = \omega^* - m_p P$ $V_{od}^* = V^* - n_p Q$ $V_{oq}^* = 0$
Strategy II	$\omega_o = \omega^*$ $V_{od}^* = V^*$ $V_{oq}^* = 0$	$\omega_o = \omega^* + m_p(P^* - P) \rightarrow \omega_o = \omega^*, P^* = P$ $V_{od}^* = V^* + n_p(Q^* - Q) \rightarrow V_{od}^* = V^* + (n_p + \frac{k_{np}}{s})(Q^* - Q)$ $V_{oq}^* = 0$	$\omega_o = \omega^* - m_p P$ $V_{od}^* = V^* - n_p Q$ $V_{oq}^* = 0$

Strategy I: $\omega^* - m_p$P → ω^*, v_{od}^*, v_{oq}^* has big step changes

Strategy II: $\omega^* - m_p$P → ω^*+$\Delta\omega$, v_{od}^* has small step change

v_{oq}^*=0 all the time without change

- Both strategies are expected to have transients
- Strategy I should have better transients

ω^*→$\omega^* - m_p$P for both strategies

Strategy I: v_{od}^*, v_{oq}^* has big step changes

Strategy II: v_{od}^* has small step change

v_{oq}^*=0 all the time without change

Strategy II should have better transients

Comparison of These Two Strategies

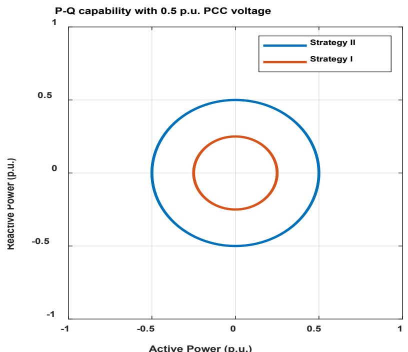
Generated using the GFM inverter angle instead of its own angle

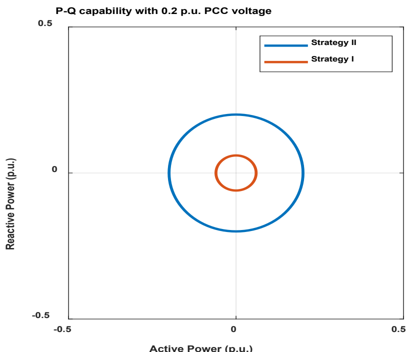
Control Strategy	Grid-Connected	Power Tracking Performance
Strategy I	$\omega_o = \omega^*$ $V_{od}^* = V_{gd} + R_i i_{od}^* + K_{po}(i_{od}^* - i_{od}) - \omega_o L_i i_{oq},\ i_{od}^* = \frac{2}{3}\frac{P^*}{V_{gd}}$ $V_{oq}^* = V_{gq} + R_i i_{oq}^* + K_{po}(i_{oq}^* - i_{oq}) + \omega_o L_i i_{od}, i_{oq}^* = -\frac{2}{3}\frac{Q^*}{V_{gd}}$	$V_{gd} \approx V'_{gd}, V_{gq} \neq V'_{gq} = 0$ • Active power tracking can be acceptable • Reactive power tracking has discrepancy
Strategy II √	$\omega_o = \omega^* + m_p(P^* - P) \rightarrow \omega_o = \omega^*, P^* = P$ $V_{od}^* = V^* + n_p(Q^* - Q) \rightarrow V_{od}^* = V^* + (n_p + \frac{k_{np}}{s})(Q^* - Q)$ $V_{oq}^* = 0$	• Active power must track P^* to reach steady-state frequency for stability • Reactive power can track the Q^* because of PI control

Strategy I: terminal voltage dependent

Strategy II: less dependent on the terminal voltage

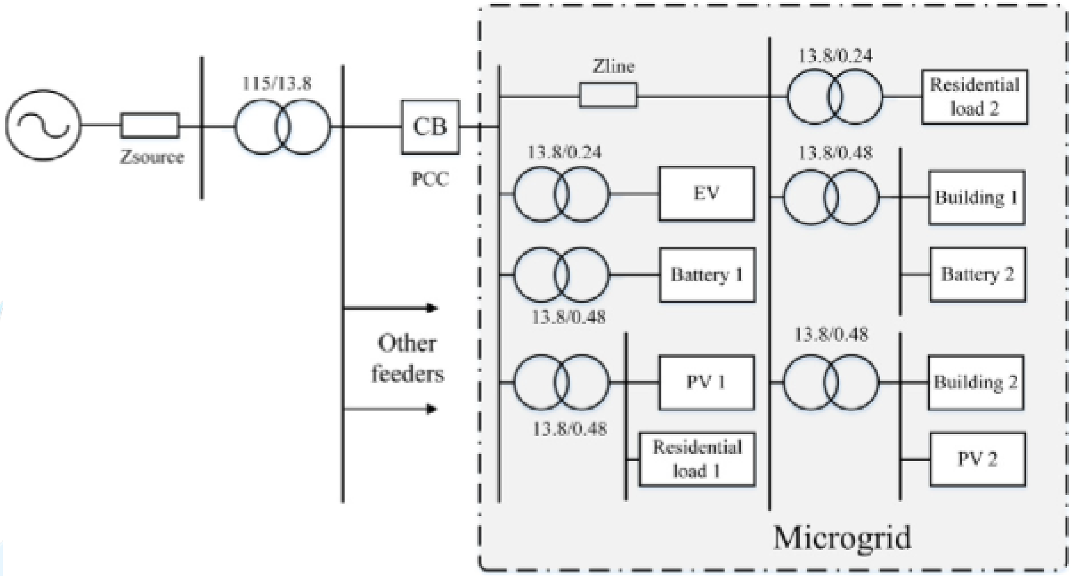
Strategy II should have better P-Q capability under low PCC voltages



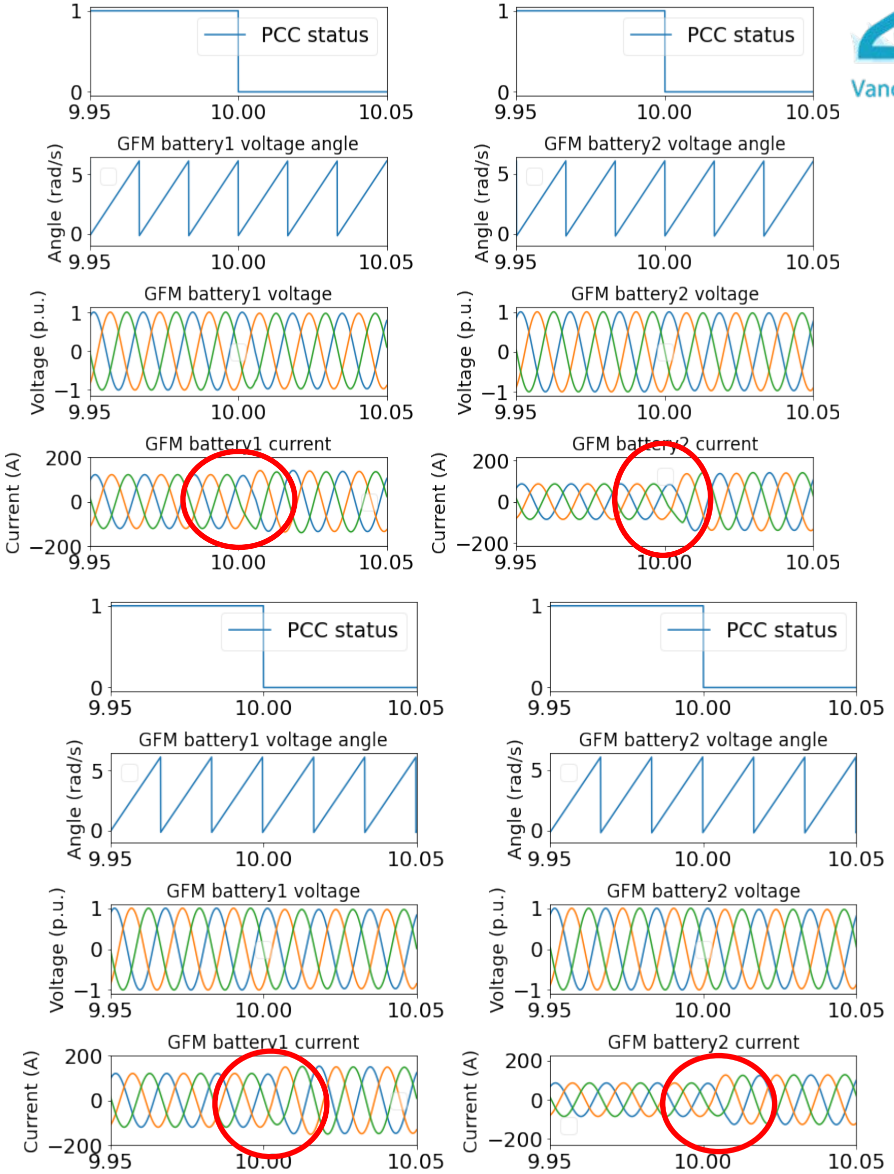


Simulation Results

- Microgrid: two GFM battery inverters, PVs grid-following, residential and commerical loads
- Simulation software: Matlab Simulink
- Events: grid-connected, unplanned islnding at 10 s, planned reconnection at 15 s, reconnect to the grid.



Unplanned islanding operation

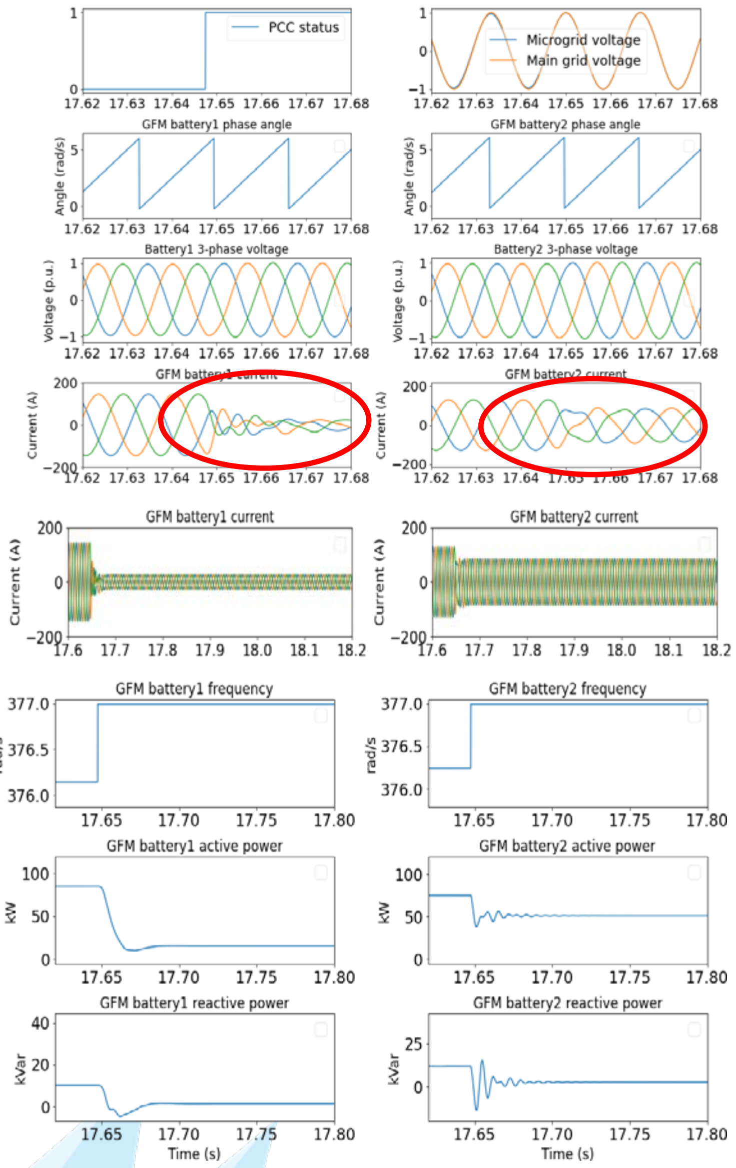


Strategy I

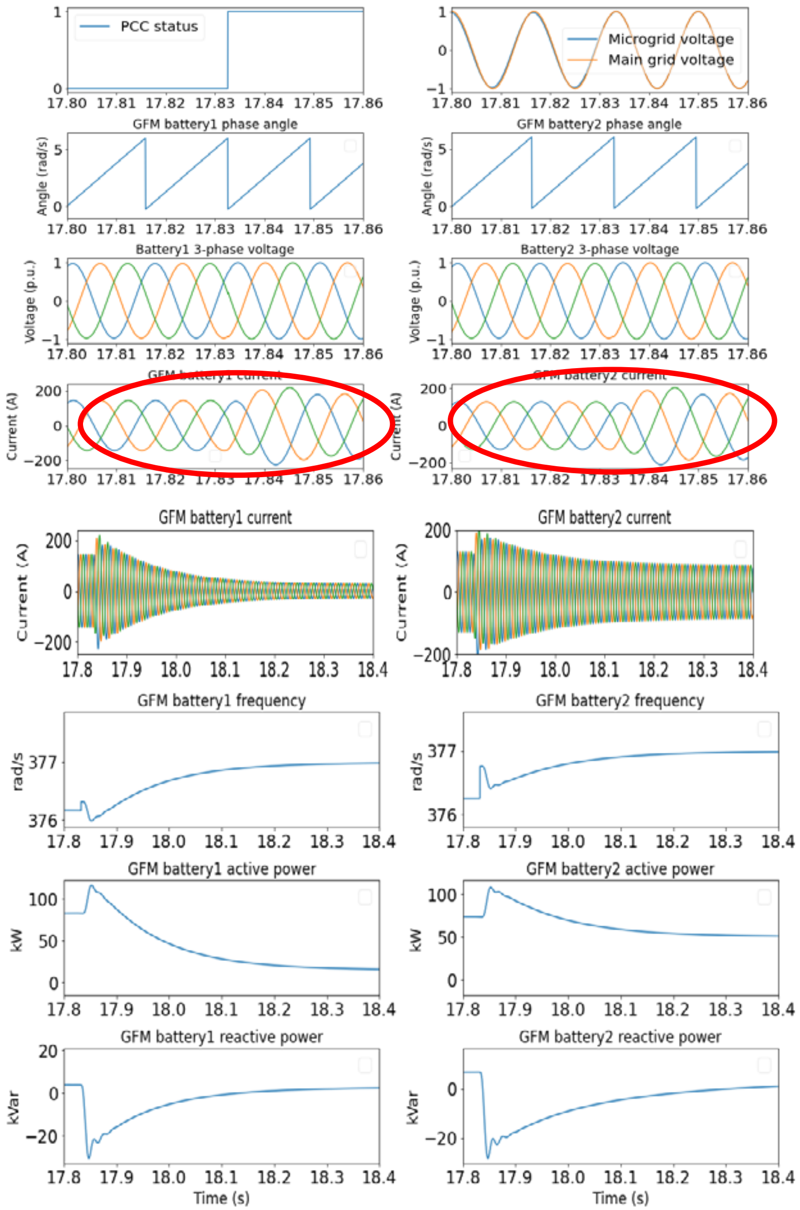
Strategy II

Simulation Results – Reconnection to the Grid

Strategy I



Strategy II



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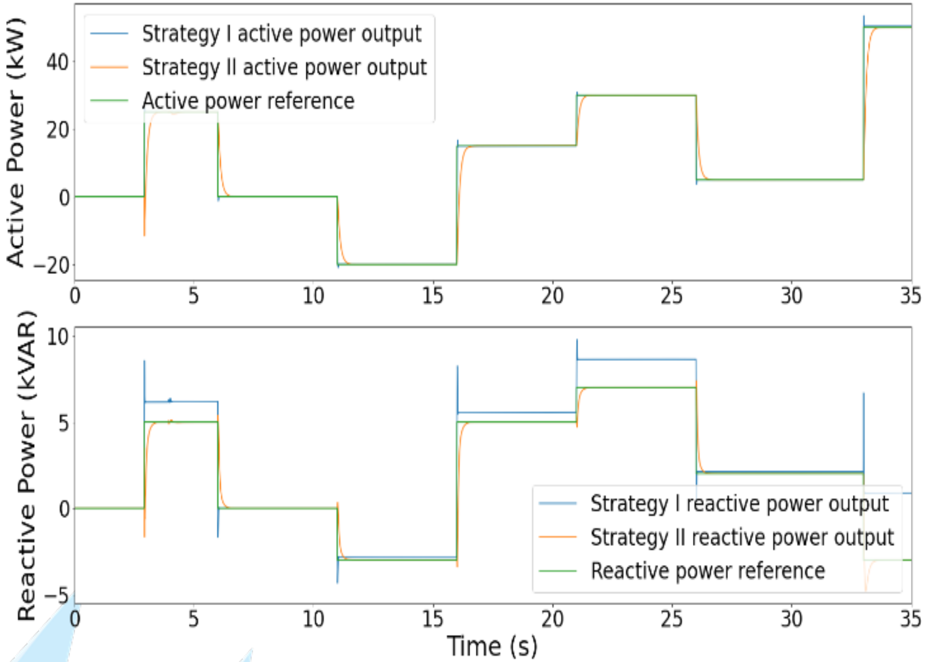
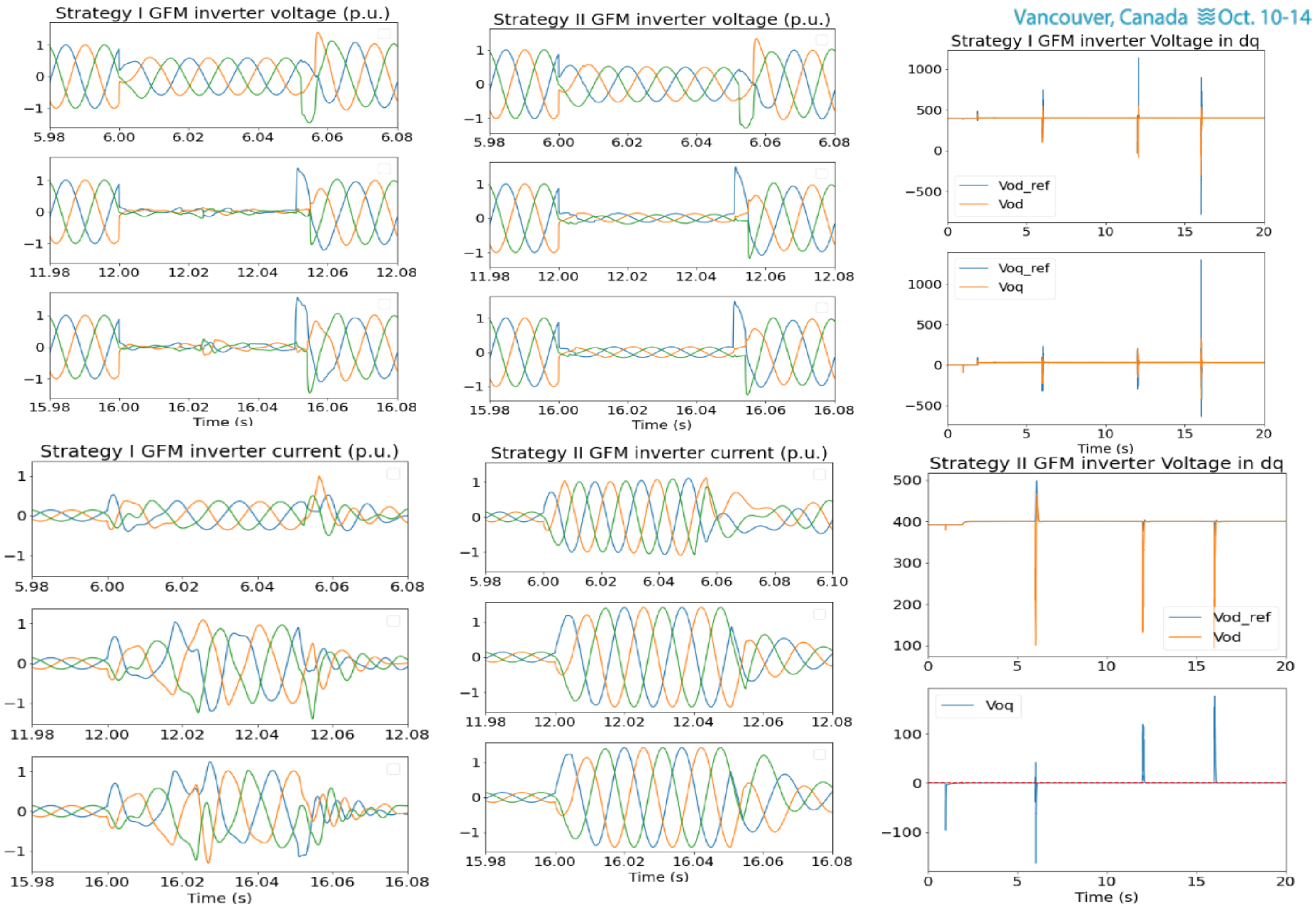
Simulation Results

- Power tracking performance in grid-connected mode



- P-Q capability with low PCC voltages in grid-connected mode



Conclusion

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Circumstance	Strategy Comparison
Unplanned islanding	Both have smooth transients. Strategy II has slightly better transients in the output current.
Reconnection operation	Strategy I has better transients in frequency, output current, and power.
Power tracking	Strategy I reaches steady state faster with overshoots and has a tracking error in the reactive power. Strategy II has good tracking performance for both active and reactive power with an acceptable settling time.
P-Q capability with low PCC voltage	The low PCC voltage has a larger impact for Strategy I because its power control loop is a current control loop, and the current references depend on the PCC voltage. Strategy II has a larger P-Q capability with low PCC voltages and can maintain stability during fault ride-through. Strategy I can maintain stability only when the voltage is not less than a certain level.

- Overall, Strategy II is recommended for microgrid applications
  - Comparable transition operation performance
  - Better power tracking in grid-connected mode
  - Better P-Q capability under faults or low PCC voltages
  - Easy for implementation.

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