Performance of Grid-forming Control of Grid-edge DERs in Distribution Grids

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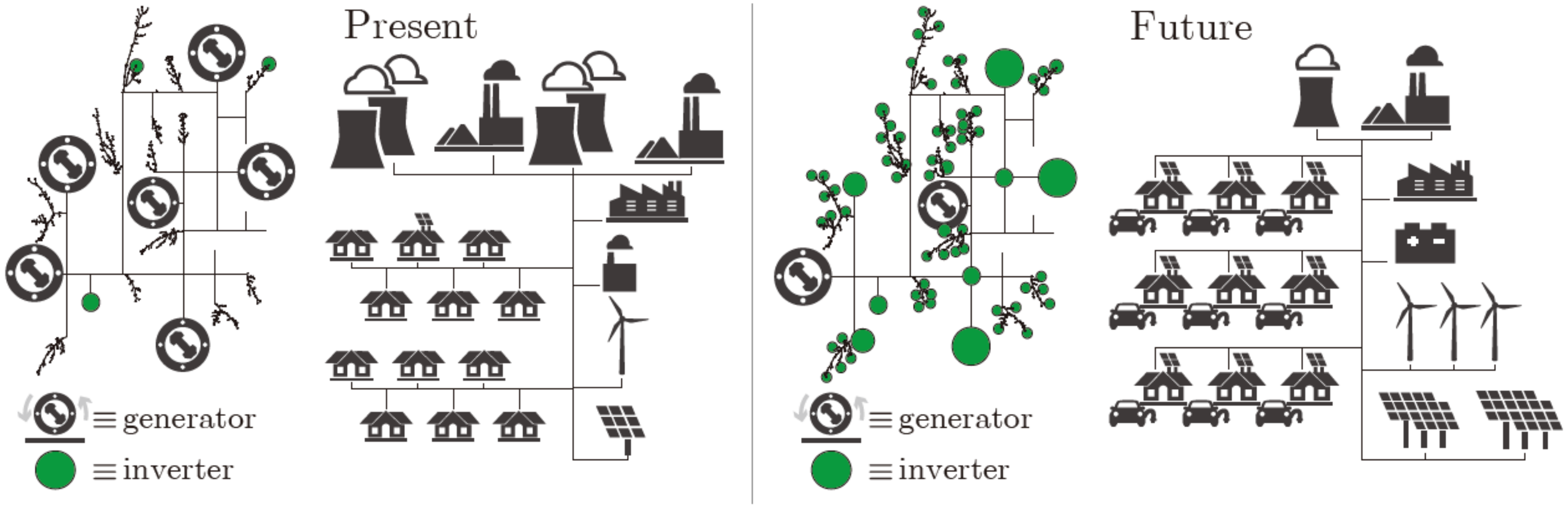
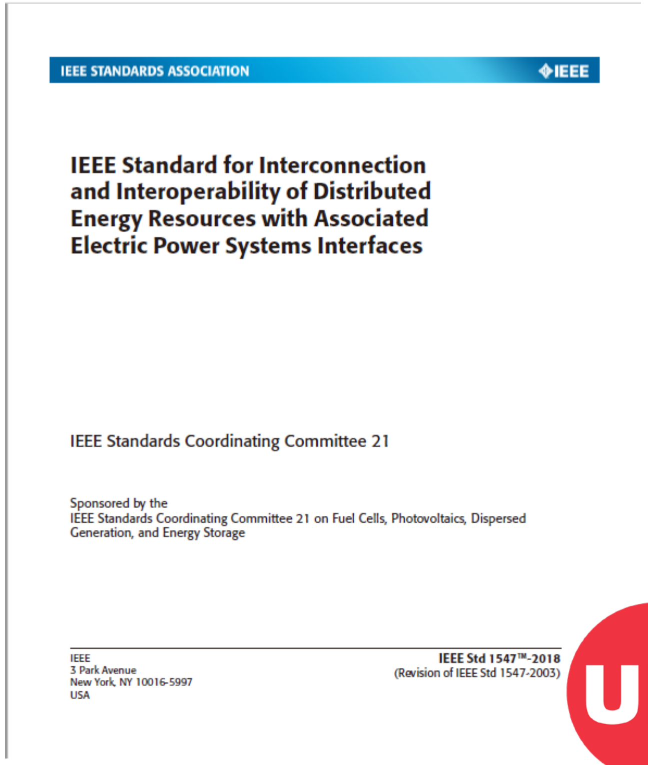
DERs in next-generation distribution grids

- Cumulative distributed energy resource (DER) capacity in the United States will reach 387 gigawatts by 2025
  - Solar, EV infrastructure, battery storage
- Power electronics greatly decrease the system inertia
  - Frequency oscillations
  - Device damages
  - Widespread power outages, 2019 U.K. blackout (low inertia)

The DERs, especially the utility-scale ones are required to provide f and V regulation services---IEEE1547




IEEE STANDARDS ASSOCIATION

IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

IEEE Standards Coordinating Committee 21

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3 Park Avenue
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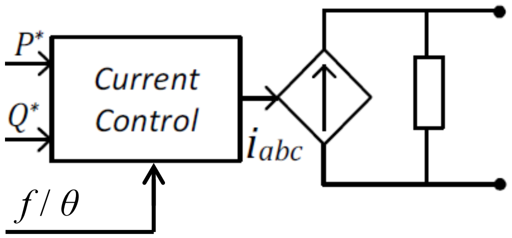
IEEE Std 1547™-2018
(Revision of IEEE Std 1547-2003)

Current DER control methods

Grid following control

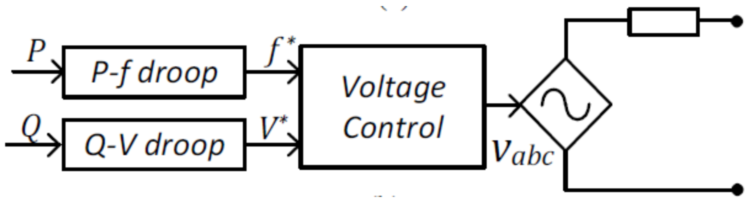
Input: P, Q commands & grid frequency/angle



Grid frequency/angle via Phase-locked-loop (PLL)

Grid forming control

Input: inverter output P, Q measurement



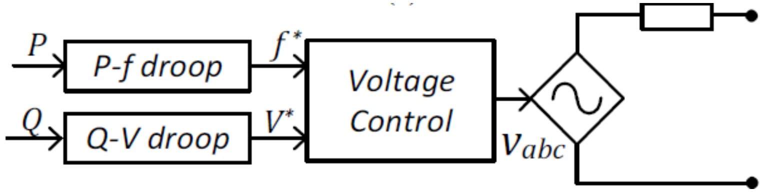
Grid forming control can independently control the f&V without grid side signals, thus can provide f&V support

Grid following control	Grid forming control
Inverter acts as a current source	Inverter acts as a voltage source
Control output current and active & reactive power	Control output voltage magnitude and frequency
Rely on the frequency/angle signal from grid side	Does not rely on grid side signals
Need additional outer loop coordination controls to determine P and Q commands	Autonomously balances loads without outer coordination controls
Cannot operate standalone	Can operate standalone

Existing grid-forming control

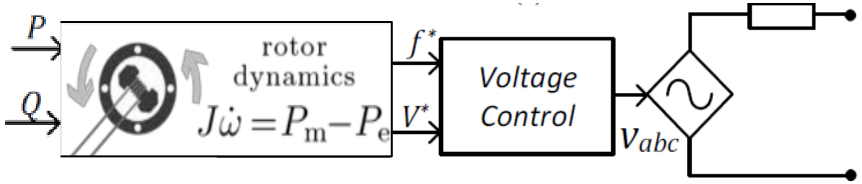
- Droop control (P-f, Q-V droop)

-----mimic droop of synchronous generator (SG)



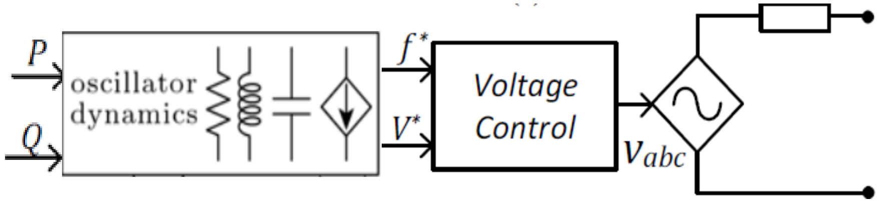
- Virtual synchronous generators (VSG)

-----add a virtual rotor to mimic the rotate inertia of SG

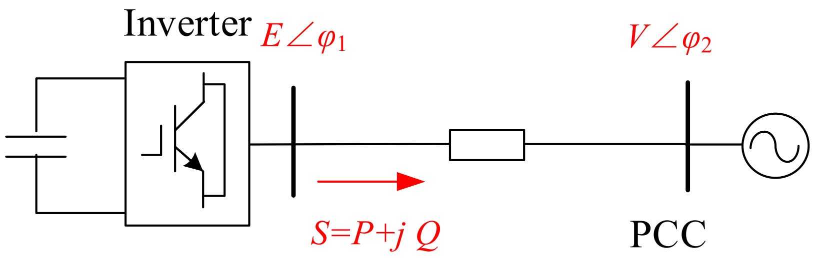


- Virtual oscillator controllers

-----use a virtual oscillator to mimic oscillator dynamics for automatic synchronization



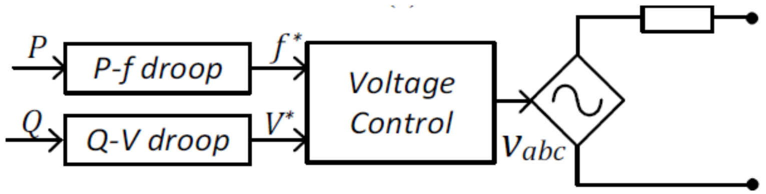
All are designed based on a model, which treats the distribution grid as a Thevenin equivalent circuit
Cannot reflect complex dynamics and characteristics of distribution grids with distributed generations and loads



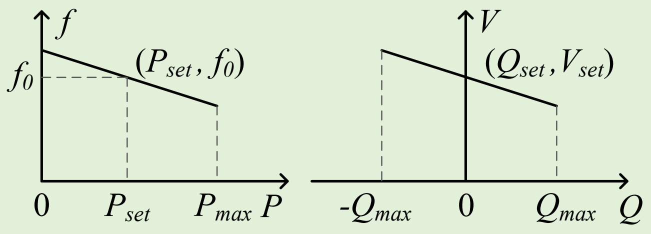
Compatibility of grid forming control in realistic distribution grid???

Compatibility in distribution grid

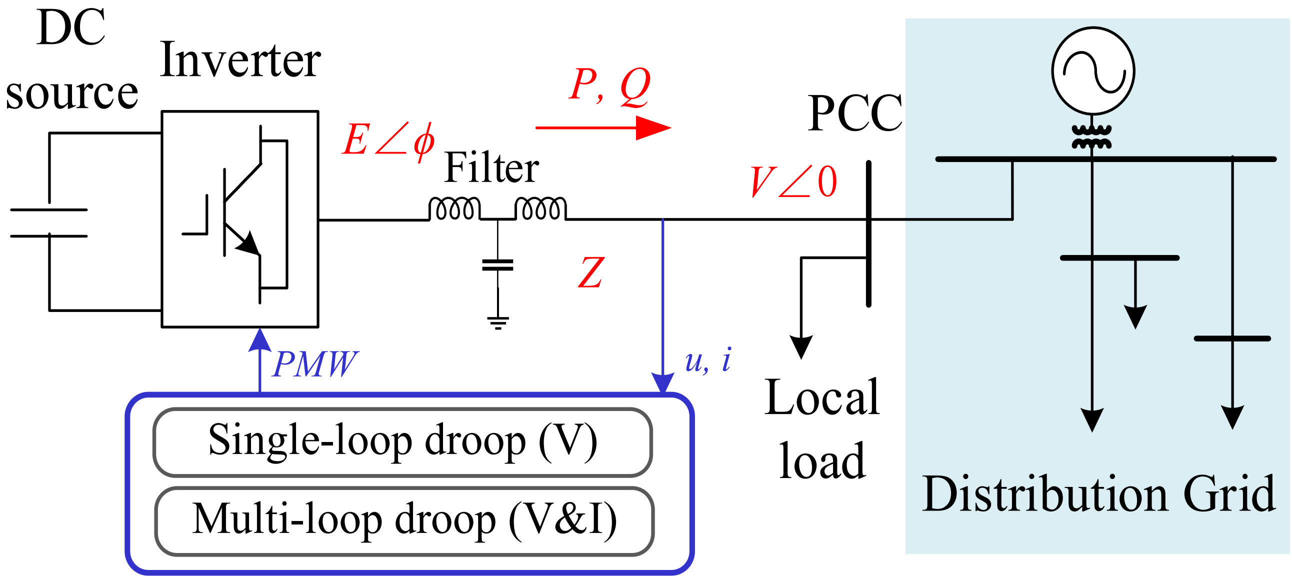
- We investigated the performance of droop-based grid forming control when it connected to a distribution grid model.



- P-f and Q-V droop laws



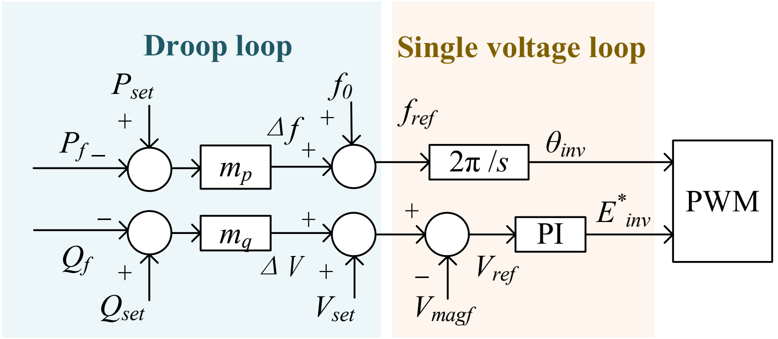
$$\begin{cases} P = VE\,\phi/Z \\ Q = V\,(E - V)/Z \end{cases}$$



- Two droop control configurations:
  - Single-loop droop: inner voltage control + outer droop
  - Multi-loop droop: inner voltage&current control + outer droop

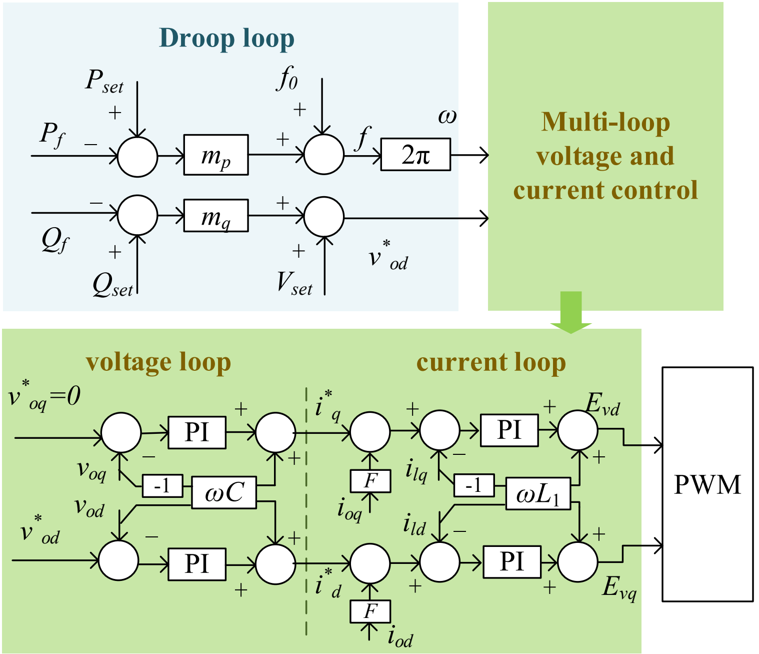
Droop control - two typical configurations

Single-loop droop control



- Outer droop loop + Inner voltage loop
  - Simpler control structure
  - Study shows the system has a larger small signal stability boundary using single loop control

Multi-loop droop control

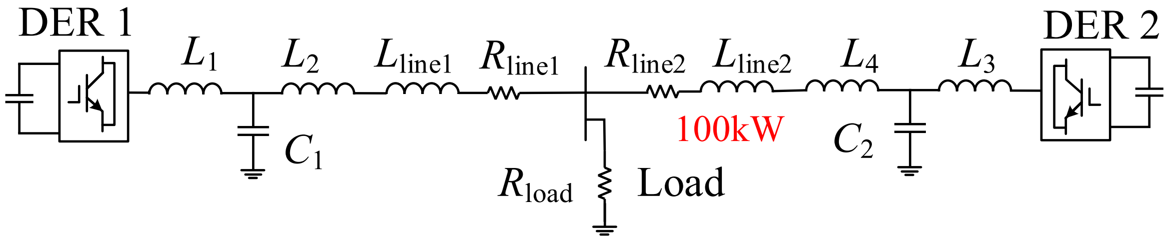


- Outer droop loop + Inner voltage & current loops in the d-q frame
  - The inner current loop improves the dynamic response speed
  - The inner current loop allows current limiters for protecting the switches during contingencies, such as faults and overloads.

Case study -- System configuration

- Compare droop control performance in different system model (single loop droop &multi-loop droop)

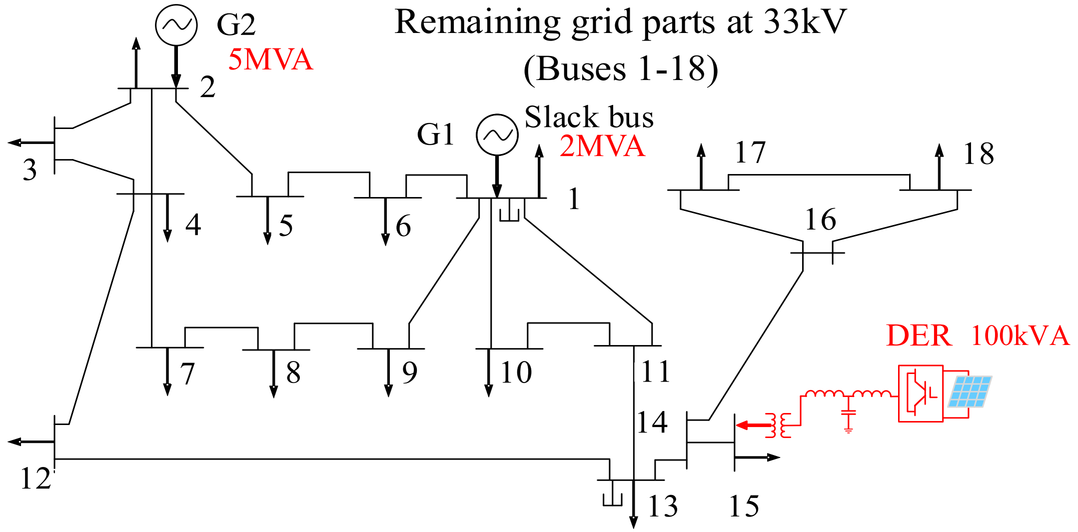
Case1: grid model represented by a passive load



Two parallel-connected inverters and a passive load

- Used in the existing studies

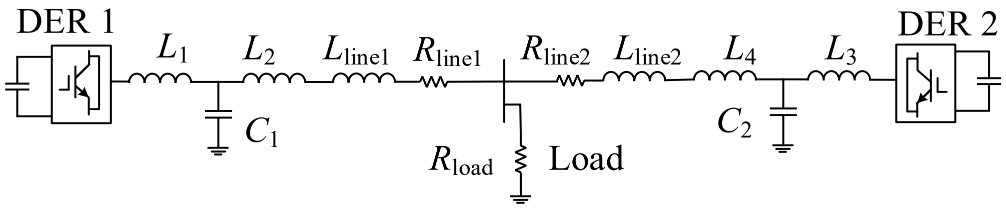
Case2: Modified IEEE 30 bus distribution grid benchmark



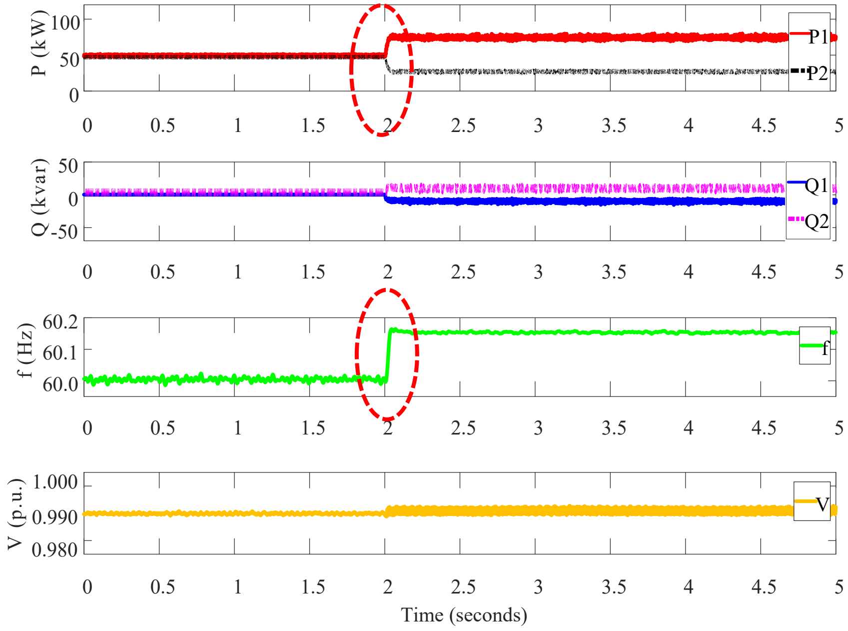
Distribution grid system

- consisting of one inverters and a modified IEEE 30 bus system model

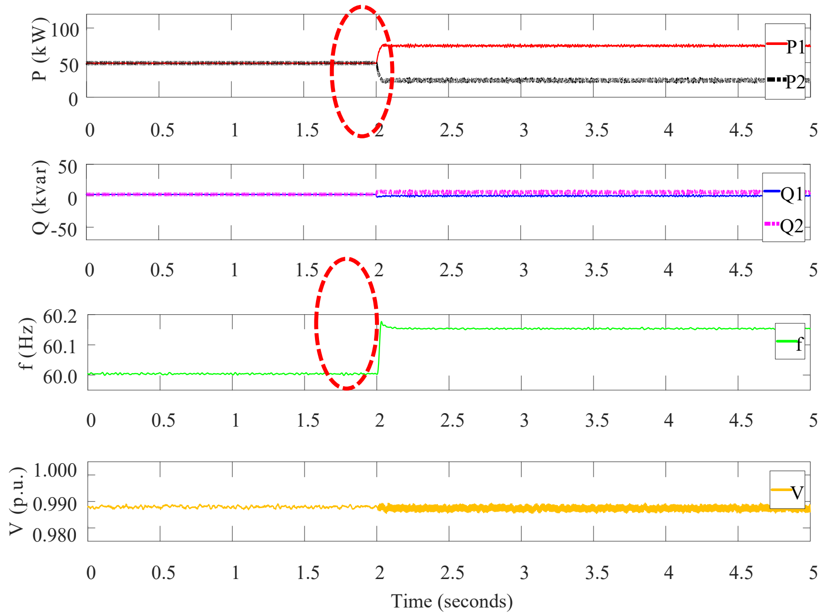
Case study – Parallel-connected inverters



- Single-loop droop



- Multi-loop droop



- **Event**: Pref step of DER1

  Both single/multi-loop droop

  ✓ DER1 (P1) increases following P reference

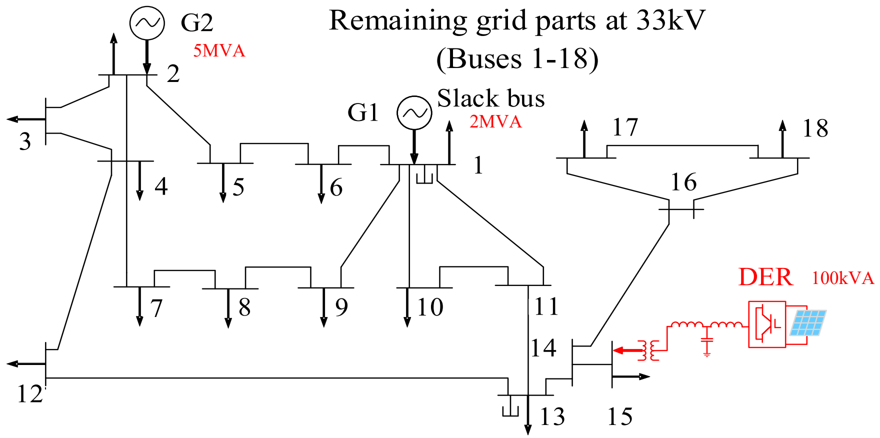
  ✓ DER2 (P2) decreases due to the coordination of droop control

  ❖ f increases abiding with P-f droop control

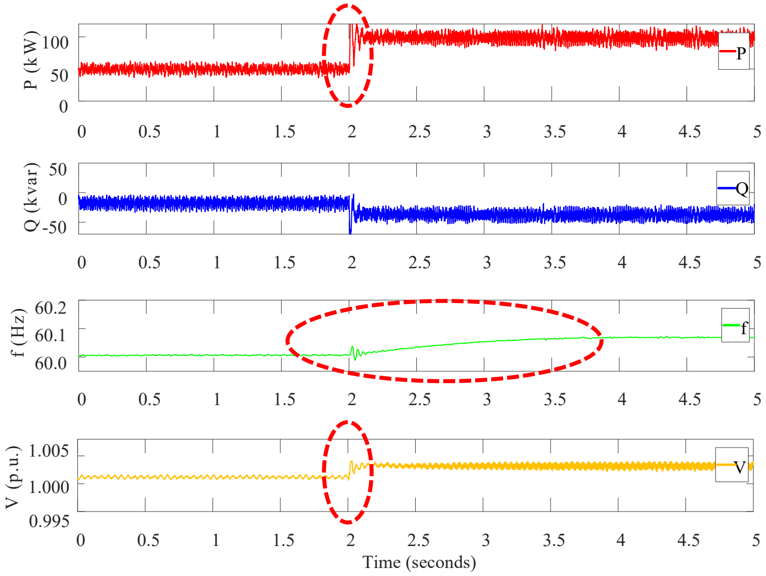
  ❖ V and Q remains the same

  ➢ f and V Good performance in this model

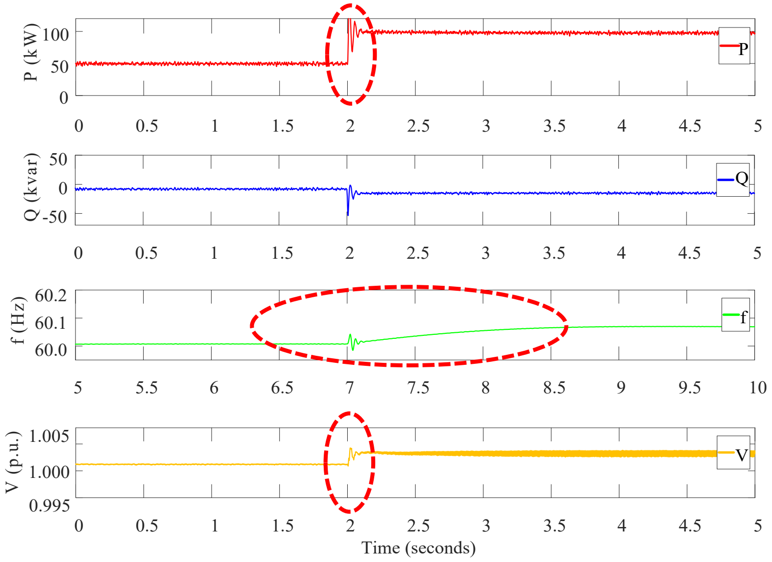
Case study – distribution grid benchmark



- Single-loop droop



- Multi-loop droop



- **Event:** Pref step of DER
  - ✓ DER follows P reference
  - ❖ Both f and V are affected (f slowly ramps up due to SG inertia)

----P should only affect f, but V is also affected with a step

- ➢ Coupled f&V control & transient oscillations when connected to grid
- ➢ *Performance?*

Conclusion

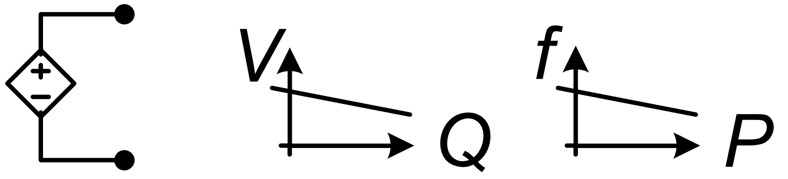
- The control of f and V are coupled associated with P and Q when connected to distribution systems
- The existing droop based GFM control schemes cannot enable DERs to provide independent and effective f and V regulation in distribution grids

Reason:

- Existing GFM control schemes: all based on P-f and Q-V droop laws

------- *only valid in the highly inductive transmission system.*

  - In the distribution grid, the f and V controls become coupled with the P and Q due to the high R/X ratio.
  - Complex dynamics and changing operating conditions in the distribution grids are also challenges.



[1] S. Yu, S. Rong and L. He, "Performance of Grid-forming Control of Grid-edge DERs in Distribution Grids," *2022 IEEE PES General Meeting*, Jul. 2022, Denver, USA.