



Power Systems with 100% Inverter-Based Generation

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Mehrdad Yazdanian (now at Smart Wires)

Based on Research Sponsored by EPRI



PSERC Webinar • Nov. 6, 2018

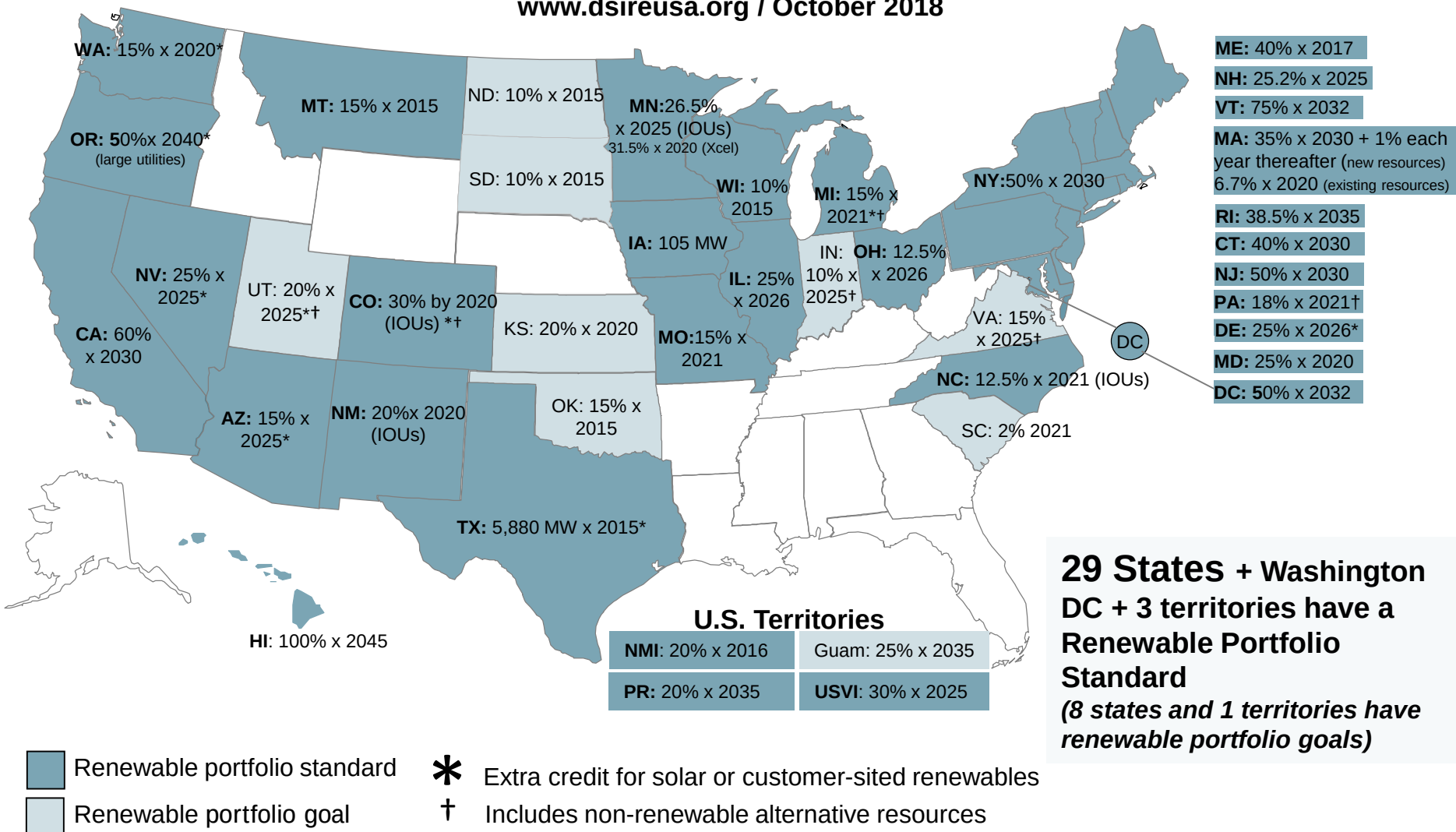


Acknowledgement

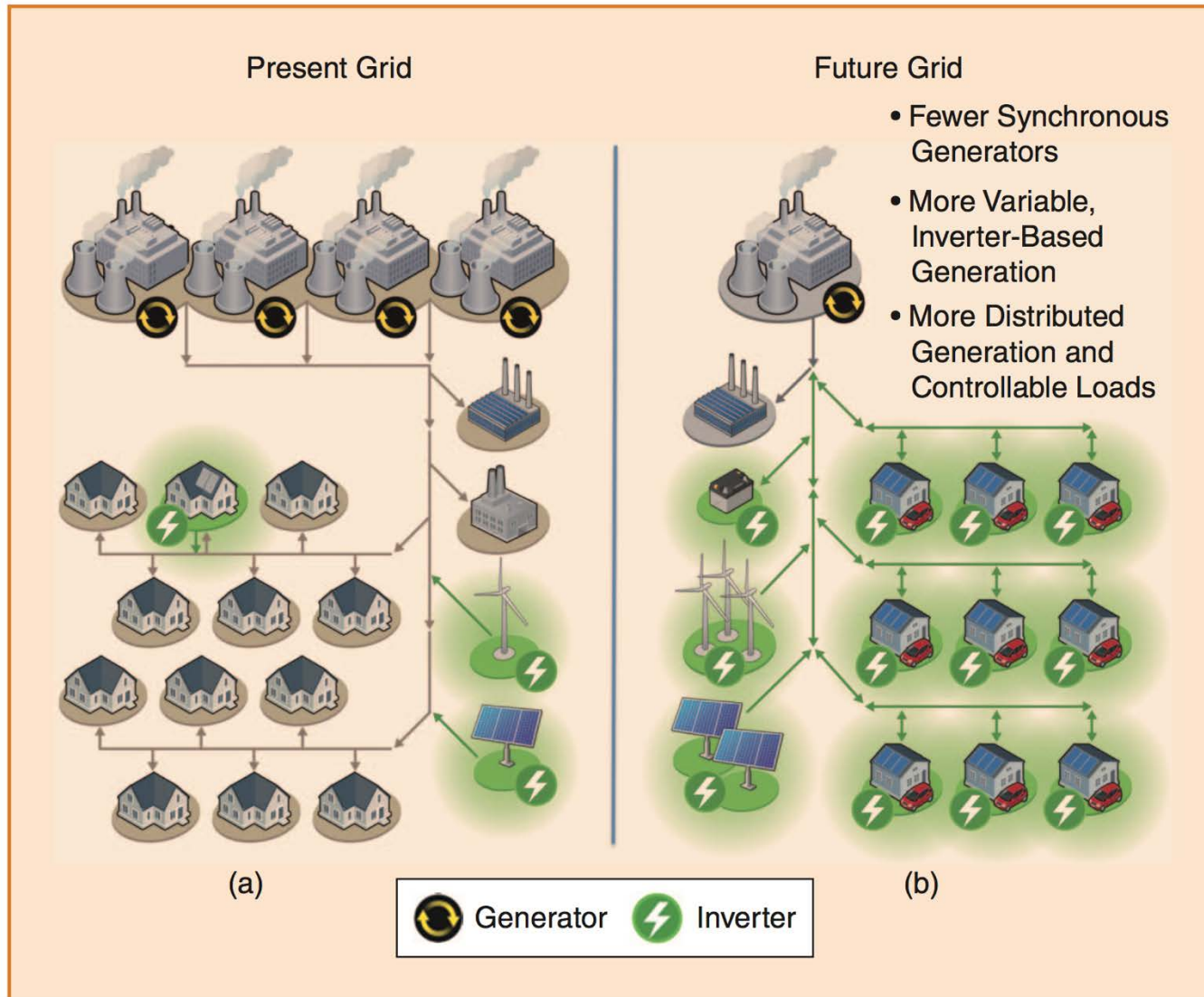
- Financial support from EPRI.
- Numerous hours of technical discussion with EPRI's Dr. Evangelos Farantatos and Dr. Deepak Ramasubramanian.

Renewable Portfolio Standard Policies

www.dsireusa.org / October 2018



Inverter-Dominated Grid

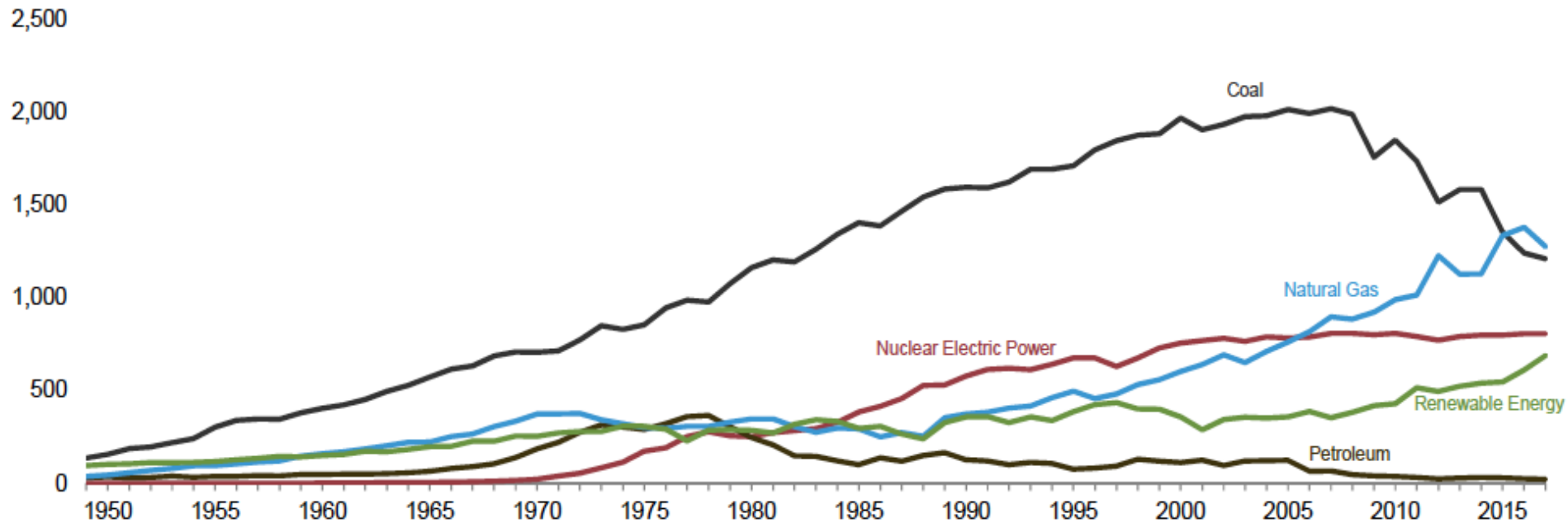


B. Kroposki et al.,
"Achieving a 100% renewable grid,"
Power & Energy M.,
2017.

Electricity Generation Trend in the U.S.

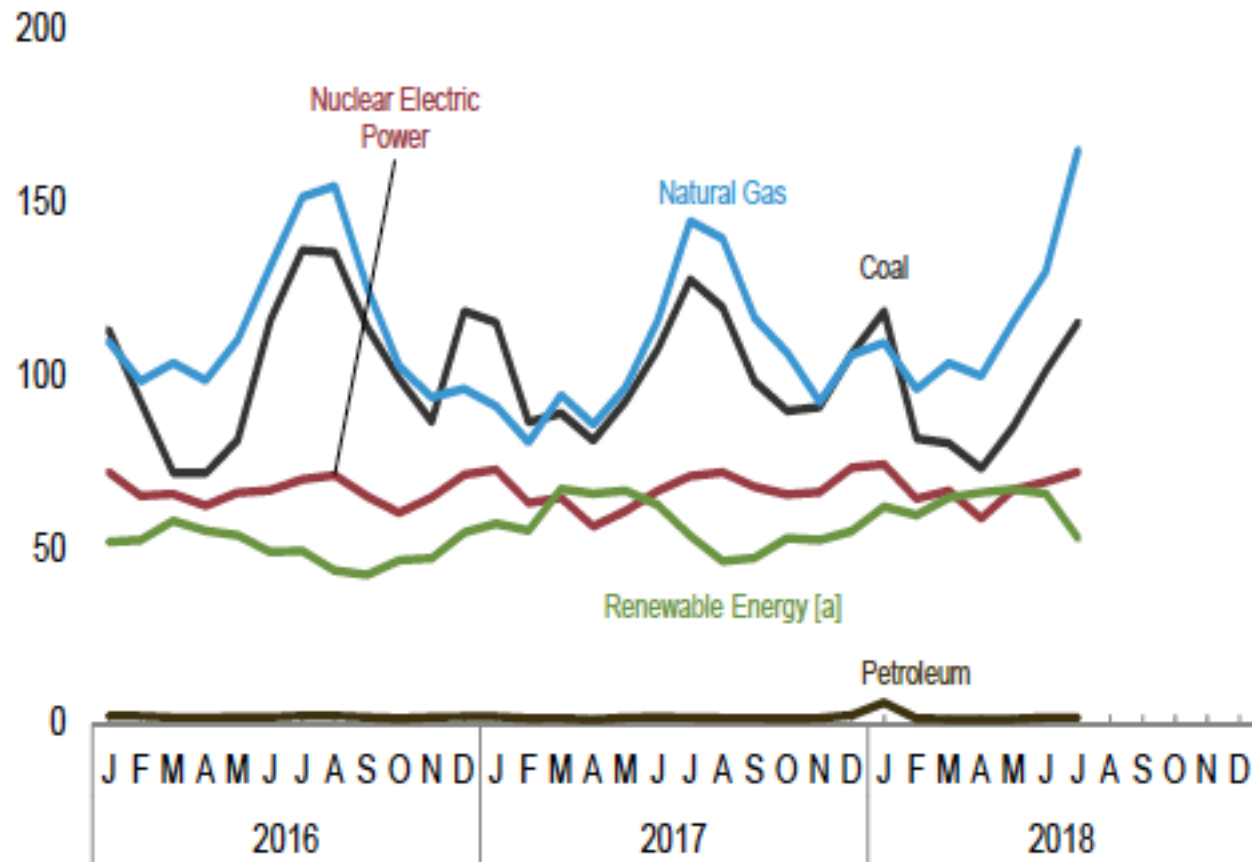
👉 Billion kWh

Total (All Sectors), Major Sources, 1949–2017



Monthly Data

Total (All Sectors), Major Sources, Monthly





Challenge

- ➡ **Conventional power sharing algorithms are geared toward electromechanical generation. Power sharing in a system dominated by inverter-based resources introduces challenges due to differences in the notion of frequency, stringent limits of the power electronics devices, and lack of inertia.**



Background

- ➔ **Power system is (was) designed for operation with bulk electromechanical energy conversion.**
 - Generators: Synchronous generators
 - Loads: Induction motors



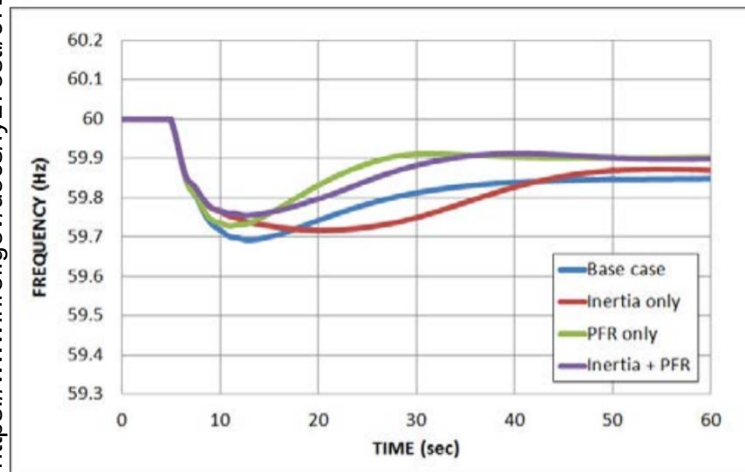
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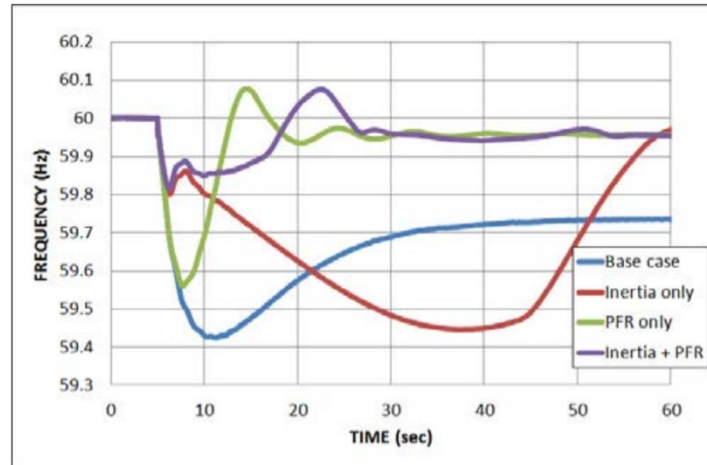
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WECC with 15% wind generation



WECC with 80% wind generation





Changing Generation Scenery



Generation:

- More power electronics-based renewables

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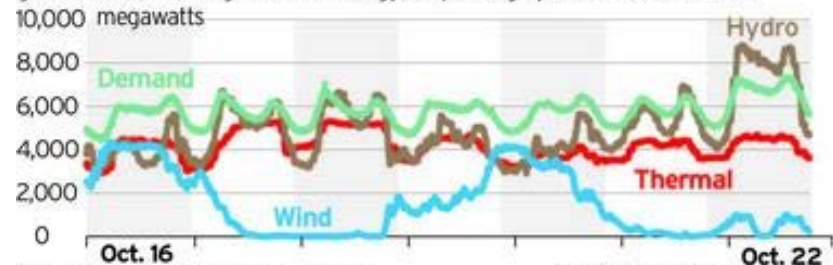
➤ Examples

- The BPA service area has several times experienced 100% wind generation.



Power generation

Last week's energy generated in the region included a record on Oct. 16 - wind generated 4,289 megawatts of energy, surpassing hydro for the first time.



Source: Bonneville Power Administration

MARK GRAVES/THE OREGONIAN

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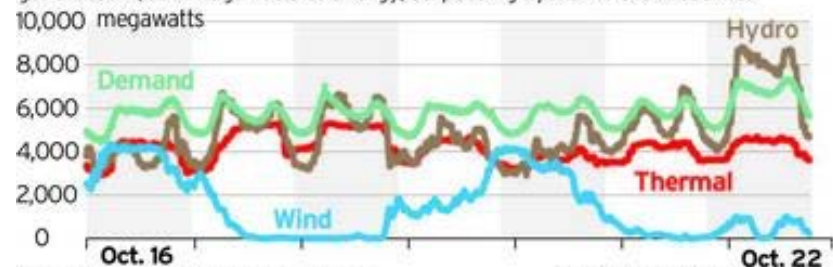
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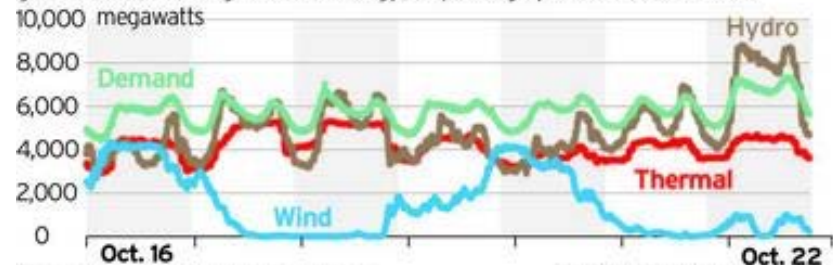
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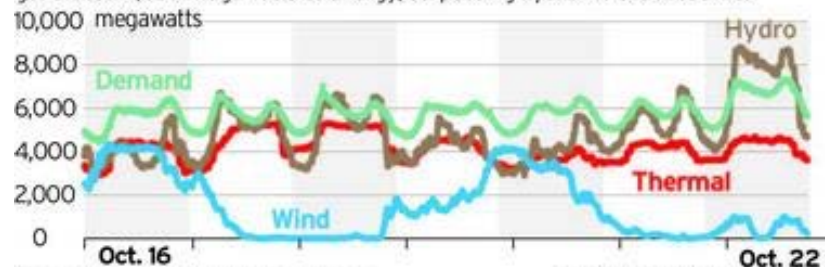
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- In Ireland, the operators are expected to accommodate up to 75% instantaneous inverter-based generation by 2020.



Power generation

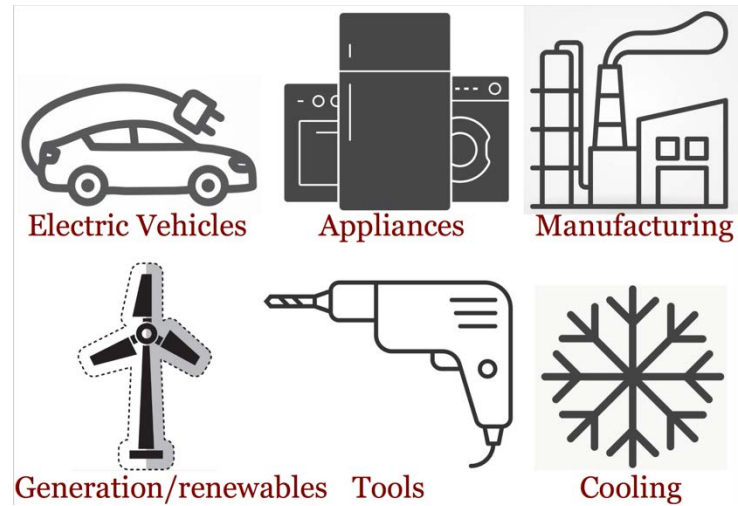
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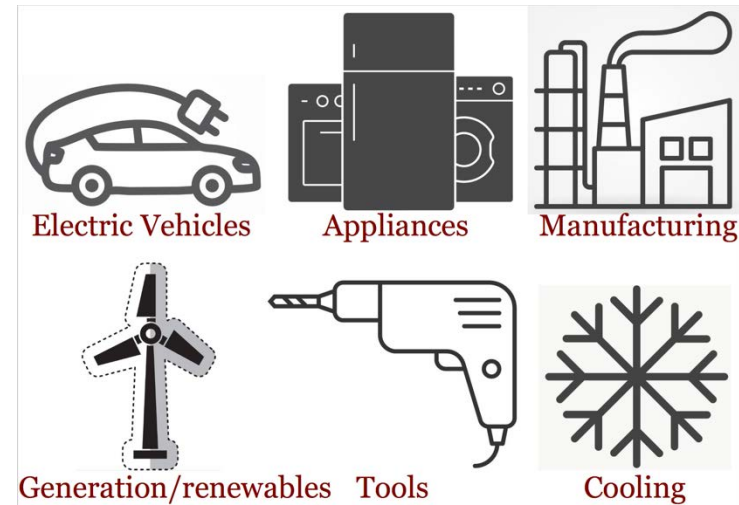
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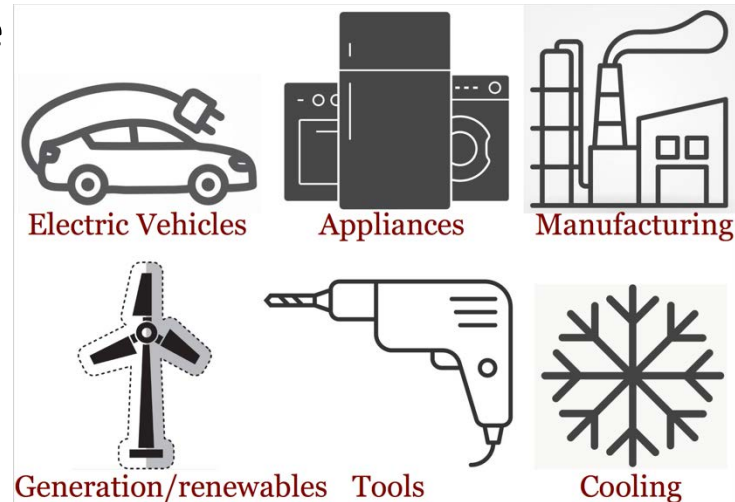
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- Electric drives (motor + inverter) are the largest consumer of electricity (about 64%) in the United States.
- Lights: multicolor LED, e.g., Philips Hue
- Modern appliances



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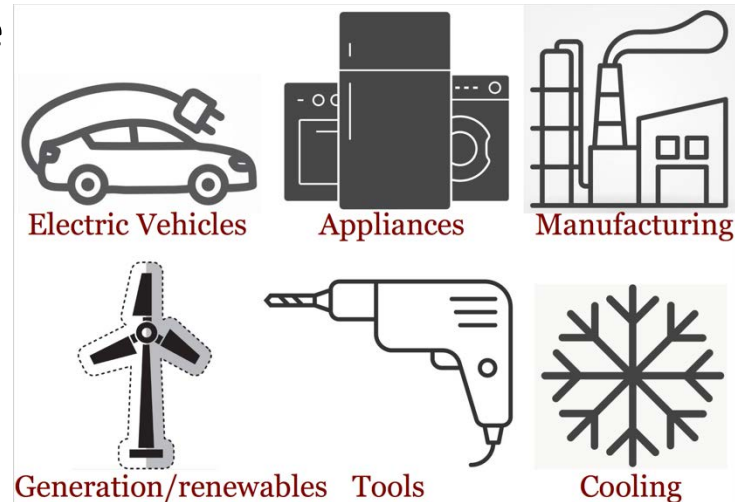
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- **This shift toward inverter-based resources brings about significant challenges in power system dynamics, stability, and control.**





Outline

- ➔ **Problem**
- ➔ **Basics**
 - Inverter Types
 - Power Sharing Methods
- ➔ **Our Proposed Method**
- ➔ **Results**
- ➔ **More Results**



Problem



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- ➔ **One of the grand energy challenges is to enable integration of large amounts of renewable energy resources at a competitive cost in the power grid (in the U.S., 80% by 2050 per NREL).**
 - CA: 60% of electricity from renewables by 2030.



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 - Intermittency and variability
 - Susceptibility to violation of operational limits
 - Lack of inertia and changes in ways to meet demand
- **This work addresses the latter:**
 - How can we still achieve power sharing without mechanical inertia and without needing communication?



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Grid-supporting

Dispatchable and responds to the grid commands, e.g., by changing its injected real power, to participate in power sharing. Can be voltage source.

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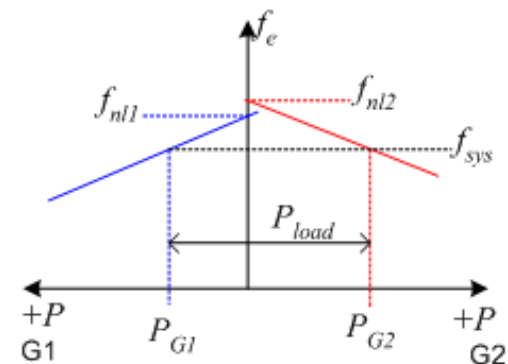
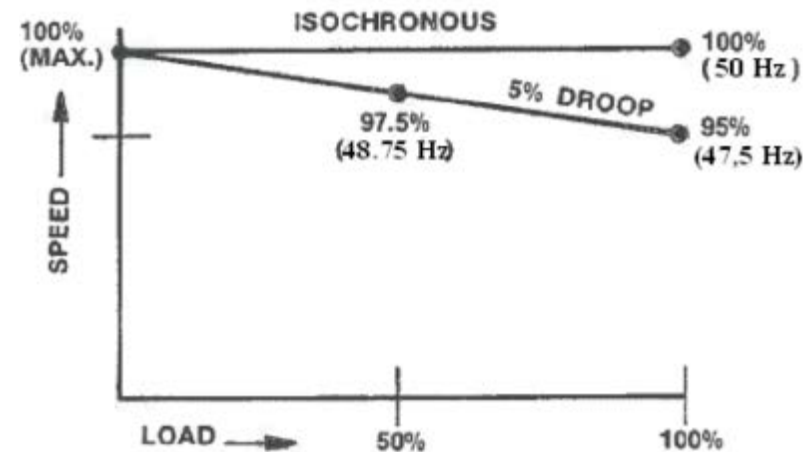
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- **Grid-following units need a stiff grid voltage and frequency to synchronize to using a PLL.**
- **In contrast, a grid-forming unit establishes and controls the grid voltage and frequency and is controlled as a voltage source.**
- **How to achieve autonomous power sharing with this mix of inverters?**

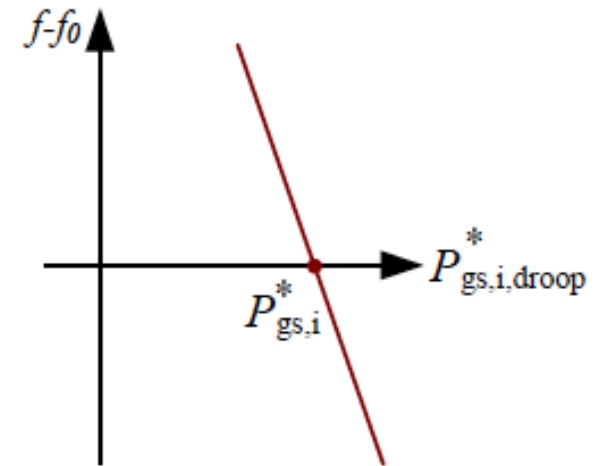
Power Sharing: Existing Approaches

➤ Good, old (frequency) droop:

- Based on a synchronous generator's intrinsic relationship between power (generation/load mismatch) and frequency (rotor speed).
- This power-frequency droop can also be adopted for an IDPS via converter controls emulating an SG.
- European MIGRATE project uses the concept of threshold virtual impedance (TVI) to improve the transient behavior.
- Droop in general needs a secondary controller to bring the frequency back to nominal values.



1. Droop Control

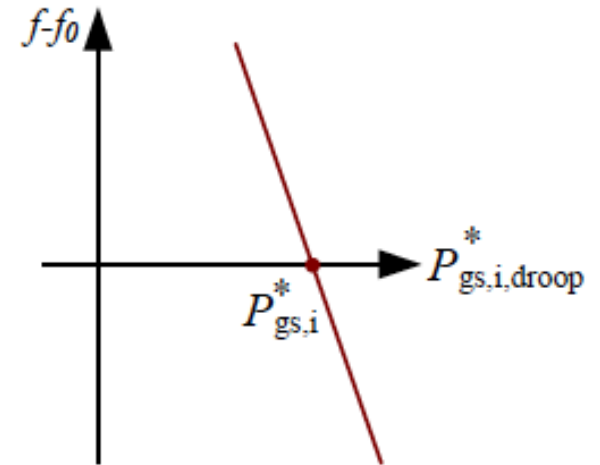




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➔ The Good

- Structurally simple
- Plug and play capability
- Based on local measurement
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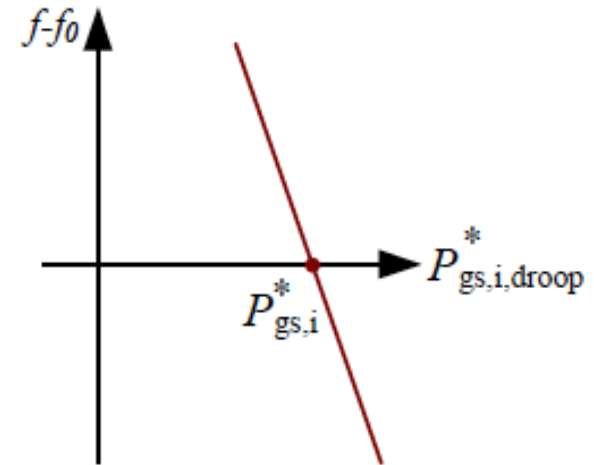
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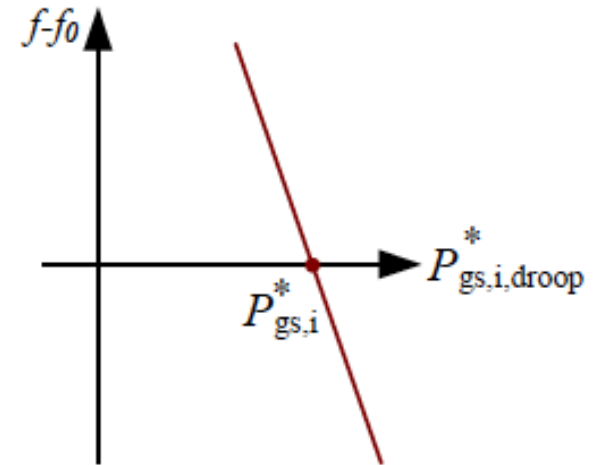
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➤ In addition, in a 100% inverter-based system, the notion of frequency is relevant only for electrical quantities (rate of change of voltage angle), and there is no rotor to define mechanical frequency.





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- These equations ensure power sharing in the steady state, but they can not account for restoration of voltage and frequency.



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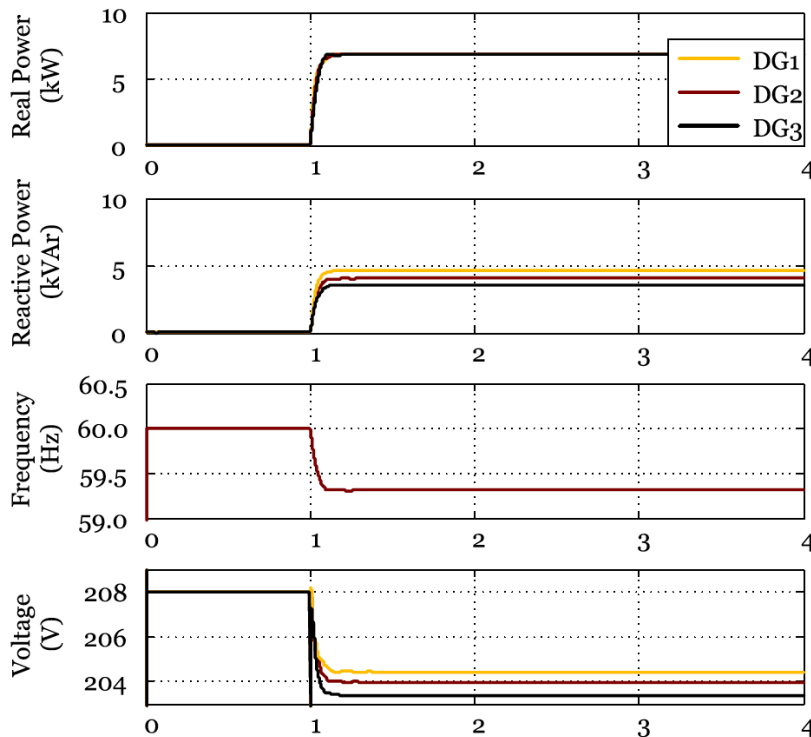
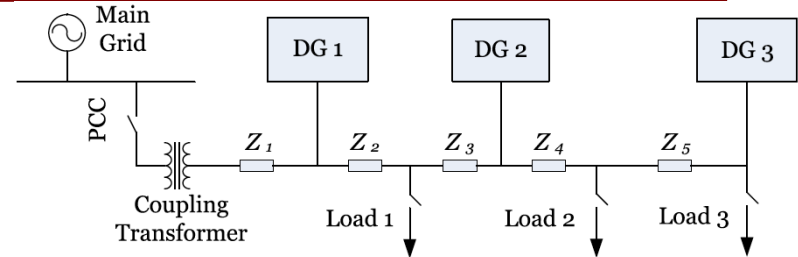
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- That is, we utilize a dynamic feedback based on a washout filter (a first-order high-pass filter): robust with respect to uncertainties.

Results

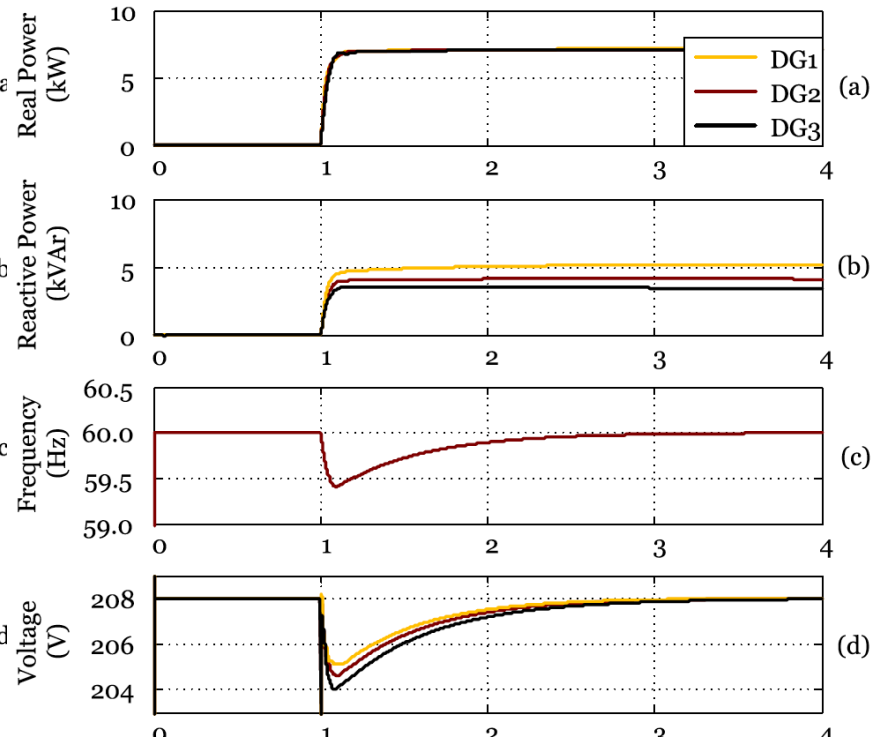
Loads connect at $t = 1$.

$$\omega_i = \omega^* - \frac{m_p s}{s + k_p} (P_i - P^*)$$



Conventional Droop

Steady state deviation of frequency.



Washout Filter

Frequency restoration in 2 s.

3. Angle Droop

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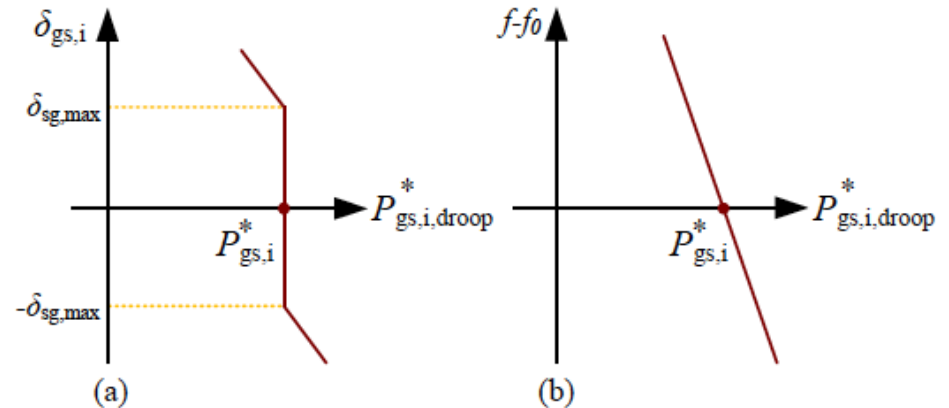
- **No need to frequency restoration as when angles stop changing, the frequency ($d\delta/dt$) is already back to its original value.**



Proposed Solution

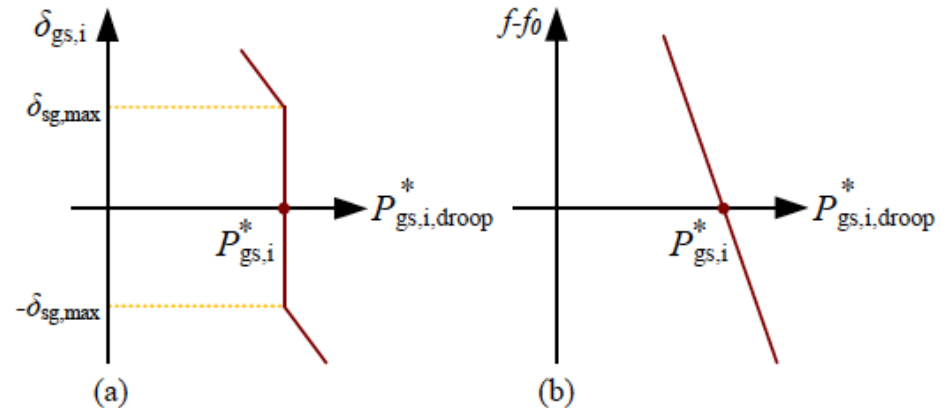
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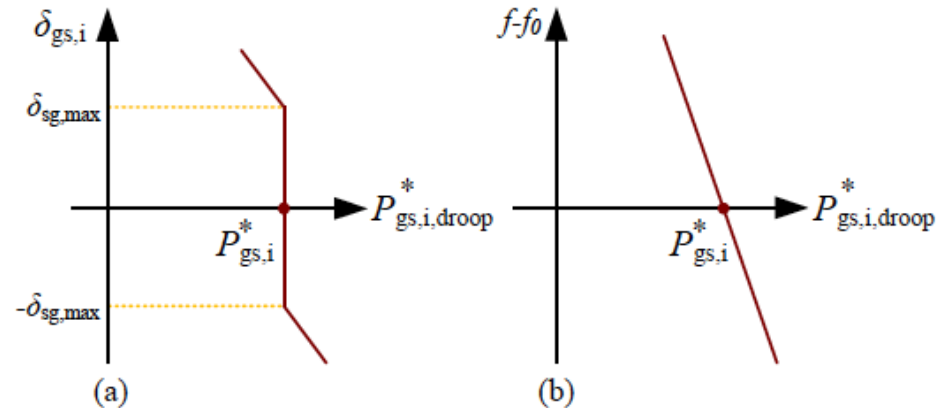
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- ➔ This method allows the inverters to deviate from their locally determined (or preferred) set points to participate in real power sharing when needed.
- ➔ Features:
 - Utilizing only local signals and without requiring wide-area communication during transients;
 - Explicitly considering current and real power limits of inverters;
 - Ability to control power contribution of each inverter.



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- The sum of changes should equal the difference between the total demand and power supplied by the grid-forming units and preferred powers of the grid-supporting units:

$$\begin{aligned}\sum \Delta P_{\text{gs},i}^* &= P_{\text{demand}} - P_{\text{gf}} - \sum P_{\text{gs},i}^* \\ &= P_{\text{gs-total-change}},\end{aligned}$$

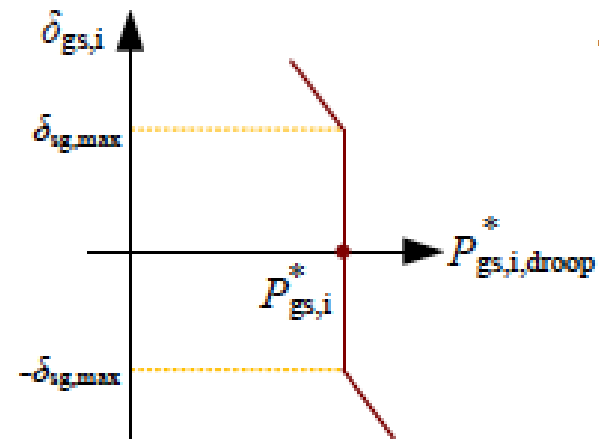
where

$$P_{\text{gf}} \leq P_{\text{gf,max}}$$

Angle Change

$$\Delta P_{\text{gs}}^* = \begin{cases} 0, & \delta_{\text{gs,min}} < \delta_{\text{gs}}(t) < \delta_{\text{gs,max}} \\ D (\delta_{\text{gs,max}} - \delta_{\text{gs}}(t)), & \delta_{\text{gs,max}} < \delta_{\text{gs}}(t) \\ D (\delta_{\text{gs,min}} - \delta_{\text{gs}}(t)), & \delta_{\text{gs,min}} > \delta_{\text{gs}}(t), \end{cases}$$

where D is the angle droop gain. With multiple grid-supporting units, D of each unit determines its power share.

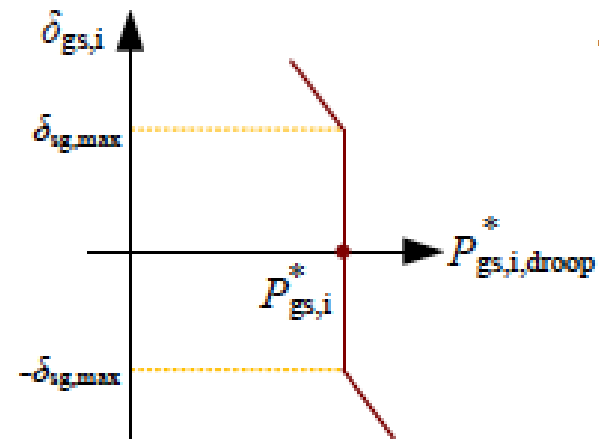


Angle Change

$$\Delta P_{gs}^* = \begin{cases} 0, & \delta_{gs,min} < \delta_{gs}(t) < \delta_{gs,max} \\ D(\delta_{gs,max} - \delta_{gs}(t)), & \delta_{gs,max} < \delta_{gs}(t) \\ D(\delta_{gs,min} - \delta_{gs}(t)), & \delta_{gs,min} > \delta_{gs}(t), \end{cases}$$

where D is the angle droop gain. With multiple grid-supporting units, D of each unit determines its power share.

- ➔ The choice of $\delta_{gs,max}$ is a trade-off between power sharing accuracy based on D coefficients and the time it takes to reach the steady state. We will come back to this.



Design Principles

Design Principles

- ▶ **Principle 1: The power limits of all grid-forming and grid supporting units should be met.**

Design Principles

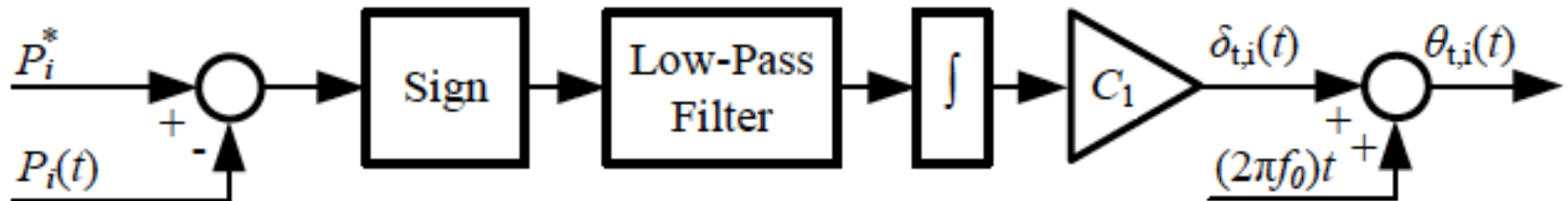
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Design Principles

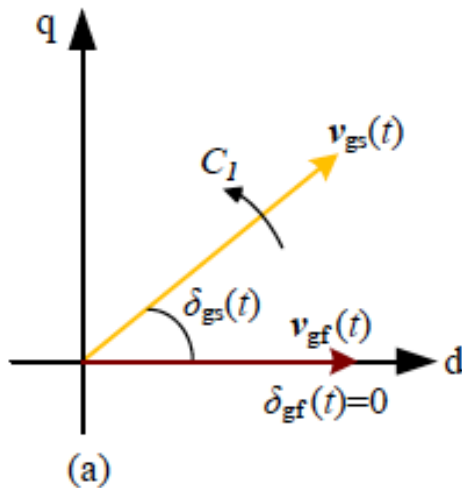
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- **Principle 3: The share of grid-supporting units in power sharing should be based on their droop characteristic.**

Large Grid-Forming Unit?

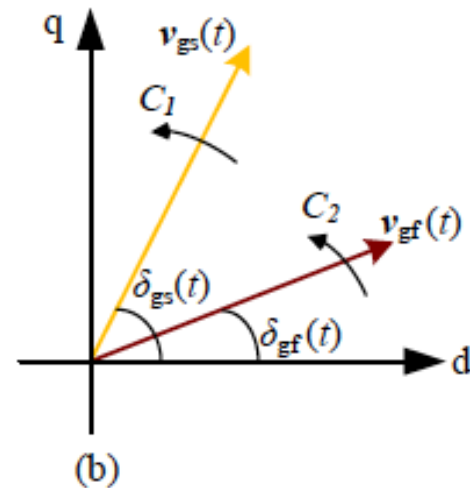
- If the grid-forming unit is large enough, the grid-supporting units continue to inject their preferred real power values $P_{gs,i}^*$
- In this case, the grid-forming unit's voltage angle $\delta_{gf}(t)$ is maintained at zero, and the angles $\delta_{gs,i}(t)$ of the grid-supporting units are changed in a ramp at rate C_1 until $P_{gs,i}(t)$ reaches $P_{gs,i}^*$



Limited GF? GS Shares Power



Big grid-forming inverter



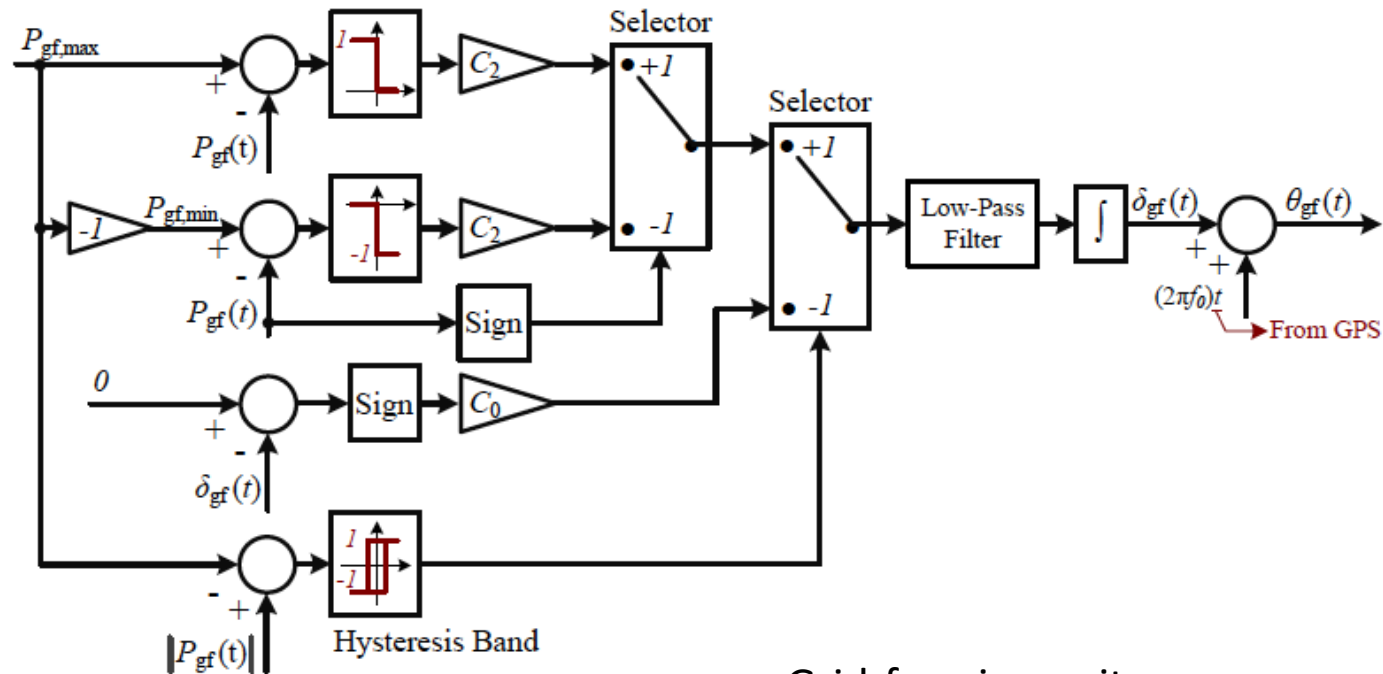
Limited grid-forming inverter

GS ramps its angle at C_1 to meet P_{gs} ; GF monitors its power to make sure it doesn't exceed the limit.

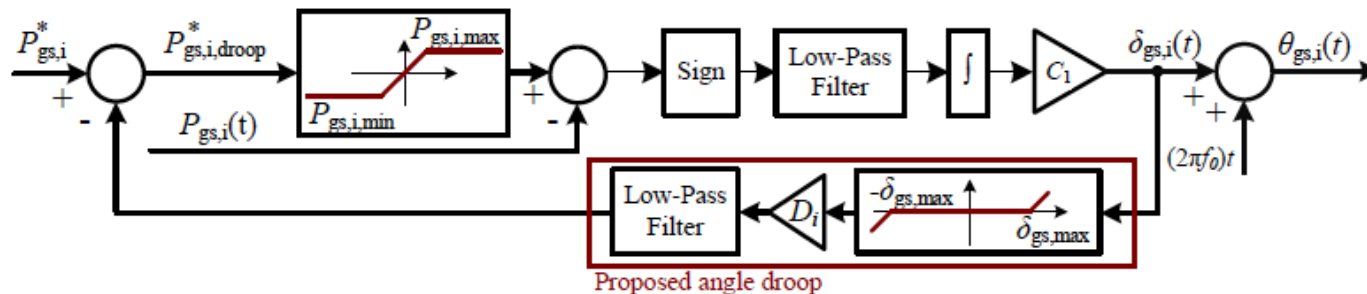
If it does, it also changes its angle at rate C_2

$$C_2 > C_1$$

Generalized Controls



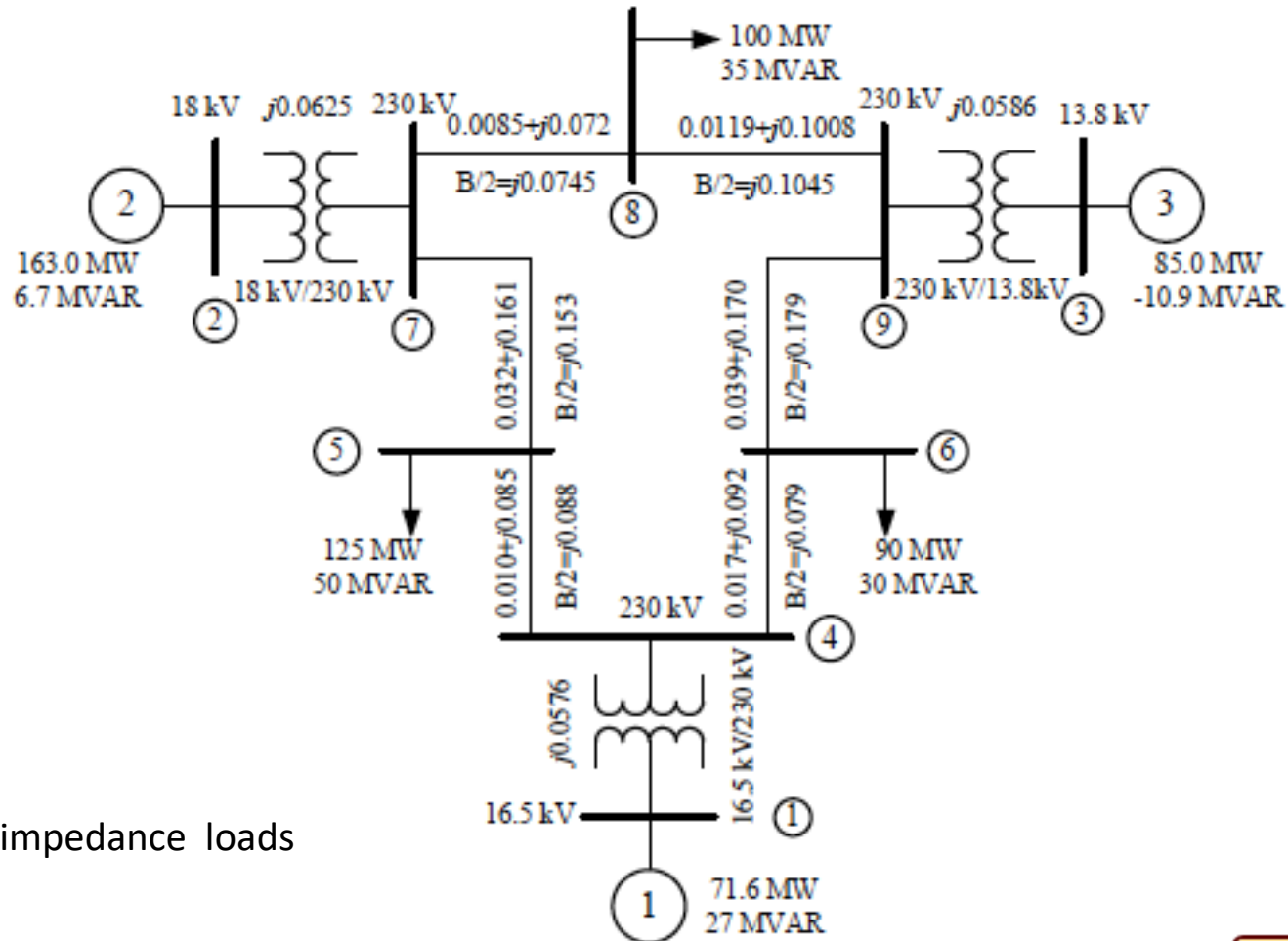
(a) Grid-forming unit



(b) Grid-supporting unit

Study System

IEEE/WSCC 9-bus system

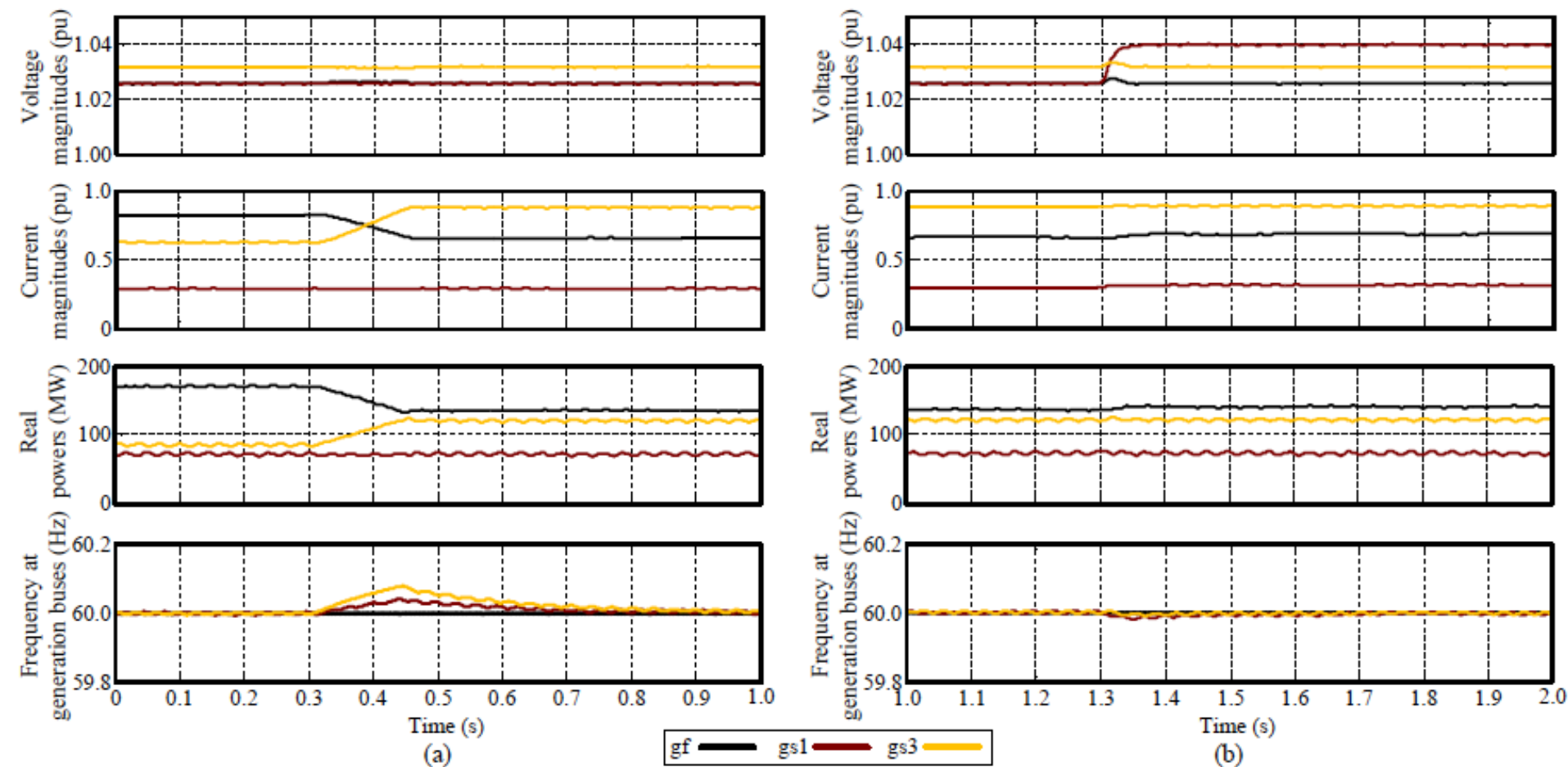


- GF2
- GS1, GS3
- Constant-impedance loads

System Parameters

Voltage controller	$G_1 = 10, G_2 = 2$ $i_{t,i,\text{threshold}} = 1.5 \text{ pu } (i = 1, 2, 3)$
Real power controller	$C_0 = 0.75, C_1 = 1.00$ $C_2 = 1.25, C_3 = 5.00$ $P_{\text{gs},1,\text{max}} = 250 \text{ MW}, P_{\text{gs},3,\text{max}} = 128 \text{ MW}$ $P_{\text{gf},\text{max}} = 192 \text{ MW}$
Angle droop	$D_1 = 5.0 \times 10^3 \frac{\text{MW}}{\text{rad}}, D_3 = 2.5 \times 10^3 \frac{\text{MW}}{\text{rad}}$ $\delta_{\text{gs},\text{max}} = -\delta_{\text{gs},\text{min}} = 0.75 \text{ rad}$

Case Study I: Step Change in P_{gs} and V_{gs}



At $t = 0.3$ s, $P_{gs,3}^*$ increases in a step from 85 to 120 (35 MW), and at $t = 1.3$ s, $V_{gs,1}^*$ increases in a step by 0.014 pu. Same loads.

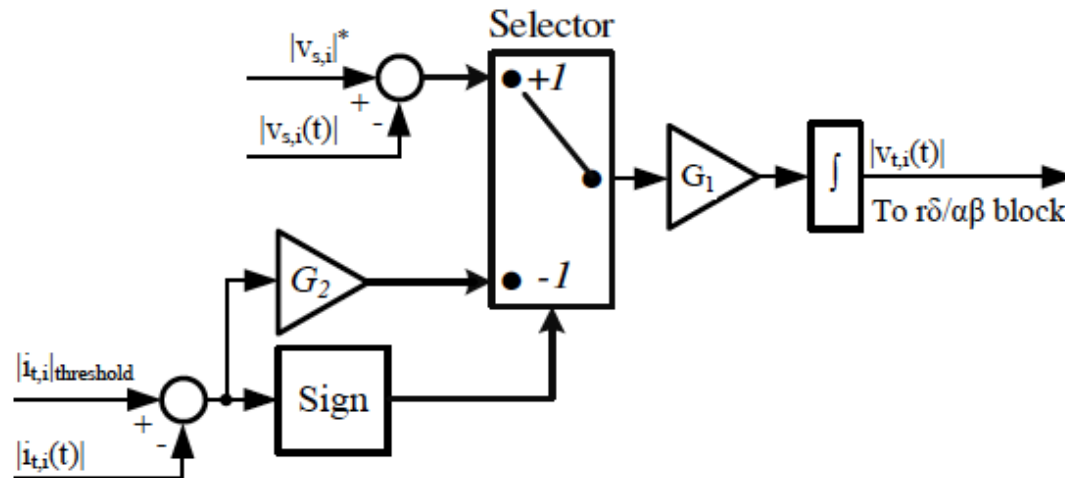
$P_{gs,3}$ settling time = 150 ms (inversely proportional to C_1); P_{gf} decreases to maintain power balance.

$V_{gs,1}$ settling time = 50 ms.

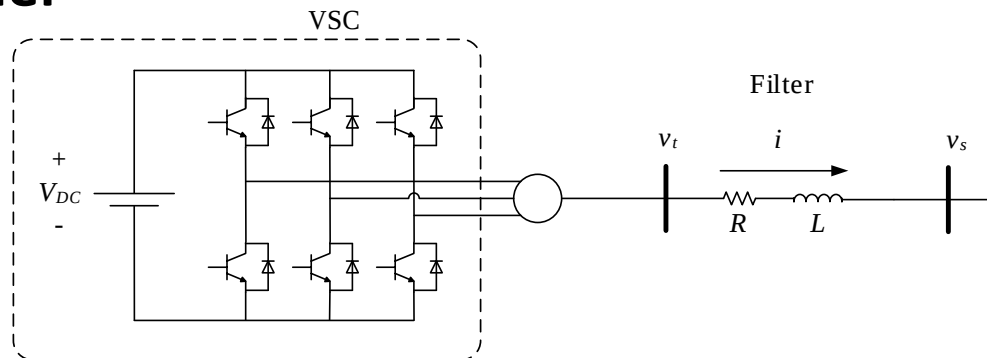
f returns to its rated value (60 Hz) in the steady state.

VSC Modeling and Control

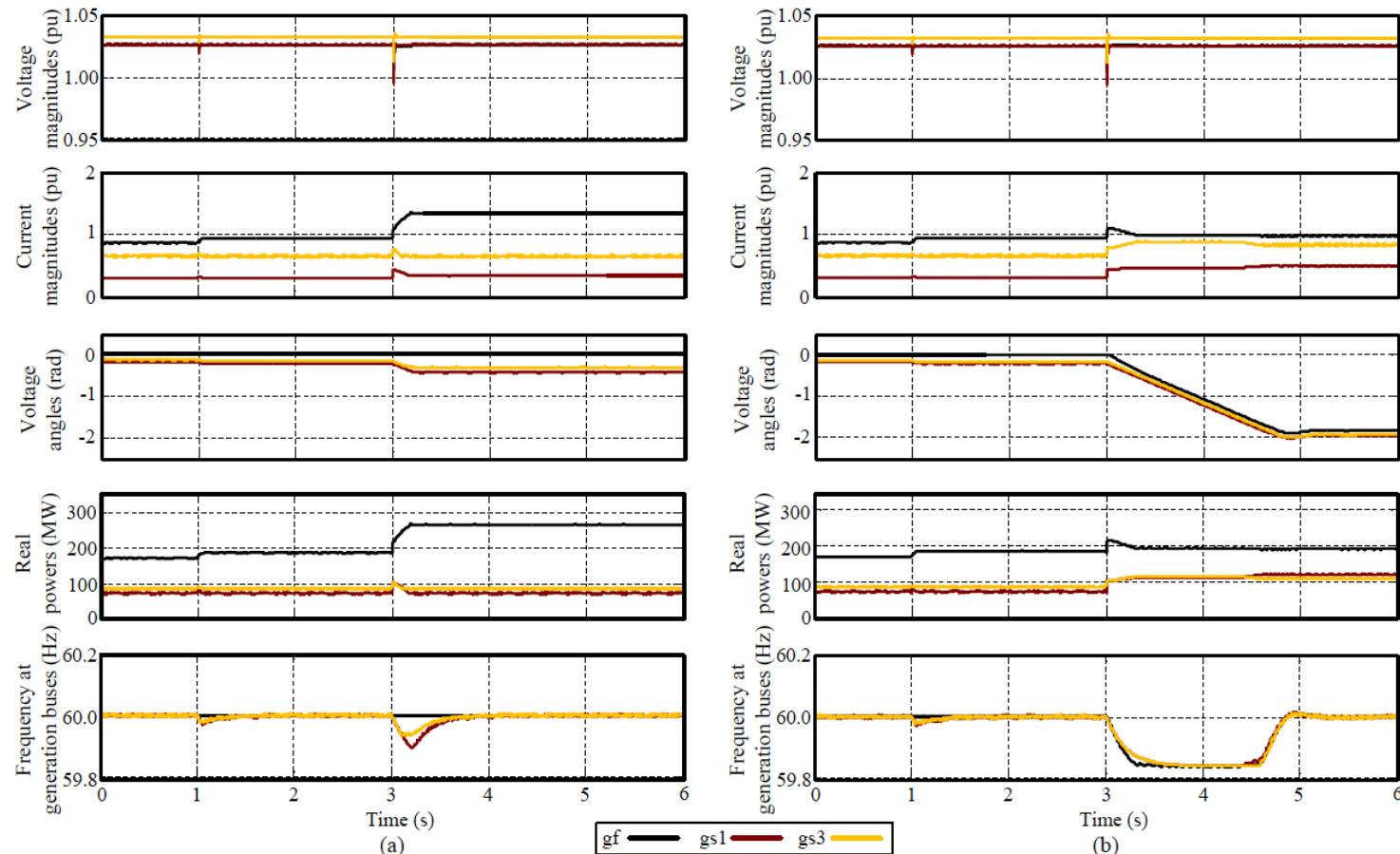
➤ Voltage Regulator and Current Limiter



➤ VSC Model



Case Study II: Load Increase



Load at bus 6 increases by 15 MW at $t = 1$ s and the load at bus 5 increases by 80 MW at $t = 3$ s.

Large grid-forming unit

$t = 1$: load picked up by gf.

$t = 3$: load picked up by gf.

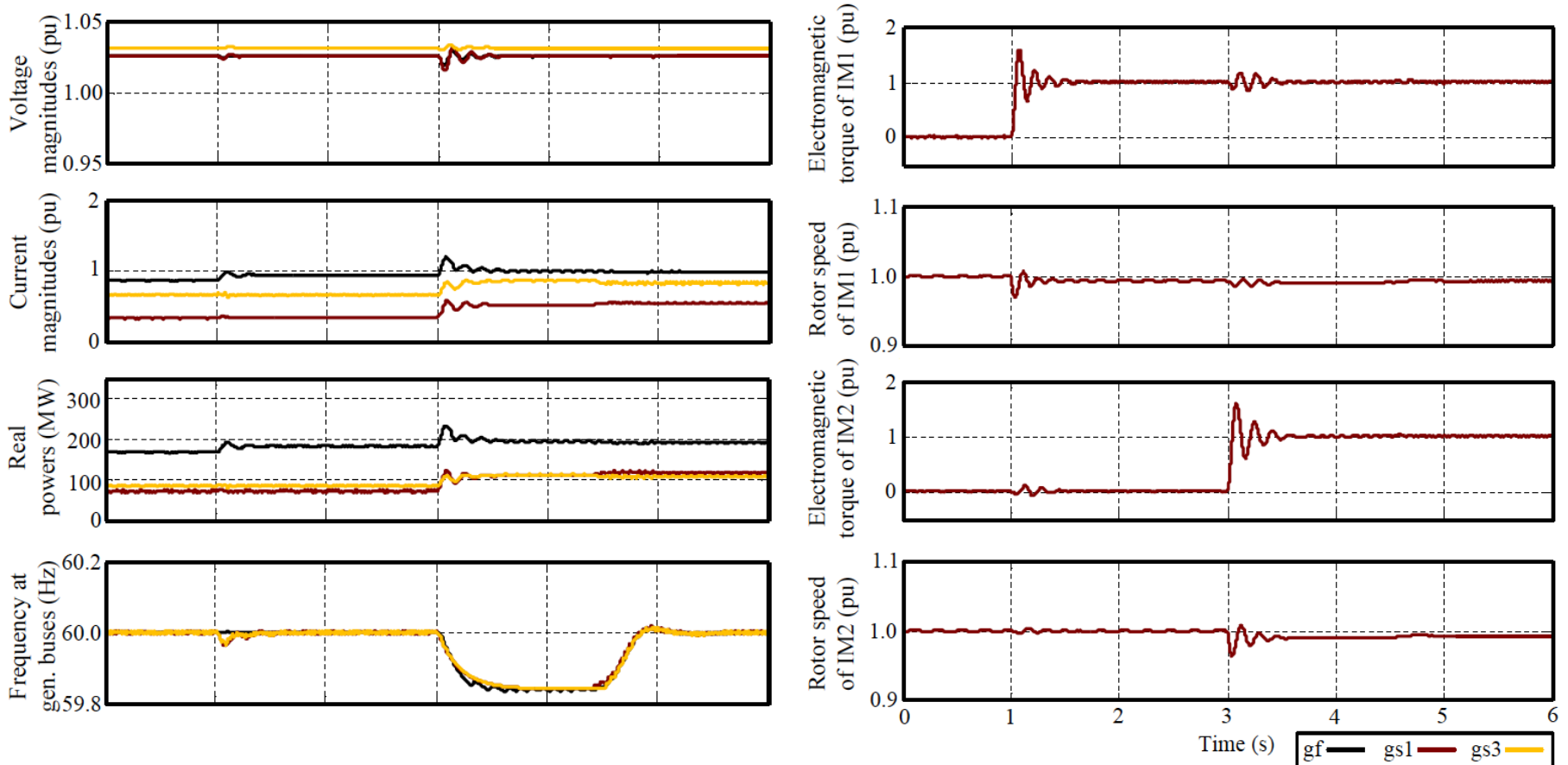
Small grid-forming unit

$t = 1$: load picked up by gf.

$t = 3$: shared (48, 23 MW) by
inverters based on D ratios (=2)

Case Study III: Dynamic Loads

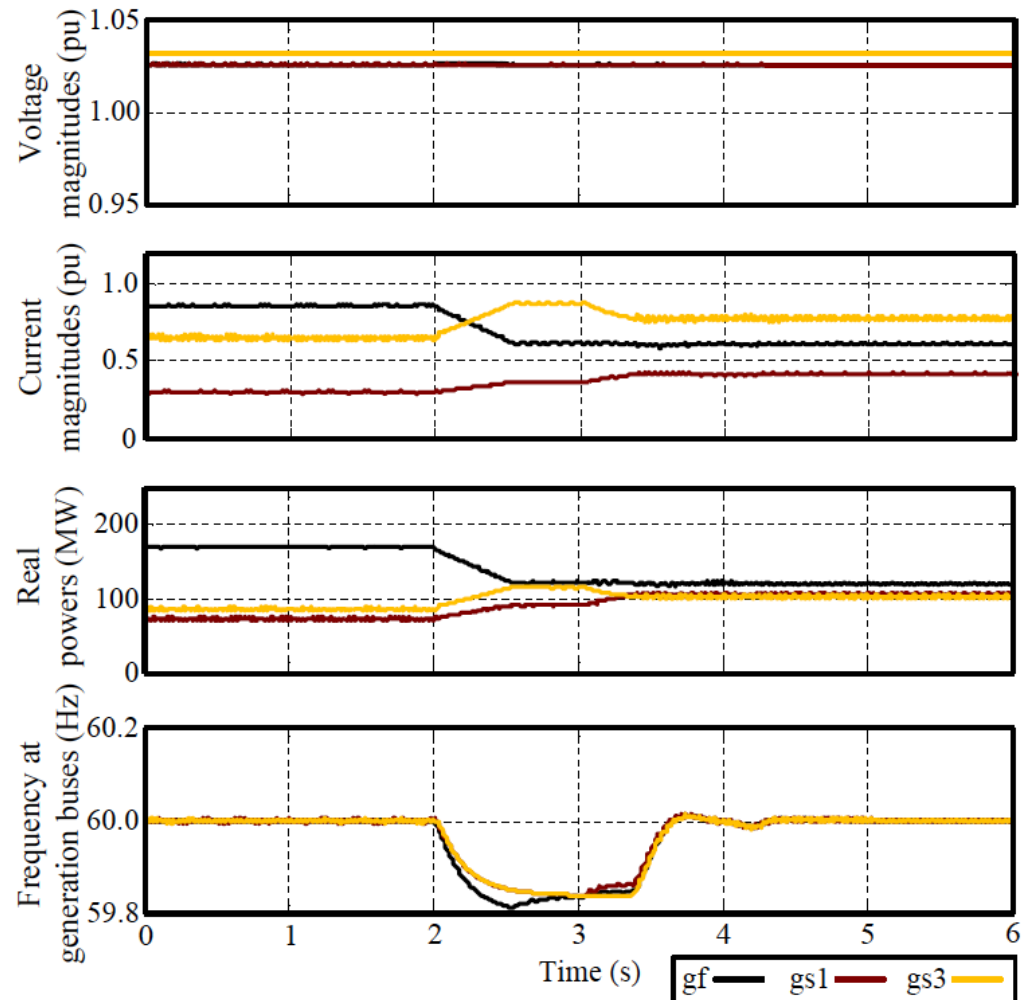
- IM1 at bus 6 (15 MW; $t = 1$ s) and IM2 at bus 5 (80 MW, $t = 3$ s).



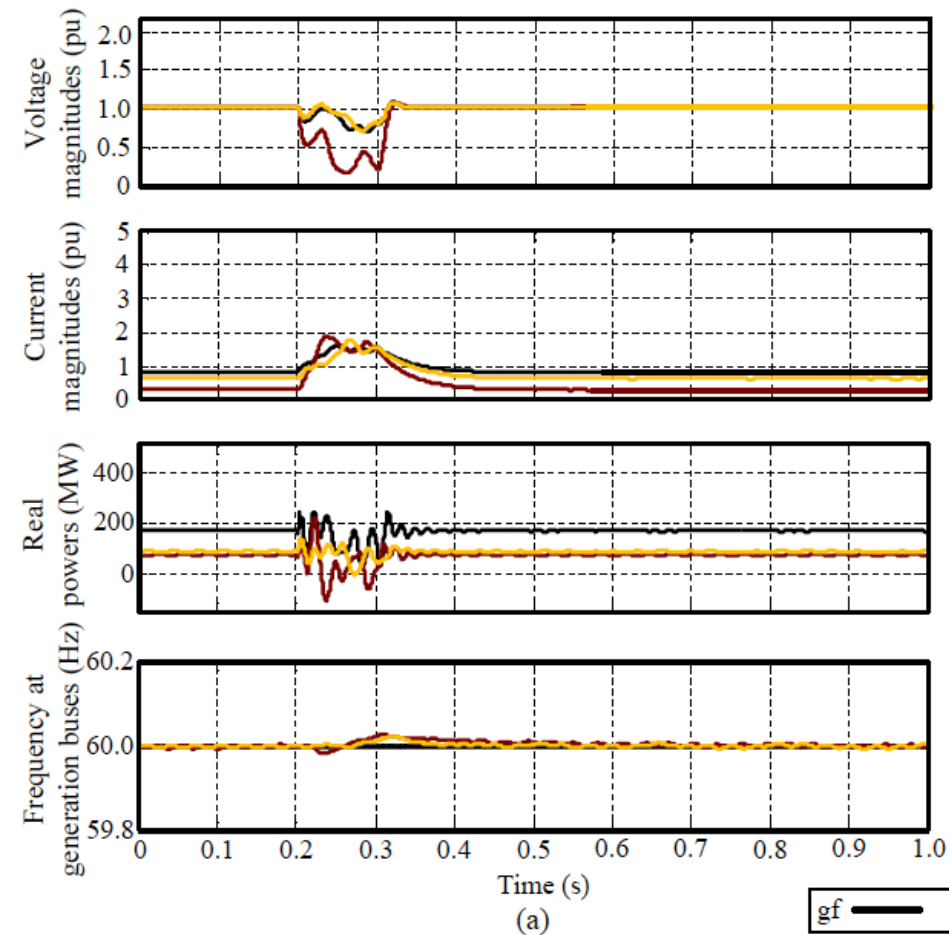
GF provides power for IM1. GS units need to pitch in for IM2.

Case Study IV: Power Redispatch

- ➔ P_{gf} is initially 170 MW.
- ➔ At $t = 2$, $P_{gf,max}$ reduces from 192 MW to 120 MW.
- ➔ The load needs to now be supplied by GS units.
- ➔ They increase by 33 MW and 17 MW (ratio almost 2).

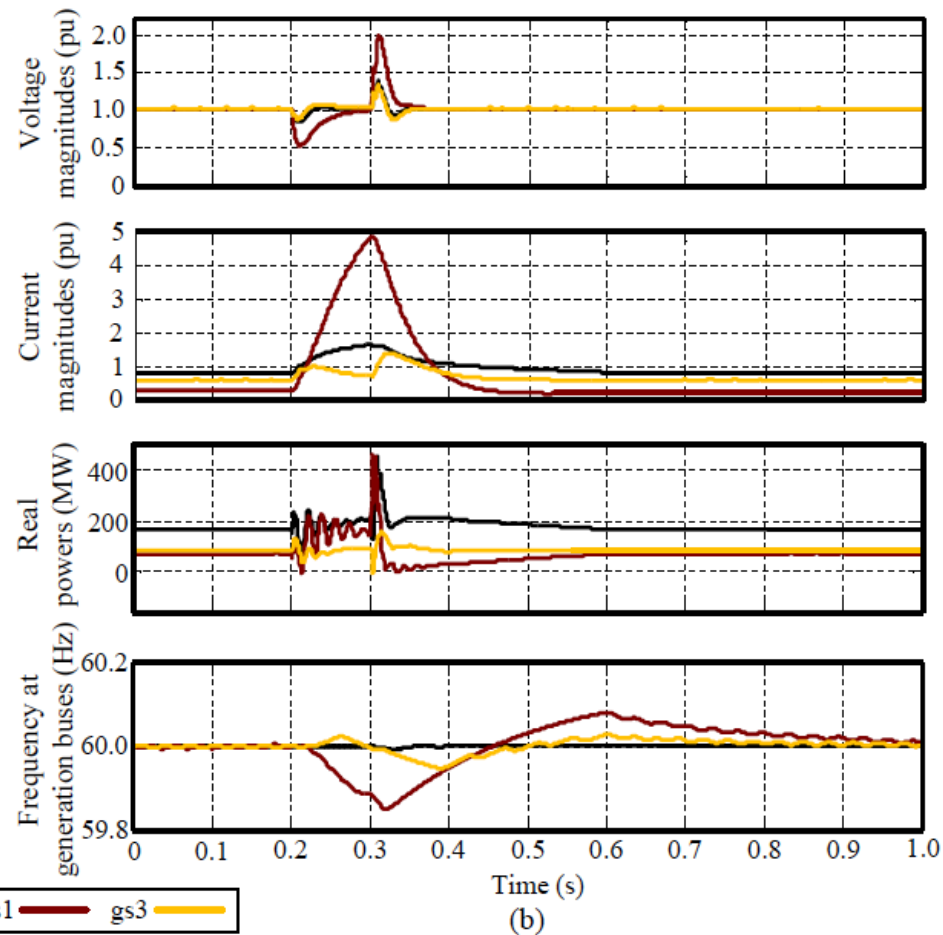


Case Study V: Fault



With current limiter (not protection!)

$$i_{\max} = 1.8 \text{ pu}$$
$$0.2 \text{ pu} < V < 1.1 \text{ pu}$$



Without current limiter

$$i_{\max} = 4.8 \text{ pu}$$
$$0.5 \text{ pu} < V < 2.0 \text{ pu}$$

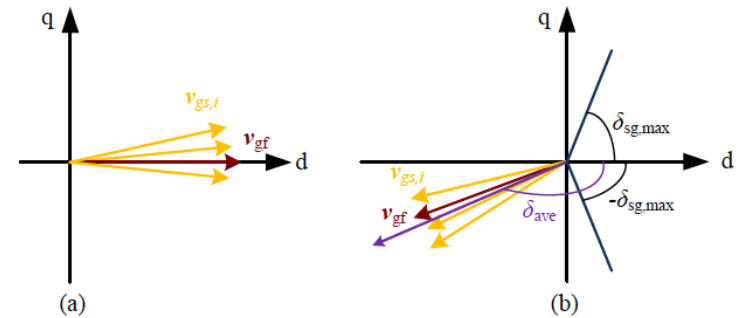
Parameter Design: Droop D_i

$$P_{\text{gs-total-change}} = \sum \Delta P_{\text{gs},i}^* = \sum D_i (\delta_{\text{gs,min}} - \delta_{\text{gs},i})$$

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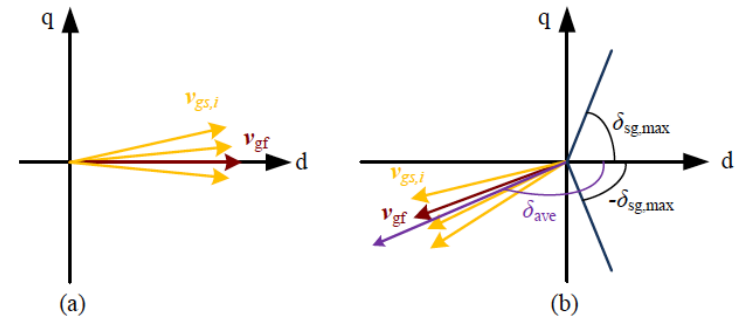
- ➔ If $P_{\text{gs-total-change}} = 0$ (i.e., GF is large), $\delta_{\text{gf}} = 0$ and voltage vectors cluster around it.



Parameter Design: Droop D_i

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- ➔ If $P_{\text{gs-total-change}} = 0$ (i.e., GF is large), $\delta_{\text{gf}} = 0$ and voltage vectors cluster around it.
- ➔ Otherwise, they cluster around a hypothetical average vector. If D_i values are small, δ are large

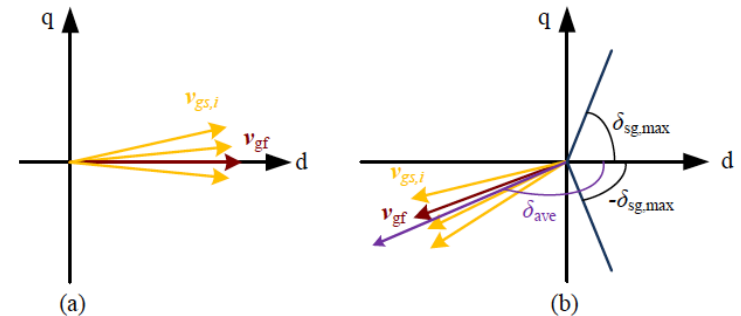


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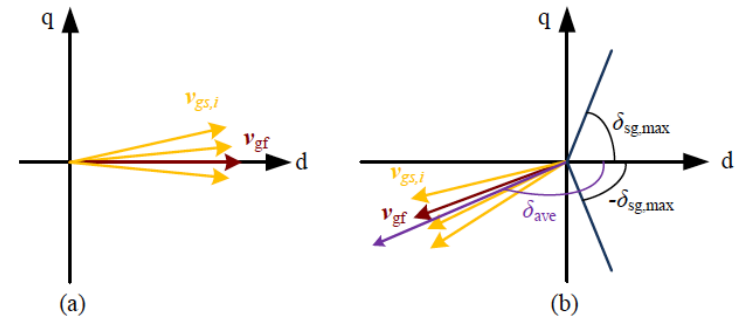
- ➔ And

$$\Delta P_{\text{gs},i}^* = \frac{D_i}{\sum D_i} P_{\text{gs-total-change}}$$

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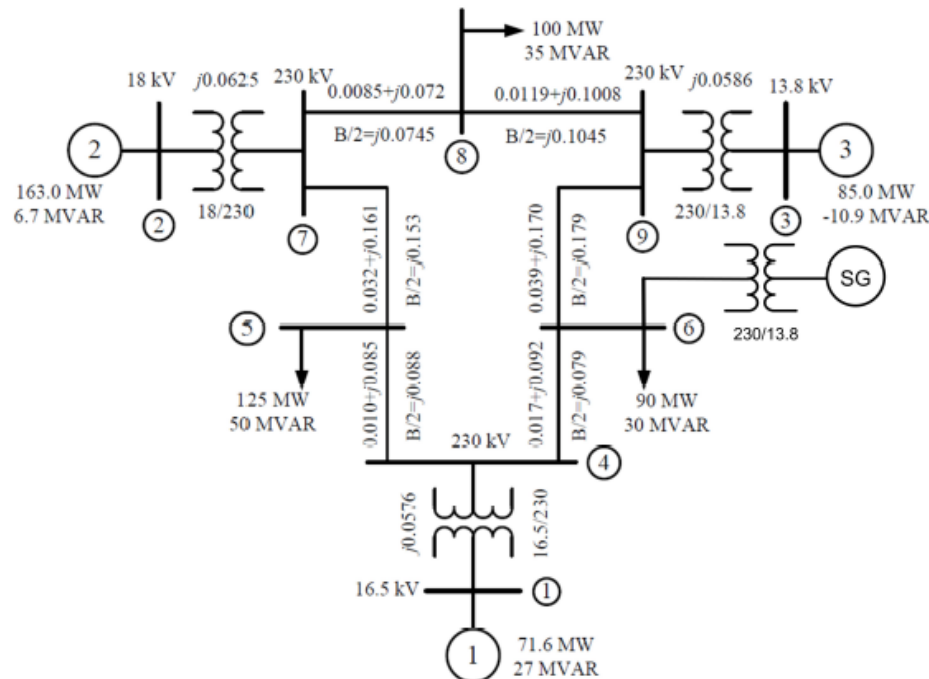
$$\Delta P_{\text{gs},i}^* = \frac{D_i}{\sum D_i} P_{\text{gs-total-change}}$$

- ➔ That is, the real power change is proportional to D_i .

What We Haven't (Systematically) Done (Yet)

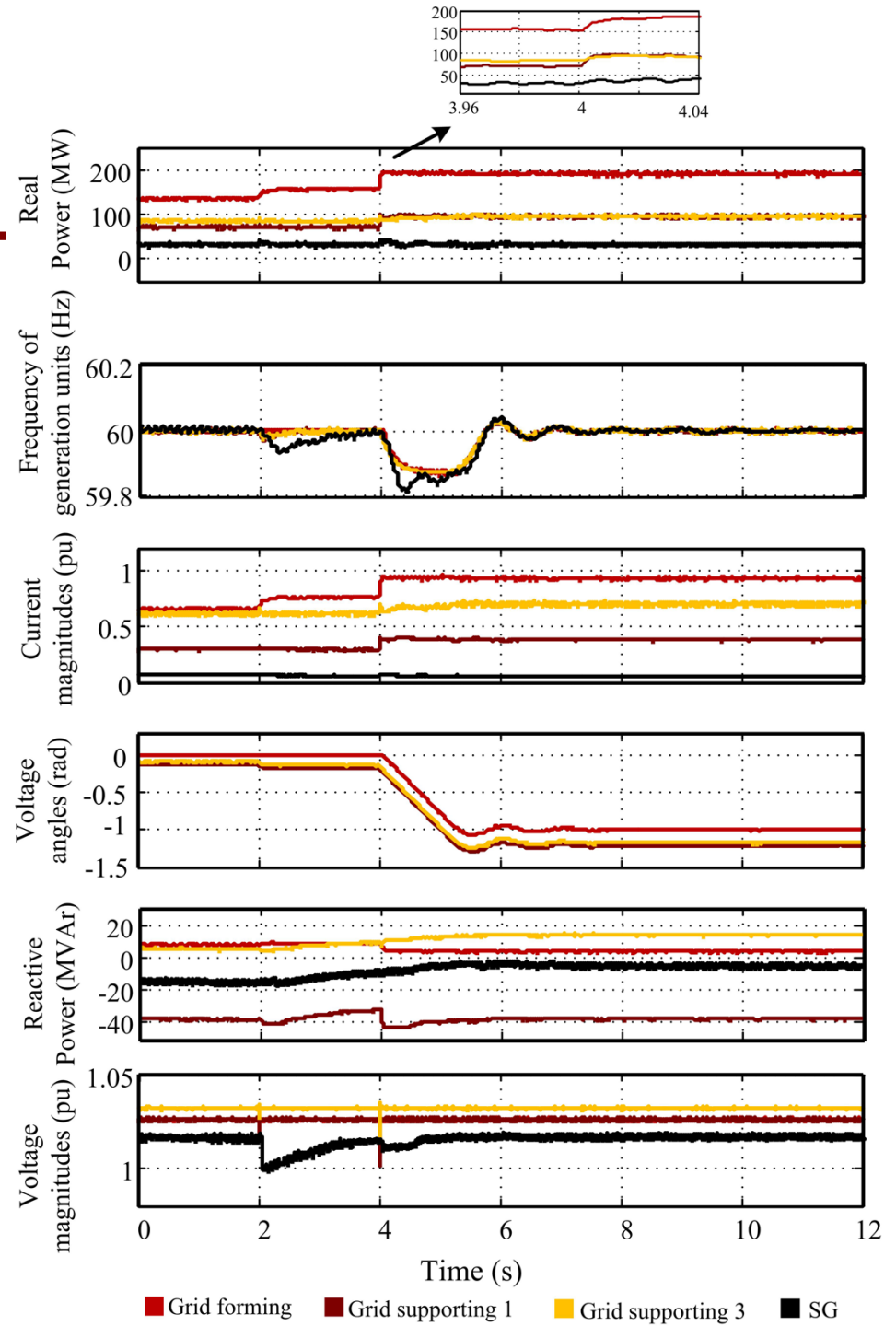
🔴 How About Inverter-Dominated Systems?

- Say, 90% inverters and 10% synchronous generators
- We have done case studies.
- SG = 33 MVA

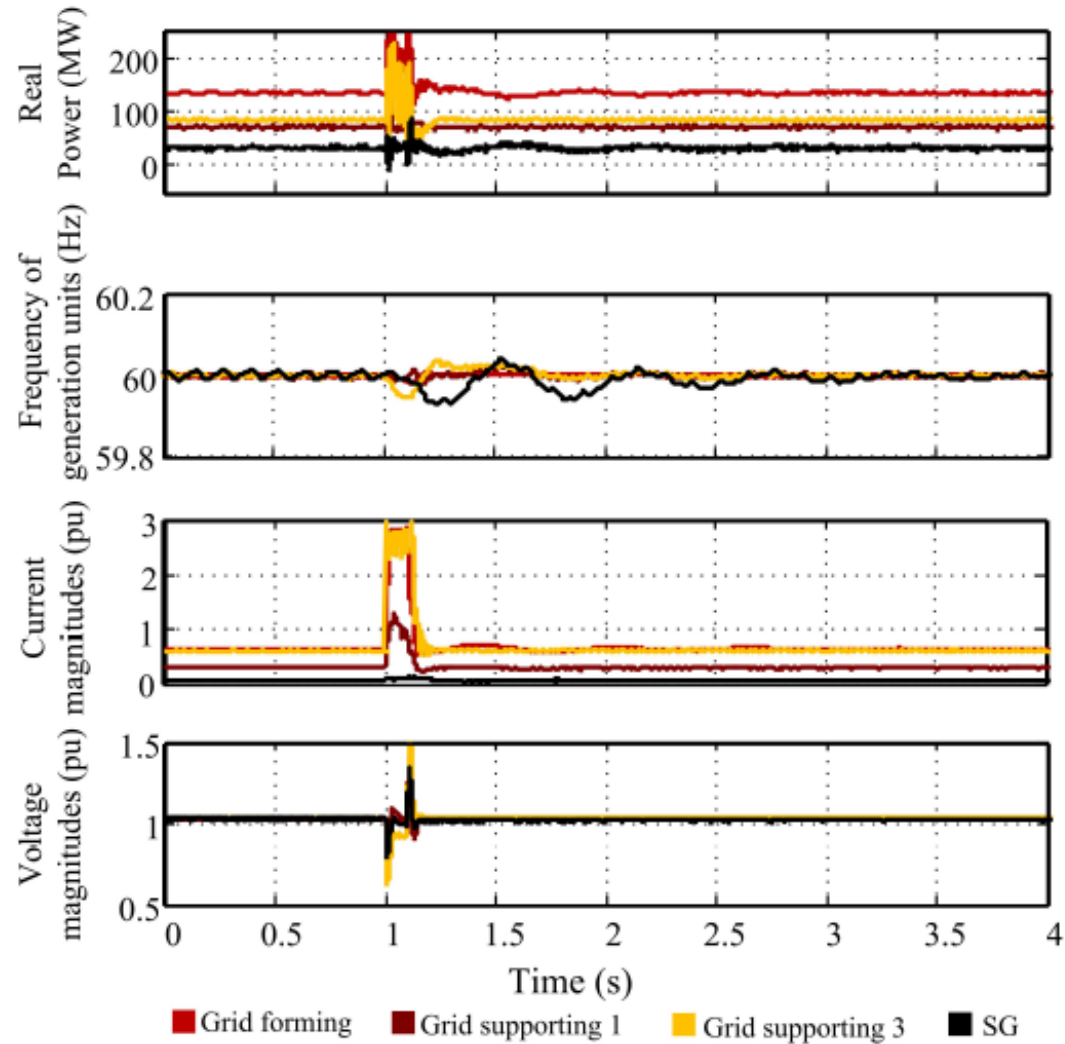


A: Load Increase

- Load at bus 6 increases by 20 MW at $t = 2$ s, and the load at bus 5 increases by 70 MW at $t = 4$ s.
- The first increase is picked up by GF. Second is shared by GS units. SG does not participate in power sharing.
- f and V are restored.

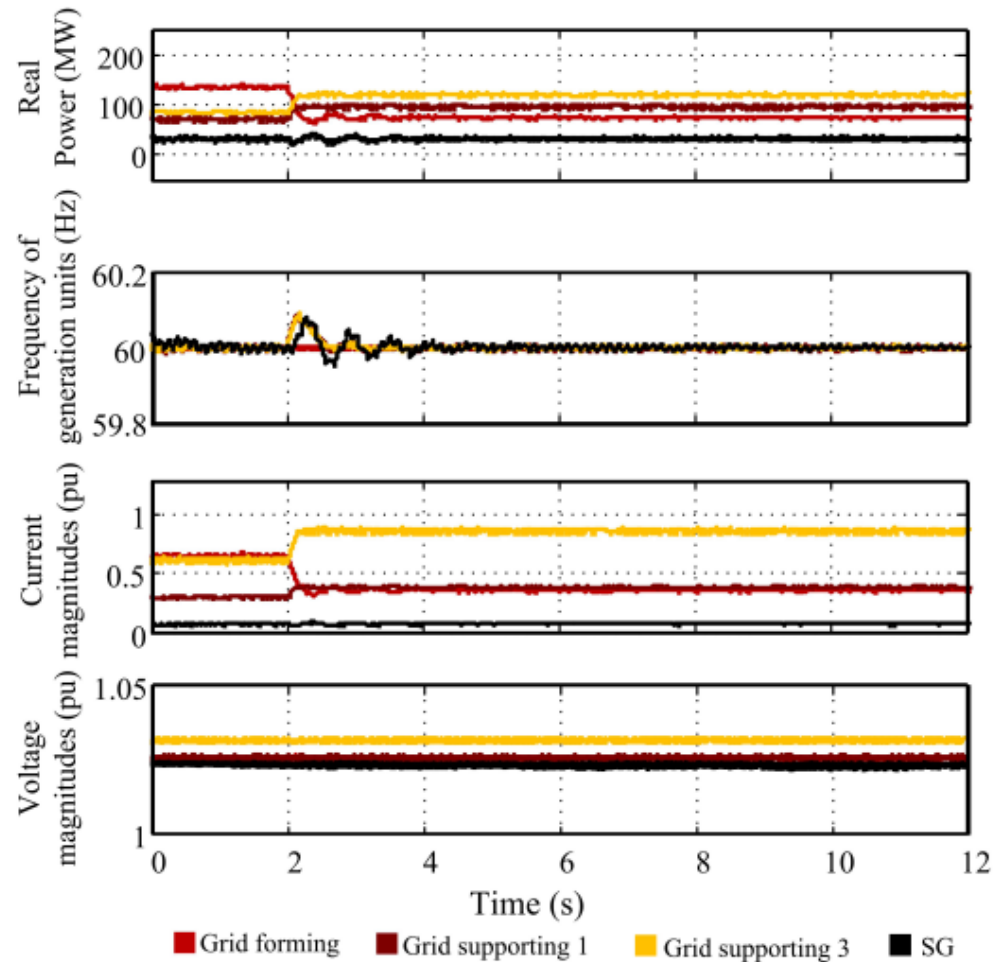


Case Study B: Fault



Case Study C: Power Dispatch

- ➔ The set points for grid-supporting units change.
 - GS1: 72 to 97 MW
 - GS2: 85 to 120 MW
- ➔ The grid-forming unit adjusts its power accordingly.
 - GF: 142 to 82 MW





Conclusions



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- ➔ **We discussed an algorithm for constant-frequency power sharing in a 100% (and 90%) inverter-based transmission system.**



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- The proposed algorithm takes into consideration the current and real power limit of inverters and generation sources and respects their preferred set points as much as possible.



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- The proposed algorithm employs an angle droop method, but it does not need central coordination or communication except for availability of a GPS signal.
- The proposed algorithm takes into consideration the current and real power limit of inverters and generation sources and respects their preferred set points as much as possible.
- Simulation results demonstrate the effectiveness of the proposed algorithm in different scenarios.

Power Systems with 100% Inverter-Based Generation

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Evolution of the IEEE 1547 Standard

- ➔ In response to disturbances, **DISTRIBUTED** ERs should
- ➔ **2003: Disconnect**
 - Low penetration case
- ➔ **2015: Ride through**
- ➔ **2018: Provide support**
 - “Smart” inverter (the “smart” trend: grid, home, phone, appliance)
Or “thoughtful”?
 - Smart inverters at minimum should have the following features: voltage ride-through, frequency ride-through, voltage support, frequency support, and start-up ramp rates. Other features are power quality, fault behavior and islanding, and communications.

