Impact of supervisory control inputs in multi-inverter distribution systems

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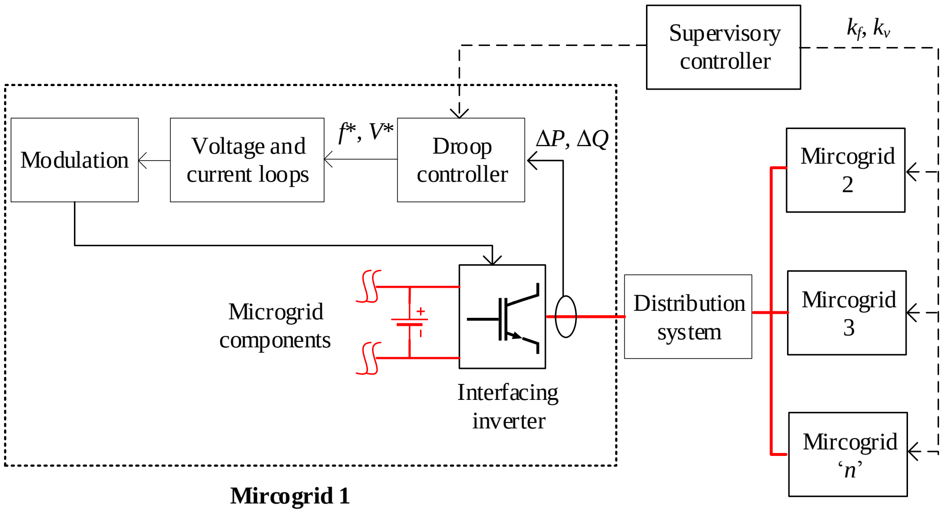
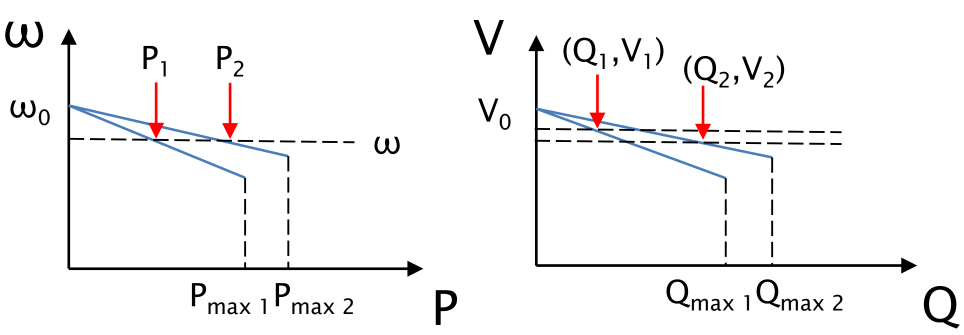
Presentation summary

- Description of multi-microgrid scenario
- Motivation
- Proposed sensitivity criterion
- Simulation results
- Hardware verification

Multi-microgrid scenario



- Future distribution viewed as a collection of MGs all connected to the wiring infrastructure
- Each interfacing inverter is operated with droop control



$$\omega = \omega_0 - k_\omega (P - P_0)$$

$$V = V_0 - k_v (Q - Q_0)$$

Small-signal stability

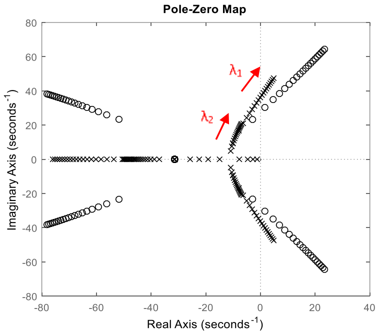
$$\Delta f = -k_f \Delta P = -\left(\frac{\omega_c}{s+\omega_c}\right) k_f \Delta P_{meas}$$

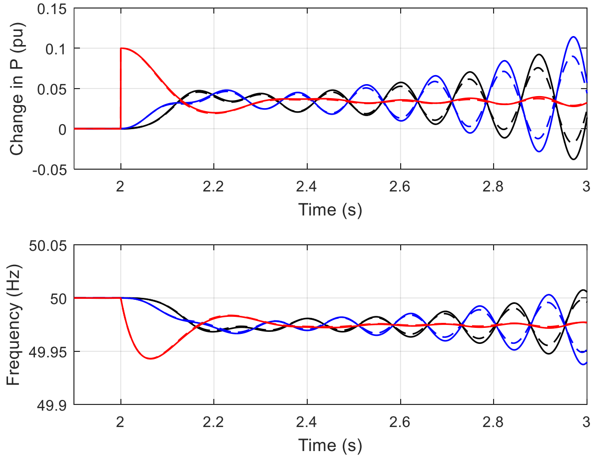
$$\Delta V = -k_v \Delta Q = -\left(\frac{\omega_c}{s+\omega_c}\right) k_v \Delta Q_{meas}$$

$$2\pi\,\Delta f = \frac{d}{dt}\Delta\delta$$

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix}$$

- Small-signal instability caused by interaction between different droop controllers through the network lines
- **Damping of critical modes depend on:**
  1. Network impedances
  2. Inverter droop gains
  3. Number of inverters

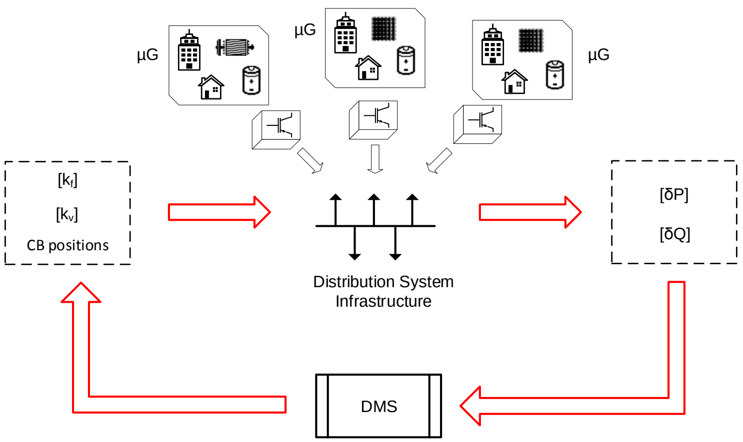




Possibility of undamped power flows!

Motivation

- Some degree of communication vital to maintain global stability
  - Need for supervisory control (esp. brownfield projects)
- Node vulnerability to be considered during design of communication infrastructure
- **How to quantify node "importance"?**
  - View system from "supervisory control" perspective, not "disturbance rejection" perspective
  - Equivalently: how to quantify "sensitivity" of system damping to droop coefficients?
- Potential applications:
  - Planning of communication network
  - Devising contingency response schemes



MMG system with supervisory control

Conventional methods

- Calculation of eigenvectors and participation factors
  - *O(n³)* complexity of EV calculation
  - Impractical to evaluate in real-time for large systems (Nodes>1000)

- Online methods should be:
  - Computationally inexpensive
  - Scalable to number of nodes

$$\delta\dot{\theta} = \omega - \omega_0$$

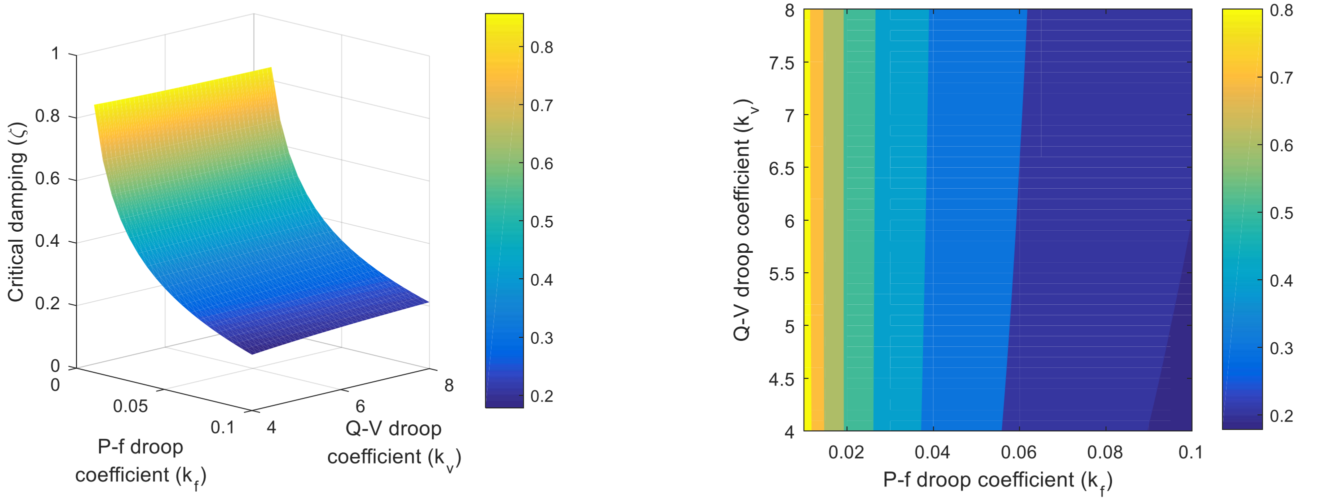
$$\frac{1}{\omega_c}\frac{d\omega}{dt} = -\delta\omega - k_f\delta P$$

$$\frac{1}{\omega_c}\frac{dV}{dt} = -\delta V - k_v\delta Q$$

$$\begin{bmatrix}\delta P\\ \delta Q\end{bmatrix} = \begin{bmatrix} B & G\\ -G & B\end{bmatrix}\begin{bmatrix}\delta\theta\\ \delta V\end{bmatrix}$$

Node sensitivity to supervisory control inputs

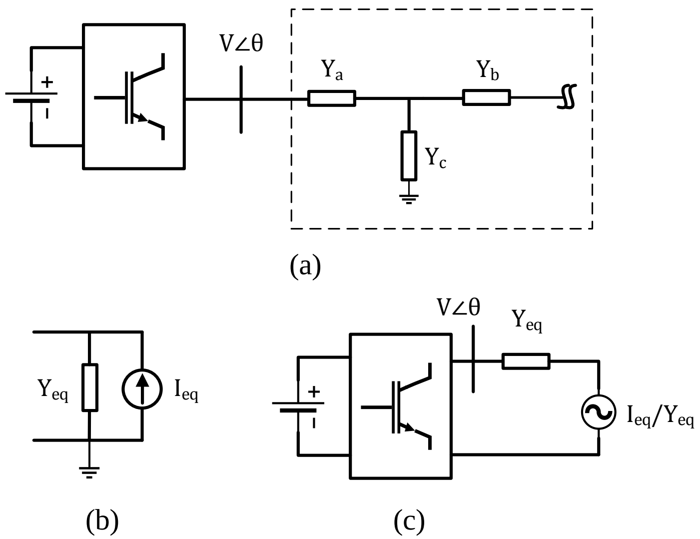
- Droop coefficients of some inverters have higher influence on critical mode damping
- Assumption:
  - P-f droop coefficient has much more influence than Q-V droop coefficient on critical-mode damping



Derivation of sensitivity- single inverter case

1. Start with f and V droop equations
2. Incorporate power flow equations
3. Approximation of solution for voltages
4. Derive of angle dynamics
5. Determine sensitivity of critical mode damping to supervisory control input

Sensitivity for multi-inverter case



(a) Inverter connected to generic MMG network
(b) Network Norton equivalent
(c) Equivalent MMG model

$$\frac{\partial D}{\partial k_f} = -\frac{k_v G^2}{(1 + k_v B)^2}$$

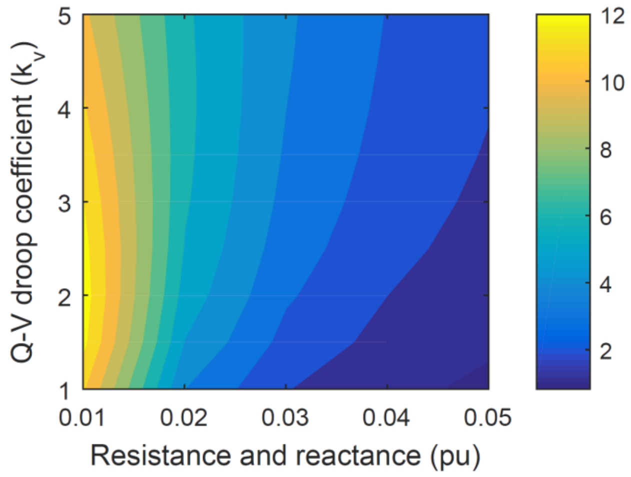
- Replace G and -B with real and imaginary parts of Y_{eq}
- Equivalent admittance for n^th inverter:

$$Y_{eq} = Y_{bus}(n, n)$$

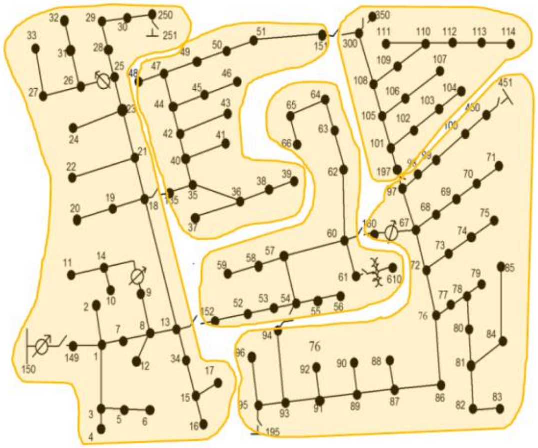
Properties of sensitivity

$$\frac{\partial D}{\partial k_f} = -\frac{k_v G^2}{(1 + k_v B)^2}$$

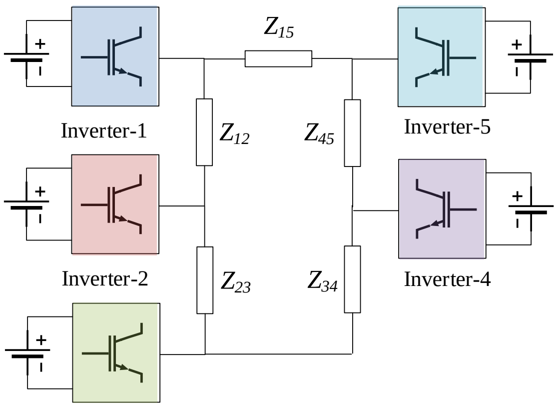
1. Sensitivity of one node is independent of other node parameters
2. Computational complexity is small
3. Lower the interconnecting admittance, lower the sensitivity



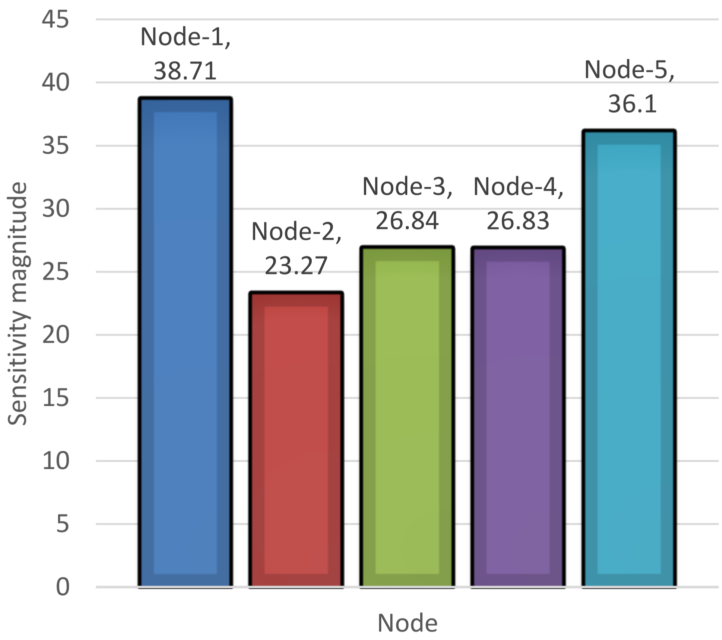
Demonstration- IEEE 123 bus system



V_{base}=4.16kV

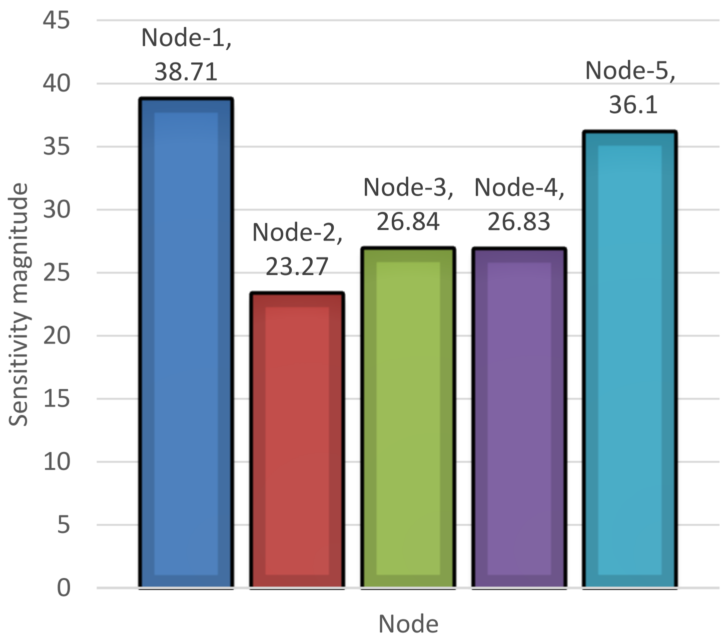


$$\frac{\partial D}{\partial k_f} = -\frac{k_v G^2}{(1 + k_v B)^2}$$



Node sensitivity order: 1>5>3>4>2

Sensitivity verification



Node	Damping ratio, ζ	$\Delta\zeta$	Sensitivity rank
Initial	0.0380		
1	0.0328	-0.0052	1
2	0.0380	-0.0000	5
3	0.0379	-0.0001	3
4	0.0379	-0.0001	4
5	0.0337	-0.0043	2

Node sensitivity order: 1>5>3>4>2

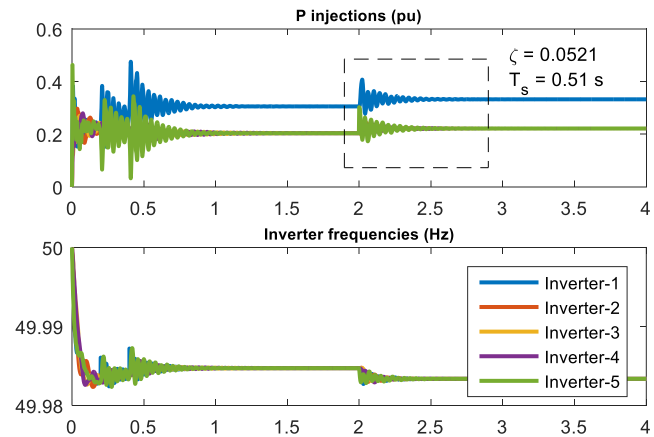
Supervisory input at the more sensitive nodes have higher impact on the damping!

Sensitivity implication

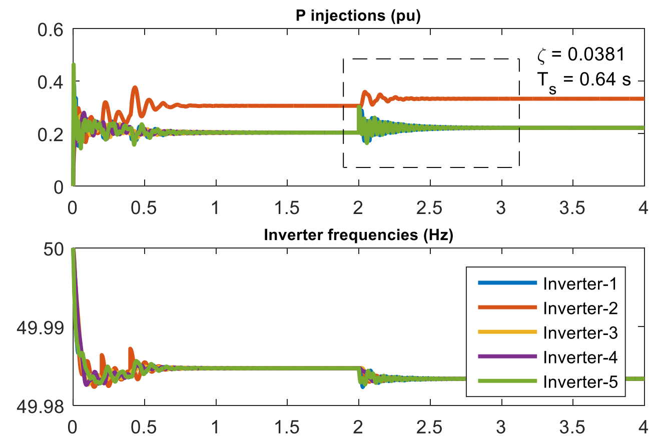
Start with kf=0.15% and kv=5%.
Initial ς=3.8%
Desired ς=5.0%

Node sensitivity order: 1>3>4>5>2

Apply supervisory control inputs to the most and least sensitive node to achieve the above objective.

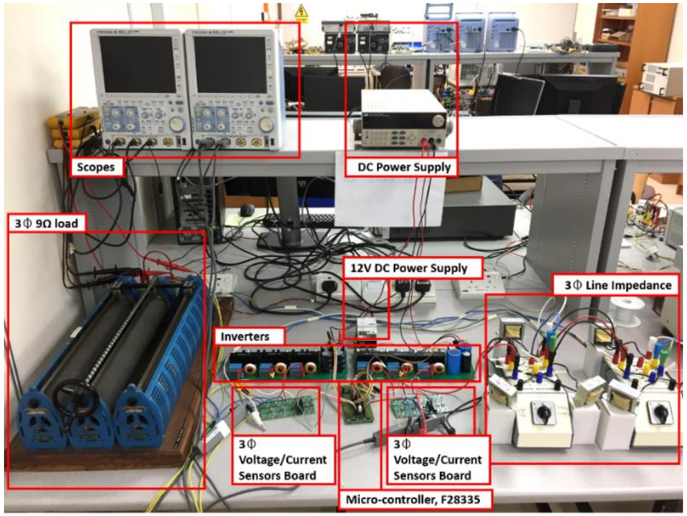


Best-case

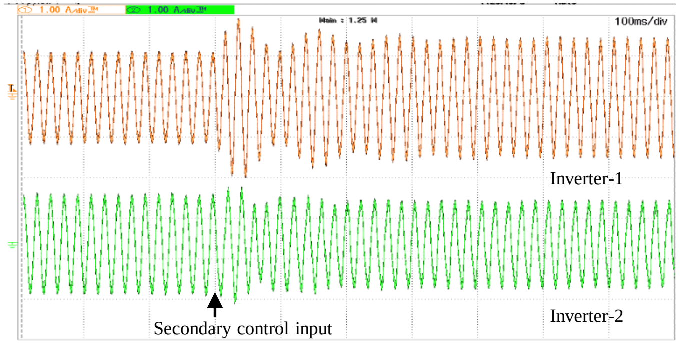


Worst-case

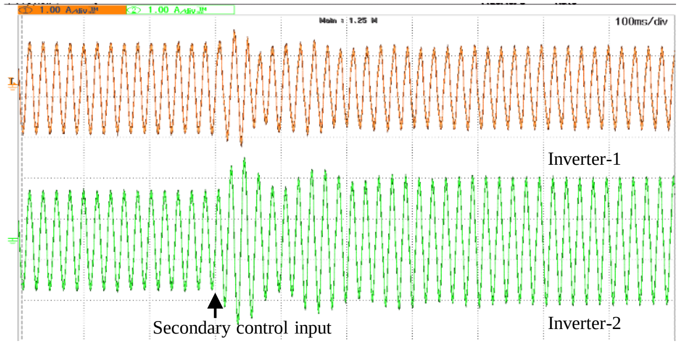
Sensitivity verification



	k_f (%)	k_v (%)	Damping ratio, ζ	Settling time, t_s (s)
Initial	10, 10	2, 5	0.0737	0.442
Perturb Node-1	5, 10	2, 5	0.0862	0.595
Perturb Node-2	10, 5	2, 5	0.0873	0.499



(a) Perturb less sensitive node (Node-1)



(b) Perturb more sensitive node (Node-2)

Supervisory input at the more sensitive nodes have higher impact on the damping!

Summary

- Novel sensitivity criterion was proposed
- Sensitivity measure was demonstrated with practical test cases

- Key strengths:
  - Wide applicability to practical R/X
  - Scalable to network size
  - Reduced computational complexity compared to numerical sensitivity analysis

- Most vulnerable communication lines can be designed to improve the robustness of the distribution system
- Optimal contingency response sequence can be determined using sensitivity order