A Strategy for Forced Oscillation Suppression

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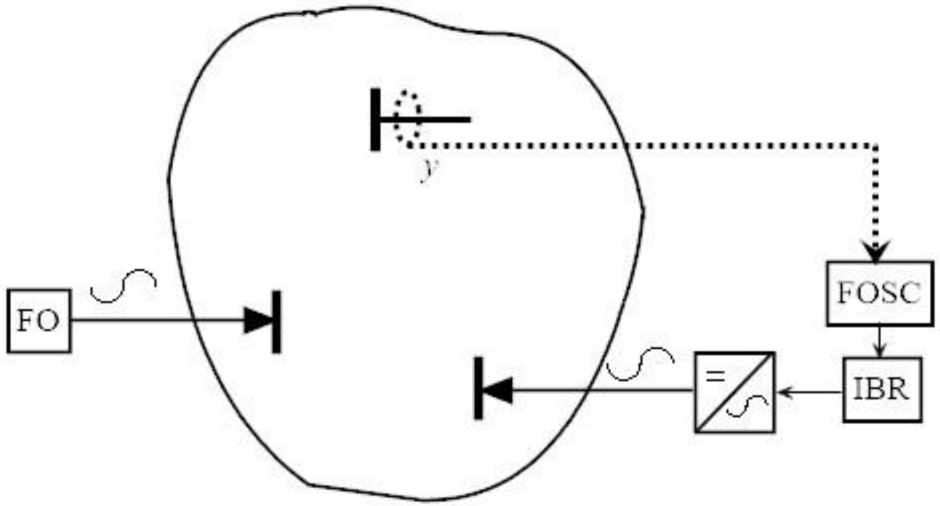
D. Trudnowski and R. Guttromson, "A Strategy for Forced Oscillation Suppression," *IEEE Trans. Pwr Sys*, vol. 35, no. 6, pp. 4699-4708, Nov. 2020

Introduction

- Forced oscillations are can be represented as a steady-state input into the system, typically with an unknown location.
- Typical mitigation strategy: find the location of the FO source and remove it.
- Another mitigation strategy: introduce a 2nd steady-state input into the system to "suppress" the FO's impact.
    - Akin to "noise cancelation"
    - This is NOT damping control
    - Implemented as a tuned-feedback controller based upon *adaptive gain scheduling* and the *internal model principle*.

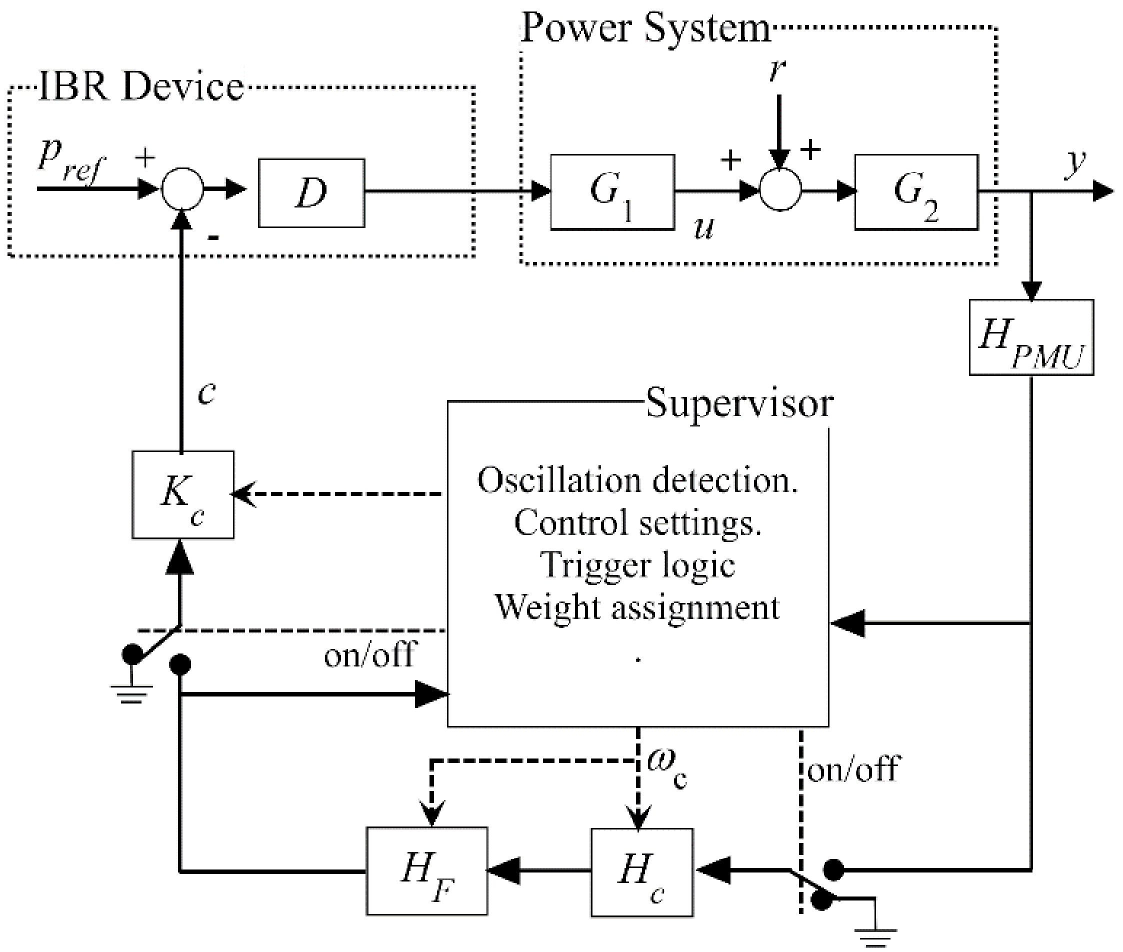
Overview



- FO = forced oscillation at an unknown location
- *y* = measurement point within system
- FOSC = forced oscillation suppression controller
- IBR = inverter based resource

- Goal: Inject power from the IBR to cancel the FO as measured at *y*

The control concept



D = IBR transfer function.

G_1 and G_2 = transfer functions with an arbitrary division of the synchronous power system, G_1G_2.

r = A “rogue” FO being injected at an unknown location.

ω_c = fundamental frequency of r in rad/s (note $f_c = \omega_c/2\pi$ Hz).

y = A measurement point in the power system.

H_{PMU} = transfer function of a measurement device (e.g., PMU).

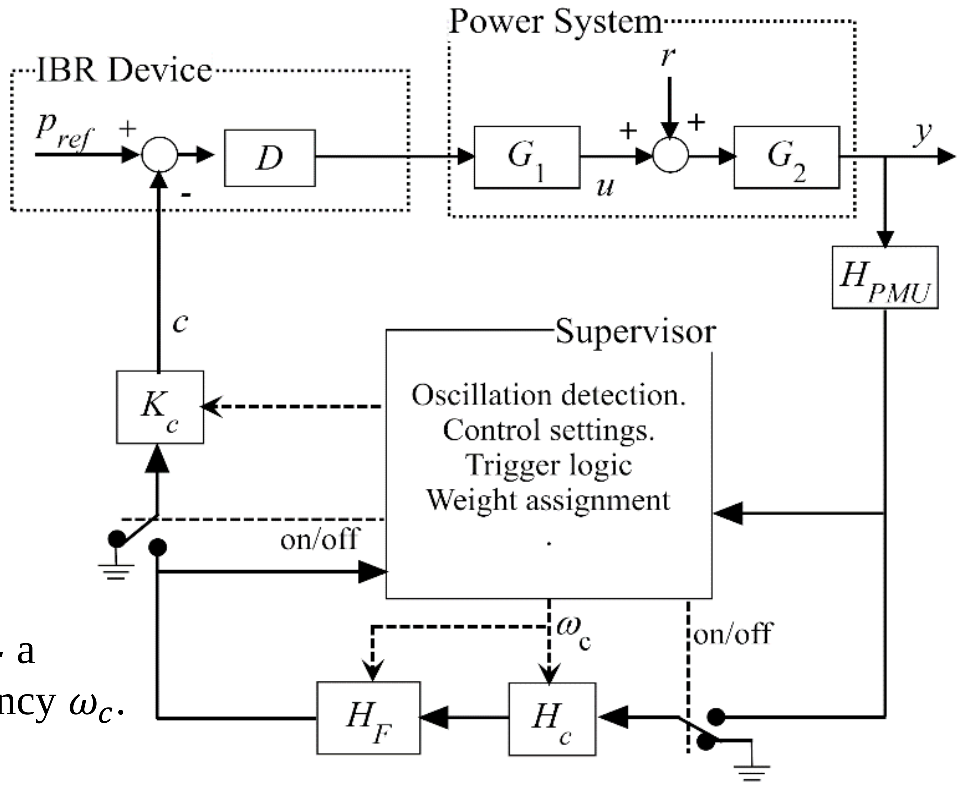
H_F = transfer function of a band-pass filter tuned to frequency $\omega_c \pm$ 10%.

H_c = Control compensator transfer function.

K_c = Control gain.

c = controller output added to the P_{ref} of the IBR device

The control concept – cont.



Let $Y_R(s)$ = the component of y due to r transformed to the s domain.

In open loop

$$Y_R(s) = G_2(s)R(s)$$

In closed loop

$$Y_R(s) = \frac{G_2(s)R(s)}{1 + L(s)}$$

$$L(s) = D(s)G_1(s)G_2(s)H_{PMU}(s)H_c(s)H_F(s)K_c$$

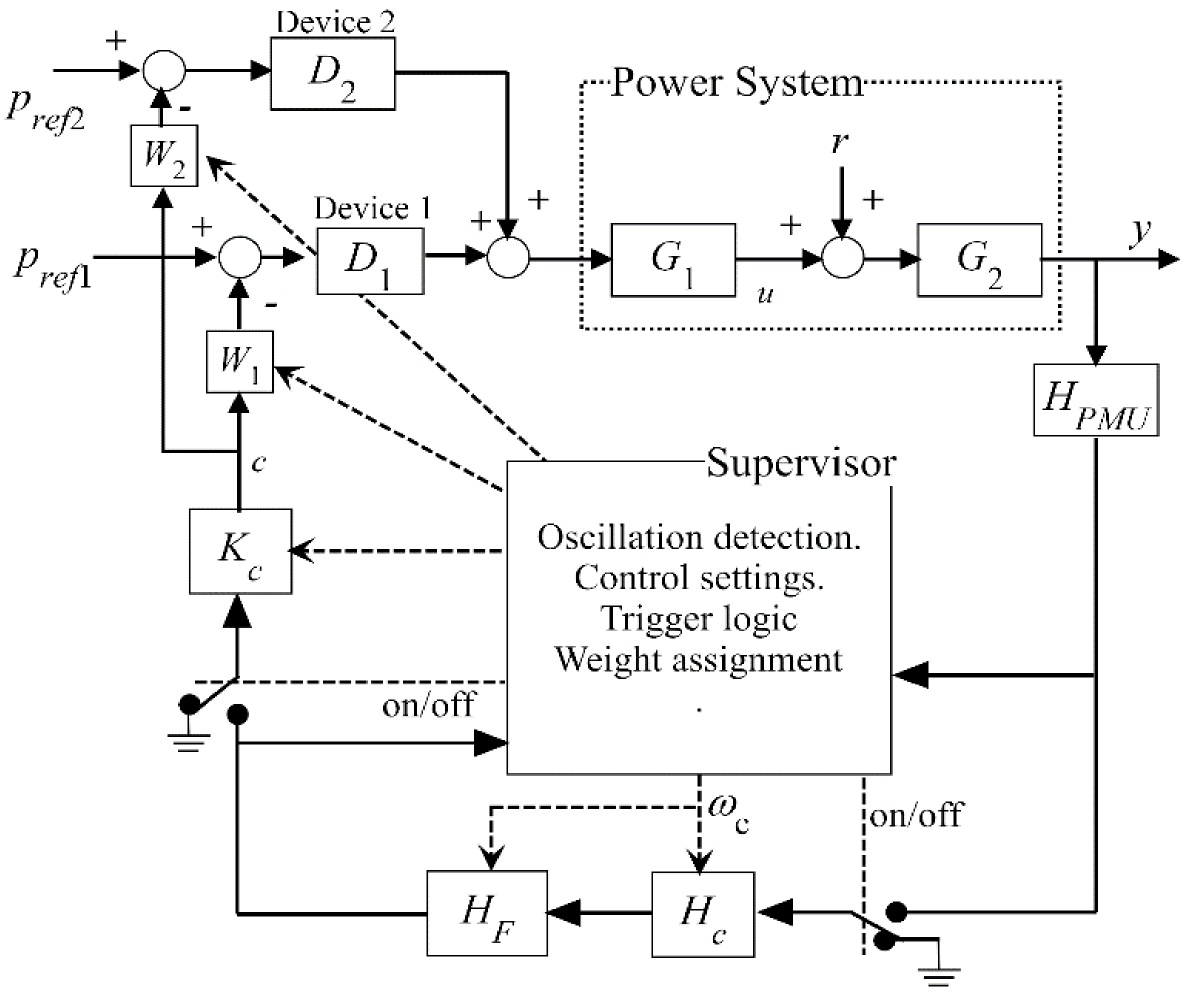
Clearly, the larger $|L(j\omega_c)|$, the more y_R is suppressed. This is achieved by making H_F a damped oscillator and designing H_C to cancel the phase of $G \triangleq DG_1G_2H_{PMU}$ at frequency ω_c.

$$H_F(s) = \frac{2\varsigma\omega_c s}{s^2 + 2\varsigma\omega_c s + \omega_c^2}$$

$$H_c(s) = \frac{K(\alpha Ts + 1)}{Ts + 1}$$

where α, T, and K are automatically tuned such that $H_c(j\omega_c) = {}^{1}/_{G(j\omega_c)}$. The damping ratio ζ is 0.1 to enable errors in the estimated FO frequency. The loop gain is then $L(j\omega_c) = K_c$. The gain K_c is automatically selected to the maximum while maintaining the loop's gain margin at 6 dB and a minimum phase margin of 45°.

Extending to multiple IBRs



Control effort is distributed to multiple IBRs via weights W_i such that

$$\sum_{i=1}^{n} W_i = 1$$

The design is the same as before where

$$D(s) = \sum_{i=1}^{n} W_i D_i(s)$$

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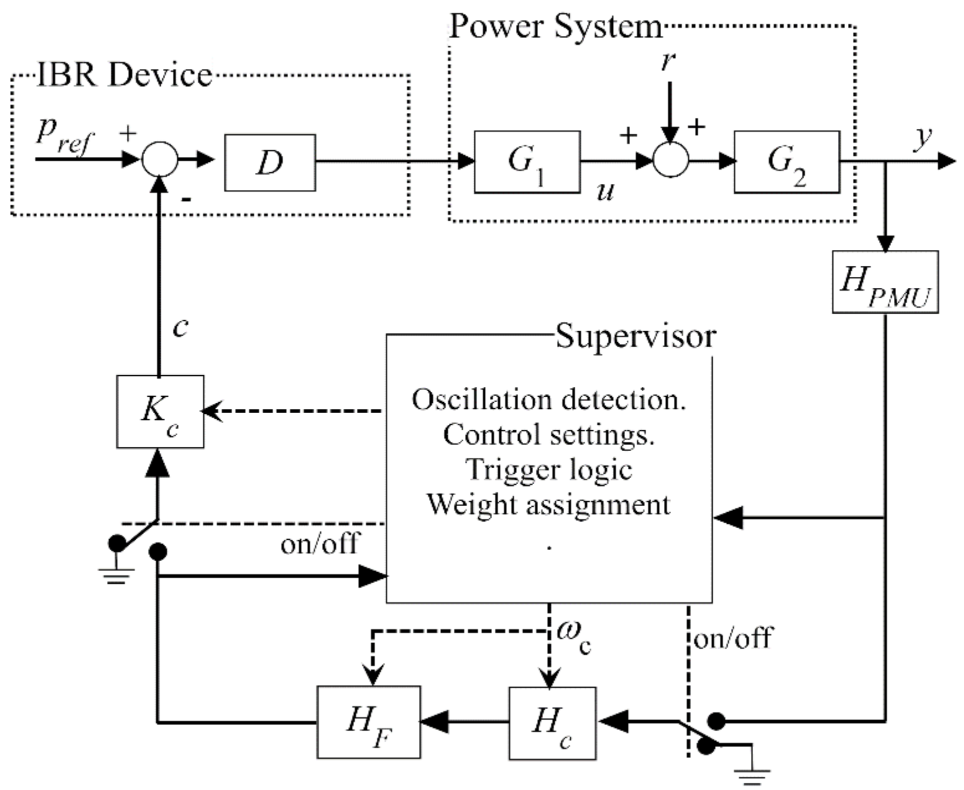
The automated supervisor



Apriori, develop an estimate of $G(j\omega)$ where $G = DG_1G_2H_{PMU}$.

The supervisor is an automated system that:

1. Detects an FO and quantifies its fundamental frequency ω_c.
2. Set the feedback control parameters H_F, α, T, K, and K_c.
3. Set device weights W_1 thru W_n.
4. Ramp in the control gain K_c.
5. Monitor the controller to shut down when the FO has ceased or its fundamental frequency has changed.

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Simple example

Consider a system with a 1 Hz FO and parameters

$$D = \frac{20}{s+20}, \quad G_1 G_2 = \frac{10}{s+10}, \quad H_{PMU} = 1$$

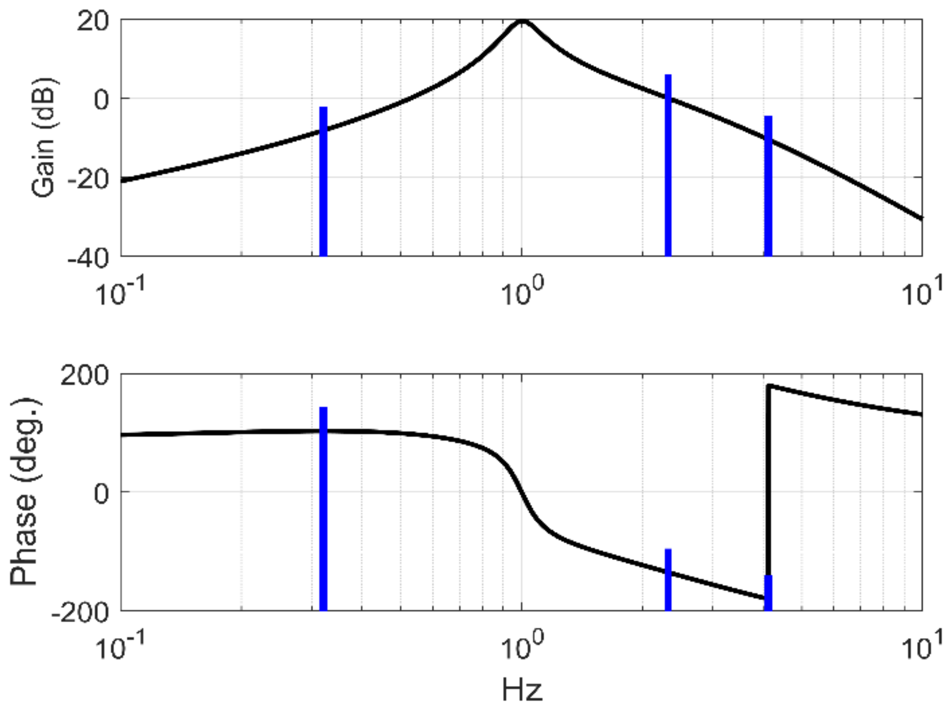
The resulting controller, gain, and filter are:

$$H_c = \frac{0.455(0.432s+1)}{0.0586s+1}$$

$$K_c = 9.40$$

$$H_F = \frac{1.26s}{s^2+1.25s+39.5}$$

$L = DG_1G_2H_{PMU}H_cH_FK_c$



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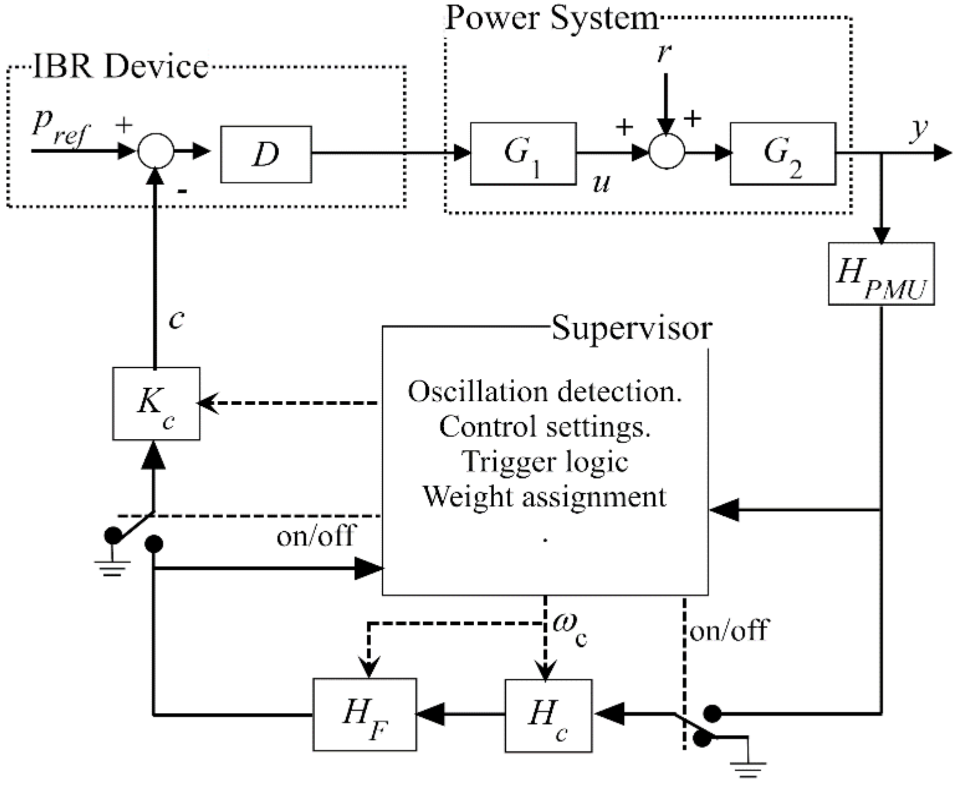
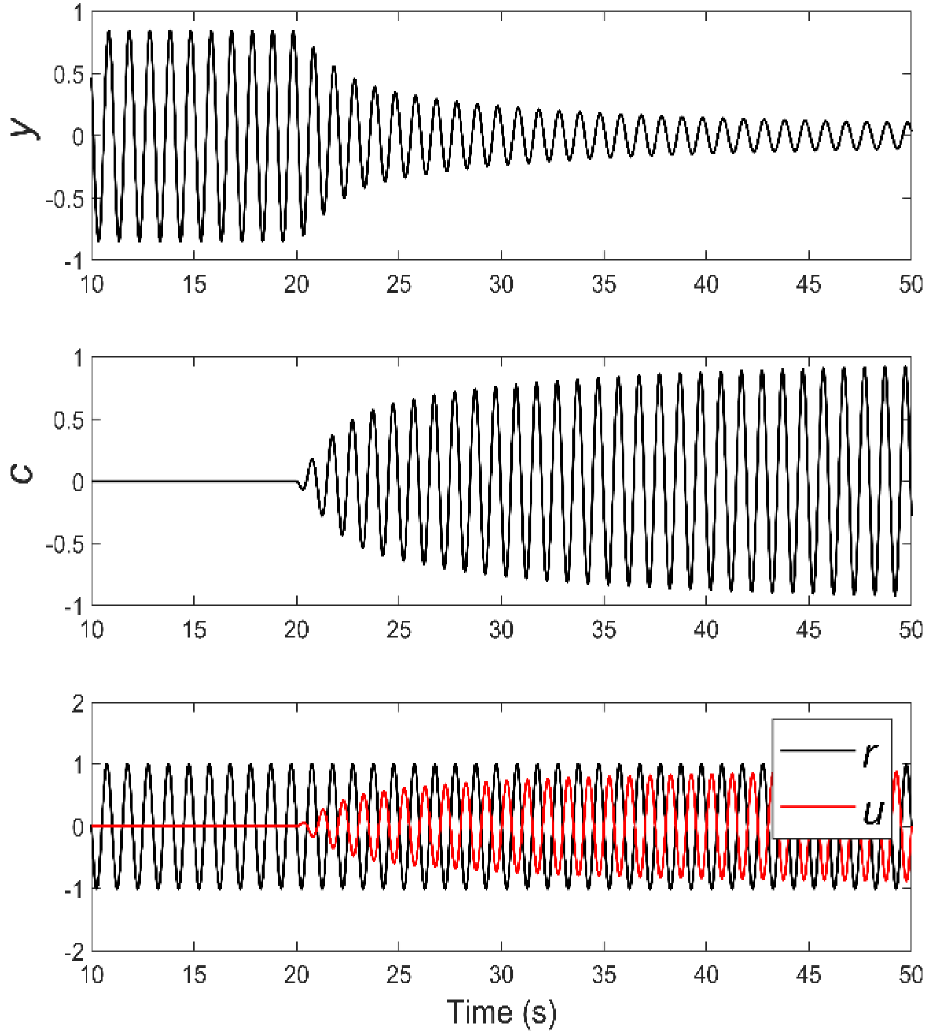
Simple example – cont.





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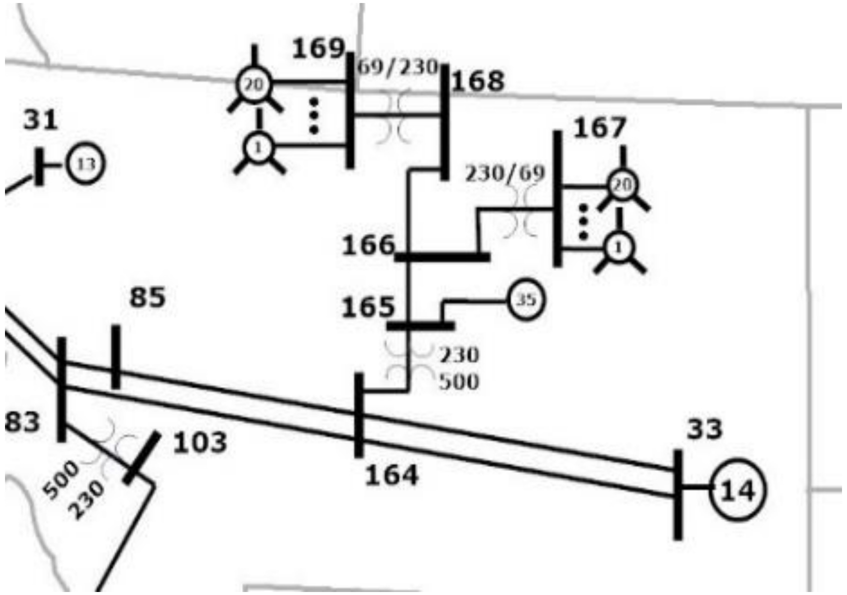
Power system example



- Consider a radial interconnect to a 500kV bulk system consisting of:
  - A 400-MW gas-fired-turbine synchronous generator connected at bus 165 (generator 35).
  - 20 IBRs connected at bus 167; max rating of 3 MW each.
  - 20 IBRs connected at bus 169; 10 with a max rating of 3 MW each; 10 with a max rating of 1.5 MW each.
- FOSC is added to the 20 IBRs on bus 169. The W_i's are scaled according to the power rating of each unit.
- $y = P_{165-164}$ = real power-flow from bus 165 to 164.

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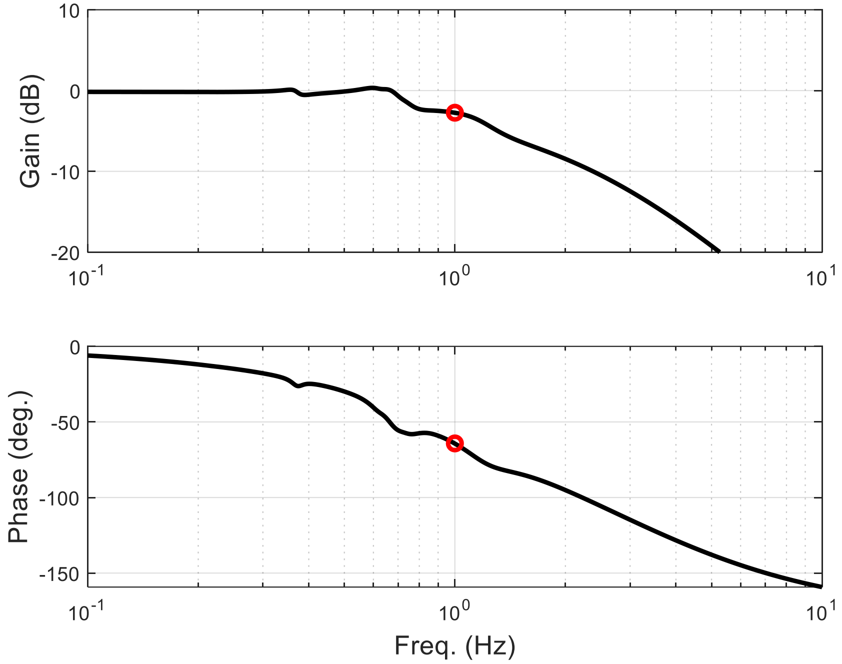
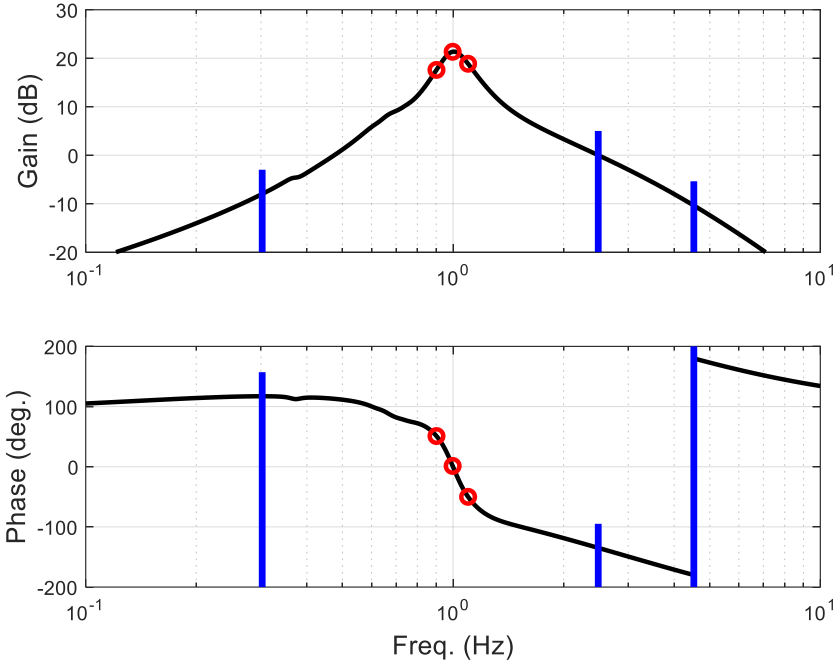
Power system example – cont.

$DG_1G_2H_{PMU}$



$L = DG_1G_2H_{PMU}H_cH_FK_c$



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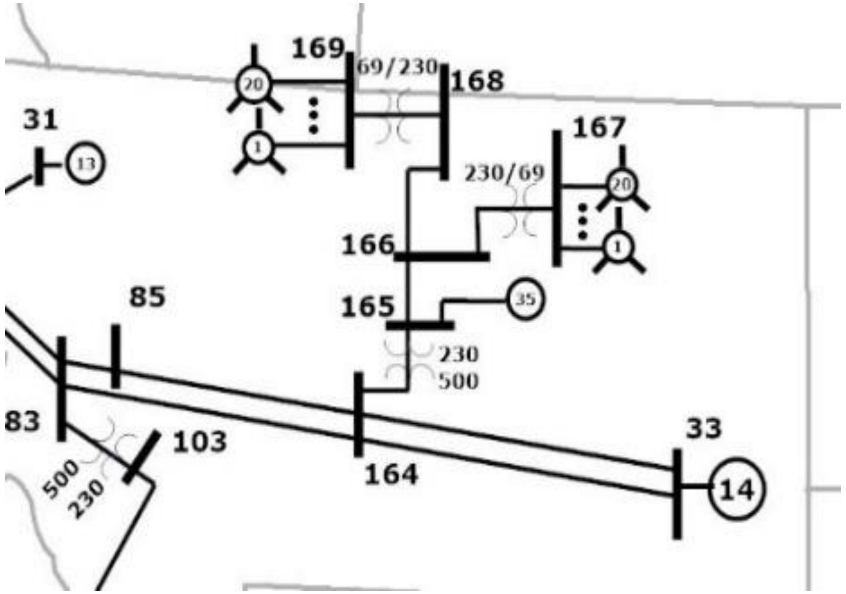
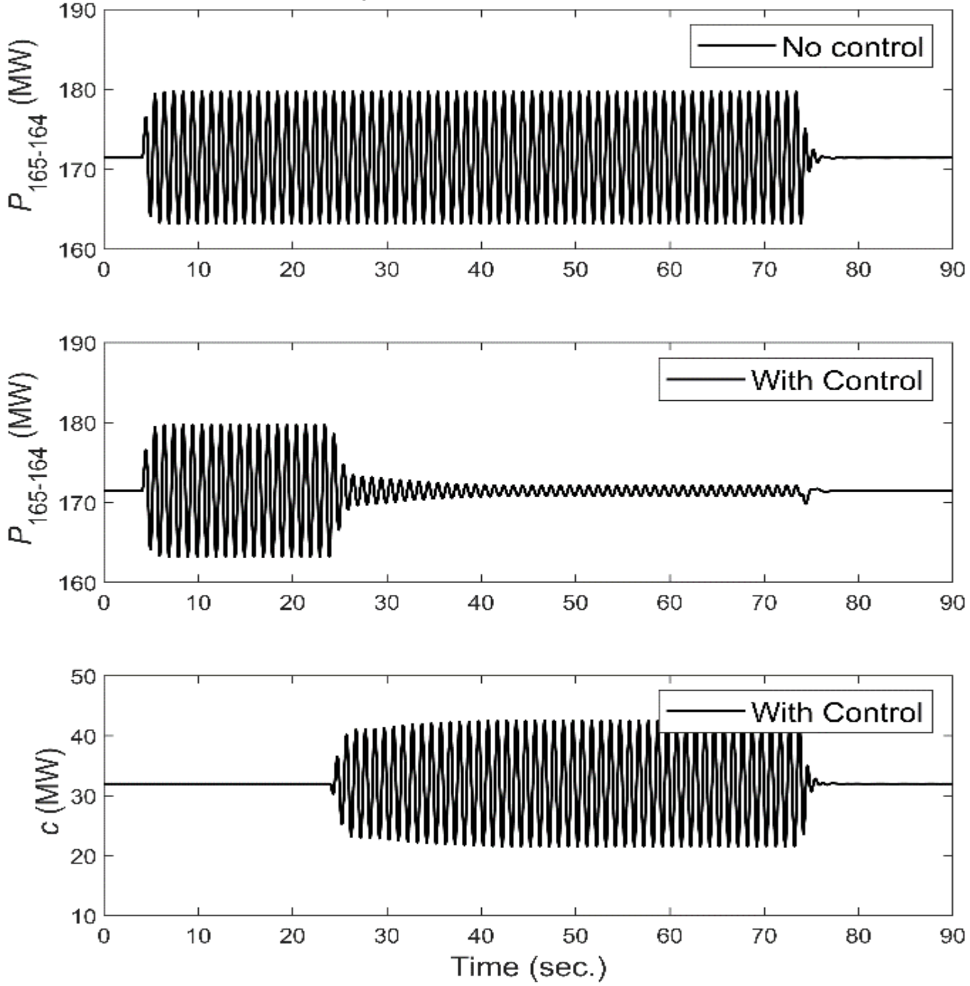
Power system example – cont.

A 1.0-Hz FO is induced into the turbine of gen. 35 starting at t = 5 sec. and continuing until the t = 74 sec.



f_c estimated at 1 Hz



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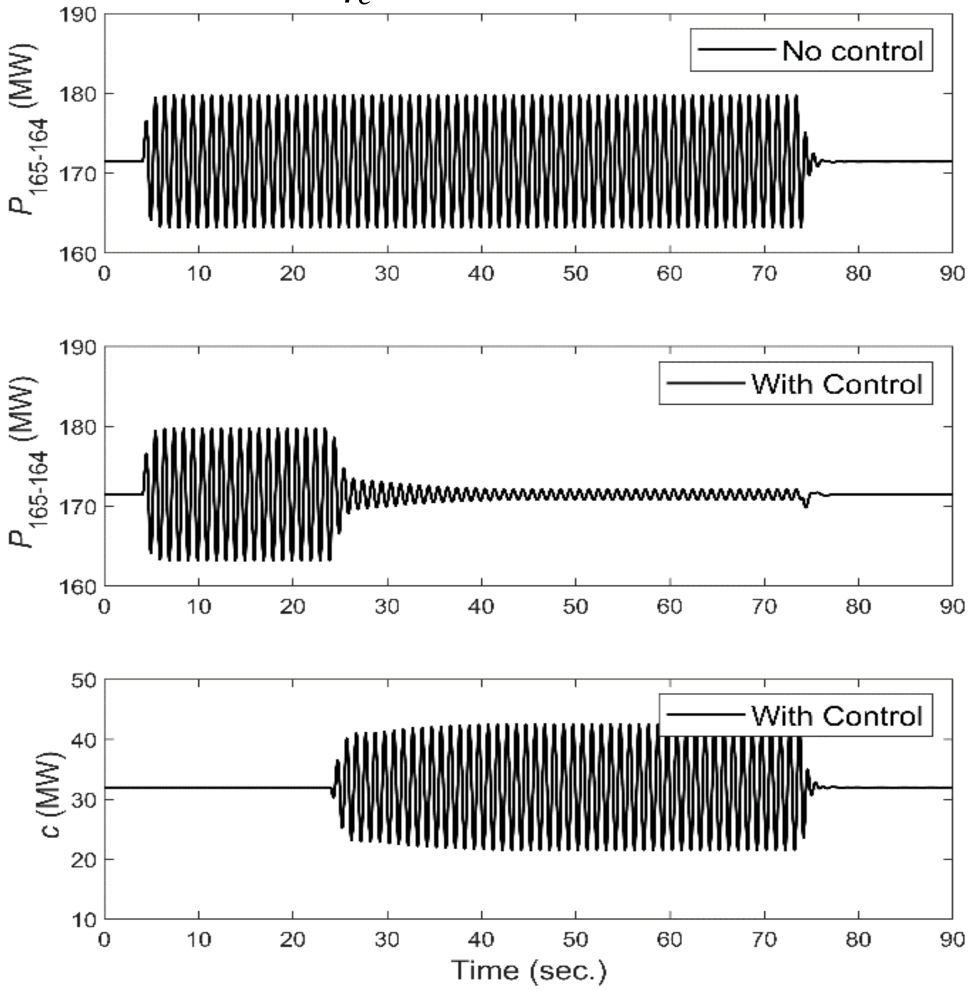
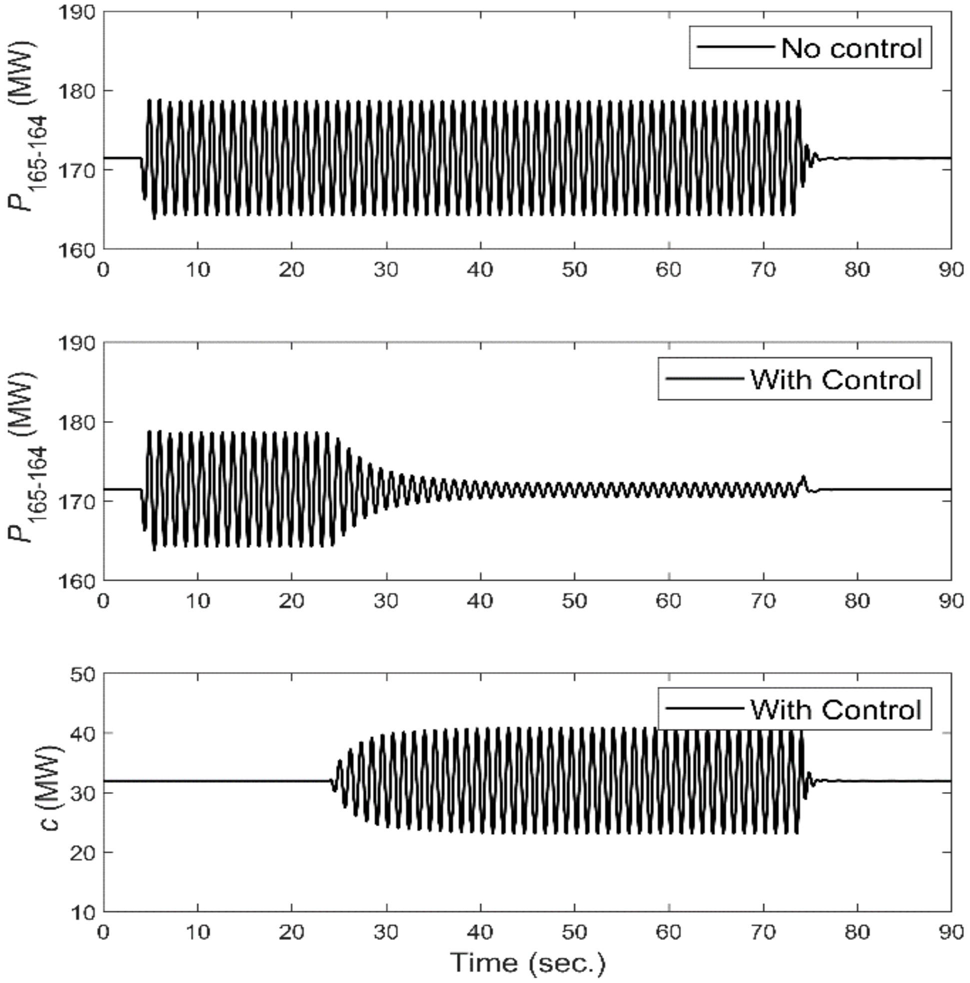
Power system example – cont.

f_c estimated at 1 Hz



f_c estimated at 0.9 Hz



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Conclusions

- Unique FO suppression control strategy.
- Implemented as a tuned-feedback controller based upon *adaptive gain scheduling* and the *internal model principle*.
- Designed to have excellent robustness properties
  - errors in the estimated plant
  - errors in the estimated FO frequency.
- Extended to multiple IBRs.
- Detailed radial system example.
- Future work:
  - application to meshed systems
  - higher frequency FOs
  - suppression based on other measurements (Q, V, and f) or a combination of measurements
  - noise impacts
  - field testing

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