Energy-Based Damping Evaluation for Exciter Control in Power Systems

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Outline

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- Motivation
- Dynamic Model of Synchronous Generators
- Transient Energy Concept and Its Analogy
- Energy Based Damping Analysis
- Proposed Index for Damping Evaluation
- Simulations
- Summary

Introduction

- Low-frequency oscillation
  - In power systems, the low-frequency electromechanical oscillation is a major issue on the reliability and security of modern bulk electric systems.
  - In 1996, two major events of WECC on July, 2 and August 10 demonstrated that unstable low-frequency oscillations could potentially lead to large disturbances or even black out.

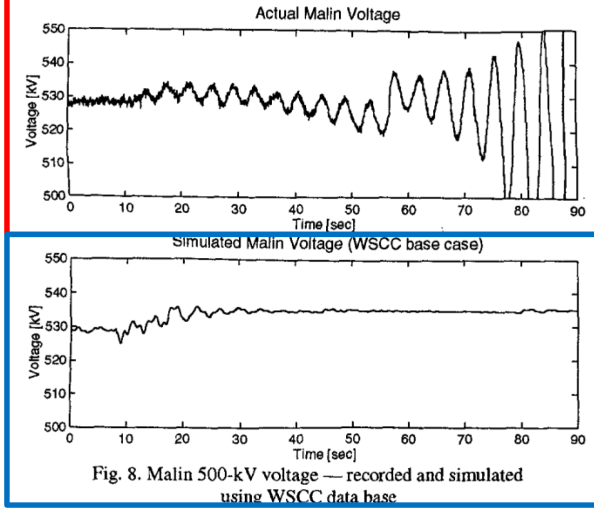


Fig. 8. Malin 500-kV voltage — recorded and simulated using WSCC data base

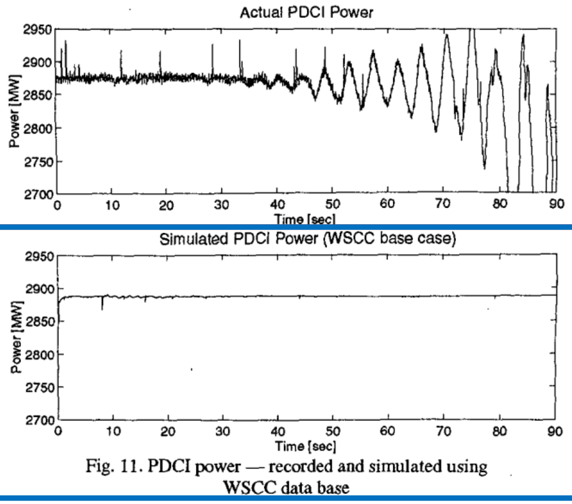


Fig. 11. PDCI power — recorded and simulated using WSCC data base

Actual

Simulated

Introduction (cont.)

- Two major issues
  - Model problem: The simulation results based on dynamic model CANNOT correctly match the actual situation of the system.
  - Monitoring problem: The online awareness of the dynamic situation of the whole system needs to be enhanced.
- Recent progress and development
  - Wide PMU deployment
    - PMUs provide real-time synchronized raw materials of the entire system
  - Wide area monitoring
    - Mode meters are developed to monitor the modes of low-frequency oscillation online based on synchronized measurements [Zhou-*et al*'08]
  - Model validation and calibration
    - Signal processing tools are applied in model validation, such as nonlinear Kalman filter, particle filter [Kalsi-*et al.*'12]

[Zhou-*et al.*'08] N. Zhou, D. J. Trudnowski, J. W. Pierre, and W. A. Mittelstadt, "Electromechanical mode online estimation using regularized robust RLS methods," *IEEE Trans. on Power Systems*, vol. 23, no. 4, pp. 1670–1680, 2008.

[Kalsi-*et al.*'12] K. Kalsi, P. Du and Z. Huang, "Model calibration of exciter and PSS using Extended Kalman Filter," in *Proceeding of IEEE Power and Energy Society General Meeting*, pp.1-6, San Diego, CA, July 2012

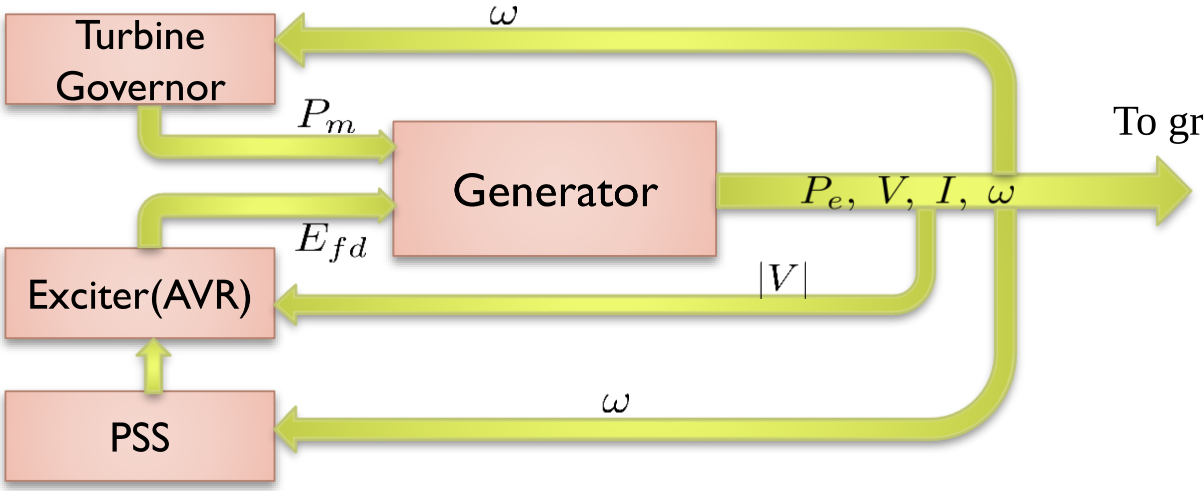
Motivations

- Location of oscillation source
  - To know which parts of the system induce the lightly damped oscillation is essential
  - The traditional damping torque evaluation based on the assumption of single machine infinite bus is hardly applied to multi-machine interconnected system
- Generator control: exciter and power system stabilizer (PSS)
  - Prone to be badly tuned and may contribute negative damping, and leads to lightly damped oscillations
  - Usually calibrated and tuned offline and might not be able to adapt to every operating situation of power systems

The damping contribution of exciter and PSS should be evaluated

Synchronous Generator and Its Controller

- Overview of synchronous generator and its controllers



- Exciter: to create magnetic field for generator and directly related to the output voltage
  - Automatic voltage regulator (AVR): to maintain the stability of output voltage during a disturbance
  - Power system stabilizer (PSS): to provide more damping to improve the stability of the system
- Turbine Governor: to maintain the frequency by controlling the mechanical power when the demand of electric power varies
  - Usually not considered in the transient stability analysis, due to its slow response
  - Assumed to be constant

Mathematical Model

- Four-order dynamic model

$\nu = \omega - \omega_0$

Output of Turbine Governor

$$\left.\begin{aligned}\dot{\delta}_i &= \omega_0\nu_i \\ M_i\dot{\nu}_i &= \boxed{P_{m,i}} - P_{e,i} - D_i\nu_i\end{aligned}\right\}\text{Swing Equations}$$

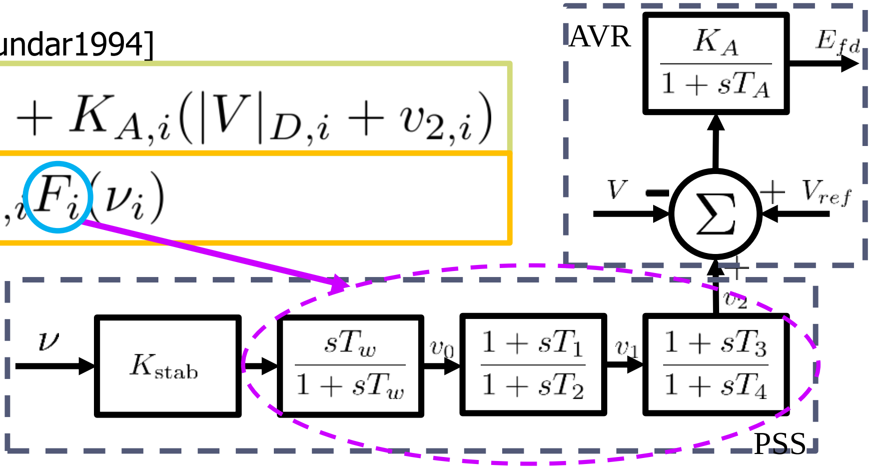
Output of Exciter

$$\left.\begin{aligned}T'_{d0,i}\dot{E}'_{q,i} &= \boxed{E_{fd,i}} - E'_{q,i} - (x_{d,i} - x'_{d,i})I_{d,i} \\ T'_{q0,i}\dot{E}'_{d,i} &= -E'_{d,i} + (x_{q,i} - x'_{q,i})I_{q,i}\end{aligned}\right\}\text{Field Winding}$$

  - The output power is directly related to terminal voltage and current

- Model of AVR and PSS [Kundar1994]

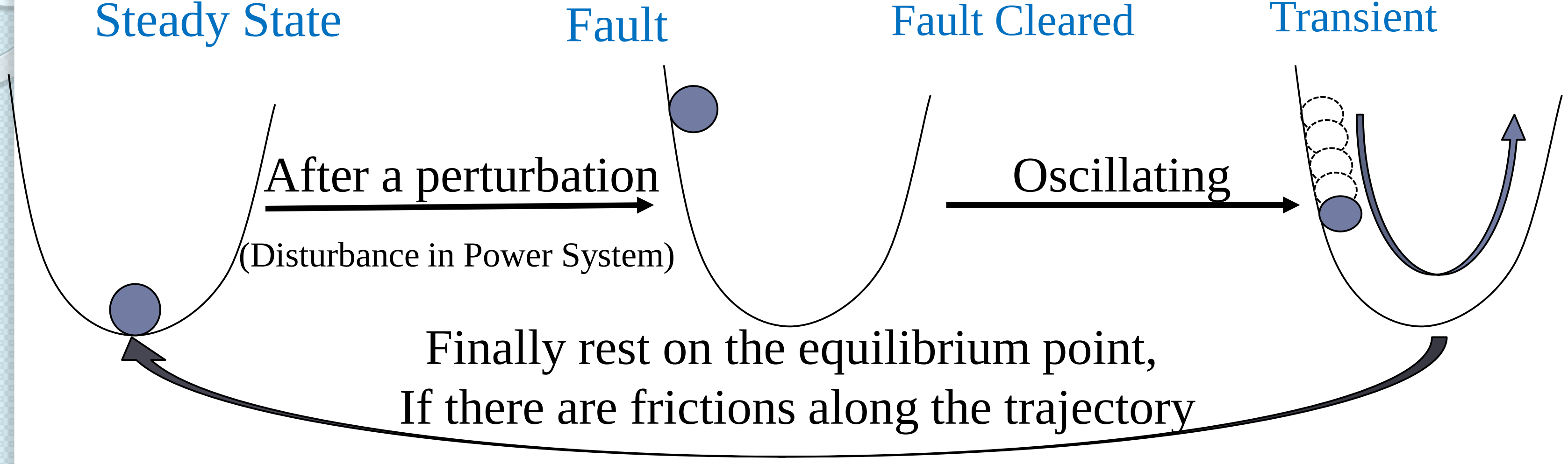
AVR	$T_{A,i}\dot{E}_{fd,i}$	$=$	$-E_{fd,i} + K_{A,i}(\lvert V\rvert_{D,i} + v_{2,i})$
PSS	$v_{2,i}$	$=$	$K_{\text{STAB},i}\boxed{F_i}(\nu_i)$



Kundur, Prabha. *Power system stability and control*. Eds. Neal J. Balu, and Mark G. Lauby. Vol. 7. New York: McGraw-hill, 1994.

Transient Energy Concept

- An Analogy of Transient Energy of Power Systems



Steady State

Fault

Fault Cleared

Transient

After a perturbation

(Disturbance in Power System)

Oscillating

Finally rest on the equilibrium point,
If there are frictions along the trajectory

- Bottom: equilibrium point (the operation point of power systems)
- Perturbation: disturbance in power systems (line loss, gen tripping, etc.)

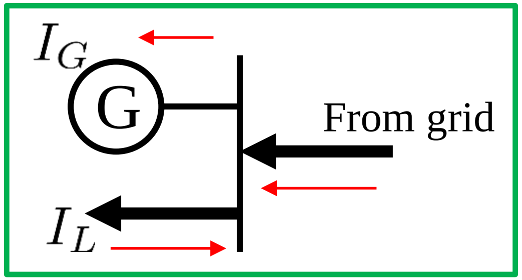
- Transient Energy

Transient Energy = Kinetic Energy + Potential Energy with respect to Equilibrium Point

  - The transient energy does NOT depend on the path or trajectory, it only depends on its status, such as speed and level difference
  - The energy dissipation (by friction) will indicate the performance of damping
  - The damping performance is directly related to the system

Transient Energy Construction of Power Systems

- KCL and Law of Conservation
  - KCL



$$\boldsymbol{Y}_N \boldsymbol{V}_{\mathrm{BUS}} - \boldsymbol{I}_G + \boldsymbol{I}_L = 0$$

  - Law of Conservation

$$\int \mathrm{Im}\left\{ \underbrace{[\boldsymbol{Y}_N \boldsymbol{V}_{\mathrm{BUS}} - \boldsymbol{I}_G + \boldsymbol{I}_L]}_{\text{zero}}^{H} \underbrace{d\boldsymbol{V}_{\mathrm{BUS}}}_{\text{perturbation}} \right\} = 0$$

- Construction of Energy Function [Moon-*et al*'99]

$$\int \mathrm{Im}\left\{ \boxed{\sum_{i=1}^{n}\left(\sum_{j=1}^{n} Y_{ij}^{*} V_j^{*} dV_i\right)} - \underbrace{\boxed{\sum_{i \in I_G} I_{Gi}^{*} dV_i}}_{\text{From Generators}} + \underbrace{\boxed{\sum_{i \in I_L} I_{Li}^{*} dV_i}}_{\text{From Loads}} \right\} = 0$$

- Transient energy can flow from one device to the other through the grid
- The sum of the transient energy and energy dissipation is always zero

[Moon-*et al*'99] Y.-H. Moon, B.-H. Cho, Y.-H. Lee, and H.-S. Hong, "Energy conservation law and its application for the direct energy method of power system stability," *in Proceeding of IEEE Power Engineering Society Winter Meeting*, vol. 1,1999, pp. 695–700.

Generator Components

From Swing Equation

- Based on dynamic model of generator

$$-\int \mathrm{Im}[I_{Gi}^{*}dV_i] = \boxed{\underbrace{\frac{1}{2}M_i\nu_i^2}_{\text{Kinetic Energy}} - \underbrace{\int P_{mi}d\delta_i}_{\text{Potential Energy}} + \underbrace{\int D_i\nu_i^2 dt}_{\text{Energy Dissipation}}} - \underbrace{\int (I_{di}dV_{qi} - I_{qi}dV_{di})}_{\text{From Field Winding and Controllers}}$$

- Response of rotor field winding [Chen-*et al*'14]

$$-\int (I_q dV_d - I_d dV_q) = -\frac{1}{x_d - x_d'}\int E_{fd}dE_q'$$

Due to the exciter control

$$+\frac{T_{d0}'}{x_d - x_d'}\int \dot{E}_q' dE_q'$$

Energy dissipation from the resistance of field winding

$$+\frac{T_{q0}'}{x_q - x_q'}\int \dot{E}_d' dE_d'$$

Energy dissipation from the resistance of damping winding

$$+\frac{1}{2}\left(\frac{(E_q')^2}{x_d - x_d'} + \frac{(E_d')^2}{x_q - x_q'} + x_d' I_d^2 + x_q' I_q^2\right)\Bigg|$$

Potential energy stored in field winding

[Chen-*et al*'14] L. Chen, Y. Min, Y. Chen, and W. Hu, "Evaluation of generator damping using oscillation energy dissipation and the connection with modal analysis," *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1393–1402, May 2014.

Impact of Exciter Control on Energy Dissipation

- Integration by Parts

$$-\frac{1}{x_d - x'_d}\int E_{fd}dE'_q = -\frac{1}{x_d - x'_d}\left(E_{fd}E'_q - \int E'_q dE_{fd}\right)$$

$$= -\frac{1}{x_d - x'_d}\left(\boxed{E_{fd}E'_q} - \int \boxed{E'_q\dot{E}_{fd}}dt\right)$$

Potential Energy

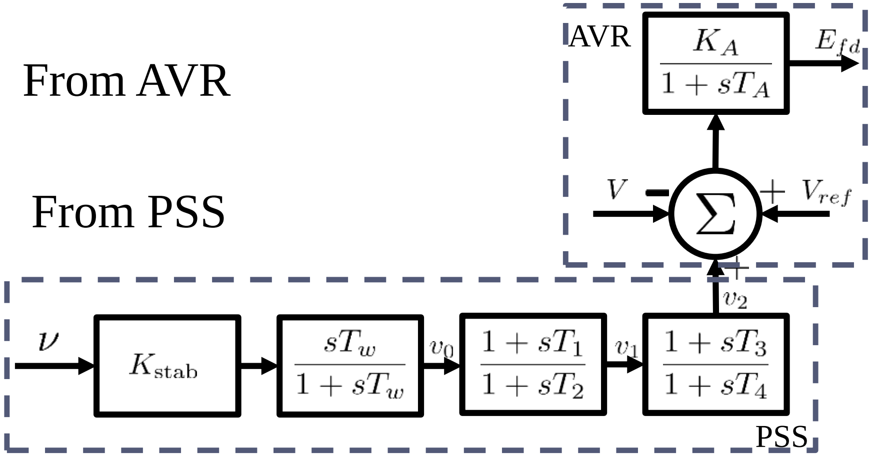
Energy dissipation from exciter control

- Dynamic model of exciter control

$$\frac{1}{x_d - x'_d}\int E'_q\dot{E}_{fd}dt = \frac{1}{T_A(x_d - x'_d)}\int E'_q[K_A(|V|_D + v_2) - E_{fd}]dt.$$

$$\int E'_q(K_A|V|_D - E_{fd})d\tau$$ ➡ From AVR

$$\int E'_q K_{\mathrm{STAB}}F(\nu)d\tau$$ ➡ From PSS



Damping Analysis for Exciter

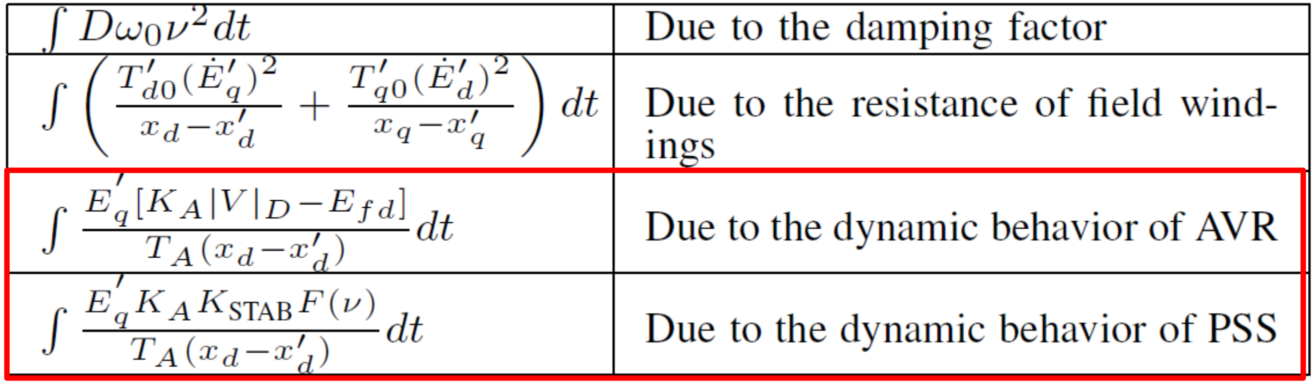
- Recall that the PSS is designed to damp the oscillation in the system
- The AVR will introduce negative damping if the energy dissipation of AVR $\int E_q'(K_A|V|_D - E_{fd})d\tau$ is negative
- Energy dissipation of PSS $\int E_q' v_2 d\tau$ must be positive and large enough to guarantee

$$\int E_q'[K_A(|V|_D + v_2) - E_{fd}]d\tau > 0$$

- Then, the generator will provide positive damping to the system (dissipate transient energy)
- Remark
  - The result of damping analysis based on energy is consistent with the one of traditional damping torque without the assumption of single machine infinite bus

Proposed Damping Evaluation Index for Exciter

- Summary of Energy Dissipation (Damping) of a generator



$\int D\omega_0 \nu^2 dt$	Due to the damping factor
$\int \left(\frac{T'_{d0}(\dot{E}'_q)^2}{x_d - x'_d} + \frac{T'_{q0}(\dot{E}'_d)^2}{x_q - x'_q} \right) dt$	Due to the resistance of field windings
$\int \frac{E'_q [K_A \lvert V \rvert_D - E_{fd}]}{T_A (x_d - x'_d)} dt$	Due to the dynamic behavior of AVR
$\int \frac{E'_q K_A K_{\text{STAB}} F(\nu)}{T_A (x_d - x'_d)} dt$	Due to the dynamic behavior of PSS

From Exciter

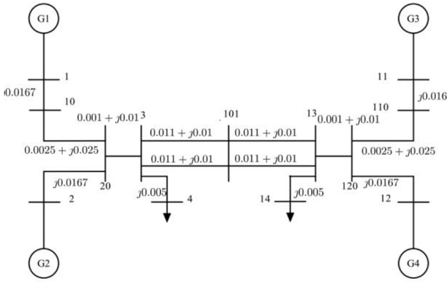
$$\frac{1}{x_d - x'_d} \int E'_q \dot{E}_{fd} dt$$

- Proposed Damping Evaluation Index for Exciter
  - by calculating the energy dissipation within a time window during the transient

$$\Xi = \frac{\int_{t_a}^{t_b} E'_q \dot{E}_{fd} d\tau}{x_d - x'_d}$$

- Remark
  - The proposed is a general damping evaluation method, which can be applied to any type of exciter controller

Simulations



- Classic four-machine-two-area system
- Time-domain dynamic simulations by power system toolbox (PST)
- Event Sequence

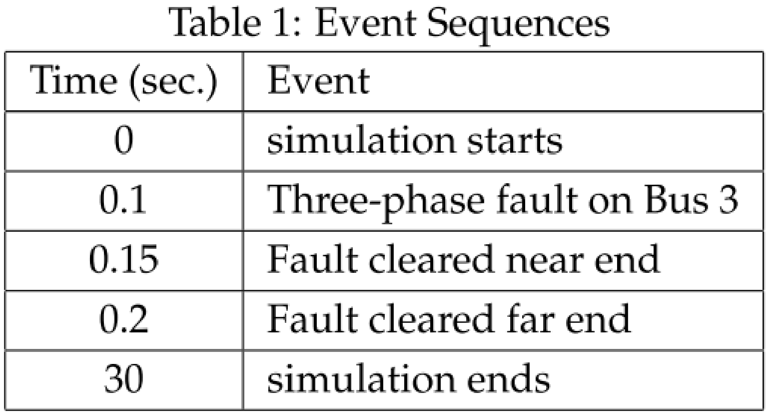


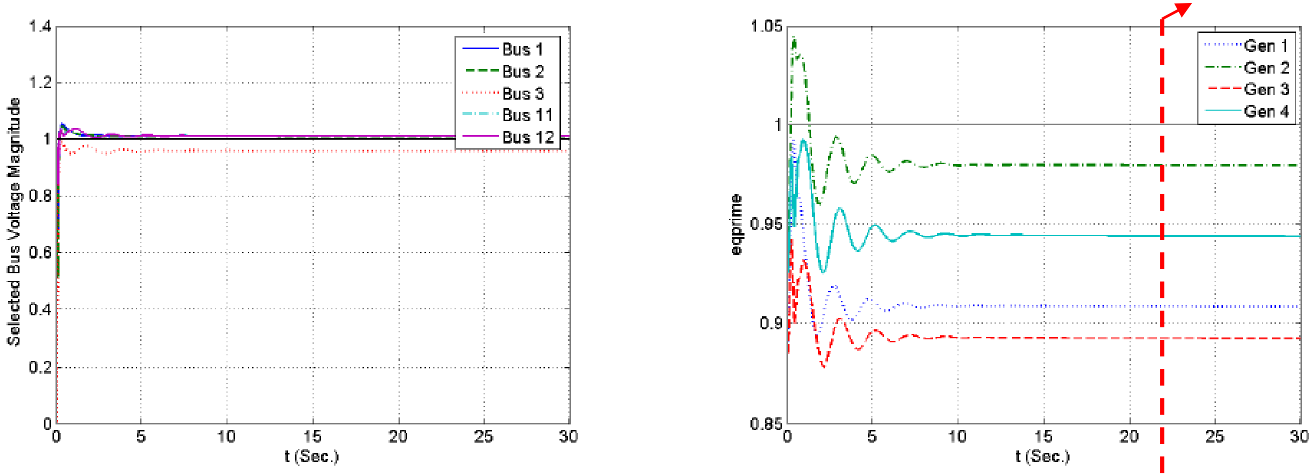
Table 1: Event Sequences

Time (sec.)	Event
0	simulation starts
0.1	Three-phase fault on Bus 3
0.15	Fault cleared near end
0.2	Fault cleared far end
30	simulation ends

- The gain K_{stab} of PSS is badly tuned on purpose to test our proposed index
- The index is calculated by the time window [0.2, 30]

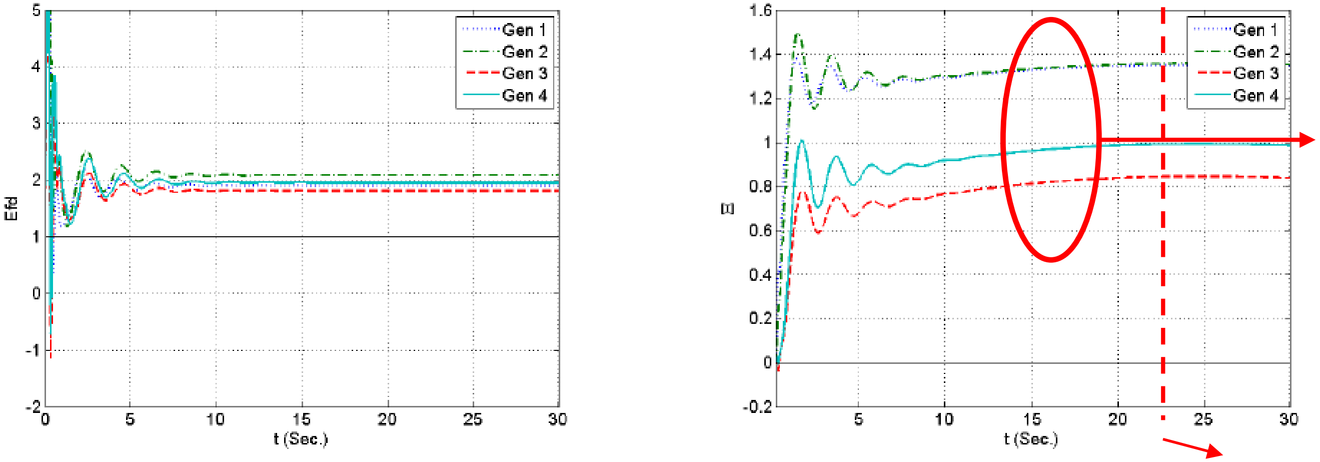
All the PSS Well Tuned

Converge to steady state



(a) Selected Bus Voltage Mag.

(b) E'_q



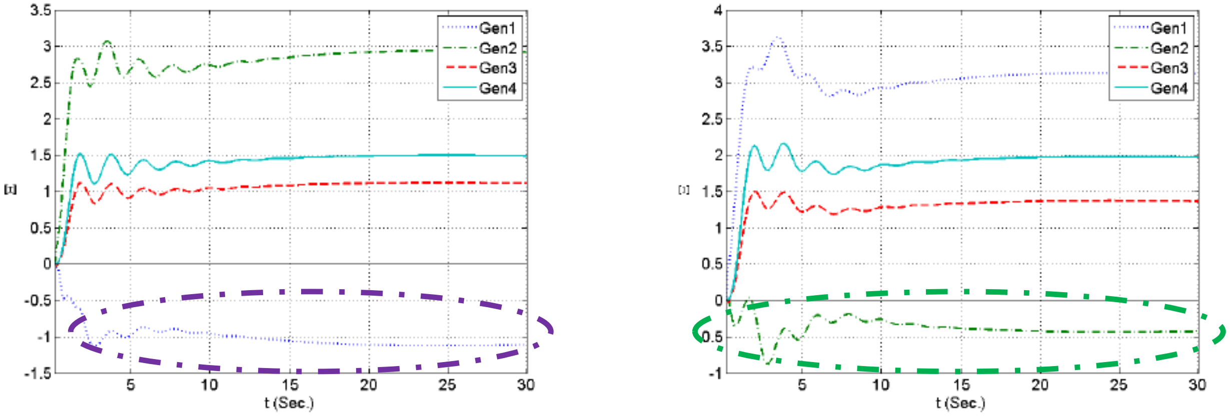
All are greater than zero

(c) E_{fd}

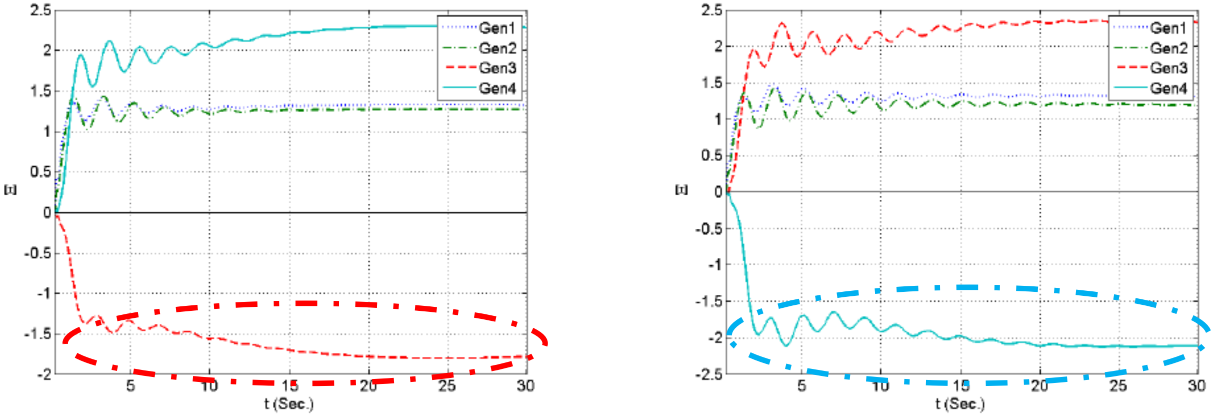
(d) Ξ

No more absorb energy

One PSS Badly Tuned



(a) Gen 1 PSS improperly tuned (b) Gen 2 PSS improperly tuned

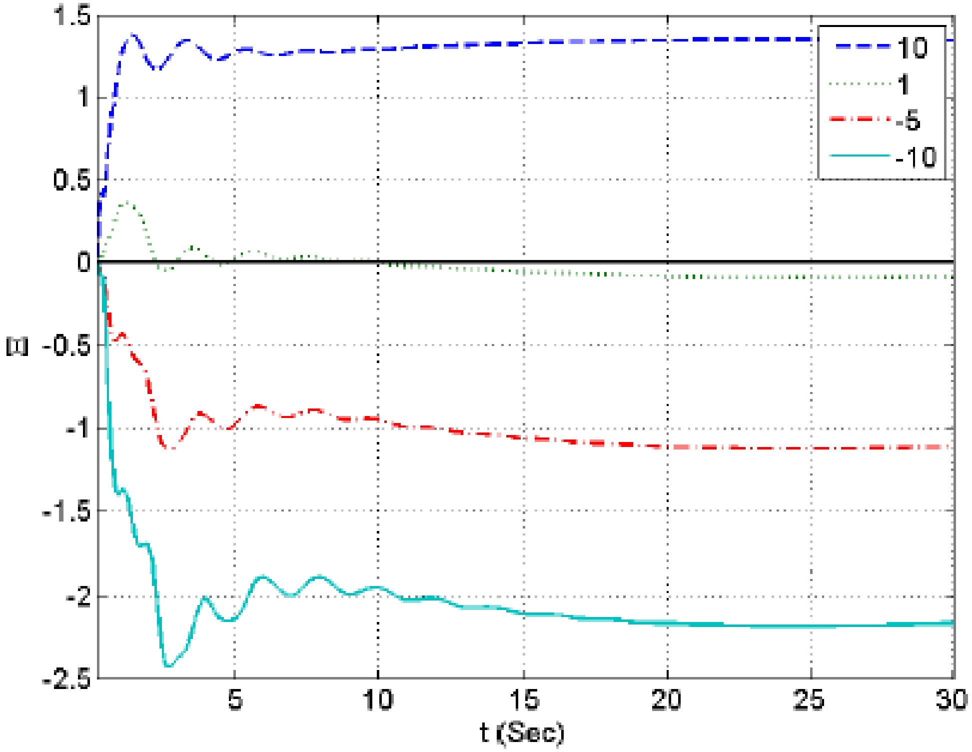


(c) Gen 3 PSS improperly tuned (d) Gen 4 PSS improperly tuned

Correctly indicate which PSS is badly tuned

Different PSS Gains in Gen 1

Typical well tuned gain $K_{\text{stab}} = 10$



(a) Gen 1

Energy dissipation increases with the increment of PSS gains – provide more damping

Summary

- We first analyze the damping performance of each component in the synchronous generator based on energy dissipation
- Then, we propose a damping evaluation index for exciter controller including AVR and PSS, which is verified in simulations
- In addition, the proposed index is only related to internal field voltage and q-axis transient voltage and is independent on the type of AVR and PSS

Thank you!

Transient Energy Function

$$\begin{aligned} W \quad = \quad & \sum_{i\in I_G}\left\{\frac{1}{2}M_i\Delta\omega_i^2 - \int P_{mi}d\delta_i\right\} + \sum_{i\in I_L}\left\{\int\left(P_{Li}d\theta_i + Q_{Li}d\ln V_i\right)\right\} \\ & -\left(\sum_{i=1}^{n}\int B_{ii}V_i dV_i + \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\int B_{ij}d(V_iV_j\cos\theta_{ij})\right), \end{aligned}$$

$$W + \sum_{i\in I_G}\int D_i\Delta\omega_i^2 dt = \int \mathrm{Im}\left\{\left[\tilde{\boldsymbol{Y}}_N\tilde{\boldsymbol{V}}_{\mathrm{BUS}} - \tilde{\boldsymbol{I}}_G + \tilde{\boldsymbol{I}}_L\right]^H d\tilde{\boldsymbol{V}}_{\mathrm{BUS}}\right\} = 0$$

$$\frac{dW}{dt} + \sum_{i\in I_G} D_i\omega_i^2 = 0 \Rightarrow \frac{dW}{dt} = -\sum_{i\in I_G} D_i\omega_i^2 < 0$$

[Chen-et al 2013] L. Chen, Y. Min, and W. Hu, “An energy-based method for location of power system oscillation source,” *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 828–836, May 2013.