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An Adaptive Wide-Area Power System Damping Controller using Synchrophasor Data

Scott G. Ghiocel and Joe H. Chow

Rensselaer Polytechnic Institute
Electrical, Computer, and Systems Engineering Department

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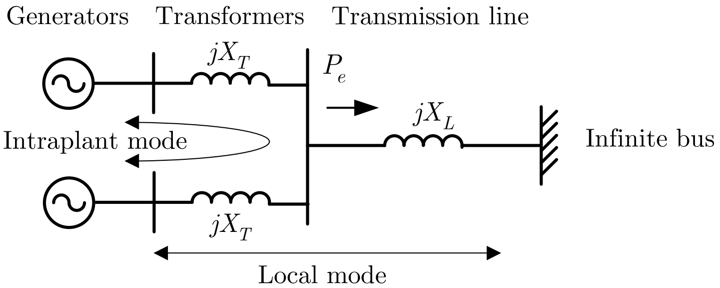
Outline

- Overview of power system electromechanical mode damping controllers
- Synchrophasor data as inputs to damping controllers
  1. Synchrophasor data latency
  2. Geographical coverage
  3. Data loss
- An adaptive damping controller
  1. Latency-based controller switching
  2. Phase compensation design
- A design example of a Thyristor-Controlled Series Compensator (TCSC)

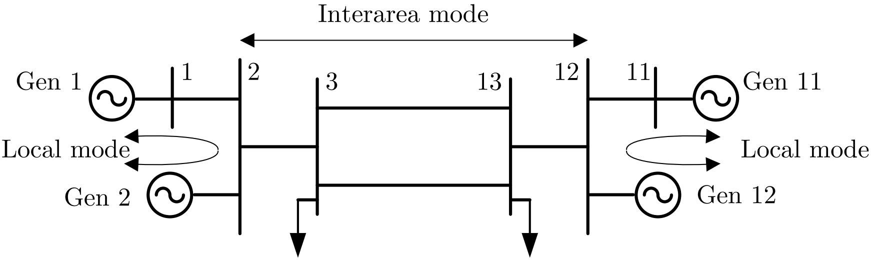
Power System Electromechanical Mode Oscillations

1. Electromechanical modes are the oscillations of the multiple generator inertias against each other through the electrical network
2. Three types of electromechanical modes
    1. Intraplant modes: 2-3 Hz
    2. Local mode: 1-2 Hz
    3. Interarea modes: 0.2-0.6 Hz

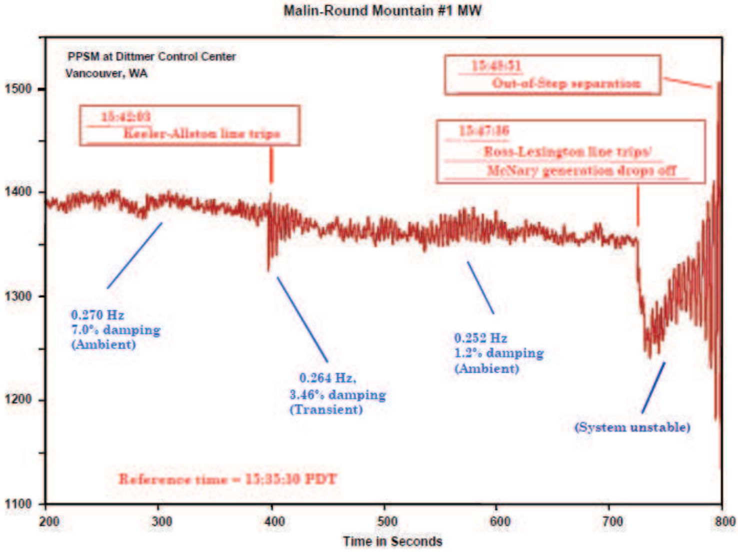
A simple power system showing a local mode and an intraplant mode



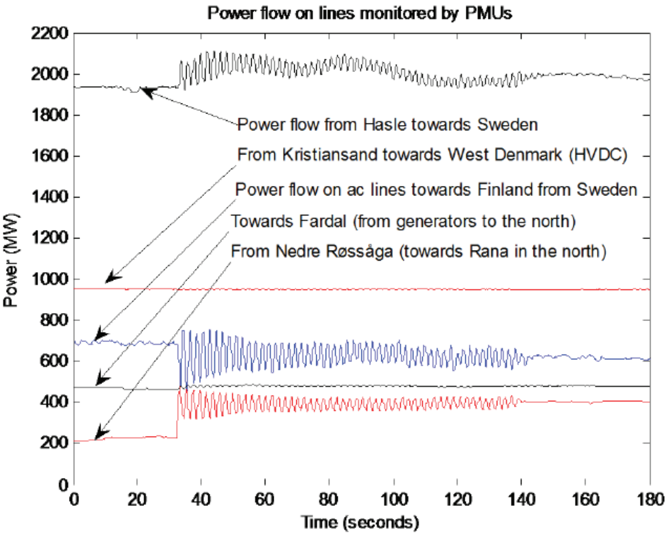
Interarea mode: Klein-Rogers-Kundur 2-area, 4-machine system



US Western System Breakout - August 10, 1996



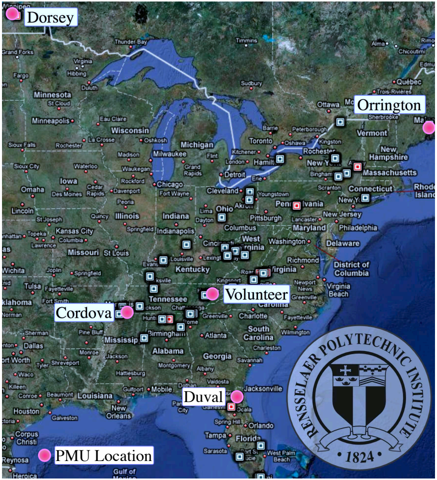
Nordic System

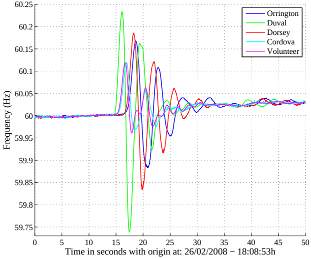


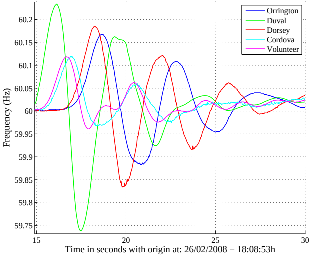
Kjetil Ulhen

Nature of Network Oscillations

The 2008 Florida Disturbance

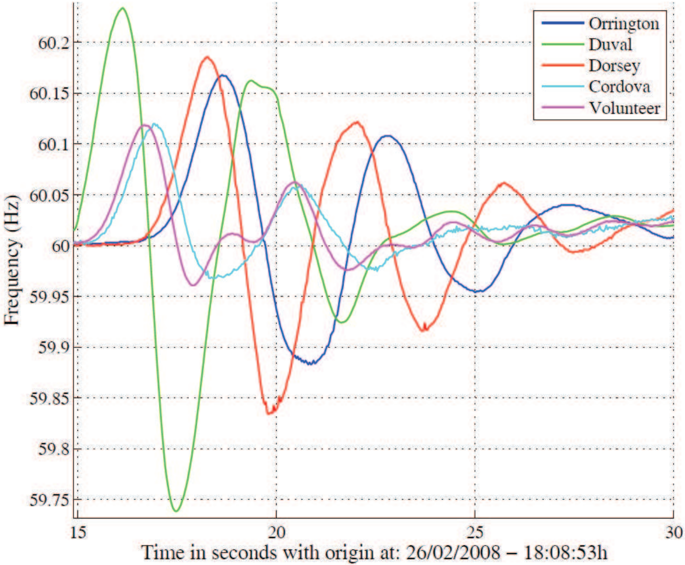






f propagation:
Duval $\rightarrow$ Volunteer $\rightarrow$ Cordova $\rightarrow$ Dorsey $\rightarrow$ Orrington

US Eastern Interconnection, Florida event, February 26, 2008

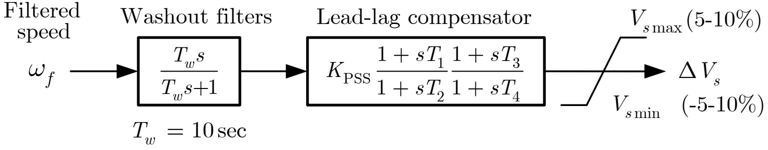


Luigi Vanfretti

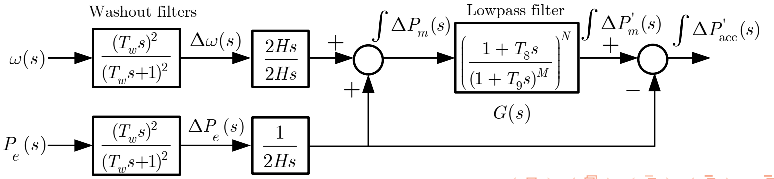
Electromechanical Model Damping Controllers

Power system stabilizers (PSS): provides damping signal via the voltage regulator summing junction; mostly for local mode damping, but also beneficial to interarea modes; PSS design focuses on phase-lead compensation; US WECC requires PSS on every generating unit/cluster greater than 30/70 MVA.

Speed-input PSS



Integral of accelerating power PSS



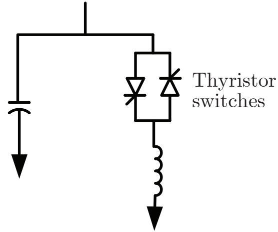
Flexible AC Transmission Systems (FACTS) Controllers

High-voltage, high-power power-electronic switches to provide reactive power support and provide interarea damping control.

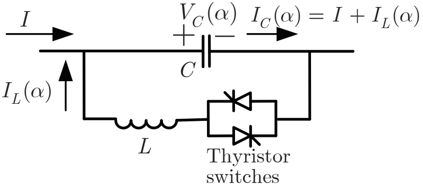
(a) Shunt controllers: static var compensator (SVC), static synchronous compensator (STATCOM)

(b) Series controllers: thyristor-controlled series compensator (TCSC), static synchronous series compensator (SSSC)

(c) Coupled controllers: unified power flow controller (UPFC), interline power flow controller (IPFC), back-to-back (B2B) STATCOM

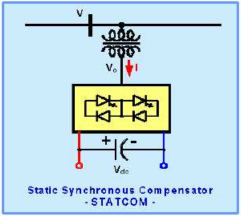


(a) SVC schematic

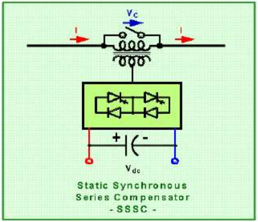


(b) TCSC schematic

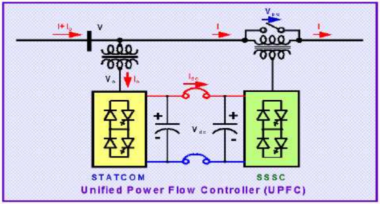
VSC-based FACTS Controllers



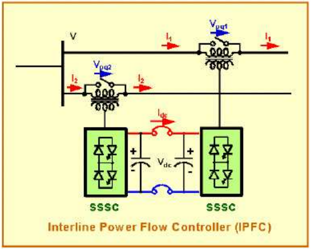
STATCOM



SSSC



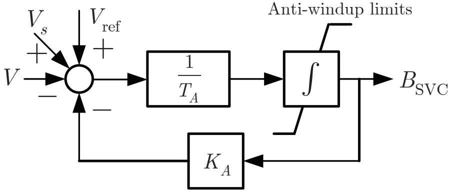
UPFC



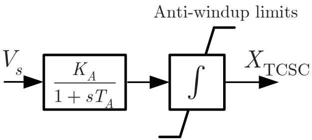
IPFC

Interarea Mode Damping using Shunt and Series FACTS Controllers

1. As FACTS controllers are located in power transfer paths between two areas, supplementary signals V_s can be used in FACTS Controllers to enhance interarea damping.
2. Machine speeds are normally not available to FACTS controllers, because they are not located next to generator buses. Thus a FACTS controller would need to use other signals that are available locally, or sometimes, remotely.



(a) SVC control loop



(b) TCSC control loop

Candidate Damping Control Input Signals for SVC/TCSC

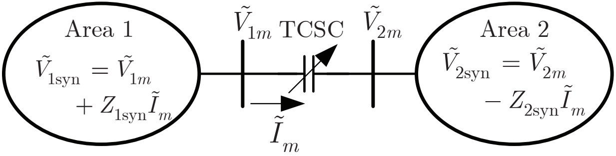
1. Local bus voltage magnitude V
2. Local bus frequency f
3. Active power transfer P
4. Active component of line current I_a
5. Line current magnitude I_m
6. Synthesized angular difference between two areas
7. Remote bus voltage or machine angles as measured by phasor measurement units

Selection criteria

- The observability of the interarea mode in the signal should be high (the interarea mode should be clearly visible or no zeros near the interarea mode).
- The damping controller should be robust with respect to changes in power transfer direction and line impedance.

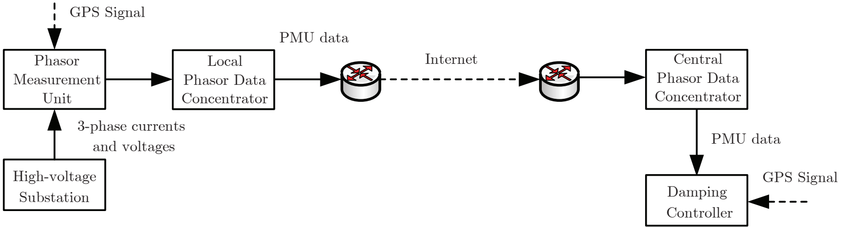
Synthesized angle difference between two areas

1. Use local voltage and current measurements to extrapolate to the "center-of-angle" of remote coherent areas.



2. With the availability of synchrophasor measurements, the "center-of-angle" can be directly measured and communicated to the controller.

PMU Data Communication Path



- PMU data are time stamped with GPS clock signal
- A typical architecture with local PDCs sending PMU data to a central/regional PDC
- Latency due to PMU signal processing, data transmission (UDP or TCP/IP), and data concentration

Latency Estimate of Hydro Quebec WACS

From Charles Cyr and Innocent Kamwa (HQ)

PMU filter delay	73 ms
Local data concentration	16 ms
2,000 km in optical fiber	10 ms
Central data concentration	10 ms
Total estimated latency	109 ms

- Longest delay is PMU data processing of current and voltage phasors - to reduce noise, magnitude and phase of a single phase are estimated over a 1-2 cycles (sometimes even longer) data window.
- Transmission propagation time - 1,000 km of dedicated optical fiber: UDP 5 ms; TCP/IP 15 ms
- Impact of latency for interarea mode damping - a 150 ms latency for an oscillation of period 2 sec is like a phase lag of

$$0.150/2 \times 360^\circ = 27^\circ$$

Geographical Coverage of PMU Data

- PMUs are mostly located on high-voltage transmission buses, not at generator terminals, although neighboring PMUs can estimate generator terminal quantities
- Generator rotor angles and speeds not included in PMU data - the aggregate machine rotor angle δ_a and speed ω_a can be calculated using the Interarea Model Estimation method.
- Beneficial to use a weighted sum of PMU variables, such as the weighted average of the bus voltage angles in a coherent area

$$\theta_a = \sum_{i=1}^{N_a} \alpha_i \theta_i \tag{1}$$

where N_a is the number of buses, and the α_i's are selected to eliminate the local mode components in θ_a.

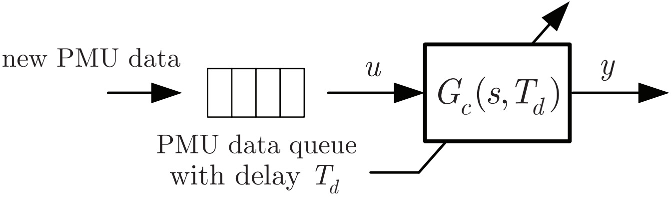
PMU Data Loss

- PMU data loss
  - a PMU not in service
  - loss of GPS signal reception
  - communication network congestion
- A phasor data concentrator (PDC) assembles PMU data from time stamps.
  - Time-out function - PMU data not arriving within a specified time will be dropped
- Two prototype PMU systems in Brazil reported 0.01% to 14% data loss during peak internet traffic periods.
- If an input signal consists of several PMU measurements, like θ_a, it can still be constructed if one of the component PMU data is lost.

Control Schemes Accounting for Input Signal Latency

- Control of delayed system has been studied by control community for many years.
- Recent interests in power system community, typically related to use of remote signals requiring data transmission
- Sometimes remote signals are used to complement local signals to remove unfavorable zeros.
- Stahlhut et al. studied the impact of latency on electromechanical mode damping.
- Chaudhuri, Ray, Majumder, and Chaudhuri proposed a forward phase rotation in the time domain to compensate for latency.

Adaptive Control Scheme



2 main components

1. Latency monitoring: continuously monitor the latency T_d of arriving PMU data by comparing the time stamp with the GPS clock signal.
2. Use T_d to determine the controller $G_c(s, T_d)$, which is a set of controllers to provide phase compensation for $T_d = T_{d1}, T_{d2}, \ldots$.

Adaptive Control Algorithm

At time $t = t_k$,

where t is the time at the controller

$G_c(s, T_{di})$ is used

for $t = t_k + \Delta t$,

where Δt is the sampling period of the PMU data if data is already in buffer, or the incremental time of arrival of the next data point for empty buffer

if $T_d > T_{di}$, switch to a new controller with the lowest latency $T_{dj} > T_d$

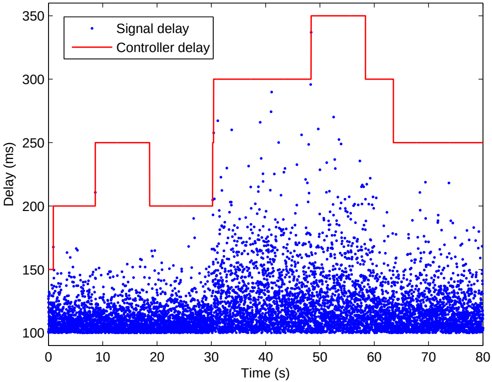
elseif the maximum latency of all the data in the last T_r sec is less than $T_{dj} < T_{di}$, switch to $G_c(s, T_{dj})$

else continue with the same controller

end

End algorithm

Illustration of the Delay Selection Algorithm



- Latency level starts at 150 ms, in increments of 50 ms
- PMU data arrival (i.e., latency) is modeled as a Poisson process with a minimum total latency of 100 ms
- Latency increase is on fast time-scale; latency decrease is on slow time-scale to avoid controller transients and potential instability.

Phase Compensation Design

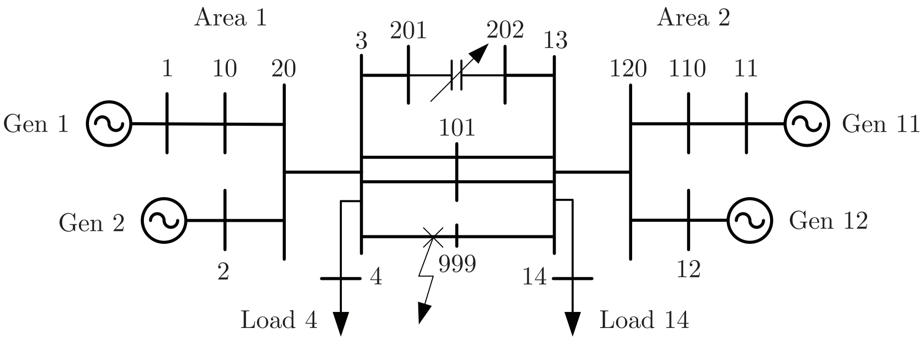
Classical 2-stage lead-lag compensators: gain K and time constants $T_i, i = 1, ..., 4$, can be made dependent on T_d

$$G_c(s, T_d) = K(T_d)\frac{1 + T_1(T_d)s}{1 + T_2(T_d)s}\frac{1 + T_3(T_d)s}{1 + T_4(T_d)s}\frac{T_w s}{1 + T_w s} \quad (2)$$

- Let phase compensation at the interarea mode without input signal latency be θ_{comp}
- For input signal with latency T_d, the new phase compensation is $\theta_{\text{comp}} + \theta(T_d)$
  - For PSS, θ_{comp} is a lead compensation. Thus $\theta_{\text{comp}} + \theta(T_d)$ means more lead compensation.
  - For FACTS controllers, θ_{comp} is a lag compensation. Thus $\theta_{\text{comp}} + \theta(T_d)$ means less lag compensation, at least for small T_d.

Design Illustration

2-area, 4-machine system, adapted from Klein, Rogers, and Kundur



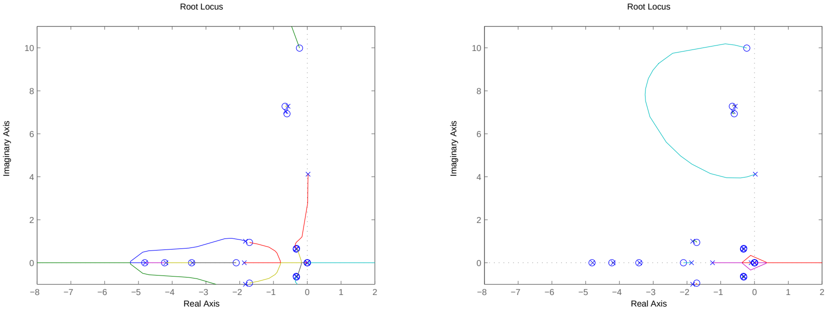
- At 400 MW of power transfer, the interarea mode at $0.0230 \pm j4.119$ is unstable.
- Local modes: $-0.6327 \pm j7.0378$ and $-0.5698 \pm j7.2802$.
- The TCSC is used to damp the interarea oscillations between the 2 areas.

TCSC Input Signals and Effectiveness

Input signal	Zeros close to the interarea mode
V_{m201} (local)	$0.379 \pm j2.19$
V_{m101}	none
V_{m13}	$0.126 \pm j5.09$
$I_{m(201-202)}$ (local)	$0.0311 \pm j3.80$
$\theta_3 - \theta_{13}$	$-0.0786 \pm j5.63$
$0.5(\theta_1 + \theta_2) - 0.5(\theta_{11} + \theta_{12})$	none (used as input signal)
$0.5(\delta_1 + \delta_2) - 0.5(\delta_{11} + \delta_{12})$	$-0.125 + j1.99$
$0.5(\omega_1 + \omega_2) - 0.5(\omega_{11} + \omega_{12})$	none

V_m denotes the bus voltage magnitude, I_m the line current magnitude, θ the bus voltage angle, δ the machine angle, and ω the machine speed. The number in the subscript of these variables denotes either the bus number or the machine number.

Root-Locus Analysis - Without Latency

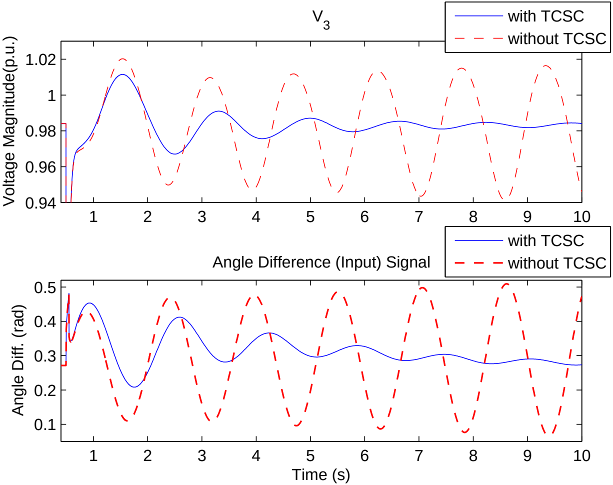


(a) (b)

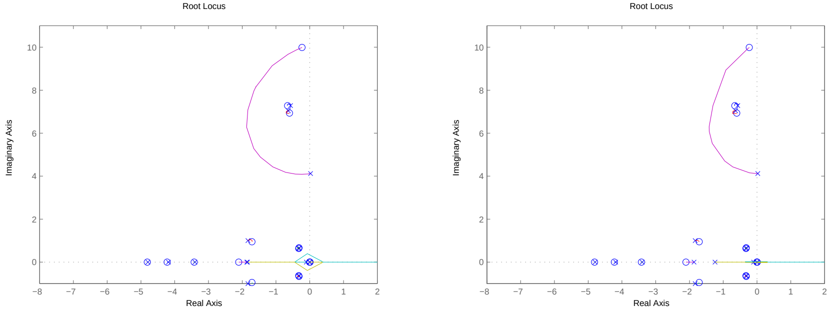
Root-locus plots: (a) no phase compensation, (b) with phase-lag compensation

Damping Controller Performance

TCSC damping control performance with no data latency, a three-phase short circuit fault on Bus 999 at $t = 0.1$ sec, cleared in 3 cycles by removing Line 4-999



Root-Locus Analysis - With Latency



(a) (b)

Root-locus plots: (a) phase compensation for latency, (b) no phase compensation for latency

Phase compensation $\theta(T_d)$ for $T_d = 150$ ms:

$$0.150/(2\pi/4.119) \times 360^\circ = 35.4^\circ \tag{3}$$

TCSC Damping Controller with Latency Compensation

$$G_c(s, T_d) = K(T_d)\frac{1 + T_1(T_d)s}{1 + T_2(T_d)s}\frac{T_w s}{1 + T_w s} \qquad (4)$$

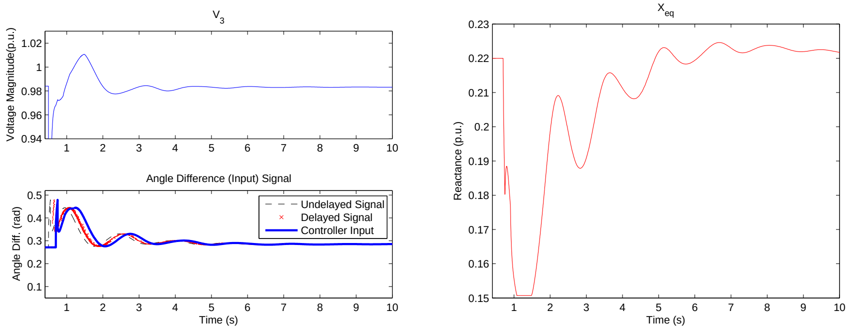
where $T_w = 10$ sec

Table: Adaptive phase compensation (preliminary)

Latency ms	Controller	$T_1(T_d)$ ms	$T_2(T_d)$ ms	compensation
$T_{d1} = 150$	$G_{c150}(s)$	0.1085	0.5425	$-42°$
$T_{d2} = 200$	$G_{c200}(s)$	0.1401	0.4202	$-30°$
$T_{d3} = 250$	$G_{c250}(s)$	0.1716	0.3431	$-19.5°$
$T_{d4} = 300$	$G_{c300}(s)$	0.2050	0.2871	$-9.6°$

$K(T_d)$ has to be set accordingly to achieve the appropriate damping.

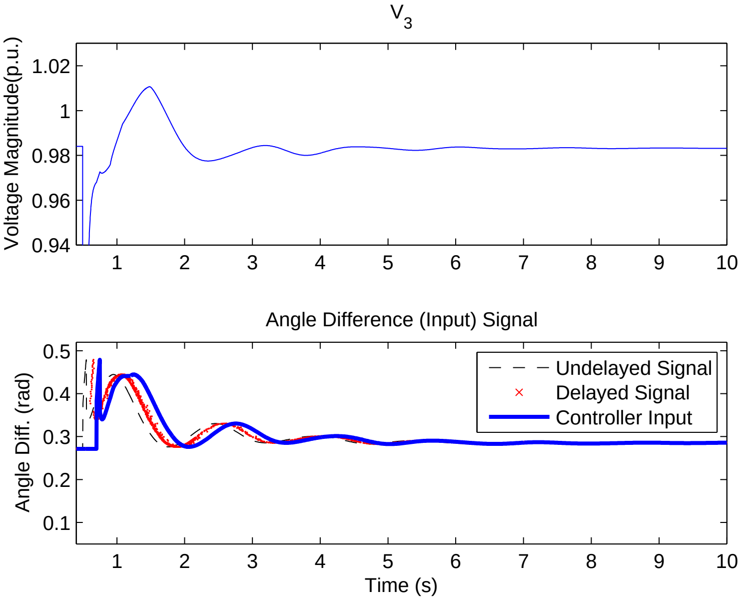
TCSC Controller Response with Latency Compensation



(a) (b)

TSCS performance plots: (a) controller performance, (b) control action

An Expanded Look



Conclusions

- An adaptive control scheme for an interarea damping controller to counter the variable PMU data latency
    - a controller switching algorithm based on the latency of PMU data
    - a phase compensation design of the controller for a given set of latency
- Algorithm illustrated for a TCSC
- Future work – apply the adaptive control algorithm to PSSs.