Robust Control of Oscillations in Power Systems

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Presentation Overview

• Robust power transmission control
  – Inter-area oscillations
  – Design specifications
  – Modelling
  – Design Methodology
    • Mixed-sensitivity
    • Pole-placement
  – Solution: LMI
  – Performance validations
  – Design Issues
    • Centralized Vs decentralized
Presentation Overview (contd)

• Issues in design
  – Loop shaping
    • Performance validations
  – Signal transmission delays
    • Predictor based design
    • Performance validation
  – Complexities
    • Real time simulator
    • Results and discussions

• Conclusions
Inter-area oscillations

• The rest of the network meets the energy need of the nation but pushed to their capacity limit
• Transmission system is stressed
Consequence?
Consequence of inter-area oscillation

Puts the limit on the transfer capacity of the transmission lines

An example: 400KV, 500KM line

Thermal capacity limit: 1500 MW

Small signal stability limit: 450 MW
Inter-area oscillations

- System-wide oscillations are caused by interactions among large groups of generators.
- Large interconnected system usually have inter-area oscillations in the range of 0.1 to 1 Hz.
- Involves swinging of a group of machines in one part of the system against another group in the other part.
- Inadequate damping is the primary factor leading to system separation.
- Amount of damping and the frequency of oscillation varies with change in system operating conditions.
- It is a control problem requiring robust damping control solution.
- Traditionally performed through standard model-based design.
Incidents of system outages

- South East Australia (1975)
- Scotland-England (1978)
- Western Australia (1982, 1983)
- Taiwan (1985)
- Ghana-Ivory Coast (1985)
- Southern Brazil (1975-1980, 1984)
- Brazil 11th March 1999
  - A lightning bolt hit a power substation close to Bauru, angle instability, 97 million people affected in Rio and Sao Paulo
- USA 10th August 1996
  - Line into tree, angle instability, 7.5 million people affected in Los Angeles
Design Steps

• Develop a comprehensive model of an interconnected power system with integrated FACTS devices
• Analyze the behaviour of the system using modal analysis
• Choose appropriate feedback signals for FACTS controllers
• Design robust damping controller
• Validate controller performance with the original system
• Building a test bench for validation of control algorithms
• Implement the designed controller and validate in HIL configuration
Design specifications and methodologies

• Damping must be adequate for various operating scenarios
  – Power flow
  – Load characteristics
  – Inter-connector strength

• Control efforts should be constrained (non-interference with transient stability)

• Methodologies
  – $H_\infty$ mixed-sensitivity
  – Loop shaping in $H_\infty$
  – Multiple model adaptive control
  – Robust pole-placement approach
New York & New England interconnected test system
- 16 Machine
- 68 Transmission Bus
- 5 Area
- 1 TCSC
Test power system model
Modelling

- **Machines**
  - Classical
  - Electromechanical (flux decay)
  - Transient
  - Sub-transient
- **Excitation systems**
  - Manual
  - DC
  - Static
  - Other IEEE types

- **Loads**
  - Constant impedance (CI)
  - Constant current (CC)
  - Constant power (CP)
  - Dynamic (induction motor type)

- **FACTS devices**
  - Series (CSC, CPS, SSSC)
  - Shunt (SVC, STATCOM)
  - Series-shunt (UPFC)
FACTS device model: CSC

\[
\overline{S}_k = \overline{V}_k \left( - I_s \right)^* \\
\overline{S}_m = \overline{V}_m \left( I_s \right)^* \\
k_{csc} = \frac{X_c}{X}
\]
System characteristics

- Base case operation
  - 500 MW between NETS-NYPS
  - SVC (117 MVAR), CSC (50%) and CPS(10) degree
  - Constant impedance load
  - MW flows in lines as feedback signals

<table>
<thead>
<tr>
<th>Inter-area Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ratio</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Freq. (Hz)</td>
<td>0.39</td>
<td>0.51</td>
<td>0.62</td>
<td>0.79</td>
</tr>
</tbody>
</table>
H-infinity design

• Why H-infinity?
  – Prior knowledge about possible range of operating conditions is not essential
  – Guarantees stability over a wider range of operating conditions at design stage
  – Constraints on control effort can be imposed
  – A numerical estimate of the degree of robustness is obtained

• Why LMI approach?
  – Additional performance specifications e.g. a minimum damping ratio for the CL modes can be guaranteed
$H_\infty$ mixed-sensitivity approach: formulation

Objective

\[ \min \left\| \frac{W_1 S}{W_2 KS} \right\|_\infty \leq \gamma \]

\[ \frac{z}{d} = W_1 S = W_1 (I - GK)^{-1} \]

\[ \frac{z}{u} = W_2 KS = W_2 K (I - GK)^{-1} \]
**H\(_\infty\) mixed-sensitivity: solution**

- **Analytical**
  - Solution point
  - Weights selection challenging

- **Numerical (LMI)**
  - Solution space
  - Tractable
  - Frequency and time domain objective

![Diagram of S-plane with Iner Angle \(\theta\) and -infinity, indicating all poles should be placed within the conic sector.]
Conic sector for pole-placement

• Inner angle is chosen as
  \[ \theta = 2 \cos^{-1}(\zeta_{\text{min}}) \]

All the closed-loop poles must be placed within the conic sector.

This can be imposed as an LMI constraint.
Model simplification and frequency response

Full plant: 137\(^{th}\) order

Model reduction: Balanced/Schur/residualization/Hankel

Reduced plant 13\(^{th}\) order
Damping control performance

- Controller for CSC only
- Controller for CSC and SVC
- Controller for CSC, SVC and CPS
Damping robustness under varying operating scenarios

![Graph 1: Power flow from NETS to NYPS (MW)]

- **Mode 1**
- **Mode 2**
- **Mode 3**

![Graph 2: Outage of line](image)

- **60-61**
- **53-54**
- **27-53**

![Graph 3: Type of load](image)

- **CI**
- **CC**
- **CP**
- **Dynamic**

![Graph 4: Damping ratio](image)
Performance validation: non-linear simulation

![Graphs showing angle variations over time for different simulations](image-url)
Performance validation: non-linear simulation

- Line flow from 60 to 61 in MW
- Percentage compensation of CSC
- Susceptance of SVC (MVAR)
- Phase shifter angle (deg)
Centralized approach
Performance validation: non-linear simulation
Performance validation: non-linear simulation
Issues in mixed-sensitivity design

• Decentralized
  – Single input and single output (SISO)
  – Local control, more reliable
  – More devices: control efforts are shared
  – Controllers are of large order

• Centralized
  – Multivariable remote feedback, reduced reliability
  – Single FACTS device
  – Needs signal transmission: Wide Area Measurement Systems (WAMS)
  – Delay in signal transmission is an important issue
  – Weight selection is difficult as shaping the closed loop over entire frequency range is attempted: Open Loop shaping is a better alternative
Loop shaping

• Current work incorporated a centralised loop shaping control design for a CSC device

• The technique is based upon normalised co-prime factorisation (MacFarlane & Glover), extended within the LMI frame-work (Apkarian)

• Aim is to find a controller which achieves closed loop specifications by appropriately shaping the singular values of the open loop
Loop-shaping control

a) Shaped plant

\[ W_1 \xrightarrow{G} W_2 \]

b) Compensated plant

\[ W_1 \xrightarrow{G} W_2 \]

\[ K \]

\[ G_s \]

c) Equivalent controller

\[ W_1 \xrightarrow{K} W_2 \]

\[ K_{eq} \]

\[ \frac{\min_{K \in \Phi} \left\| \frac{I}{K} \right\|_{\infty} \left( I - GK \right)^{-1} M^{-1} }{K} = \left\| \begin{bmatrix} S & SG \\ KS & KSG \end{bmatrix} \right\|_{\infty} \]
Damping robustness validation in frequency domain
Performance validation in time domain
H-infinity control design considering feedback signal transmission delay
Motivation

• WAMS technology along with fast data communication hardware is still not in use everywhere in a large commercial scale

• Utilities with dedicated fibre optics network will not have this problem

• With existing third party communication channels delays as high as 0.5-0.75 s can be encountered in the worst case

• The effect is a RHP zeros: control is not easy

• Substantial delays, if any, needs to be considered in the control design stage
Significance of the problem
Formulation: Predictor approach

\[ P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \]

\[ T_{zd}(s) = P_{11} + P_{12}Ke^{-sh}(I - P_{22}Ke^{-sh})^{-1}P_{21} \]

At time \( t = 0 \sim h \) after \( d \) is applied the performance index is likely to be dominated by a response which cannot be controlled.
Smith predictor approach

- A Smith predictor block $Z$ is introduced in path 2
- A delay block is introduced in path 1 during the generalized regulator formulation
- Uniform delay in both the paths
Smith predictor approach (contd)

- Controller is designed based on the generalized plant which includes the Smith predictor $Z(s)$
- Equivalent controller is the feedback combination of the designed controller $K(s)$ and the Smith predictor $Z(s)$
Test system model
Performance validation

Fault at bus 60 with autoreclosing

Fault at bus 53 with line 53–54 out

Fault at bus 53 with line 27–53 out

Fault at bus 60 with line 60–61 out
Effect of variable delays on the control performance

Signal transmission delay: 0.65s

Signal transmission delay: 0.75s

Signal transmission delay: 0.90s

Signal transmission delay: 1.0s
Real time implementation and test results
Motivation

- Damping controller obtained from norm minimization based design is quite complex in structure.
- Controller designed considering signal transmission delay becomes more complex in conjunction with predictor block.
- Non availability of the actual system for validating the performance of the controllers in real time.
- Development of a real time dynamic emulator of inter-connected power system.
Features of real time emulator

• It can emulate the dynamic process of any plant as long as the mathematical representation of the plant is given and as long as the workload stays within the computational limit of the emulator.

• Its input and output signals can directly interface with the controller under test or any external hardware for hardware-in-loop application.

• The emulator is made of commercially available processor and electronic components, which makes it cost effective and affordable.
RT LAB real time station

- PC running on real time operating system Red-Hawk RT-Linux
- Dual-Xeon processor of 3.2 GHz
- Processors shares a common memory
Study system model

K controller to be designed

remote signal links
A three phase to ground fault is created at 1 s at bus #27 and the fault is cleared after 80 ms followed by opening of one of the tie line connecting bus #27 and #53.
Hardware-in-loop configuration

Dual Xeon 3.2 GHz processor
real time station (RTS)

Pentium 4 3.2GHz Processor
rapid prototyping controller (RPC)

Power system
16 machine 68 bus inter-connected system

Robust FACTS controller

Control input

Hardware coupling between two platforms

Measured signals
deviation of active power flows

ADC
DAC
DAC
DAC
DAC
ADC
ADC
ADC
ADC

TCSC

16 machine 68 bus inter-connected system

DAC
DAC
DAC
DAC

TCSC

Pentium 4 3.2GHz Processor
rapid prototyping controller (RPC)
Other low order control design methodologies
Multiple model adaptive control (MMAC)
Robust pole placement: Simultaneous stabilization

\[ P_x = \delta_{cl} \]

\[ F(x) = \sum_{i=1}^{n+m} c_i \frac{\|\mu_i - \lambda_i(x)\|}{\|\mu_i\|} \]

\[ \min \max_{x \in j} F_j(x) \]
Suggested reading
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