Coordinated Wide-Area Polytopic Control Design using Linear Matrix Inequality

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PSERC Webinar
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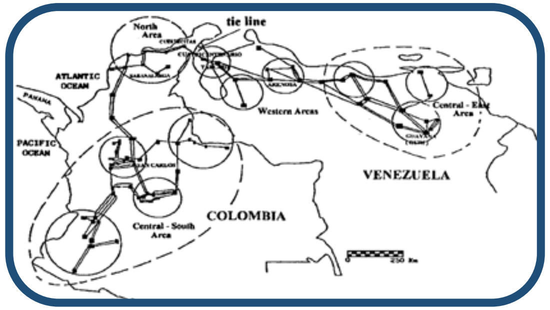
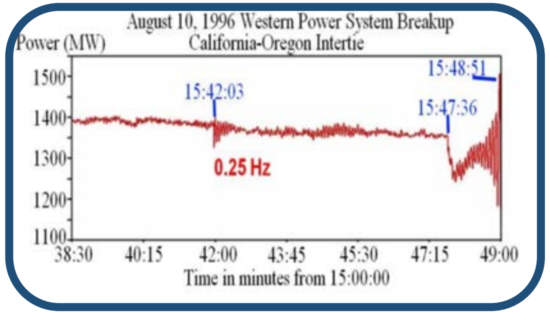
Related Publications

- P. Gupta, **A. Pal**, C. Mishra, and T. Wang, “Design of a coordinated wide area damping controller by employing partial state feedback,” in *Proc. IEEE Power Eng. Soc. General Meeting*, Atlanta, GA, pp. 1-5, 4-8 Aug. 2019.
- T. Wang, **A. Pal**, J. S. Thorp, and Y. Yang, “Use of polytopic convexity in developing an adaptive inter-area oscillation damping scheme,” *IEEE Trans. Power Syst.*, vol. 32, no. 4, pp. 2509-2520, Jul. 2017.
- T. Wang, **A. Pal**, J. S. Thorp, Z. Wang, J. Liu, and Y. Yang, “Multi-polytope based adaptive robust damping control in power systems using CART,” *IEEE Trans. Power Syst.*, vol. 30, no. 4, pp. 2063-2072, Jul. 2015.
- **A. Pal**, J. S. Thorp, S. S. Veda, and V. A. Centeno, “Applying a robust control technique to damp low frequency oscillations in the WECC,” *Int. J. Elect. Power Energy Syst.*, vol. 44, no. 1, pp. 638-645, Jan. 2013.
- **A. Pal**, and J. S. Thorp, “Co-ordinated control of inter-area oscillations using SMA and LMI,” in *Proc. IEEE Power Eng. Soc. Conf. Innovative Smart Grid Technol.*, Washington D.C., pp. 1-6, 16-20 Jan. 2012.

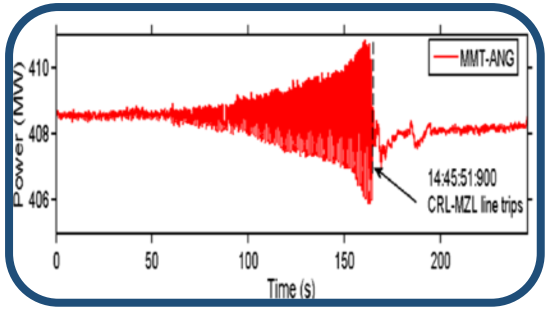
Introduction–Low Frequency Oscillations



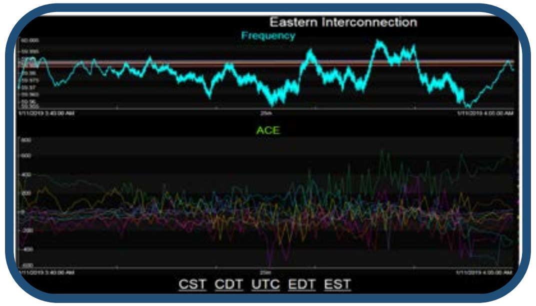
1993[1]
Colombia-Venezuela Interconnection



1996[2]
Western Electricity Coordinating Council (WECC)



2008[3]
Mexican Interconnected System



2019[4]
Eastern Interconnection

New ***Challenges*** *in a Modern Grid*

- Increased penetration of renewables
- Decommissioning of large thermal units

Overview of Damping Controllers

Power System Stabilizers (PSSs) **[5]-[6]**

- Traditional control for damping local modes
- Require careful tuning for damping inter-area modes

Flexible Alternating Current Transmission System (FACTS) **[7]-[8]**

- Primarily for voltage support
- **Supplementary Damping Control (SDC)** added

High-Voltage DC systems, Energy Storage Systems **[9]-[11]**

- **SDC** added for damping inter-area modes
- Controlled modulation of power flows

- **Coordinated** control implemented **[12]-[14]**
- **Wide-area signals** employed **[15]-[19]**

Methods

- Larsen & Swan
- Optimization techniques such as particle swarm optimization, genetic algorithms
- Linear Matrix Inequality (LMI) based control

Motivation and Objectives

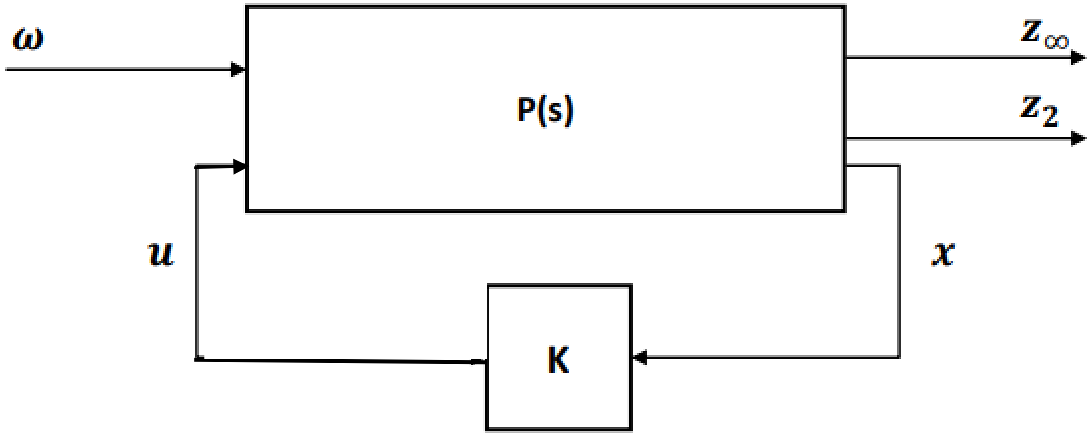
- Most control designs:
  - Focused on only one type of controller and/or were operating point specific
  - Required changing the configurations of existing controls
  - Had higher-order complexity

Objectives

- To coordinate individual controllers such as HVDC based SDCs, Static VAr Compensators (SVCs), and PSSs
- To design a coordinated wide-area damping controller (CWADC) using LMI-based polytope having mixed H_∞/H_2 control
- To develop a methodology for the selection of suitable stabilizing signals for the CWADC
- To provide flexibility in selection of feedback signals

Mathematical Background-State Space Model

State-space model with H_∞/H_2 formulation*



$$T_\infty = (C_1 + D_{12}K)(sI - A - B_2K)^{-1}B_1 + D_{11}$$
$$T_2 = (C_2 + D_{22}K)(sI - A - B_2K)^{-1}B_1$$

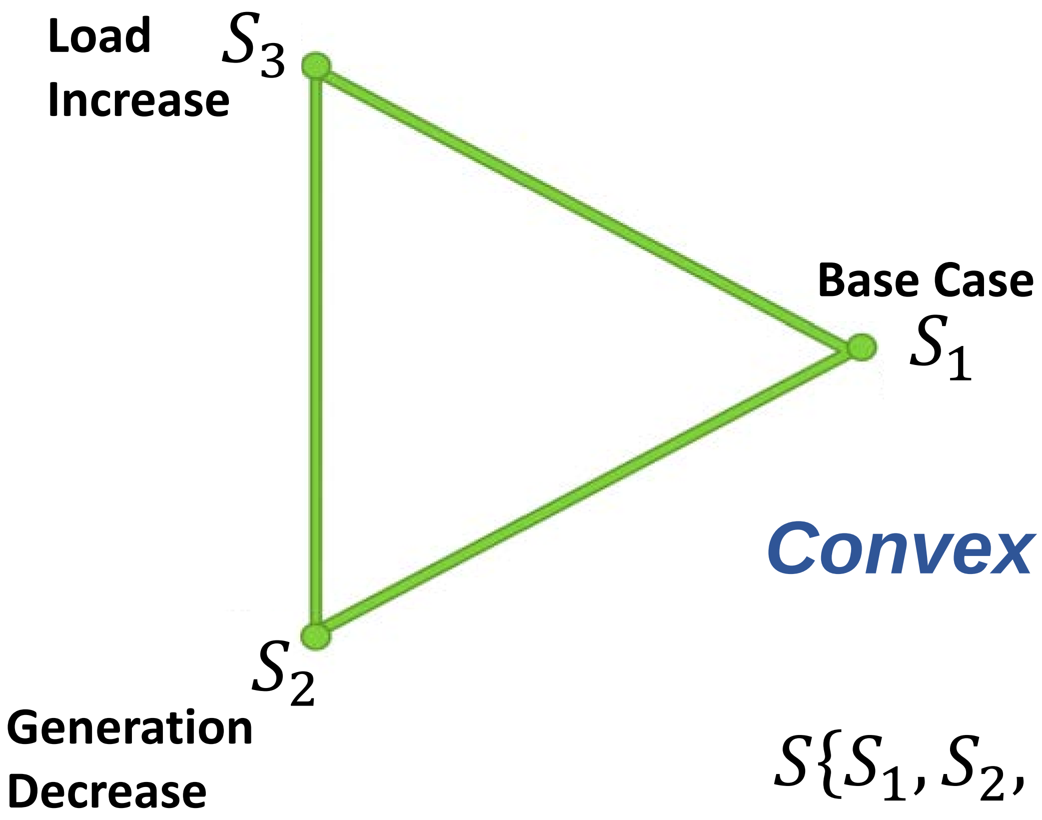
$$\dot{x} = Ax + B_1\omega + B_2u$$
$$z_\infty = C_1x + D_{11}\omega + D_{12}u$$
$$z_2 = C_2x + D_{22}u$$
$$y = C_yx + D_{y1}\omega + D_{y2}u$$

where:
x is the system state
u is the control
ω is a disturbance
z_∞ and z_2 are for H_∞/H_2 optimization
y is the system output

* The H_∞ analysis is used to evaluate how robust a system is when exposed to dynamic uncertainty. The H_2 design parameters are tailored more towards measuring the control effort and providing disturbance rejection.

Polytope Formation-Extension to Multiple Operating Points

Three vertex polytope



Vertex of each polytope, S_i

$$S_i = \begin{bmatrix} A_i & B_{i1} & B_{i2} \\ C_1 & D_{i11} & D_{i12} \\ C_{i2} & 0 & D_{i22} \\ C_{iy} & D_{iy1} & D_{iy2} \end{bmatrix}$$

Convex combination of the systems:

$$S\{S_1, S_2, \dots S_n\} = \left\{ \sum_{i=1}^{n} \alpha_i S_i : \sum_i \alpha_i = 1, \alpha_i \geq 0 \right\}$$

Theoretical Background-Linear Matrix Inequality

- An LMI is any constraint of the form $A(p) := A_0 + p_1 A_1 + p_2 A_2 + \ldots + p_n A_n < 0$ where $p_1, p_2, \ldots, p_n$ are unknown vectors comprising of optimization variables; $A_0, A_1, \ldots, A_n$ are known symmetric matrices; < 0 implies "negative definite"

Primary Advantage	Primary Disadvantage
• Any solution to a problem obtained using LMIs is a global optimum	• Inherent computational complexity of the optimization

LMI for the State Space Model

$$\begin{bmatrix} A_i X + X A_i^T + B_{i2} Y + Y^T B_{i2}^T & B_{i1} & X C_{i1}^T + Y^T D_{i12}^T \\ B_{i1}^T & -I & D_{i11}^T \\ C_{i1} X + D_{i12} Y & D_{i11} & -\gamma^2 I \end{bmatrix} < 0$$

$$\begin{bmatrix} Q & C_{i2} X + D_{i22} Y \\ X C_{i2}^T + Y^T D_{i22}^T & X \end{bmatrix} > 0$$

$$(V \otimes W) + \big(W \otimes (A_i X + B_{i2} Y)\big) + W^T \otimes (A_i X + B_{i2} Y)^T < 0$$

where X is the Lyapunov matrix, Q is a positive definite matrix, and $\otimes$ is the Kronecker product*

* http://en.wikipedia.org/wiki/Kronecker_product

Model Reduction Technique

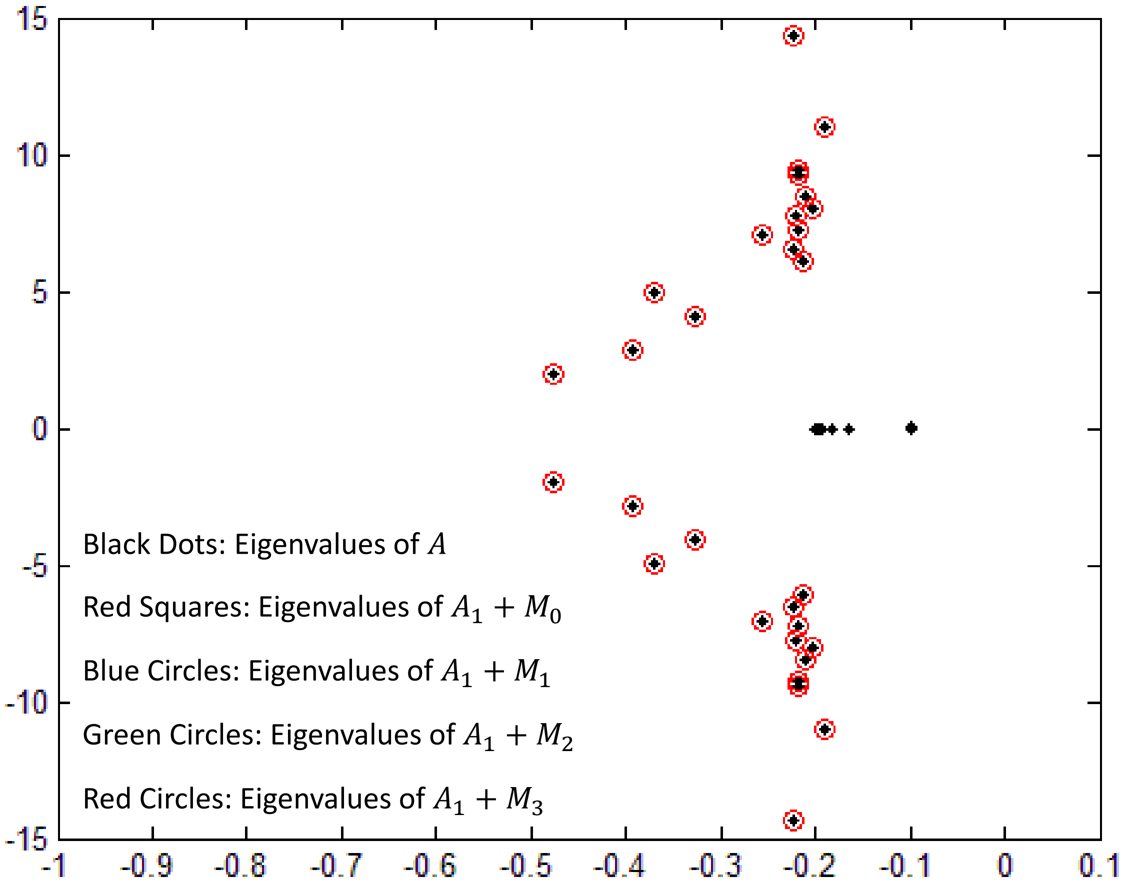
Selective Modal Analysis

- An iterative process that simplifies the dynamic model to the oscillatory modes of interest

A1 A2

$$^{*}A = \left[\begin{array}{cc|cc} 0 & \omega_0 I & 0 & 0 \\ A_{21} & A_{22} & A_{23} & A_{24} \\ \hline A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{array}\right]$$

A3 A4



* A is the state matrix of the original system, while $A_1 + M_i$ is the state matrix of the reduced system, where M_0 is the null matrix

Model Reduction Technique

Selective Modal Analysis

Comparison of LMI optimization without and with SMA approach on the 4 machine – 2 area system

	LMI Control	LMI Control + Traditional SMA
System Size (A/A_1)	19×19	6×6
Size of individual LTI system	24×22	11×9
Size of Polytopic System	24×116	11×51
Size of Closed Loop System	24×111	11×46
CPU Time* (seconds)**	29.286383	1.209831

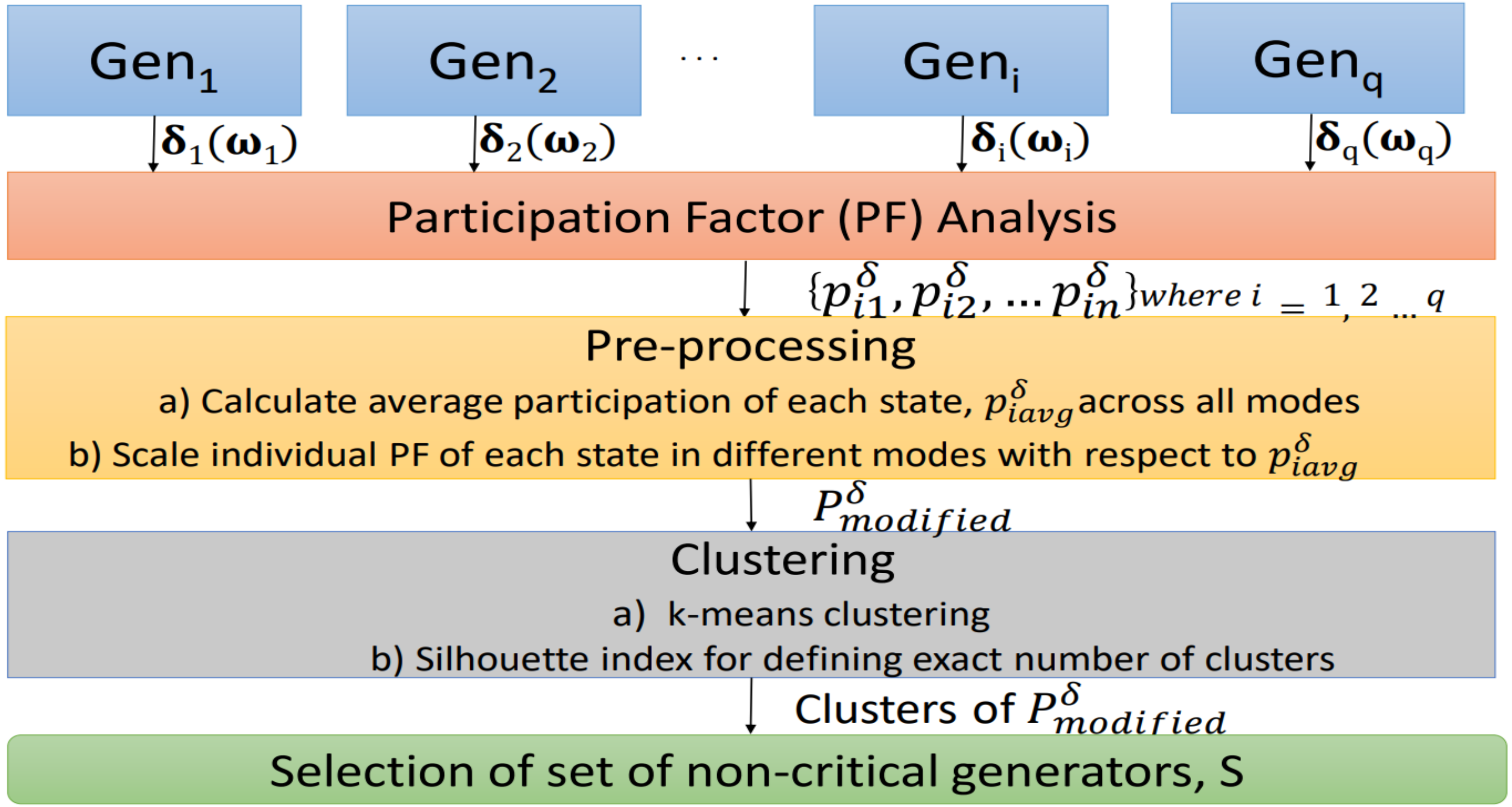
*** The computations were performed on an Intel (R) Core ™ i5 Processor having a speed of 2.40 GHz and an installed memory (RAM) of 5.86 GB

Control Effort Minimization-Partial State Feedback

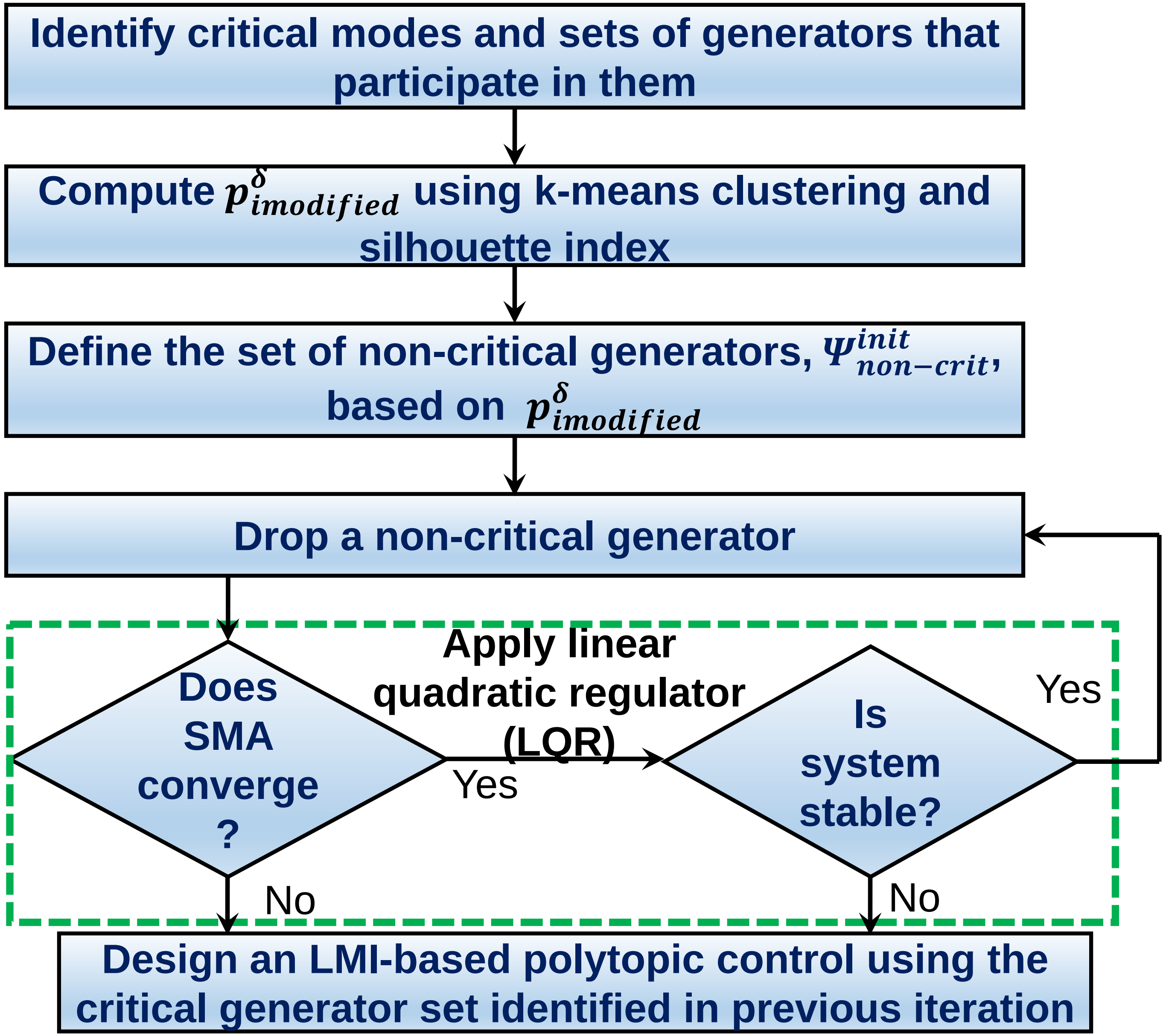
- **Focus**-To control generator states which are influencing a greater number of modes by having higher participation in them

Identify ***minimum*** number of states that must be controlled for improving stability of the system

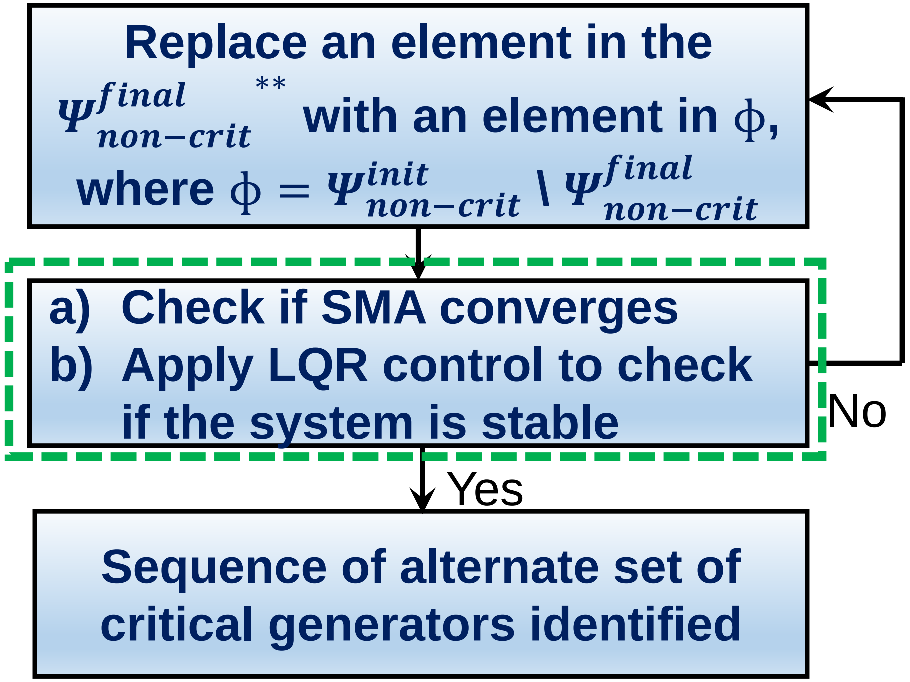
Enhanced SMA-Proposed methodology for generator selection [20]



Proposed Control using Partial State Feedback



Alternate Feedback Control Scheme

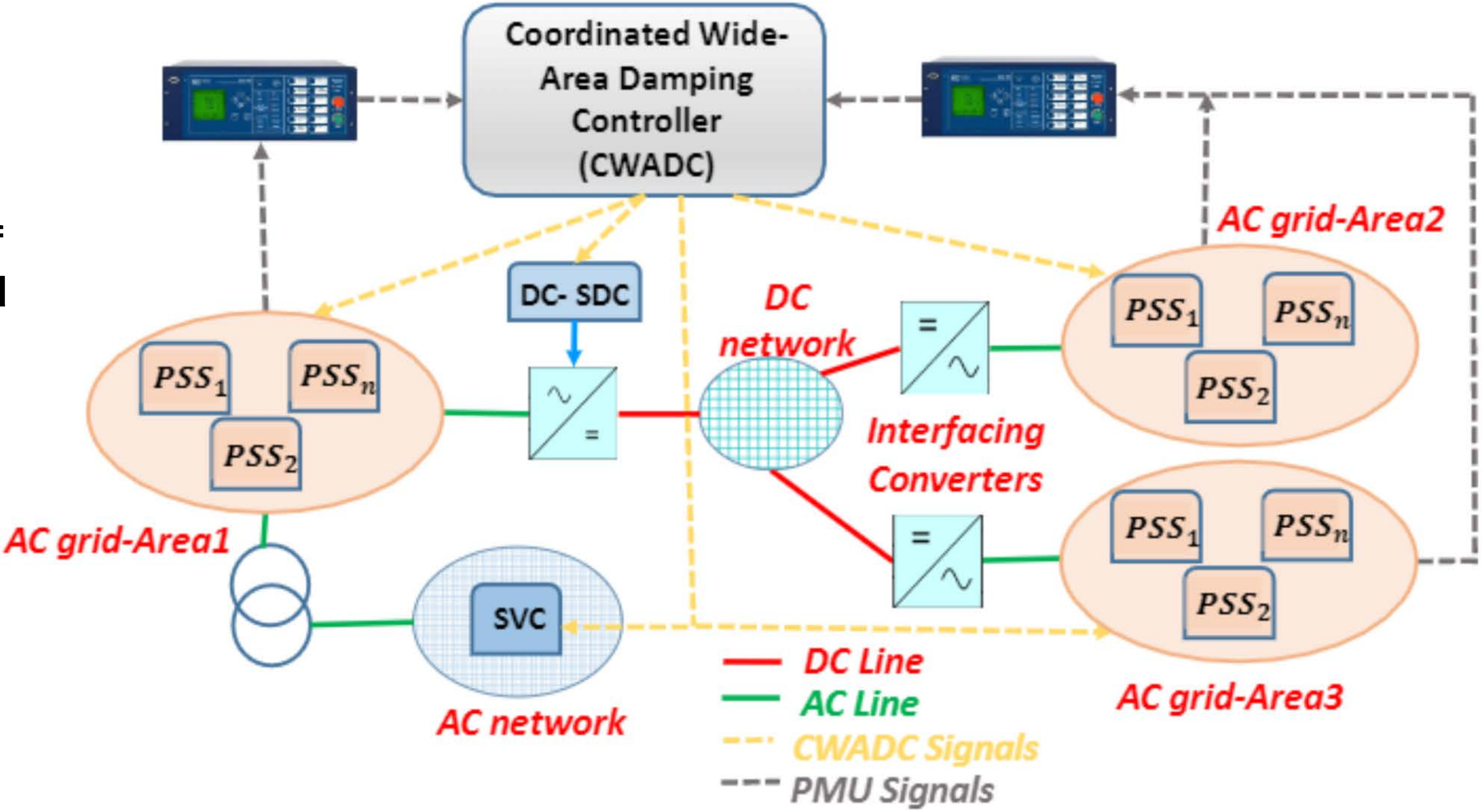


** $\Psi^{final}_{non-crit}$ is the first set of non-critical generators dropped from control

Controller Synthesis

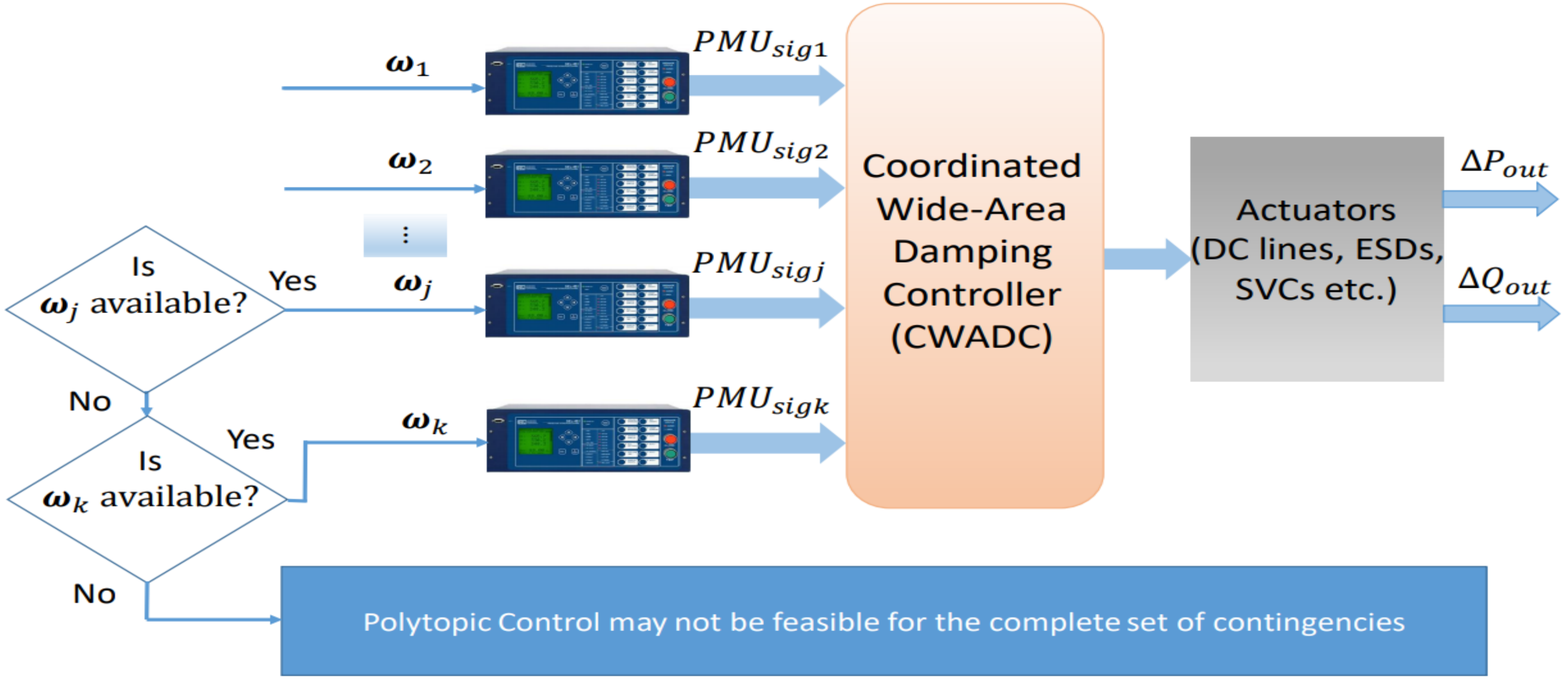
- **Bi-level** controller design

Schematic of the proposed Coordinated Wide-Area Damping Controller (CWADC)



Flexibility of Feedback Selection

- Taking PMU measurements from alternate locations in case the primary locations encounter a problem [20]

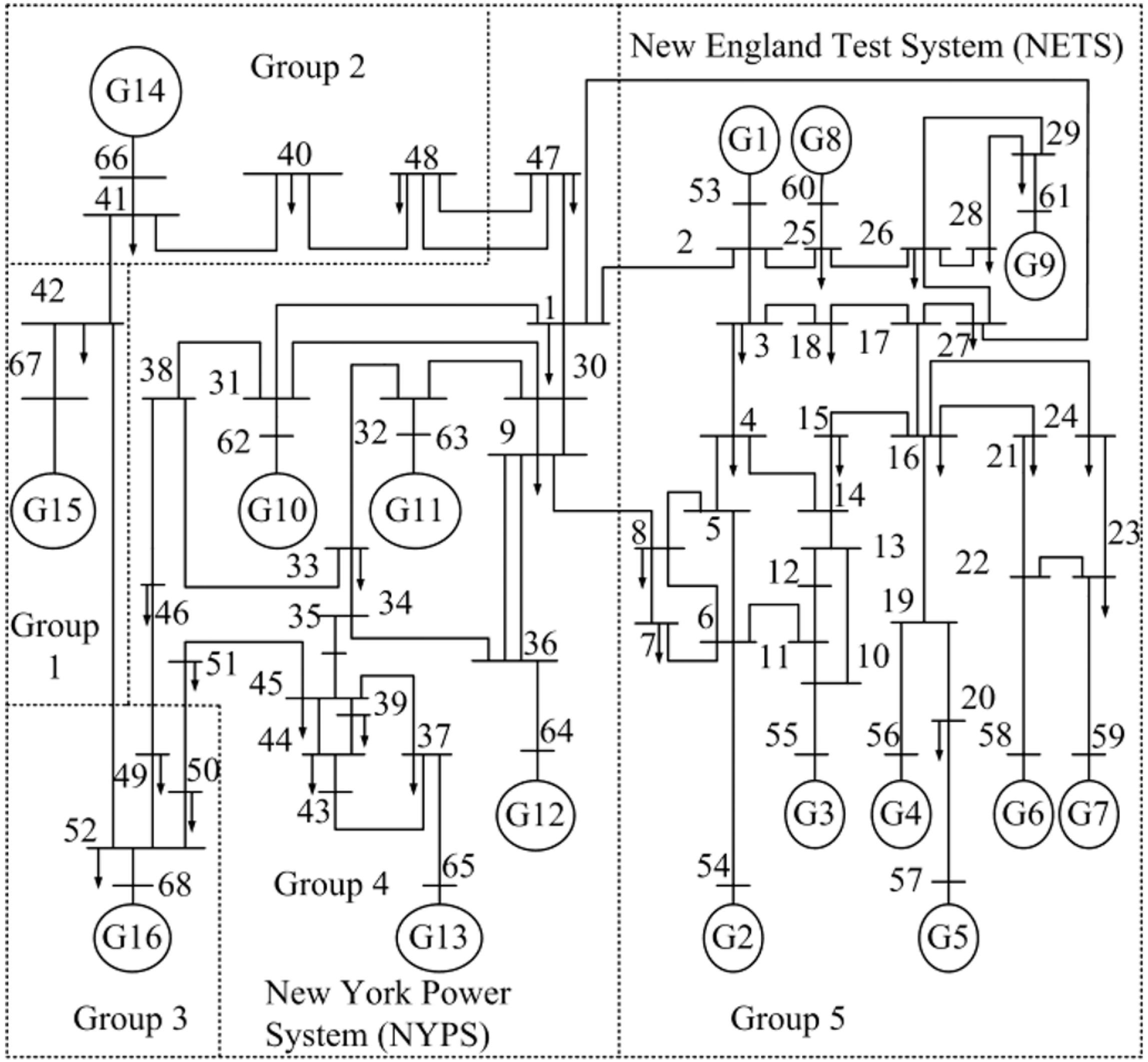


Coordinated controller can ***switch*** between the primary and alternate control sets in case the data quality of the primary set deteriorates

Small Test System

16 machine, 68-bus system

- **System Details:**
  - Represents the reduced-order equivalent model of five separate areas
  - Two types of actuators, namely, DC lines and SVCs employed for implementing the control
  - The DC lines are modeled as active power and reactive power injections
  - SVC is modeled as a reactive power injection
- **Type of Analysis Performed:** ***Modal analysis*** for testing the performance of CWADC



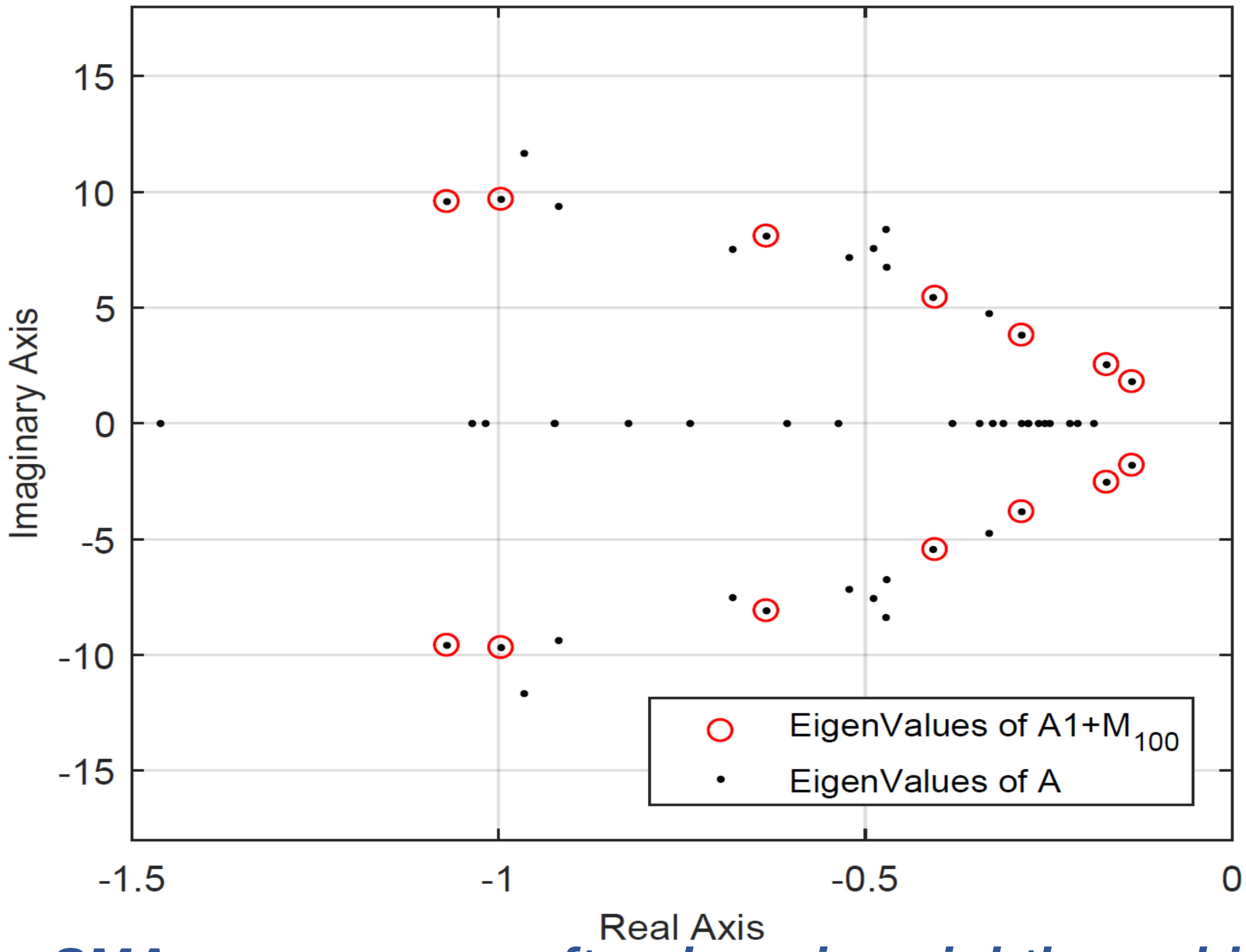
Results-16 Machine, 68-Bus System

Test Cases

Number	Contingency Details
1	Base Case
2	Flow in line 50-52 is increased from 700 to 900
3	Flow in line 50-52 is decreased from 700 to 455
4	Outage of Tie-line 1-2
5	10% increase in inertia of Machine at Bus 66
6	10% decrease in inertia of Machine at Bus 66
7	All loads decreased in the system to 90%
8	All loads increased in the system to 103%

Results-16 Machine, 68-Bus System

Enhanced SMA Results



SMA convergence after dropping eighth machine for Base Case

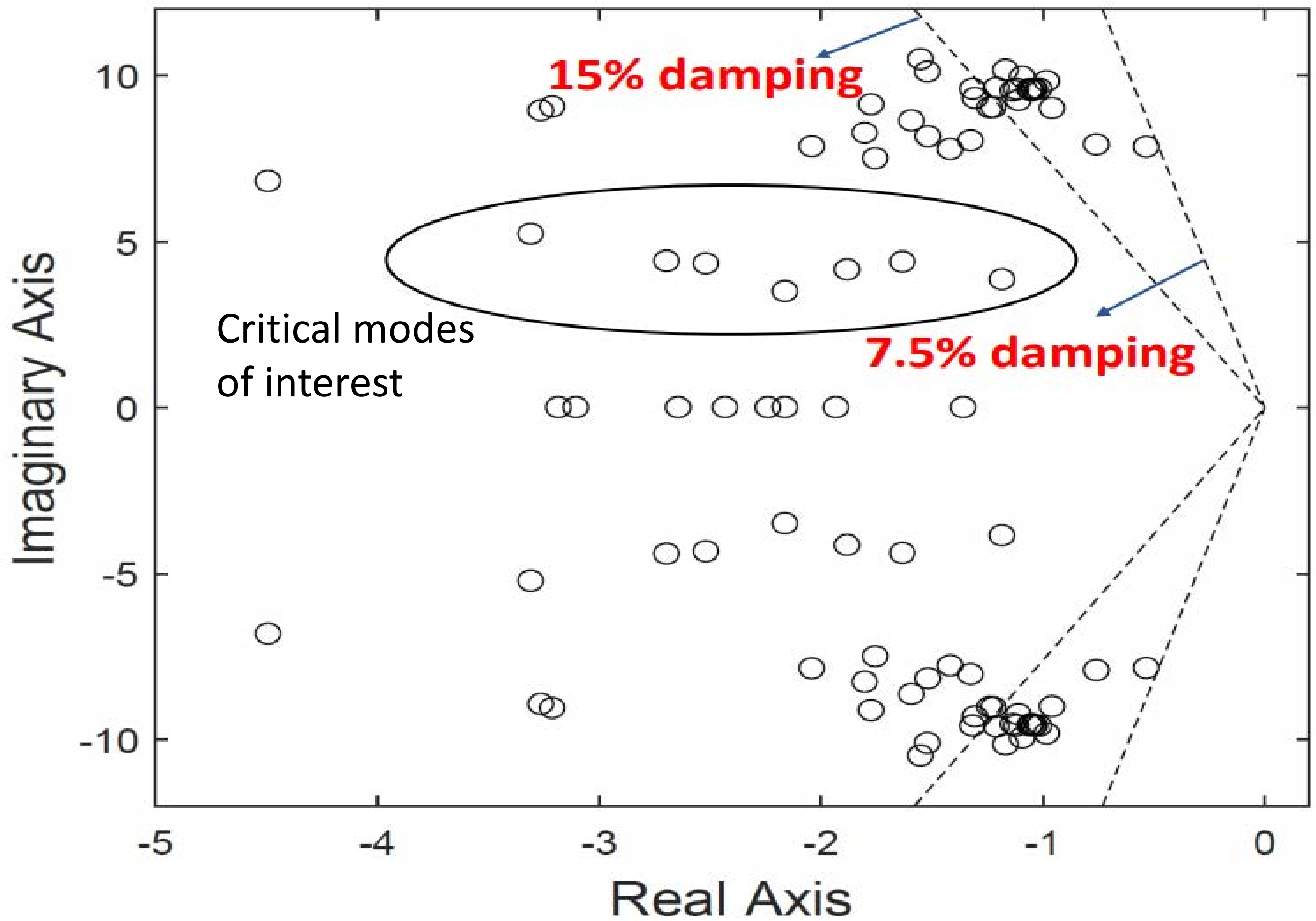
Results-16 Machine, 68-Bus System

Number	Sequence for dropping generators	Reduction in stabilizing signals(%)
1	63, 62, 60, 61, 64, 53, 55, 57	50
2	63, 62, 64, 53, 55, 57	37.5
3	63, 62, 60, 64, 53, 55, 57	43.75
4	63, 62, 64, 53, 60, 55, 57	43.75
5	63, 62, 64, 53, 55, 60, 57	43.75
6	63, 62, 64, 53, 55, 57	37.5
7	63, 62, 64, 53, 55, 57	37.5
8	63, 62, 64, 53, 55, 57	37.5

- The number of machines which can be dropped **varies** with the test cases
- Minimum number of same six machines were chosen to be dropped, **reducing** the state feedback signals by **37.5%**

Results-16 Machine, 68-Bus System

Designed LMI Control

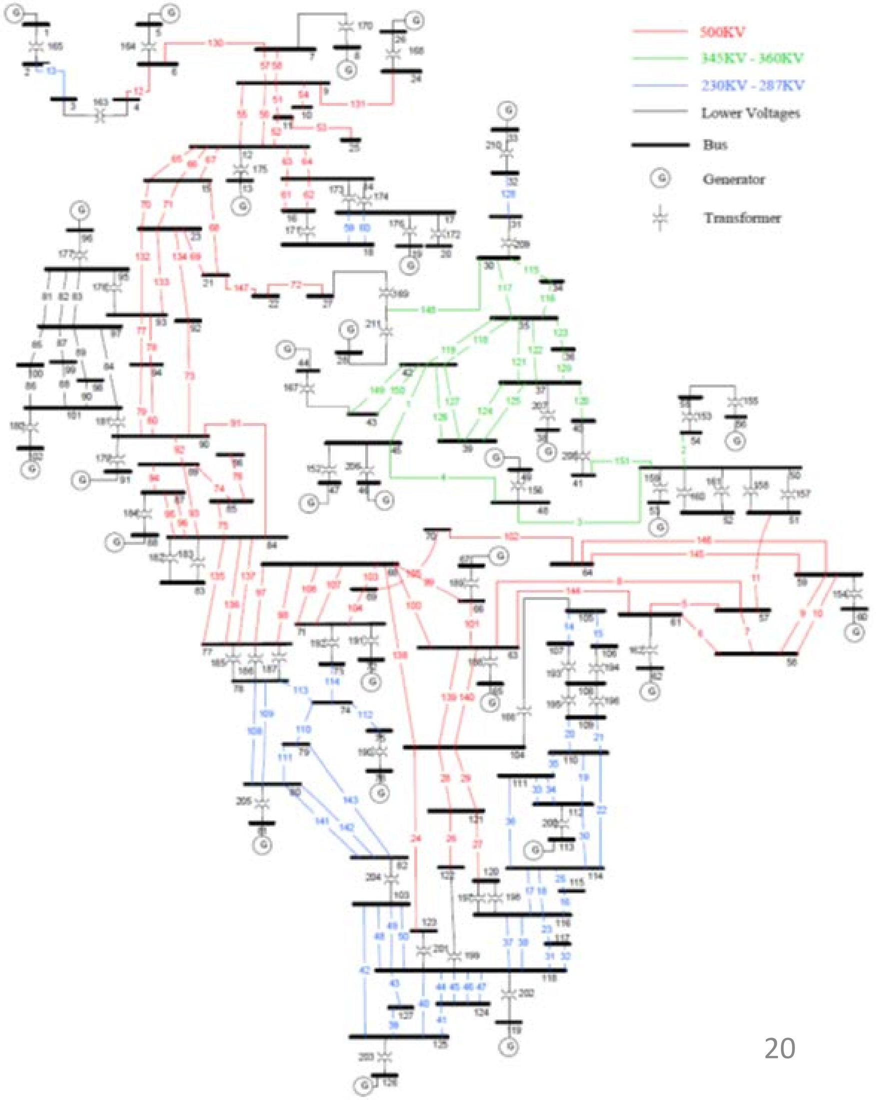


Closed-loop modal analysis

Large Test System

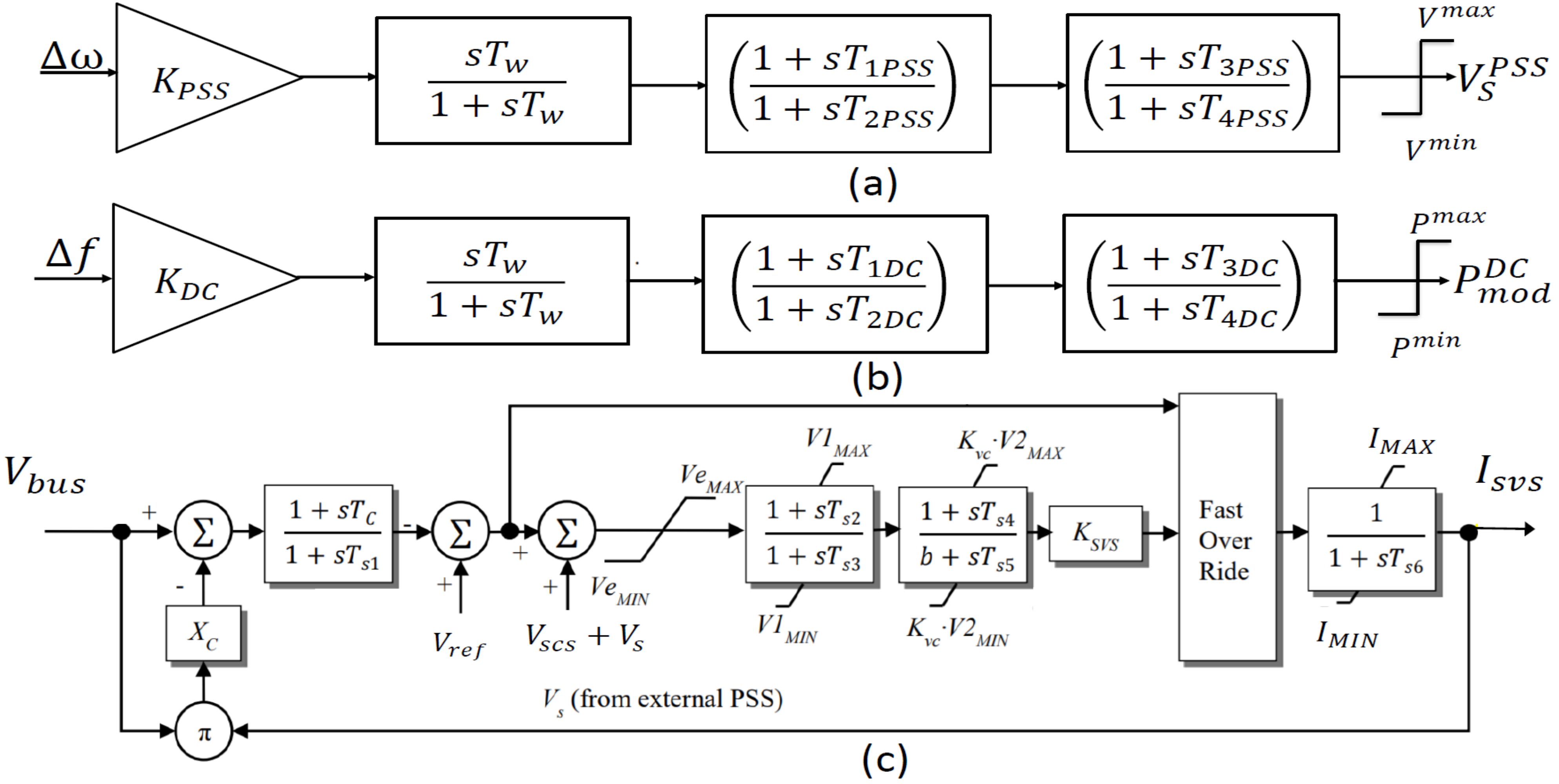
Reduced order WECC Model

- **System Details:**
  - Two-axis model of synchronous machines with type ST1 excitation control, **PSS** models, and turbine-governor models
  - **Two wind farms** represented using Type 3 WTG generator and electric control modules
  - **HVDC lines** representing the multi-terminal Pacific DC Intertie (PDCI) and the two-terminal Intermountain Power Project (IPP); SDC is added to the multi-terminal DC line
  - One **SVC** is also present in the system



Reduced Order WECC System

Different Types of Controllers



(a) PSS (b) DC-SDC (c) SVC

Test Cases-Reduced Order WECC System

Focus: To create change in power transfers in and around WECC Intertie Path #26

	Parameter Variation	
Number	**Generation**	**Load**
1	No Change	No Change
2	#91-Increase by 250 MW	#71-Increase by 250 MW
3	#91-Decrease by 250 MW	#71-Decrease by 500 MW
4	#8881-Increase by 250 MW	#69-Increase by 250 MW
5	#8881-Decrease by 500 MW	#69-Decrease by 500 MW
6	#8881-Increase by 250 MW #91-Increase by 250 MW	#78-Increase by 400 MW
7	#8881-Decrease by 250 MW #91-Decrease by 250 MW	#78-Decrease by 500 MW

Results-Open-loop Eigenvalue Analysis

Case No.	Damping of critical modes(%)		
	Mode 1	Mode 2	Mode 3
v_1	3.71% @1.737Hz	4.03% @0.934Hz	4.14% @1.115Hz
v_2	0.27% @0.397Hz	2.46% @0.768Hz	2.98% @0.923Hz
v_3	3.74% @1.736Hz	4.05% @0.939Hz	4.07% @1.117Hz
v_4	3.63% @1.742Hz	4.04% @0.926Hz	4.08% @1.114Hz
v_5	3.71% @1.737Hz	4.03% @0.934Hz	4.14% @1.115Hz
v_6	-0.36% @0.399Hz	2.39% @0.766Hz	2.97% @1.743Hz
v_7	3.23% @0.430Hz	3.36% @0.787Hz	3.47% @1.206Hz

Open-loop eigenvalues

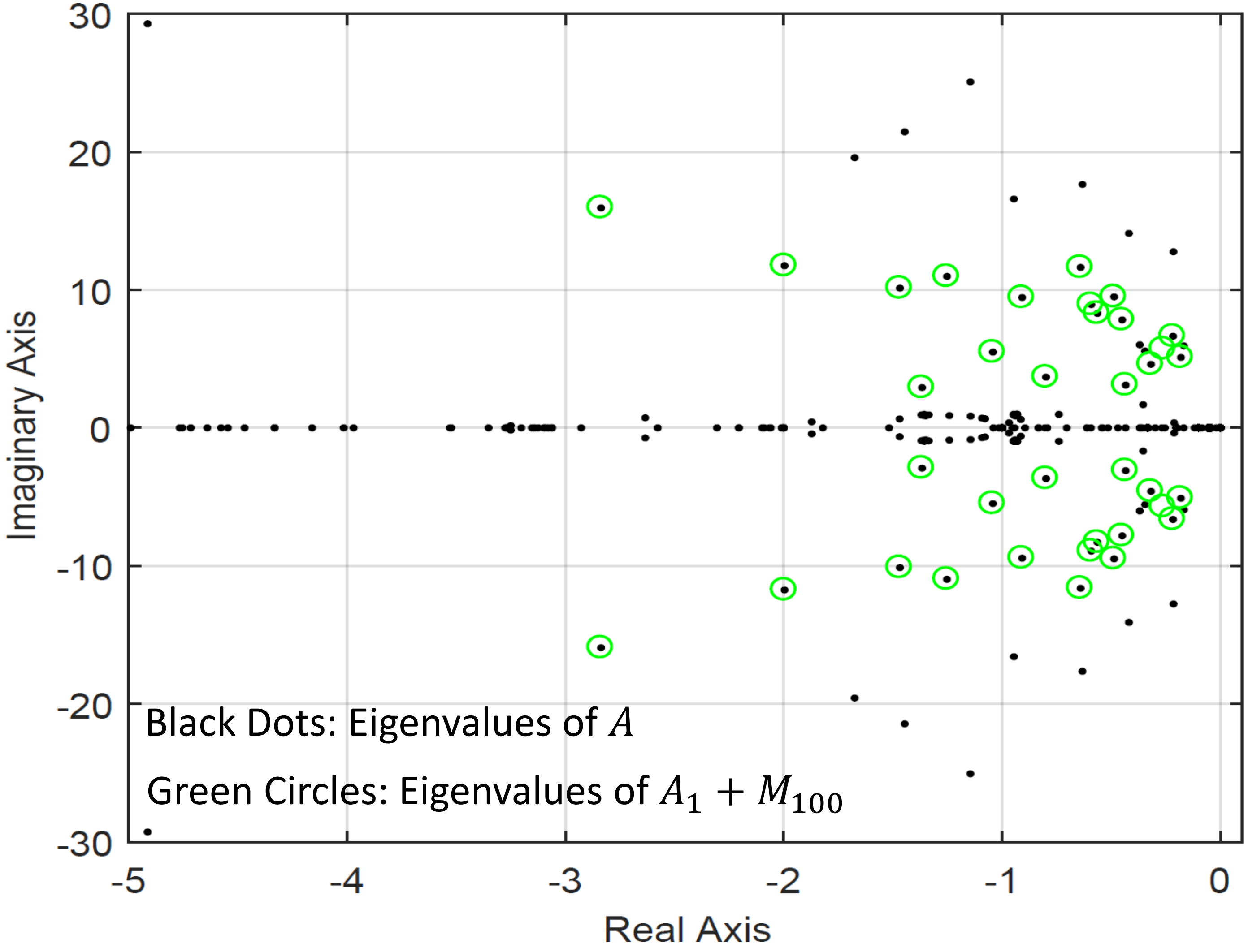
Results-Controller Interactions

Case No.	Critical Mode from Table I	Damping(%)	
		PSS + SVC	DC-SDC + PSS + SVC
v_1	Mode1	3.51	3.71
v_2	Mode1	3.47	0.27
v_3	Mode1	3.54	3.74
v_4	Mode1	3.42	3.63
v_5	Mode1	3.51	3.71
v_6	Mode1	3.46	-0.36
v_7	Mode1	3.49	3.23

Controller Interactions

Results-System Reduction

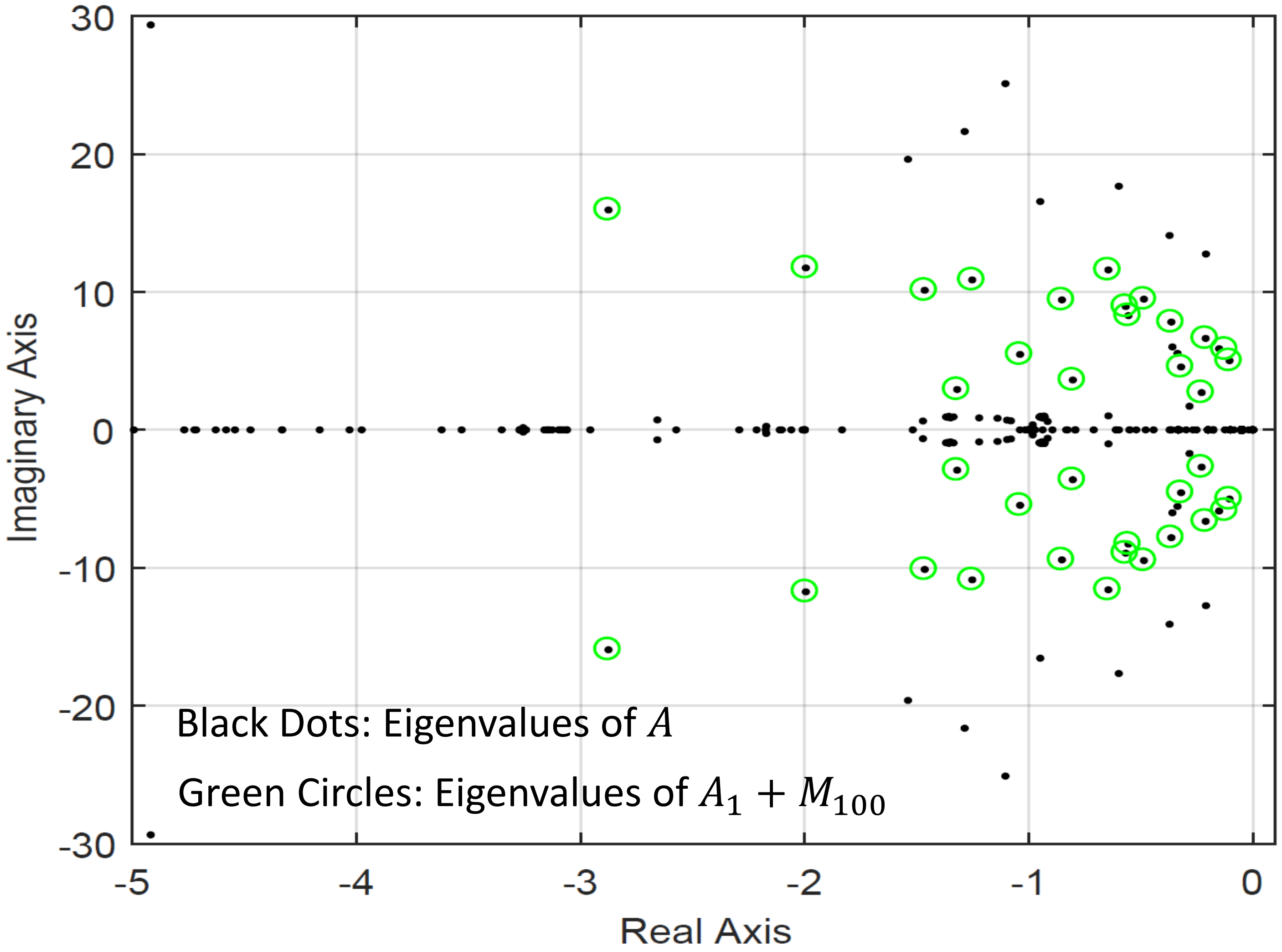
Enhanced SMA Results using Primary Control Set



SMA convergence for Base Case

Results-System Reduction

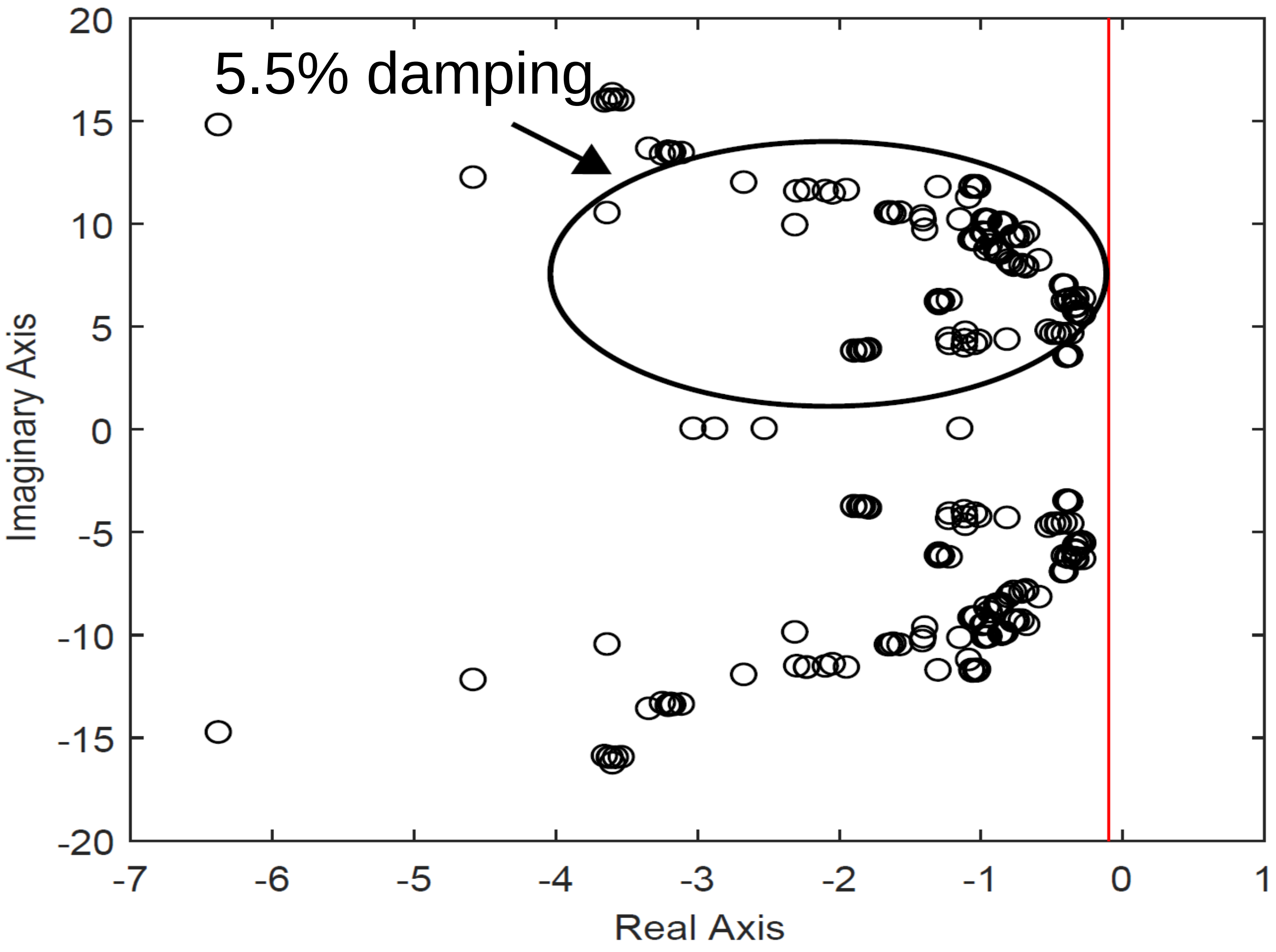
Enhanced SMA Results using Primary Control Set



SMA convergence for Case 2

Results-Modal Analysis

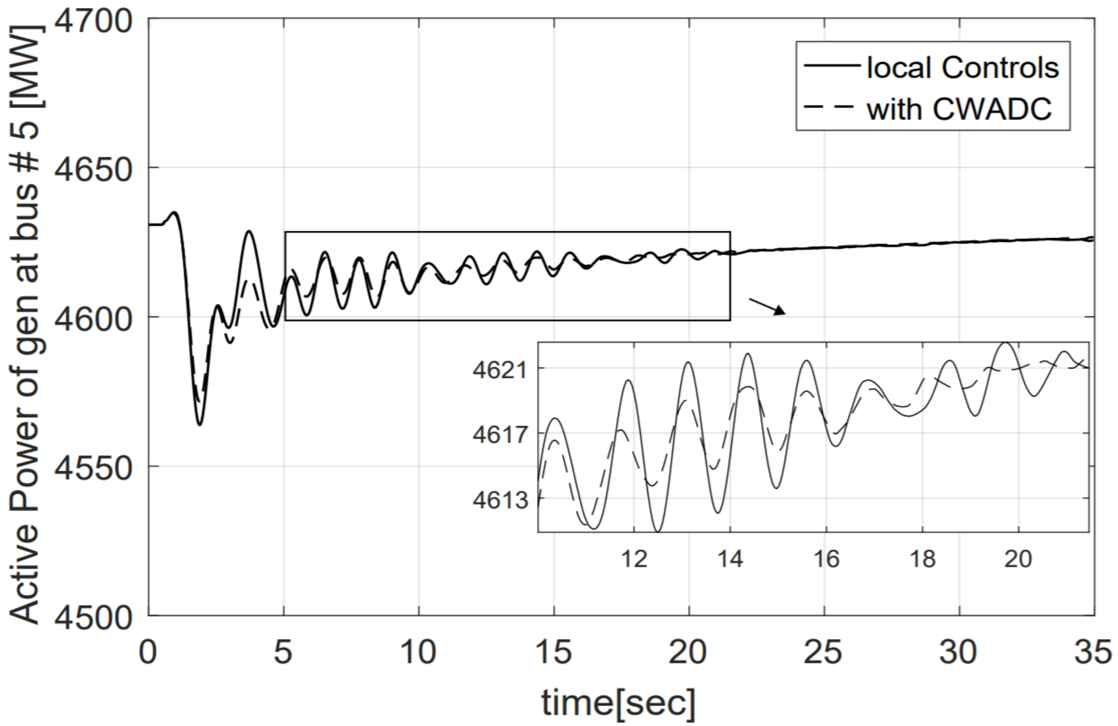
Designed LMI Control using Primary Control Set

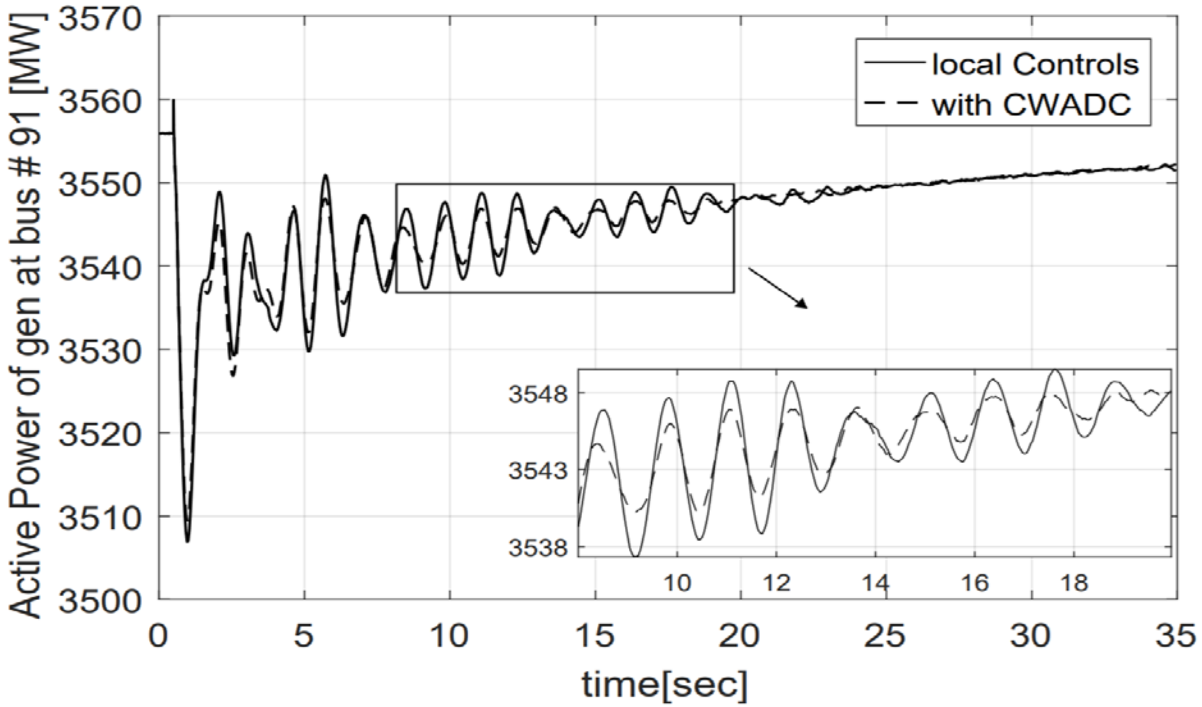


Closed-loop modal analysis

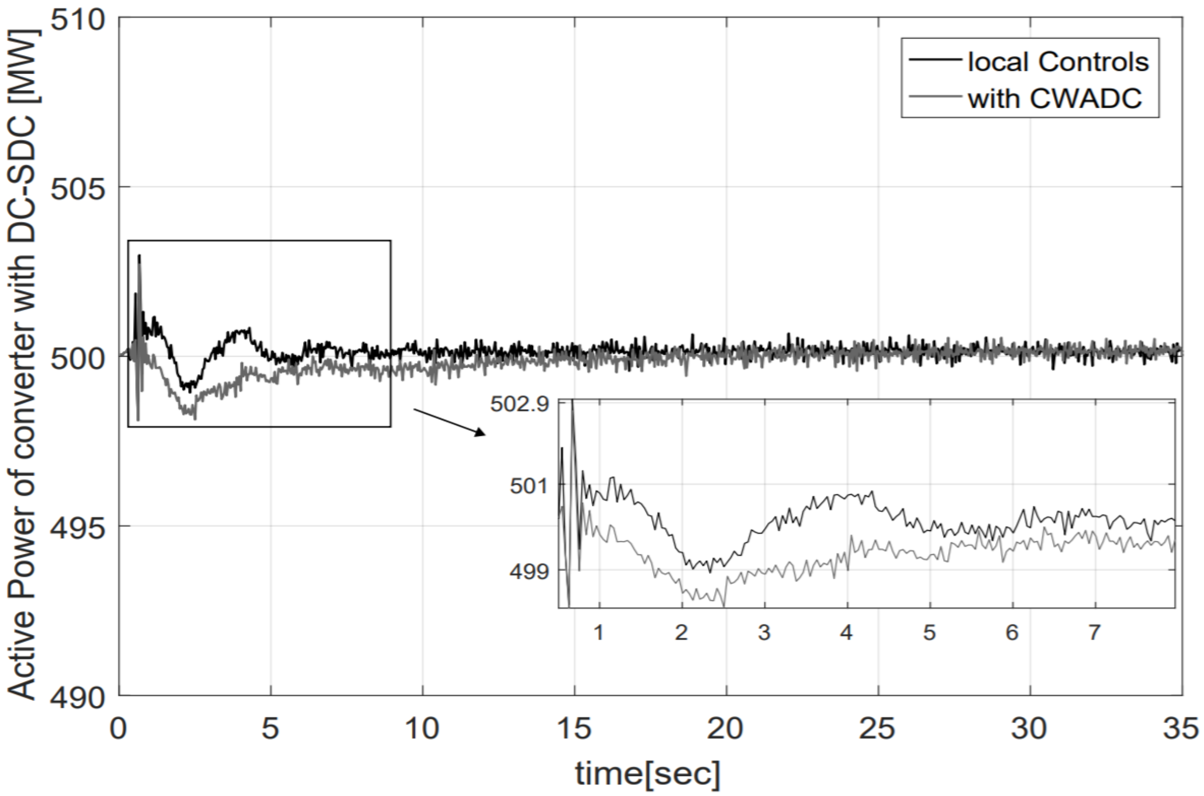
Small Disturbance-Time-Domain Analysis

Disturbance-Simultaneous increase of load at bus #78 by 200 MW and a decrease in load at bus #71 by 400 MW at time, t = 0.5 sec

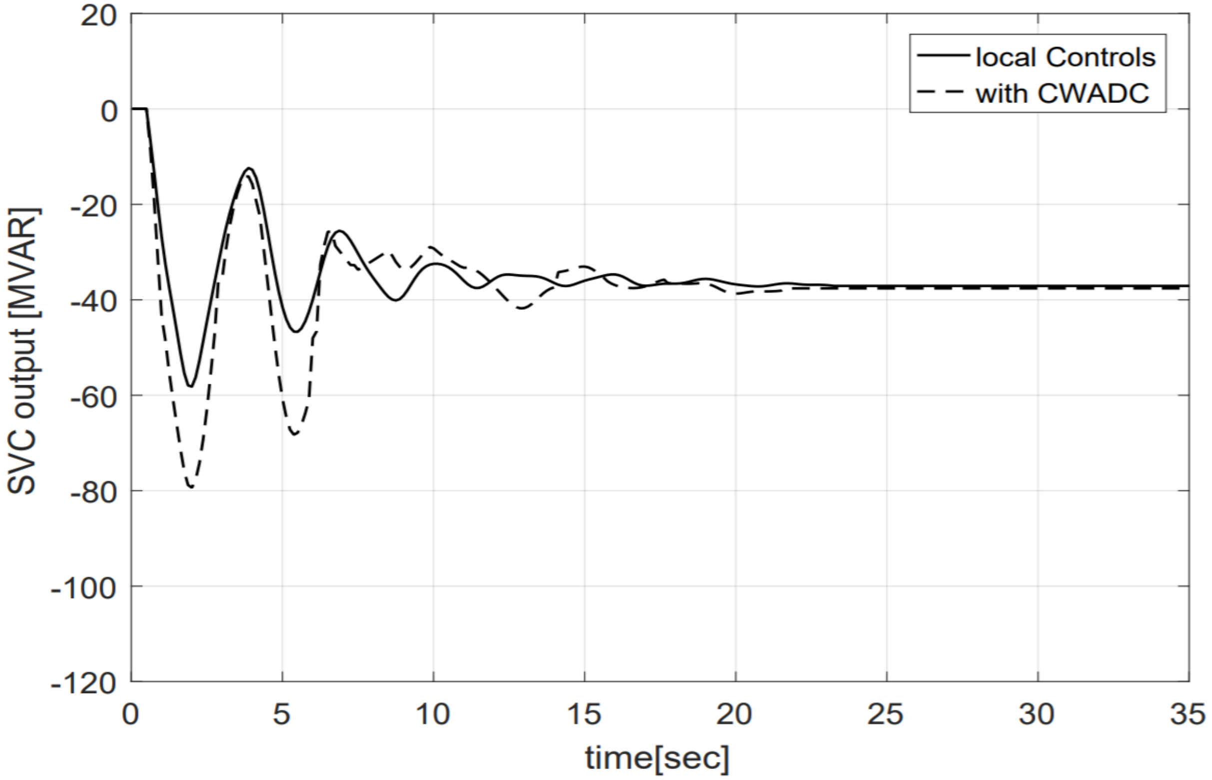




Small Disturbance-Controller Outputs*



DC-SDC Output

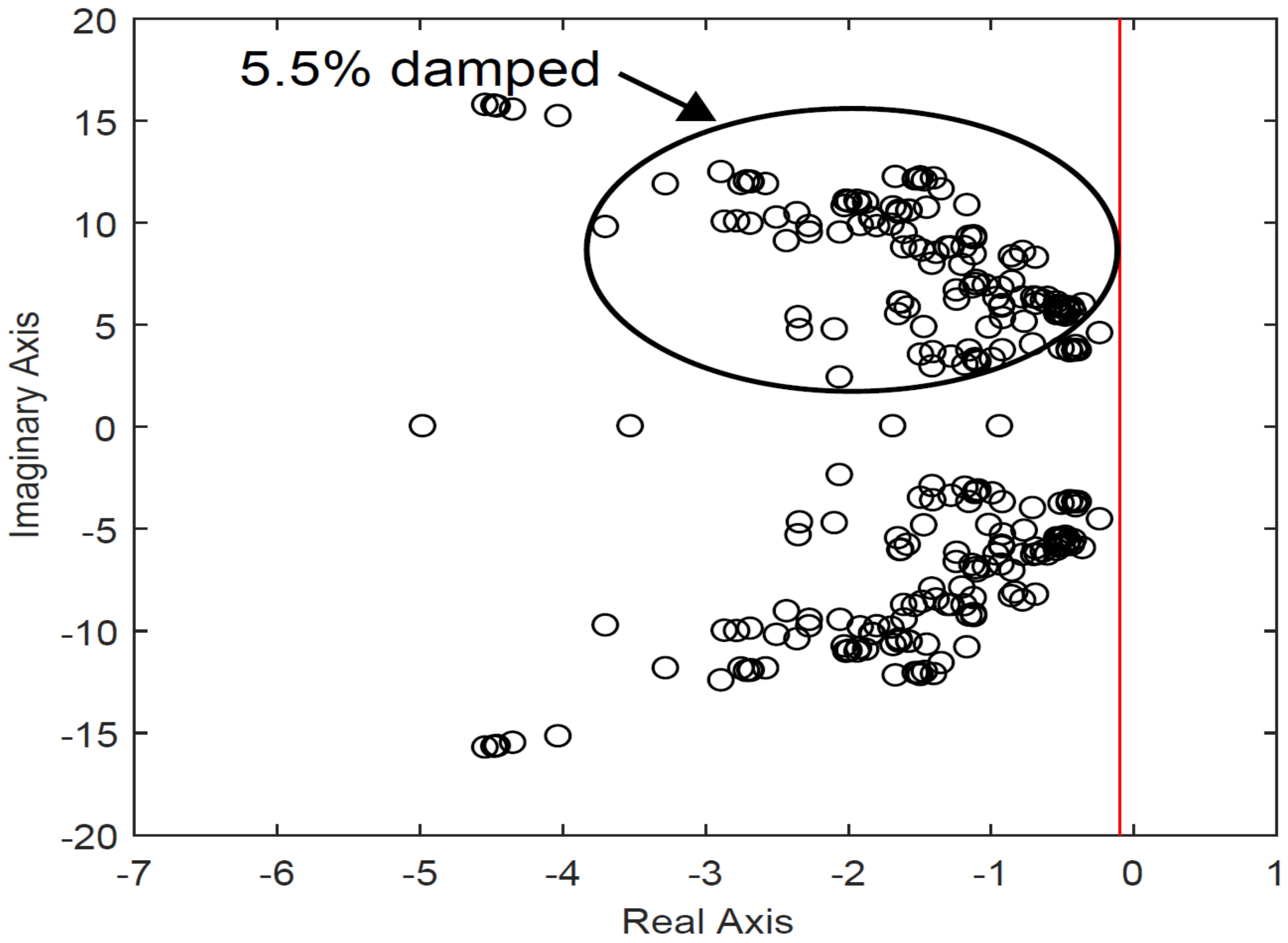


SVC Output

* The rating of the SVC is 100 MVAr. The modulation limit for DC-SDC is set to ±125 MW.

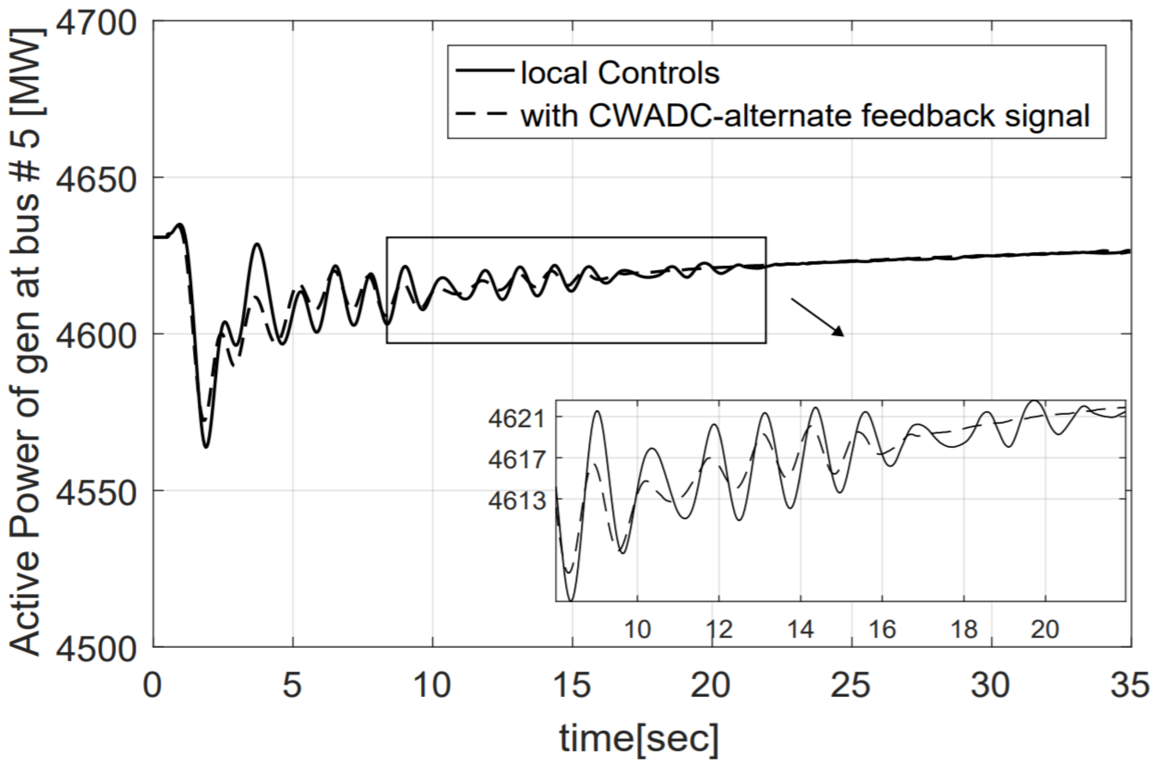
Results-Alternate Signal Control Set

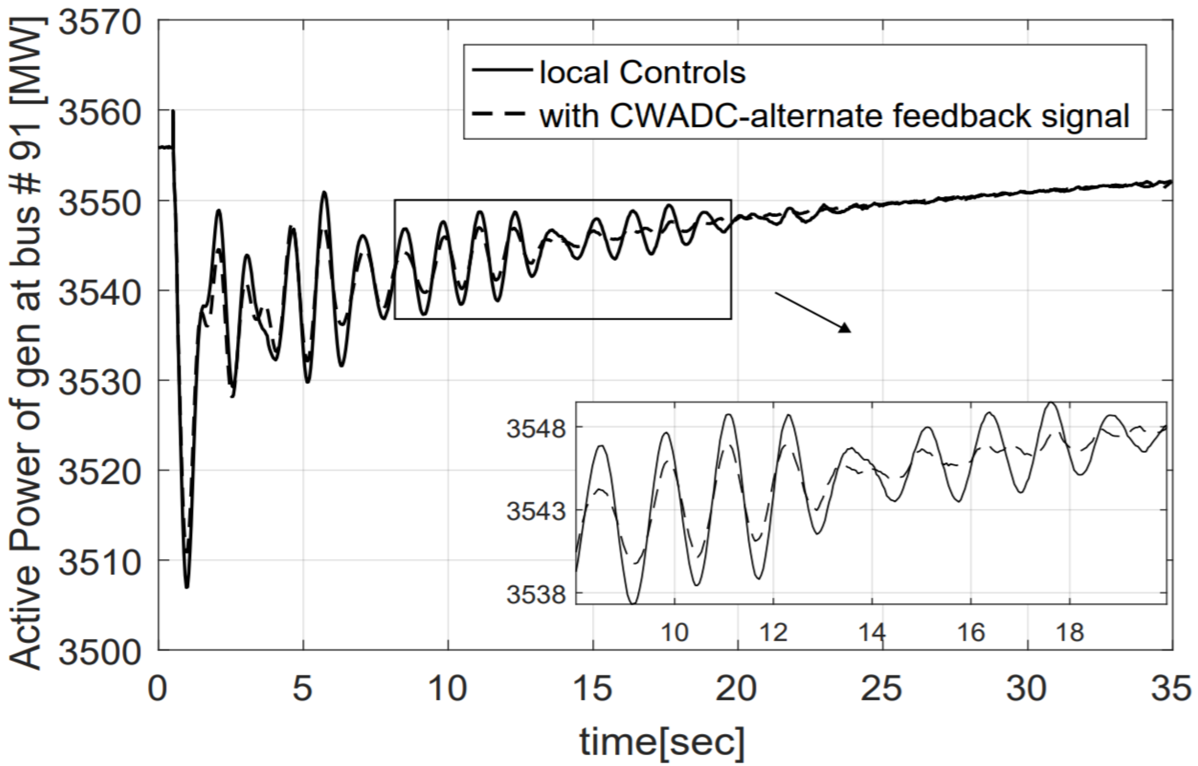
Designed LMI Control using an Alternate Control Set



Closed-loop modal analysis

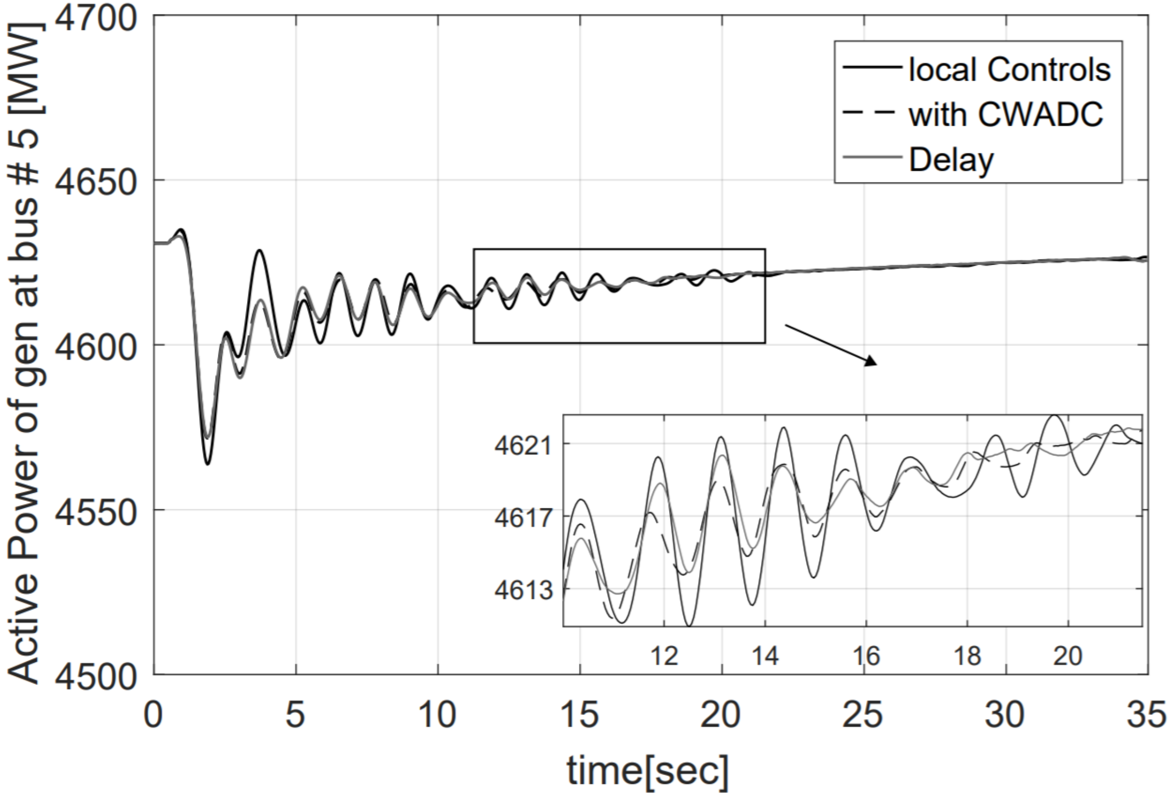
Small Disturbance-Alternate Signal Control Set

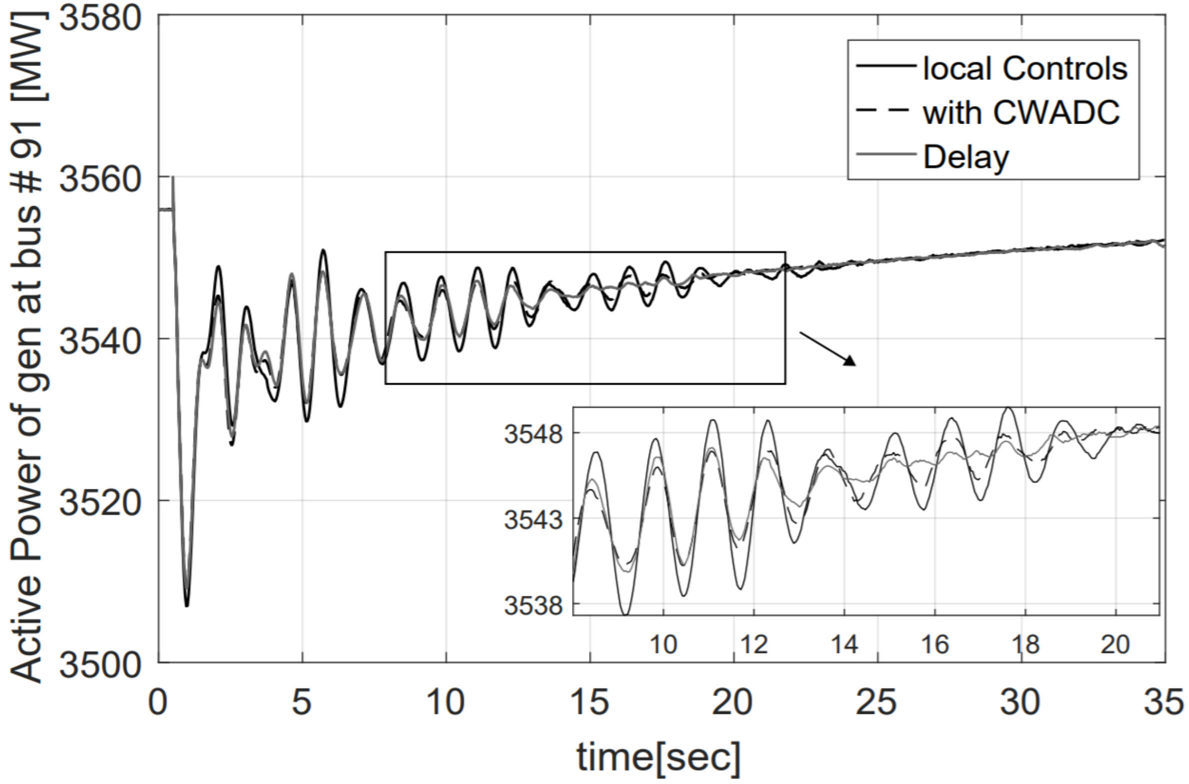




Small Disturbance-Incorporation of Delays

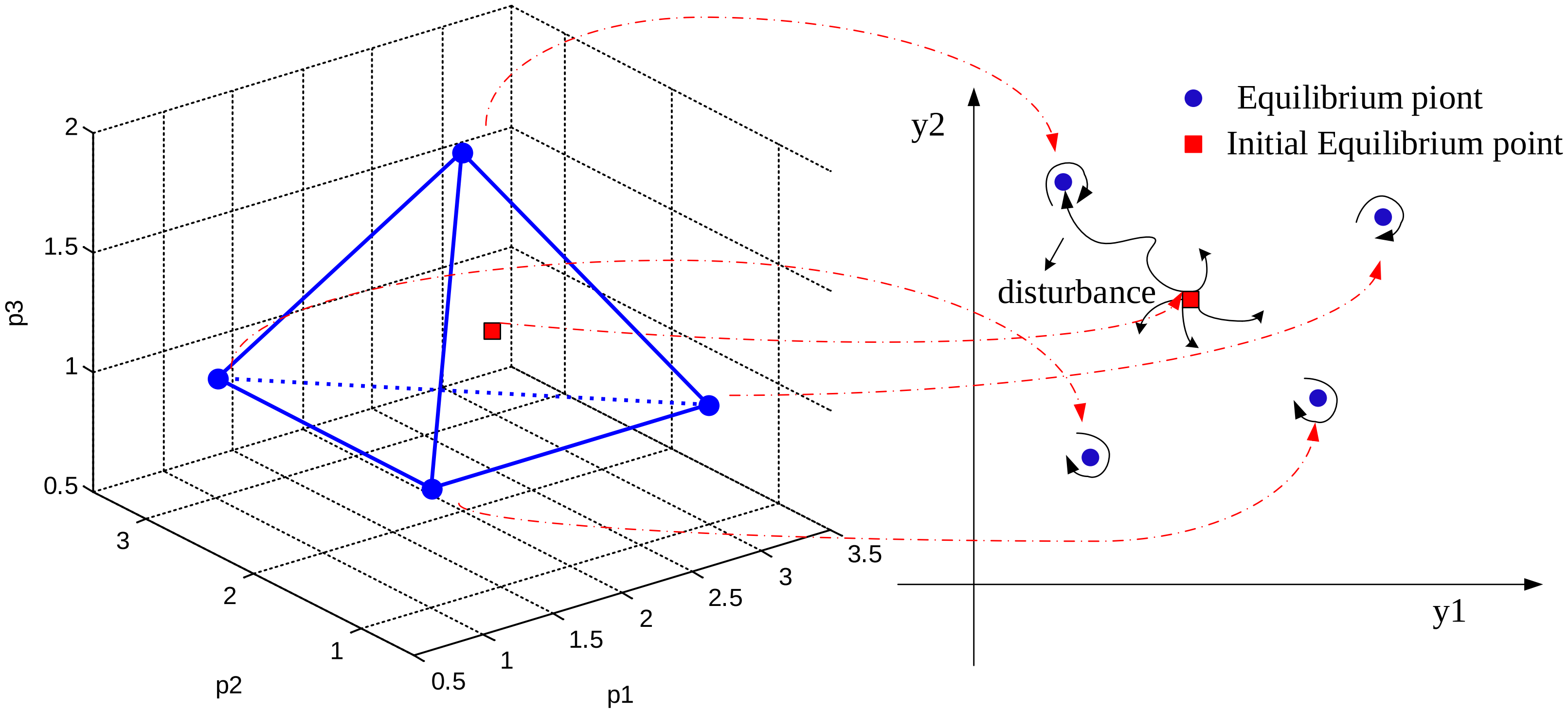
Random delay between 25 ms-100 ms added to control signals





Extensions to Multi-Polytopic Design

- Deviation of an operating point post-contingency is reflected in the measurements
- Trajectory that the current point follows to reach its destination is a measure of the domain-of-attraction of the different equilibrium points



(a) parameter space (b) measurement space

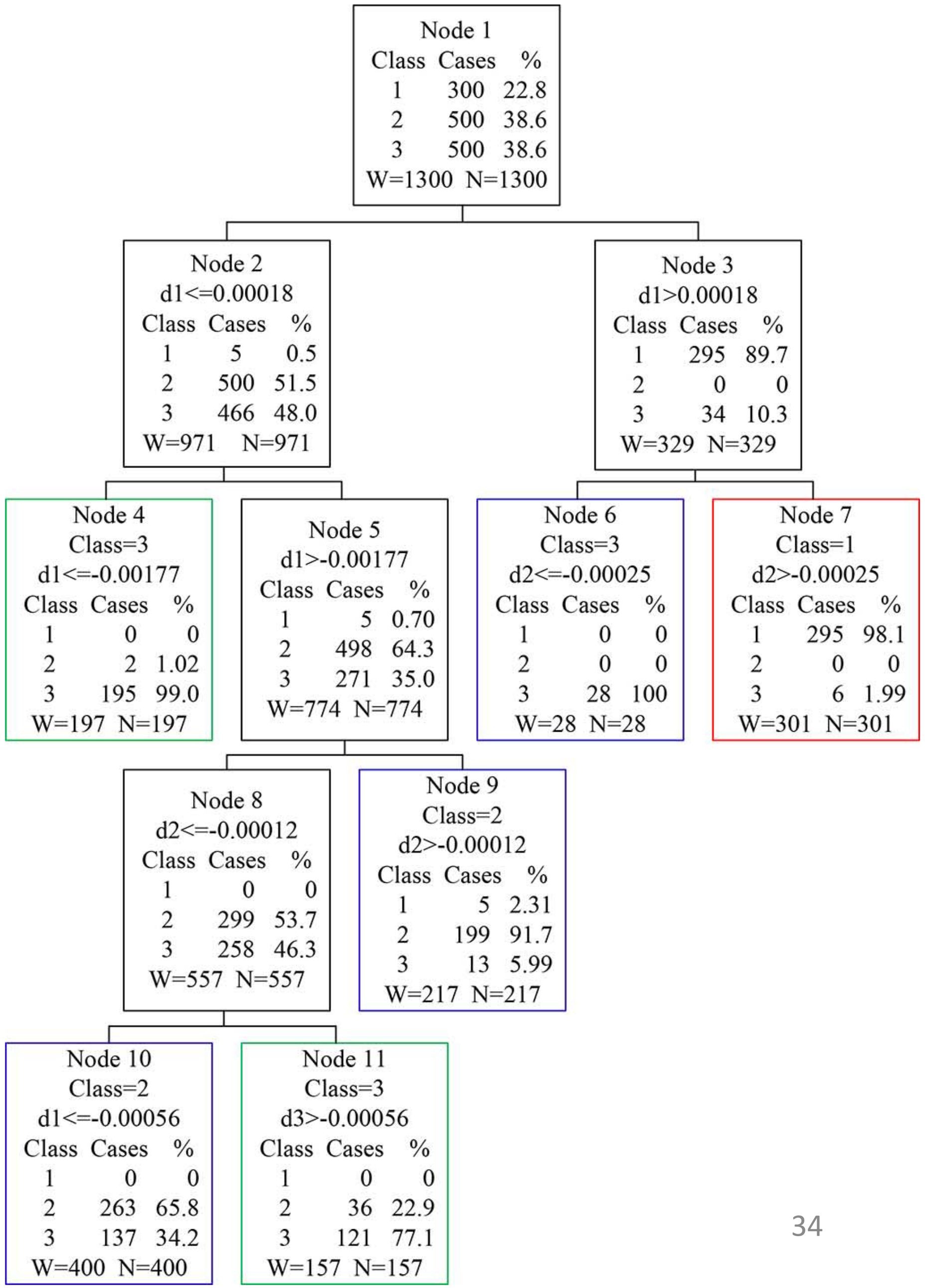
- By employing this trajectory as a guideline, the most suitable equilibrium point for different disturbances can be identified

Multi-Polytopic Design using CART [21]

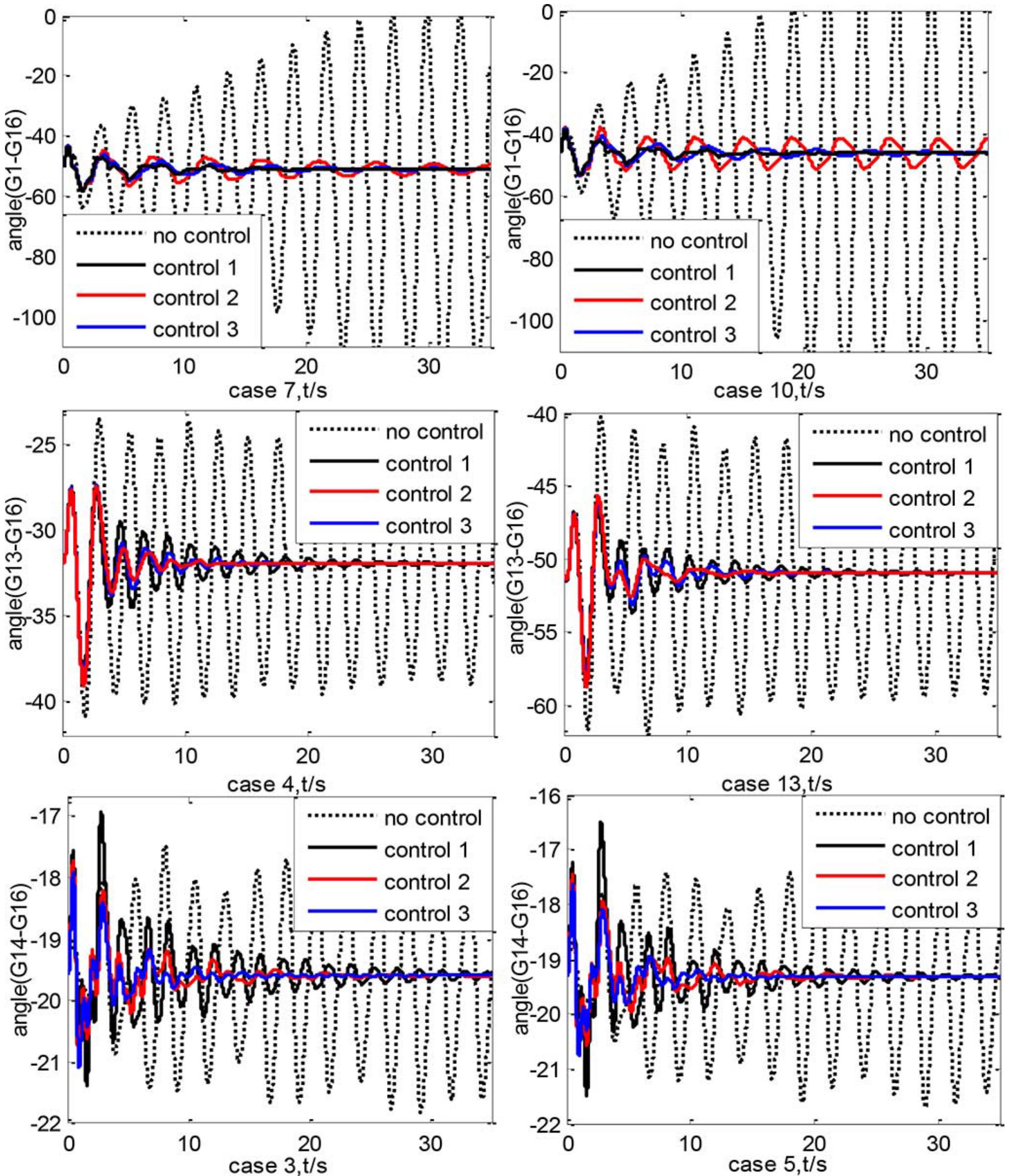
- CART used to identify the polytope inside which the operating point lay

Test cases for 16 machine, 68-bus system

Number	Contingency Details
1	Base case
2	One of double circuit line 1-2 is outage
3	One of double circuit line 8-9 is outage
4	Load of group 4 increased by 20%
5	Load of group 5 increased by 10%
6	Generation of group 4 increased by 20%
7	Generation of group 5 increased by 10%
8	10% constant power + 10% constant current + 80% constant impedance
9	20% constant power + 40% constant current + 40% constant impedance
10	Load of group 4 decreased by 20%
11	Generation of group 4 decreased by 10%
12	Generation of group 5 decreased by 10%
13	Load of group 5 decreased by 10%

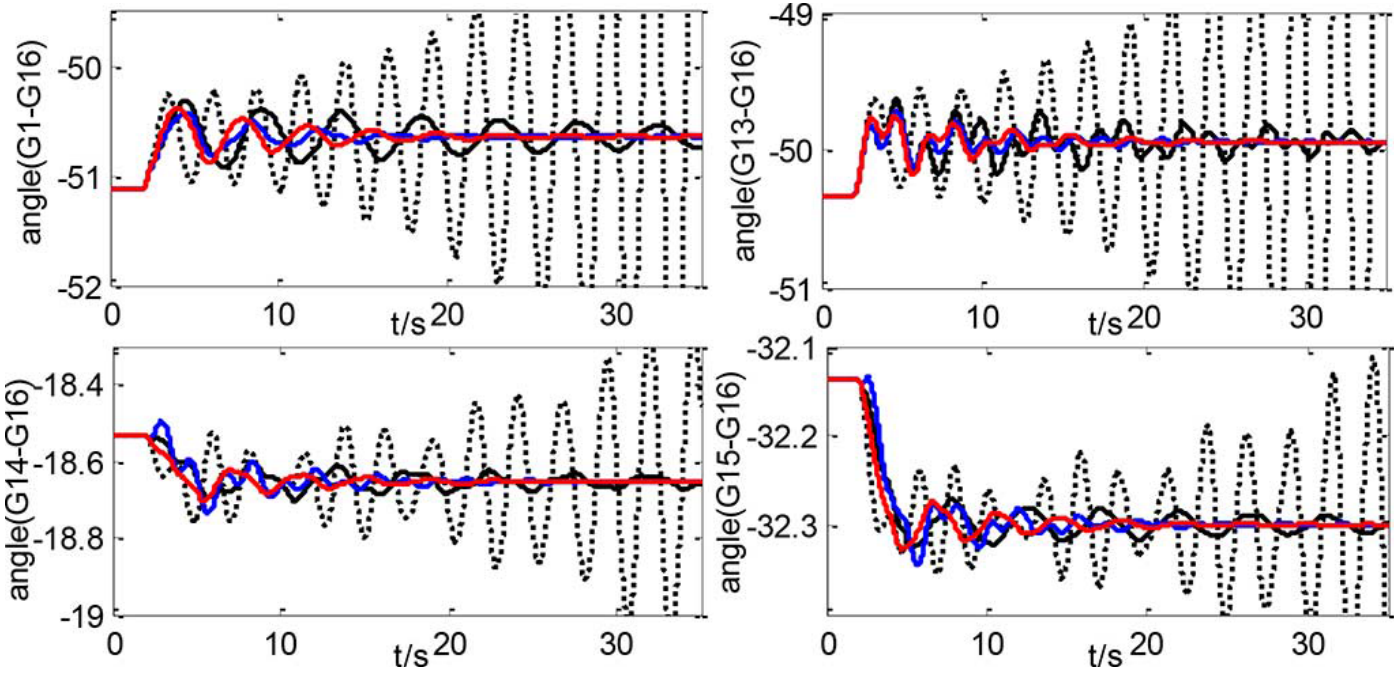


Results-16 Machine, 68-Bus System [21]



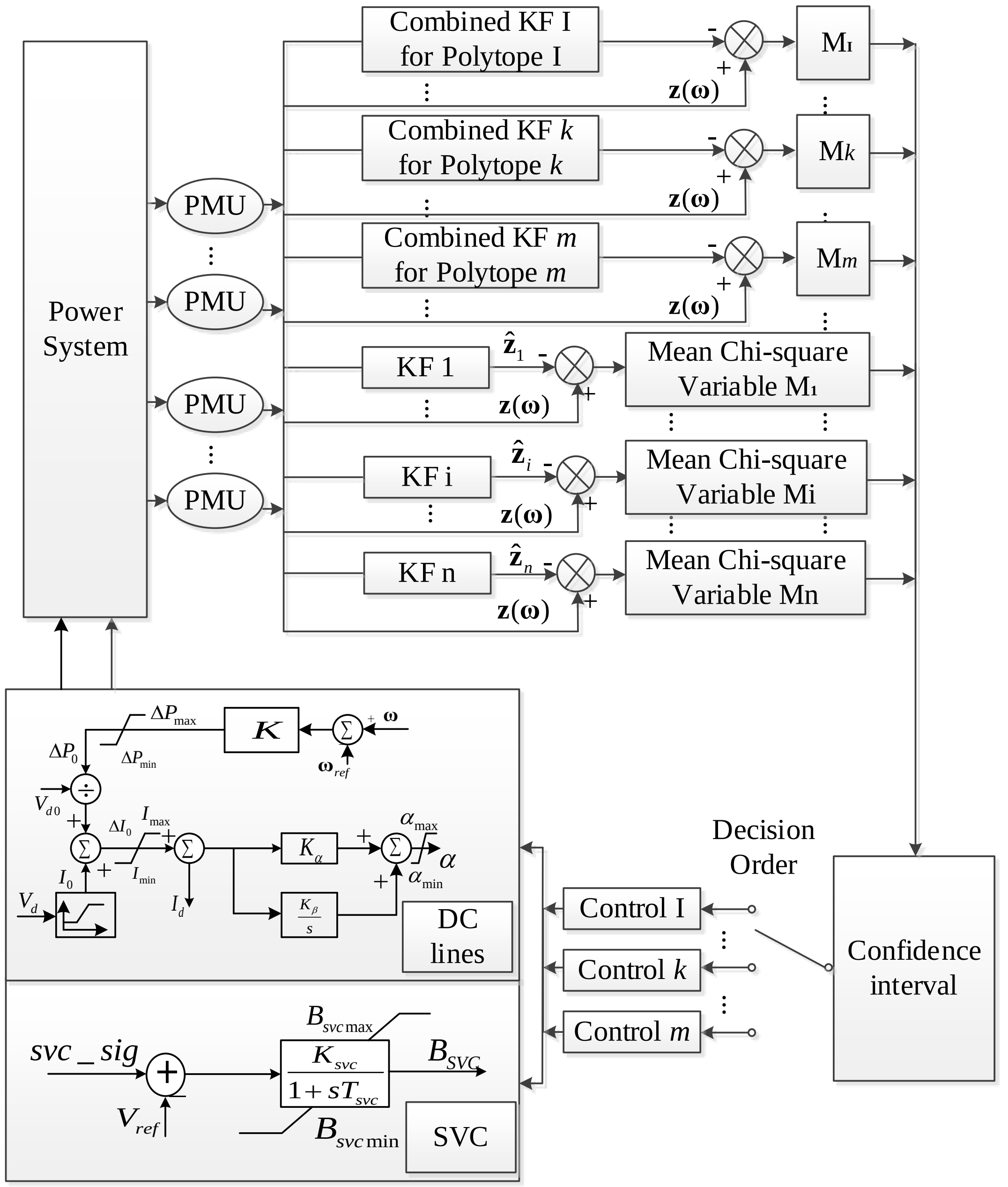
Output of CART

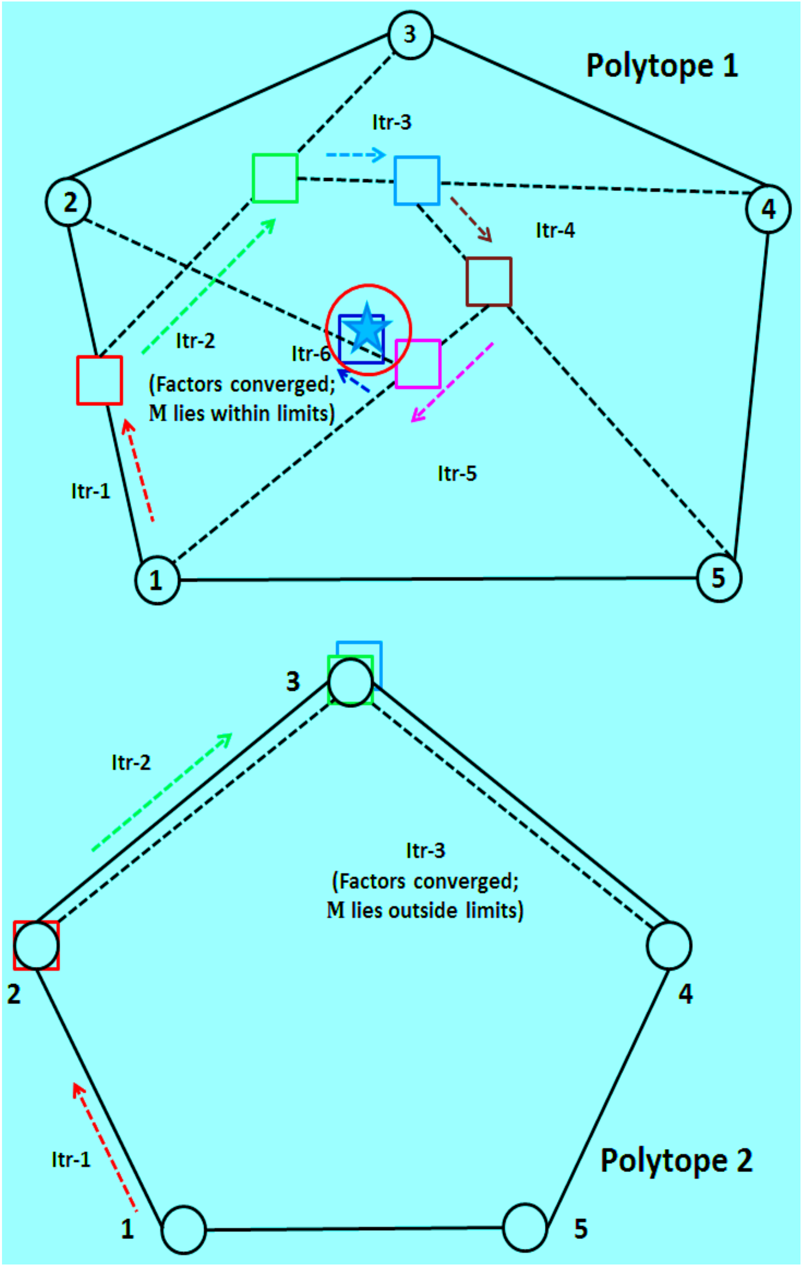
Samples	1	2	3	4	5	6	7	8	9	10
Pol. No.	3	3	3	3	2	1	3	2	3	2
Samples	11	12	13	14	15	16	17	18	19	20
Pol. No.	3	2	2	3	3	3	3	3	2	3
Samples	21	22	23	24	25	26	27	28	29	30
Pol. No.	3	3	2	2	3	2	3	3	3	3



Dynamic response of closed-loop system for different polytopic controllers

Multi-Polytopic Design using Kalman Filters [16]

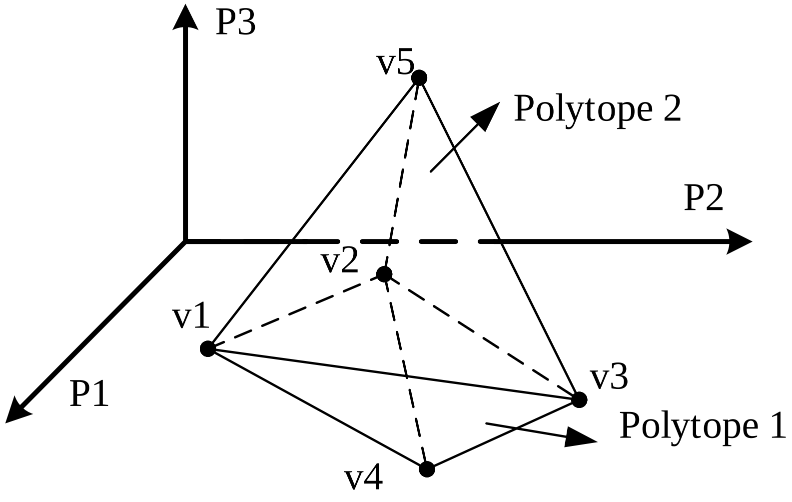




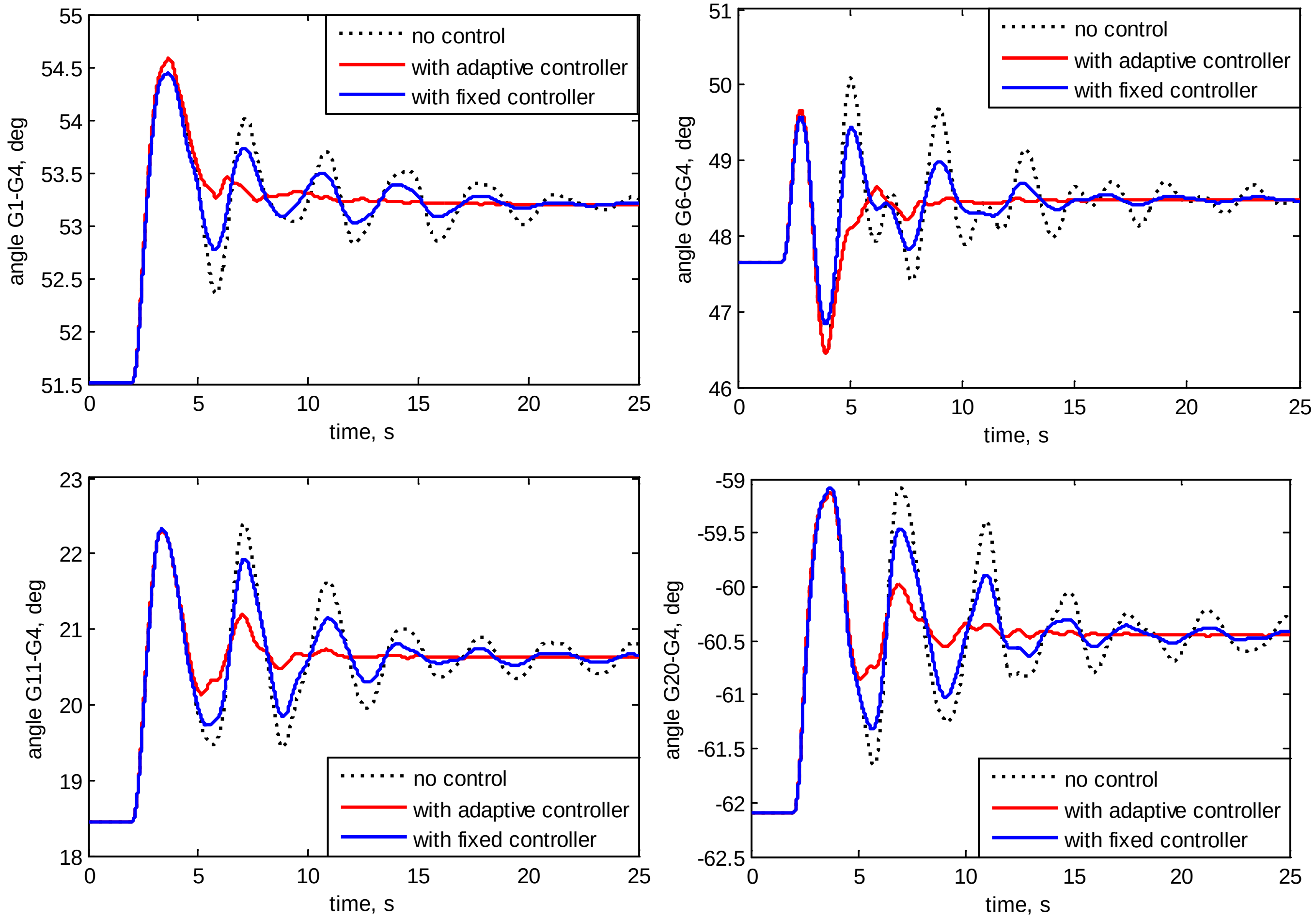
Results-Reduced Order WECC System [16]

Test Cases

Vertex No.	Parameters		
	P1 (Load 1-10)	P2 (Outages of line 118-124)	P3 (Generation 1-3)
v1	100%	No outages	100%
v2	95%	One (out of the four) line is out	100%
v3	105%	Three (out of the four) lines are out	100%
v4	100%	One (out of the four) line is out	95%
v5	100%	One (out of the four) line is out	105%



Polytopes in parameter space for the Reduced Order WECC System



Dynamic responses of closed-loop system for unknown scenario with no control, fixed control, and adaptive control

Conclusions

- Designed coordinated controls for mitigating inter-area oscillations using an enhanced SMA and LMI-based polytopic design
- Coordinated operations of different controllers already present in the system
- Differentiated non-critical set of generators from the critical set, and created a partial state feedback for the complete system, with the aid of only the critical set
- Identified alternate feedback sources in case of loss of primary feedback signals
- Effectively damped critical oscillatory modes under changing operating conditions

Ongoing Work

- Solve the control problem using a machine learning (ML)-based polytopic control design:
  - Take advantage of large amounts of historical data being collected
  - Combine LMI-based control with load and renewable generation forecasts to better account for systemic uncertainty

- An ML-based approach would:
  - ***Relieve*** the computational burden of LMIs
  - Offer ***scalable*** performance

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Thank You !

Questions??

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