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Security Enhancement through Direct Non-Disruptive Load Control

Ian Hiskens (UW – Madison)
Vijay Vittal (ASU)

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Security Enhancement through Direct Non-Disruptive Load Control

PROJECT NUMBER: ***S-16***

PROJECT TEAM MEMBERS

- *Ian Hiskens (University of Wisconsin – Madison) : Lead*
- *Vijay Vittal (Arizona State University)*

INDUSTRY TEAM MEMBERS

- *Innocent Kamwa (Hydro Quebec, IREQ)*
- *Nick Miller (GE Power Systems)*
- *Sharma Kolluri (Entergy)*

PROJECT PERIOD

- *May 1, 2002 to April 30, 2005*

TOTAL BUDGET BY YEAR

- *$65,000*

Objective

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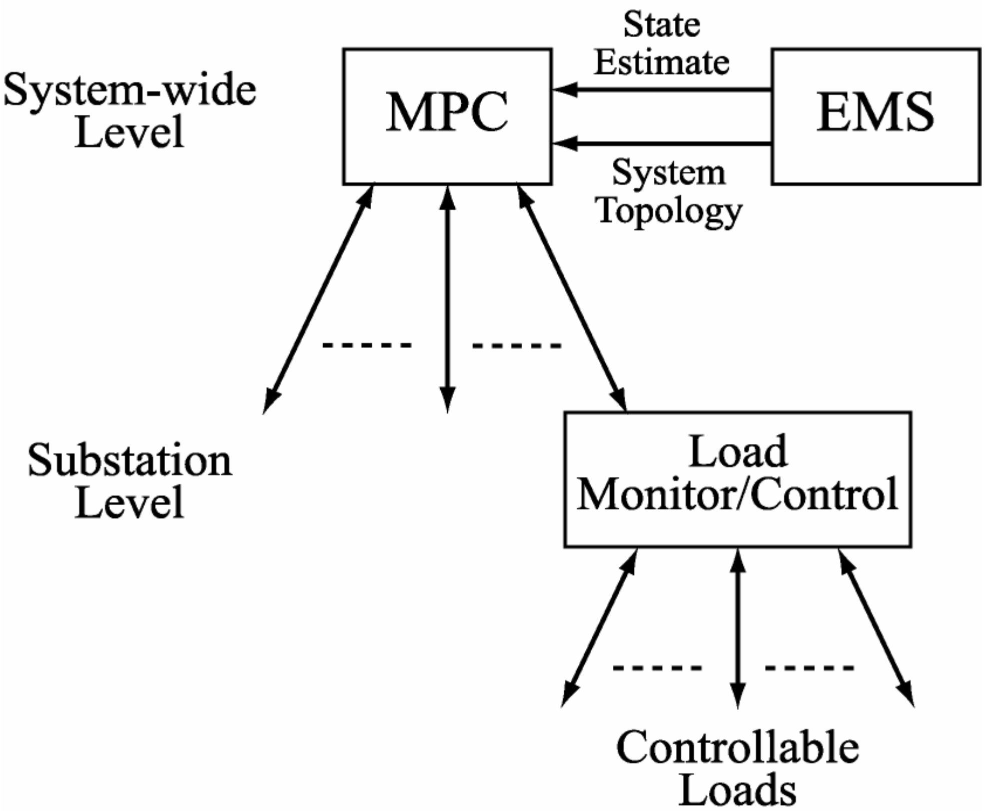
- Examine benefits and analytical issues in utilizing *direct non-disruptive load control* to enhance power system dynamic performance.
- Design candidate control schemes for direct load control.

Non-Disruptive Load Control

- Many loads are partially controllable (switchable.)
  - Air-conditioning, lighting.
  - Distributed generation augments demand regulation.
- A hierarchical control structure is required.



Voltage Stability Enhancement Using Model Predictive Control

(University of Wisconsin-Madison)

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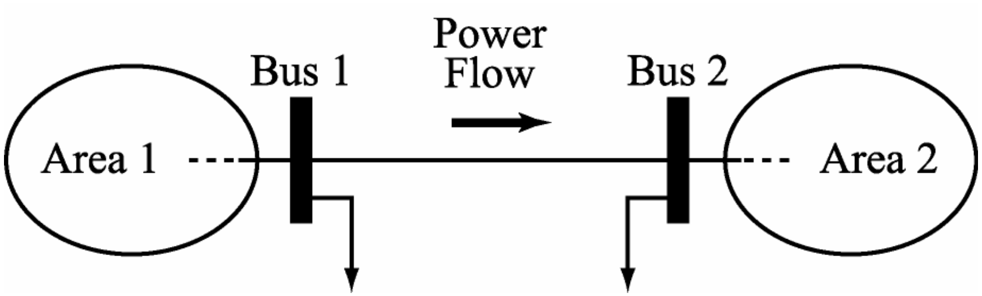
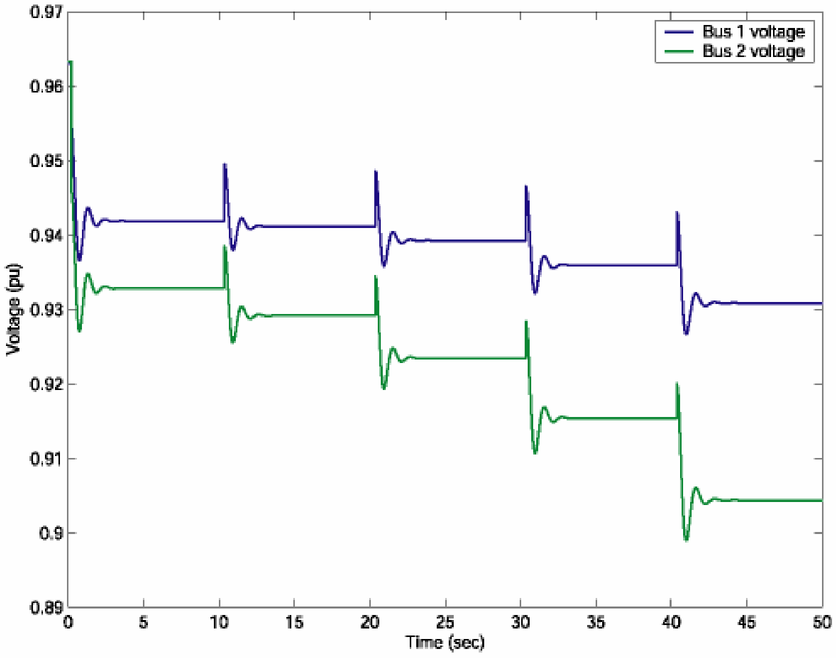
- Motivation:
  - Undervoltage load shedding does not always provide the correct action.
  - Special protection schemes are typically designed for specific outage scenarios.
    - Difficult to alter or extend.

- Model predictive control offers a possible alternative.

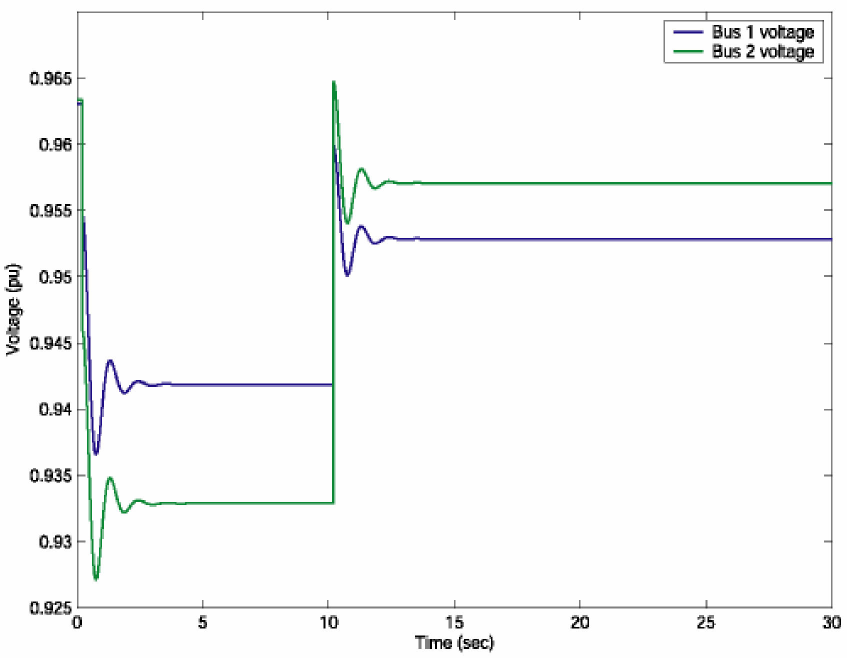
Undervoltage Load Shedding

Simple two bus example





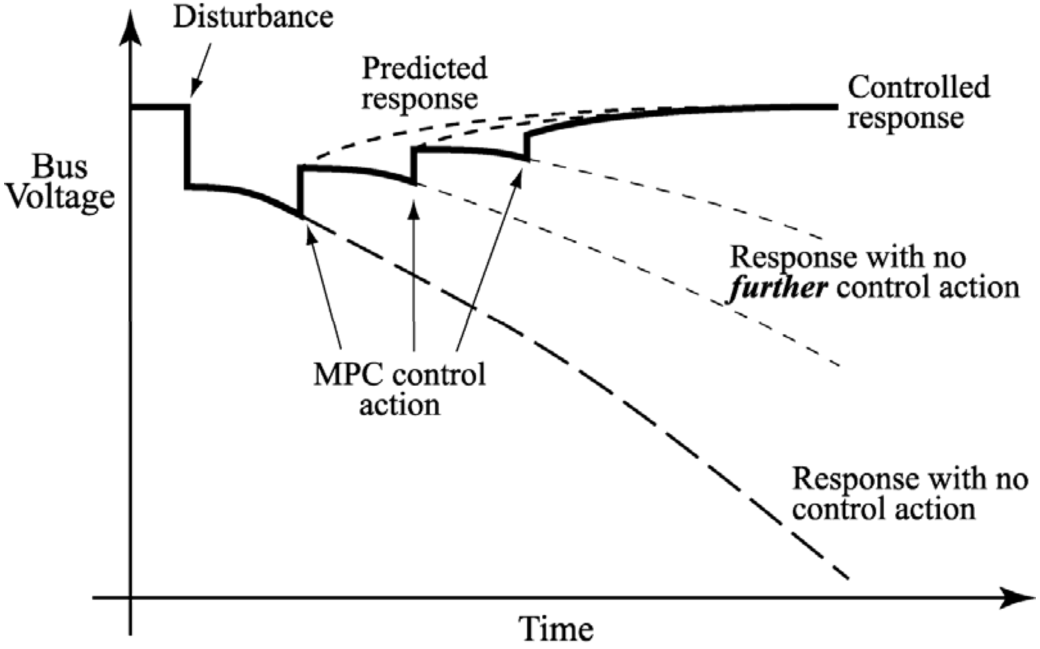
Bus 1 load shedding



Bus 2 load shedding

Model Predictive Control (MPC)

- System state is estimated.
- Predict system dynamic response.
  - Optimal control problem that determines the minimum load changes required for stabilization.
- Telemeter load setpoints to lower-level load controllers.
- Obtain new state estimate, and repeat process.

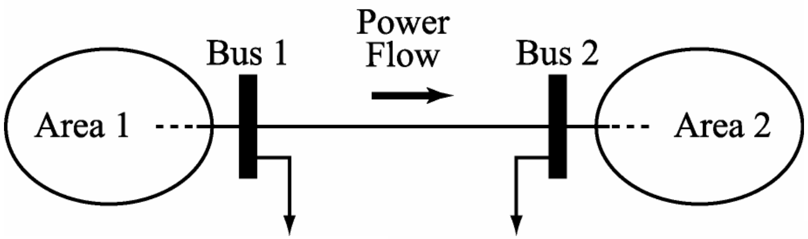


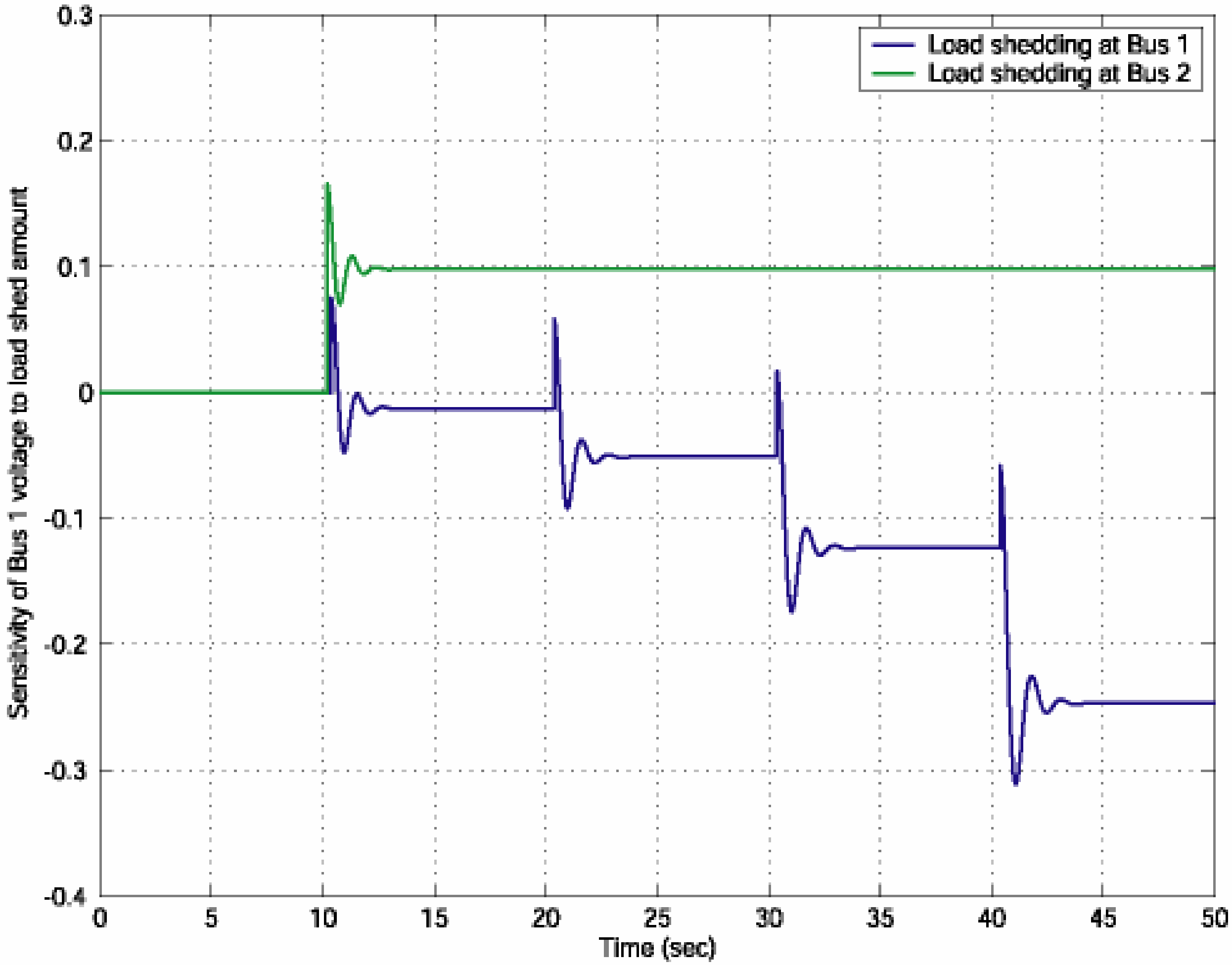
- Extensively used in chemical/process industries since 1970s

Trajectory Sensitivities

- Most MPC applications and analysis build on a linear systems framework.
  - Chemical processes are not linear, but perturbations are relatively small.
- However voltage stability enhancement cannot avoid large disturbance, nonlinear behaviour.
- Trajectory sensitivities are used to provide a “linearization” around the nonlinear trajectory.
  - This is NOT the usual linearization around an equilibrium point.
  - Provides a first-order approximation of the change in the nonlinear trajectory induced by a change in each controllable load.

Trajectory Sensitivities for the Two Bus Example





MPC Strategy

1. Estimate the current system state.
2. Calculate load control action:
    1) Obtain an initial guess of load control action using a strategy such as undervoltage load shedding or closest bifurcation boundary concepts.
    2) Predict the corresponding system response (and calculate sensitivities.)
    3) Use trajectory sensitivities to optimally correct the initial guess of the load-shedding requirements.
3. Enact load control action.
4. Return to step 1.

MPC Optimization

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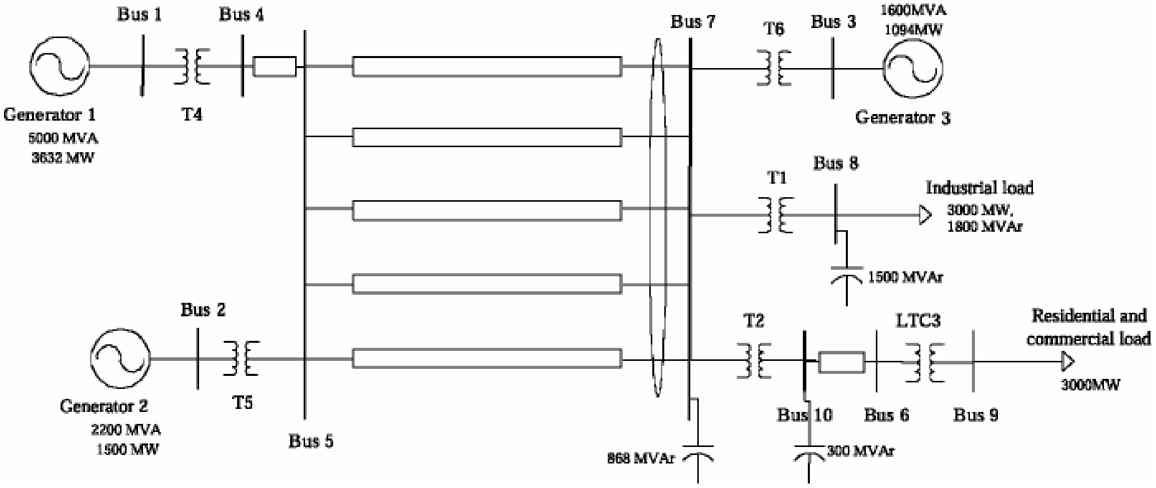
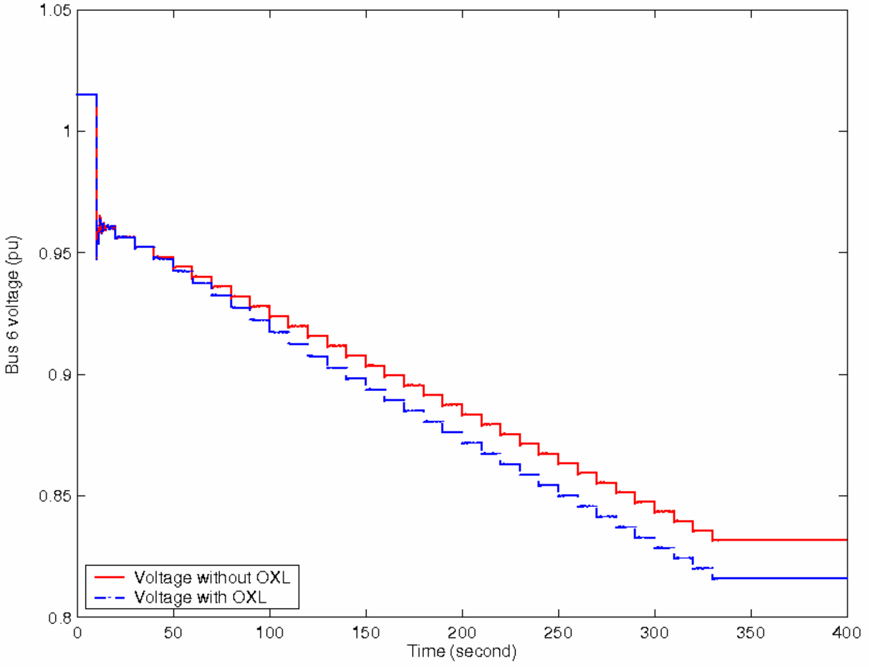
Objective: Determine the minimum load shedding required to restore voltages to acceptable levels.

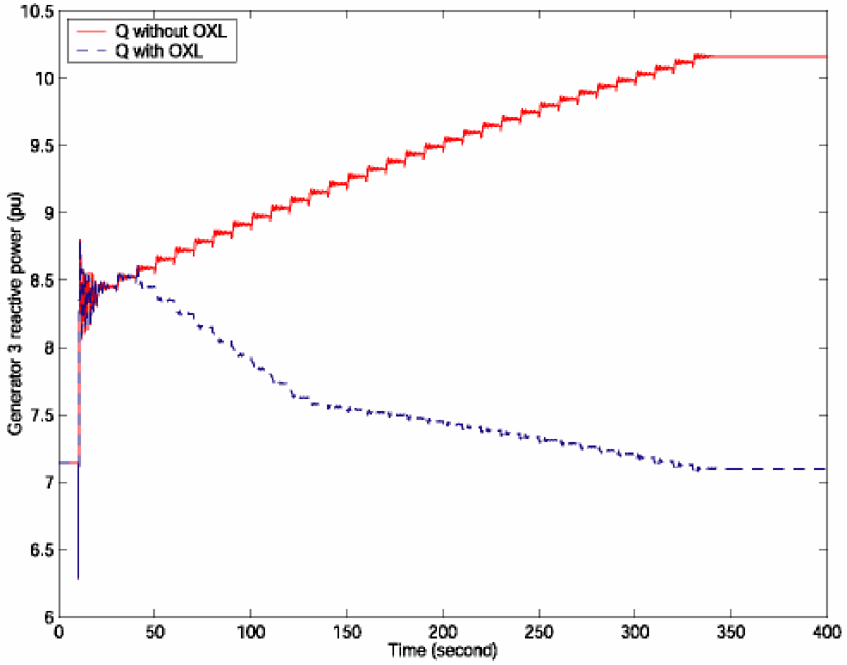
- The influence of loads on voltages is given (to first order) by trajectory sensitivities.
- Using this approximation, the optimization problem can be formulated as a linear program.
- Errors introduced through the linearization are corrected at the subsequent MPC iteration.
- Errors in load response are similarly corrected.
- The MPC model of the system does not have to be precise.
  - On-going research to determine the appropriate level of accuracy.

MPC Example

No load control

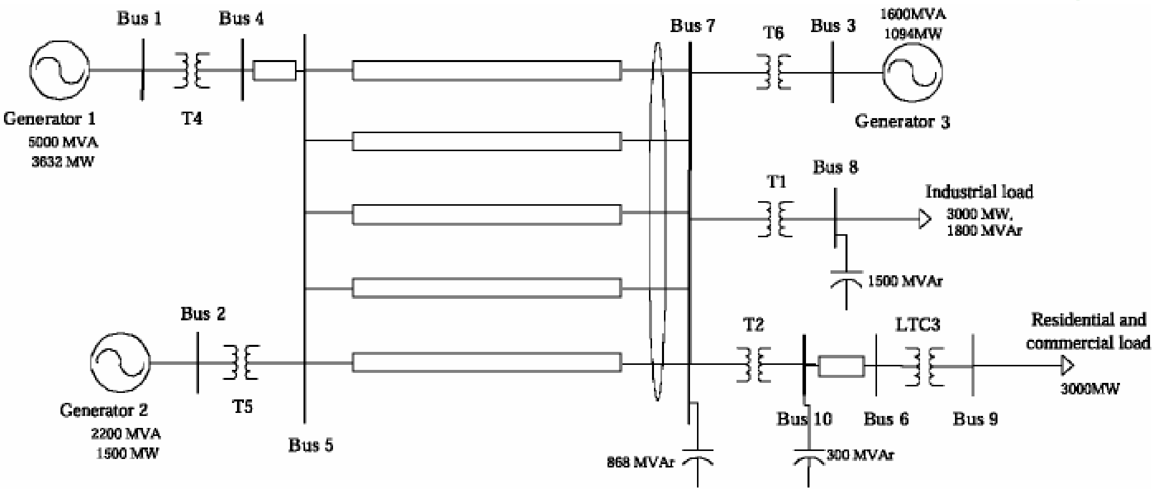


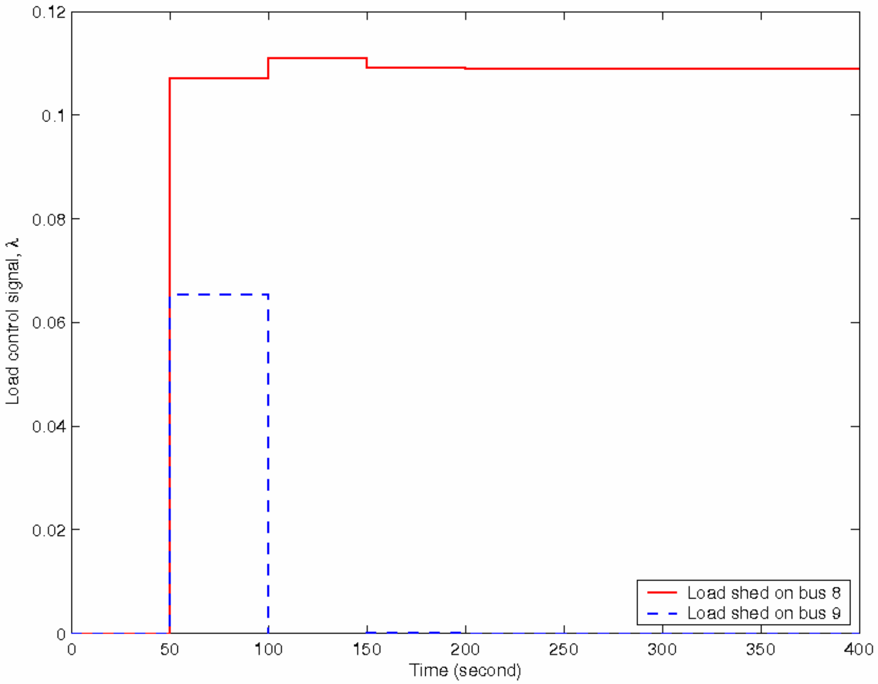


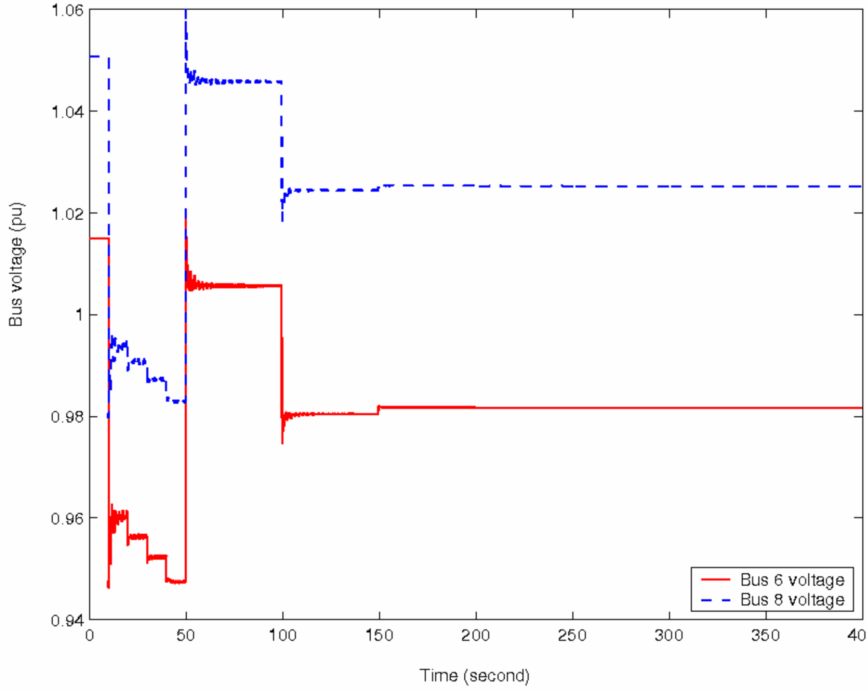


MPC Example

MPC-based load control







Conclusions and Future Work

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- MPC provides an effective load control strategy
  - Predictive rather than responsive.
- Numerous open questions are being addressed through ongoing research
  - Stability: What conditions are required to ensure stability?
  - Robustness: What level of accuracy is required for the internal MPC model?
- Distributed control
  - Centralized decision-making is unreasonable.
  - Distributed control strategies can achieve equivalent performance, provided interactions between area controllers are cooperative.

Analysis of Stability Robustness and Design of Control Schemes for Angle Stability Enhancement (Iowa State)

- Application of Structured Singular Value (SSV or *μ*) theory in developing underlying analysis framework for load modulation
  - Powerful tools and techniques for analyzing and designing control systems in the presence of uncertainties
  - Steadily matured to a level suitable for application to large engineering problems

Design of Control Strategies

- Development of a linear model for direct load control problem
  - Part of the active power load modeled as system input
  - Comprehensive modal analysis for selection of load buses for control implementation
  - Validated with MASS
- Characterization of uncertainty in the linear model in Linear Fractional Transformation (LFT) form
- Development of a framework for analyzing the amount of load modulation through the application of robust performance theorem (μ theory)
  - Skewed – μ framework in the context of μ theory
  - Building block for control strategies

Design of Control Strategies

- Two conceptually different control strategies for load modulation based on skewed-*μ* framework
  - Objective is to determine amount of load modulation to perform to satisfy desired small-signal stability performance in the presence of uncertainties
  - Approach I – Determination of worst-case load levels for given performance
  - Approach II – Determination of worst-case performance for given uncertainty (in load, generation or any parameter), modulation of load to satisfy desired performance
  - Selection and modulation of loads based on Eigenvalue sensitivities (Linear model for direct load control)
  - Test systems – CIGRE Nordic system (augmented with distribution feeders) & WECC system

Load Control Algorithms (Iowa State)

- Pre-study of direct load control programs recently executed by utilities and state-of-the-art in load control systems
- Developed different algorithms for control of thermostatic loads with minimum disruption/discomfort
  - Optimization framework
  - Loads modeled using physical models to take into account “Cold load pickup” phenomenon
  - Dynamic Programming algorithms for air-conditioner loads, decision-tree based algorithm for water-heater loads
  - Monte Carlo simulation of the effect of different constraints and variables on the effectiveness of control

LFT Representation of A and B Matrices

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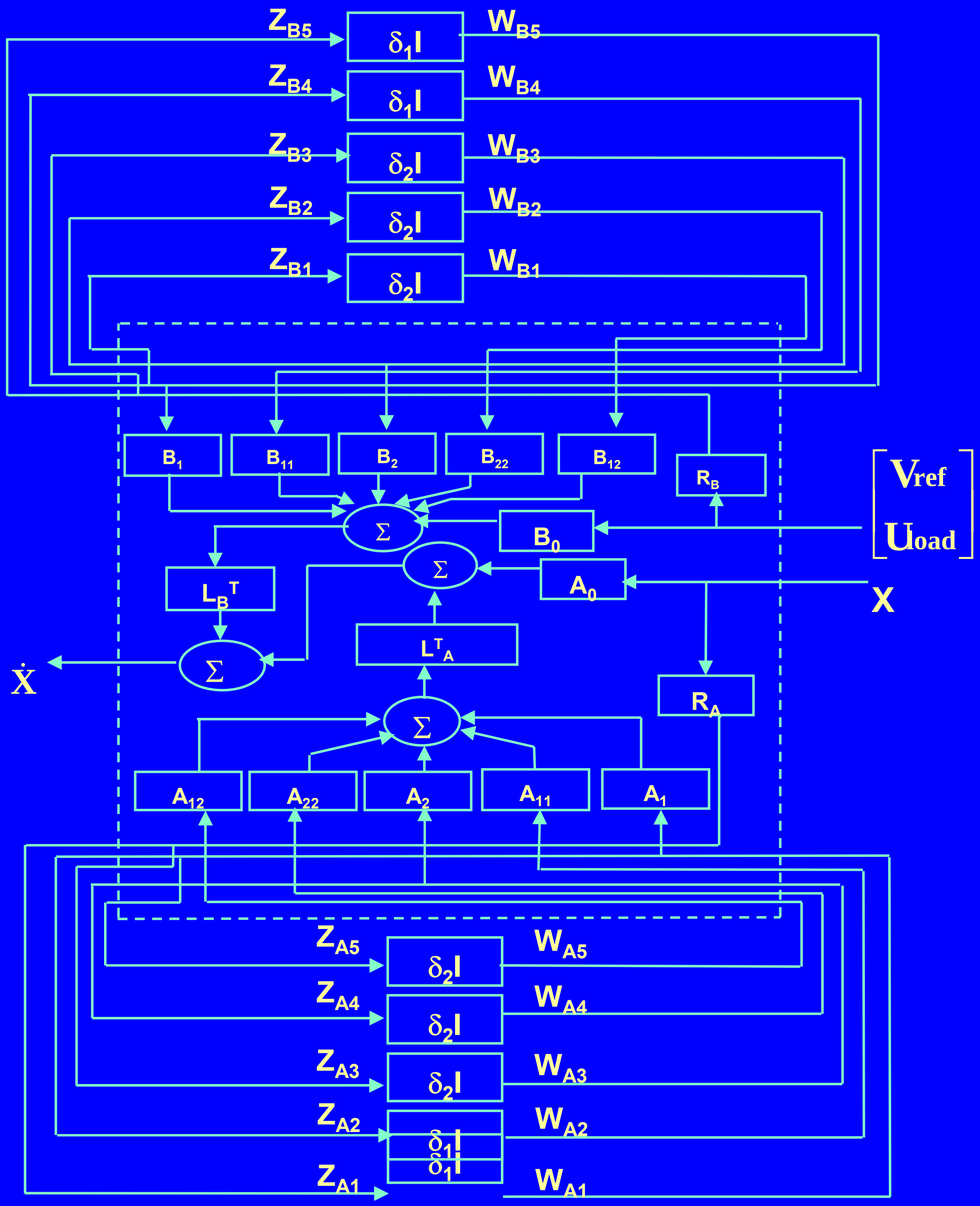

Approach I – Worst-Case Uncertainty for Given Performance

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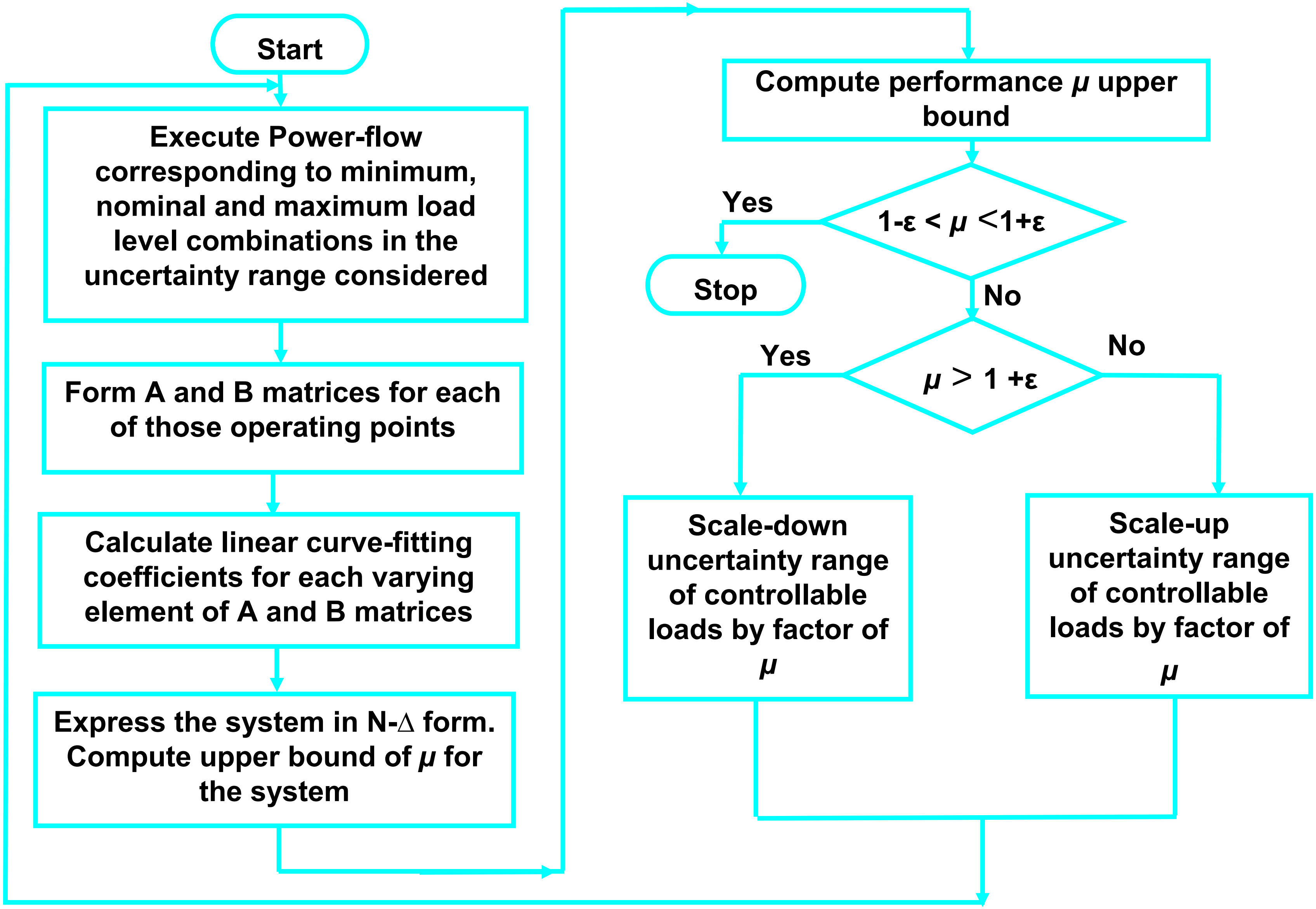
- Load buses for control selected based on Eigen value sensitivities
- Uncertainty assumed to exist in the controllable part of active power loads at selected buses
- Uncertainty levels varied until the desired performance is satisfied
- Analytical proof of the concept
    - Choice of a performance level less stringent than nominal performance (with no uncertainty) can be satisfied through scaling of parametric uncertainty
    - Factoring of performance weight, application of Schur’s formula, and definition of μ

Approach I: Algorithm



Start

Execute Power-flow corresponding to minimum, nominal and maximum load level combinations in the uncertainty range considered

Form A and B matrices for each of those operating points

Calculate linear curve-fitting coefficients for each varying element of A and B matrices

Express the system in N-Δ form. Compute upper bound of μ for the system

Compute performance μ upper bound

$1-\varepsilon < \mu < 1+\varepsilon$

Yes

Stop

No

$\mu > 1+\varepsilon$

Yes

No

Scale-down uncertainty range of controllable loads by factor of μ

Scale-up uncertainty range of controllable loads by factor of μ

Results – Approach I – Nordic System

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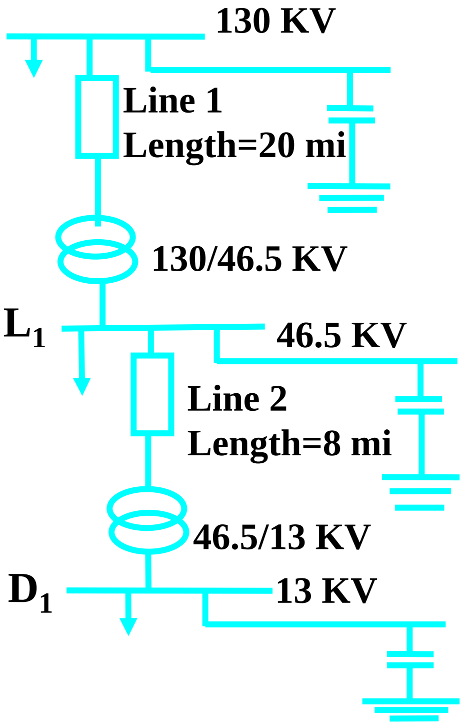
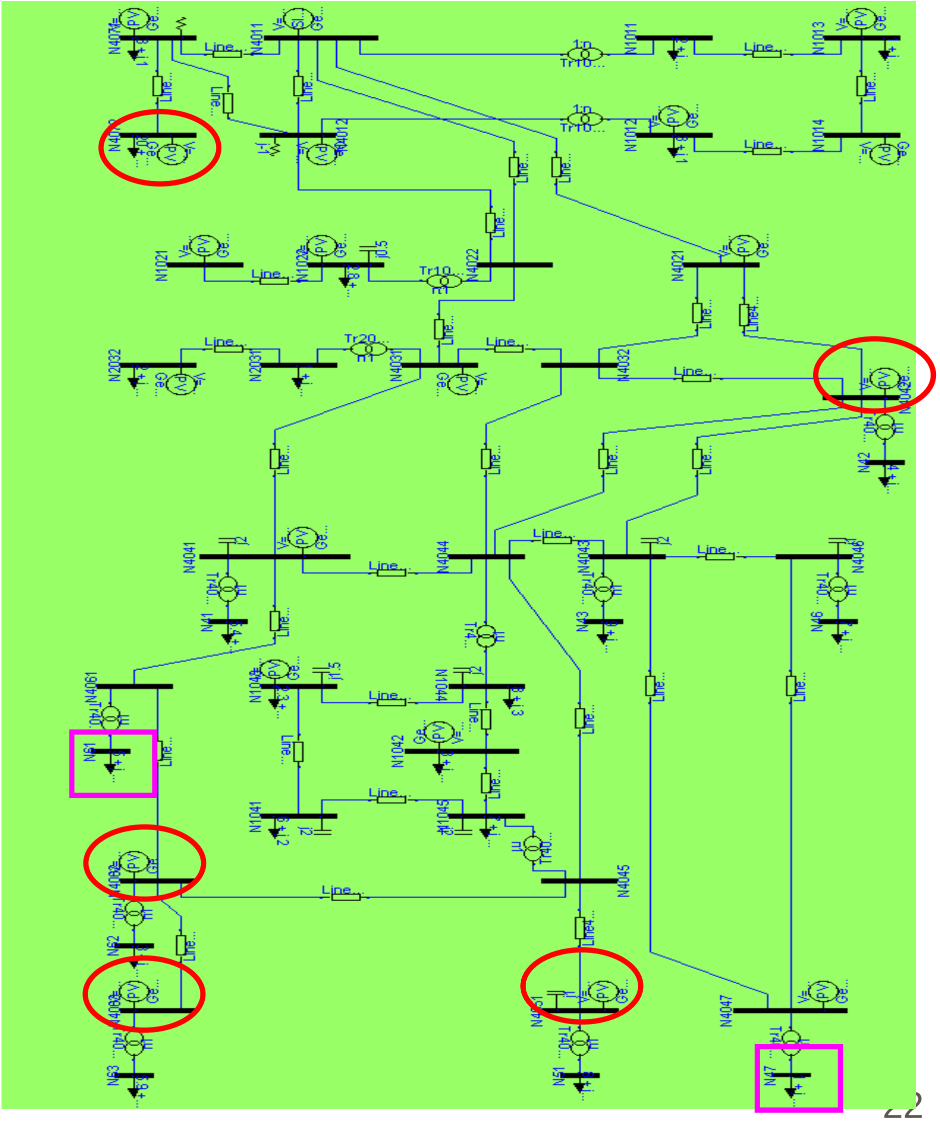
Nordic32 System
20 generators, 41 buses

Distribution feeder





141 state variables in this model
Numerous modes of oscillations
Critical mode around 2.6 rad/s

Results – Approach I – Nordic System

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- Loads for control
  - N51 and N61 at 130 kV
  - S51_1 – S51_5 and S61_1 – S61_5 at 46.5 kV
  - D51_1 – D51_5 and D61_1 – D61_5 at 13 kV

- Error signal chosen is the inertia-weighted average of angular speeds of generators 6, 8, 9, 10 and 12 (Verified using SIMGUI – Section 4.8.2.1)

- Objective is to demonstrate
  - Accuracy of the overall analysis framework and the analysis approach
    - Correctness of uncertainty characterization
    - Correctness of the error signal and performance weight for performance characterization
  - Robustness of the scheme

- Choose arbitrary nominal as well as uncertain ranges for controllable loads and show that when performance μ is one, overall system damping performance is what was desired (in terms of Damping ratio).

- $W_{\text{perf}} = 0.0145 \dfrac{s+1}{s+20}$ **<u>Desired least damping is 2%</u>**

Results – Approach I – Nordic System

Load(s)	Uncontrollable load in MW	Uncertain range of controllable load in MW	Uncertain range for the total load in MW
N51	60	[-40 – 40]	[20 – 100]
N61	120	[-90 – 90]	[30 – 210]
S51_1 – S51_5	40	[-15 – 15]	[25 – 55]
D51_1– D51_5	20	[-5 – 5]	[15 – 25]
S61_1 – S61_5	40	[-15 – 15]	[25 – 55]
D61_1– D61_5	20	[-5 – 5]	[15 – 25]

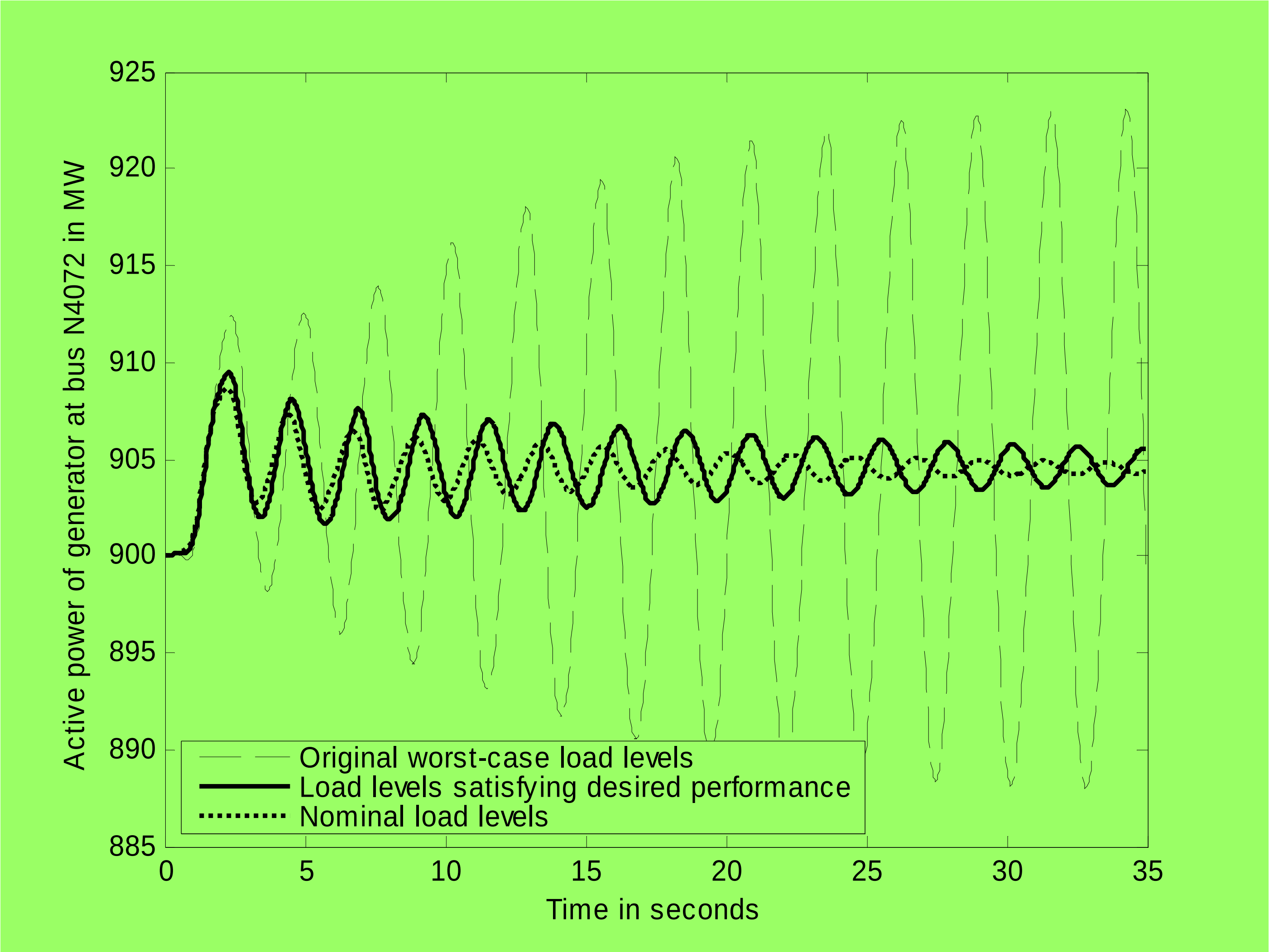
- Least damped critical inter-area mode for nominal load levels:

  - 0.1179 ± j2.9403 (Damping ratio = 4%)

- Critical mode for worst-case load levels: 0.1198±j2.4003 (Damping ratio = -5%) Robustly unstable
- Results of algorithm I:
  - N51 = 88.29 MW, N61 = 183.67 MW, S51_1 – S51_5 = 50.61 MW D51_1 – D51_5 = 23.54 MW, S61_1 – S61_5 = 50.61 MW D61_1 – D61_5 = 23.54 MW
- Inter-area mode for the above load levels: -0.053 ±j2.65
- Corresponding damping ratio : 2%

Results – Approach I – Nordic System

Response of active power generated at N4072 for 0.1 p.u. change in excitation input of generator 12 at bus N1012



Results – Approach I – WECC System

- Number of state variables 260

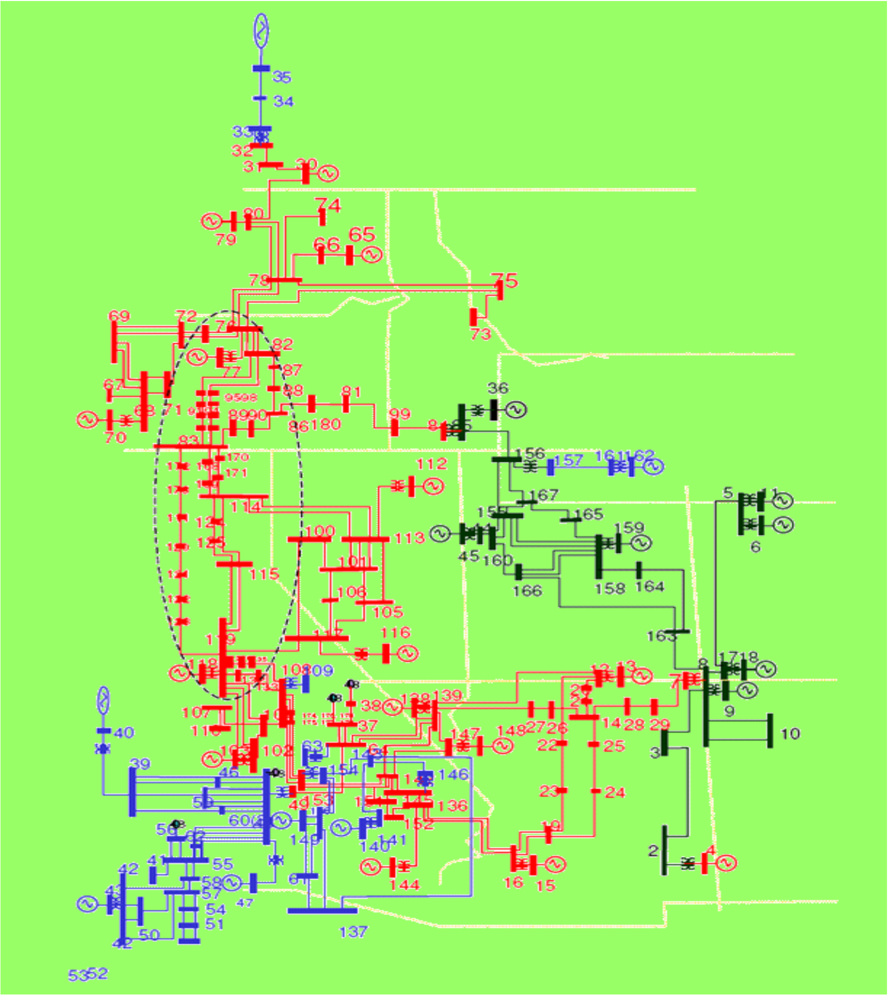
Mode	Mode frequency in rad/s	Participating generators
1	1.83	4, 8, 9, 15, 18, 24
2	5.52	8, 17, 18, 22
3	6.59	17, 18, 22

- Error signal selected is the inertia weighted average of angular speeds of generators 8, 15, 17, 18 and 22

- Performance weight $\dfrac{0.89s^2}{4.5s^2+34s+189}$

- Results in 2% damping for mode 1, 1% damping for mode 2 and 0.9% damping for mode 3

Western Interconnection (WECC)
29 generators, 179 buses



Results – Approach I – WECC System

Load bus	Uncontrollable load in MW	Uncertain range of controllable load in MW (15% of total load)	Uncertain range of total load in MW
2	1248	[-239.2 – 239.2]	[1008.8 – 1487.2]
5	1310.4	[-251.16 – 251.16]	[1059.2 – 1561.6]
106	102.92	[-19.73 – 19.73]	[83.195 – 122.65]
107	228.96	[-43.88 – 43.88]	[185.08 – 272.84]
117	773.38	[-148.23 – 148.23]	[625.15 – 921.61]
137	151.2	[-28.98 – 28.98]	[122.22 – 180.18]
141	2757	[-528.43 – 528.43]	[2228.6 – 3285.5]
145	2388.7	[-457.83 – 457.83]	[1930.8 – 2846.5]
166	327.46	[-62.762 – 62.762]	[264.69 – 390.22]
167	159.84	[-30.64 – 30.64]	[129.2 – 190.48]

Bus	Basecase generation in MW	Modified Generation in MW
6	748	708
65	2210	2610
103	765	465
116	594	294
118	3267	2867
140	3195	3295
144	1290	1190

Results – Approach I – WECC System

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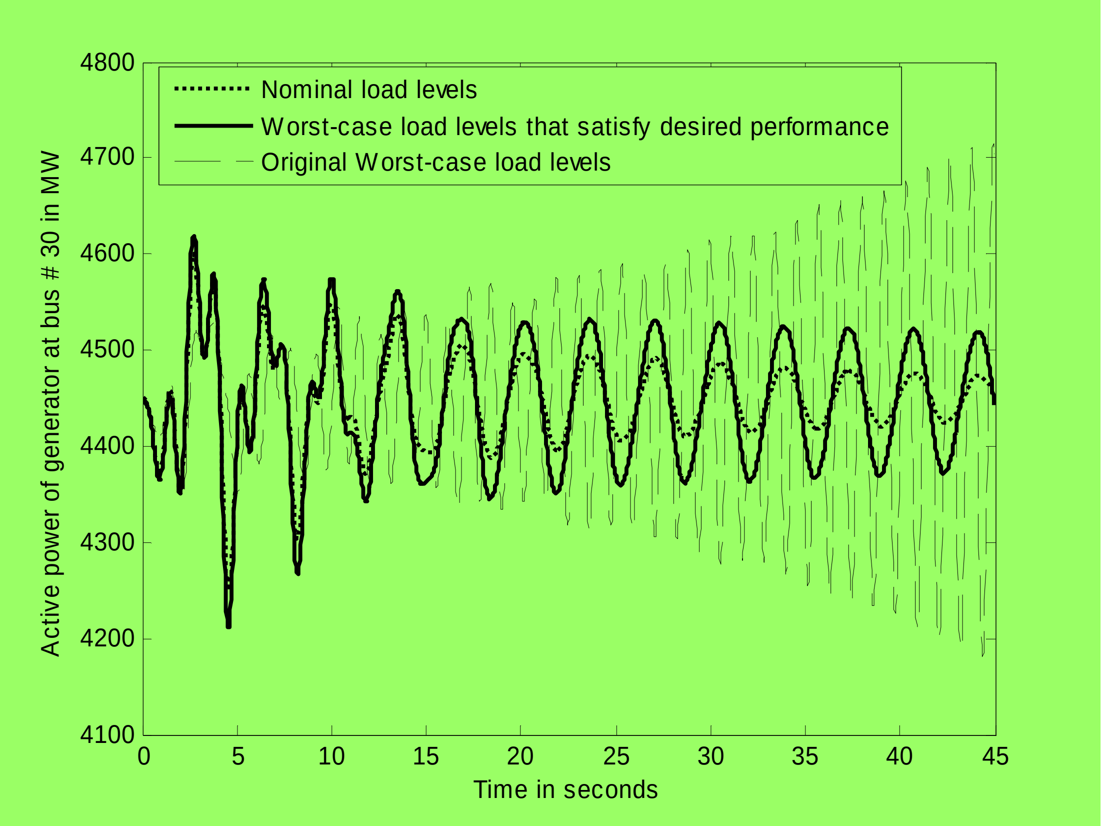
Response of active power generated at bus # 30
for 50 ms 3-phase fault at bus # 44

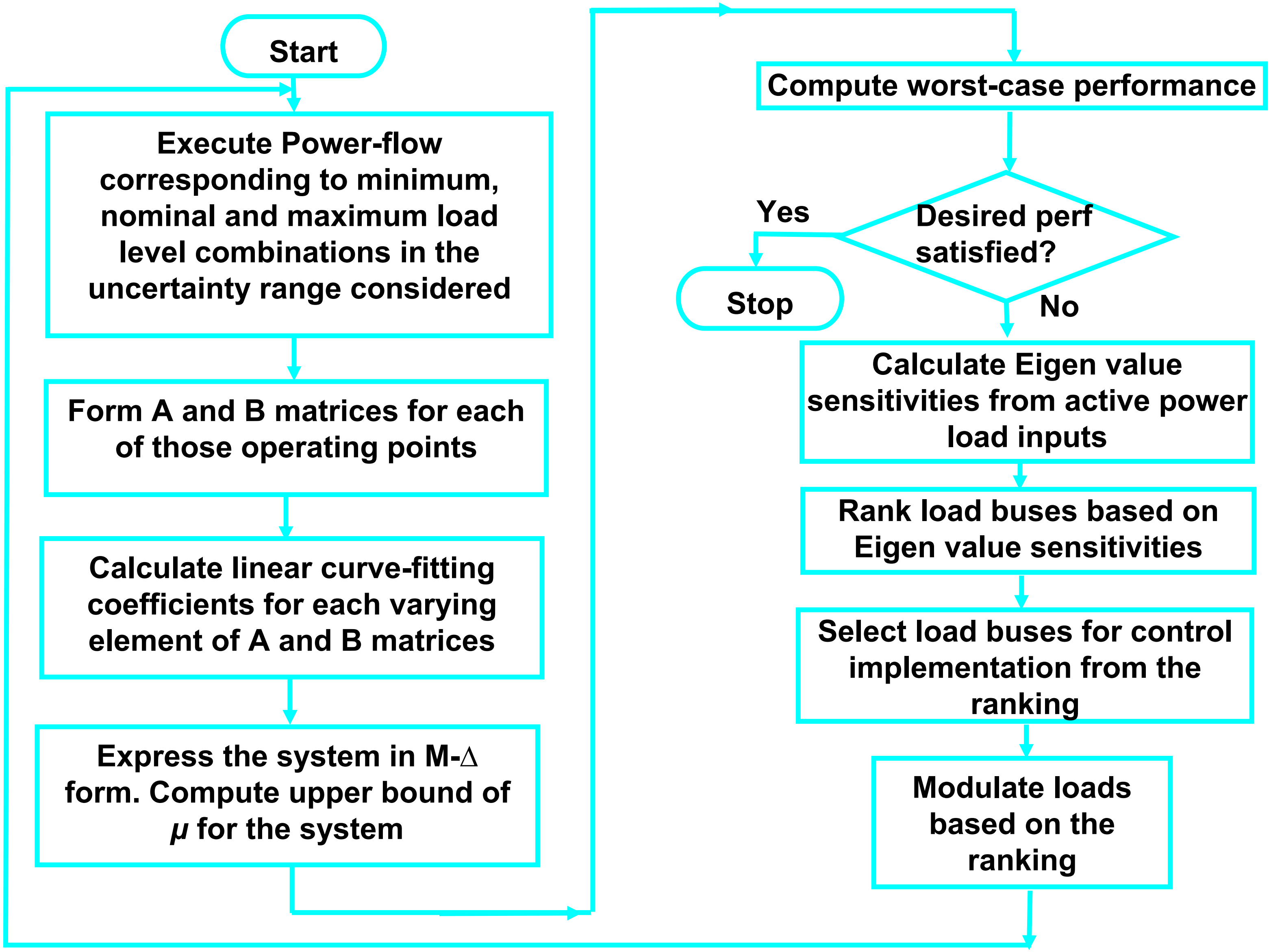


Mode	Eigen value	Damping ratio in %
1	**–0.037 ± j1.84**	**2.01**
2	–0.097 ± j5.54	1.75
3	–0.155 ± j6.73	2.3

Approach II – Worst-case Performance for Given Uncertainty

- Uncertainty could exist in load, generation or any model parameter
- System required to satisfy the chosen performance specifications over the range of uncertainty
- Fundamental premise – Strong correlation between performance *μ* upper bound peaking frequencies and critical mode frequencies
- Overall damping performance enhancement through modulation of loads for each critical mode identified
- Load modulation performed based on sensitivities of controllable active power loads to critical Eigen values
- Load modulation is iterative and is performed until the worst-case performance satisfies desired performance
- Skewed - *μ* of **N** evaluated for determining worst-case performance by varying just the performance part of the augmented uncertainty
  - Defining $K_n = \begin{bmatrix} I & 0 \\ 0 & k_n I \end{bmatrix}$ and iterate on k_n until performance *μ* is unity

Approach II: Algorithm



Start

Execute Power-flow corresponding to minimum, nominal and maximum load level combinations in the uncertainty range considered

Form A and B matrices for each of those operating points

Calculate linear curve-fitting coefficients for each varying element of A and B matrices

Express the system in M-Δ form. Compute upper bound of μ for the system

Compute worst-case performance

Desired perf satisfied?

Yes

Stop

No

Calculate Eigen value sensitivities from active power load inputs

Rank load buses based on Eigen value sensitivities

Select load buses for control implementation from the ranking

Modulate loads based on the ranking

Results – Approach II – WECC System

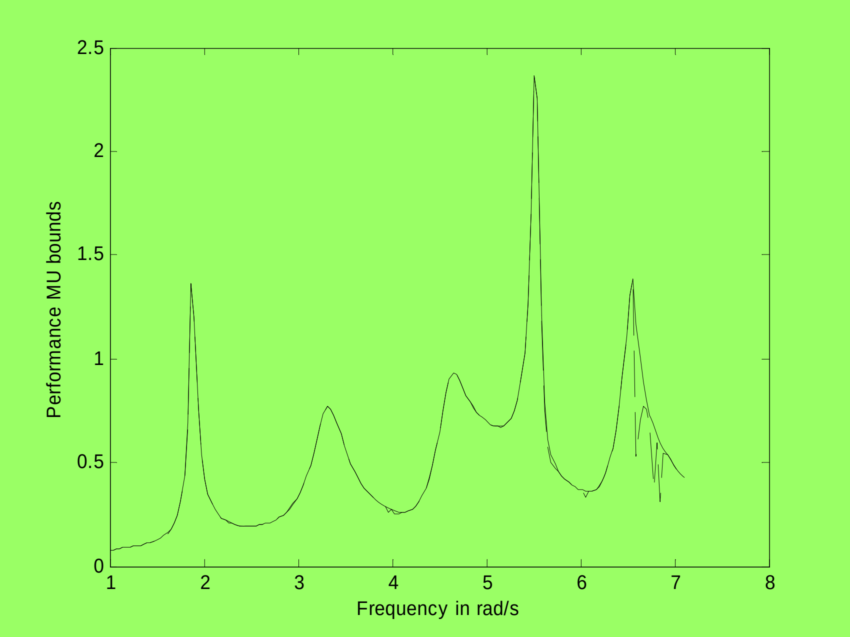
- Uncertainty in generation at buses 140 and 144

Generation	Nominal generation in MW	Uncertain in generation levels in MW (8% uncertainty)
140	**3195**	**[2939.4 – 3450.6]**
144	**1290**	**[1186.8 – 1393.2]**

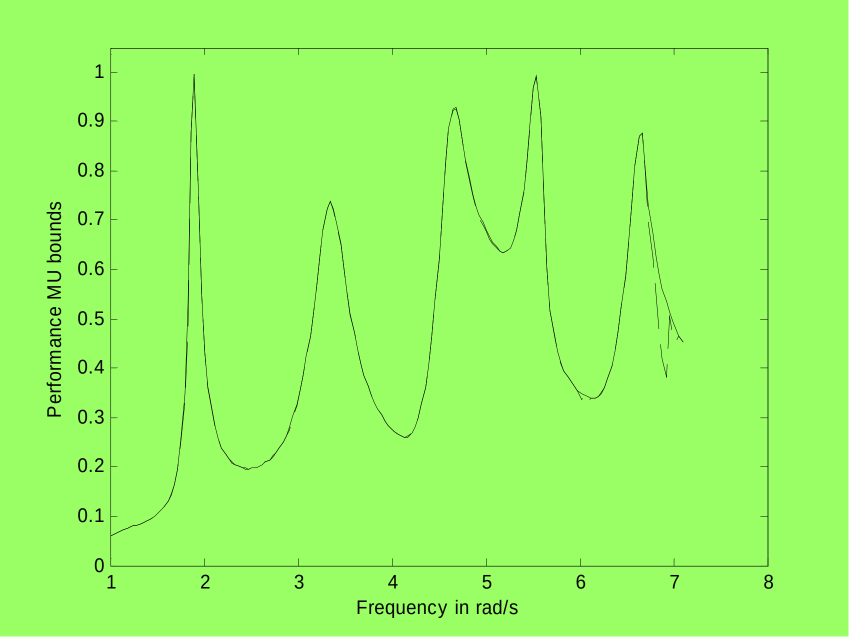
- Eigen value sensitivities
  - 2, 141, 143, 145, 136, 150, 50, 51 (All –ve for Mode 1)
  - 143, 51, 154, 50, 55, 109, 150, 41 (All +ve for Mode 2)
  - 113, 66, 109, 50, 51, 55, 65, 41 (All +ve for Mode 3)

- Performance weight $\dfrac{0.73s^2}{6s^2+21s+189}$

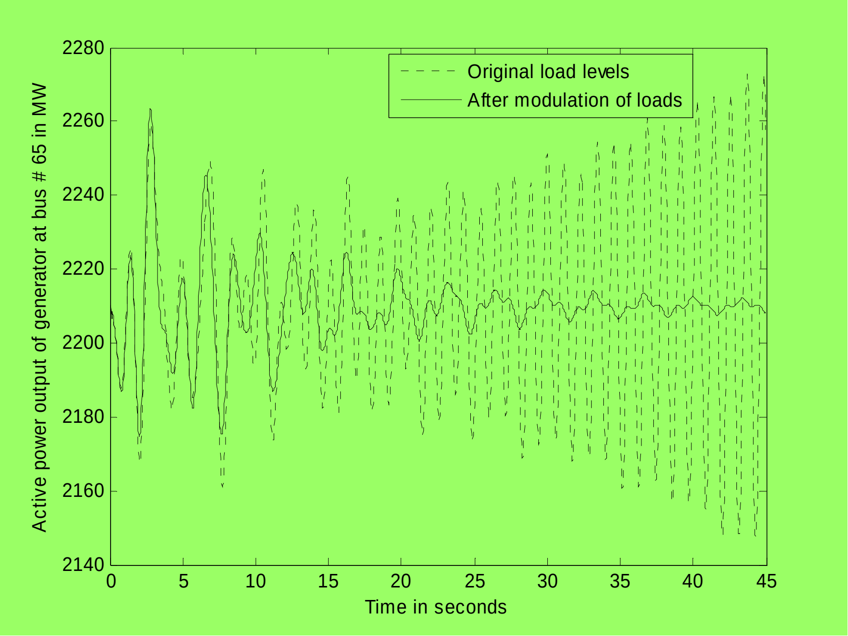
- Based on ranking and amount of load available for modulation
  - 2, 5, 16, 17, 51, 136, 139, 141, 143, and 152



Results – Approach II – WECC System



Performance μ bounds with 5.9% of each load modulated



Response of active power generated at bus # 65 for 50 ms 3-phase fault at bus # 44

Mode	Eigen value	Damping ratio in %
1	–0.0378 ± j1.89	2.00
2	–0.0554 ± j5.54	1.00
3	–0.0793 ± j6.61	1.19

Load Control Algorithms

- To modulate different controllable loads in real-time
- Controllable loads
  - Residential and commercial air-conditioners
  - Residential water-heaters
- Cold-load pickup
  - Sudden surge of load in a distribution feeder after a planned or unplanned outage when supply is restored
  - Caused as a result of loss of diversity among thermostatic loads
  - Well studied in distribution system design
  - Need for continuous control and an optimization approach
  - Load control problem rather than a load shedding problem

Load Control Algorithms – High-level Overview

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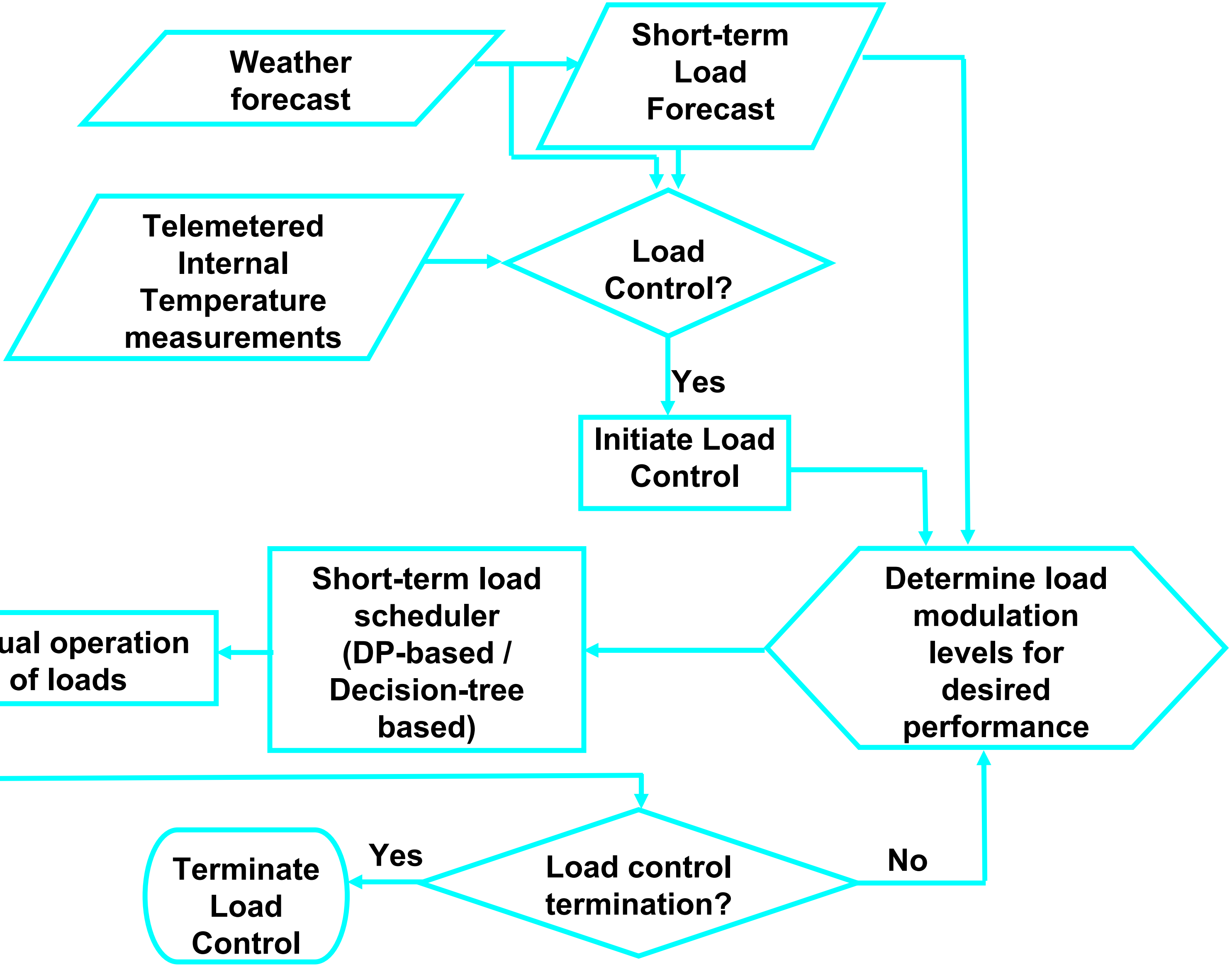
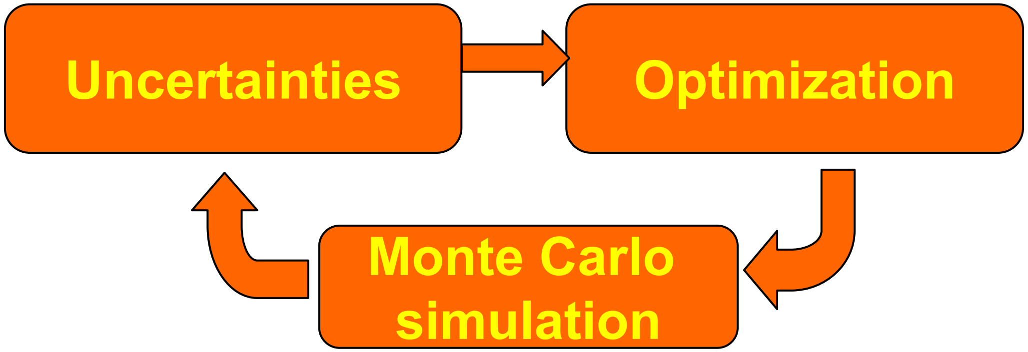


Regarding the Results

- Typical scenarios for control at the distribution level with emphasis on the framework developed, type of studies and conclusions drawn
- Optimization problem
  - Minimize amount of load modulation
  - Effective cycling of loads
  - DP based optimization for air-conditioner, Decision-tree algorithm for water-heaters



- Optimization framework for performing Monte Carlo simulations
  - Impact of artificial constraints introduced for effective cycling
  - Impact of different uncertain parameters on the effectiveness of control
    - Thermostat set point distribution, parameters of the model for air-conditioners, and internal temperature distribution

DP Optimization Problem

- There are multiple feeders for control
- A feeder is assumed to supply several large air-conditioner loads or groups of air-conditioner loads
- A group of air-conditioner load is an aggregation of several individual smaller air-conditioners that have the same thermostat setting and similar duty cycles
- Dynamic model for air-conditioner loads applied in optimization algorithm (proposed by Schweppe and Ihara in 1982)
- Small-signal stability boundary for Nordic system at the distribution level

$$0.50953(P_{51\_1}+P_{51\_2}+P_{51\_3}+P_{51\_4}+P_{51\_5}) = 100-0.51715(P_{61\_1}+P_{61\_2}+P_{61\_3}+P_{61\_4}+P_{61\_5})$$

- Add artificial constraints that ensure effective cycling among different load circuits

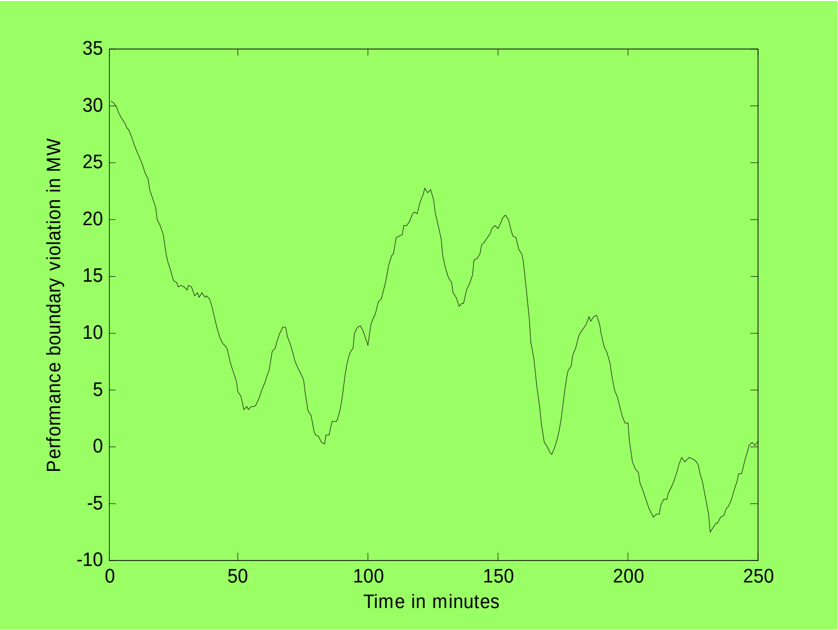
  A) Maximum Off-time and Minimum On-time

  B) Constraint on internal temperature excursion

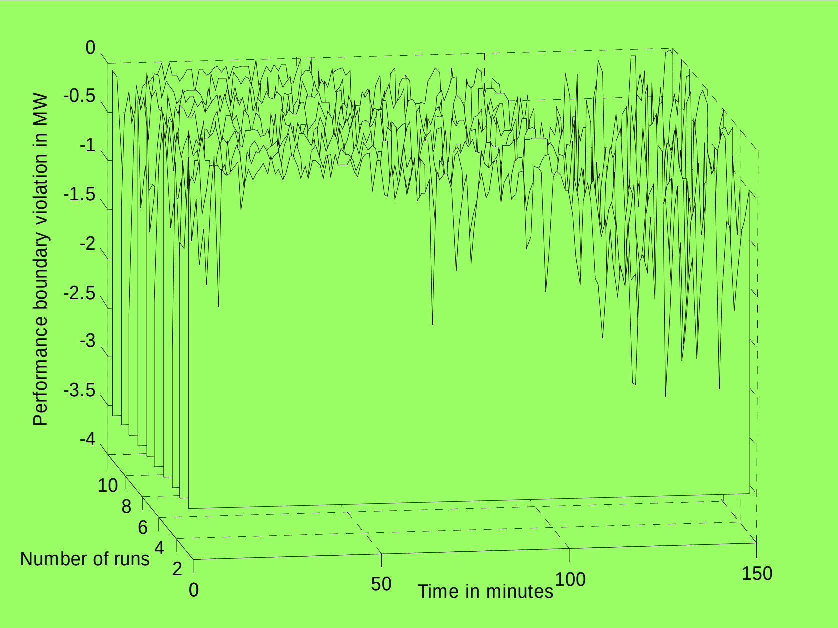
  (LIPAEdge direct load control program in 2002)

DP Results – Cycling Time Constraints

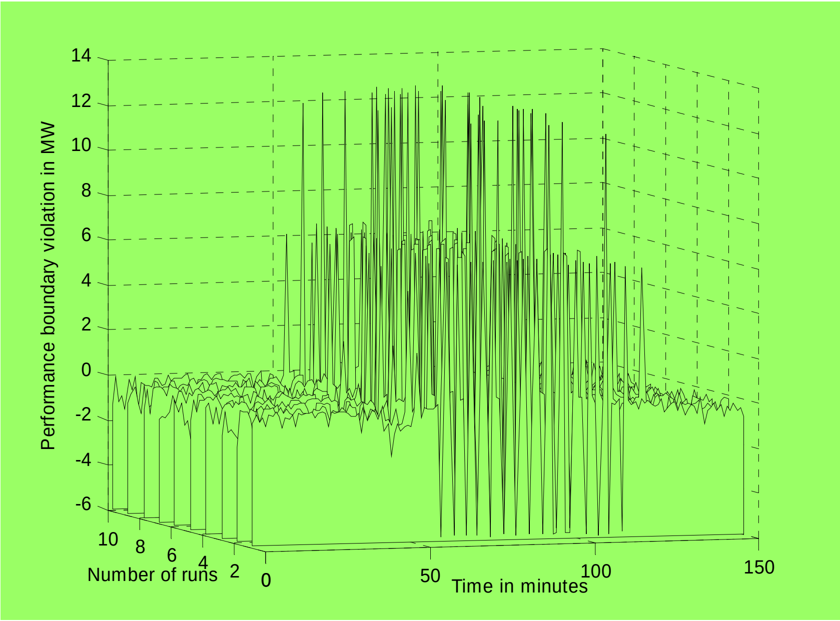
Without control



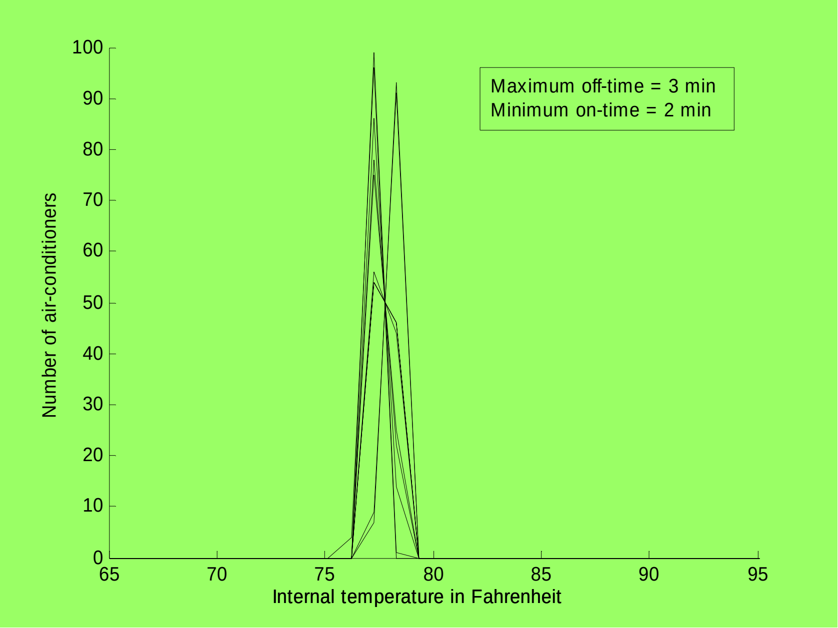
Max. OFF time = 4 min, Min. ON time = 2 min

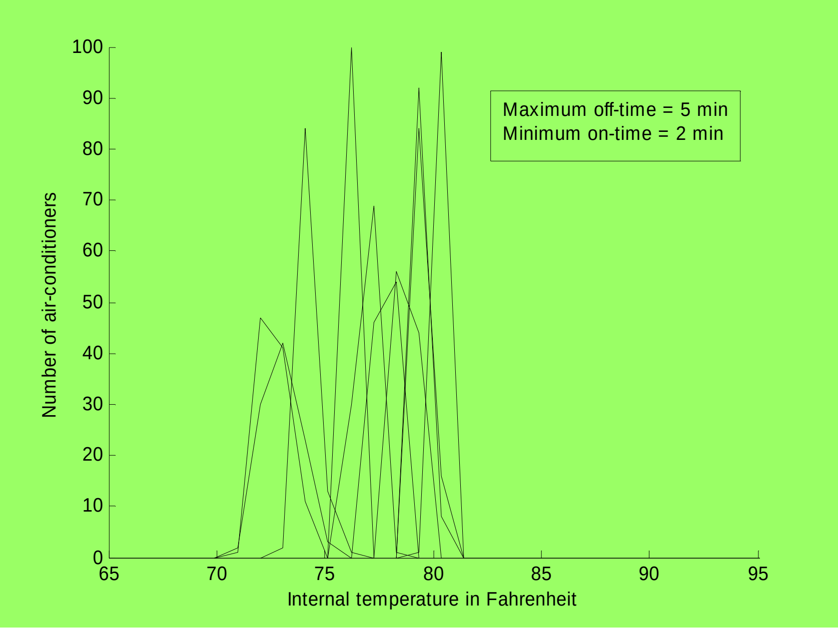


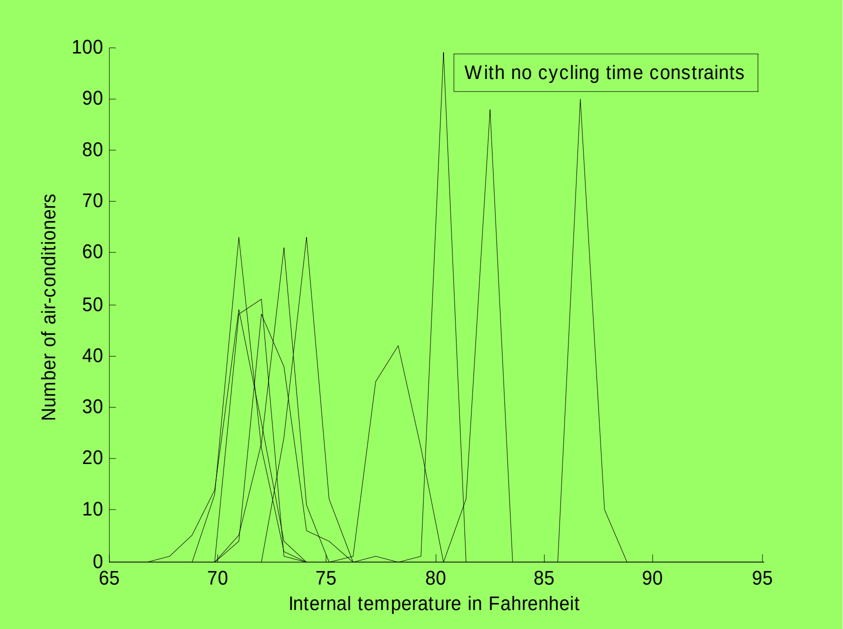
Max. OFF time = 2 min, Min. ON time = 2 min

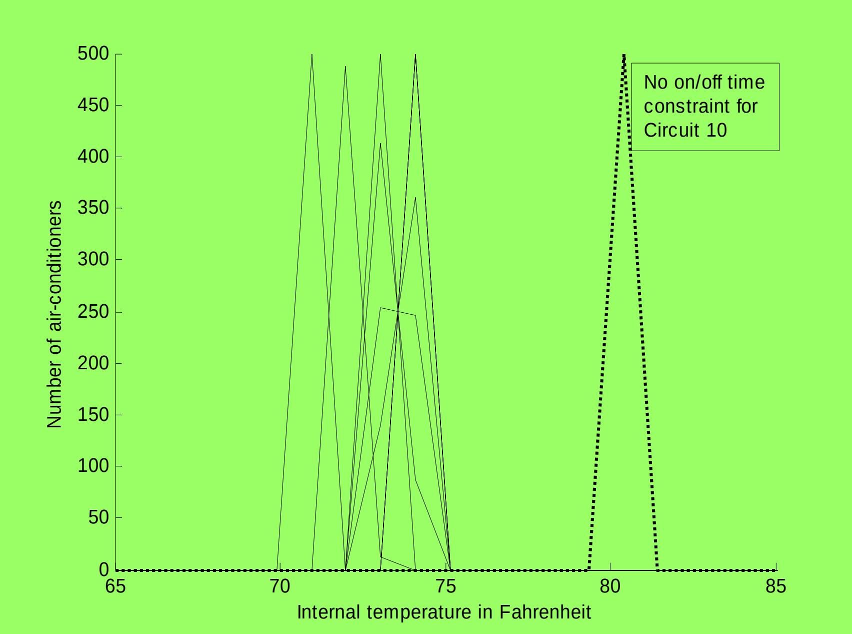


DP Results – Cycling Time Constraints

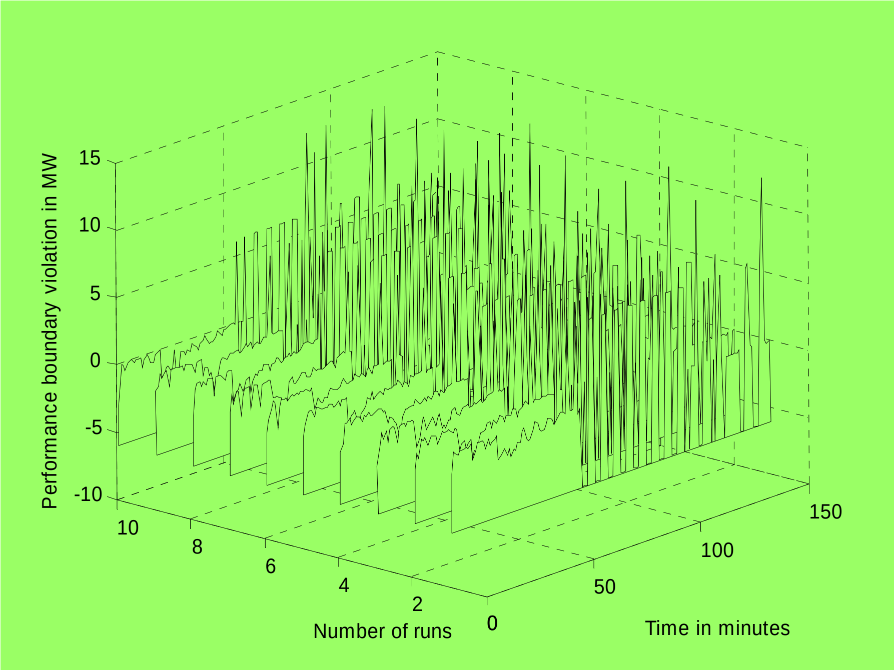






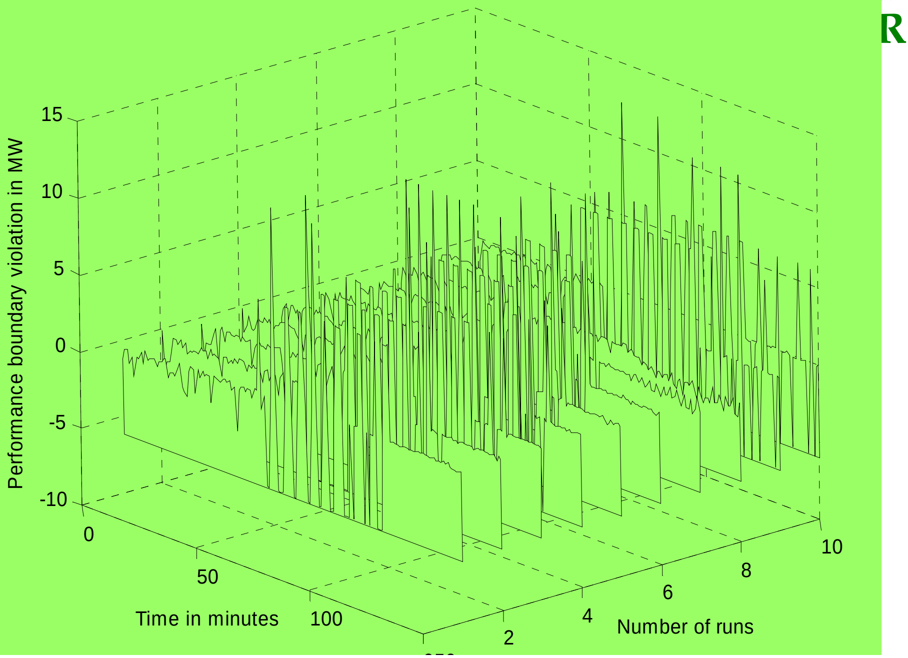


DP Results – Effect of Diversity



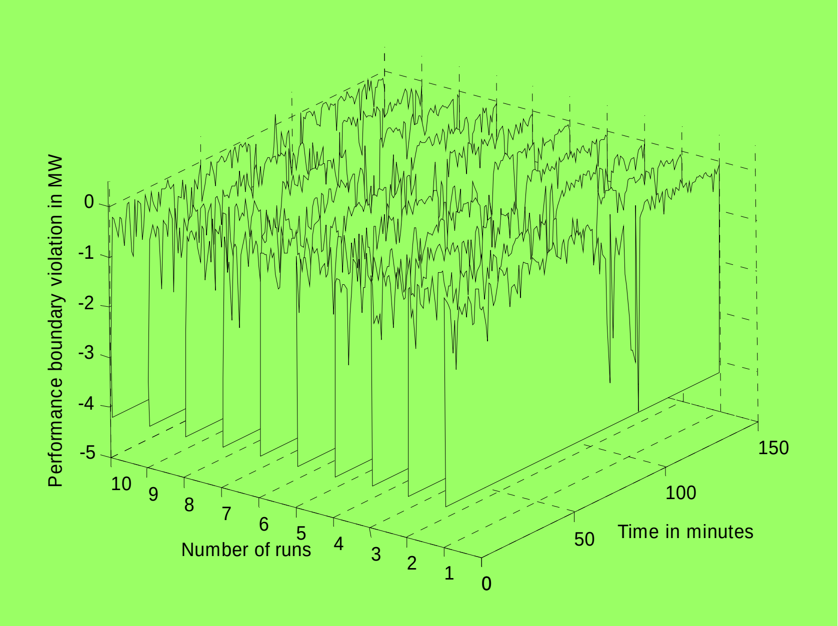
Initial temp. N(79,4)

Thermostat N(72,2)



Initial temp. N(79,20)

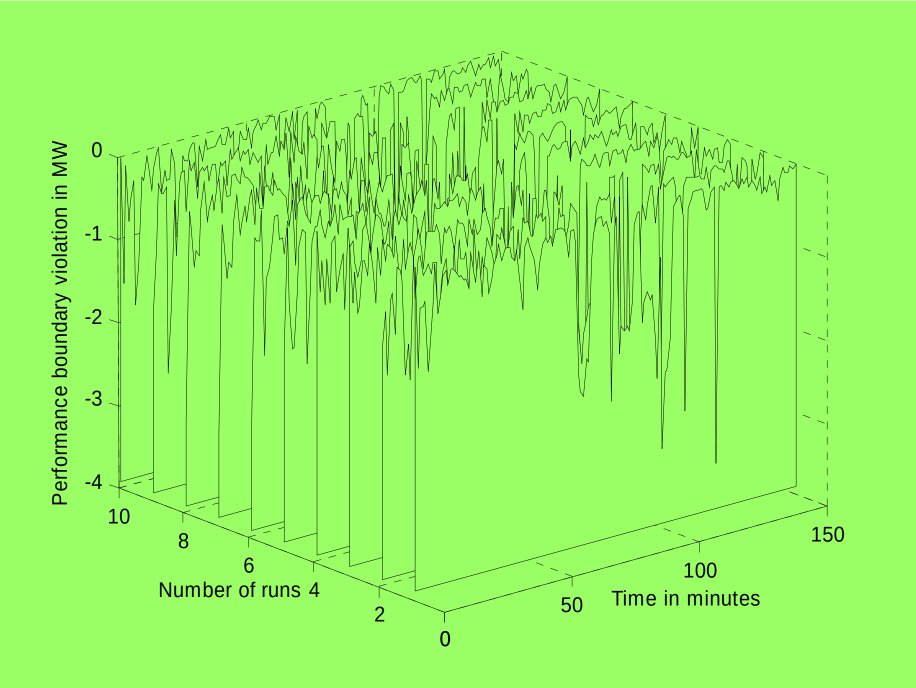
Thermostat N(72,2)



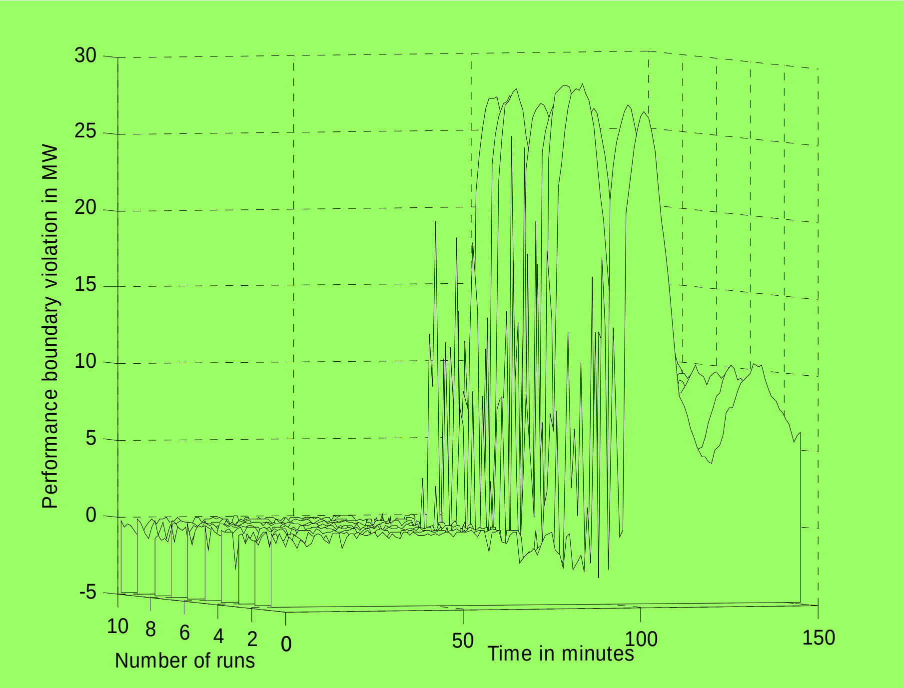
Initial temp. N(79,4)

Thermostat N(72,5)

DP Results – Temperature Excursion Constraints

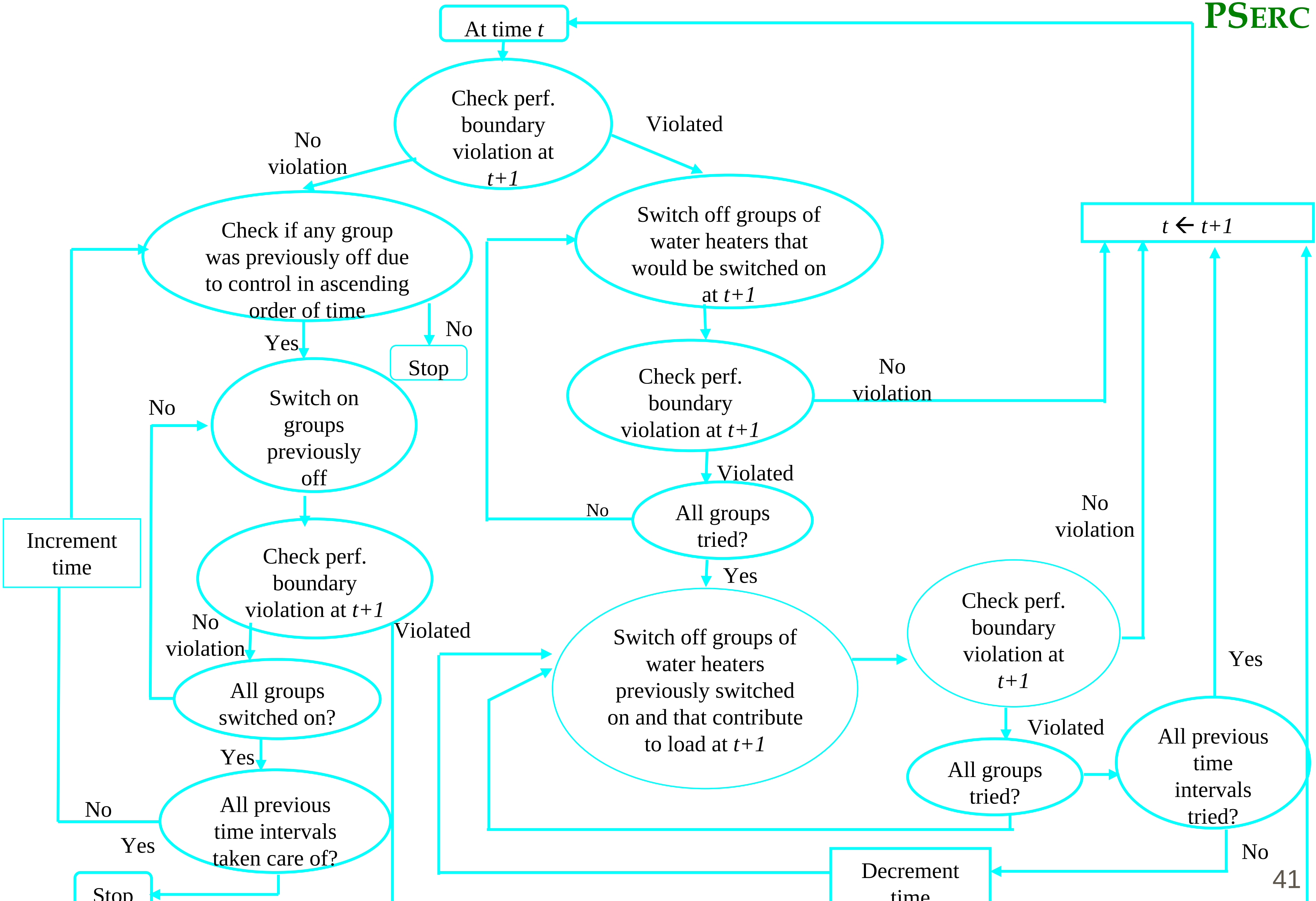


Avg. temp constraint of 78 F for all circuits



Avg. temp constraint of 75 F for all circuits

Water Heater Control Decision Tree Algorithm



At time *t*

Check perf. boundary violation at *t+1*

No violation

Violated

Check if any group was previously off due to control in ascending order of time

Yes

No

Stop

Switch on groups previously off

Check perf. boundary violation at *t+1*

No violation

Violated

All groups switched on?

No

Yes

All previous time intervals taken care of?

No

Yes

Stop

Increment time

Switch off groups of water heaters that would be switched on at *t+1*

Check perf. boundary violation at *t+1*

No violation

Violated

All groups tried?

No

Yes

Switch off groups of water heaters previously switched on and that contribute to load at *t+1*

Check perf. boundary violation at *t+1*

No violation

Violated

All groups tried?

All previous time intervals tried?

Yes

No

Decrement time

t ← *t+1*

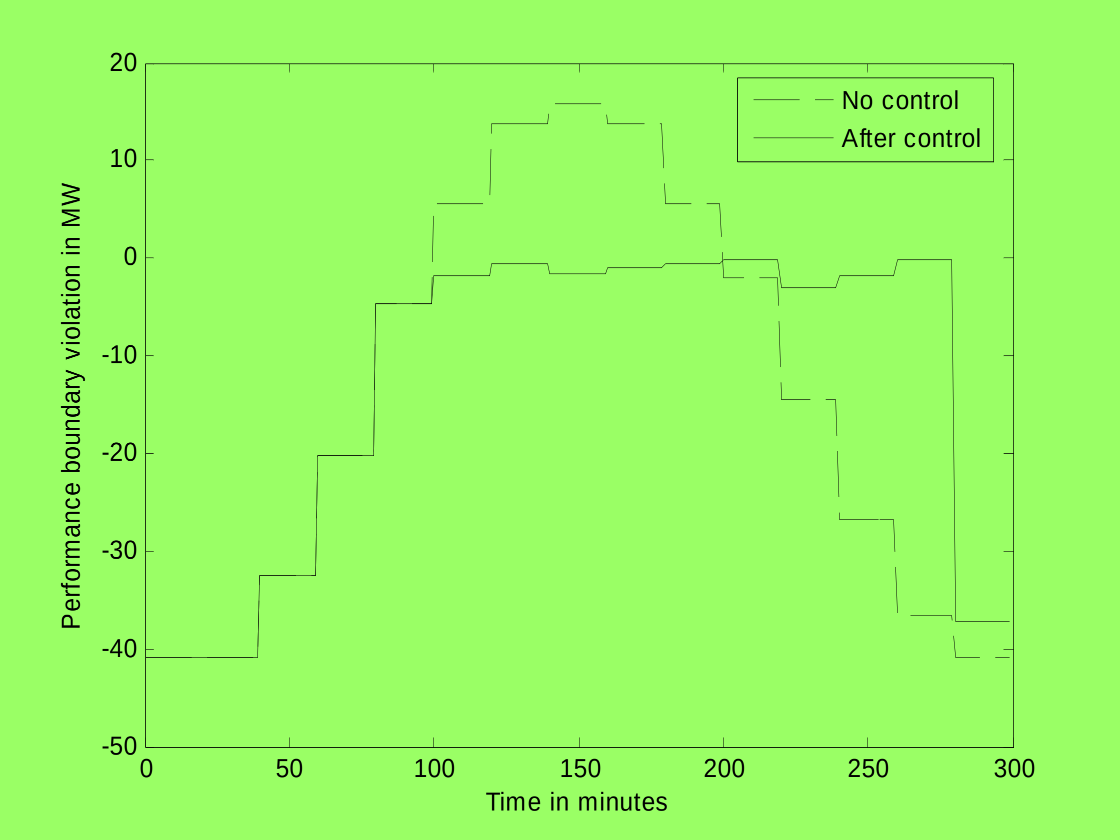
Example: Water Heater Usage Pattern

PSERC

Time interval (in minutes)	Usage (in Numbers)	Cumulative usage considering on time (= 60 minutes)	Water heater load (controllable load) in MW(Avg. heater rating = 4 kW)
0 – 20	0	0	0
20 – 40	0	0	0
40 – 60	400	400	1.6
60 – 80	600	1000	4
80 – 100	750	1750	7
100 – 120	900	2250	9
120 – 140	1000	2650	10.6
140 – 160	850	2750	11.0
160 – 180	800	2650	10.6
180 – 200	600	2250	9
200 – 220	480	1880	7.52
220 – 240	200	1280	5.12
240 – 260	0	680	2.72
260 – 280	0	200	0.8
280 – 300	0	200	0.8

Example: Control Algorithm

Performance boundary



Conclusions

- Direct load control for stability enhancement
  - Robustness
  - Ease of coordination
  - Technology has evolved to make control of distributed resources feasible
  - Economic viability as DA infrastructure can be utilized
  - Market-based operation resolves issues related to security costs
  - Institutional framework being developed
    - Good potential to utilize market framework developed for other load control programs

Conclusions – Contributions of this Work

- Comprehensive effort to examine the feasibility, framework and issues for the application of direct load control for stability enhancement

- Direct load control on power system dynamic security

  - Development of analysis framework for preventive load modulation
  - Development of two fundamentally different approaches for analyzing amount of load modulation for desired stability performance
  - Demonstrated accuracy of framework, analysis approaches, robustness of the scheme

- Specialized algorithms for implementing real-time control of thermal loads
  - Optimization approach for load modulation in real-time
  - Detailed study of the impact of constraints and parameters involved using Monte Carlo simulations
  - Useful insights for demand side management with minimum disruption
  - In line with recent direct load control programs executed recently