Thank

You!

Real-Time Simulation and Modern Power System Operational Studies

G. Kumar Venayagamoorthy, PhD, MBA, FIET, FSAIEE

Duke Energy Distinguished Professor &
Director and Founder of the Real-Time Power and Intelligent Systems Laboratory
Clemson University, Clemson, SC 29634, USA

Honorary Professor of the School of Engineering
University of KwaZulu-Natal, Durban, South Africa
gkumar@ieee.org
http://rtpis.org

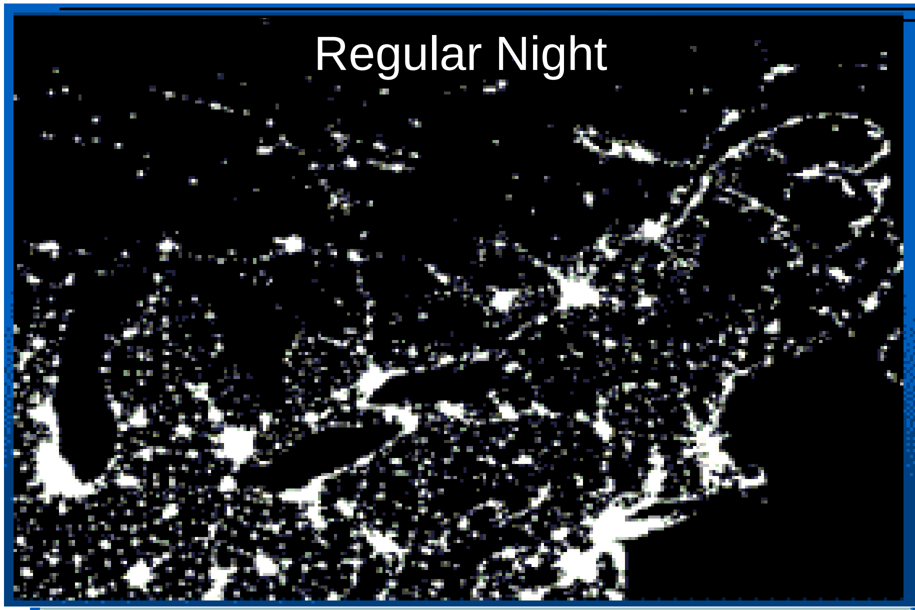
Acknowledgement: US NSF, US DOE and US AFOSR

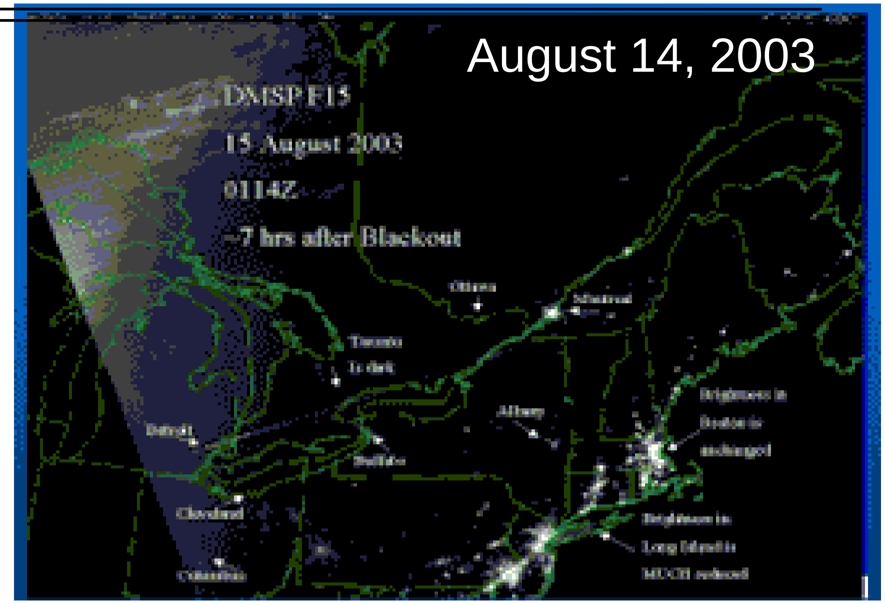
Outline

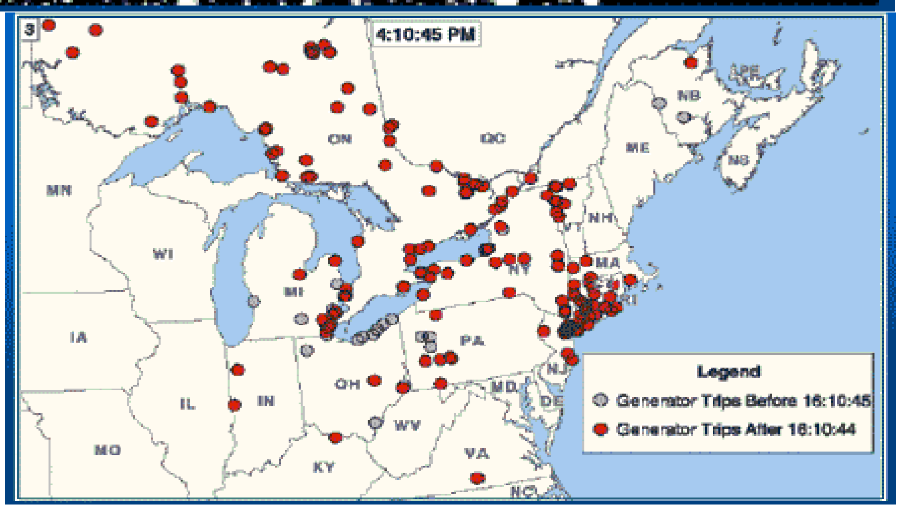
- Introduction
- RTPIS Lab @ Clemson
  - Optimal Controller Tuning
  - Enhanced AGC Control
  - Coherency Analysis & Wide Signals based Control
  - SmartPark
  - Cyberattack
- Summary

August 14, 2003 Blackout

IEEE Spectrum February 2005







- > 60 GW of load loss;
- > 50 million people affected;
- Import of ~2GW caused reactive power to be consumed;
- Eastlake 5 unit tripped;
- Stuart-Atlanta 345 kV line tripped;
- MISO was in the dark;
- A possible load loss (up to 2.5 GW)
- Inadequate situational awareness.

Situational Awareness

- Situational awareness (SA) is the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future [Endsley].
- SA is an intermediate process in assessing the status of the system in order to make ‘intelligent’ decisions for future development.

Just-in-Time

- Latency – very important in building a data analytic architecture.
- Data Analytics Challenge
  - Operations
  - Energy trading
  - RT demand response
  - Asset management
- Complex Data processing and analytics environment:
  - Hierarchical to distributed
  - Multiple data classes
  - Latencies.

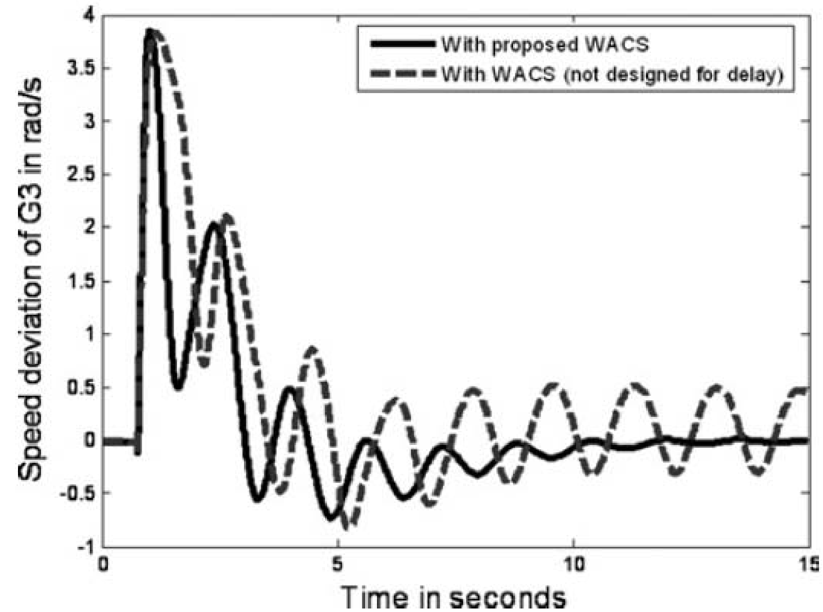


Fig. 6 *Speed deviation of generator G3 with the proposed controller and WACS not designed for the delays for a three-phase short circuit at bus 10 (Fig. 1) for ten cycles (166.67 ms) duration*

Ray S, Venayagamoorthy GK, "Real-Time Implementation of a Measurement based Adaptive Wide Area Control System Considering Communication Delays", IET Proceedings on Generation, Transmission and Distribution, Vol. 2, Issue 1, Jan. 2008, pp. 62 - 70.

IT-OT
Convergence or Bankruptcy?

- It is the smart grid infrastructure and the associated use of the data in decision-making that will ultimately decrease operational costs related to improved forecasting of demand, better ability for customers to manage their loads, enhanced service delivery and reliability, and an infrastructure that will allow new cost-recovery mechanisms.

- This requires new models of data management including the movement away from siloed storage and access amid new cyber security concerns.
  - Big Data Operational Analytics (BDOA)

- It also calls for a renewed focus on analytics to breakdown big data into descriptive, predictive and prescriptive subsets.

"The purpose of a business is to create a customer" – Peter Drucker

Models in Analytics

Models are the heart and lungs of advanced analytics.

It is a science and art to develop a model.

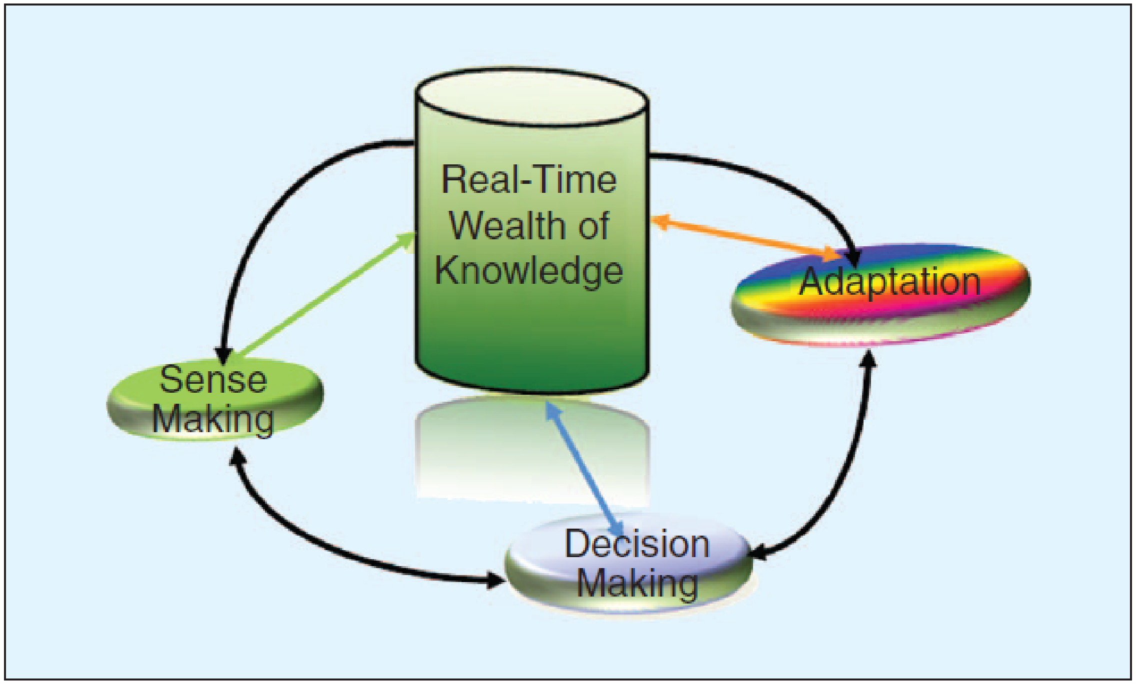
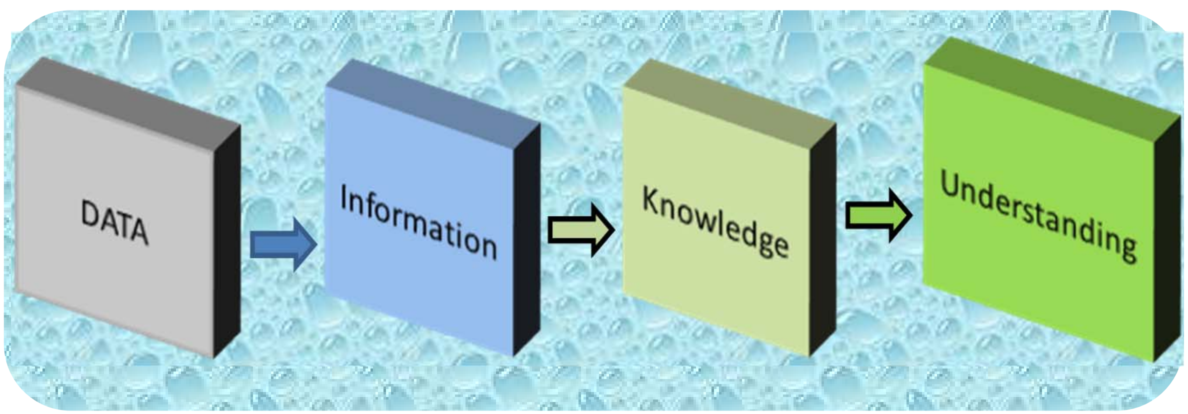


FIGURE 1 CSTM – the integrated cycle of sense-making, decision-making and adaptation. The knowledge base is the domain of expertise evolved continuously with experience accumulated.

"Dynamic, Stochastic, Computational, and Scalable Technologies for Smart Grids," Computational Intelligence Magazine, IEEE , vol.6, no.3, pp.22-35, Aug. 2011.

Mind the Gap

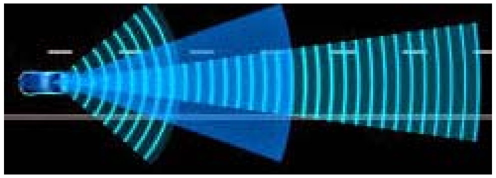
- The significant expertise deficit related to big data management, analytics, and data science is one of the major reasons utilities have not been able to effectively use smart grid data.
- Data scientists not only need to know how to data wrangle, they must also know how to operate a variety of tools on a variety of platforms fed with vast amounts of varied data.
- Energy-savvy data scientists are capable of changing the way the utility views the world and gets business done.



"Knowledge has to be improved, challenged, and increased constantly, or it vanishes."
Peter Drucker

Situational Intelligence

- Situational intelligence (SI) is looking ahead how the situations will unfold over time – *immersion into future*
- In other words, SA systems present situations based on some measurements of current states at time *t*. Whereas, SI uses SA at time *t* and predictions of future states to predict SA at a time $t+\Delta t$.
- Control centers need to handle big data, variable generation and a lot of uncertainties, and will need SI, that is to derive SA (information, knowledge and understanding) at time *t* and project it into time $t+\Delta t$.
- With SI technology implementations, real-time monitoring is possible.



Past to Future

US NSF Research Alliance/Partnership for Innovation Project: Situational Intelligence for Smart Grid Optimization and Intelligent Control – IIP #1312260

Objectives:

- Situation intelligence for real-time operations.
- Maximize penetration levels of variable and uncertain generation such as solar & wind power.
- Dynamic optimal energy & power management systems.
- Development of a rapid prototyping laboratory for real-time smart grid control centers.

Impacts:

- Energy resilience by improved reliability, sustainability and economic value.
- Rapid restoration from outages.
- Softening of negatives effects of the climate change on the economy.

Partners & Supporters:

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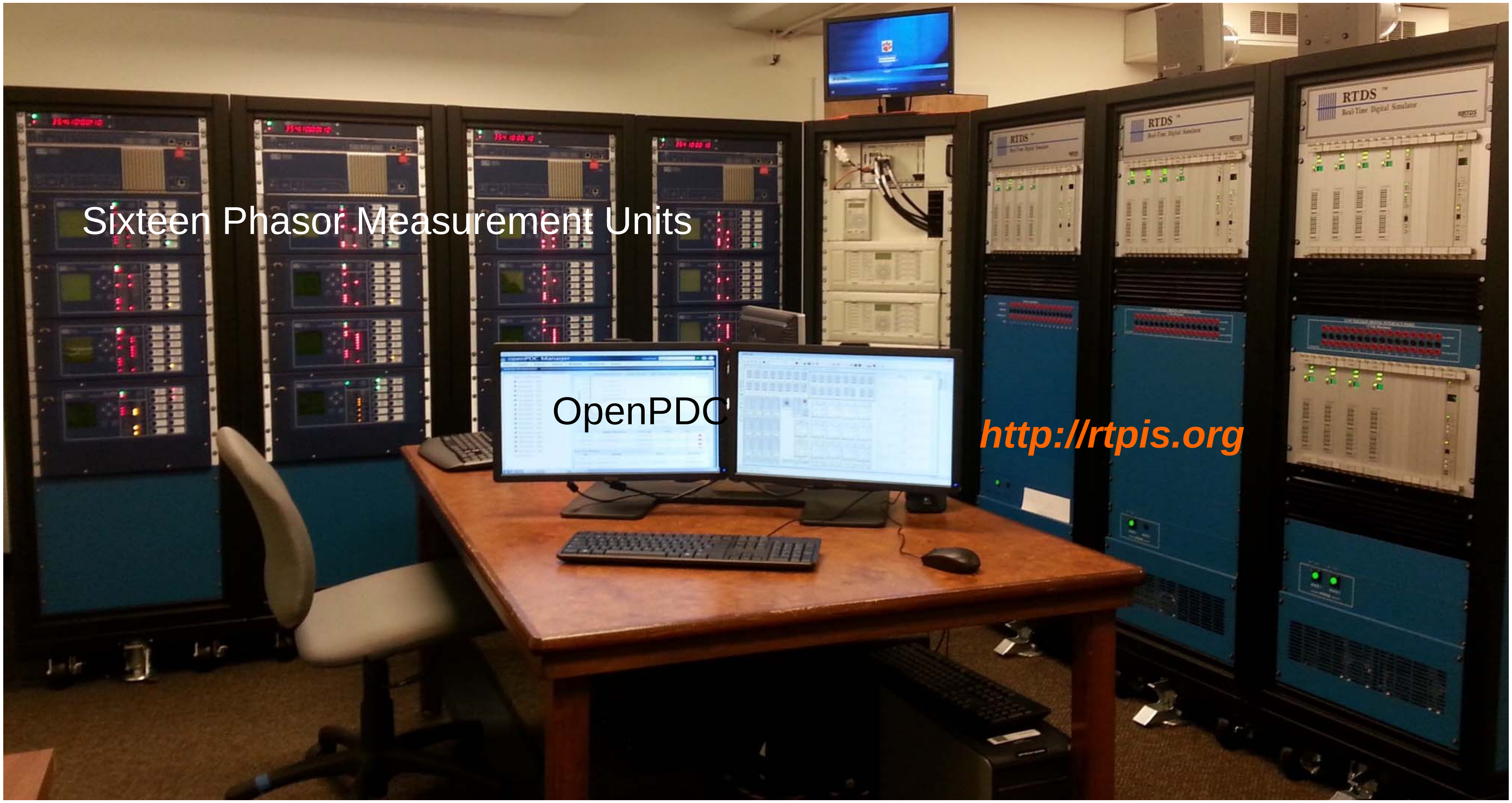
Real-Time Power and Intelligent Systems (RTPIS) Lab

Real-Time Grid Simulation Lab

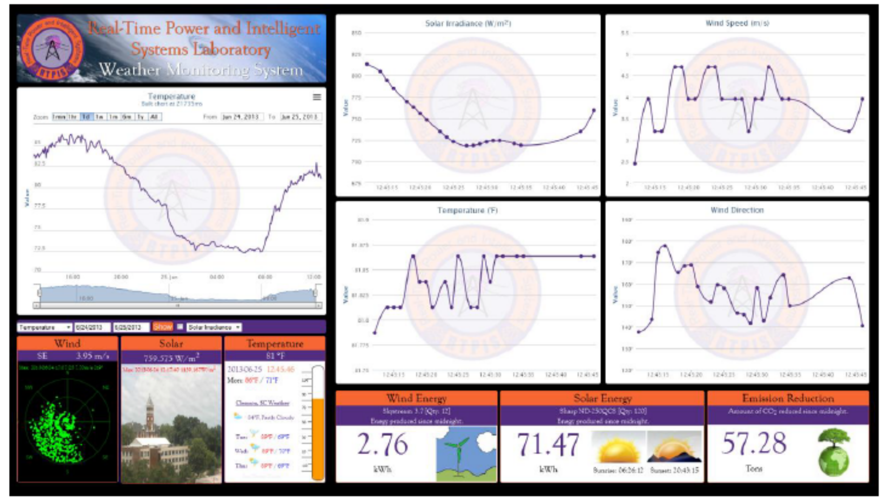


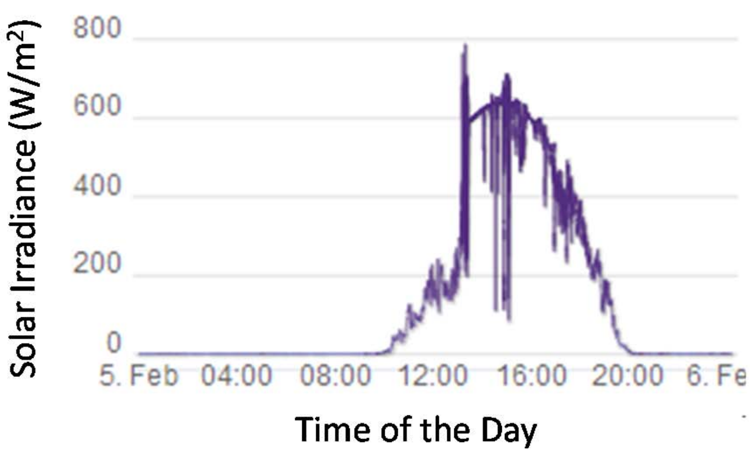
Situational Intelligence Laboratory

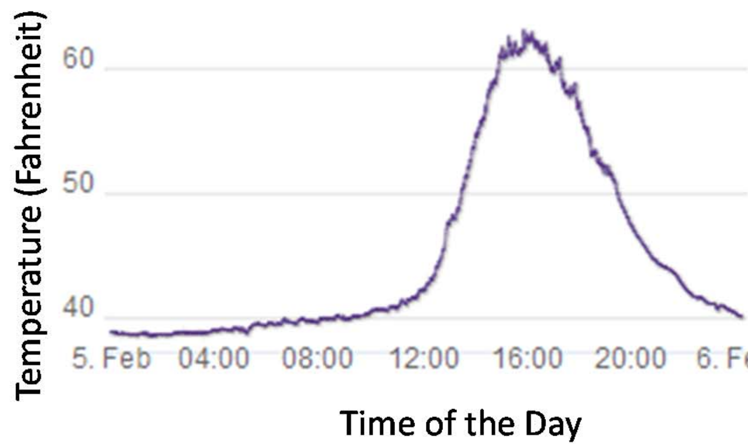
RISE Cluster

http://rtpis.org

RT-WIL with the RTDS







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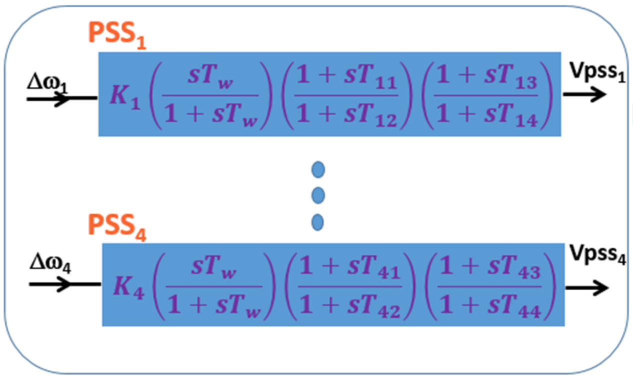
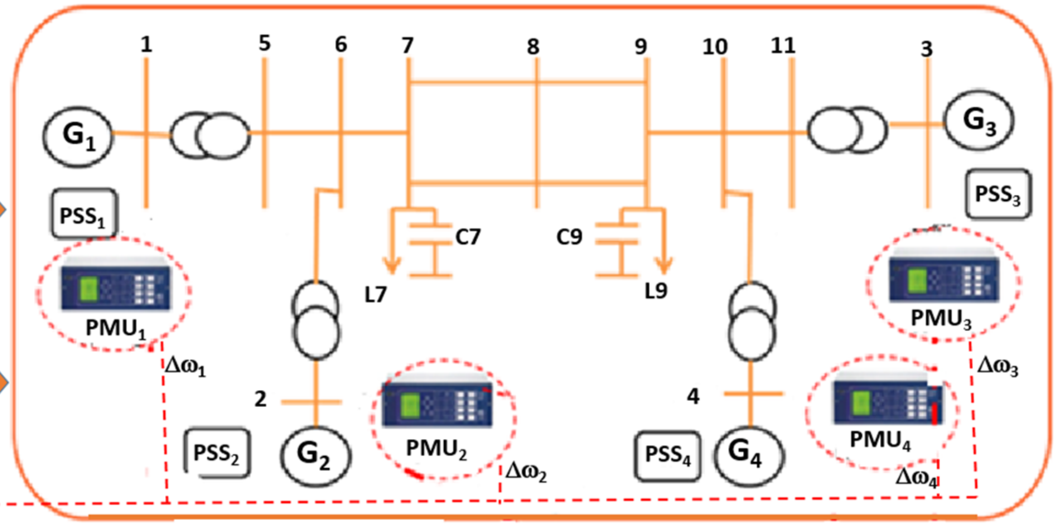
RTPIS Lab’s PSS Tuning Platform

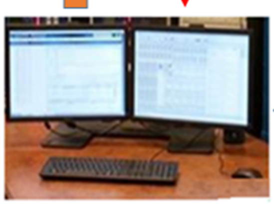
Four PSSs



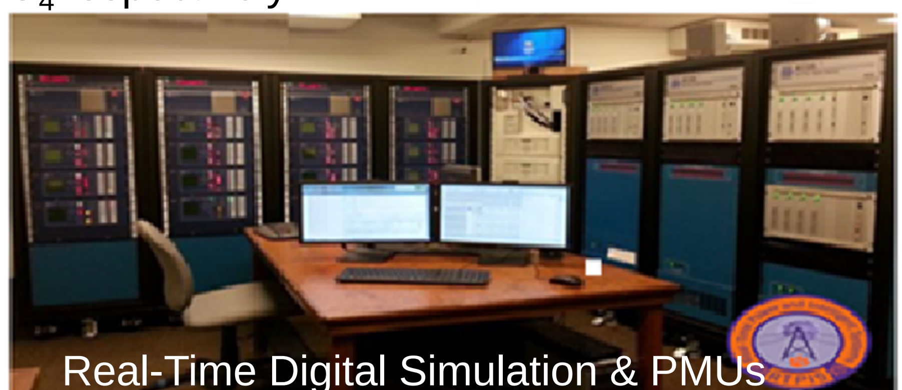


Speed deviations $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3$ & $\Delta\omega_4$ of G_1, G_2, G_3 & G_4 respectively

Tuning Algorithm (MATLAB Platform)



Time Synchronized

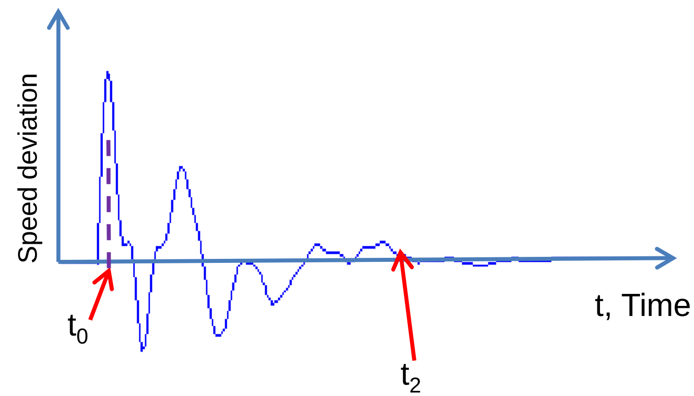


“Multiple Power System Stabilizers Tuning Using Mean-Variance Optimization”, *in Proc. 2015 IEEE Intelligent Systems Application to Power Systems (ISAP)*, Porto, Portugal, September 11-16, 2015.

Power System Stabilizer (PSS)

The function of PSS is to add an auxiliary signal to the generator's **AVR** in order to improve the damping of power system oscillations. PSSs are classified as,

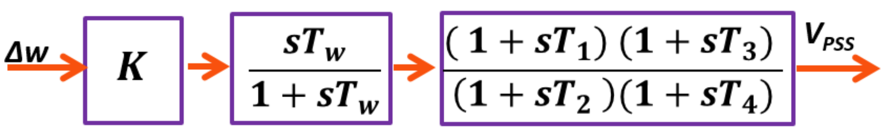
- Linear Compensators
  e.g. - Lead-lag controller
- Non-Linear Compensators



The objective function, J for simultaneous tuning of PSSs:

$$J = \sum_{i=1}^{n} \sum_{j=1}^{N} \sum_{t=t_0}^{t_2} (\Delta w(t))\, x\, (A\, x\, (t - t_0)\, x\, \Delta t)$$

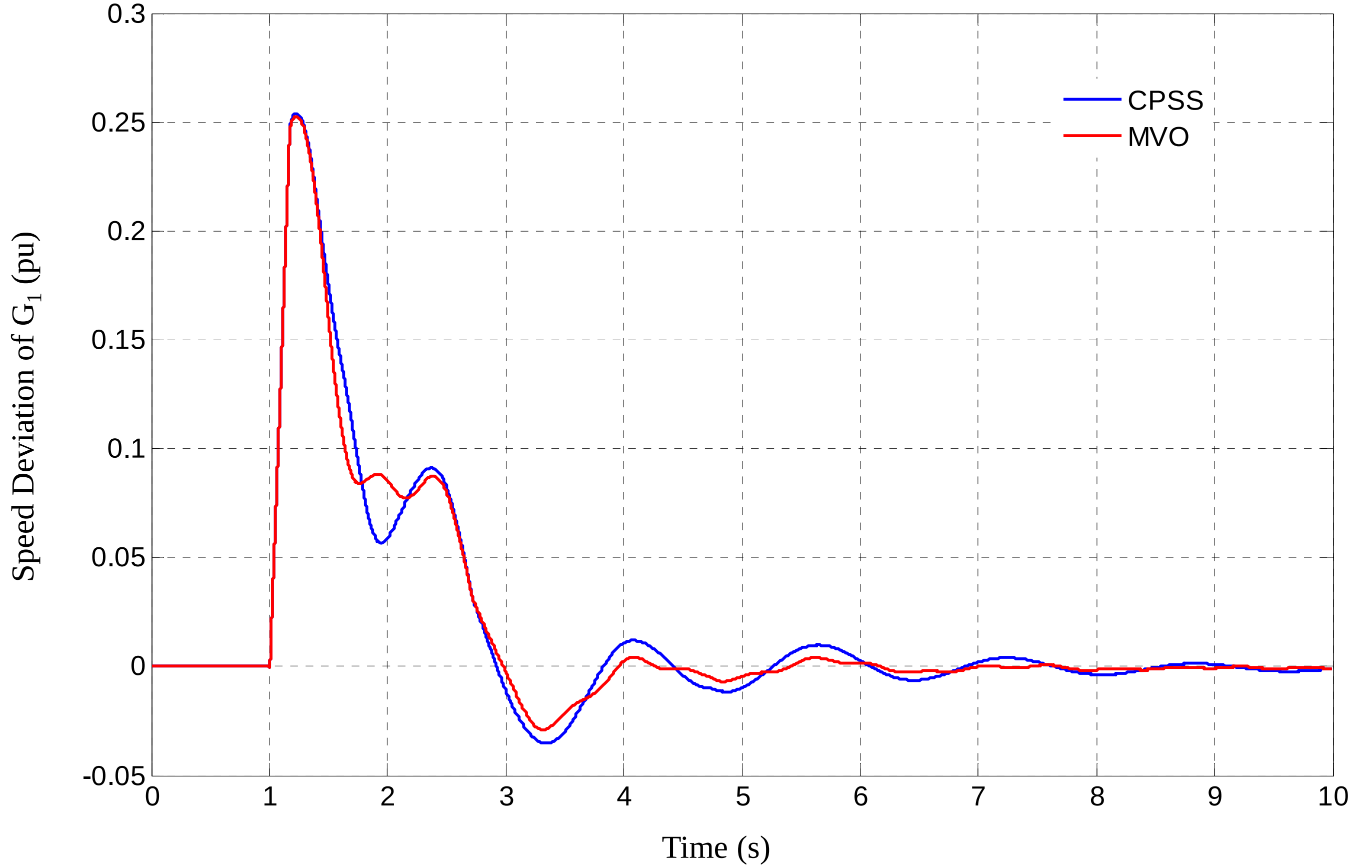
t = time,
A = constant,
N = Number of generators,
n = Number of operating conditions
t_0 & t_2 = start & stop time for area calculation respectively



K – gain
T_w – washout time constant
T_1, T_2, T_3 & T_4 – Phase compensation time constants

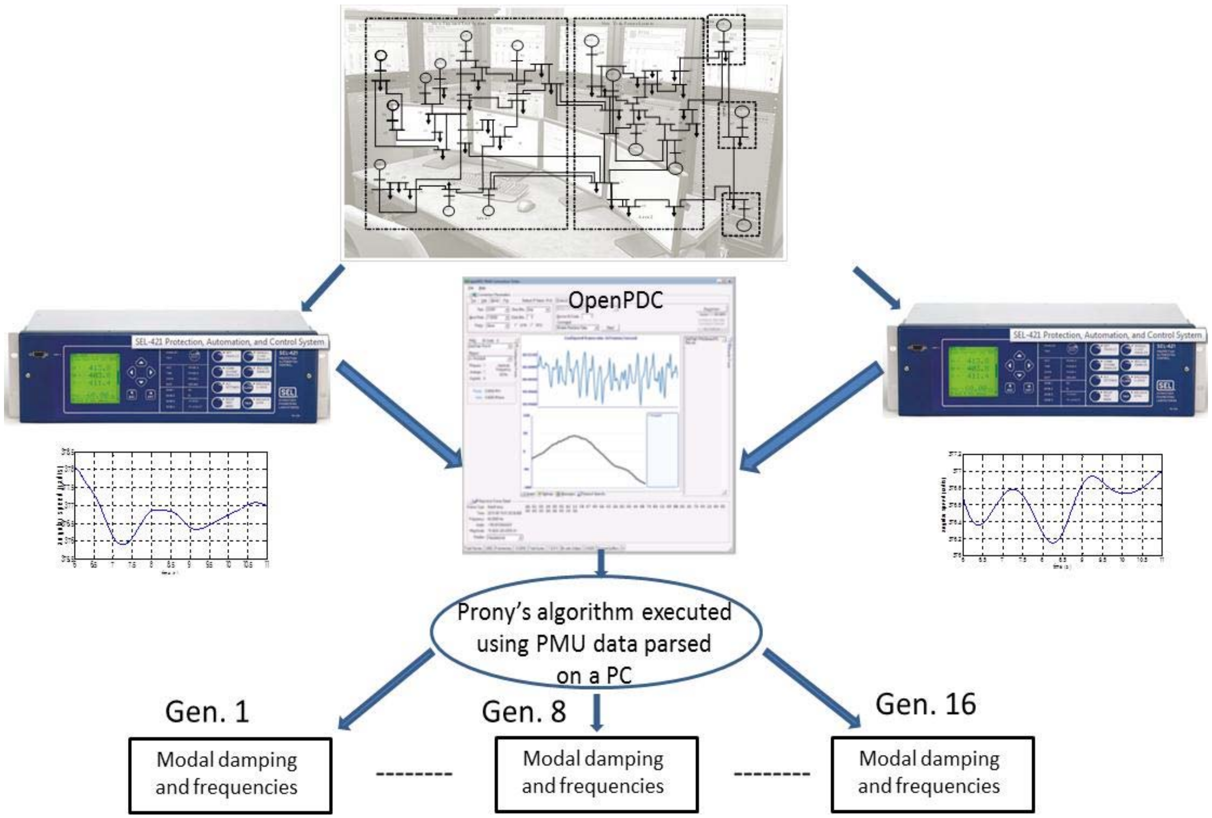
STATE-OF-THE-ART INDUSTRY POWER SYSTEM STABILIZERS NEED TO BE ADAPTIVE

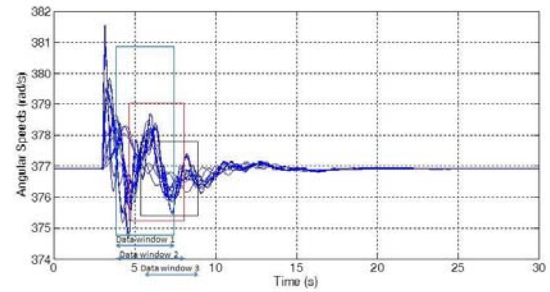
Results – Generator 1

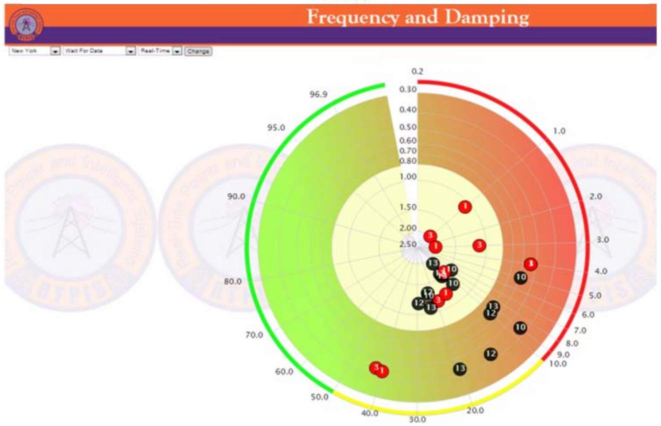


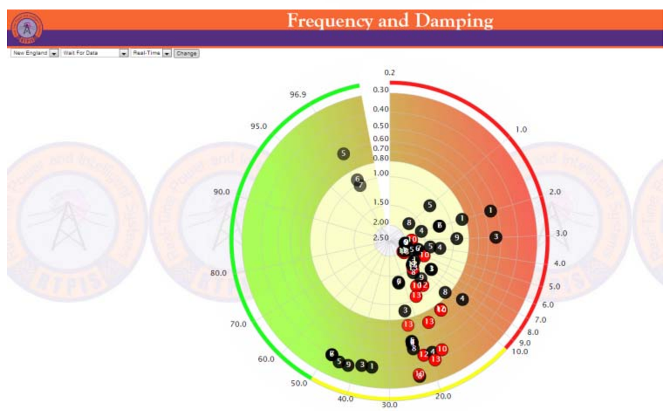
Speed deviation of G_1 with 10 cycles fault duration – Operating Condition 1 (Area 1 load at bus-7 967MW and Area 2 load at bus-9 1767MW)

Online Modal Analysis of Synchronous Generators





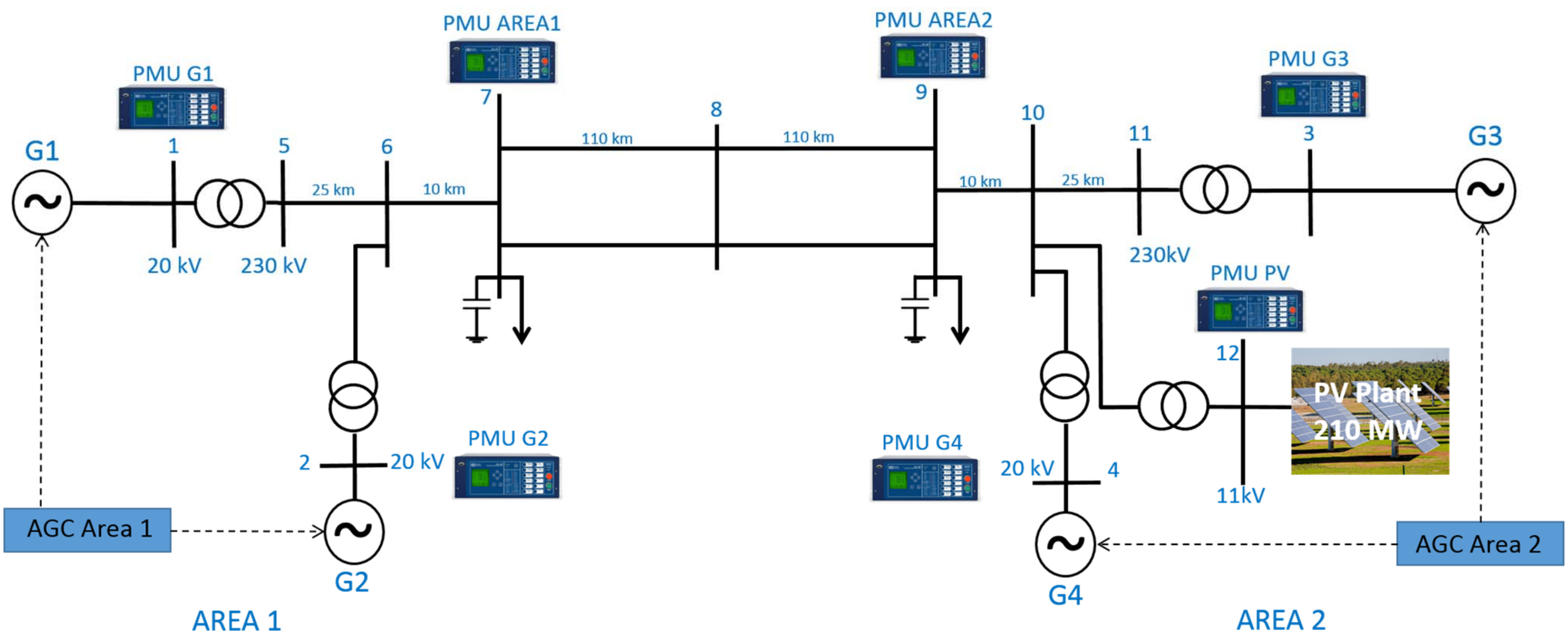




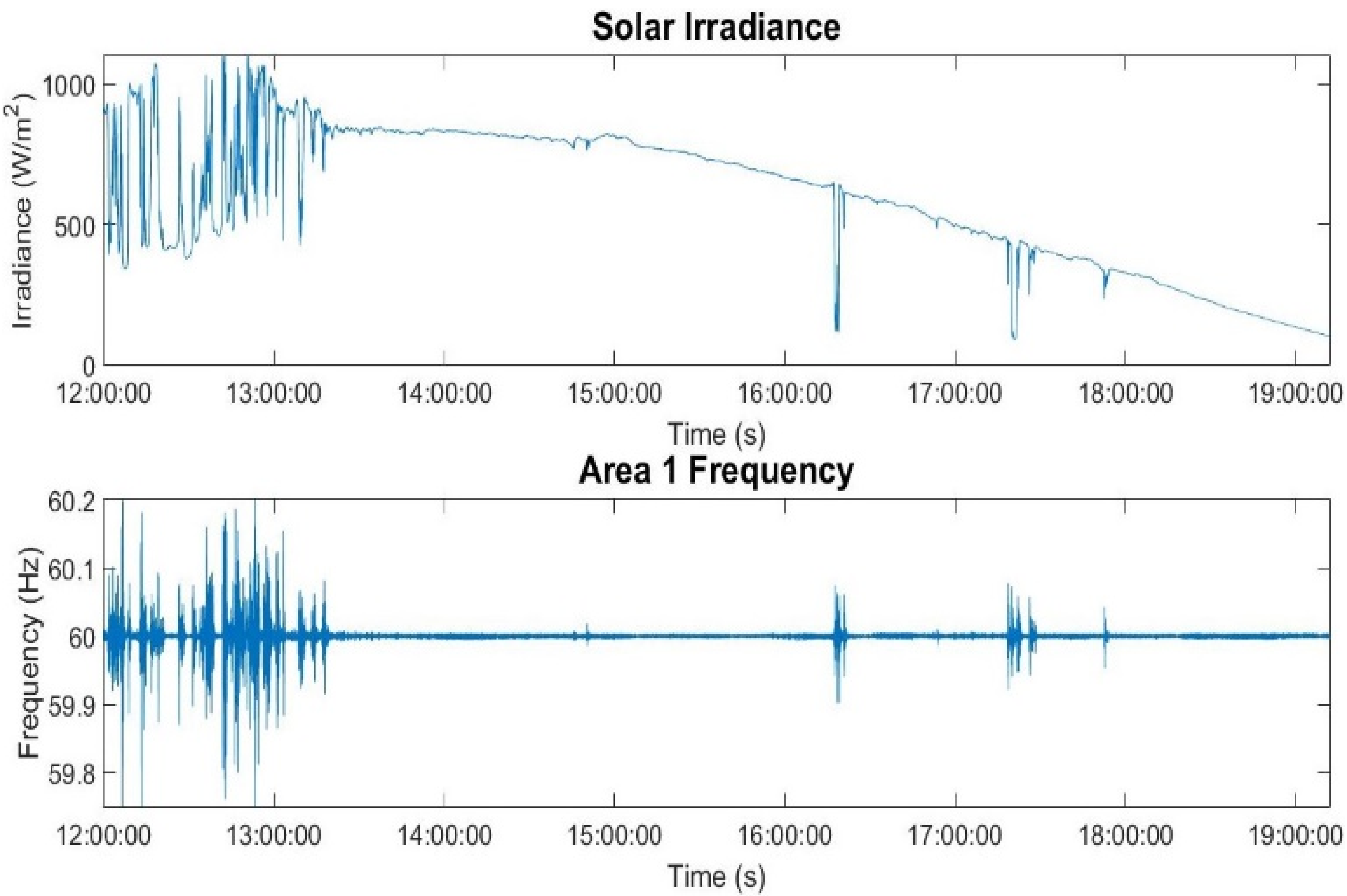
Saraf P, Venayagamoorthy GK, Luitel B, "Online oscillation monitoring of synchronous generators using parallel-prony analysis", *IEEE conference on Innovative Smart Grid Technologies (ISGT)*, February 2014, Washington DC, USA.

Power System Model with PV

Two-Area Four-Machine Test System with 210MW PV Plant

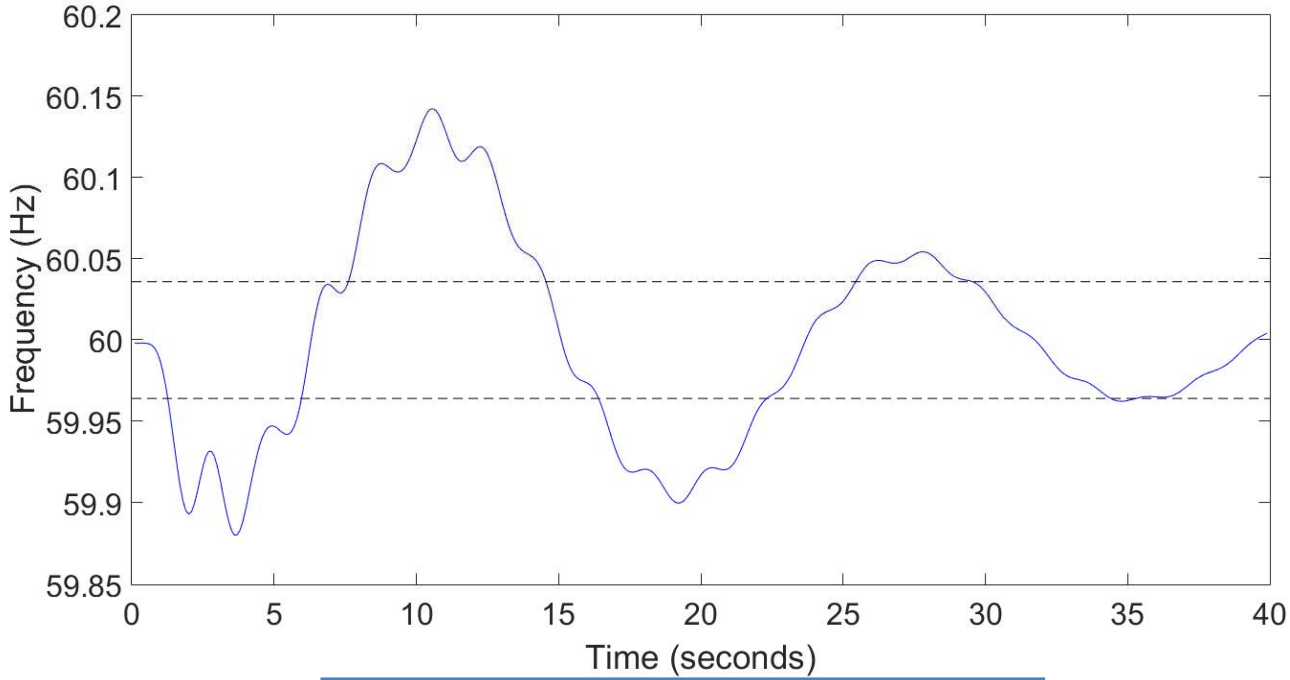


Frequency


Solar Irradiance
Irradiance (W/m²)
1000
500
0
12:00:00
13:00:00
14:00:00
15:00:00
16:00:00
17:00:00
18:00:00
19:00:00
Time (s)
Area 1 Frequency
Frequency (Hz)
60.2
60.1
60
59.9
59.8
12:00:00
13:00:00
14:00:00
15:00:00
16:00:00
17:00:00
18:00:00
19:00:00
Time (s)

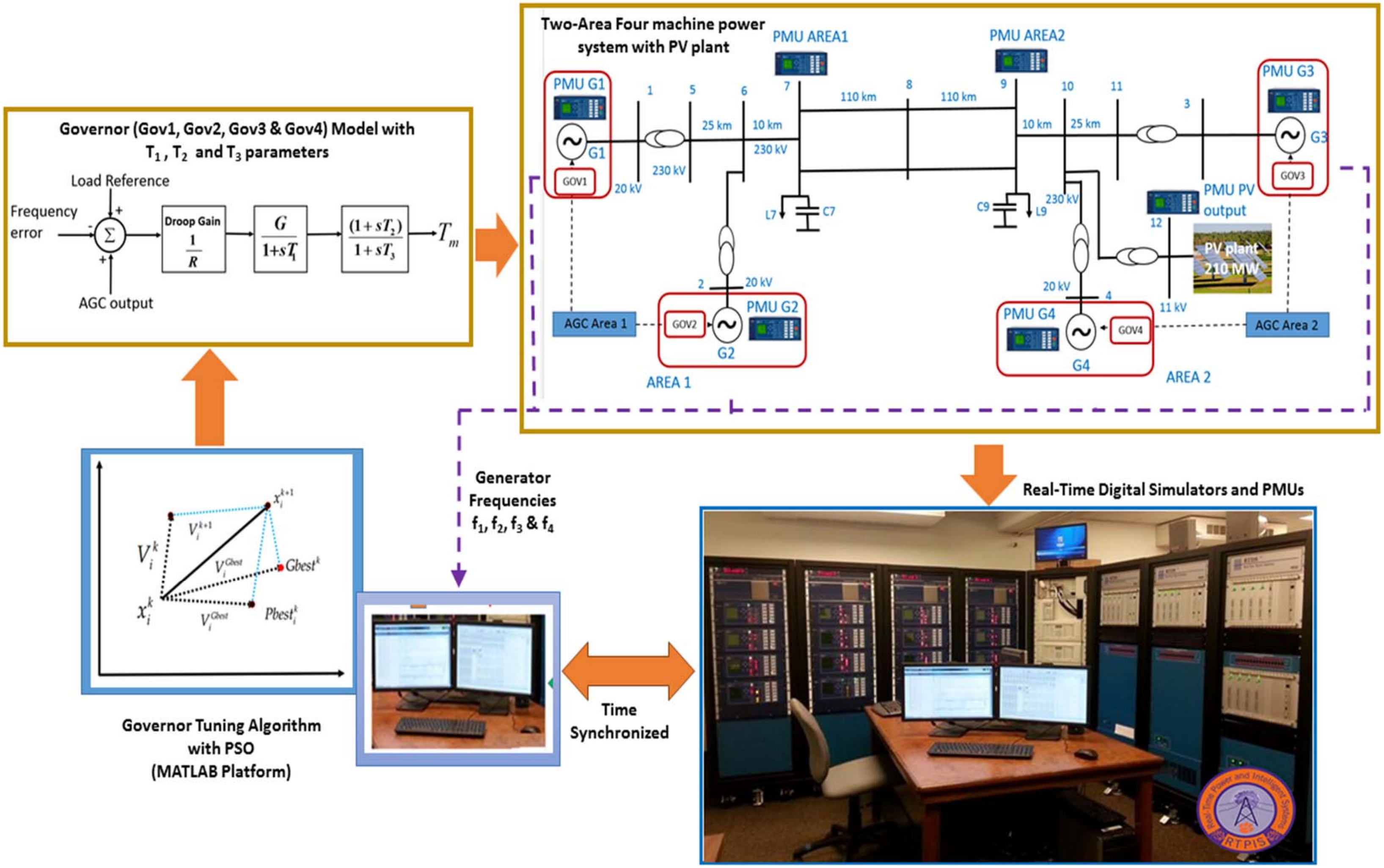
Frequency Events

Area 1 Frequency Original Governor Parameters



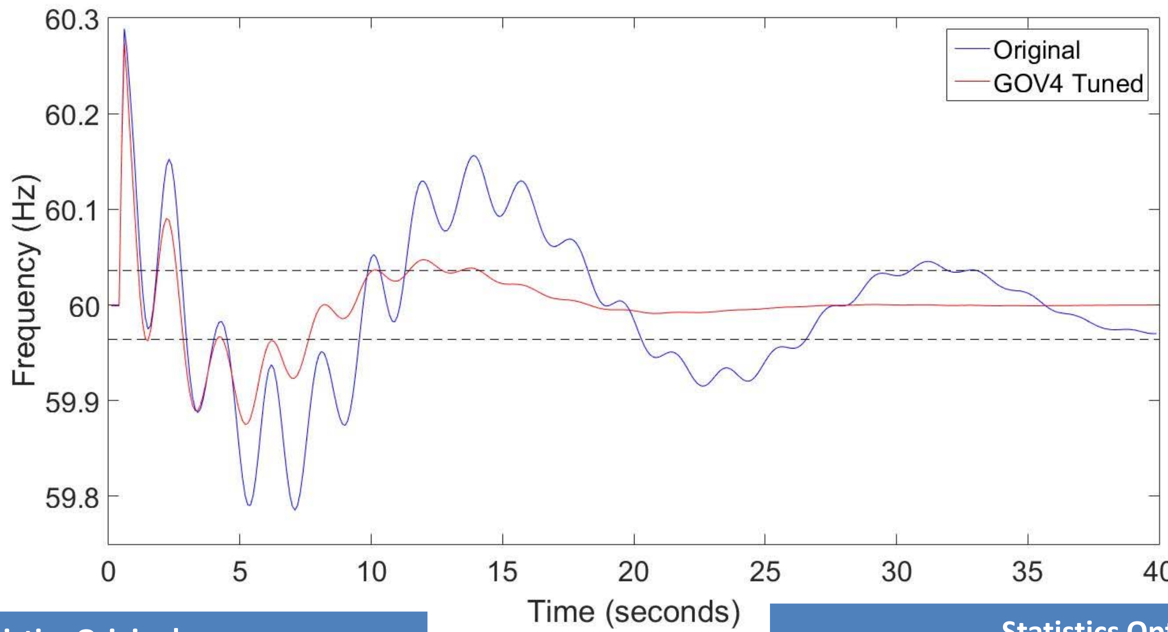
Statistics	
Frequency Events	6
Max Frequency (Hz)	60.14
Min Frequency (Hz)	59.88
Settling Time (s)	80

Governor Tuning



Improved Governors

Area 1 Frequency GOV1 - GOV4 Optimized



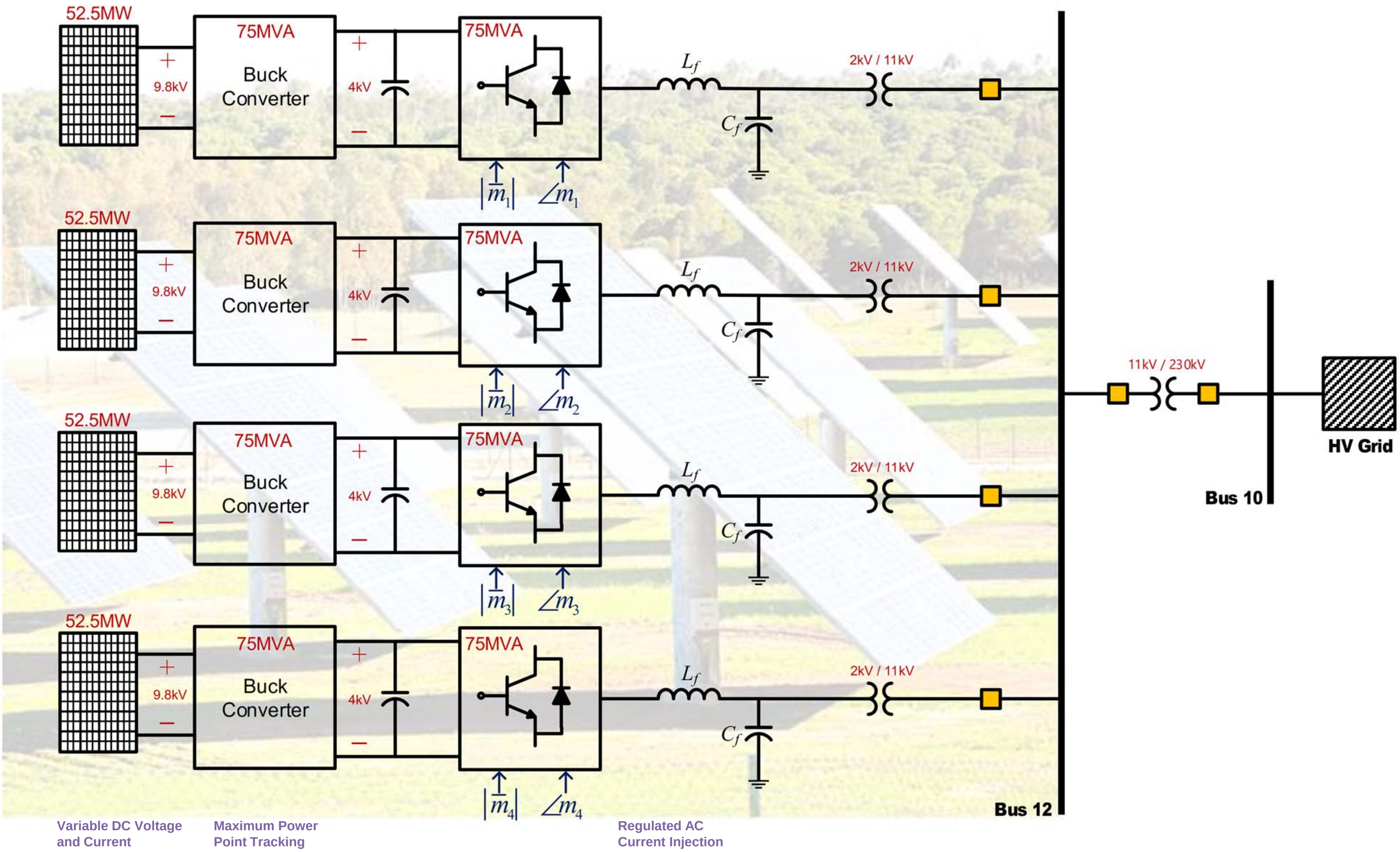
Statistics Original	
Frequency Events	6
Max Frequency (Hz)	60.29
Min Frequency (Hz)	59.79
Settling Time (s)	80

Statistics Optimized	
Frequency Events	3
Max Frequency (Hz)	60.28
Min Frequency (Hz)	59.88
Settling Time (s)	22

"Optimal Tuning of Governors on Synchronous Generators in a Multi-Area Power System with a Large Photovoltaic Plant", *IEEE PES PowerAfrica Conference*, Livingstone, Zambia, June 28 – July 2, 2016.

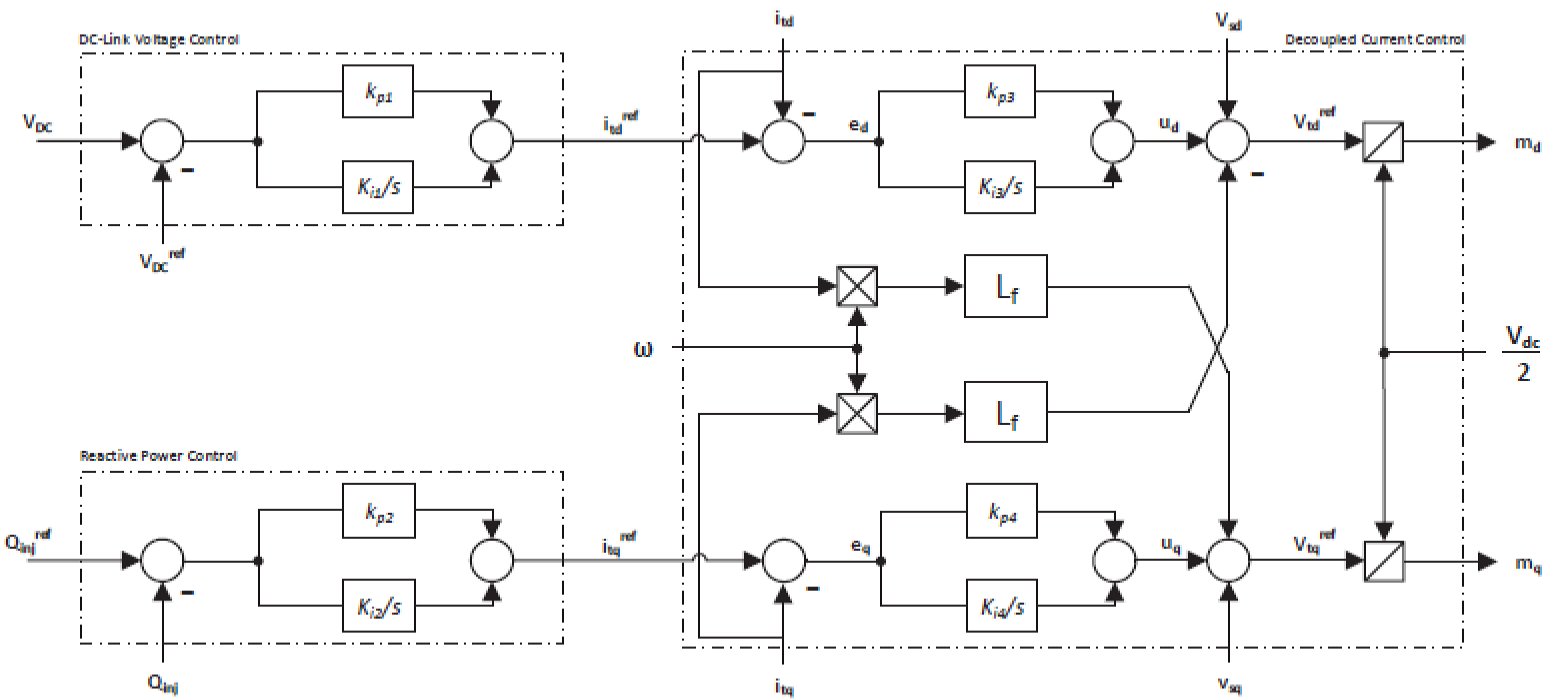
PV Plant Model and Control

210MW Utility-Scale PV-Plant in Transmission Network



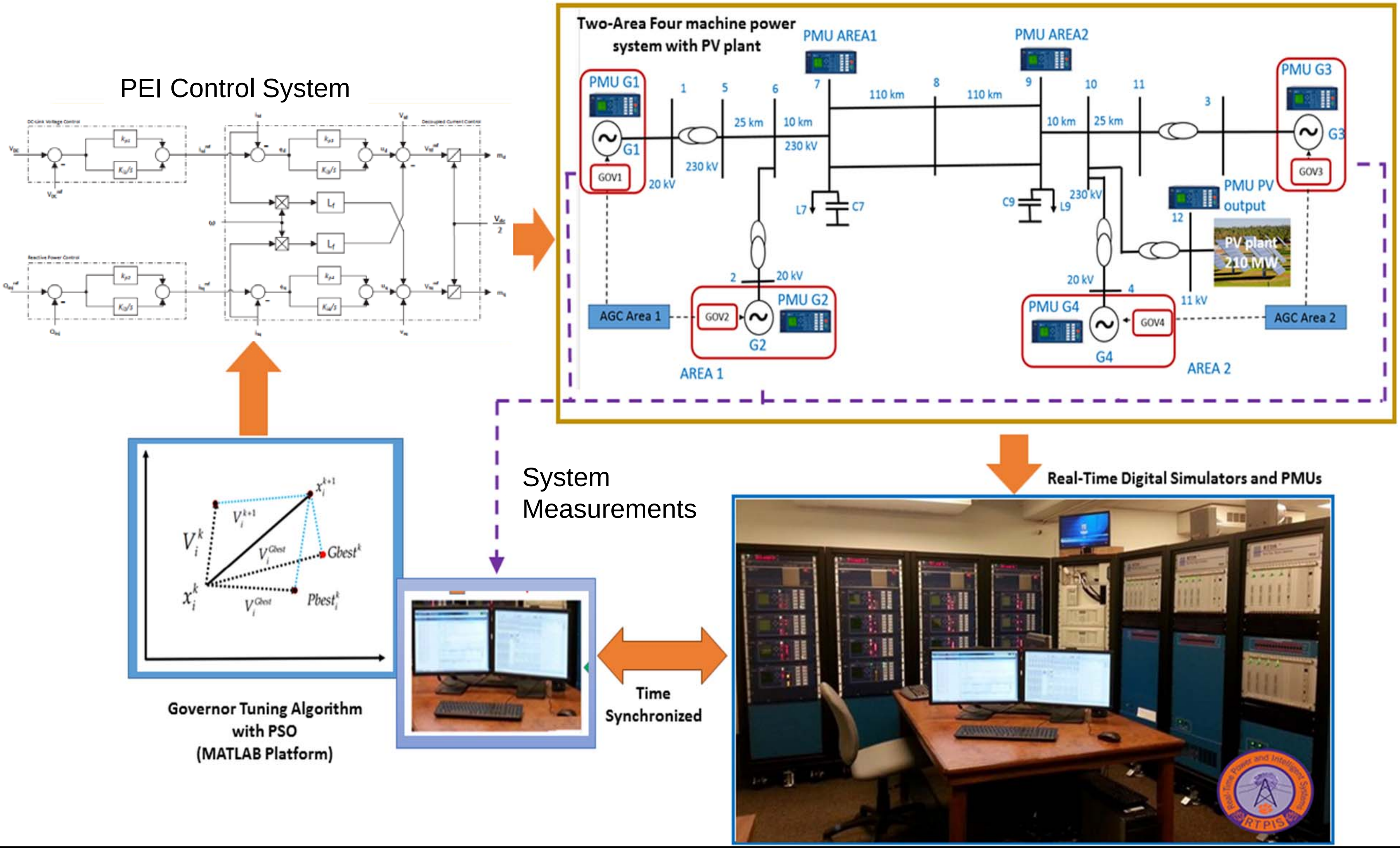
PV-SYSTEM MODEL AND CONTROL

- PV-VSI control structure in *dq*-reference frame



- Inner control loop i.e. decoupled current control
- Outer control loop:
    - DC-link voltage
    - reactive power

Tuning PI Controllers



"Dynamic Performance Enhancement of a Utility-Scale Solar PV Plant", *IEEE PES PowerAfrica Conference*, Livingstone, Zambia, June 28 – July 2, 2016

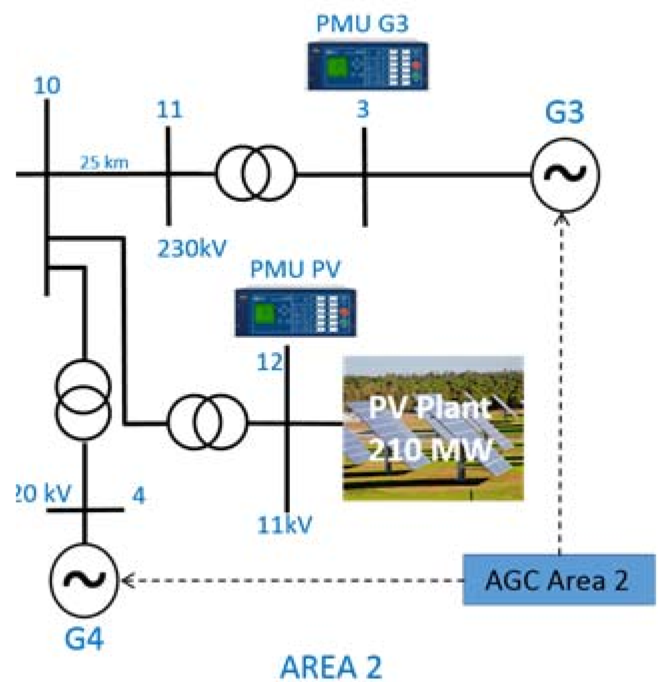
PI Controller Tuning

The objective of the tuning is to minimize the time response of the active power and reactive power oscillations at PCC which is injected at bus 12 and calculating the total fitness value for *2*-step changes in solar irradiance

$$J_1 = \sum_{t=t_0}^{\frac{t_2-t_0}{\Delta t}} \left(\Delta P(t) - c_p\right)^2 \times \left(A \times (t - t_0) \times \Delta t\right)$$

$$J_2 = \sum_{t=t_0}^{\frac{t_2-t_0}{\Delta t}} \left(\Delta Q(t)\right)^2 \times \left(A \times (t - t_0) \times \Delta t\right)$$

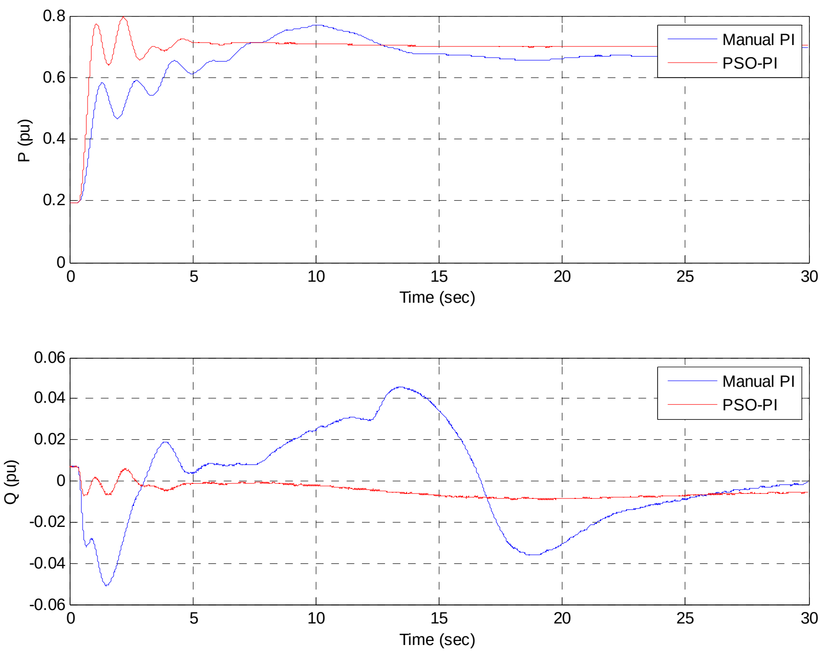
$$J_T = \sum_{k=1}^{n} (J_{1k} + J_{2k})$$



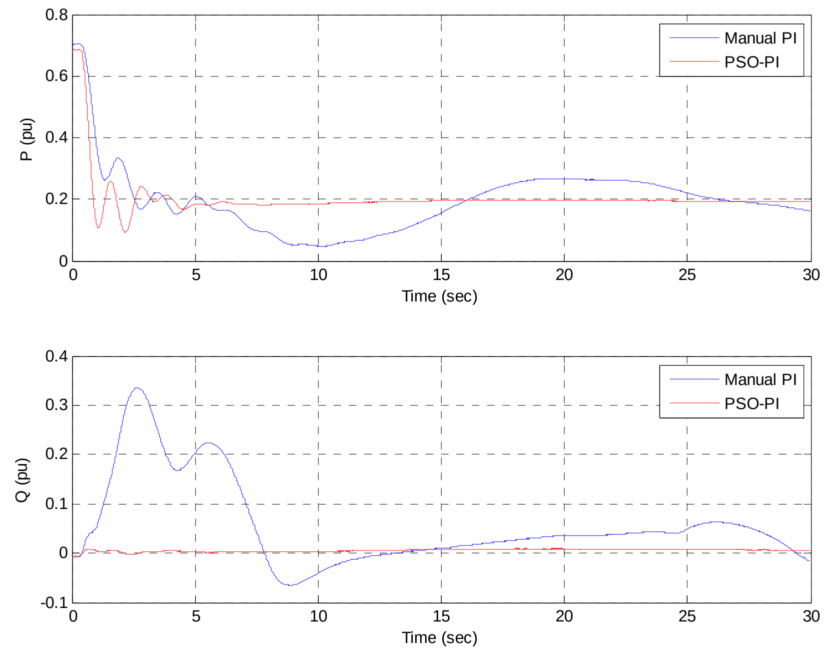
Simulation Results

Dynamic responses with respect to irradiance step-changes

250 to 750 W/m^2



750 to 250 W/m^2



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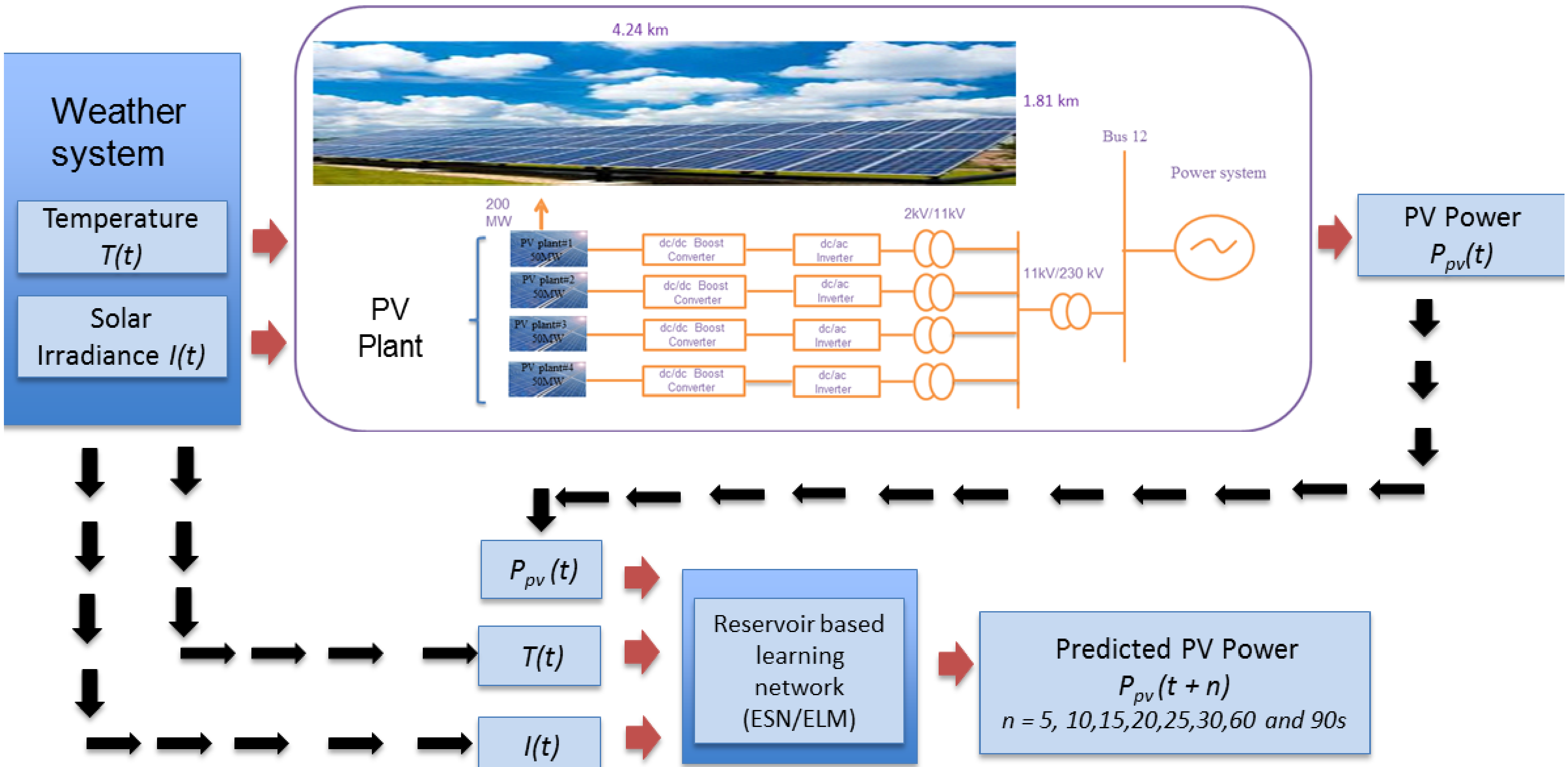
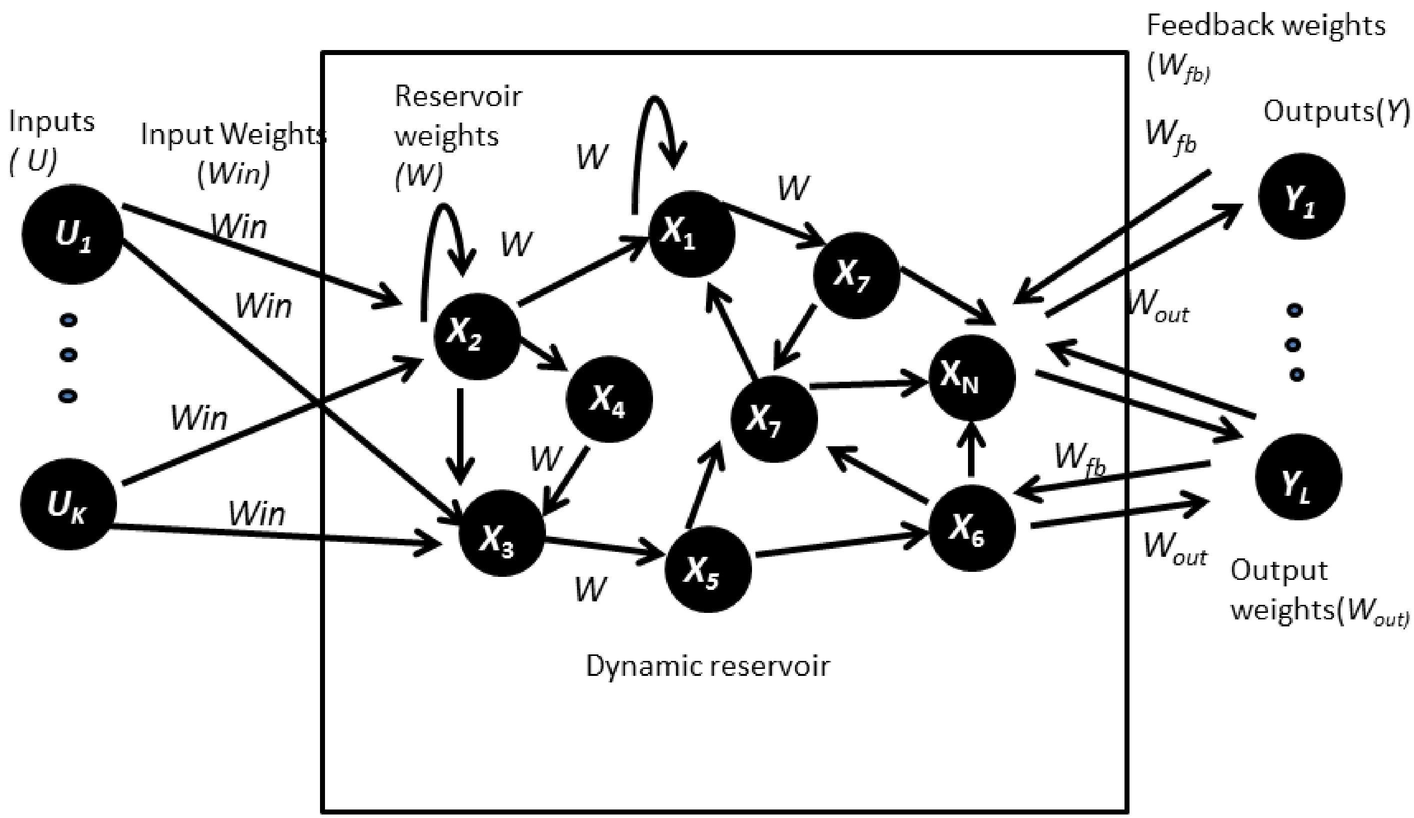
PV Plant Power Prediction



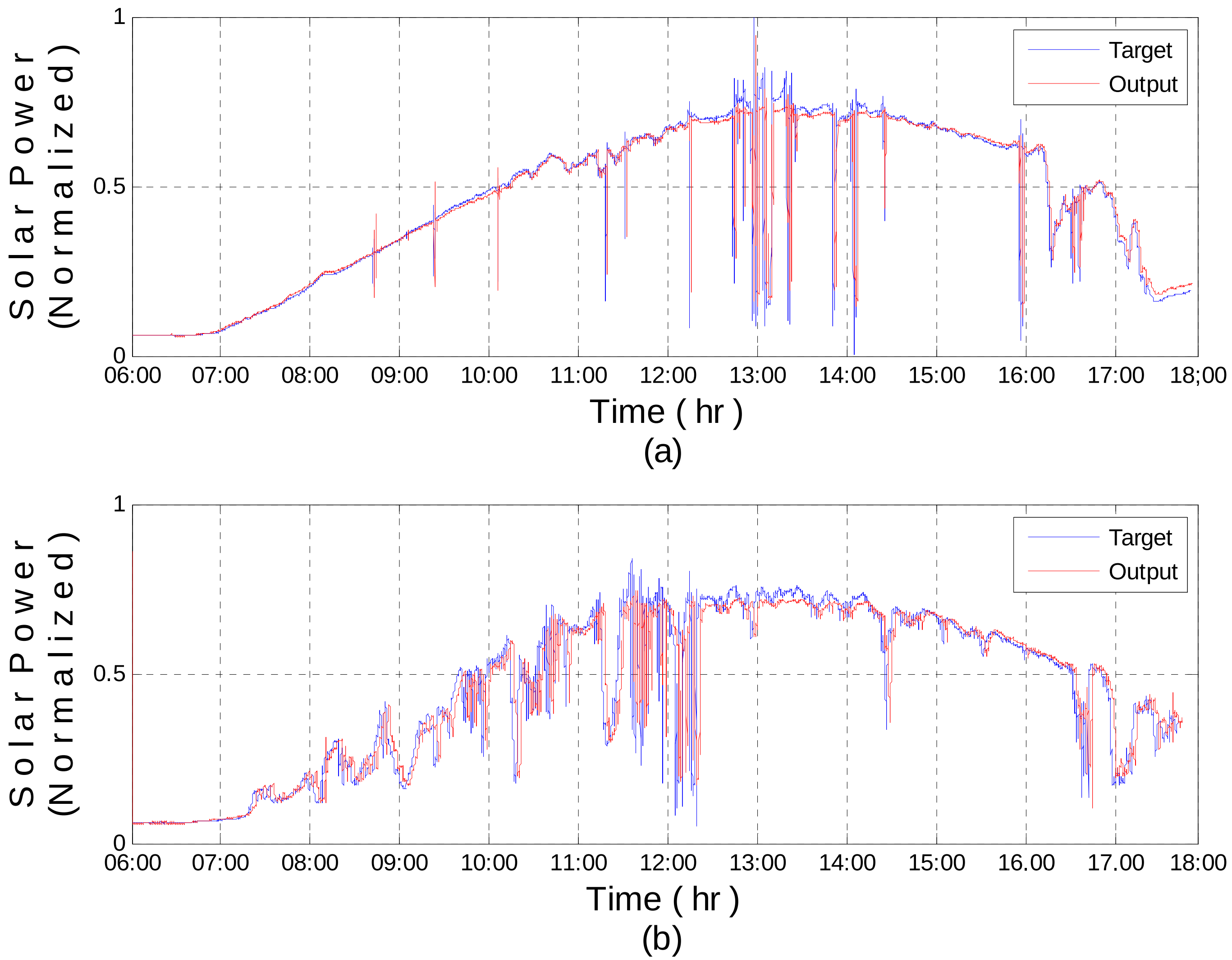
"Reservoir Based Learning Network for Control of Multi-Area Power System with Variable Renewable Generation", *Neurocomputing*, vol. 170, December 2015, pp. 428-438

Prediction of PV power - Reservoir Network

Echo State Network (ESN)



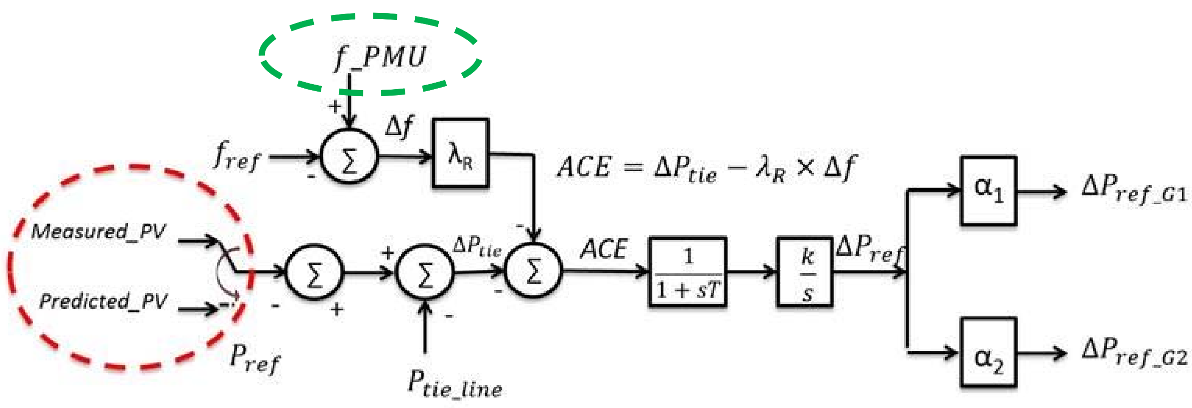
Prediction of PV power - ESN



Short Term Prediction of PV power

Prediction at time t for time instant	Testing MAPE	
	ESN (%)	ELM (%)
t+5	**1.1954**	4.4389
t+10	**2.3811**	4.5701
t+15	**2.5328**	4.6934
t+20	**3.0215**	4.7822
t+25	**3.6592**	4.5902
t+30	**3.9442**	4.3882
t+60	**6.0993**	6.3959
t+90	**7.6080**	8.6509

Areas 1 and 2 AGCs



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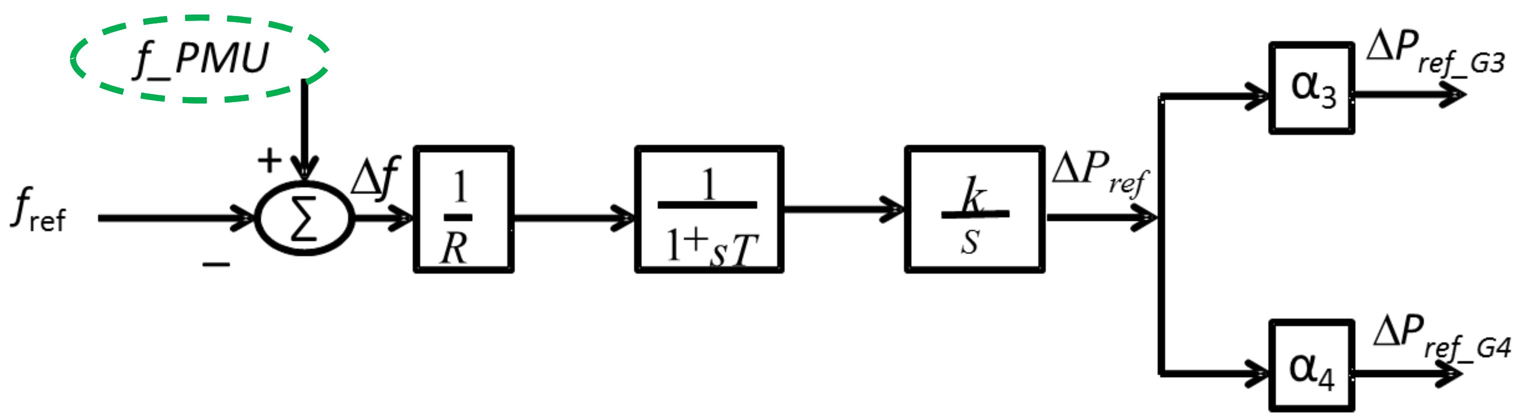
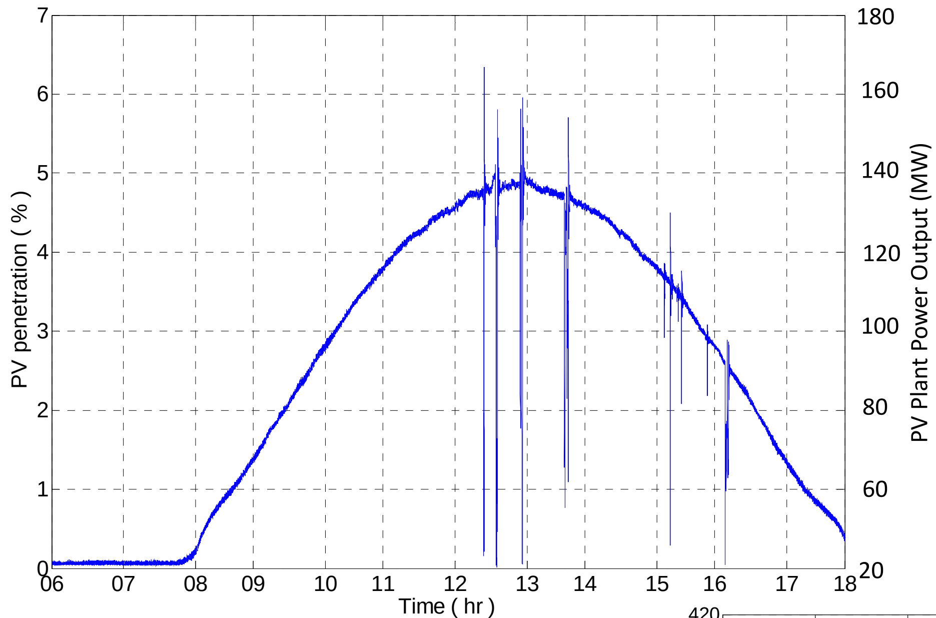


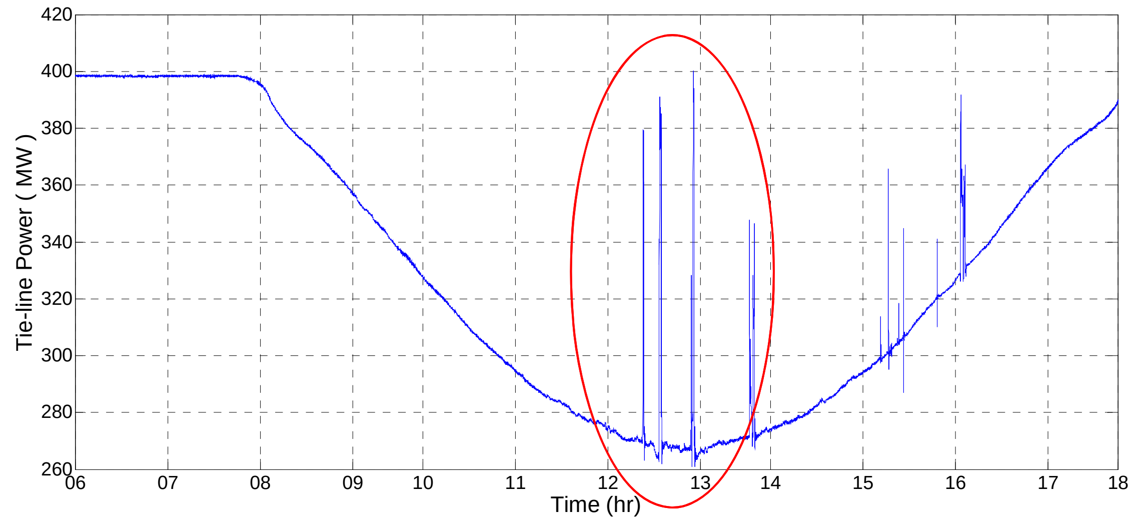
PV Power and Tie-Line Power Flow



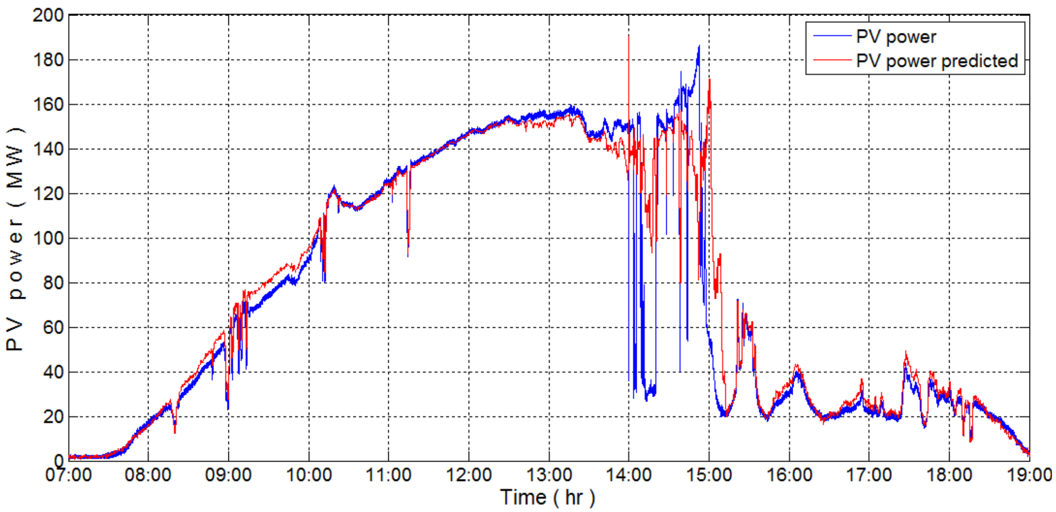
Tie-line power flow with the PV plant operation on October 21, 2014 between 06h00 and 18h00.

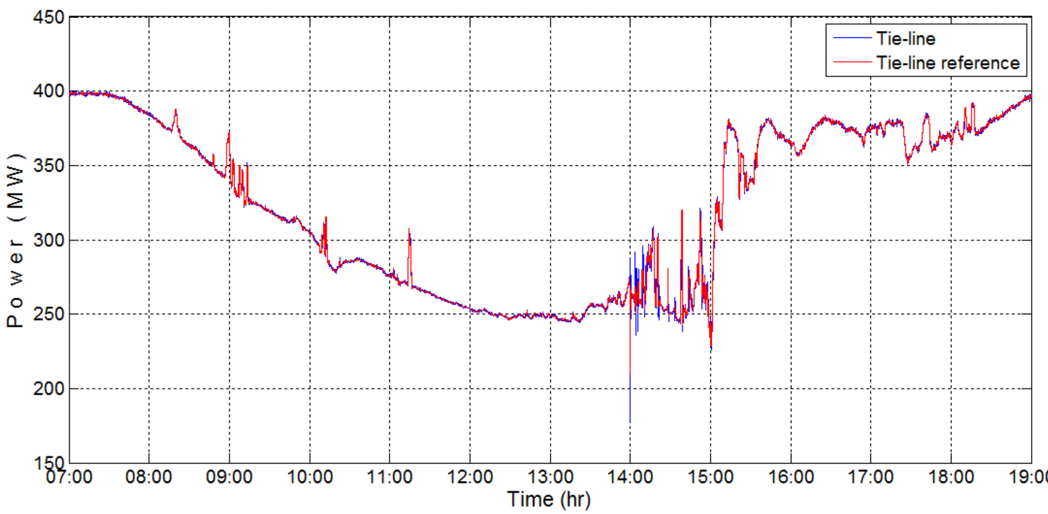
130 MW drop

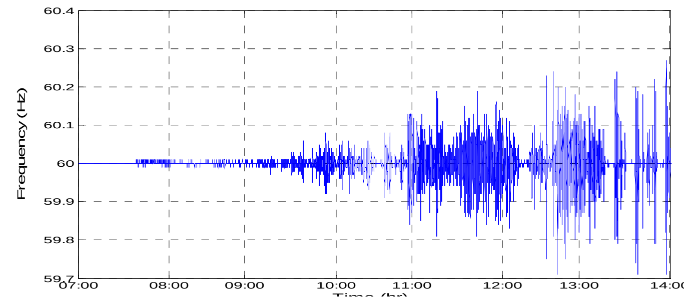
Tie-line power flow lines between buses with the PV plant operation on October 21, 2014 between 06h00 and 18h00.

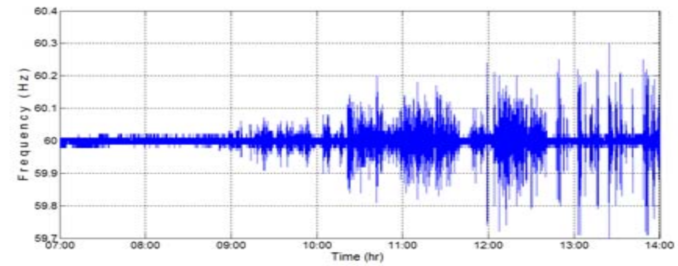


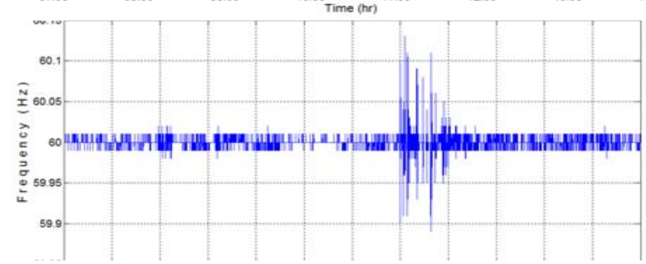
Tie-Line Power Flow Control

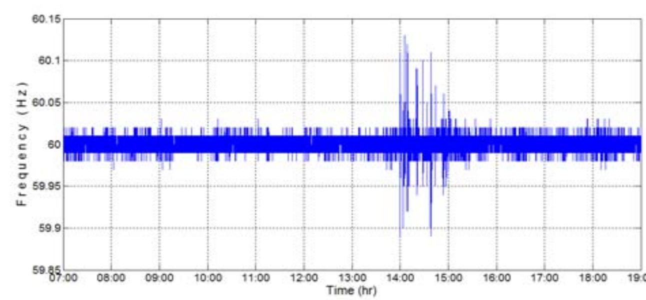












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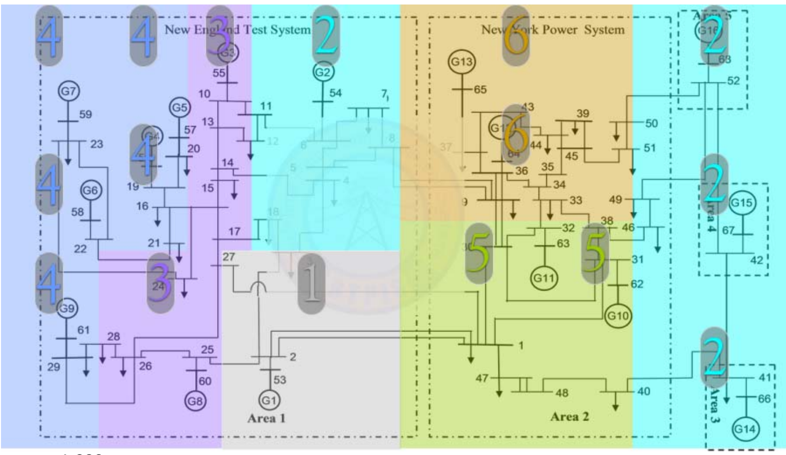
Online Coherency Analysis of Synchronous Generators

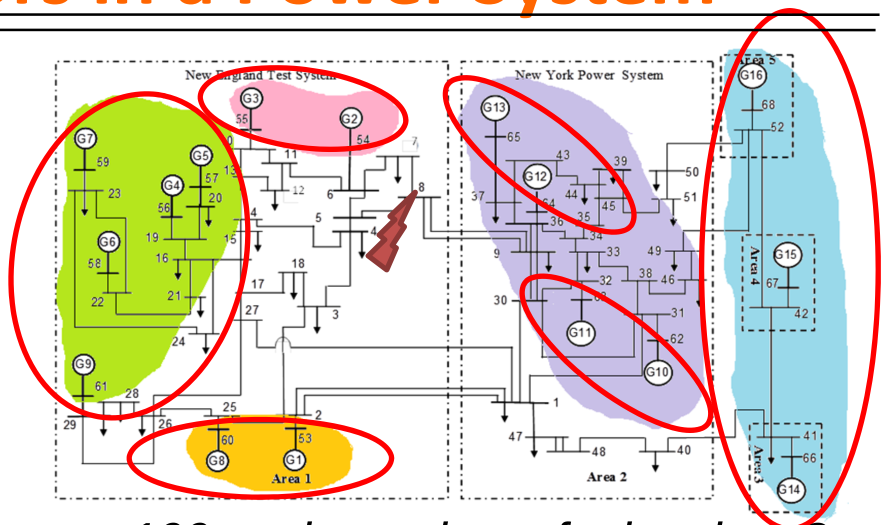
- Coherency analysis is performed offline and the groupings are used in the development of auxiliary control signals.

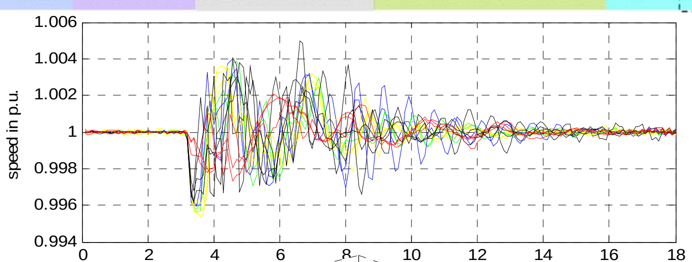
- However, in response to various events at different operating conditions, the coherent groups may differ, and it has been observed that post disturbance during the transient the generators switch groups.

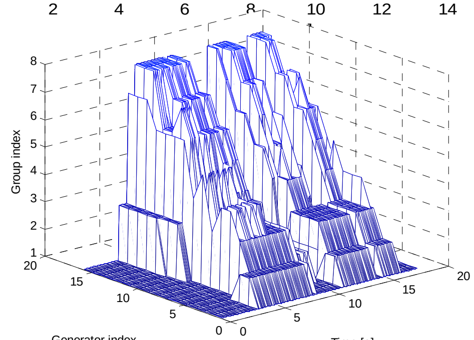
- Thus, it is important to develop the analysis to be online and be able to recognize the switching of groups by the generators in the network.

Online Coherency Analysis of Synchronous Generators in a Power System









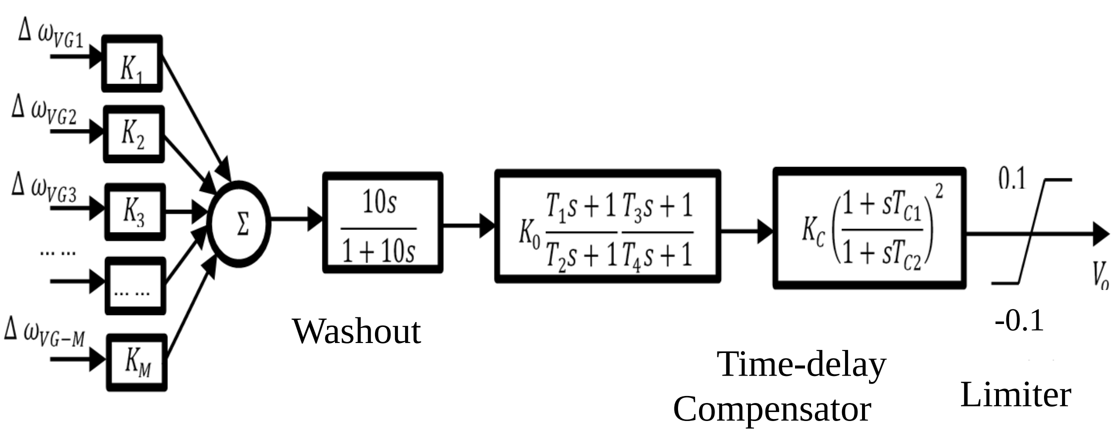
100ms three phase fault at bus 8

Group index	Offline Clustering during 0~18s	Online Clustering at 8s	Online Clustering at 10s	Online Clustering at 15s
1	G1, G8	G1,G8	G1,G2,G3, G8,G10,G11,G12,G13	G1,G8
2	G2,G3	G2,G3	G4,G5,G6, G7,G9	G2,G3
3	G4,G5,G6, G7,G9	G4,G5,G6, G7	G14,G15, G16	G4,G5,G6, G7,G9
4	G10,G11	G9		G10,G11, G12,G13
5	G12,G13	G10,G11		G14,G15, G16
6	G14,G15, G16	G12,G13		
7		G14,G15, G16		

"Online coherency analysis of synchronous generators in a power system", *IEEE conference on Innovative Smart Grid Technologies (ISGT)*, February 2014, Washington DC, USA.

Coherency based Damping Controller

- To damp inter-area oscillations, a Virtual Generator based Power System Stabilizer (VG-PSS) was developed
- Particle Swarm Optimization (PSO) is adopted to tune the VG-PSS
- To obtain the cost function for the PSO algorithm, a Stochastic Subspace Identification (SSI) based model analysis is used



"Damping Inter-area Oscillations Using Virtual Generator Based Power System Stabilizer", *Electric Power Systems Research,* vol. 129, December 2015, pp. 126-141.

Coherency based Damping Controller

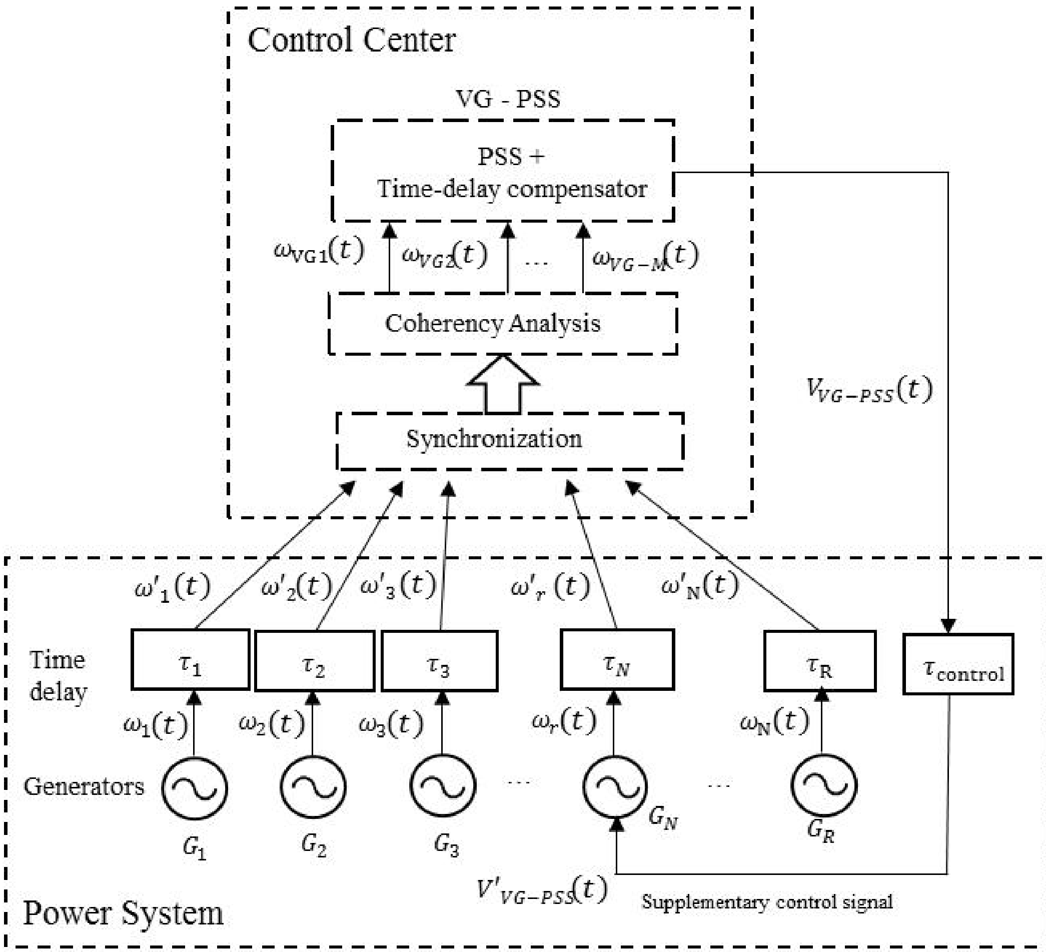
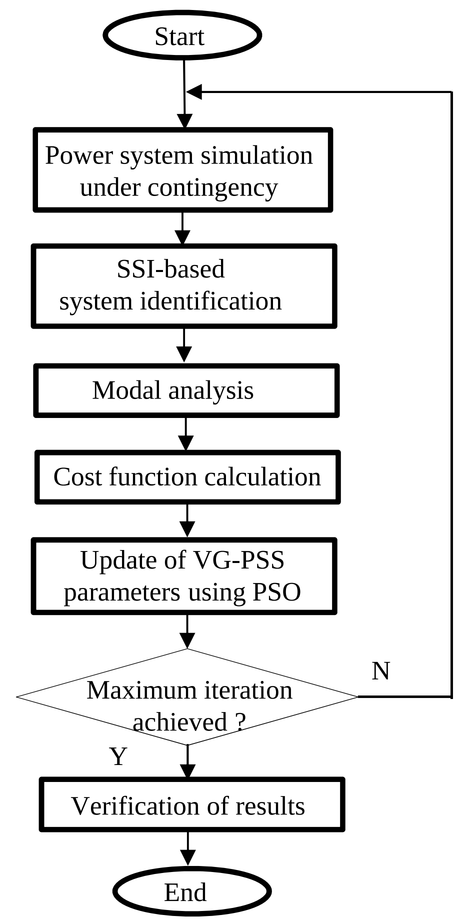


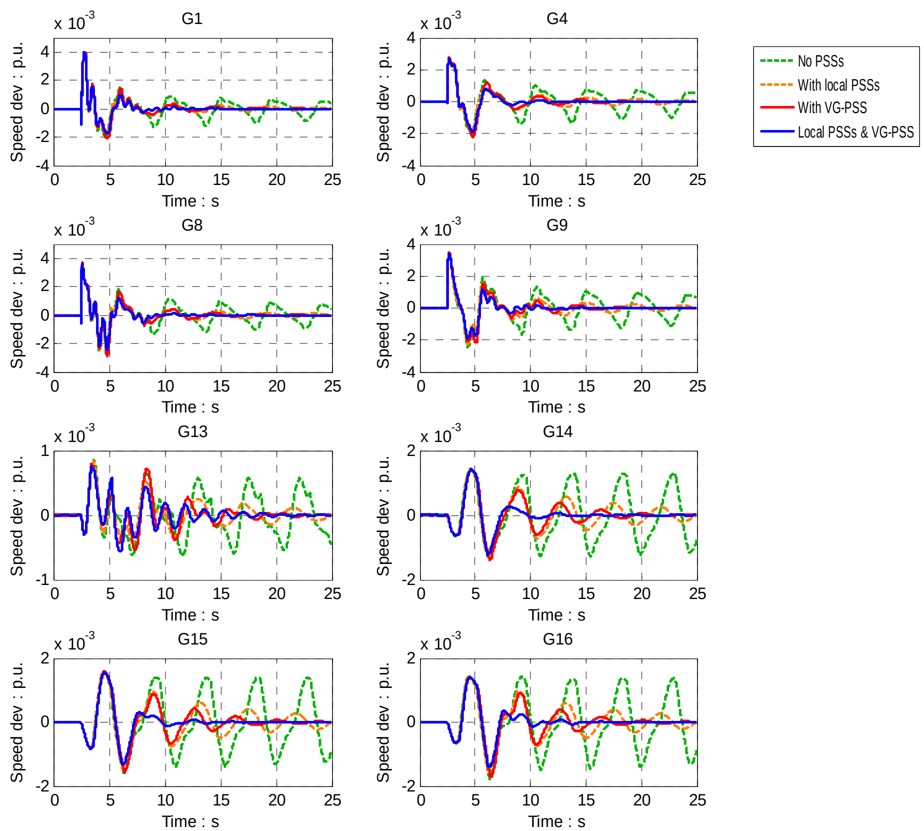
Diagram of the control scheme with VG-PSS



The overall flowchart of design approach

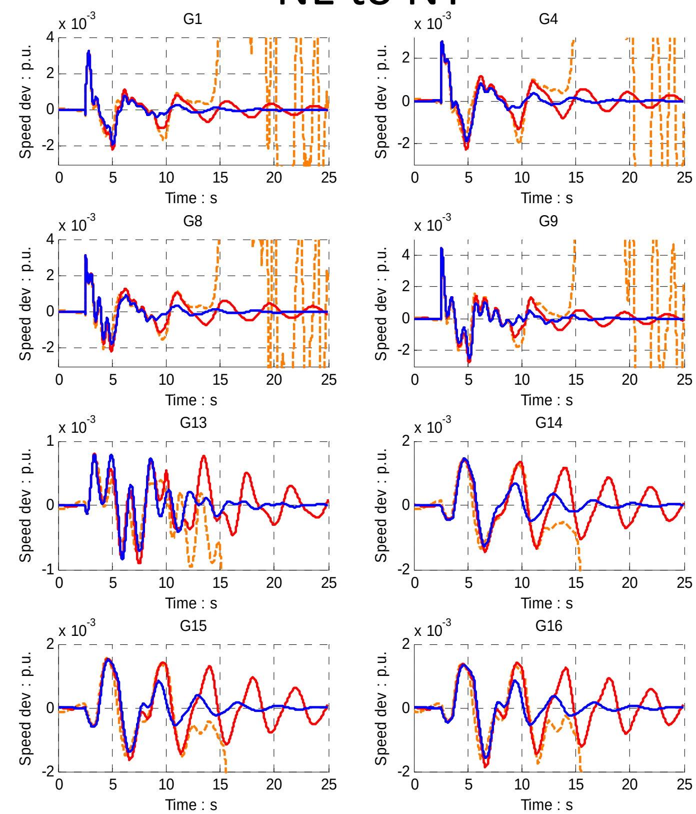
Coherency based Damping Controller

Case Study I Fault at Bus 2 and Loss of transmission line (Bus1 – Bus 2)



Speed deviations plots of selected generators with VG-PSS on G9

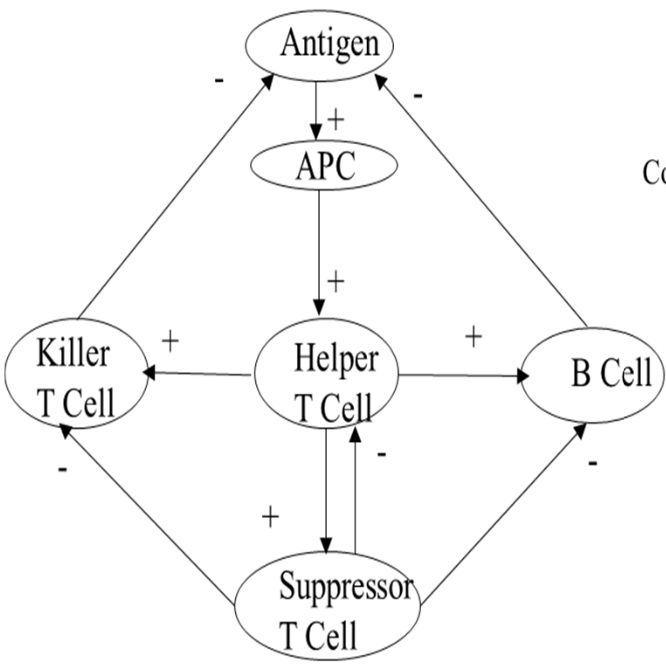
Case Study II Fault at Bus 8 under higher active power transfer from NE to NY



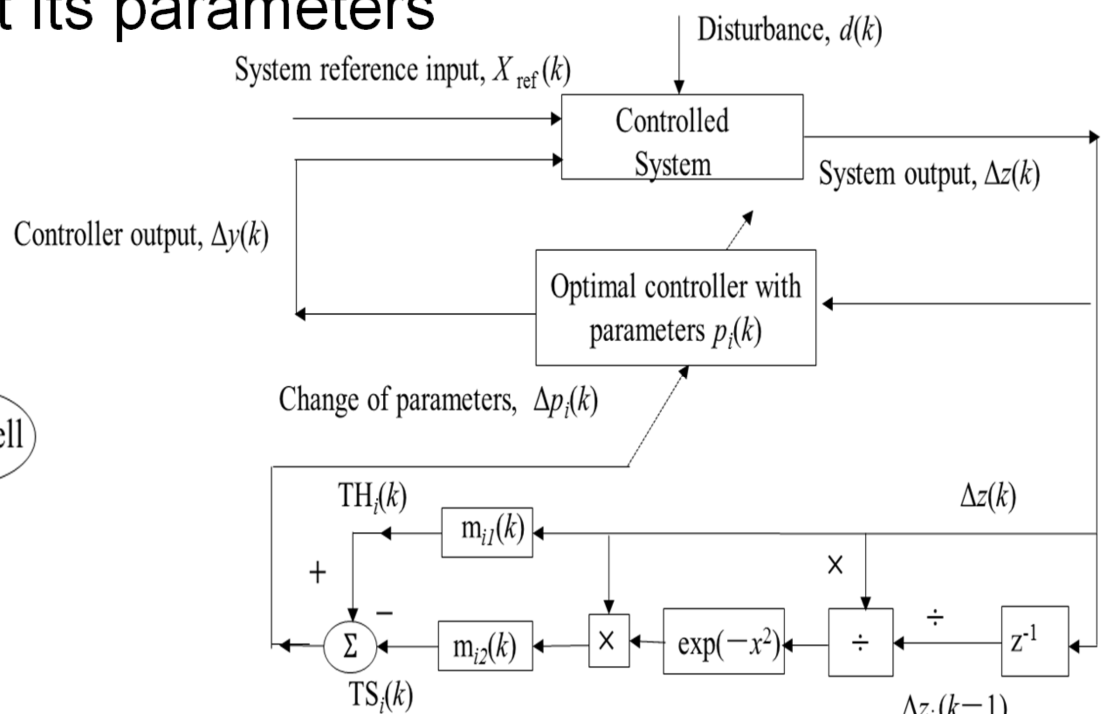
Speed deviations plots of selected generators with VG-PSS on G9

Adaptive Damping Controller

- Artificial immune system (AIS) is an emulation of biological immune system
- Adaptive controller can apply AIS concept to automatically adjust its parameters



A biological immune system

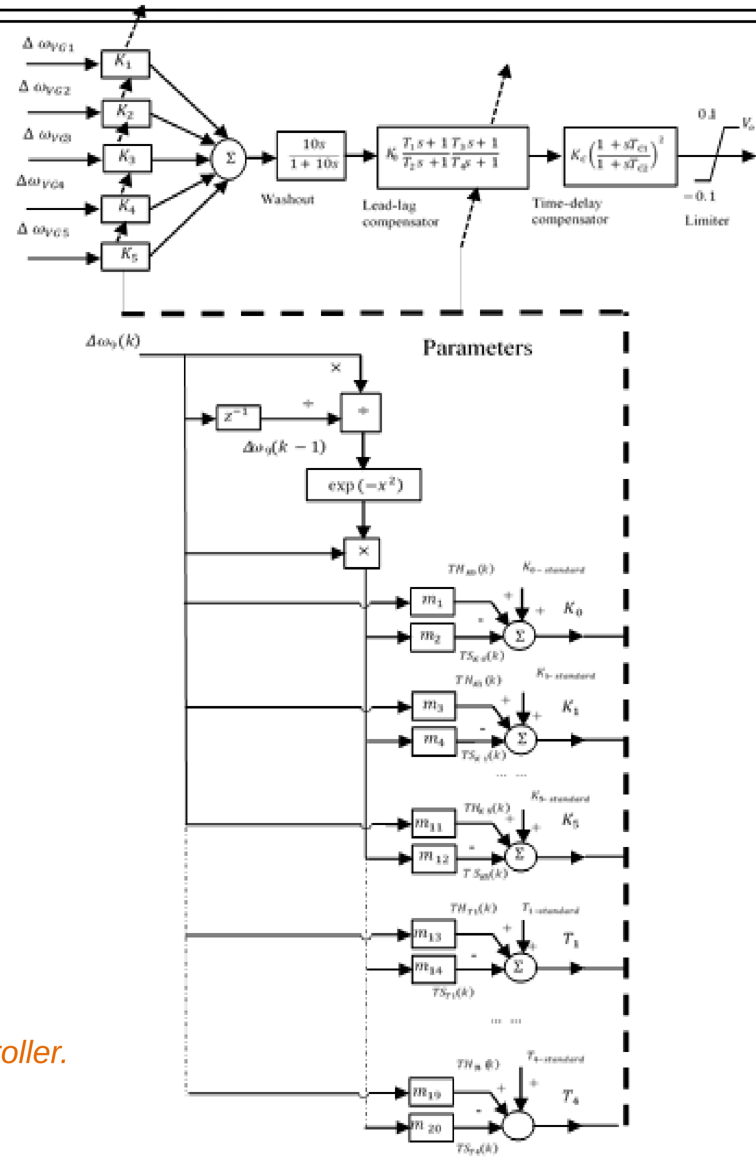


Schematic of the AIS based control for a dynamic system.

“Adaptive Inter-Area Oscillation Damping Controller for Multi-Machine Power Systems”, *Electric Power Systems Research,* vol. 134, May 2016, pp. 105-113.

Adaptive Damping Controller

- The parameters of the adaptive controller are tuned with PSO.
- During power system transients, the AIS is able to adjust the VG-PSS parameters, making the controller able to adapt to various operating conditions.



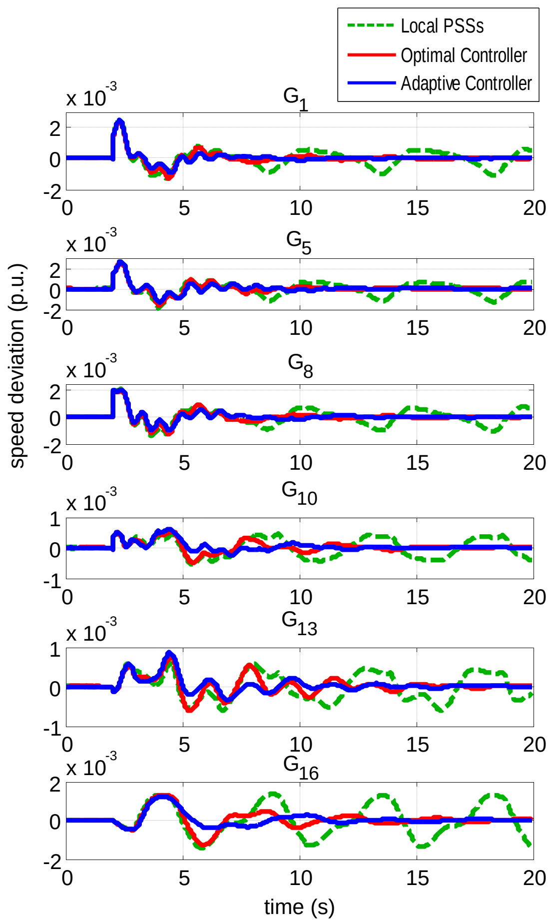
Schematic diagram of the AIS based controller.

Adaptive Damping Controller

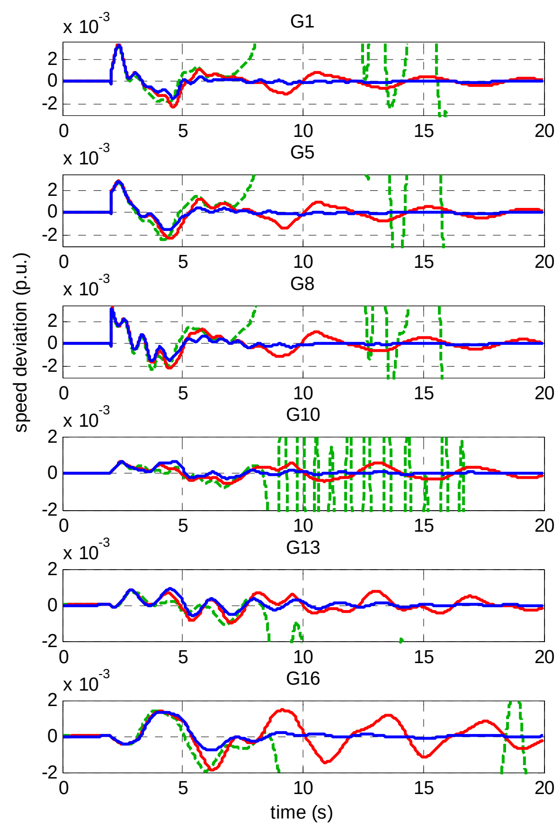
Case I three-phase fault at Bus 2

Case II 100ms three-phase fault at Bus 8 at higher active power transfer from NE to NY

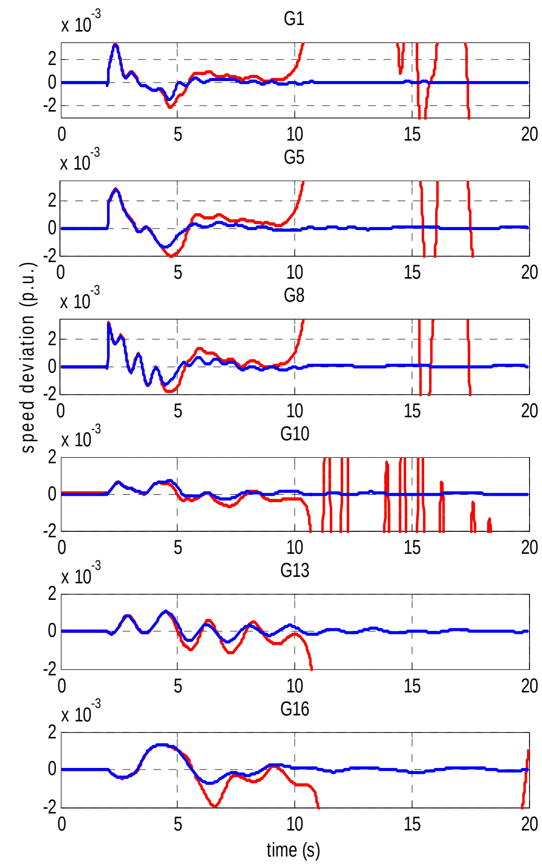
Case III 100ms three-phase fault at Bus 27 at higher active power transfer from NE to NY



Speed responses of selected generators with local PSSs installation under Case I.



Speed responses of selected generators with local PSSs installation under Case II.

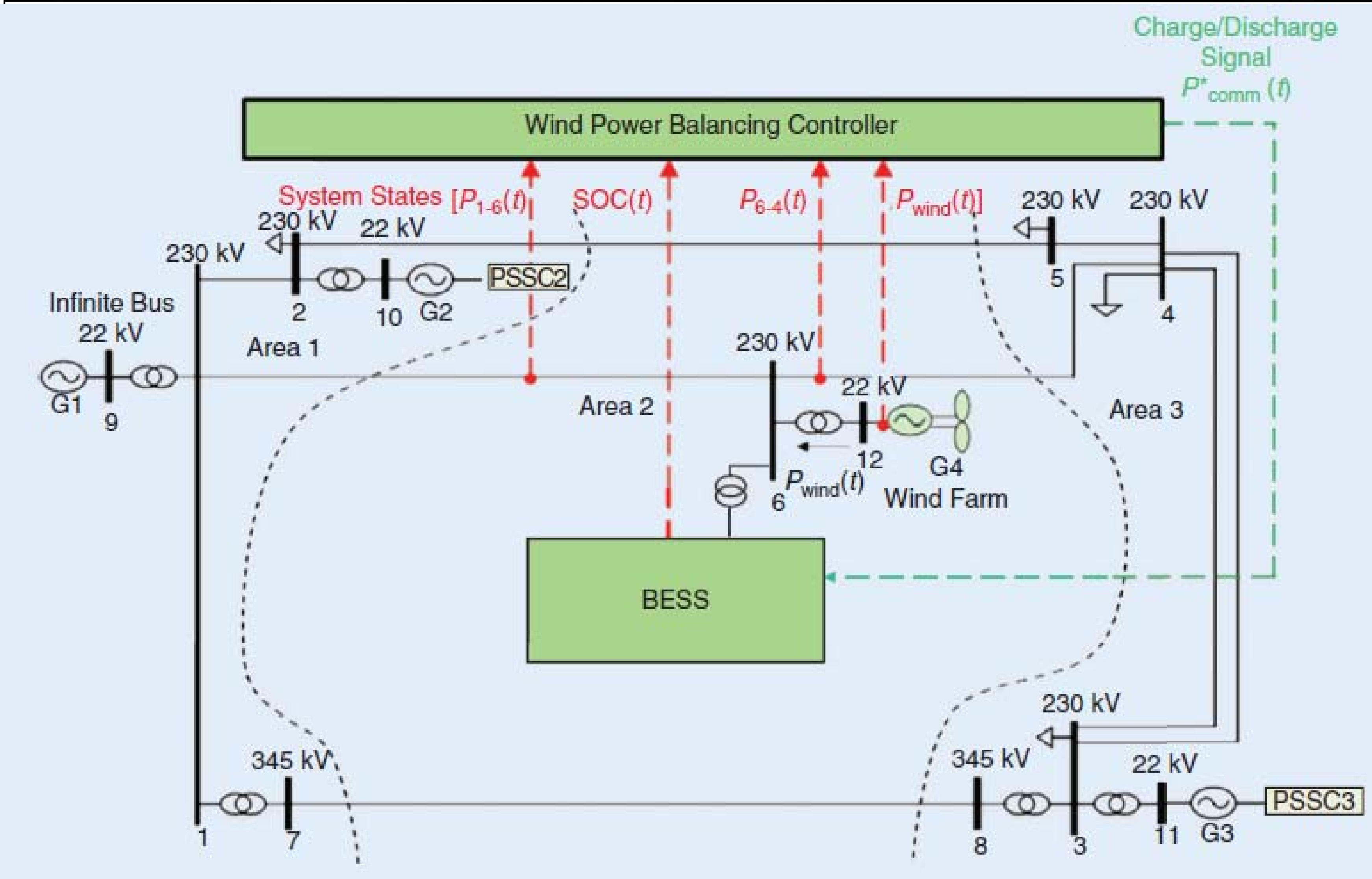


Speed responses of selected generators with local PSSs installation under Case III.

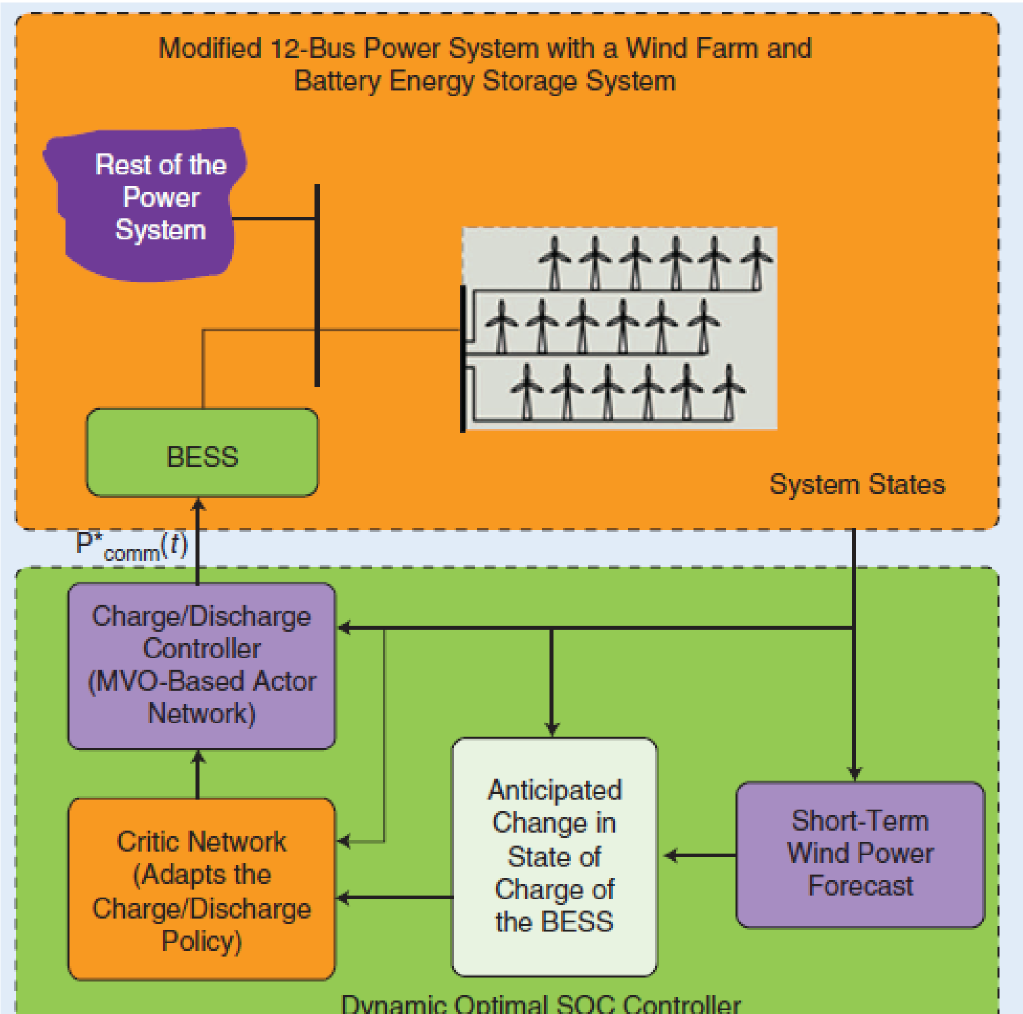
Outline

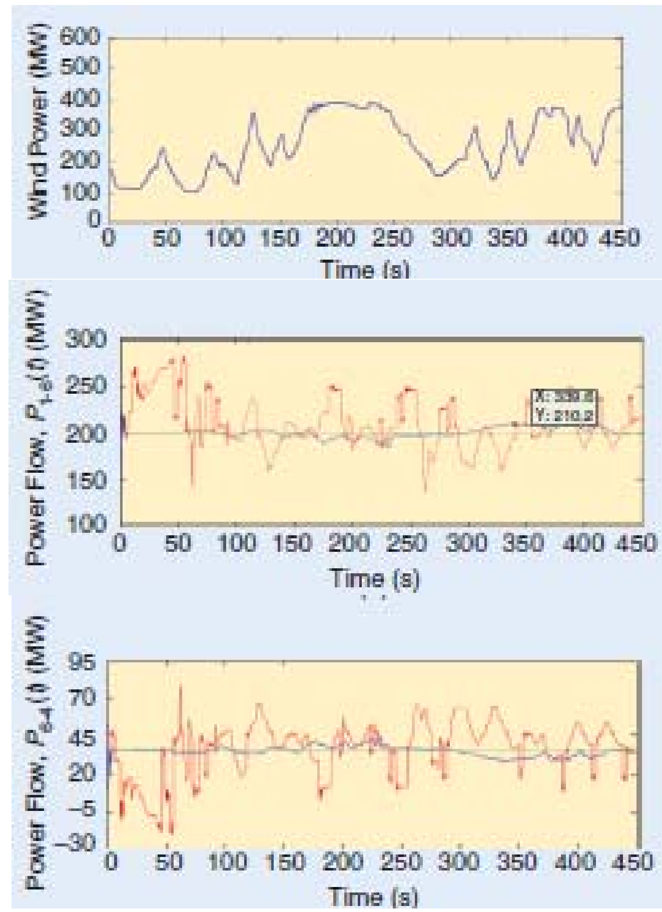
- Introduction
- RTPIS Lab @ Clemson
  - Optimal Controller Tuning
  - Enhanced AGC Control
  - Coherency Analysis & Wide Signals based Control
  - SmartPark
  - Cyberattack
- Summary

Predictive Optimal Control of Wind Power Fluctuations



Predictive Optimal Control of Wind Power Fluctuations





One Step Ahead: Short-Term Wind Power Forecasting and Intelligent Predictive Control Based on Data Analytics", *IEEE Power & Energy Magazine*, Vol. 10, No. 5, September/October 2012, pp. 70-78

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PMU Man-In-The-Attack

PMU measurements make near real-time operations possible.

However, PMU based operations also make the power system sensitive to network disturbance and cyber-physical attacks.

Side-channel analysis can be used to detect a Man-In-The-Middle (MITM) attack.

PMU Man-In-The-Attack

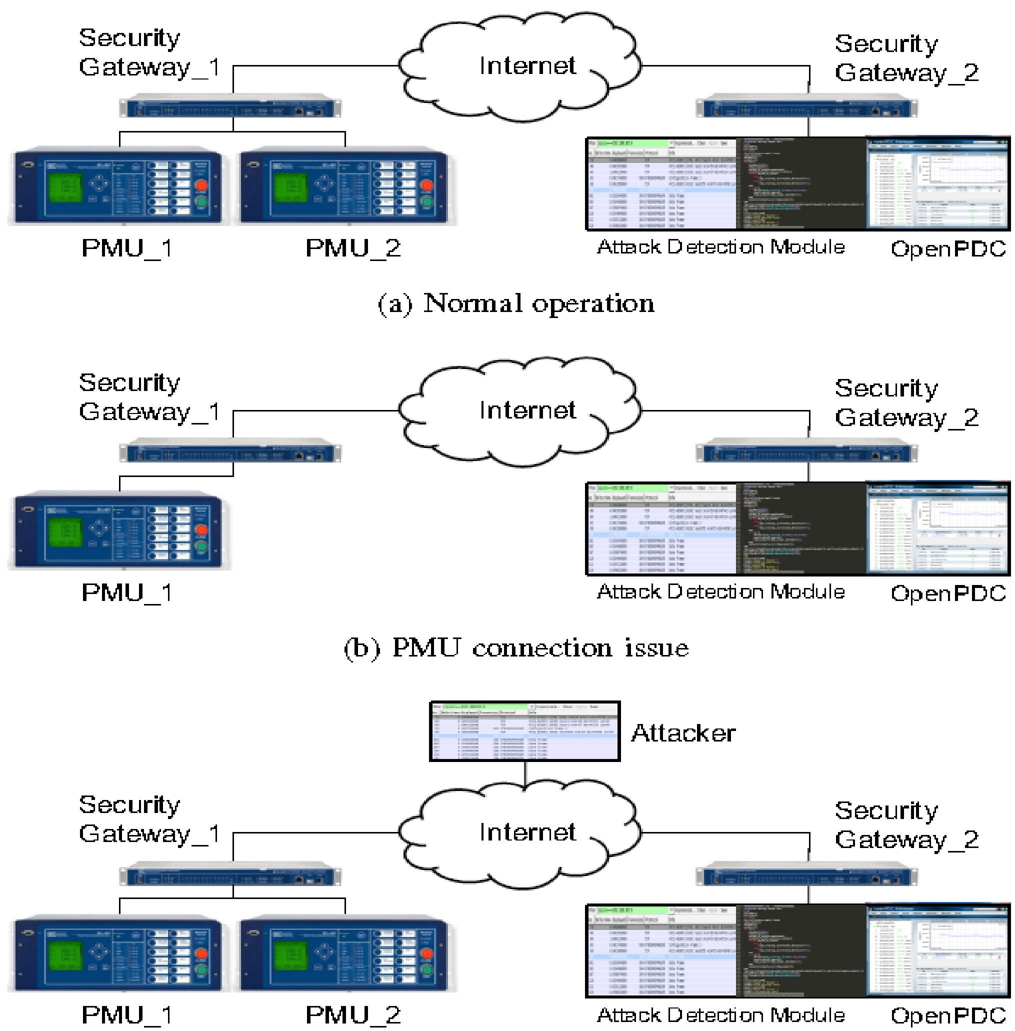
Side-channel analysis extracts information by observing implementation artifacts.

The side-channels in PMU traffics are used to identify normal traffics.

Alarm significant deviation from normal patterns and further identify MITM attacks.

Experimental results confirm the effectiveness of a method to make PMU based operation less vulnerable to attack in practical network configurations.

PMU Man-In-The-Attack

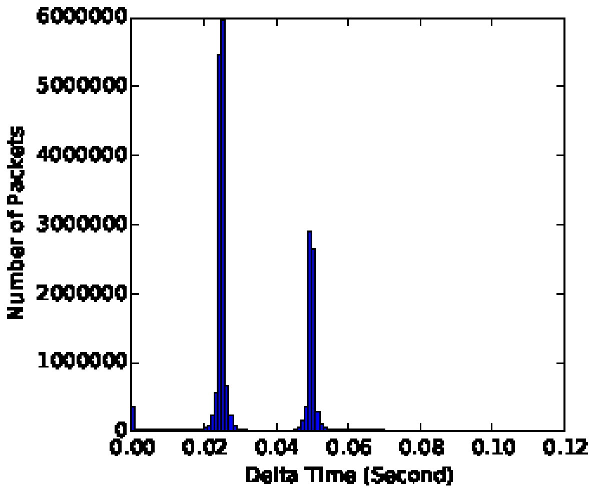


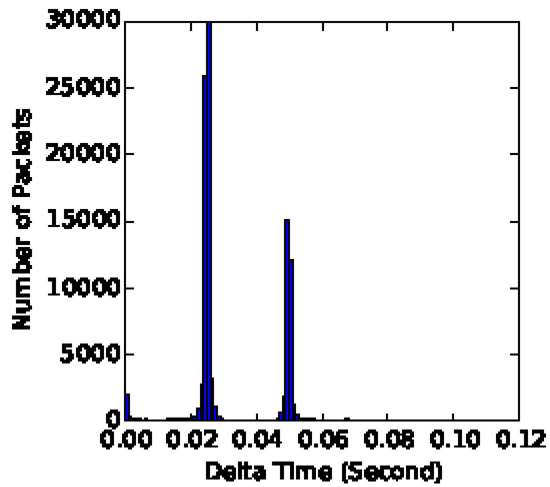
(a) Normal operation

(b) PMU connection issue

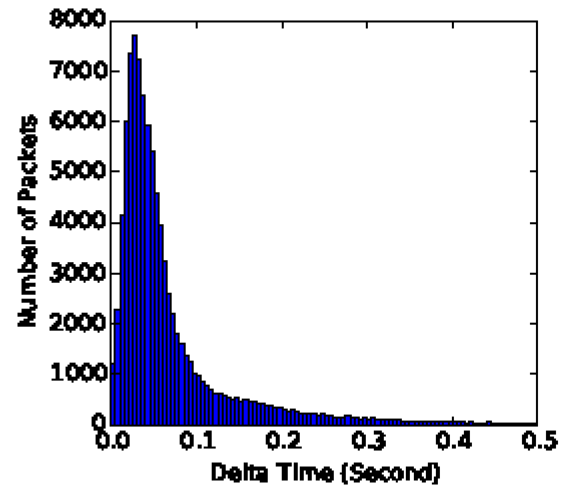
(c) MITM attack

PMU Man-In-The-Attack



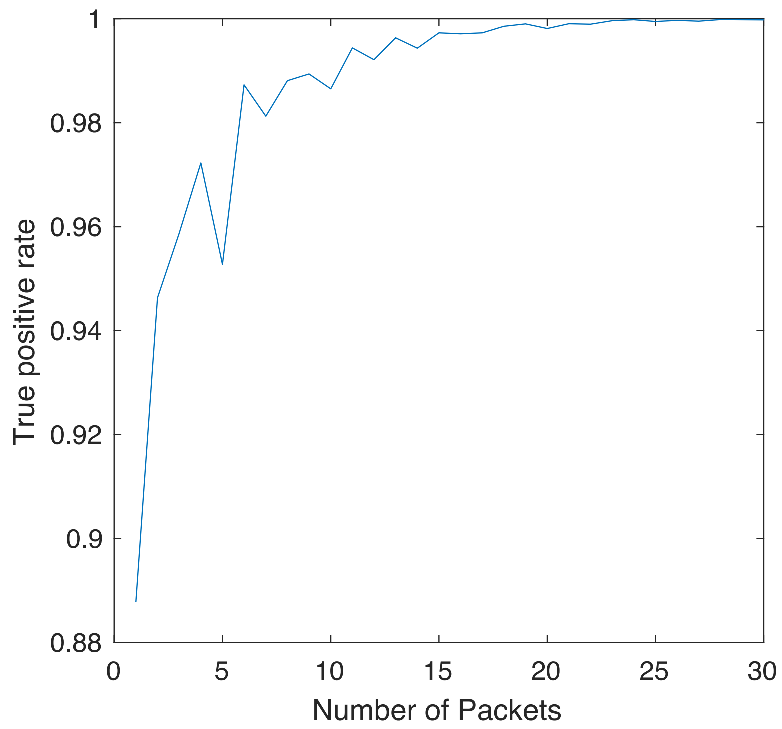


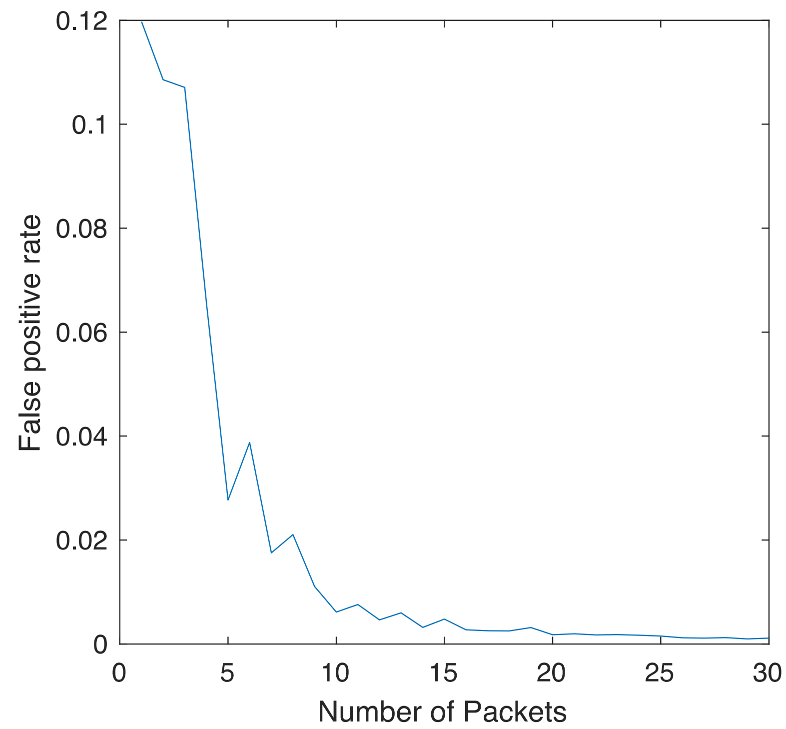
(a) PMU connection issue.



(b) MITM attack.

Results





For 30 packets:

FPR<0.0001

TPR>0.9999

One false alarm is expected for every 10000 seconds

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Summary

- Real-time simulation using the RTDS platform has played, and continues to, a major role in the RTPIS Lab’s research, education and innovation over a decade.
- Several students have learned to appreciate the value of real-time simulation and simulators.

Thank You!

G. Kumar Venayagamoorthy
Director and Founder of the Real-Time Power and Intelligent Systems Laboratory &
Duke Energy Distinguished Professor of Electrical and Computer Engineering
Clemson University, Clemson, SC 29634

http://rtpis.org
gkumar@ieee.org

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