Incremental Cost Consensus Algorithm in a Smart Grid Environment

Y3.F.C1 Distributed Control of FREEDM System

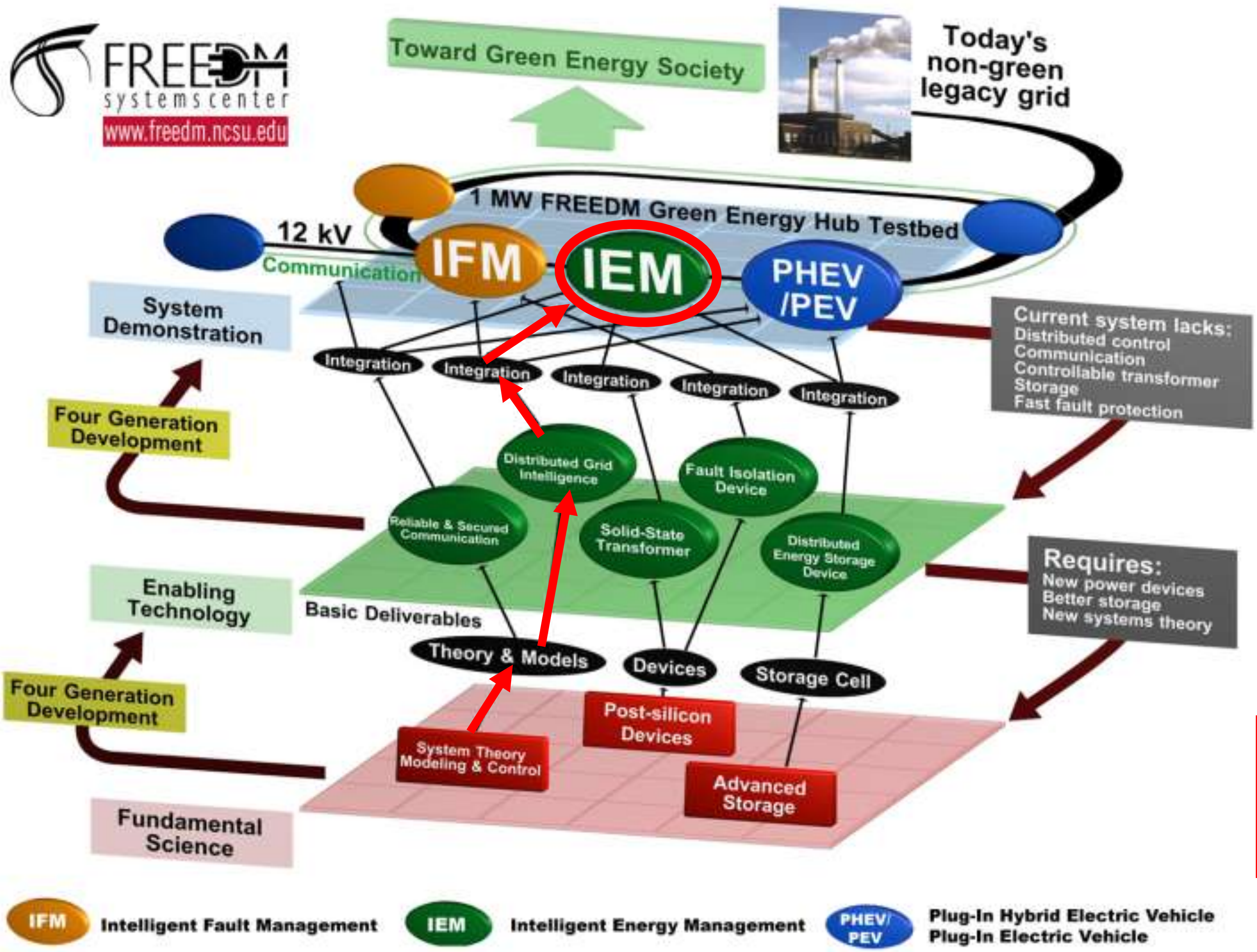
Ziang Zhang
PI: Dr. Mo-Yuen Chow
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, North Carolina

Future Renewable Electric Energy Delivery and Management Systems Center

Outline

- Background
- Motivations & Goal
- Technical Approach
- Incremental Cost Consensus Algorithm
  - Problem Formulation
  - Convergence Rate Analysis
- Future Plan

Background



System Demonstration:

- Intelligent Energy Management

Enabling Technology:

- Distributed Grid Intelligence (DGI)

Fundamental Technology:

- System Theory Modeling and Control (SMC)

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Motivation & Goal

Challenges for the Current Power Grid

- Lack of support for Distributed Generation and Renewable Energy
- Lack of flexibility and adaptability
- Vulnerability to Cyber attack, natural disasters and human errors
- $100 Billion annual loss due to power quality problems
- Aging Components

Solution:

Take advantages from the new technologies -- make the grid smarter

Project Goal

Design and implement high performance distributed controls to achieve real-time intelligent power allocation in FREEDM system.

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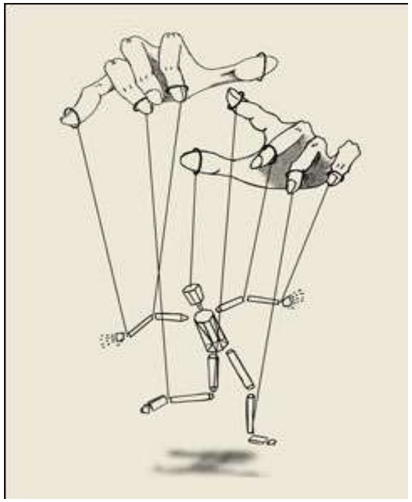
Central Control vs. Distributed Control



Puppet

vs.

School of fish

	Central Control	Distributed Control [1]
System	Puppets and Puppeteer	School of fish

groups on the move”, *Nature* 433, 513-516 (3 February 2005)

- …

Central Control vs. Distributed Control

	Central Controlled System
Pros	• Control algorithm is relatively simple • …
Cons	• Computational limitation of central controller • Communication limitation of central controller • Single point of failure will affect the entire system • …
Usages	Normally more appropriate for systems with simple control

What is consensus?

Consensus☑ [1]

A school of fish

Goal: swimming towards one same direction

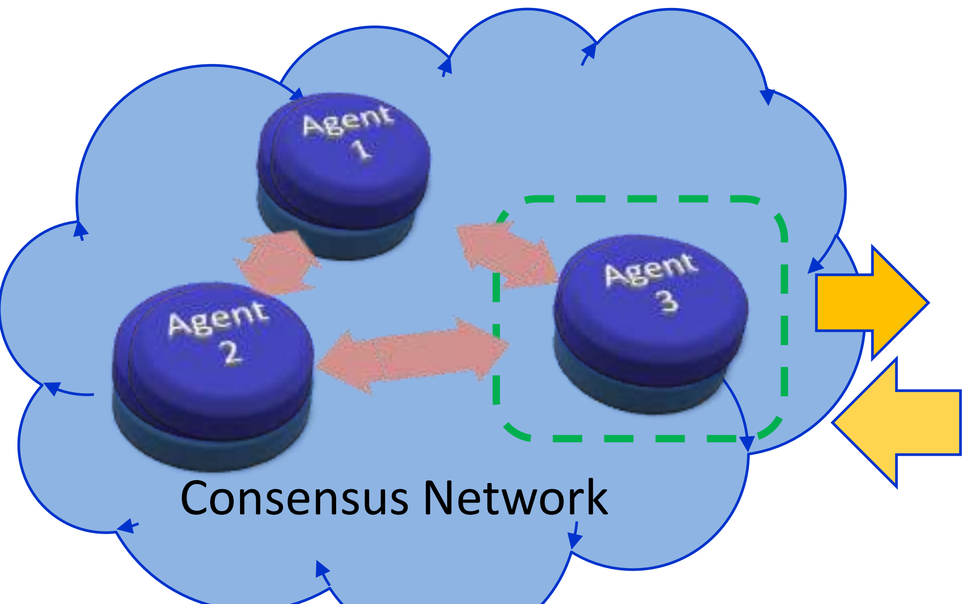
Consensus☒

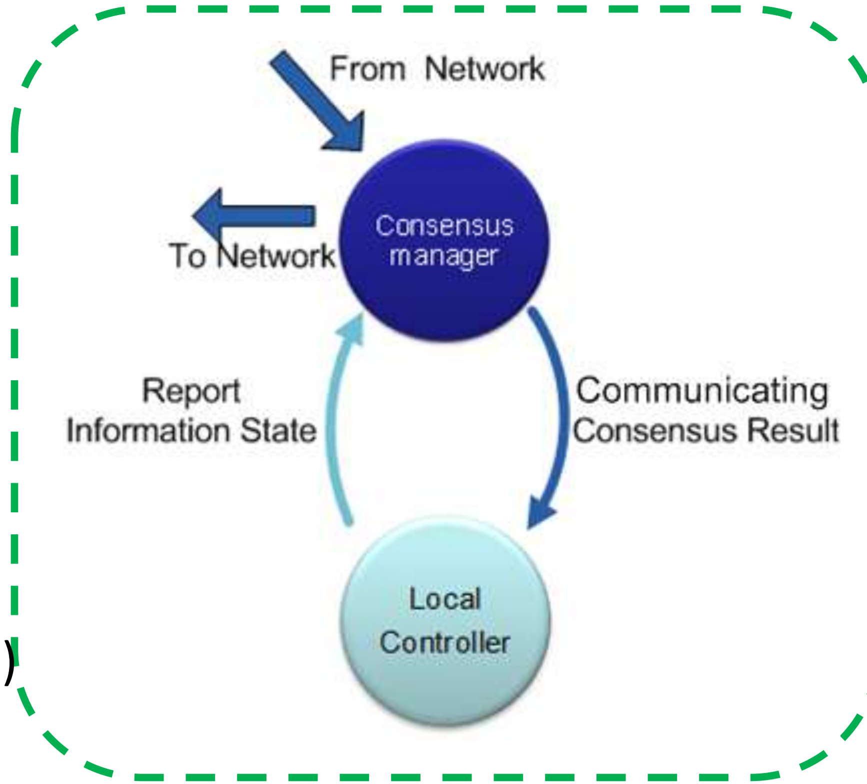
Chorus

Goal: Synchronize the melody

[1]. Larissa Conradt and Timothy J. Roper, "Consensus decision making in animals", Trends in Ecology & Evolution, Volume 20, Issue 8, August 2005, Pages 449-456.

How can consensus be reached?





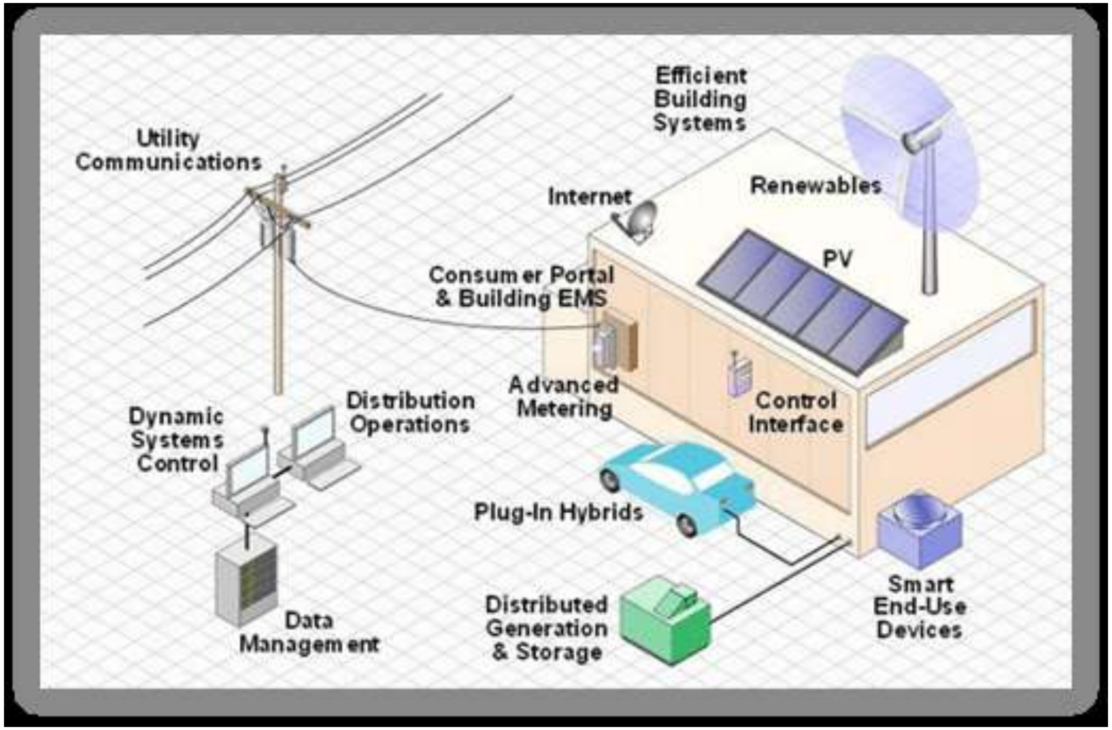
Independent Physical Systems (Generators)
Each of them follow their own dynamic

A sufficient condition for reach consensus: If there is a directed spanning tree* exists in the communication network, then consensus can be reached. **

*Spanning tree: a minimal set of edges that connect all nodes

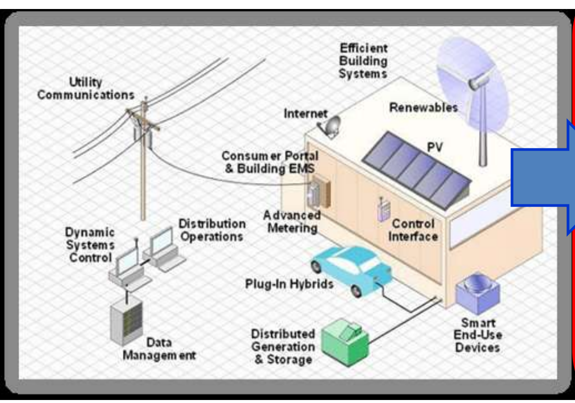
** Wei Ren Randal W. Beard Ella M. Atkins , "A Survey of Consensus Problems in Multi-agent Coordination", 2005 American Control Conference June, 2005. Portland, OR, USA

Networked Control System



Picture from EPRI

Networked Control System / Cyber Physical System



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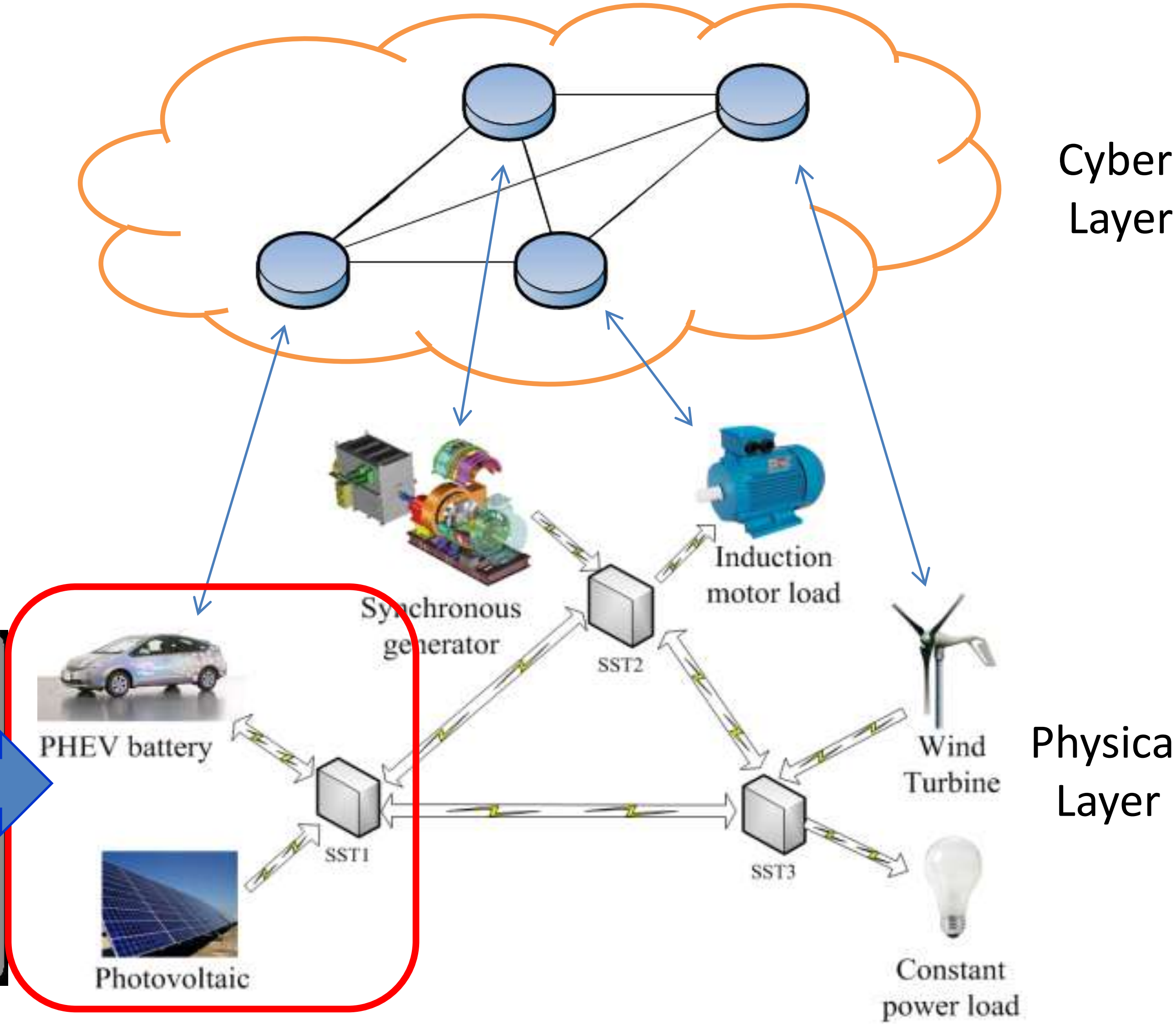
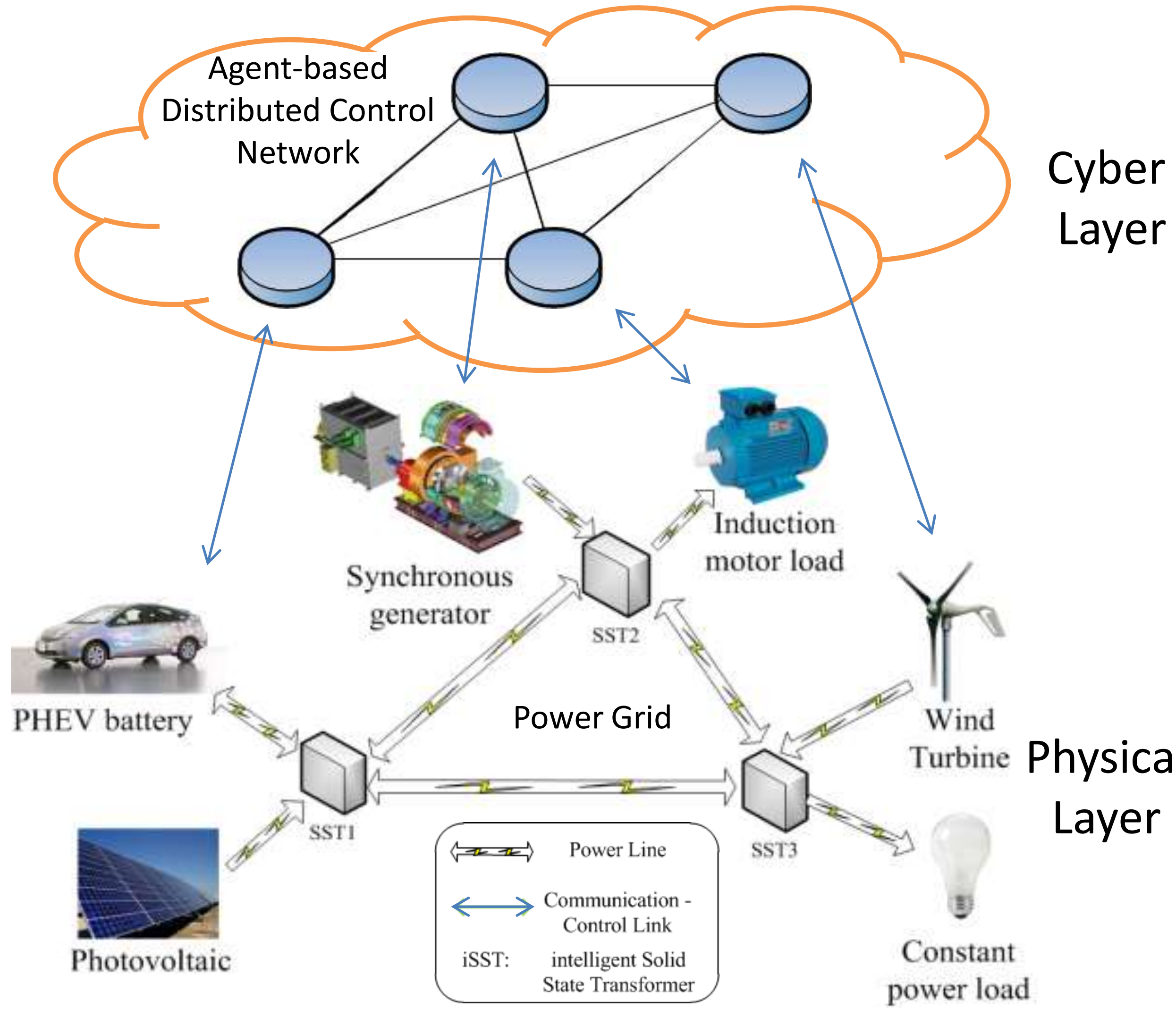



Agent-based
Distributed Control
Network
Cyber
Layer
Synchronous
generator
Induction
motor load
PHEV battery
SST2
Power Grid
Wind
Turbine
Physical
Layer
SST1
SST3
Power Line
Communication -
Control Link
iSST: intelligent Solid
State Transformer
Photovoltaic
Constant
power load

Graph Theory Modeling

- Adjacency matrix of a finite graph *G* on n vertices is the $n \times n$ matrix where the entry a_{ij} is the number of edges from vertex *i* to vertex *j*, a_{ij} =0 represent that agent *i* cannot receive information from agent *j*

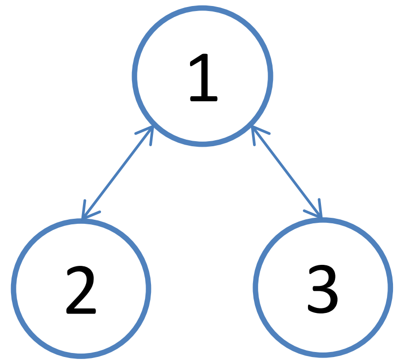
$$A = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

Adjacency matrix

$$diag(2,1,1) - A = L;$$

$$L = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Laplacian matrix



Example Network

$$D = \begin{bmatrix} \frac{1}{2} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{2} & \frac{1}{2} & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} \end{bmatrix}$$

Row-stochastic matrix

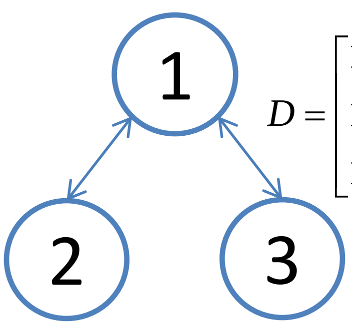
First-order Consensus Algorithm

- Consensus problem modeling
  - Local information state ξ_i
  - First-order system $\dot{\xi}_i = \xi_i, i = 1, \ldots, n$
- Consensus algorithm:

	Scalar From	Matrix Form
Continuous –time	$\dot{\xi}_i = -\sum_{j=1}^{n} a_{ij}(\xi_i - \xi_j), i = 1, \ldots, n$	$\dot{\xi} = -L_n \xi$
Discrete-time	$\xi_i[k+1] = \sum_{j=1}^{n} d_{ij}\xi_j[k], i = 1, \ldots, n$	$\xi[k+1] = D_n \xi[k]$

Where L_n is the Laplacian matrix associated with A,

and D_n is Row-stochastic matrix associated with A.



$$D = \begin{bmatrix} 1/2 & 1/4 & 1/4 \\ 1/2 & 1/2 & 0 \\ 1/2 & 0 & 1/2 \end{bmatrix}$$

k	0	1	2	3…
ξ_1	-2	-2*1/2+1/4+3/4 = 0	0	0…
ξ_2	1	-2*1/2+1*1/2 = -0.5	-0.25	-0.125…
ξ_3	3	-2*1/2+3*1/2 = 0.5	0.25	0.125…

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Decentralized Economic Dispatch

Assumptions:

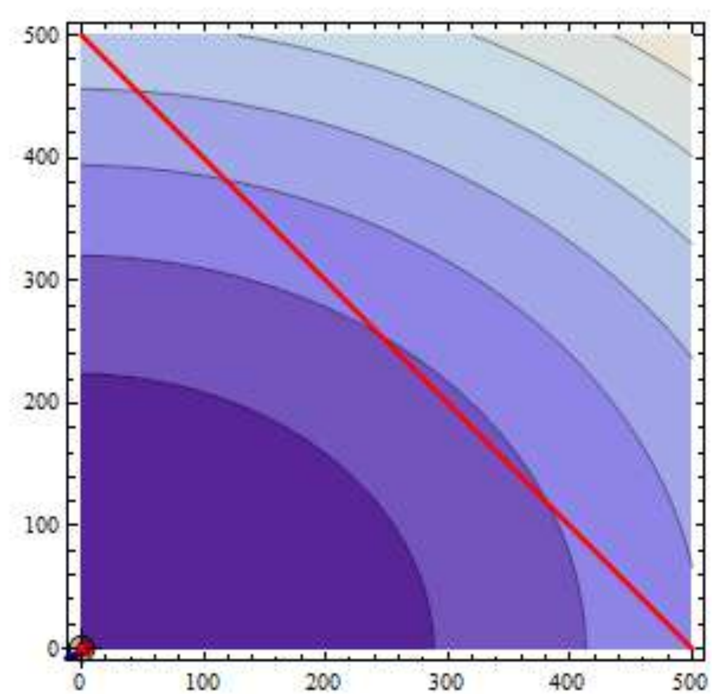
- All the signals are “good”
  - No security issue
- No generation limitation (in this presentation)
- The cost functions are quadratic
- The power grid topology is fixed

Decentralized Economic Dispatch

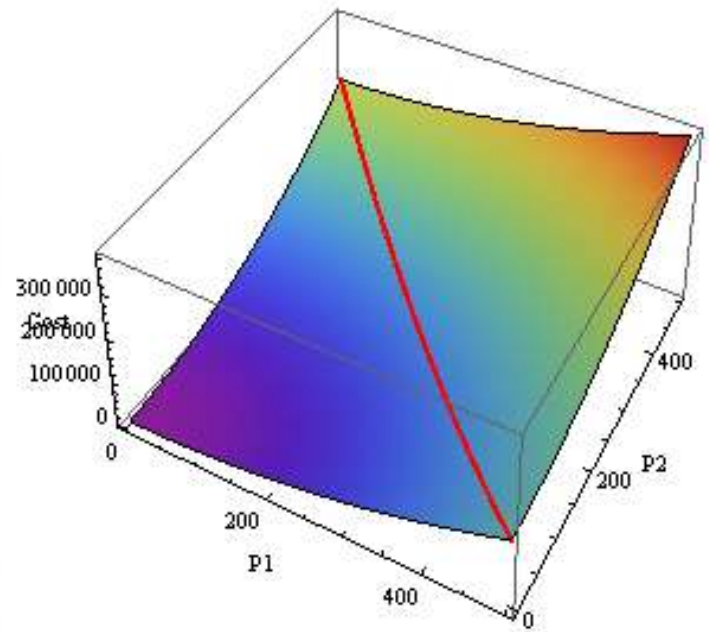
Economic Dispatch Problem -- A constrained optimization problem

$$Min: Cost = (561+7.92P_1+0.562P_1^2)+(310+7.85P_2+0.94P_2^2)$$

$$s.t.: P_1 + P_2 = 500$$



Contour Graph



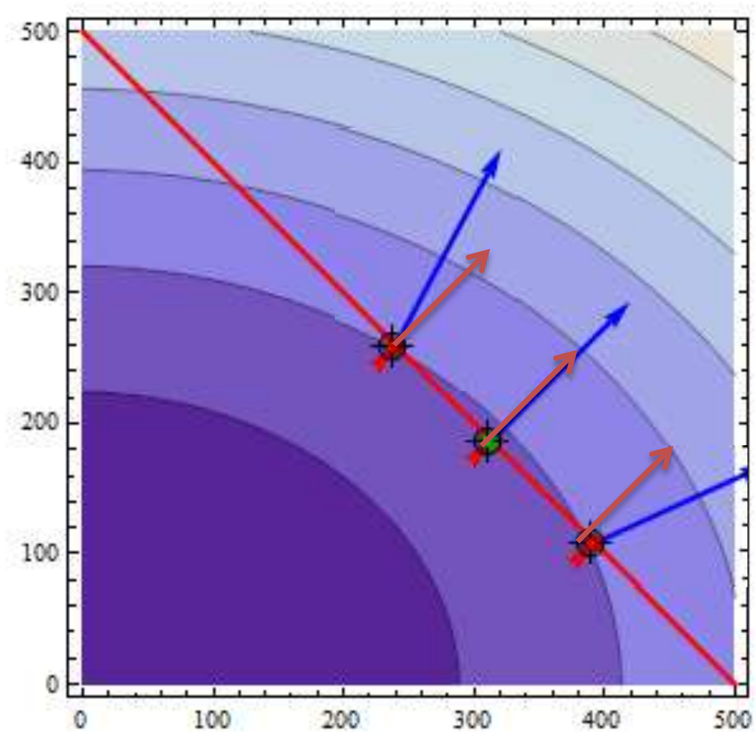
3D view

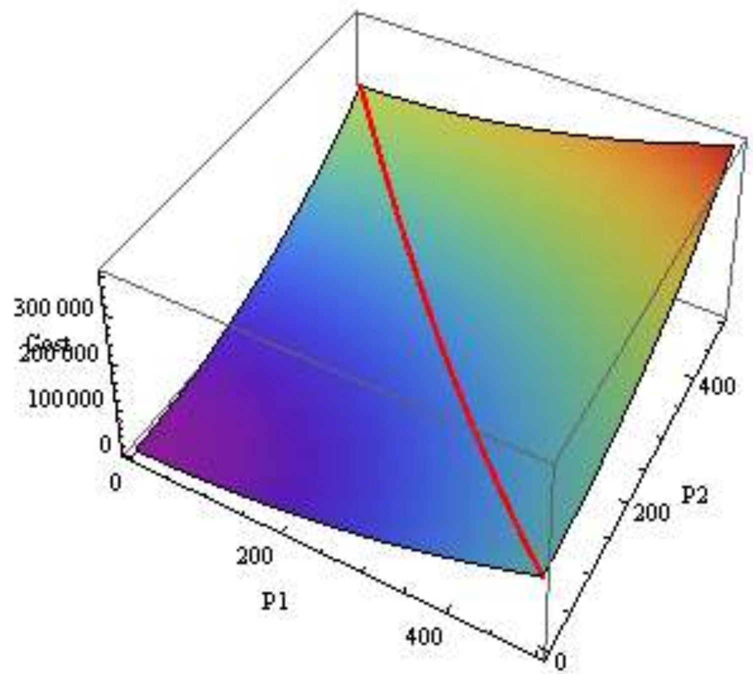
Decentralized Economic Dispatch

Economic Dispatch Problem -- A constrained optimization problem

Min: Cost $= f(P_1, P_2)$

s.t. : $g(P_1, P_2) = P_1 + P_2 - 500$





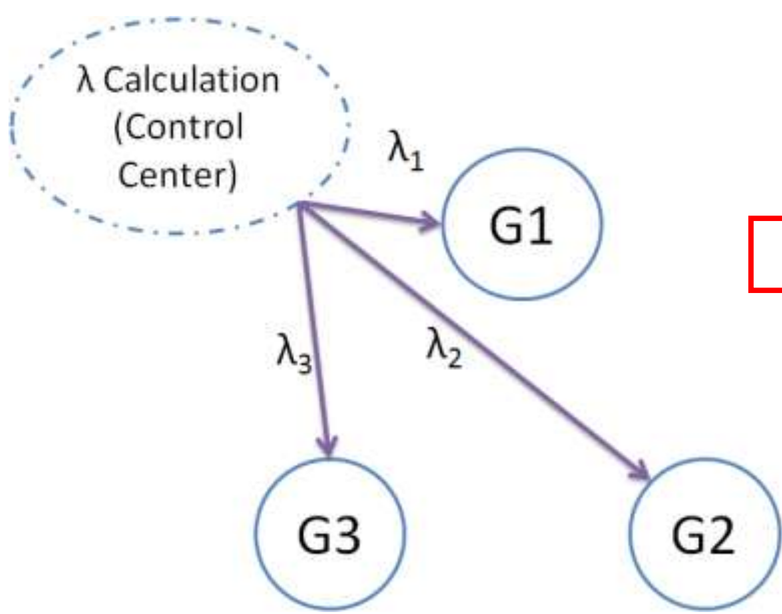
optimal solution at (312.893 , 187.107)

At the optimal point: $\nabla f(x, y) = \lambda \nabla g(x, y)$

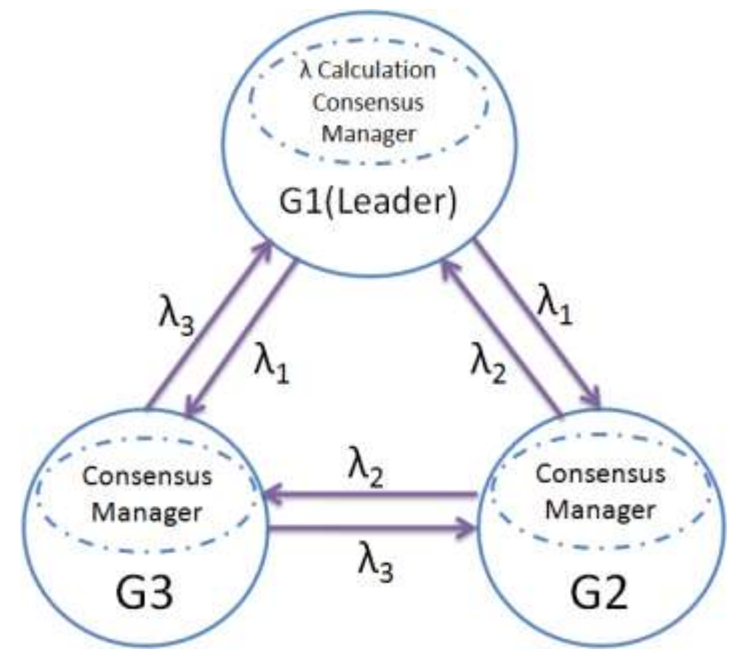
Incremental Cost Consensus

Decentralize the Economic Dispatch Problem Using Consensus Network:

When using Lagrange multiplier method solving Economic Dispatch Problem, each generator will have the same Incremental Cost at the minimum cost point



Conventional Central Controlled Communication Topology for a 3-bus system



Distribute Controlled Incremental Cost Consensus Network

Incremental Cost Consensus

Mathematical Formulation :

Assume the fuel-cost curve of each generating unit is known and expressed in terms of the output power:

$$C_i (P_{Gi})=\alpha_i +\beta_i P_{Gi} +\gamma_i P_{Gi}^2 , \quad i=1,2,\ldots m$$

where $C_i (P_{Gi})$ is the cost of generation for unit *i*.

P_{Gi} is the output power of unit *i*

The objective is to minimize total cost of operation:

$$C_T = \Sigma C_i (P_{Gi}).$$

Subject to constrains: $\Sigma P_{Di} - \Sigma P_{Gi} =0;$

From the conventional economic dispatch we know:

$$IC_i =\partial C_i (P_{Gi}) / \partial P_{Gi} = \lambda_i$$

Pick λ as the information state, use the first order discrete consensus algorithm :

$$\lambda_i [k+1]= \Sigma d_{ij} \lambda_j[k],$$

where d_{ij} is the (i,j) entry of row-stochastic matrix D_n.

The consensus algorithm for the leader (mediator/ coordinator) generator becomes:

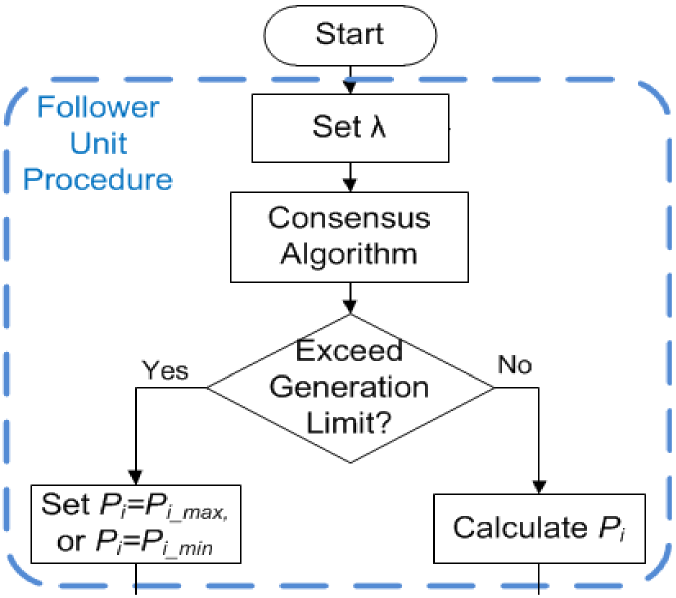
$$\lambda_i [k+1]= \Sigma d_{ij} \lambda_j[k] + \varepsilon \Delta P ,$$

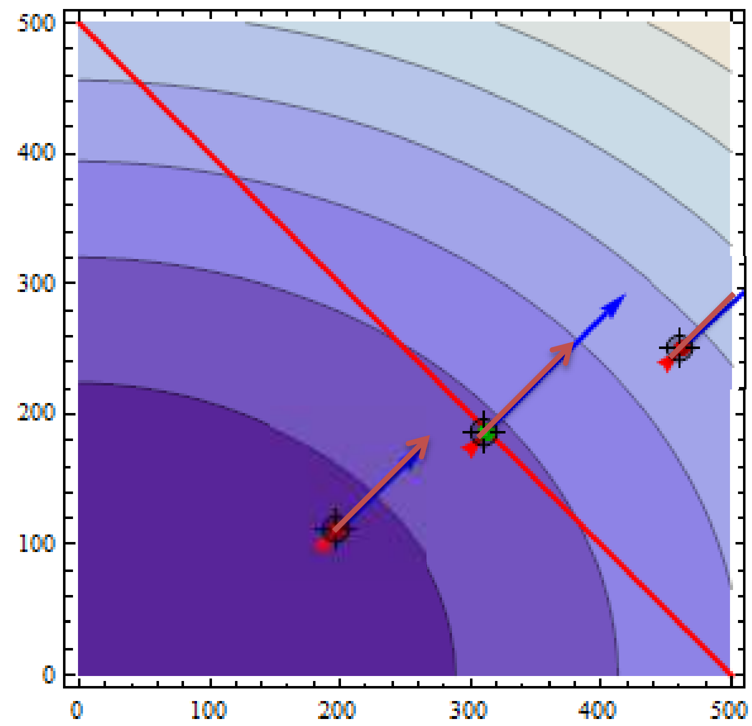
where ε is a scalar which controls the convergence speed.

$\Delta P = \Sigma P_{Di} - \Sigma P_{Gi}.$

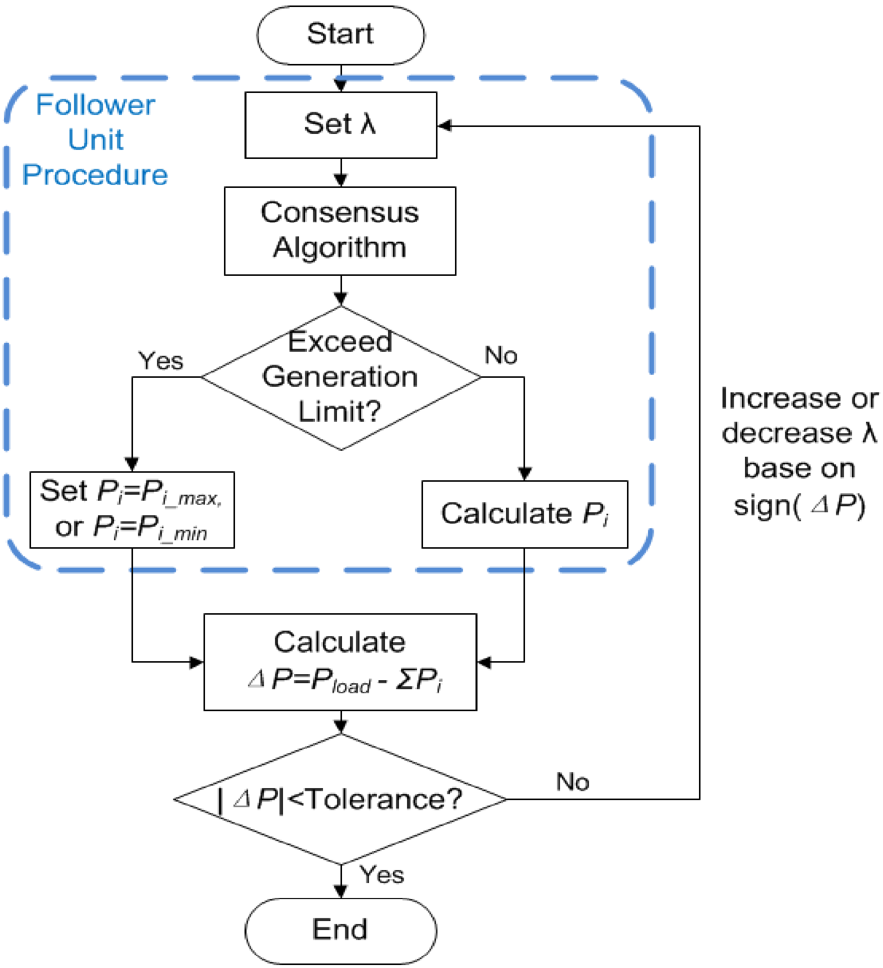
Incremental Cost Consensus

Flow Chart:

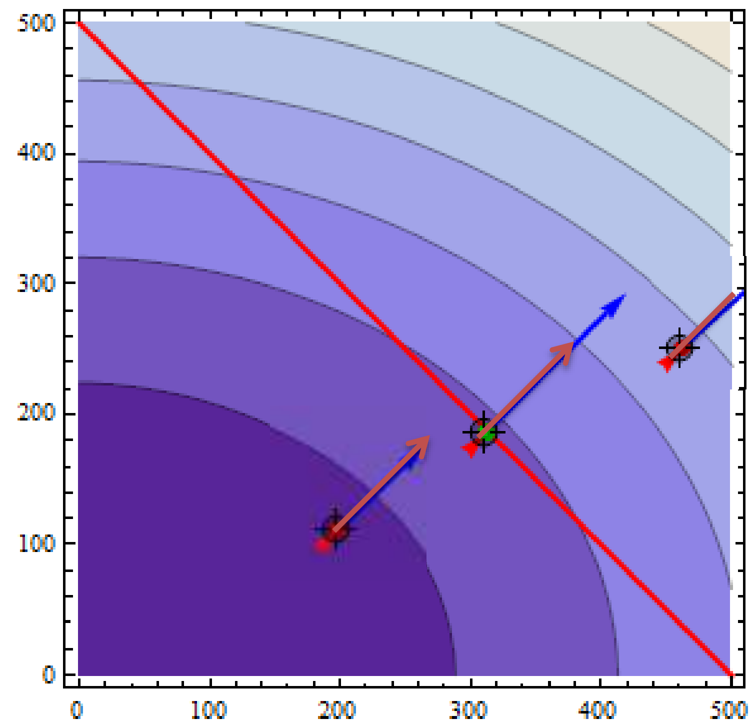




Flow Chart:



Start
Follower Unit Procedure
Set λ
Consensus Algorithm
Exceed Generation Limit?
Yes
No
Set P_i=P_{i_max}, or P_i=P_{i_min}
Calculate P_i
Calculate ΔP=P_{load} - ΣP_i
|ΔP|<Tolerance?
No
Yes
End
Increase or decrease λ base on sign(ΔP)



500
400
300
200
100
0
0
100
200
300
400
500

Simulation Results

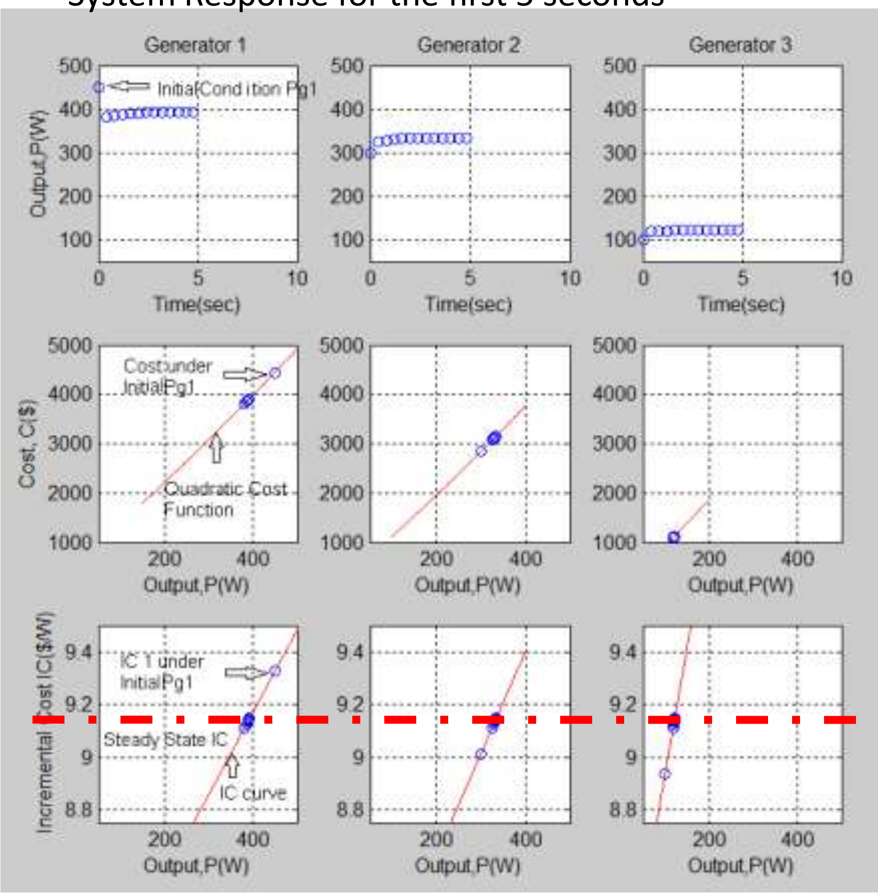
Using a fully connected 3-bus system with initial conditions:

P_D=850*MW*, $P_{G1}(0)$=450*MW*, $C_1(P_{G1})=561+7.92P_{G1}+0.001562P_{G1}^2$ *\$/hr*

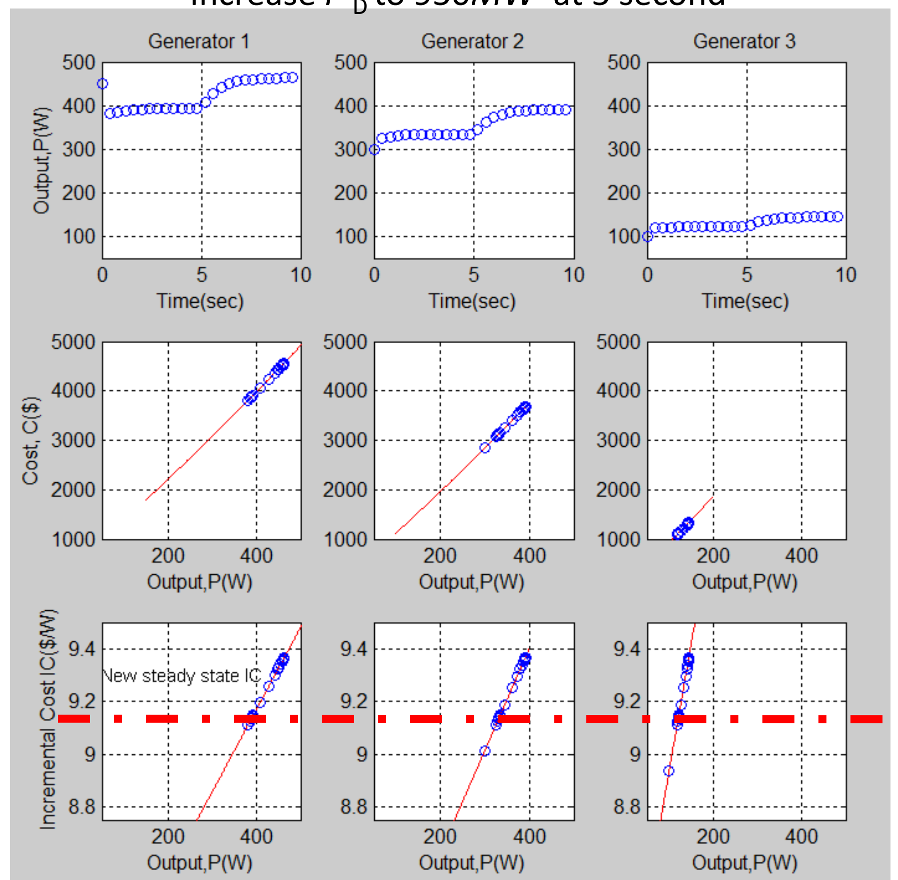
$P_{G2}(0)$=300*MW*, $C_2(P_{G2})=310+7.85P_{G2}+0.00194P_{G2}^2$ *\$/hr*

$P_{G3}(0)$=100*MW*, $C_3(P_{G3})=78+7.79P_{G3}+0.001482P_{G3}^2$ *\$/hr*

System Response for the first 5 seconds



Increase P_D to 950*MW* at 5 second



When IC Consensus algorithm reach the steady state, the final IC we obtained is equal to the λ which calculated by using the Lagrange multiplier method

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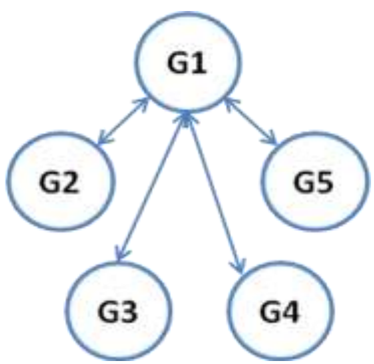
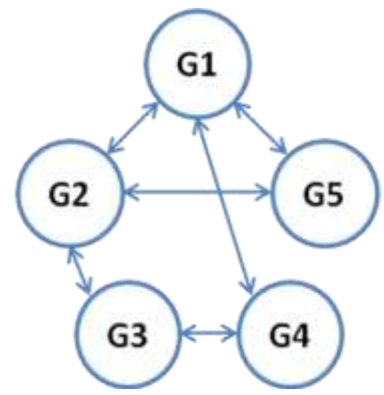
Convergence Rate Analysis

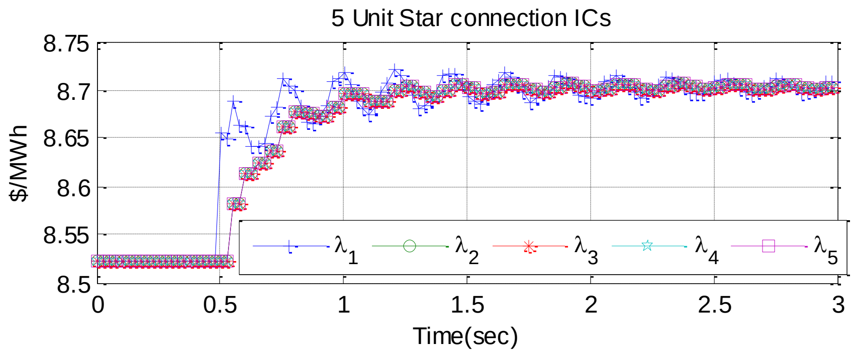
The convergence rate of Incremental Cost Consensus (ICC) algorithm can be affected by following configurations:

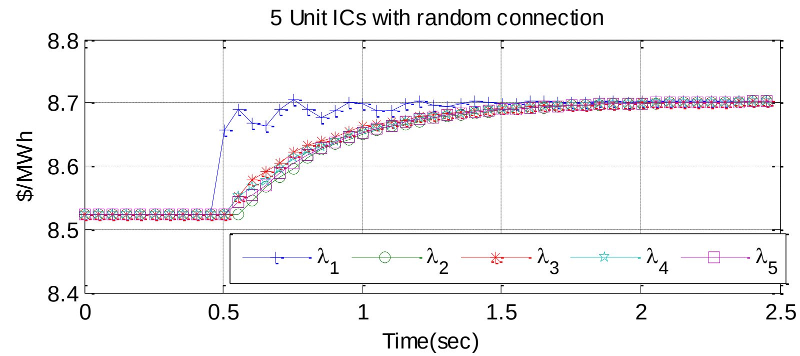
- General configurations(which also apply to conventional EDP):
  - Inertia of synchronous generators
  - Power grid topology
  - System sampling rate
  - Signal transmission delay
- Feature configurations (which only valid when using ICC):
  - Communication topology
  - Location of leader
  - Weighting of the edges of communication network

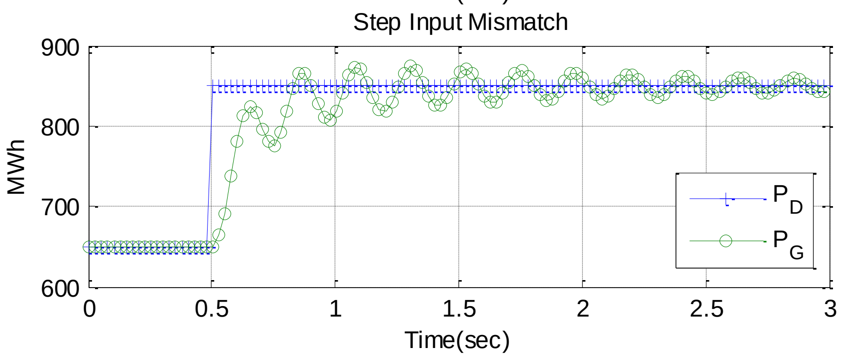
Communication Topology

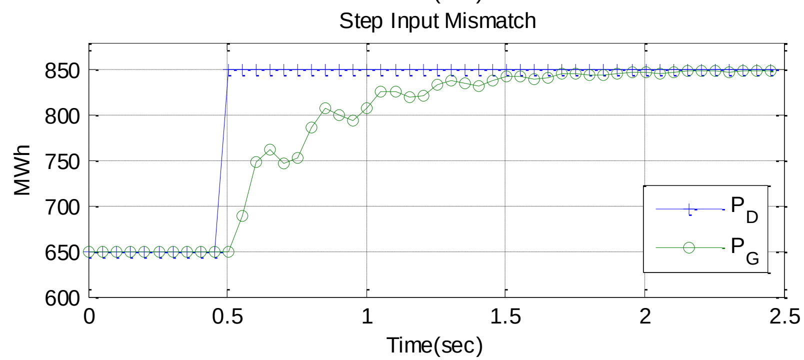












The Location of Leader

Centrality indices have been tested:

C_D: Degree centrality (Nieminen 1974)

C_B: Betweenness centrality (Anthonisse 1971, Freeman 1979)

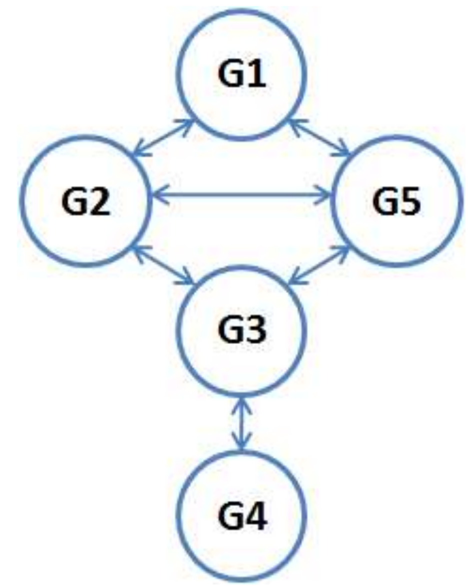
C_C: Closeness centrality (Sabidussi 1966)

C_E: Eigenvector centrality (Bonacic 1972)

C_S: Subgraph centrality (Estrada and Rodriguez-Velazquez 2005)

Example:

For a given topology:



Node centralities value calculated by different indices:
(the larger the better)

Node	C_D	C_B	C_C	C_E	C_S
1	2	0	0.14	0. 41	3.03
2	3	0.2	0.2	0. 54	4.33
3	3	0.6	0.2	0. 47	3.82
4	1	0	0. 13	0. 18	1.67
5	3	0.2	0. 2	0. 54	4.33

The ranking of five nodes based on different centrality measure are:

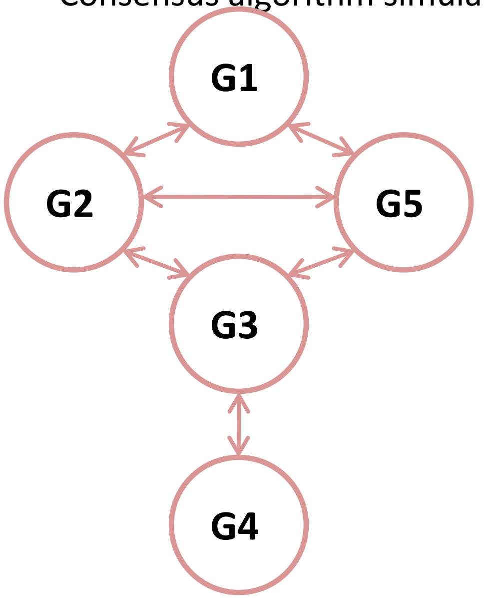
C_D and C_C : G2 = G3 = G5 >G1 > G4.

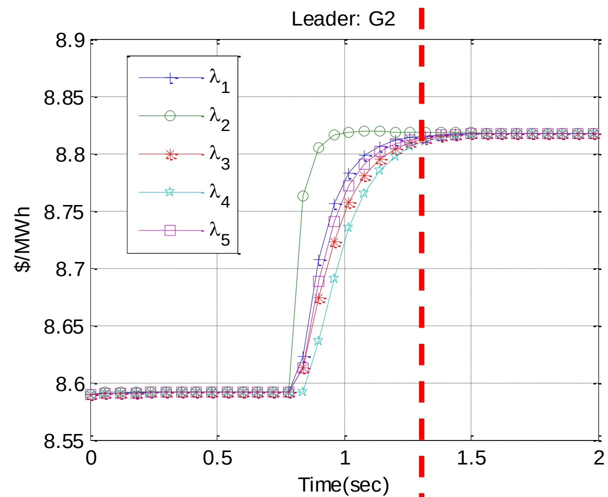
C_B : G3 > G2 = G5 > G1 = G4

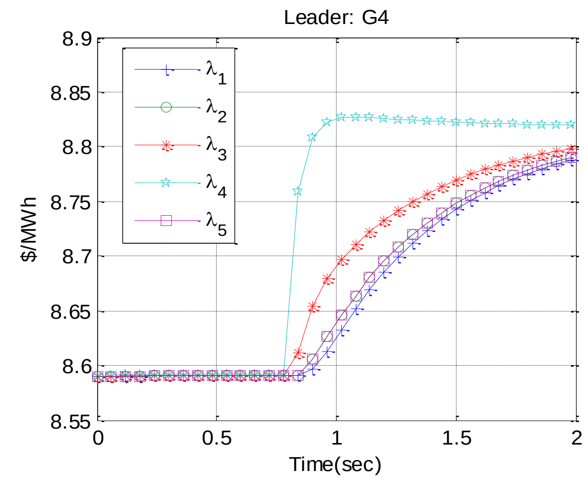
C_E and C_S : G2 = G5 > G3 > G1 > G4

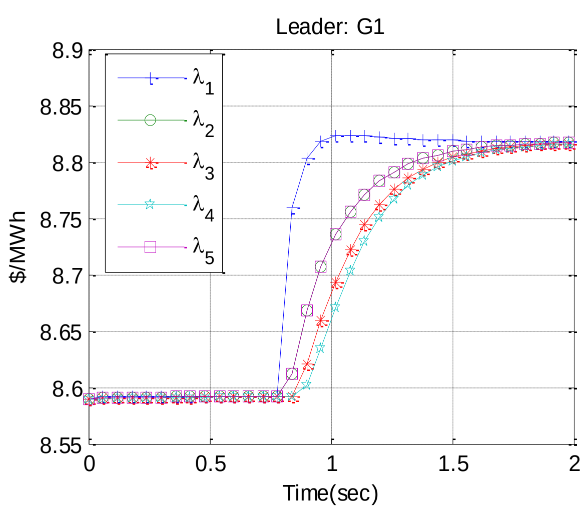
The Location of Leader

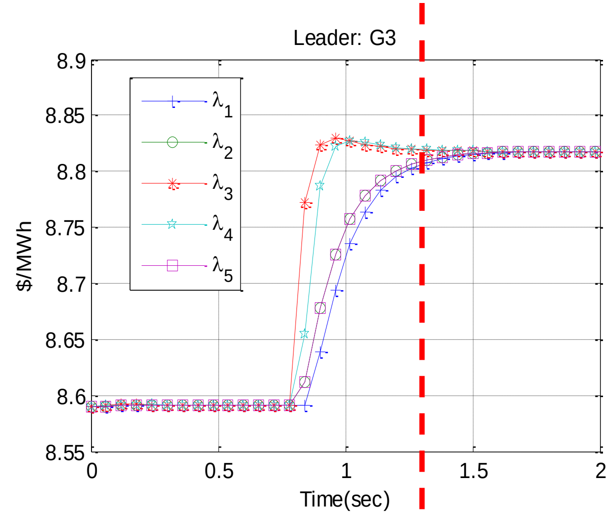
Consensus algorithm simulation results by selecting different node as leader :











Convergence rate from simulation :

G2 = G5 > G3 > G1 > G4

The convergence time is consistent with C_E and C_S's result.

Thus, we suggest use C_E or C_S for leader election.

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Threats and Future Work

- Detailed Greenhub distributed control modeling and simulation
  - Extend to full Greenhub scale
  - Include both communication network and power grid and their interactions
  - Use dynamic topology to simulate "Plug-and-Play" scenario
- Intelligent distributed control algorithms for FREEDM Greenhub
  - Effectively select leaders in the consensus algorithms to guarantee fastest convergence rate
  - Adjust appropriate weightings during consensus updating
- Analyze the robustness of algorithms
  - Package Loss
  - Link failure
  - Node failure
- Investigate the bandwidth limitation issue
  - Develop and implement adaptive sampling strategies
  - Develop and implement distributed bandwidth allocation algorithms
- Investigate network delay effects on the Greenhub distributed control
  - Develop corresponding network delay compensation algorithms

Related Publications

1. Z. Zhang, M. Chow, "Consensus Algorithms for Distributed Controlled FREEDM Systems," *Conference record, NSF FREEDM Annual Meeting*, Tallahassee, FL, May, 2010.
2. B. McMillin, *IEEE,* R. Akella, D. Ditch, G. Heydt, Z. Zhang and M-Y. Chow, "Architecture of a Smart Microgrid Distributed Operating System", *IEEE Power Systems Conference & Exposition,* Phoenix, AZ, *2011.*
3. J Mitra, N Cai, M-Y Chow, S Kamalasadan, W Liu, W Qiao, S N Singh, A K. Srivastava, S K. Srivastava, G K. Venayagamoorthy and Z Zhang, "Intelligent Methods for Smart Microgrids" panel paper, *2011 IEEE PES General Meeting, Detroit, Michigan, USA*
4. Ziang Zhang and Mo-Yuen Chow, "Incremental Cost Consensus Algorithm in a Smart Grid Environment," Proceedings of *IEEE Power & Energy Society General Meeting 2011,* under review
5. Ziang Zhang and Mo-Yuen Chow, "The Convergence Analysis of Incremental Cost Consensus Algorithm under Different Communication Network Topologies in a Smart Grid," *IEEE Transactions on Power Systems,* under review.

FREEDM website / Members Only/ Research Groups / Distributed Grid Intelligence / Distributed Control of FREEDM System

Thank you!

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