# Multi-Agent System Transient Stability Platform for Resilient Self-Healing Operation of Multiple Microgrids

Sergio Rivera
Massachusetts Institute of Technology
serivera@mit.edu

Amro M.Farid
Masdar Institute of Science and Technology
afraid@masdar.ac.ed

Kamal Youcef-Toumi
Massachusetts Institute of Technology
youcef@mit.edu

NSF Workshop
The 9th Carnegie Mellon University-Electricity Conference
February 4-5, 2014

# Presentation Outline



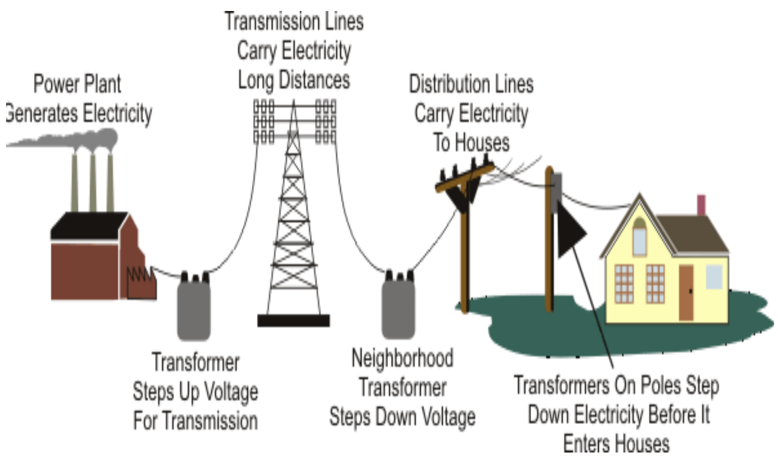
- **Goals:**
  - Coordination & Control of Microgrids and current research needs.
  - Multi-Agent System Transient Stability Platform for Resilient Self-Healing Operation of Multiple Microgrids

- **Outline**
- **Motivation**
- **Approach for Multi-Agent system Coordination & Control of Microgrids**
- **Platform for Multi-Agent System Transient Stability**
- **Case study**
- **Conclusion**

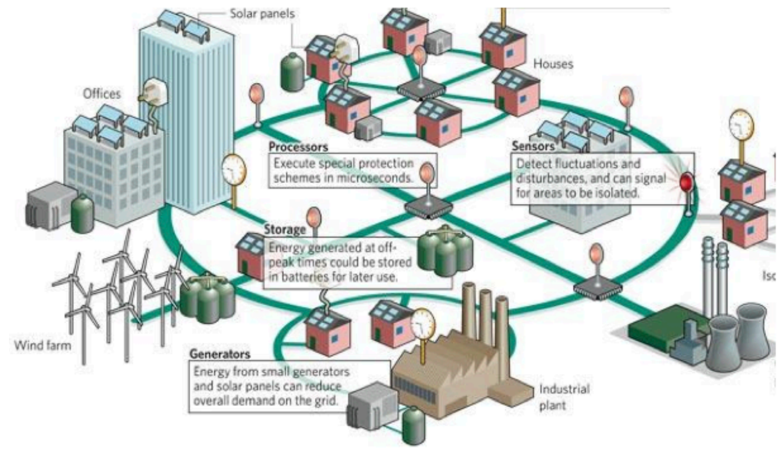
# Power Grids – Present and Future



## Present Power Grid [7A]




## Power Grid of the Future [8A]




Power Grid of the Future integrates:

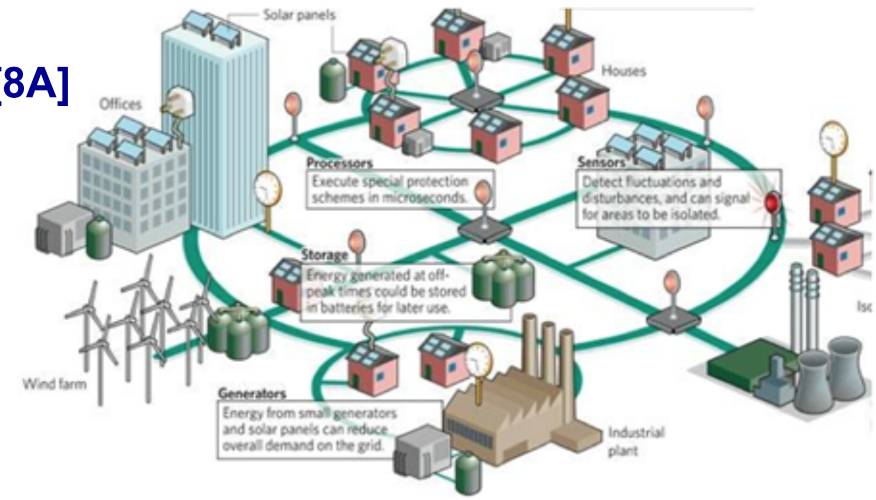
- Meshed-two-way flow in the distribution system
- Demand side management
- Renewable energy
- …

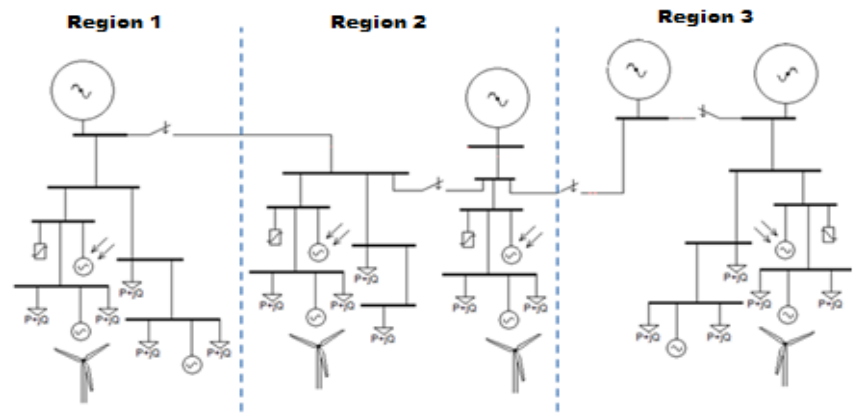
∴**Future Power Grid requires a total "rethink" to its operation!**

# Power Grid Operation with Multiple Stakeholders



[8A]



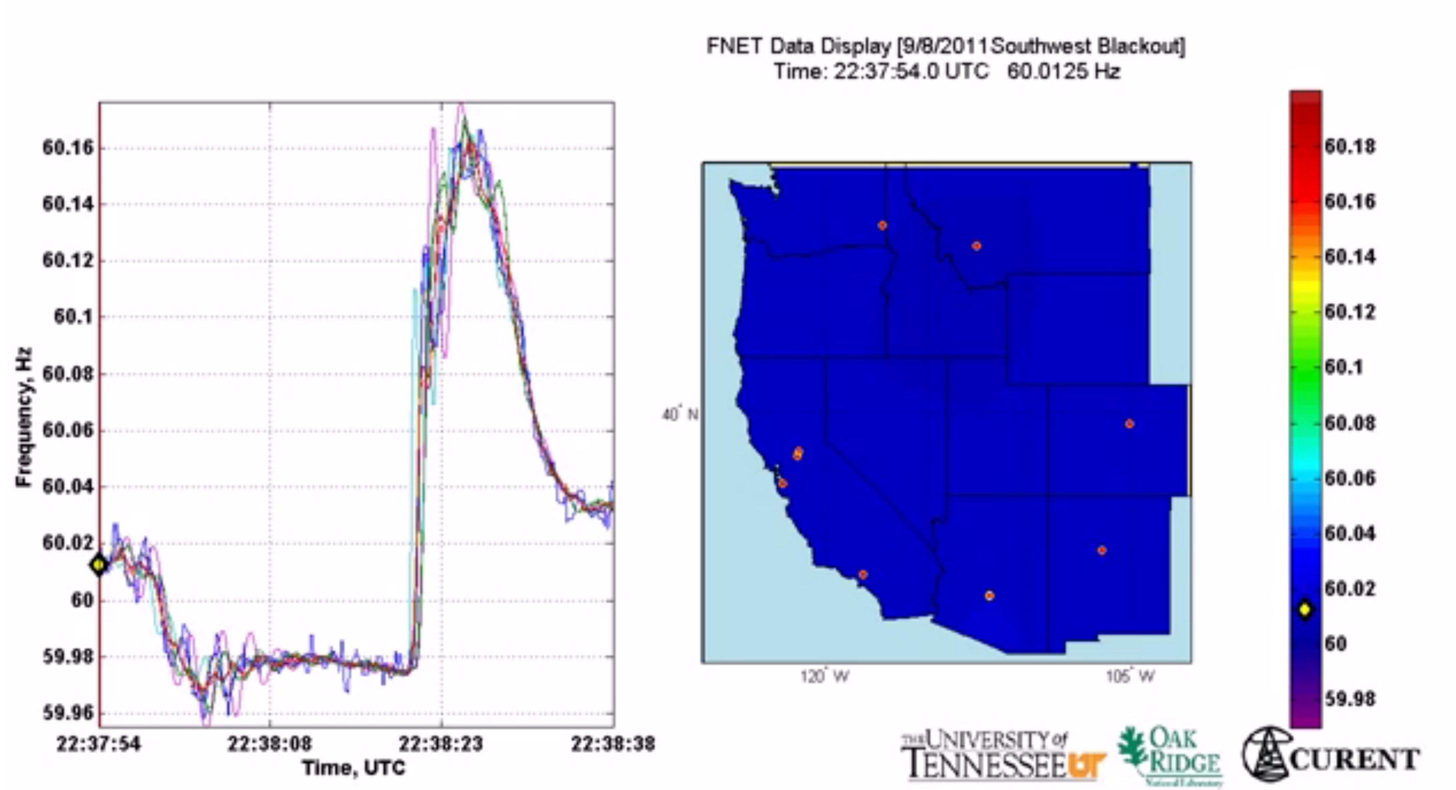

- Multiple stakeholders & multilateralism: multiple stakeholders should be able to make independent, partially & fully coordinated decisions
  - Independent power producers
  - Active demand side participants
  - Independent microgrids
  - Co-operating utilities
  - Co-operating nations
- Increasing penetration of self-controlled microgrids
- Increasing coordination between connected utilities in different countries

**∴Multiple stakeholders require robust & distributed reconfigurable control methods for reliable operation**

# Blackouts Induced by Fault Propagation



- Sept 8, 2011 Southwest Blackout Event: Operator makes an error in a routine reconfiguration of a capacitor bank. → Disrupts entire western US.

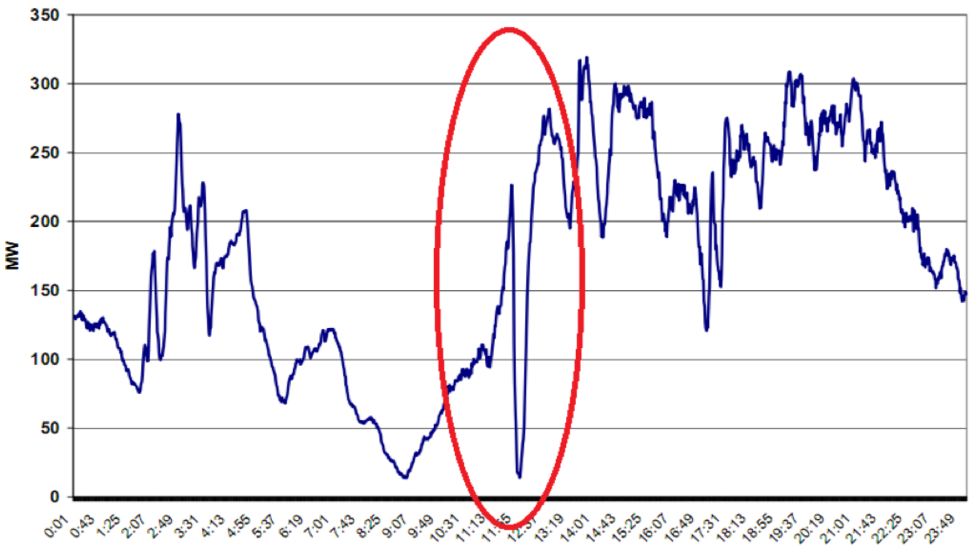



∴ **Online reconfiguration can have dramatic effects!**

# Broken Power Grid Conventional Wisdoms

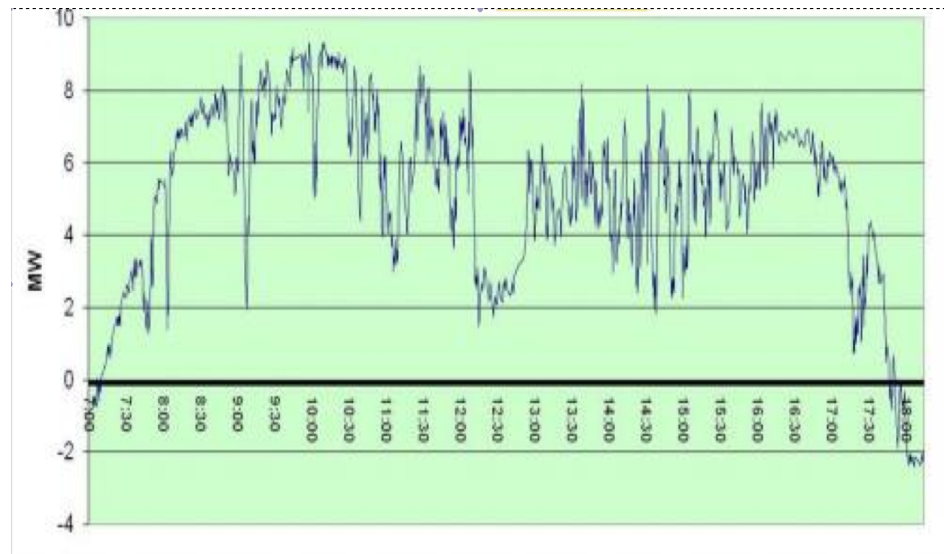


Wind Power Output




Source: ERCOT 2009

Solar Power Output on a Cloudy Day




Source: NERC 2009

∴Wind Power Output Can Vary Drastically & Suddenly

∴Solar Output on a Cloudy Day Can Vary Drastically

∴Variable Behavior of Renewable Energy Resources Stresses the Power Grid

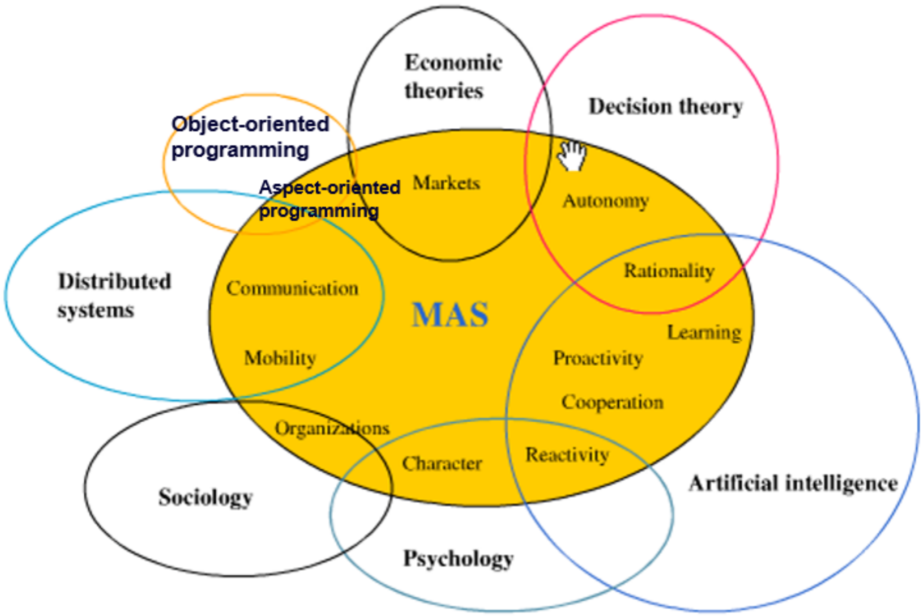
# MULTI-AGENT SYSTEMS



A **multi-agent system** is a computerized system composed of multiple interacting intelligent agents within an environment.

Multi-agent systems can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve.

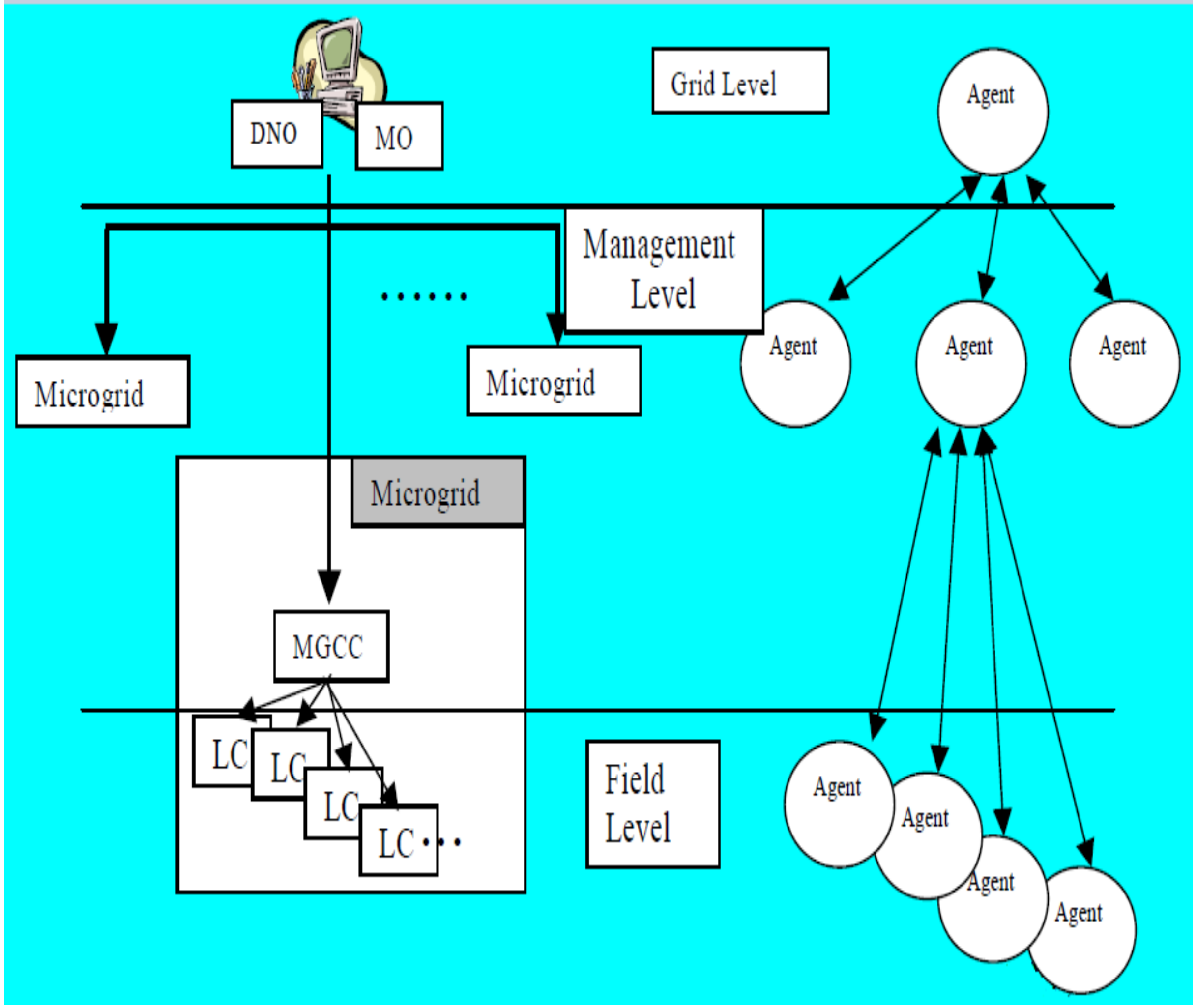
- Autonomy/Semi-autonomy
- Reactivity
- Distributed, Coordinated Decision making




[36]

# MAS - Microgrids Control and Coordination



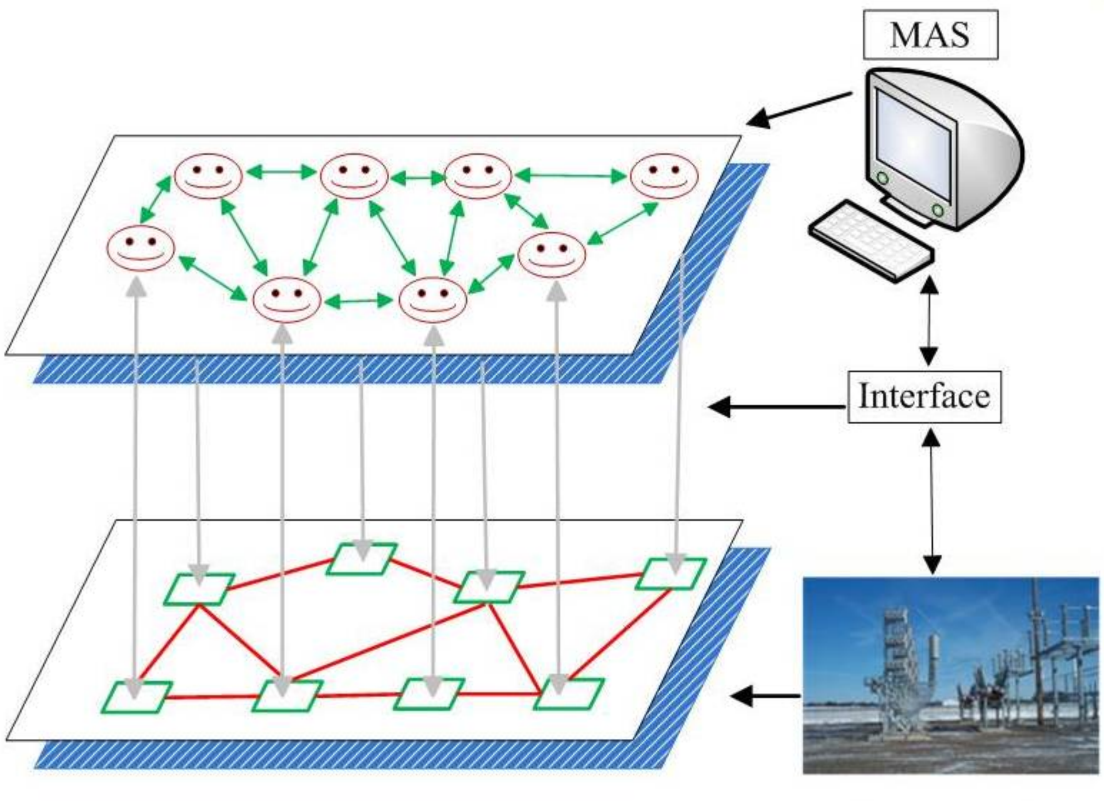



[21]-[25]

- The Distribution network Operator (DNO) refers to the operational functions of the system and the Market Operator (MO) to the Market functions, in the Grid Level.
- The MicroGrid Central Controller (MGCC) is the main responsible for the optimization of the MicroGrid operation coordinating the Local Controllers (LC), in the Management Level.
- The LC's control the Distributed Energy Resources (DER), production and storage units, and some of the local loads, in the Field Level.

# MAS - Microgrids Control and Coordination





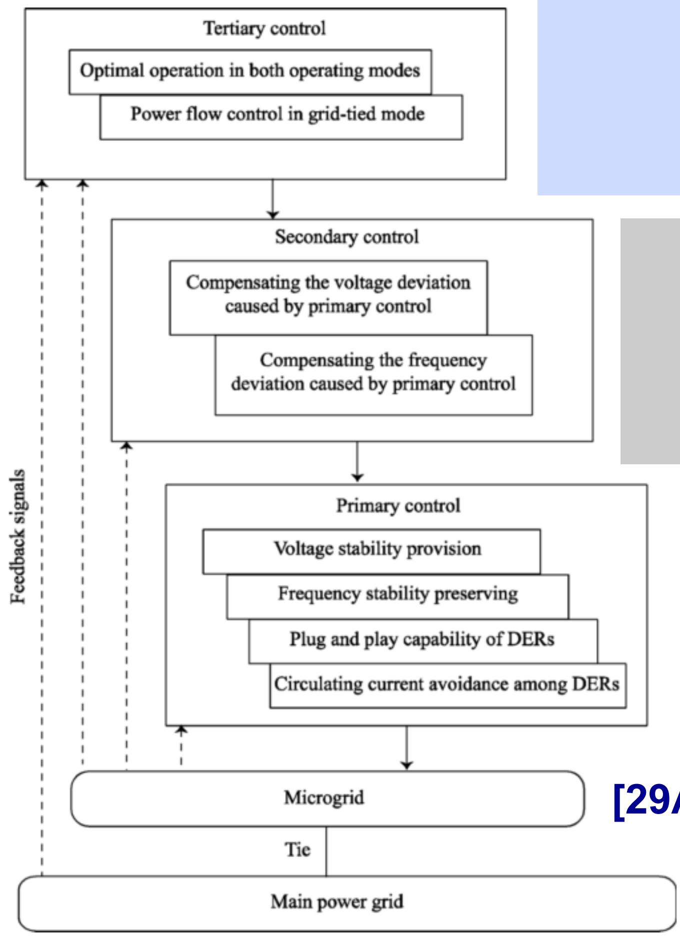

[36]

## Current Drawbacks:

- Agents have only partial representation of the environments.
- No account for the dynamic grid behavior.
- No account for Primary, secondary and tertiary control interaction.

# Multi-Layer Design Principles






[29A]

- Power grids traditionally employ primary, secondary & tertiary control – we study these together rather than independently
- We propose an agent layer for complex rule-based decision-making that mimic people and organizations
- Many open questions as to what functionality is required in each layer

**∴Enterprise control requires new & thoughtful design principles on how to best allocate different types of control functionality**

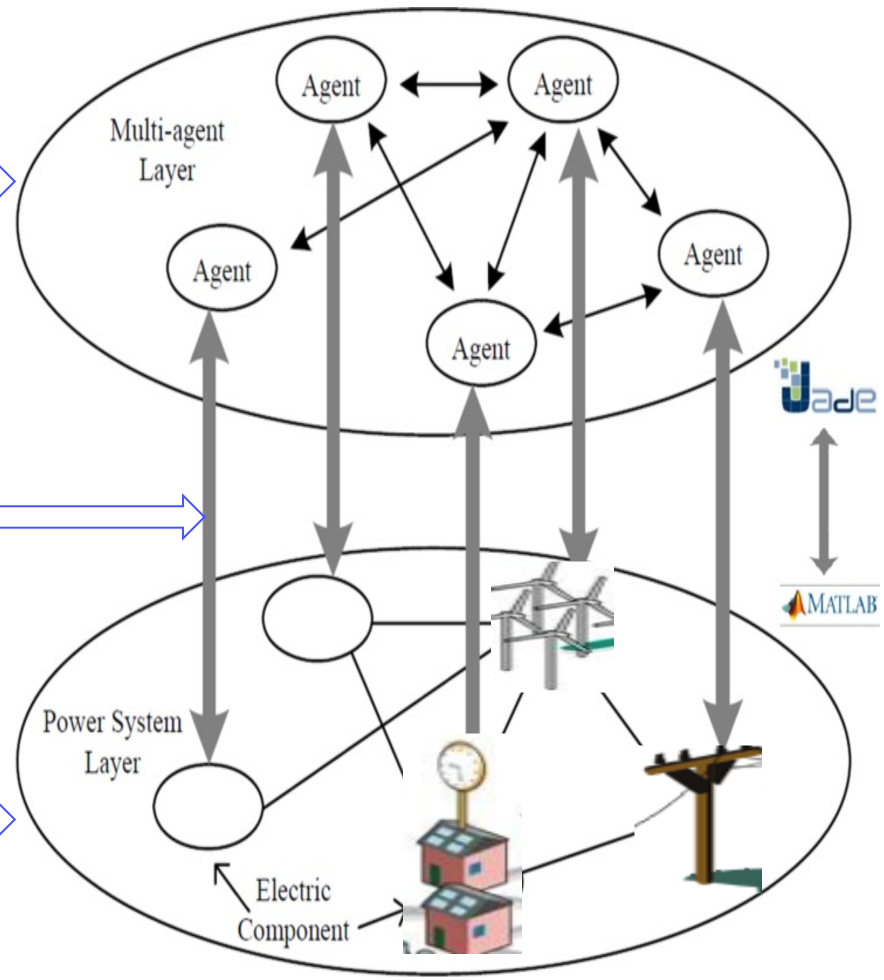
# Developed Multi-Agent System Transient Stability Platform



- Multi-agent layer
- Developed in JAVA-JADE

- Each physical component has its virtual representation in multi-agent layer
- JAVA-MATLAB interface enables communication in both ways

- Power system layer
- Developed in MATLAB



# Developed Multi-Agent System Transient Stability Platform

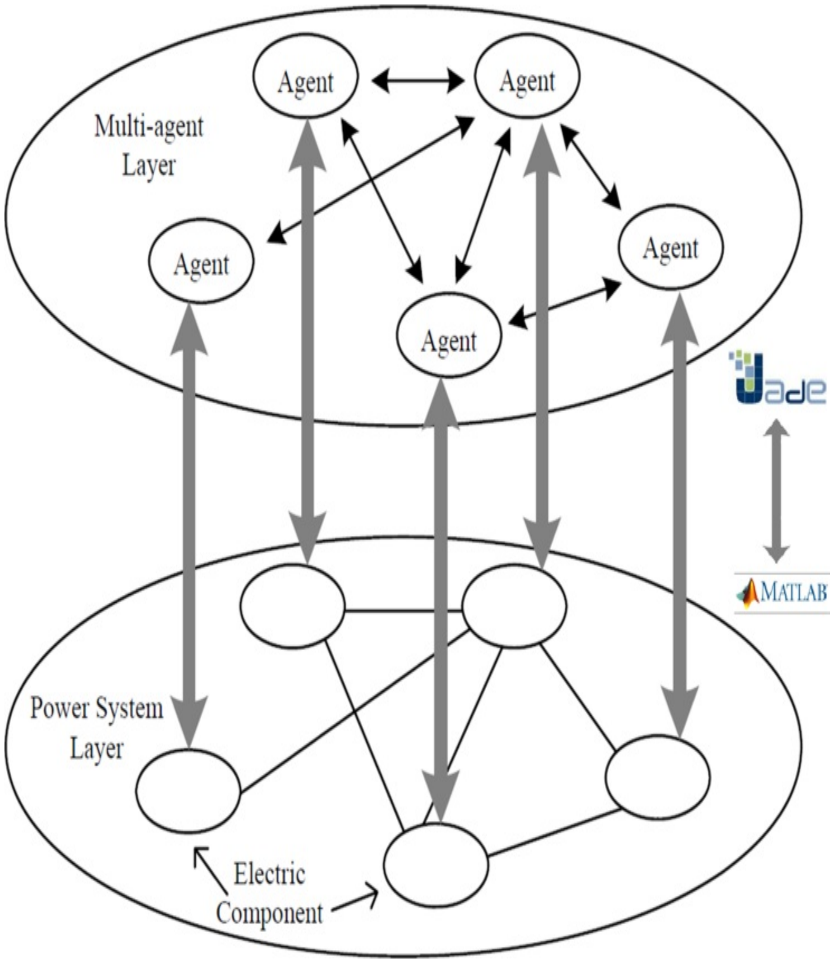


**Multi-agent layer**

- MAS allows semi-autonomous decision-making
- JAVA-JADE describes parallel decision-making of each agent as multi-thread language

**Power system layer**

- Time domain simulation of power system transient stability
- MATLAB solves Differential Equations fast and accurately

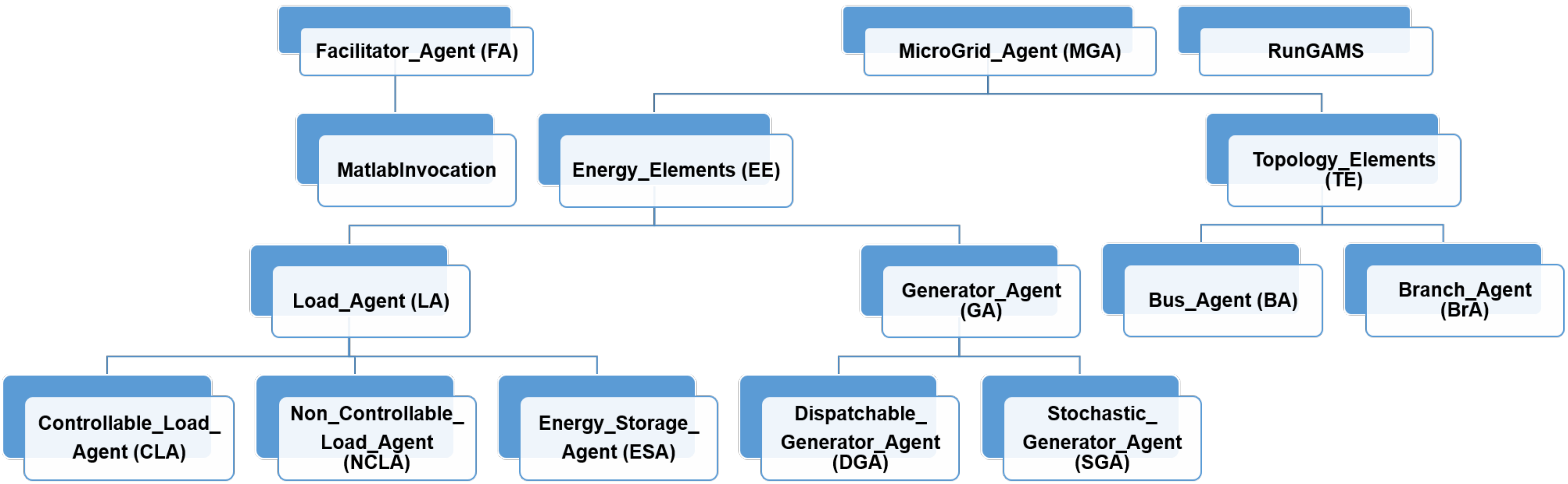


# Developed Multi-Agent System Transient Stability Platform



## Class diagram for multi-agent layer

- Tertiary control in JAVA-JADE

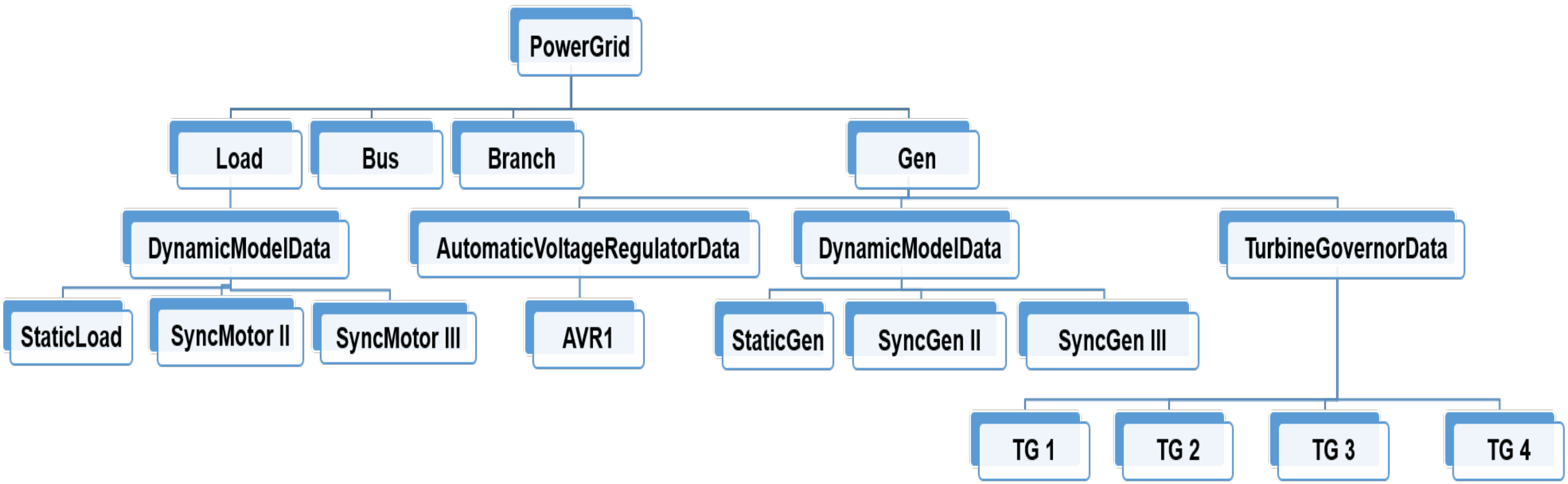


# Developed Multi-Agent System Transient Stability Platform



## Class diagram for power system layer

- Microgrid structure & dynamic models in MATLAB



# Developed Multi-Agent System Transient Stability Platform



- Dynamics of power system layer
- Primary & secondary control for transient stability
  - Each generator is described by swing equations
  - Buses are coupled by power flow equations

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_o \\ \dot{\omega}_i &= \frac{\omega_o}{2H_i}\left[P_{mi} - P_{ei}(\delta) - D_i\dot{\delta}_i\right] \end{aligned}$$

$$\mathbf{P_e} = \Re[\mathbf{E}^*\mathbf{YE}]$$

# Test cases



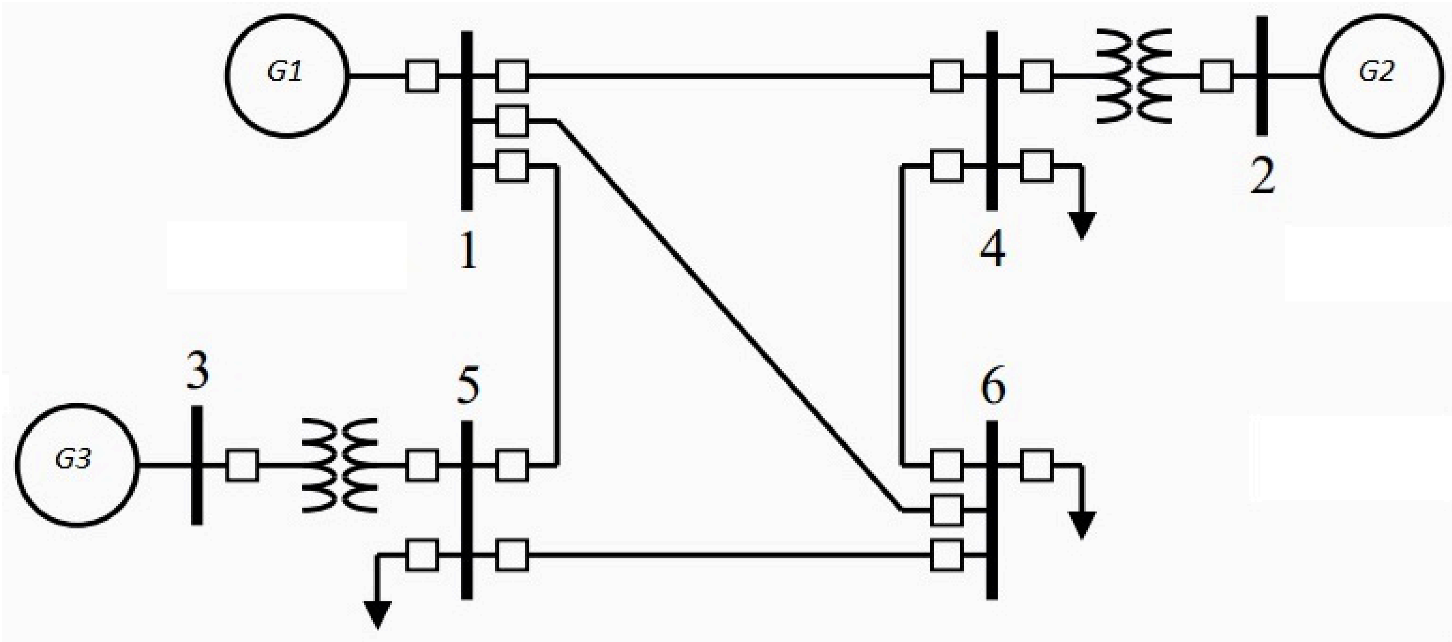
To initiate studies into resilient self-healing Microgrid operation, the MAS transient stability platform was tested with 3 case studies:

- Case 1: Dynamic Reconfiguration Capability.
- Case 2: Decentralized Dispatch of Multiple Microgrids.
- Case 3: Uncoordinated and Coordinated Microgrids under Net Load Changes.

∴ ***Multi-Agent System Decision Making is Coupled to Real-Time Power System Dynamics.***

# Case 1: Dynamic Reconfiguration Capability.

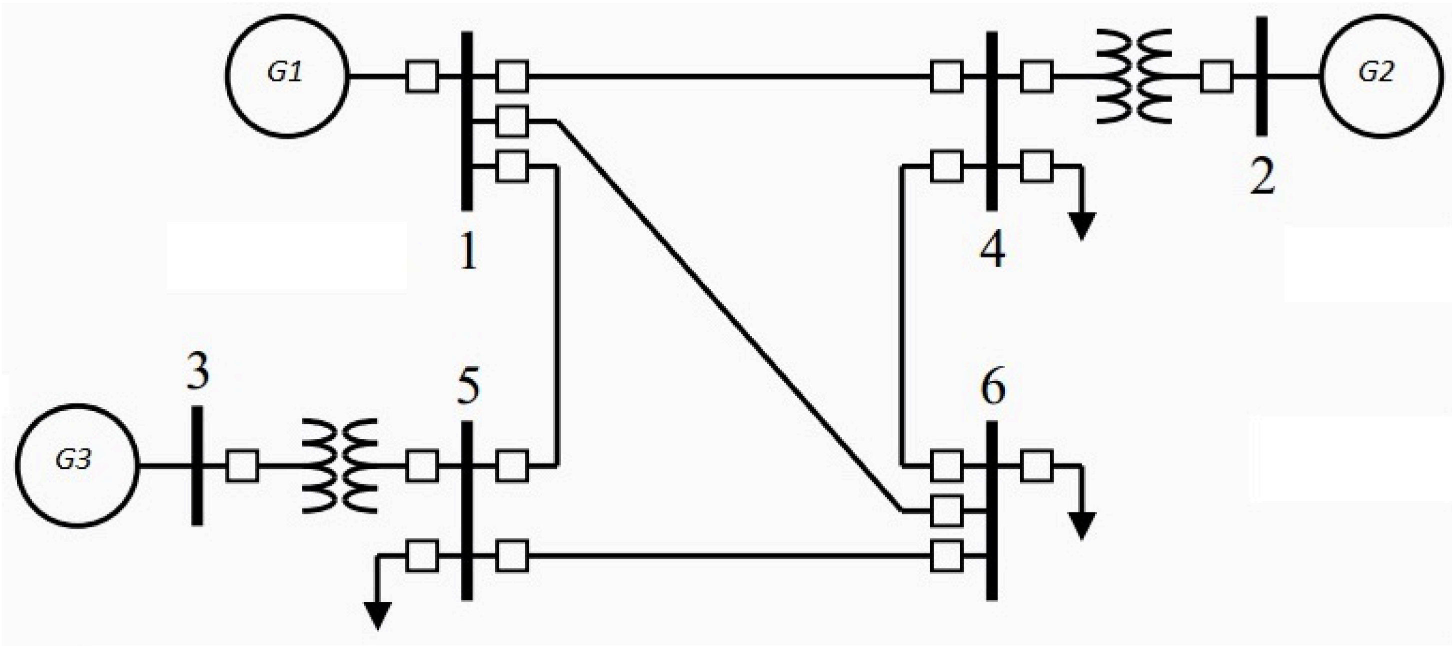





- Consider the Saadat's Microgrid as a test case.
  - 3 Dynamic Generators
  - 3 Static Loads
  - 6 Buses
  - 7 Branches

# Case 1: Dynamic Reconfiguration Capability.

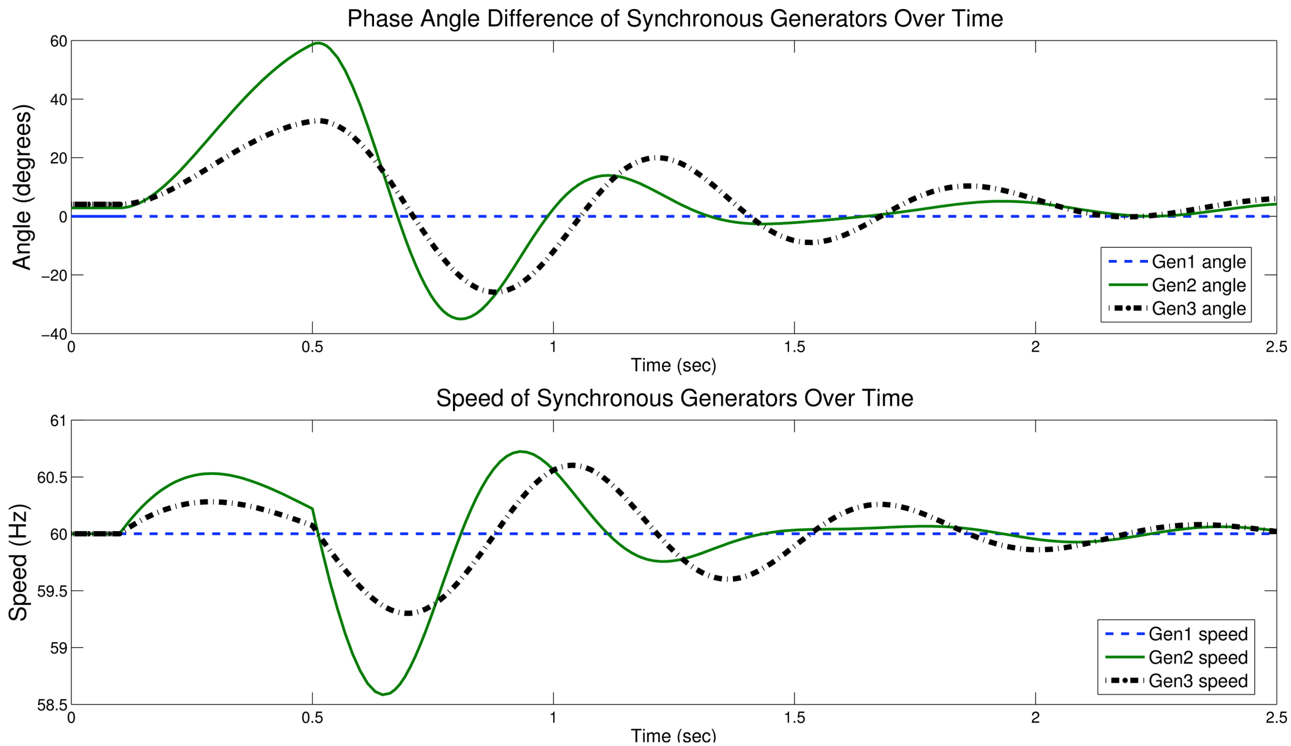





- Agents are used to model decentralized power system protection.
  - A three-phase fault in Bus 6 occurs @ T=0.1 s.
  - Line 5-6 is removed @ T=0.5 s.
  - Bus 6 brought back on to clear the fault @ T=0.5 s.

# Case 1: Dynamic Reconfiguration Capability.






***∴Here the two dynamic reconfigurations of "Fault Bus 6" and "Remove Line 5-6" were sent as scripted-commands initiated by the microgrid agent.***

***∴Multi-Agent System can be used to design Real-Time Control of Power System Protection. → Critical for Islanding***

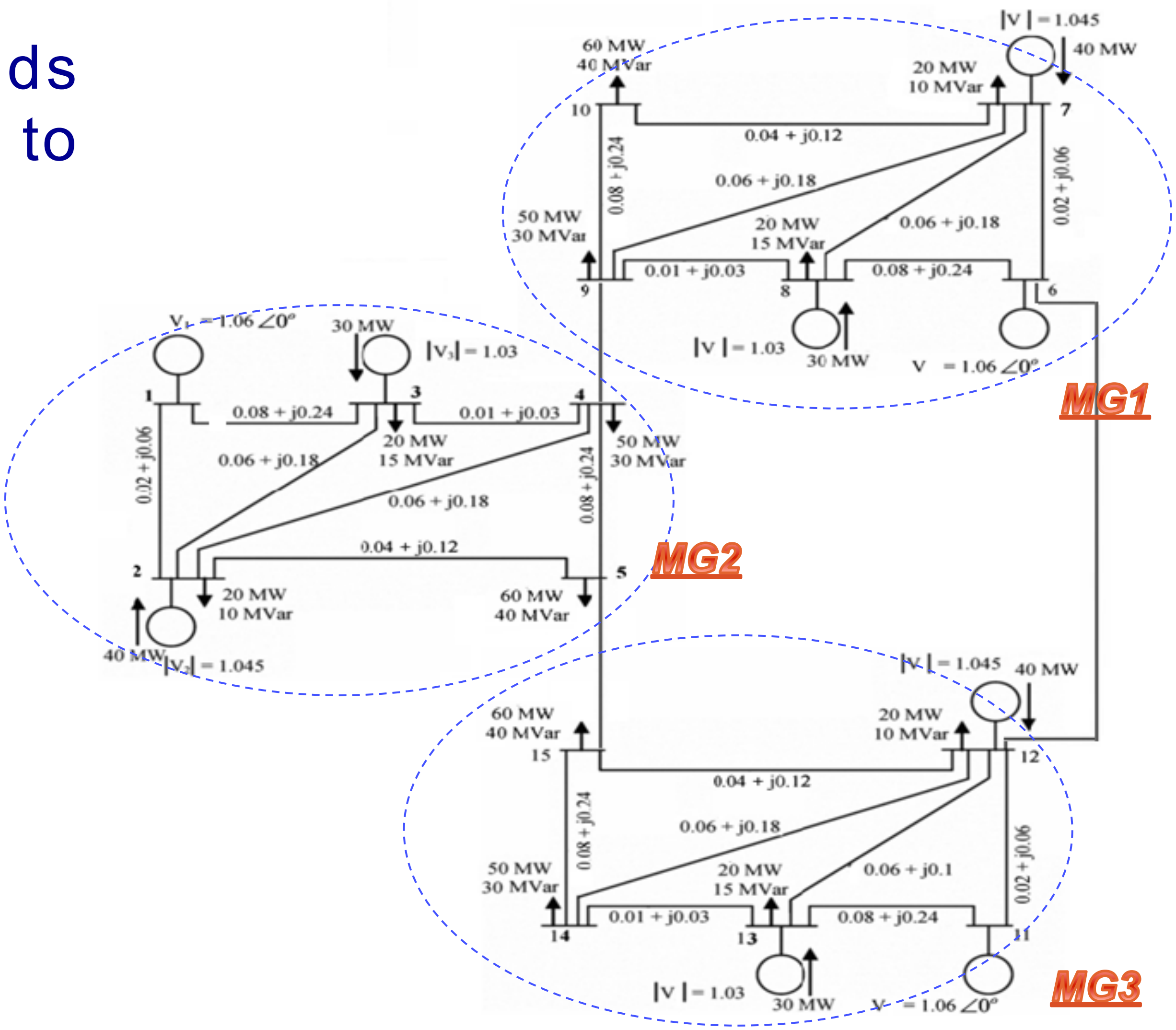
# Case 2: Decentralized Dispatch of Multiple Microgrids.



- Three Microgrids are connected to each other.

Each Microgrid has

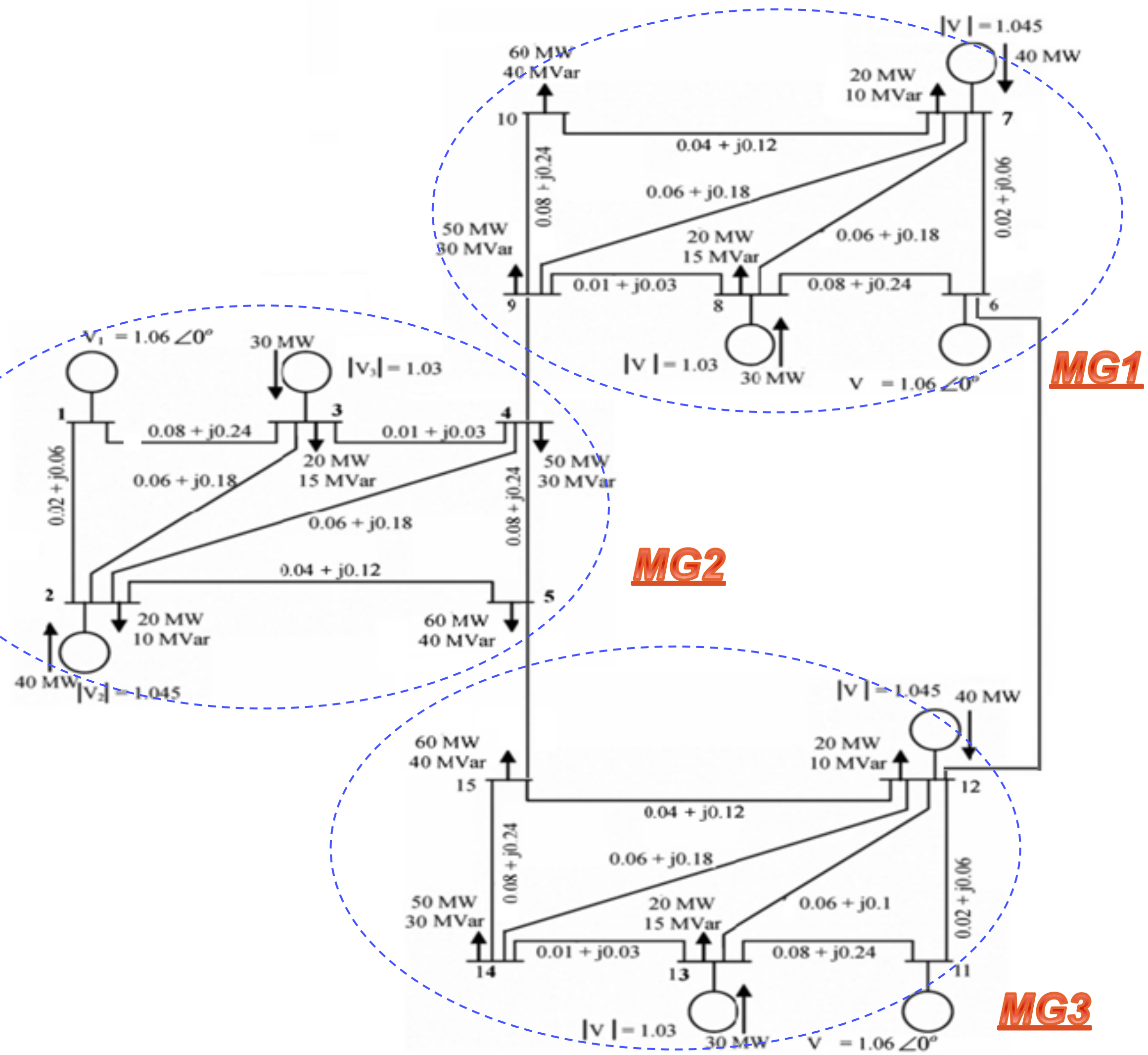
- 3 Dynamic Generators
- 3 Static Loads
- 6 Buses
- 7 Branches



# Case 2: Decentralized Dispatch of Multiple Microgrids.

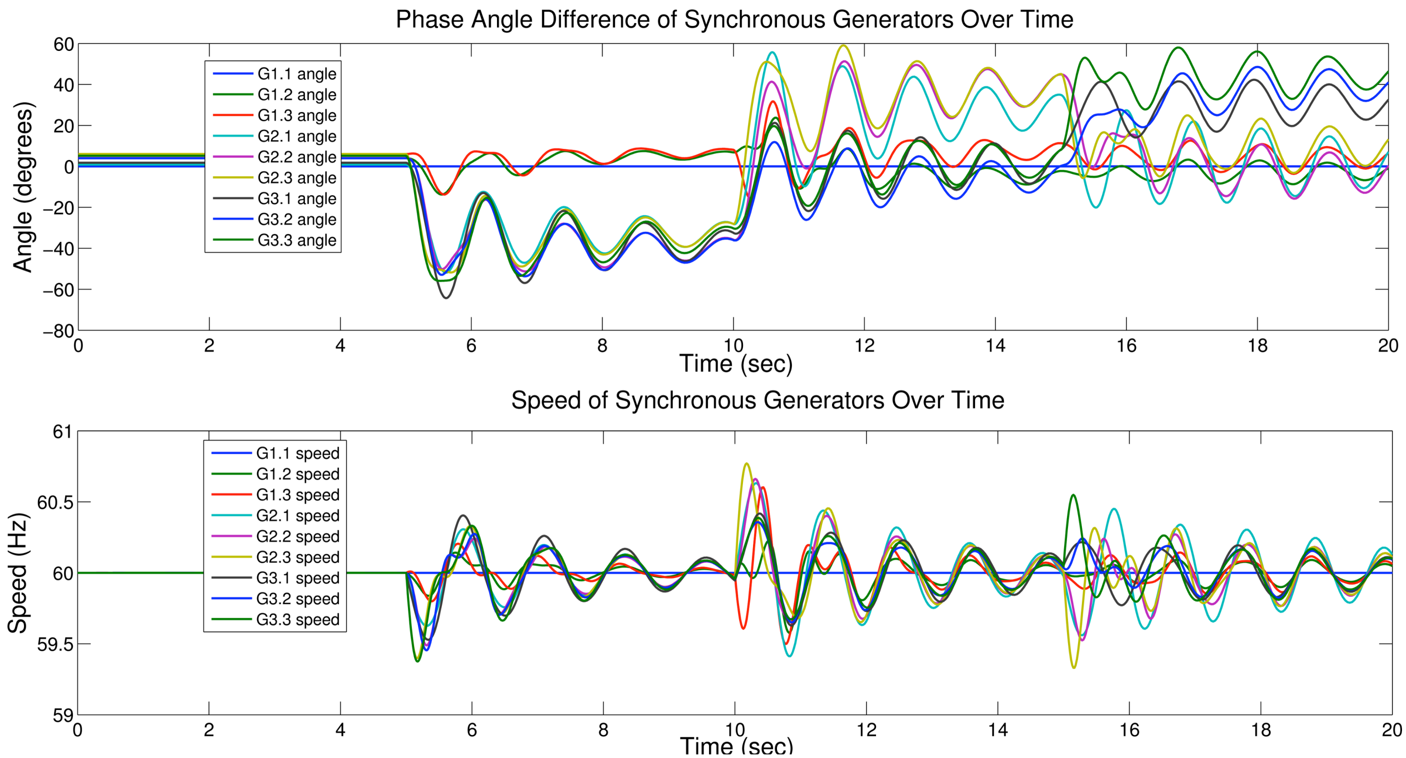


- Microgrid Agents are responsible for economic dispatch of their respective control areas.
- Each microgrid agent initiated its own economic dispatch independently in response to 10%, 5% and 15% increases in demand in microgrids 1, 2 and 3 at T= 5 s, T= 10 s, and T= 15 s respectively.



# Case 2: Decentralized Dispatch of Multiple Microgrids.






***∴Multi-Agent System Decision Making is Coupled to Real-Time Power System Dynamics.***

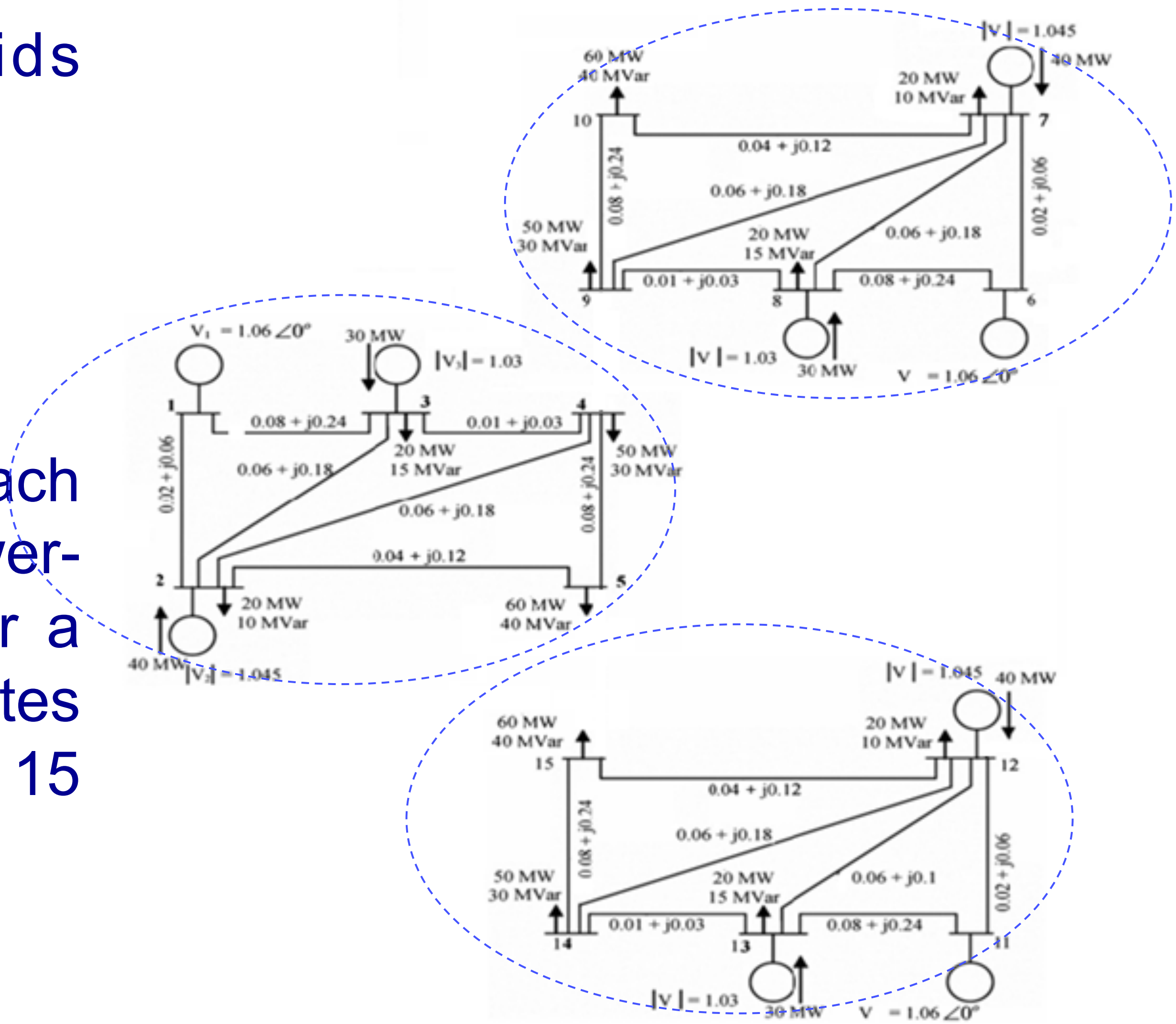
***∴Multi-Agent System Decisions Lead to oscillations in neighboring control areas.***

# Case 3: Uncoordinated Microgrids under Net Load Changes.



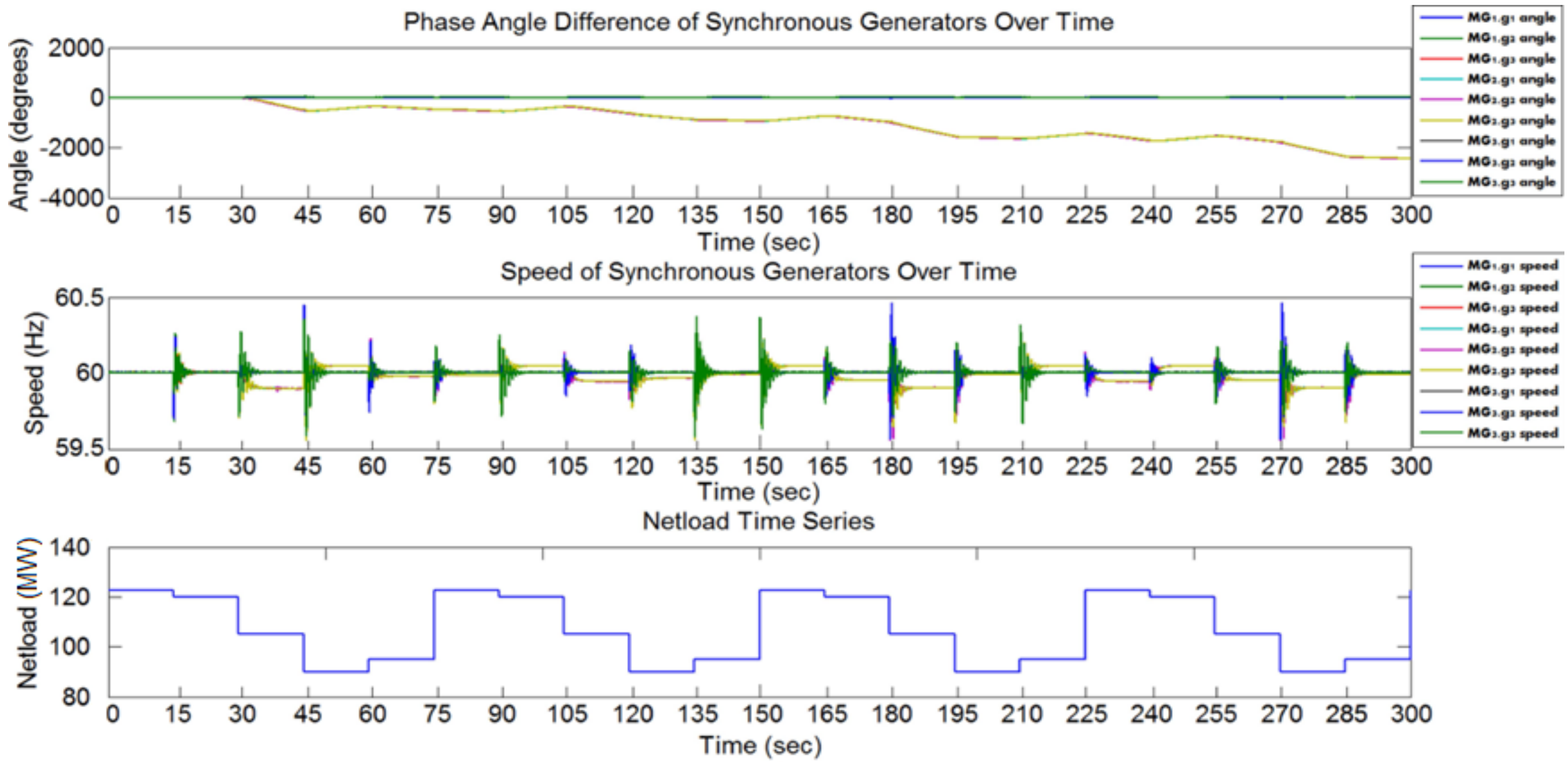
- Three microgrids are unconnected.

The net load in each microgrid has power-time series data for a duration of 5 minutes with a resolution of 15 seconds.



# Case 3: Uncoordinated Microgrids under Net Load Changes.





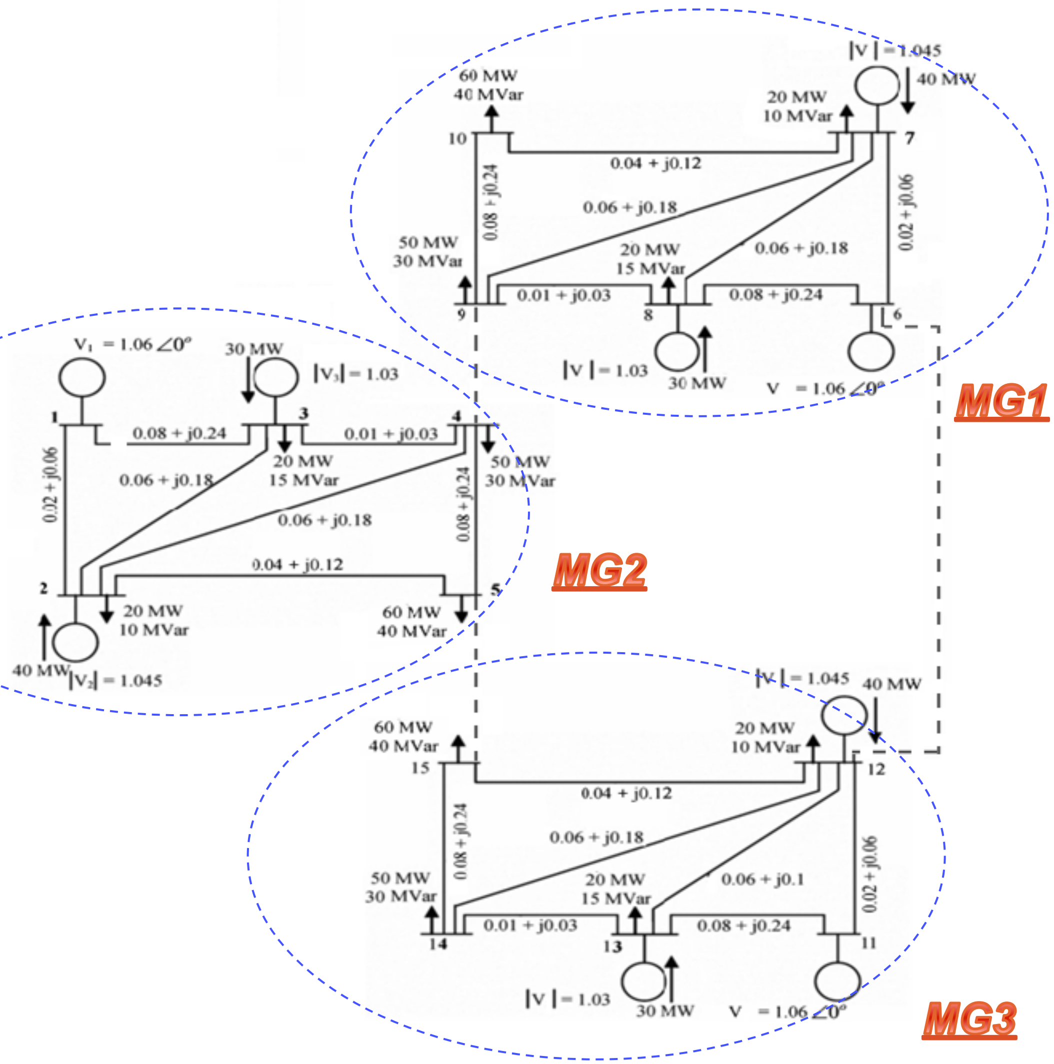

***∴Here, some generator speeds do not always return to the nominal 60Hz and instead settle at lower speeds. As a result, the associated phase angle of these generators continually fall behind in angle relative to the reference buses.***

# Case 3: Coordinated Microgrids under Net Load Changes.



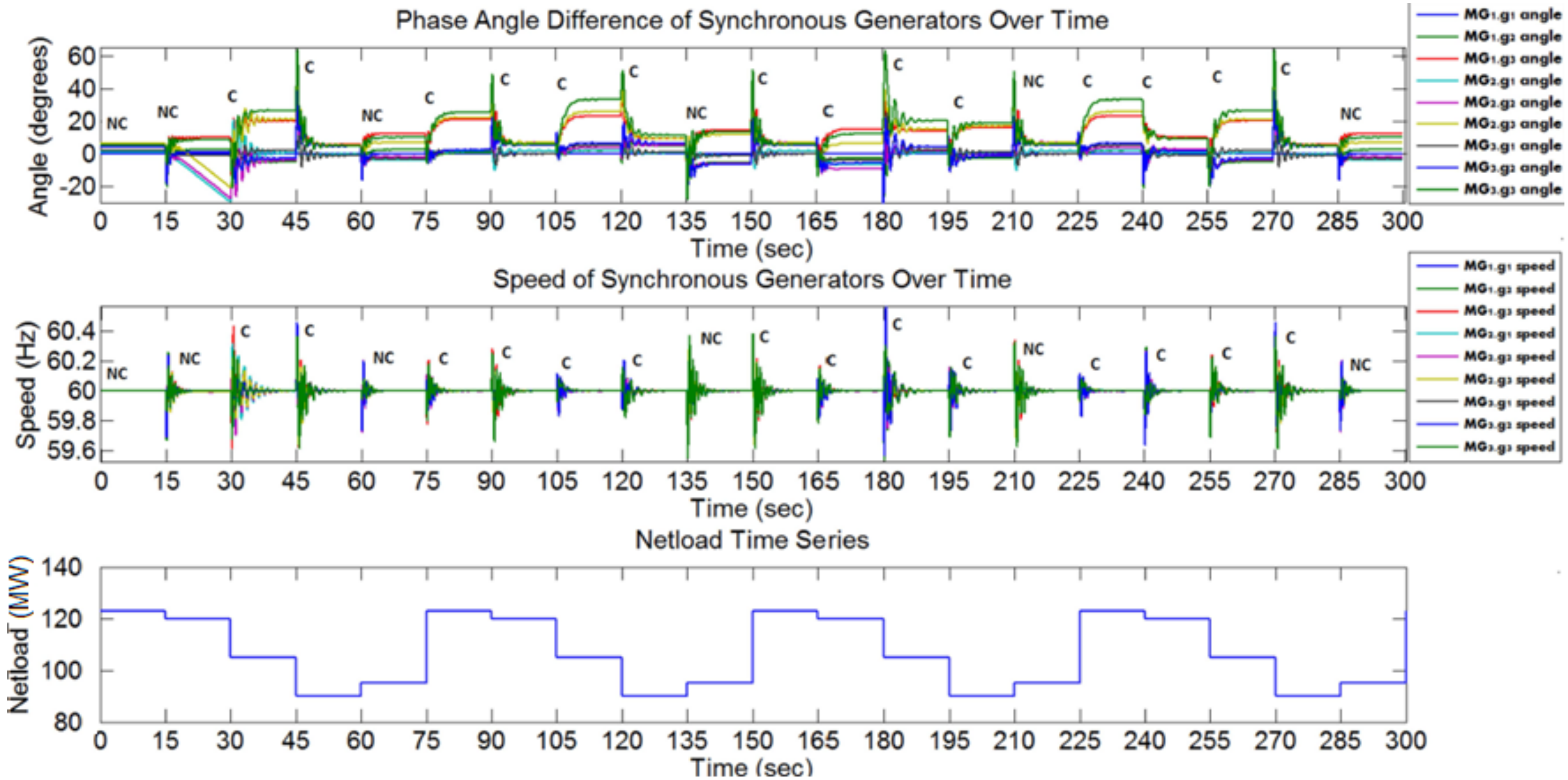
- The three microgrids have the potential to (dis)connect to each other.

- The multi-agent system's coordination strategy seeks to take advantage of the combined inertia of the three microgrids during times of high net load variability connecting the 3 microgrids.



# Case 3: Coordinated Microgrids under Net Load Changes.






***∴The markings C and NC reflect when the MAS has mutually connected (C) or disconnected (NC) the microgrids.***

***∴ Intuitively, the energy of the net load variability is "spread-out" amongst the inertias of all of the generators and not just of the local microgrid.***

# Developed Multi-Agent System Transient Stability Platform: Conclusion



- Research need: design of robust & distributed reconfigurable control methods for reliable operation of microgrids.
- Need for Multi-Agent System: Multiple Stakeholders & Multilateralism and other effects from renewables.
- Proposed a Multi-Agent Platform
  - Simulates the physical power system dynamics of the grid.
  - Simulates the decision-making of the individual actors and how they cooperate.
  - Simulates the distributed decisions of each actor affects the grid conditions of neighbors.
  - Allows actors to reconfigure their  interacts with others.
  - Can be applied at the desired level of geographical scope.
- Case Studies
- This work presents many opportunities for future developments in the domain of resilient self-healing power grids.

# Thank you

# References

## Presentations & Papers

Book Chapter:

- S. Rivera, A. Farid, K. Youcef-Toumi, Book Chapter: "An Intelligent Multi-Agent Based Architecture for Resilient Self-Healing Operation of Multiple Microgrids", submitted to Book on Industrial Agents: Emerging Applications of Software Agents in Industry, Elsevier 2014.

Journal and congresses papers:

- S. Rivera, A. Farid, K. Youcef-Toumi, "A Multi-Agent System Transient Stability Platform for Resilient Self-Healing Operation of Multiple Microgrids", 5th Innovative Smart Grid Technologies Conference, February 19-22, Washington, USA.
- S. Rivera, A. Farid, K. Youcef-Toumi, "An Intelligent Multi-Agent Based Architecture for the Coordination and Control of Multiple Microgrids", IEEE Transaction on Smart Grid (Under revision).

Presentations:

- S. Rivera, A. Farid, K. Youcef-Toumi, presentation: "Coordination and Control of Microgrids: Research Review, Trends and Needs", The 2nd World Smart grid Conference Middle East, 23 April 2013, Abu Dhabi.
- "Poster: Coordination and Control of Microgrids: Platform for resilience Operation using Multi-Agents Systems", presented at Postdocs Share their Science event, June 18th, Cambridge, USA
- Newsletter IEEE August 2013: www.ieee.org.co/1/?id=19&t=agosto-%2F-2013.

# References

## Intra-Microgrid Coordination & Control

[1] D. Kondoleon, L. Ten-Hope, T. Surles, and R. L. Therkelsen, “The CERTS MicroGrid Concept,” in *Integration of Distributed Energy Resources – The CERTS MicroGrid Concept*, 2002, no. October, p. 32.

[2] R. H. Lasseter and P. Piagi, “Microgrid: A Conceptual Solution,” in *PESC 04 Aachen, Germany, 20-25 June 2004*, 2004, no. June, p. 6.

[3] R. H. Lasseter, “MicroGrids,” in *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.02CH37309)*, 2002, vol. 1, pp. 305–308.

[4] P. Piagi and R. H. Lasseter, “Autonomous control of microgrids,” in *2006 IEEE Power Engineering Society General Meeting*, 2006, p. 8 pp.

[5] Y. Gu, P. Li, Y. Pan, H. Ouyang, D. Han, and Y. Hao, “Development of micro-grid coordination and control overview,” in *IEEE PES Innovative Smart Grid Technologies*, 2012, pp. 1–6.

[6] A. Bidram and A. Davoudi, “Hierarchical Structure of Microgrids Control System,” *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1963–1976, Dec. 2012.

[7] K. De Brabandere, K. Vanthournout, J. Driesen, G. Deconinck, and R. Belmans, “Control of Microgrids,” in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1–7.

[8] P. Basak, “Microgrid: Control Techniques and Modeling,” in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*, 2009, pp. 0–4.

[9] A. S. Dobakhshari, S. Azizi, and A. M. Ranjbar, “Control of microgrids: Aspects and prospects,” *Networking, Sensing and Control (ICNSC), 2011 IEEE International Conference on*. pp. 38–43, 2011.

[10] I.-Y. Chung, W. Liu, D. A. Cartes, and K. Schoder, “Control parameter optimization for a microgrid system using particle swarm optimization,” in *2008 IEEE International Conference on Sustainable Energy Technologies*, 2008, pp. 837–842.

[13] N. Zhi, H. Zhang, and J. Liu, “Oerview of microgrid management and control,” in *2011 International Conference on Electrical and Control Engineering*, 2011, pp. 4598–4601.

[14] S. N. Bhaskara and B. H. Chowdhury, “Microgrids — A review of modeling, control, protection, simulation and future potential,” in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–7.

# References

## Inter-Microgrid Coordination & Control

[13] C. Yuen, A. Oudalov, and A. Timbus, "The Provision of Frequency Control Reserves From Multiple Microgrids," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 173–183, Jan. 2011.

[14] T. L. Vandoorn, B. Zwaenepoel, J. D. M. De Kooning, B. Meersman, and L. Vandevelde, "Smart microgrids and virtual power plants in a hierarchical control structure," in *2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*, 2011, pp. 1–7.

[15] M. Parol and T. Wojtowicz, "Optimization of exchange of electrical energy between microgrid and electricity utility distribution network," *Modern Electric Power Systems (MEPS), 2010 Proceedings of the International Symposium*, 2010.

[16] A. Vaccaro, M. Popov, D. Villacci, and V. Terzija, "An Integrated Framework for Smart Microgrids Modeling, Monitoring, Control, Communication, and Verification," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 119–132, Jan. 2011.

[17] R. Bi, M. Ding, and T. T. Xu, "Design of common communication platform of microgrid," in *The 2nd International Symposium on Power Electronics for Distributed Generation Systems*, 2010, pp. 735–738.

[18] N. C. Ekneligoda and W. W. Weaver, "Game-Theoretic Communication Structures in Microgrids," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 2334–2341, Oct. 2012.

[19] J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, "A survey of recent results in networked control systems," *Proceedings of the IEEE*, vol. 95, no. 1, pp. 138–172, 2007.

[20] S. Bukowski and S. J. Ranade, "Communication network requirements for the Smart Grid and a path for an ip based protocol for customer driven microgrids," in *2012 IEEE Energytech*, 2012, pp. 1–6.

# References

## Multi-Agent Coordination With Microgrids


[21] A. L. Dimeas and N. D. Hatziargyriou, “Operation of a Multiagent System for Microgrid Control,” *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp. 1447–1455, Aug. 2005.

[22] A. L. Dimeas and N. D. Hatziargyriou, “A MAS Architecture for Microgrids Control,” in *Proceedings of the 13th International Conference on, Intelligent Systems Application to Power Systems*, 2005, pp. 402–406.

[23] A. L. Dimeas and N. D. Hatziargyriou, “Agent based Control for Microgrids,” in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1–5.

[24] A. Dimeas and N. Hatziargyriou, “A multiagent system for microgrids,” in *IEEE Power Engineering Society General Meeting, 2004.*, 2007, vol. 2, pp. 55–58.

[25] N. Hatziargyriou, “DER AND MICROGRIDS: RESEARCH Topics within EU Framework Programs,” in *CERTS, Berkeley 2005 Symposium on Microgrids, 17 June 2005*, 2005, no. June, p. 49.

[26] R. Duan and G. Deconinck, “Multi-agent coordination in market environment for future electricity infrastructure based on microgrids,” in *2009 IEEE International Conference on Systems, Man and Cybernetics*, 2009, pp. 3959–3964.

[27] T. Logenthiran, D. Srinivasan, and D. Wong, “Multi-agent coordination for DER in MicroGrid,” in *2008 IEEE International Conference on Sustainable Energy Technologies*, 2008, pp. 77–82.

[28] T. Logenthiran, D. Srinivasan, A. M. Khambadkone, and H. N. Aung, “Scalable Multi-Agent System (MAS) for operation of a microgrid in islanded mode,” in *2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power India*, 2010, pp. 1–6.

[29] Z. Jian, A. Qian, J. Chuanwen, W. Xingang, Z. Zhanghua, and G. Chenghong, “The application of multi agent system in microgrid coordination control,” in *2009 International Conference on Sustainable Power Generation and Supply*, 2009, pp. 1–6.

[30] T. Li, Z. Xiao, M. Huang, J. Yu, and J. Hu, “Control system simulation of microgrid based on IP and Multi-Agent,” in *2010 International Conference on Information, Networking and Automation (ICINA)*, 2010, pp. V1–235–V1–239.

[31] C.-X. Dou and B. Liu, “Multi-Agent Based Hierarchical Hybrid Control for Smart Microgrid,” *IEEE Transactions on Smart Grid*, pp. 1–8, 2013.

# References

## Multi-Agent Coordination With Microgrids


[32] G. Zheng and N. Li, "Multi-Agent Based Control System for Multi-Microgrids," in *2010 International Conference on Computational Intelligence and Software Engineering*, 2010, pp. 1–4.

[33] C. M. Colson, M. H. Nehrir, and R. W. Gunderson, "Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing," in *2011 4th International Symposium on Resilient Control Systems*, 2011, pp. 83–88.


[33] C. M. Colson, M. H. Nehrir, and R. W. Gunderson, "Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing," in *2011 4th International Symposium on Resilient Control Systems*, 2011, pp. 83–88.


[34] C. M. Colson and M. H. Nehrir, "Comprehensive Real-Time Microgrid Power Management and Control With Distributed Agents," *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 617–627, Mar. 2013.

[35] C. M. Colson and M. H. Nehrir, "A review of challenges to real-time power management of microgrids," in *2009 IEEE Power & Energy Society General Meeting*, 2009, pp. 1–8.

[36] T. Logenthiran, and D. Srinivasan, "Multi-agent system for market based microgrid operation in smart grid environment," in Smart Grid Contest, 2011.

[7A] A. M. Farid, "Future of the Electricity Grid: The Need for New Methods of Integrated Assessment," in GCC CIGRE: System Performance Development and Renewable Energy, 2013, no. January, pp. 1–45.

[8A] E. Marris, "Upgrading the grid," Nature, vol. 454, no. July, pp. 570–573, 2008.

[19A] North-American-Electrical-Reliability-Corporation, "Accomodating High Levels of Variable Generation," Princeton, NJ, 2009.

[29A] A. M. Farid, S. Rivera, and K. Youcef-Toumi, "Coordination and Control of Microgrids: Research Review, Trends & Needs," in *The 2nd World Smart Grid Conference Middle East*, 2013, no. April, pp. 1–40.