The Role of Smart Grid in the Clean Energy Revolution

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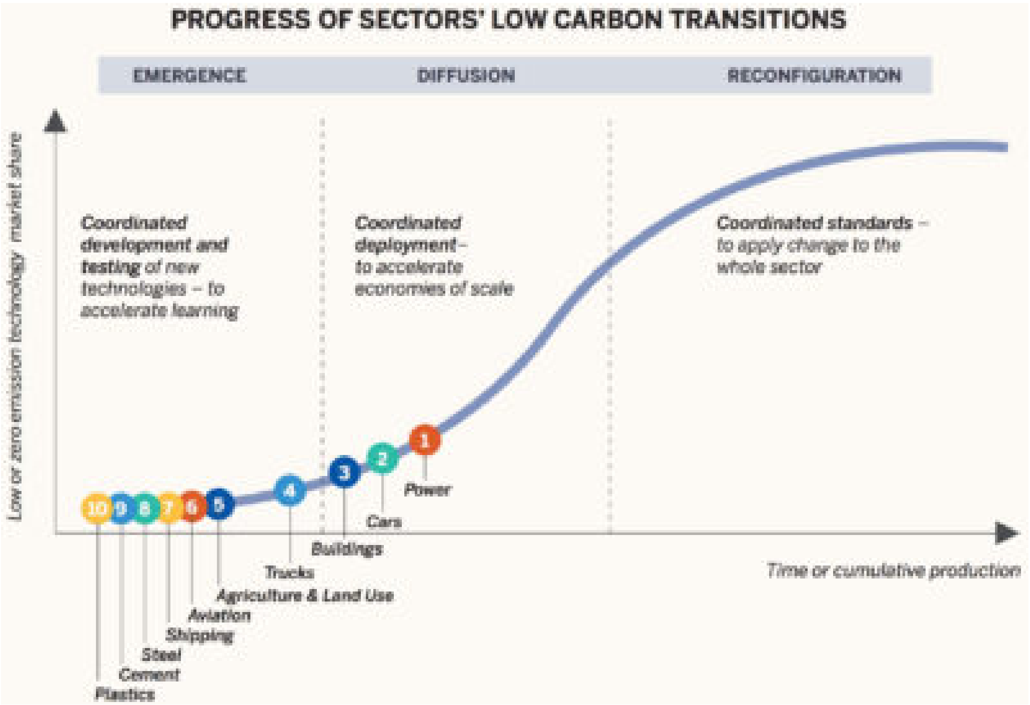
Introduction

*51 Billion to Zero:

- 51 billion tons of greenhouse gases is added annually to the atmosphere
- Direct air capture will cost ~ $5.1 trillion per year (~ 6% of the world's economy).
- Climate neutrality is a challenge.

"How to Avoid Climate Disaster" Bill Gates (2021)



https://e360.yale.edu/features/deep-decarbonization-a-realistic-way-forward-on-climate-change

Global emissions have soared by two-thirds in the three decades since international climate talks began. To make the reductions required, what's needed is a new approach that creates incentives for leading countries and industries to spark transformative technological revolutions.

David Victor, January 28, 2020

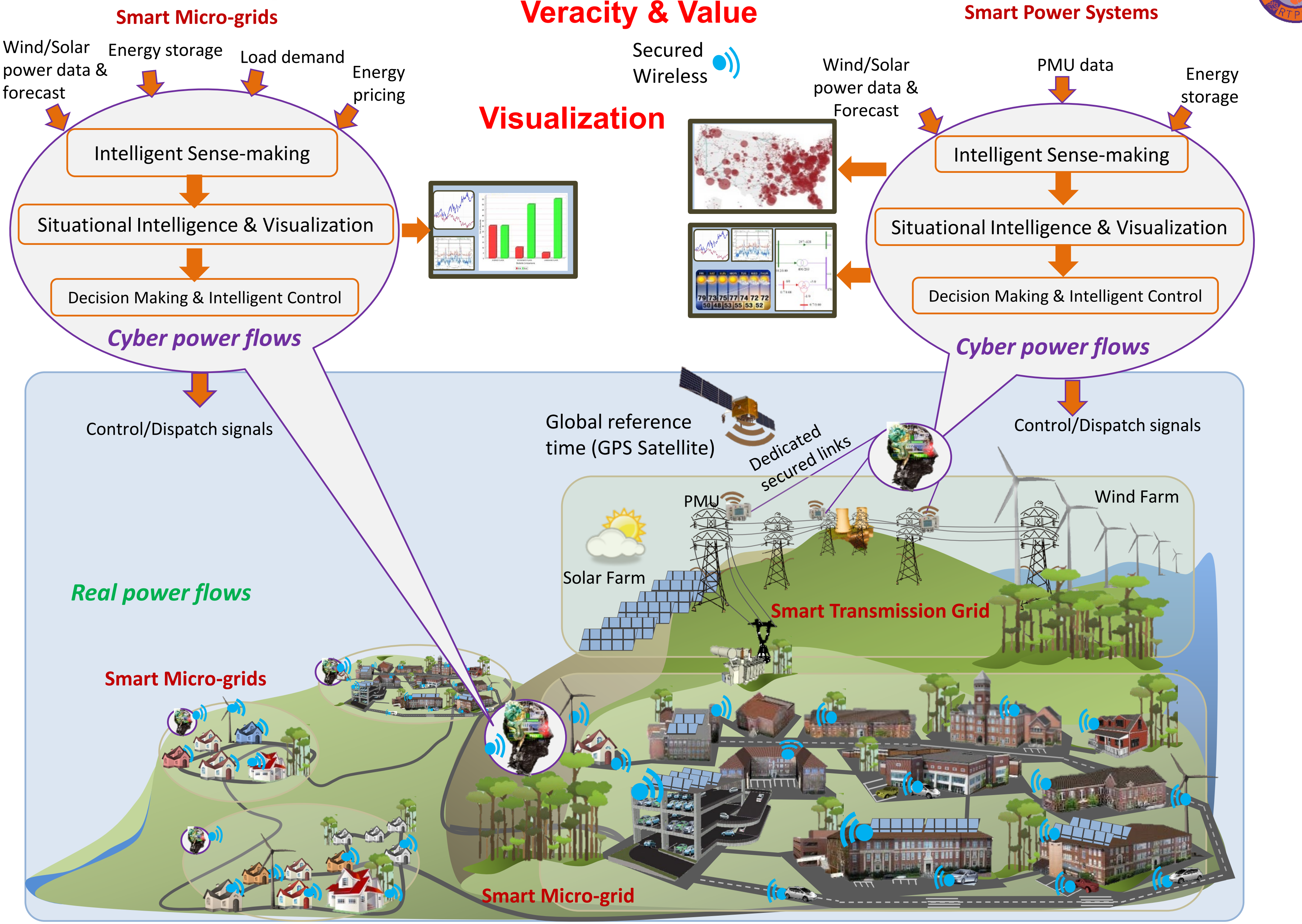
→ **Smart Grid**

Smart Grid and Clean Energy

A smart grid must have certain basic functions for modernization of the grid (as indicated in the Energy Independence and Security Act of 2007), including:

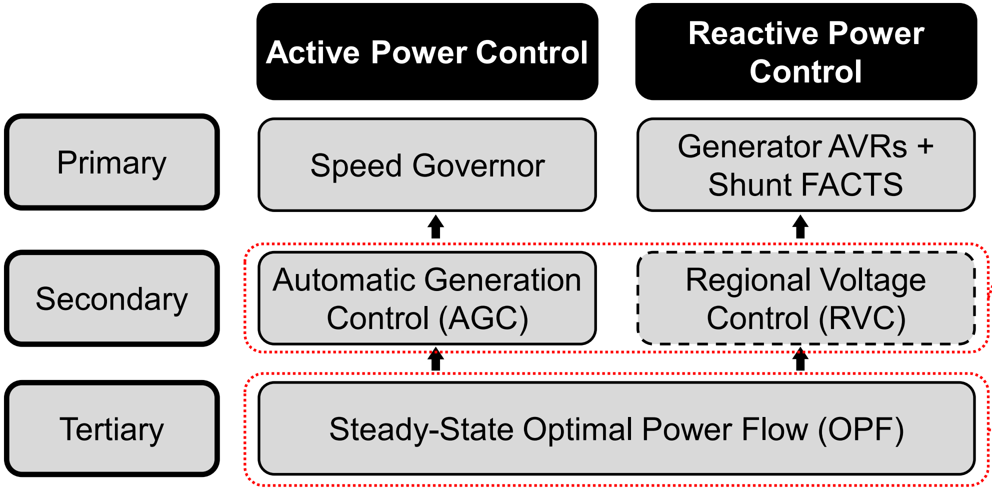
- Have a self-healing capability.
- Be fault-tolerant by resisting attacks.
- Allow for dynamic integration of all forms of energy generation and storage options including plug-in vehicles.
- Allow for dynamic optimization of grid operation and resources with full cyber-security.
- Allow for incorporation of demand-response, demand-side resources and energy-efficient resources.
- Allow electricity clients to actively participate in the grid operations by providing timely information and control options.
- Improve reliability, power quality, security and efficiency of the electricity infrastructure.

Big Data ← Volume, Velocity, Variety, Veracity & Value → Big Data

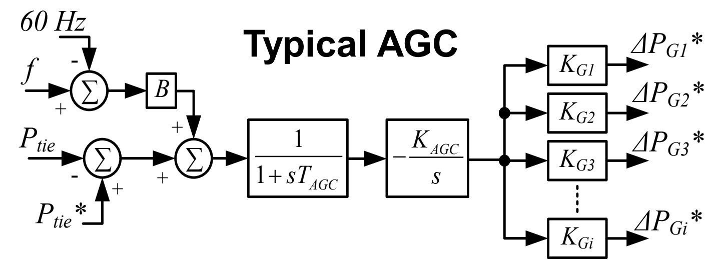


Traditional Power System Control and Operation

- Steady-state optimizations (day-ahead / intra-day / intra-hour) to min. costs with security constraints
- Linear controllers are used to regulate real-time frequency / voltage deviations



- Based on SISO linear PI controllers
- Cannot consider system constraints
- No coordination between AGC and RVC



- Steady-state optimization
- Based on forecasts
- Cannot handle fast events

Typical OPF

$$\text{Min } C(P_G, V_G)$$
$$\text{s.t. } \sum P_G = Load$$
$$0.95 < V_{busj}(P_G, V_G) < 1.05$$
$$S_{linek}(P_G, V_G) < 1$$
$$P_{Gimin} < P_{Gi} < P_{Gimax}$$
$$Q_{Gimin} < Q_{Gi}(P_G, V_G) < Q_{Gimax}$$
$$\Delta P_{Gi} < \Delta P_{Gmaxi}$$

Liang J, Venayagamoorthy GK, Harley RG, "Wide-Area Measurement based Dynamic Stochastic Optimal Power Flow Control for Smart Grids with High Variability and Uncertainty" IEEE Transactions on Smart Grid, Vol. 3, No. 1, March 2012, pp. 59-69

Traditional Power System Control and Operation – The Gap

- Challenges from Increasing Penetration of Intermittent Renewables
  - Fast changing rates
  - High forecast errors
  - Static OPF cannot handle fast events
  - AGC/local voltage control cannot guarantee system-wide security

→ More short-term variability and uncertainty

- Available/Developing Technologies:
  - Wide-area monitoring system (PMUs + SCADA)
    - What do we do with all these data?
  - Many local resources (Gens, FACTS, etc.)
    - Can we better control/coordinate them?

Missing: system-wide dynamic coordination of local resources

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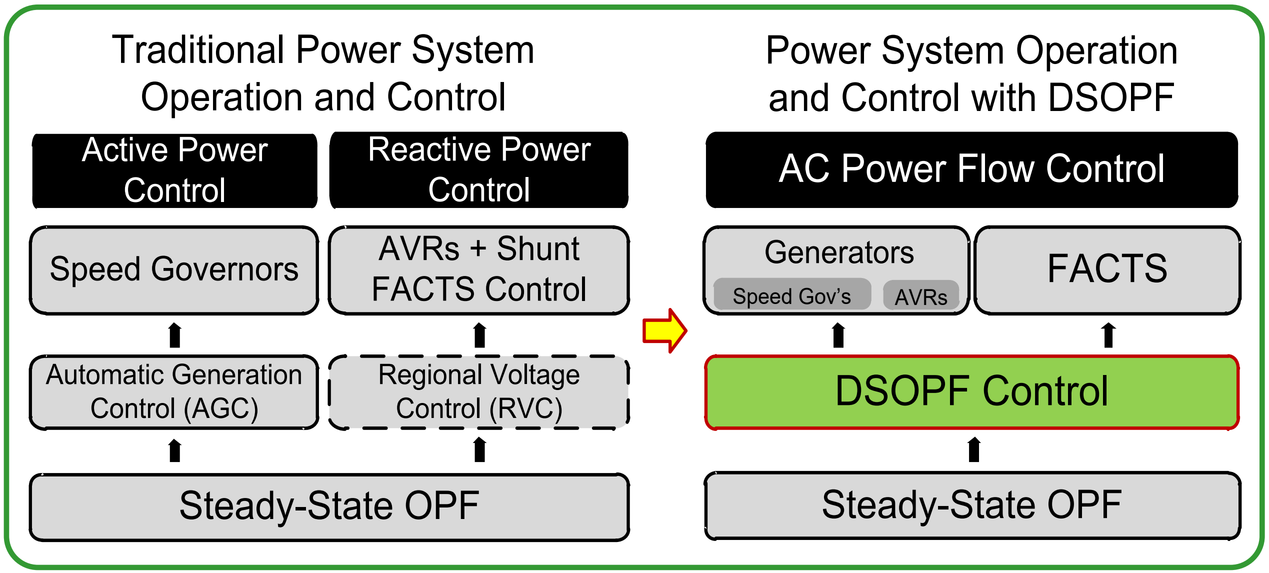
Dynamic Stochastic Optimal Power Flow

- A coordinated AC power flow control solution – replaces AGC and RVC
- Interacts with dynamics of load and local controllers
- Simultaneously considers economy, stability, and security in real-time control
- Handles fast stochastic events (e.g., wind variations, and contingencies)

→ MIMO nonlinear optimal control



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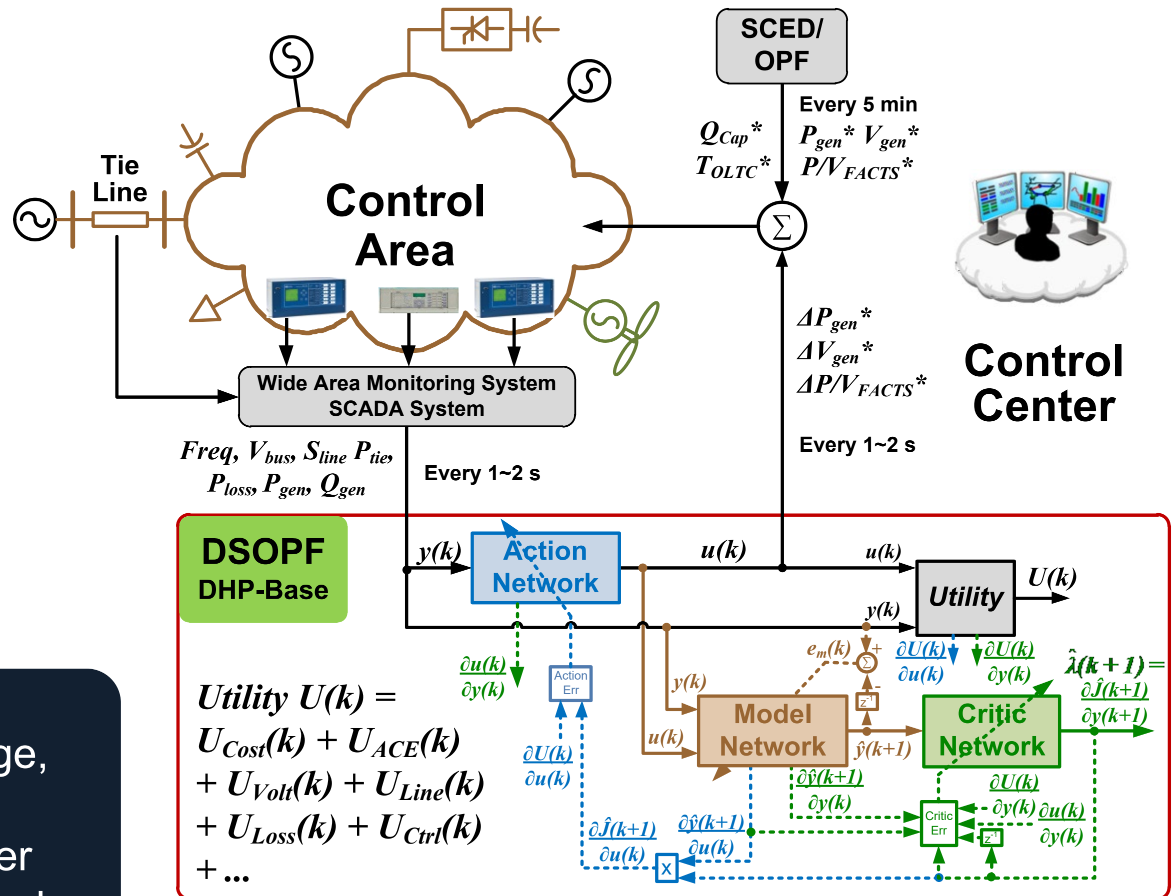
Implementation using AI

- Continuous snapshots are assumed available from WAMS
  - freq, P_{tie}, V_{bus}, S_{line}, P_{loss}, P_{gen}, Q_{gen}, etc. – plant feedbacks
- DSOPF controls continuously adjust quantities
  - P_{gen}*, Q_{gen}*, X_{FACTS}*, V_{FACTS}*, etc. – controller outputs

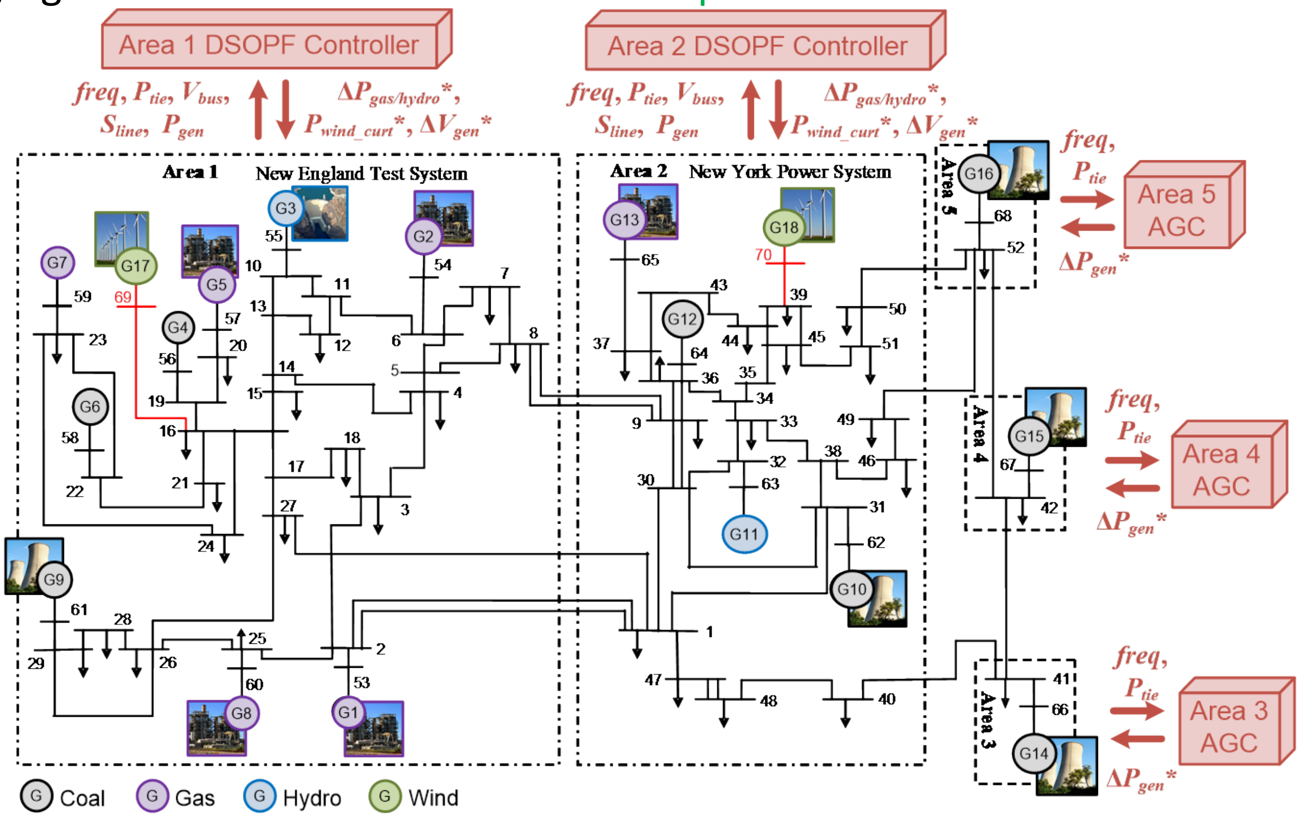


Define Control Objective:
U ~ operation cost, freq, voltage, line loading, losses, generator loading, ctrl efforts, and/or other indices of *efficiency, stability* and *security*.

Liang J, Venayagamoorthy GK, Harley RG, "Wide-Area Measurement based Dynamic Stochastic Optimal Power Flow Control for Smart Grids with High Variability and Uncertainty" IEEE Transactions on Smart Grid, Vol. 3, No. 1, March 2012, pp. 59-69

Applying DSOPF Control to a 70-Bus System

- 70-bus power system: five areas, 18 gens with coal, gas, hydro, and wind
  - Full dynamic synchronous generator model for the conventional generation units
  - Aggregated DFIG model for the two wind plants

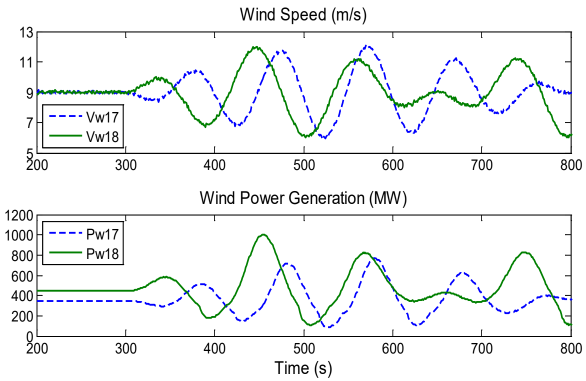


Liang J, Molina D, Venayagamoorthy GK, Harley RG, "Two-Level Dynamic Stochastic Optimal Power Flow Control for Power Systems with Intermittent Renewable Generation", IEEE Transactions on Power Systems, Vol. 28, No. 3, August 2013, pp. 2670-2678

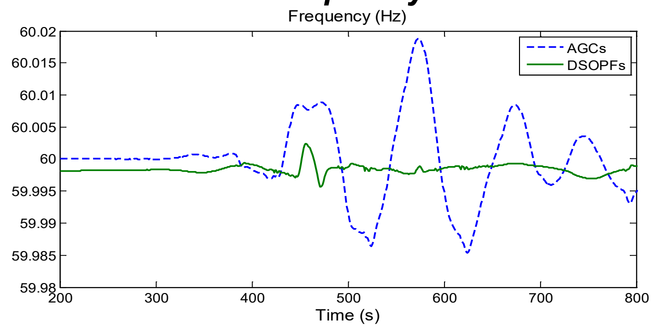
Performance of Area DSOPF Controllers

Case 1: large wind variation

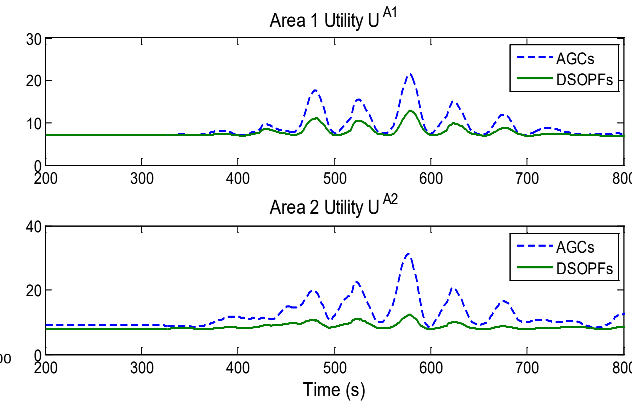
Wind Speed and Power



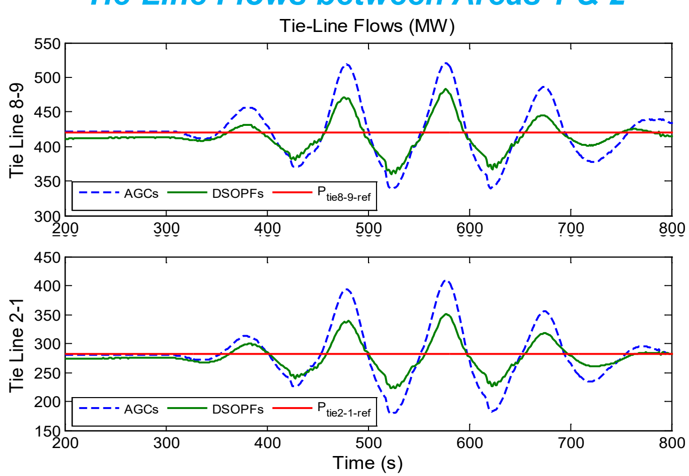
Frequency

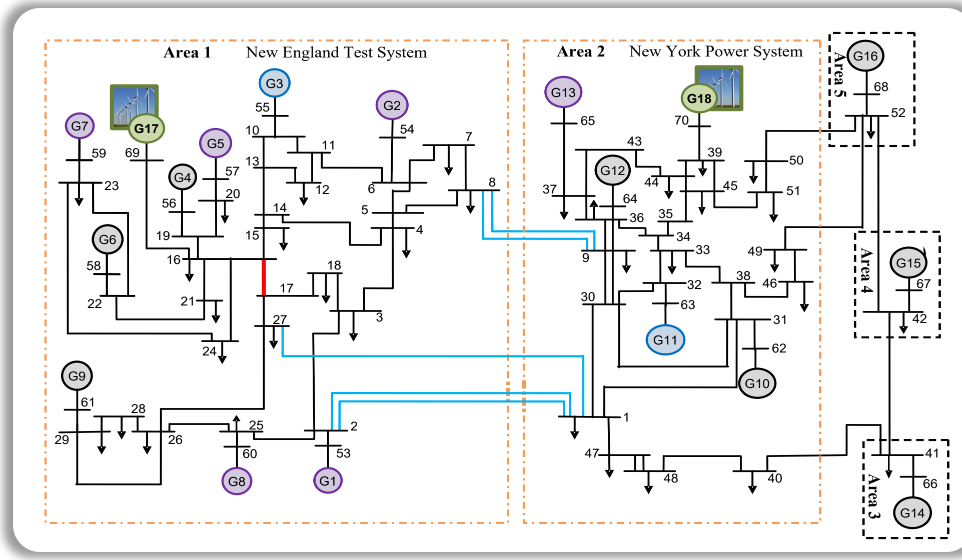


Overall Utility Index



Tie-Line Flows between Areas 1 & 2





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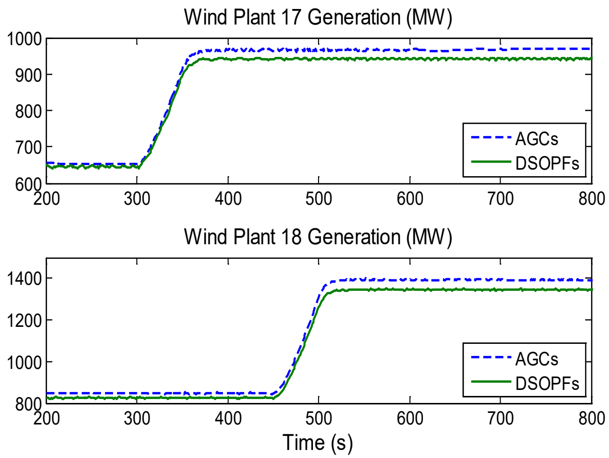
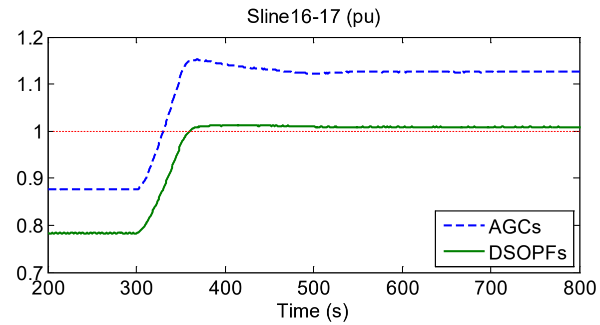
Performance of Area DSOPF Controllers

- **Case 2: large wind rise**

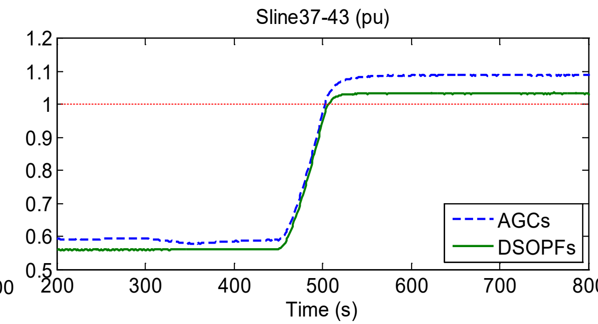
Wind Power



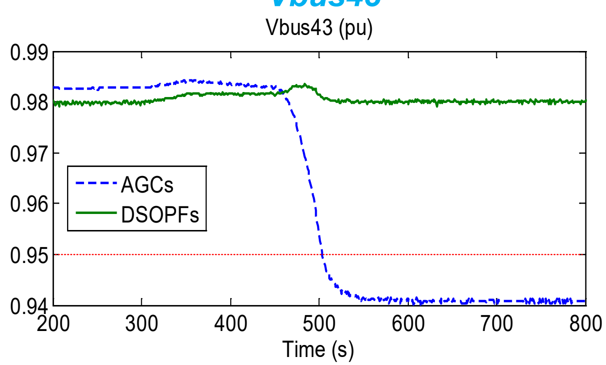
Line 16-17 Loading (close to G17)

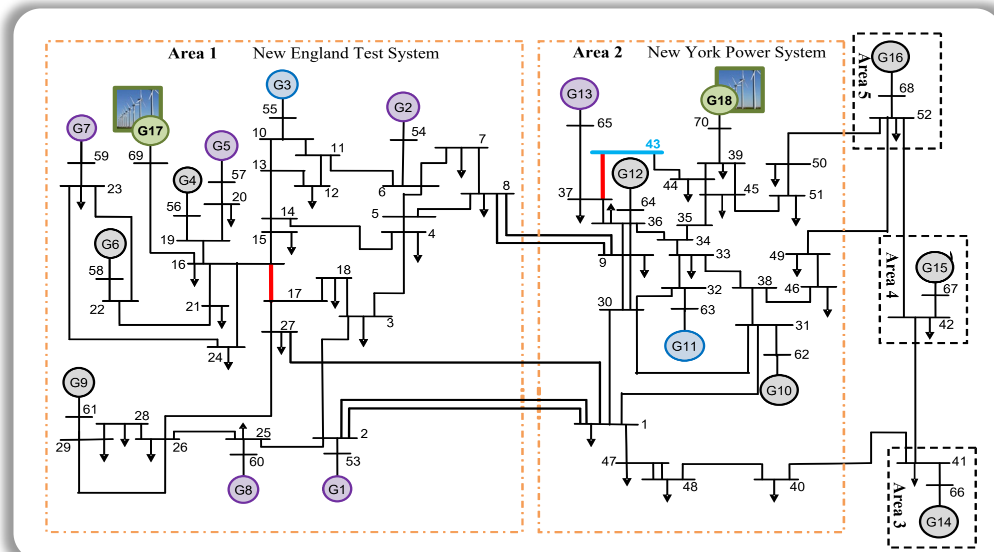


Line 37-43 Loading (close to G18)



Vbus43





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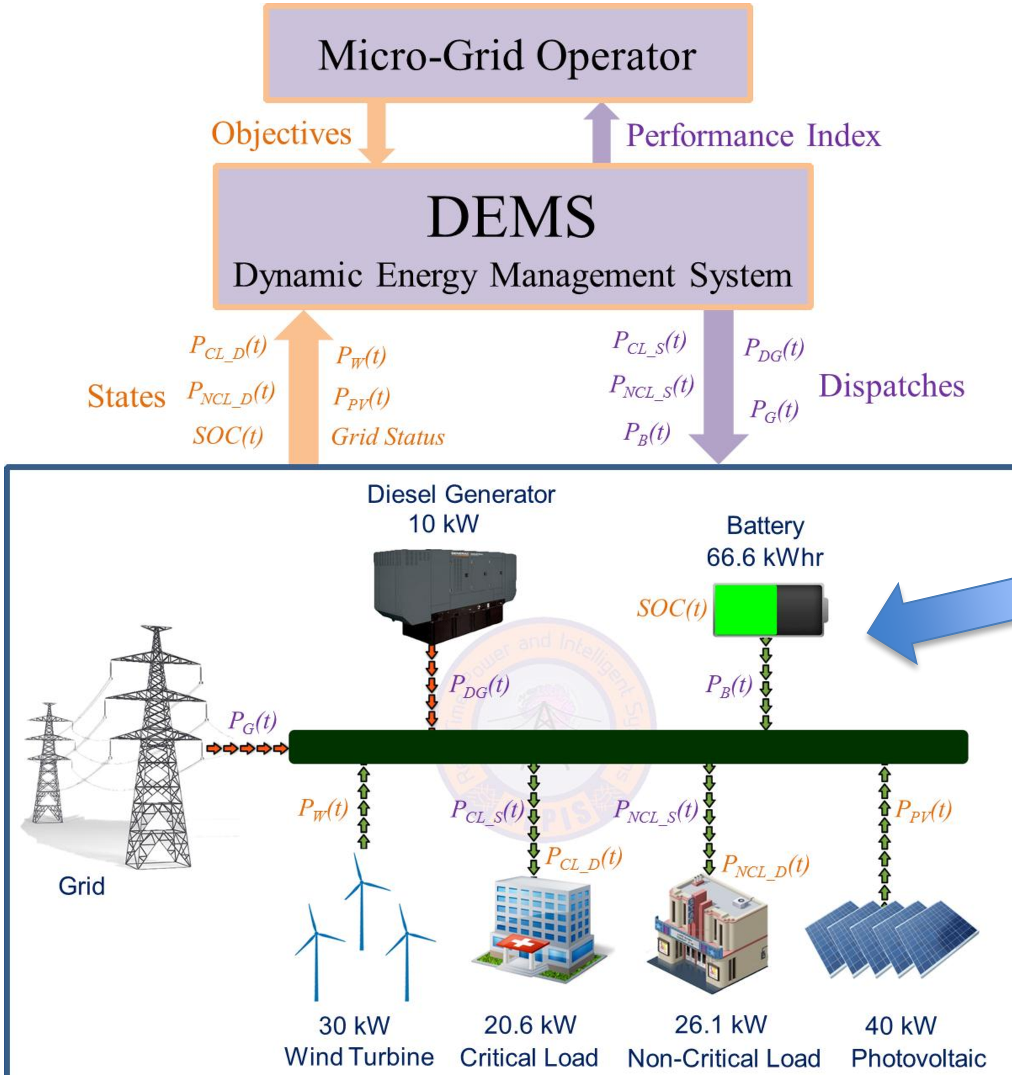
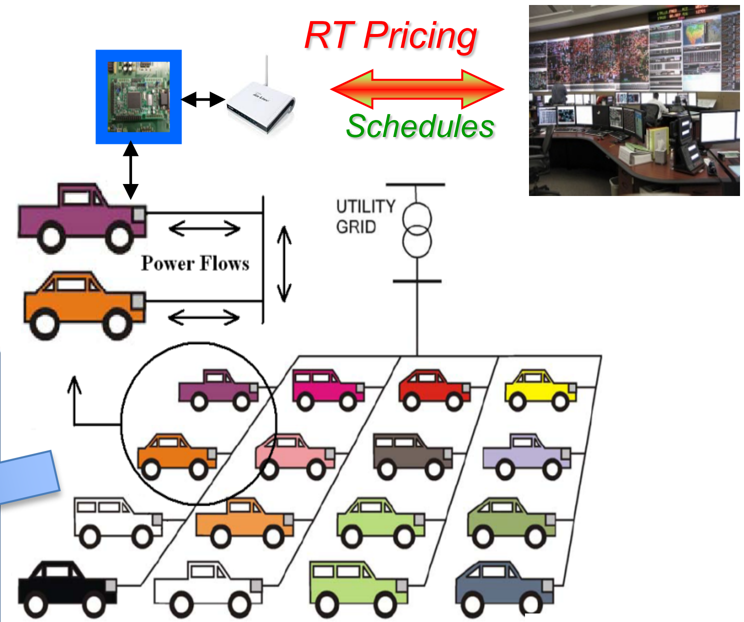
Dynamic Energy Management System (DEMS) for a Smart Micro-Grid





SmartPark

"Intelligent Scheduling of Hybrid and Electric Vehicle Storage Capacity in a Parking Lot for Profit Maximization in Grid Power Transactions", *IEEE Energy 2030*, Atlanta, GA, USA, November 17-18, 2008, pp. 1-8.

Venayagamoorthy GK, Sharma R, Gautam P, Ahmadi A, "Dynamic Energy Management System for a Smart Micro-Grid", *IEEE Transactions on Neural Networks and Learning Systems*, Vol. 27, No. 8, August 2016, pp. 1643 - 1656

Dynamic Energy Management System

Self-sustainable, reliable, <u>environment friendly</u>, and technology ready for smart grid functionality

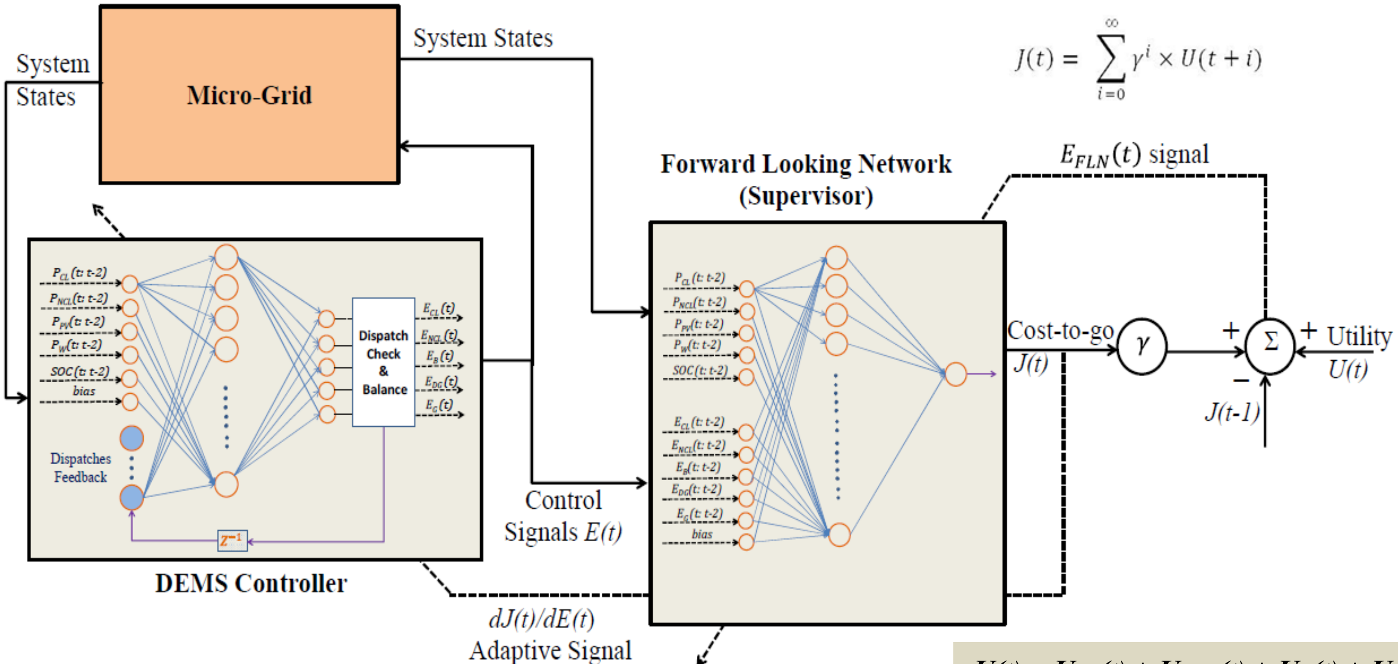
The multiple objectives of the I-DEMS are as follows:

- Supply the power requirements of the critical loads, $P_{CL\_D}(t)$, at all times. This provides 100% reliability with regard to power supply to critical loads.
- Maintain the battery SOC at an optimal level (defined by the operator through a set point for SOC). This ensures and supports meeting the reliability goal in (i) above.
- Maximize controllable load dispatch $P_{NCL\_D}(t)$. This means more customer satisfaction and it creates opportunities for demand-response capability.
- Maximize the utilization of renewable energy resources, and minimize the use of diesel generation and import/export from the grid. This means more environmental friendly and sustainable operation.
- Increase battery life by maximizing battery charging or discharging for a continuous number of states (each state is the dispatch instant, every minute in this study) and thus enhanced sustainability by reducing the rate of replenishing batteries.

Venayagamoorthy GK, Sharma R, Gautam P, Ahmadi A, "Dynamic Energy Management System for a Smart Micro-Grid", *IEEE Transactions on Neural Networks and Learning Systems,* Vol. 27, No. 8, August 2016, pp. 1643 - 1656

AI Approach - DEMS

The intelligent dynamic energy management system is based on an action dependent heuristic dynamic programming (ADHDP) type of adaptive critic design, which is a neural network based design for optimization over time using the combined concepts of adaptive dynamic programming and reinforcement learning.



I-DEMS architecture based on ADHDP framework.

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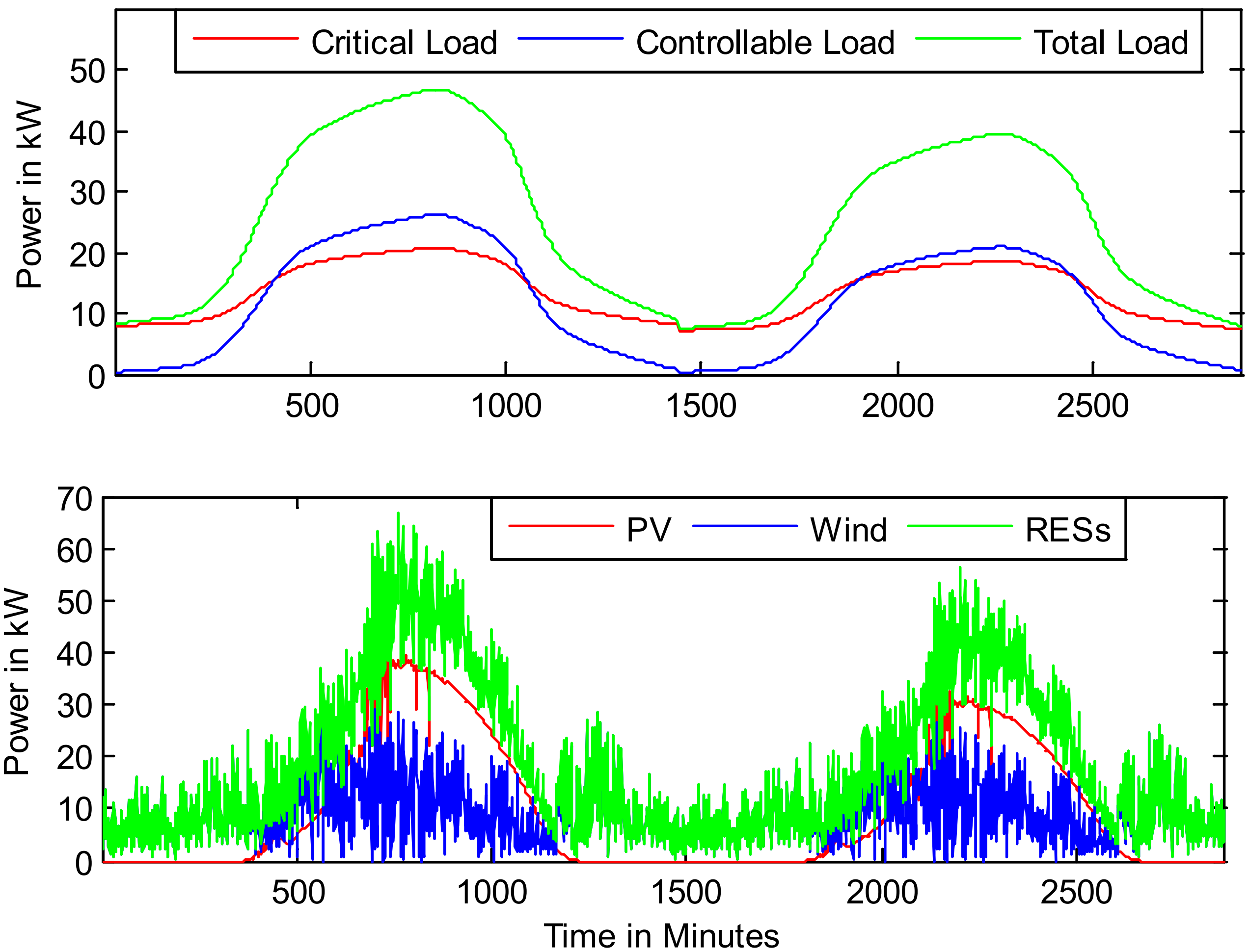
$$U(t) = U_{CL}(t) + U_{NCL}(t) + U_B(t) + U_{DG}(t) + U_G(t) + U_{BCY}(t)$$
$$= w_1(t)\times f(P_{CL\_S}(t)) + w_2(t)\times f(P_{NCL\_S}(t)) + w_3(t)\times f(SOC(t)) + w_4(t)\times f(P_{DG}(t)) + w_5(t)\times f(P_G(t)) + w_6\times f(N_{chr}(t)+N_{dschr}(t))$$

Dynamic Energy Management System



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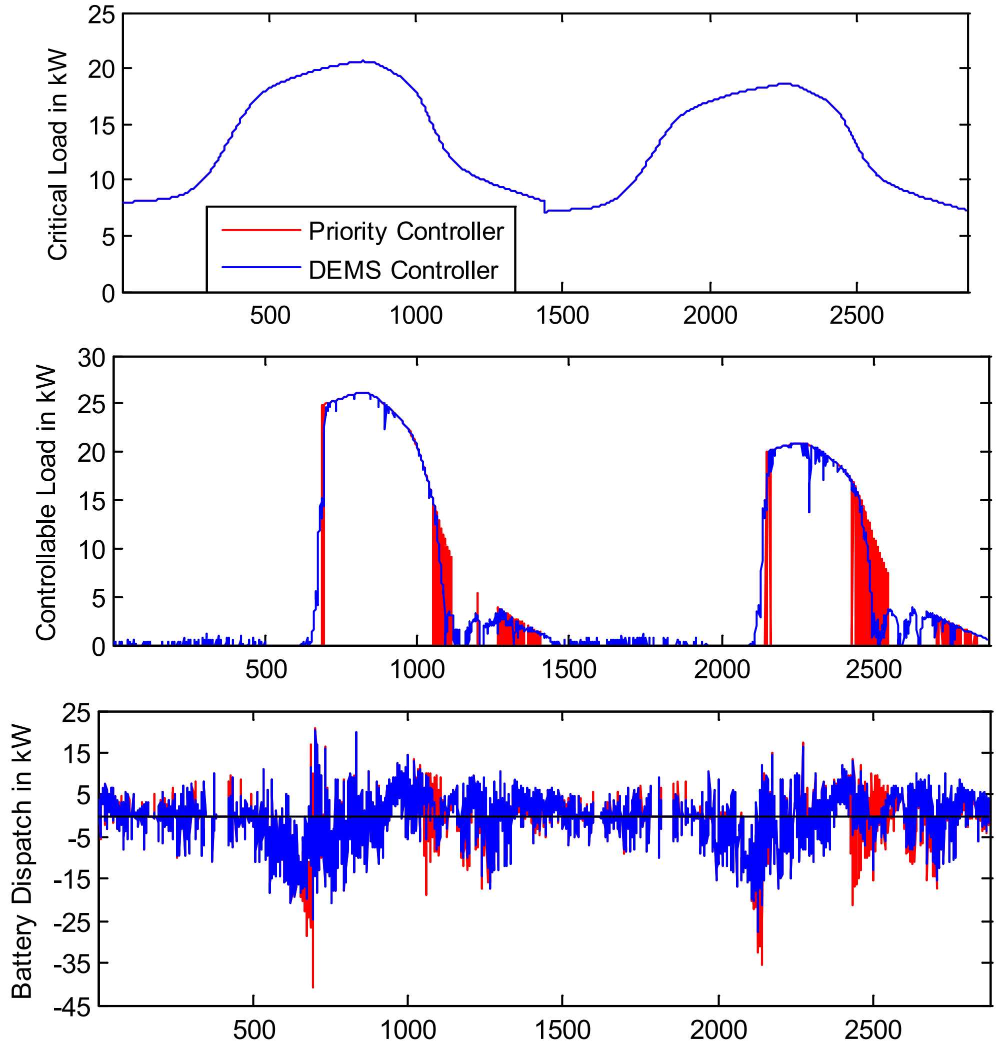
Dynamic Energy Management System



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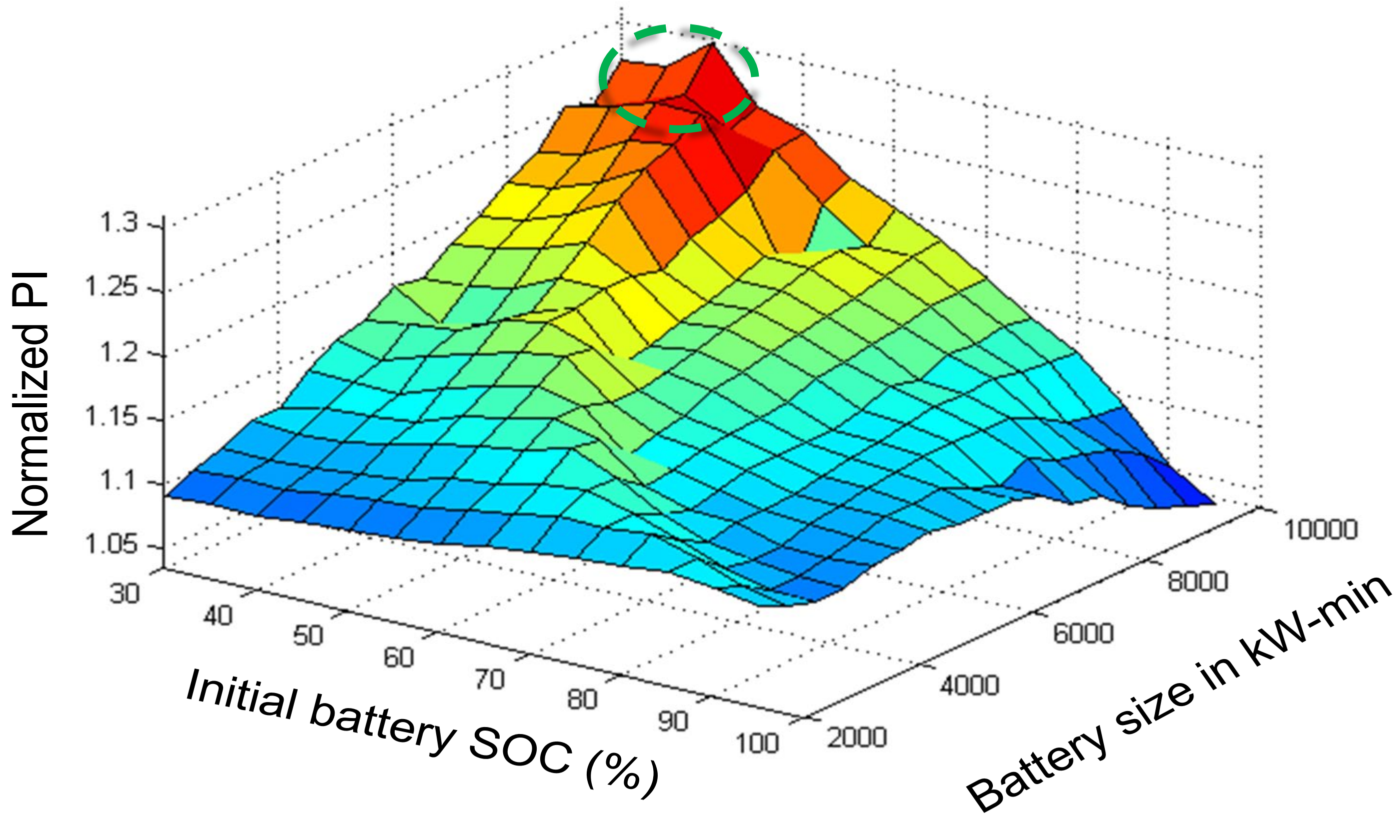
Dynamic Energy Management System

25% to 30 %



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Summary

- New smart grid technologies will play a critical role in advancing clean energy revolution
  - Integration of high-levels (to 100%) of renewable energy sources such as solar and wind power.

- Artificial intelligence will be needed to operate the smart grid in an effective manner in all aspects.

Venayagamoorthy GK, "Future Grids will not be Controllable without Thinking Machines", *IEEE Smart Grid Newsletter* – (letter), October 2011.

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Venayagamoorthy GK, "Potentials and Promises of Computational Intelligence for Smart Grids", *IEEE Power General Society General Meeting,* Calgary, AB, Canada, July 26-30, 2009, pp. 1-6