Distributed Control and Intelligence Using Multi-Agent Systems

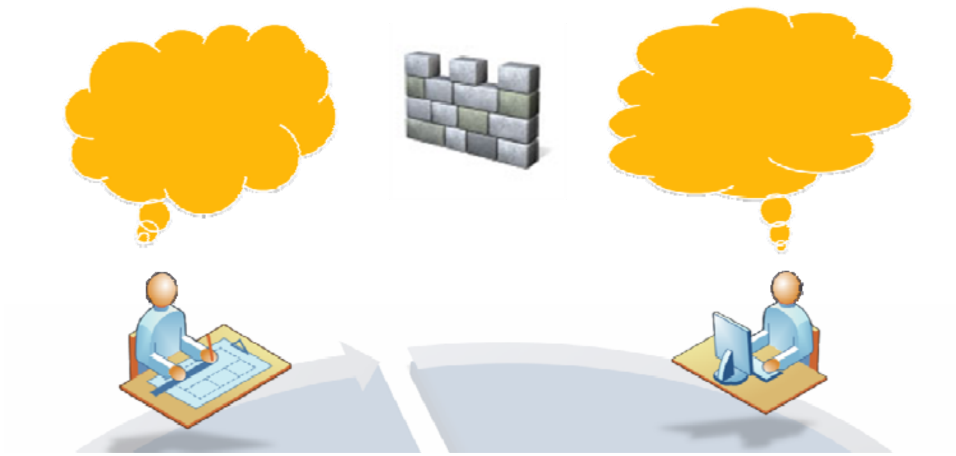
Chen-Ching Liu[1,2]

[1]**Washington State University**

[2]**University College Dublin**

Underfrequency Load Shedding (UFLS)

- Conventional UFLS schemes
  - In operation for decades;
  - Local decision by relays distributed in various locations (no communication);
  - Developed by off-line analysis;
  - Excessive or insufficient load shedding is not uncommon.



Underfrequency Load Shedding (UFLS)

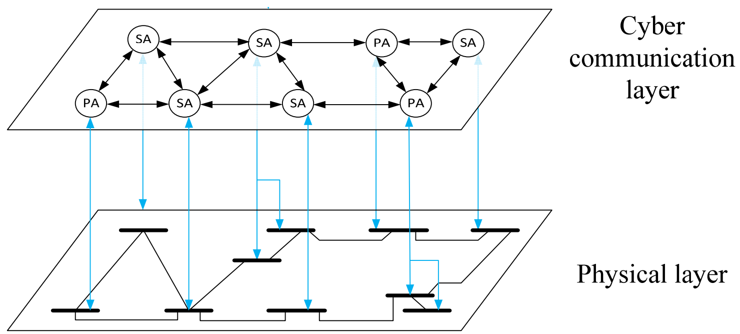
- Centralized UFLS schemes
  - Optimal load shedding decision can be achieved;
  - Relevant information must be transmitted to a central processing facility;
  - Optimization calculation is performed;
  - Delay of a measurement may result in a slow response of the global computational process.

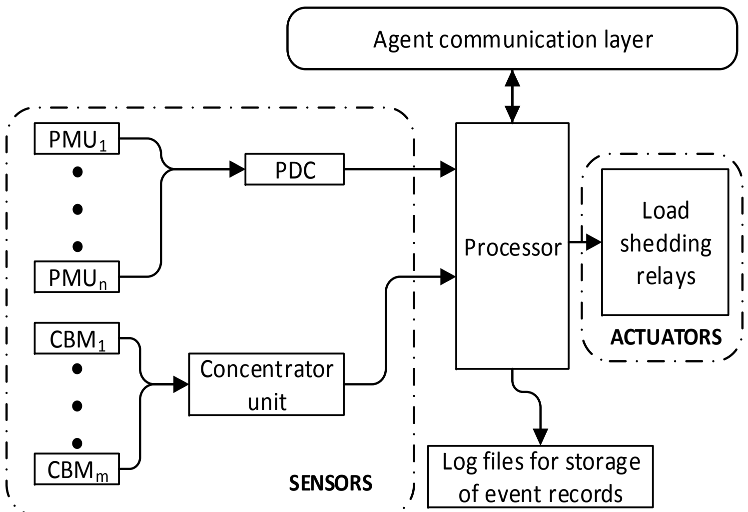
Underfrequency Load Shedding (UFLS)

- Distributed UFLS schemes
  - — Distributed computation with information sharing;
  - — Adaptive for contingency scenarios and operating conditions;
  - — Adaptive to a change in system topology;
  - — Amount of load to be shed may not be optimized for lack of global information;
  - — Effectiveness is the goal, e.g., quickly stop the frequency decay beyond a tolerance of frequency deviation.

Distributed UFLS

- Agent framework
  - Classifications
    - Power plant agent (PA)
    - Substation agent (SA)
  - Sensors
    - Phasor measurement unit (PMU)
    - Phasor data concentrator (PDC)
    - Circuit breaker monitor (CBM)
  - Actuators
    - Relays and circuit breakers





Agent framework

Distributed UFLS

- Multi-agent based UFLS scheme
  - Monitoring step
    - f_i: out of frequency range [59.8, 60.2];
    - $\frac{df_i}{dt}$: in the frequency derivative range [-1.0, -0.3];
    - Results of both triggers must be true to activate the estimating step.
  - Estimating step

—$\Delta P_{G_j}(t_0) = \frac{2H_j \cdot S_j}{f_n} \cdot \frac{df_j(t)}{dt}|_{t=t_0}$ $\quad \Delta P_i(t_0) = \sum_{j=1}^{M} \Delta P_{G_j}(t_0)$

—M is the number of generators that belong to agent i.

Distributed UFLS

- Multi-agent based UFLS scheme
  - —Distributing step
    - Distributed load shedding amounts should be determined quickly;
    - Load buses closer to generators are more effective;
    - Bus voltage magnitudes and angles are acquired from PMUs locally, and shared by *reaching agreement* among agents.

Reaching Agreement

- Sharing information among agents
  - Consensus problem
    - Each agent has an initial state and all agents must agree on the same value in the final state (not necessarily the original initial state).
  - Average-consensus problem
    - Each agent has an initial state and all agents agree on the ***average*** of their initial states;
    - If the initial state of an agent is a vector, the average of the corresponding elements among all vectors is reached and a state with the same dimension is obtained.

Reaching Agreement

- Problem formulation
  - A network of n agents is modeled as a directed graph, denoted by $G = (V, A)$;
  - $V = \{1,2, \dots, n\}$ is the set of agents;
  - The topology of this network is specified by a ***nonnegative*** $n \times n$ adjacency matrix $A = [a_{ij}]$;
  - If an active communication link exists from agent i to agent j, a_{ij} is a positive value, otherwise $a_{ij} = 0$;
  - The state of agent i at time t is denoted by $x_i(t)$, which can be a single value or a vector with m elements.

Reaching Agreement

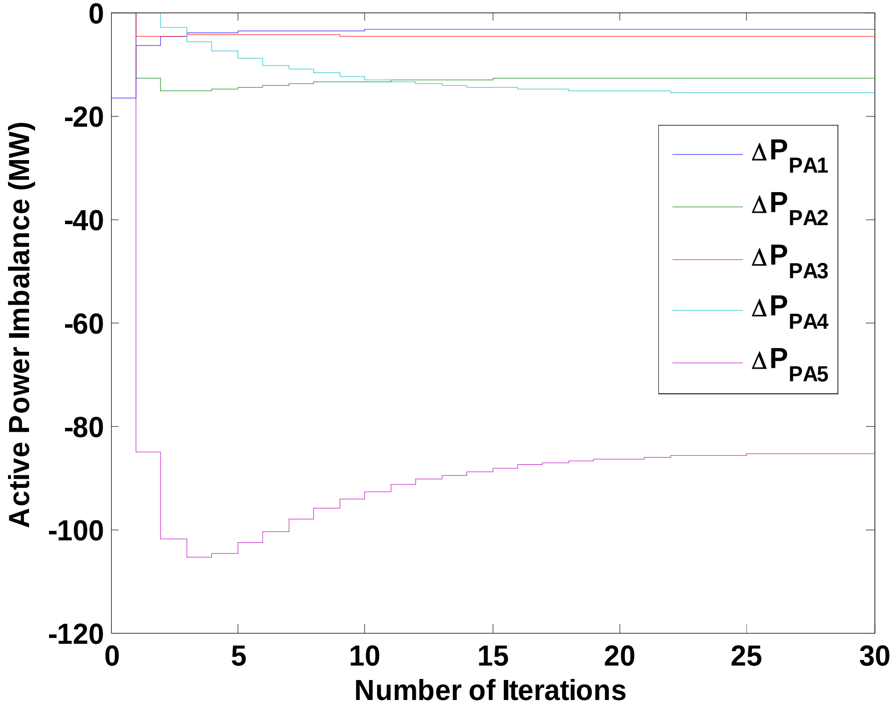
- Protocol - average consensus method
  - R. Olfati-Saber and R. M. Murray, "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Trans. Automatic Control*, vol. 49, no. 9, pp.1520–1533, Sep. 2004.
  - $\dot{x}_i(t) = u_i(t) = \sum_{j=1}^{n} a_{ij}\left(x_j(t) - x_i(t)\right)$
  - $\Delta = diag\left(\sum_{j=1}^{n} a_{1j}, \ldots, \sum_{j=1}^{n} a_{ij}, \ldots, \sum_{j=1}^{n} a_{nj}\right)$
  - $L = \Delta - A$
  - $X(t) = col(x_1(t), x_2(t), \ldots, x_n(t))$
  - $\dot{X}(t) = (A - \Delta)X(t) = -LX(t)$
  - L is the Laplacian matrix, A is the adjacency matrix, and Δ is the degree matrix;
  - The diagonal element of Δ, $\sum_{j=1}^{n} a_{ij}$, denotes the number of agents

Reaching Agreement

- Sharing information among agents
  - Average-consensus problem
    - To reach $(1/n)(\sum_{i=1}^{n} x_i(0))$ by applying inputs $u_i(t)$ that only depend on the state of agent i and the states of its neighboring agents in a dynamic graph;
    - $x_i(0)$ is the initial state of agent i at time $t = 0$;
    - Communication network topology is balanced;
    - If agents i and j are not connected directly or $i = j$, then $a_{ij} = 0$; Otherwise, $0 < a_{ij} = a_{ji}$.

Distributed UFLS

Agents	PA1	PA2	PA3	PA4	PA5
Buses	2, 30	6, 31	25, 37	29, 38	39
Initial Values	[-16.59, 0, 0, 0, 0]	[0, -63.37, 0, 0, 0]	[0, 0, -23.71, 0, 0]	[0, 0, 0, -78.72, 0]	[0, 0, 0, 0, -425.34]



Information sharing process of five PAs (from the perspective of PA1)

$$\overrightarrow{\Delta P} = 5 \times sum\{[-3.322, -12.692, -4.738, -15.672, -85.121]\} = -607.73\ MW$$

Distributed UFLS

- Comparison – “Advanced” load shedding strategy

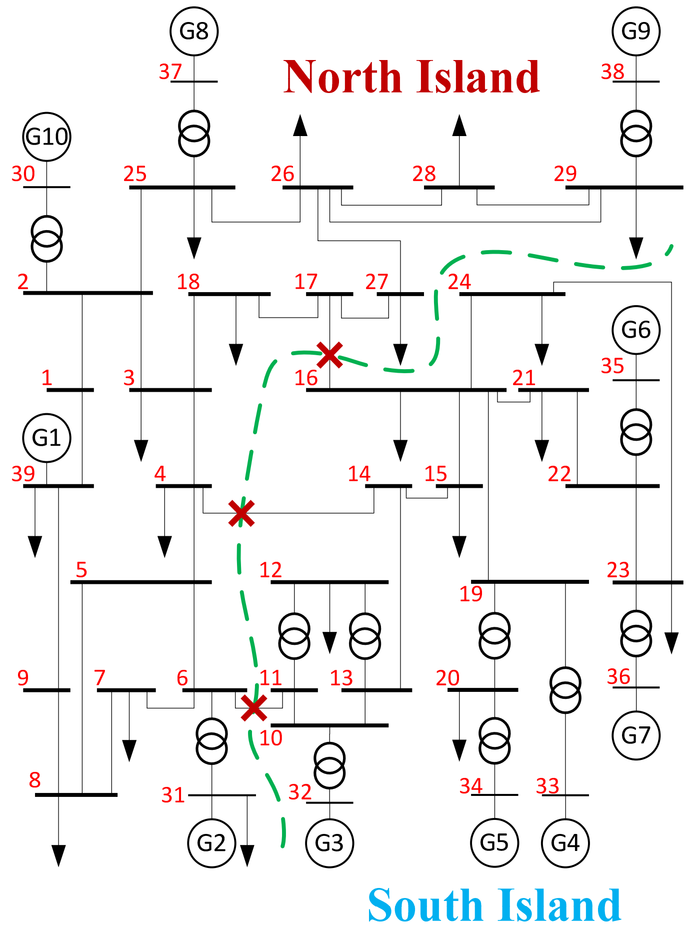
Relay Group	G1 – 1st Group	G2 – 2nd Group
Load Shedding in Each Step	2.5%	1.6%
Number of Steps	10	16
Frequency Threshold (Hz)	59.8, 59.72, 59.64, …, 59.08	59.0, 58.9, 58.8, …, 57.5
Frequency Derivative Threshold (Hz/s)	[-1.0, -0.3]	**NULL**
Time of Frequency Measurement (s)	0.1	0.1
Time to Open the Circuit Breaker (s)	0.075	0.075

Distributed UFLS

- Contingency scenario

Time (sec)	Event	Active Power from SI to NI (MW)
0.5	Tripping of line 6-11	320.48
1.5	Tripping of line 4-14	264.05
2.2	Tripping of line 16-17	238.96

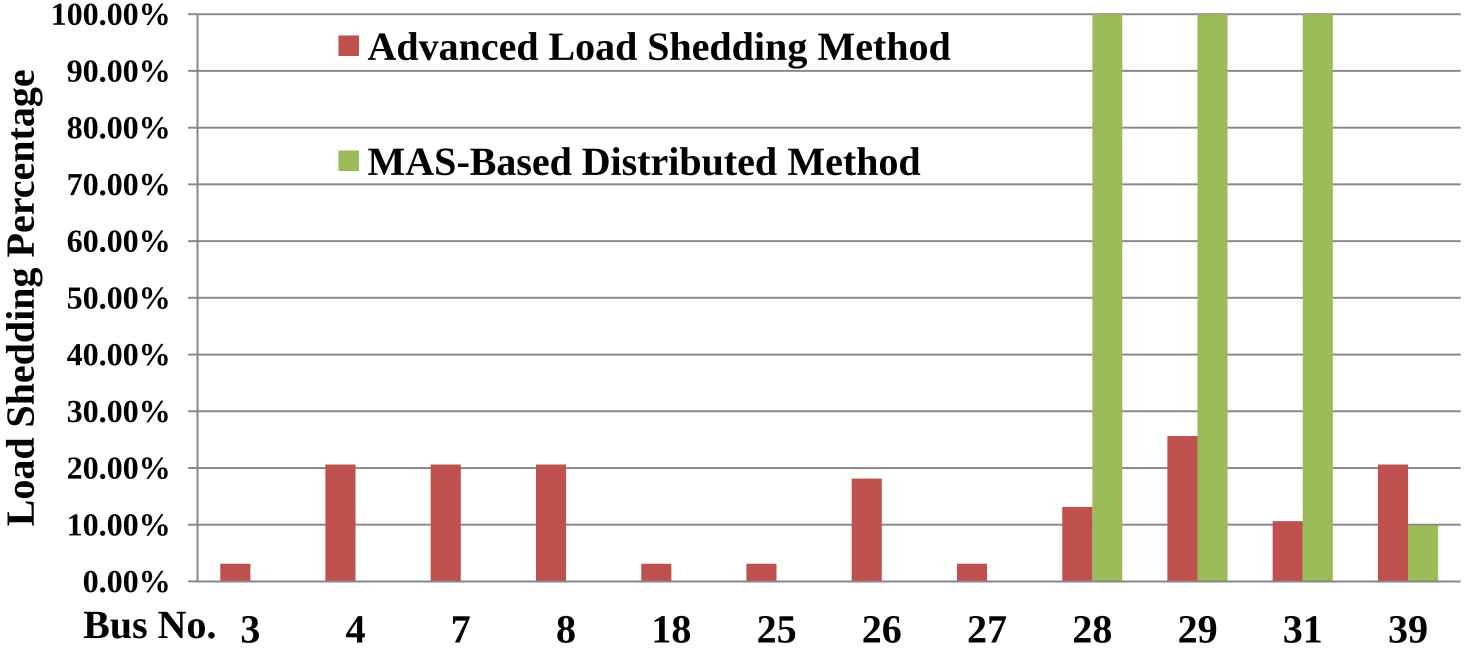
Total active power deficiency in NI: 823.49 MW



Power grid splitting

Distributed UFLS

- Comparison

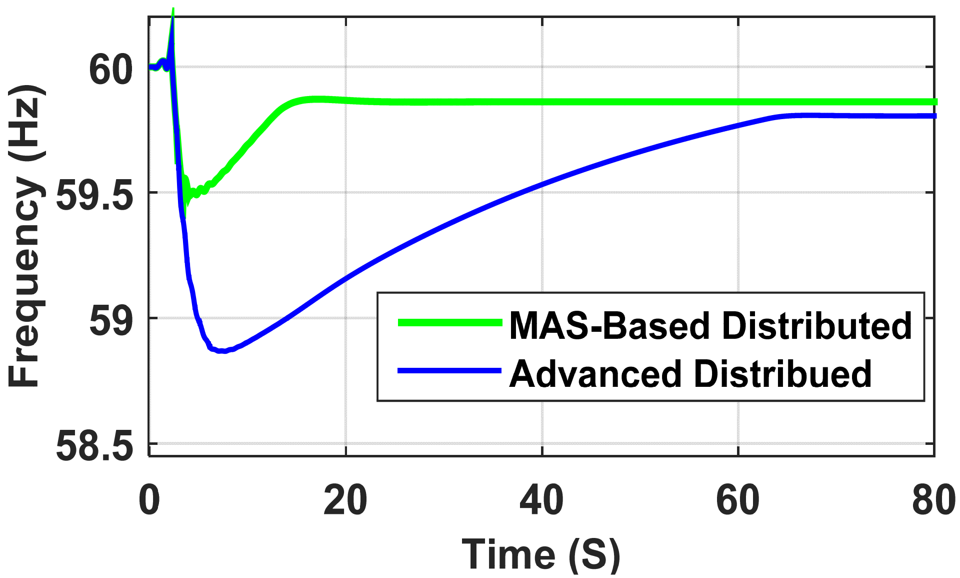


Comparison of load shedding distribution

Distributed UFLS

- Comparison

Methods	Advanced	Multi-agent based distributed
Frequency Decay Ends (sec)	8	4.5
Active Power Load (MW)	643.35	607.73
Reactive Power Load (MVAR)	162.07	83.79
Frequency (Hz)	59.8	59.86



643.35 - 607.73 = 35.62 MW
162.07 - 83.79 = 78.28 MW

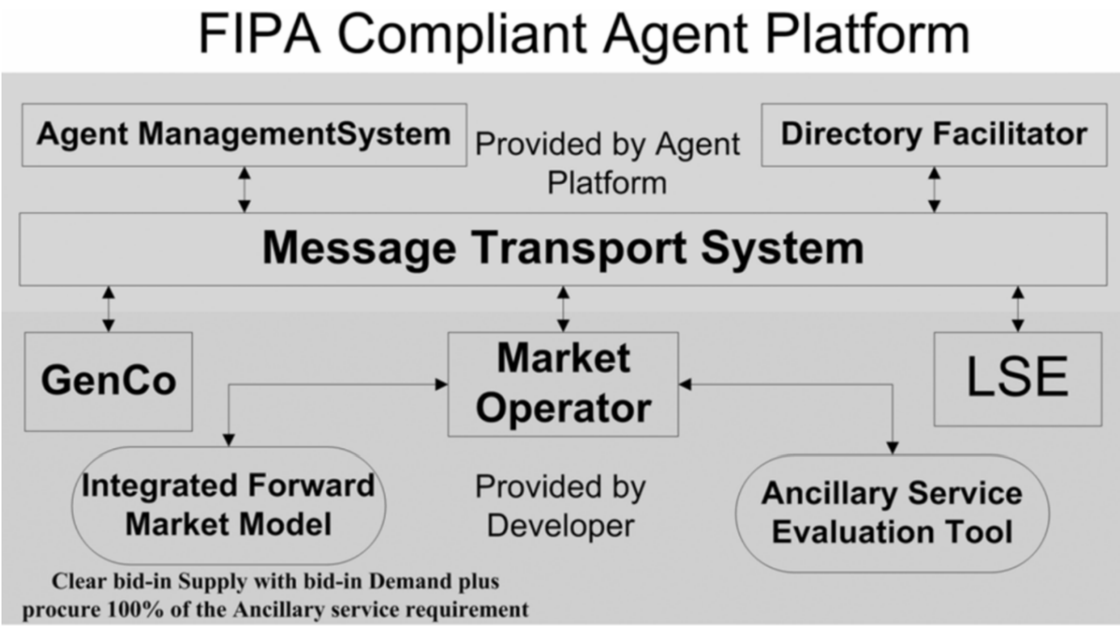
System responses (no secondary control)

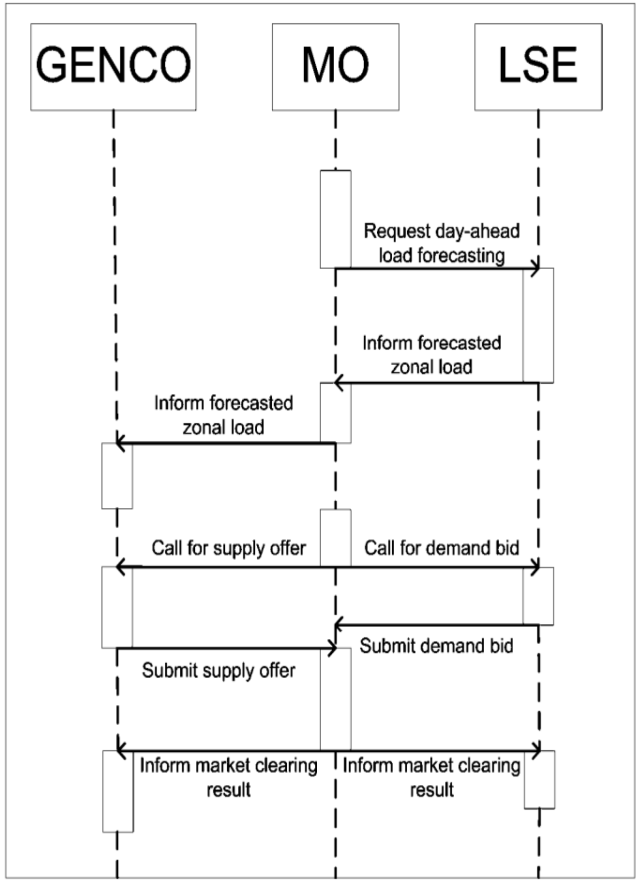
Agent-Based Modeling: Market Rules Evaluation

- Evaluation of market rules
  - Complexity of the market structure
    - Strategic interaction between participants;
    - Underlying physics.
  - Difficult to evaluate implications of potential changes to market rules;
  - Day-ahead market (DAM) is modeled as a MAS;
  - Each participant is modeled as an agent.

Agent-Based Modeling: Market Rules Evaluation

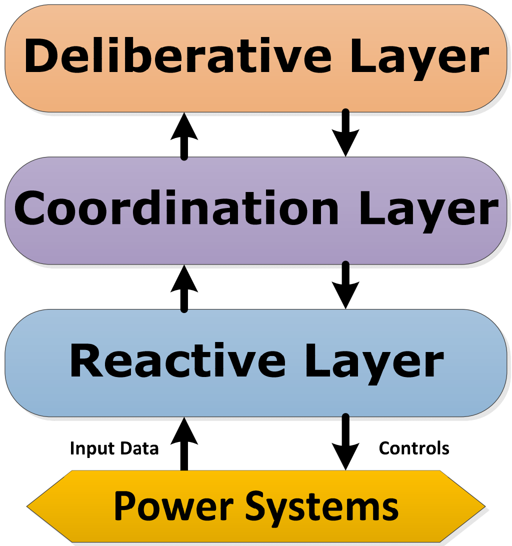
- System structure and message flowing sequence

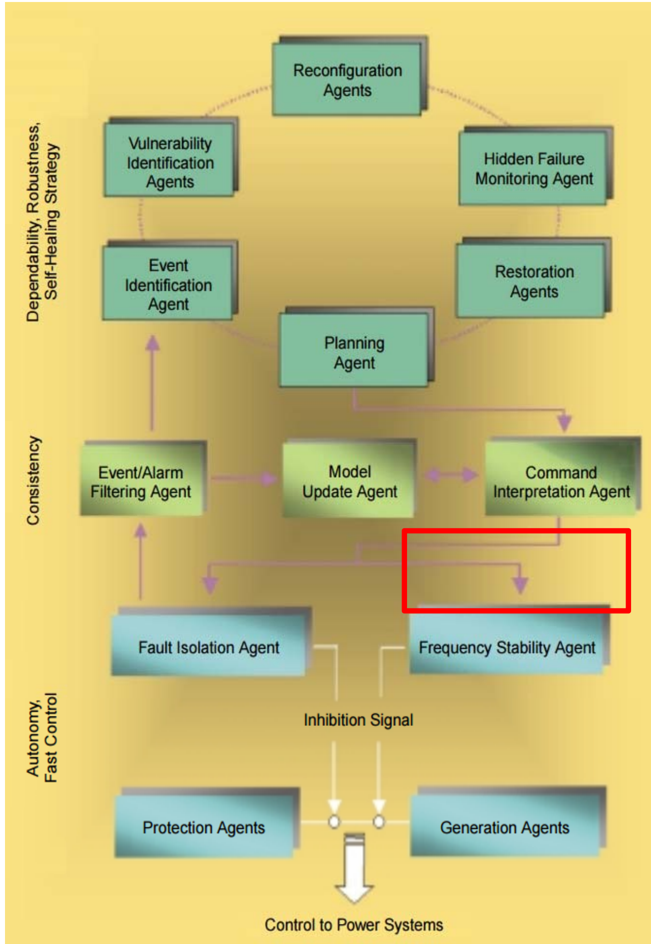




Architecture of MASs

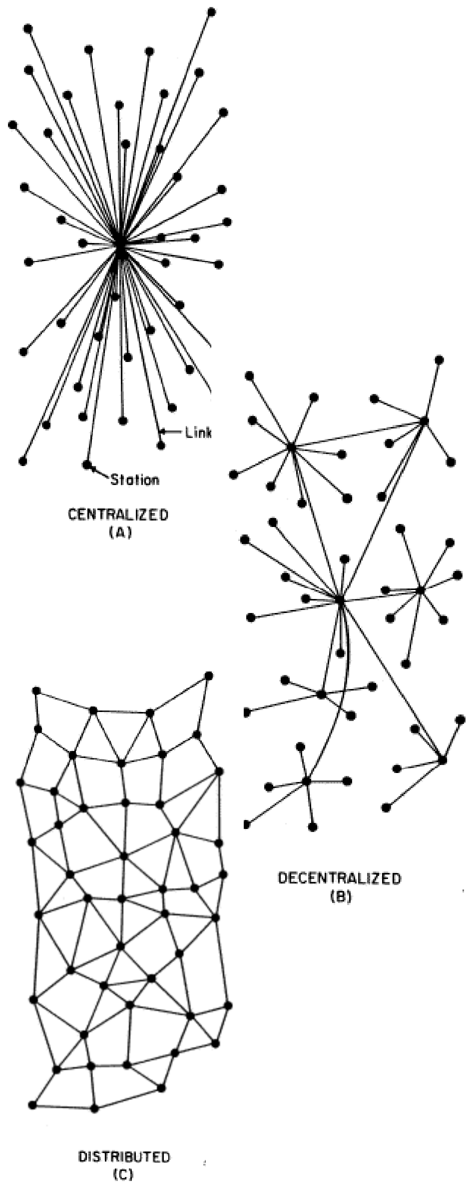
- Strategic power infrastructure defense (SPID) system
  - Hierarchical, layered multi-agent system concept;
  - Hybrid multi-agent system model.





Distributed Control

- Distributed control systems (DCSs)
  - Control units are distributed throughout the system;
  - Large, complex industrial processes, geographically distributed applications;
  - Utilize distributed resources for computation with information sharing;
  - Adapt to contingency scenarios and operating conditions;
  - Self-adapt to a change in system topology.



Distributed Intelligence

- Distributed artificial intelligence (DAI)
  - Used by distributed solutions for complex problems that require intelligence;
  - Based on different technologies, e.g., distributed expert systems, planning systems, or blackboard systems;
  - Closely related to the field of MASs;
  - Consisting of autonomous learning agents;
  - Agents are often heterogeneous.
  - Example: VOLTTRON by Pacific Northwest National Lab

For Further Information

- C.-C. Liu, J. Jung, G. T. Heydt, V. Vittal, and A. G. Phadke, "The strategic power infrastructure defense (SPID) system. A conceptual design," *IEEE Control Systems Magazine*, vol. 20, no. 4, pp. 40–52, Aug. 2000.

- H. Li, G. W. Rosenwald, J. Jung, and C.-C. Liu, "Strategic power infrastructure defense," *Proceedings of the IEEE*, vol. 93, no. 5, pp. 918–933, May 2005.

- N. Yu, C.-C. Liu, and J. Price, "Evaluation of market rules using a multi-agent system method," *IEEE Transactions on Power Systems*, Vol. 25, pp. 470-479, Feb. 2010.

- J. Xie, C.-C. Liu, and M. Sforna, "Distributed underfrequency load shedding using a multi-agent system," *Proc. IEEE PowerTech* (*POWERTECH '15*), Eindhoven, Netherlands, Jul. 2015.

- J. Xie, C.-C. Liu, M. Sforna, M. Bilek, and R. Hamza, "Intelligent physical security monitoring system for power substations," *Proc. 12th Intell. Syst. Appl. Power Syst.* (*ISAP '15*), Porto, Portugal, Sep. 2015.