
Energy Processing and Control Systems

Joint Past, Common Future

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Some terms and definitions

Control addresses the use of algorithms and feedback in engineered systems - an engineering science.

Energy processing - power systems, electric drives, power electronics.

Control structures, including feedback, are tools for **uncertainty management**.

Key **design** issues - stability (bounded disturbances give bounded errors), and dynamics that have the desired behavior (good disturbance rejection, fast responsiveness to changes in the operating point).

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Examples of energy system reliability targets:

Reliability %	N "nines"	Down time
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Events from real life (G.T. Heydt):

Losing in roulette	N=1.6
Losing the PowerBall lottery	N=6
FAA design for aircraft	N=9-12

Presentation Map

- Background and Definitions,
- **ENERGY SYSTEMS AND CONTROLS - PAST,**
- Energy Systems and Controls - Present,
- A personal interlude - Dynamic Phasors,
- Energy Systems and Controls - Future.

The Prologue - A Gallery of Engineers

James [Watt](#) - Steam engine is a power application.

Gabriel [Kron](#) - Diacoantics for large networks and tensors for analysis of circuit transients.

Nathan [Cohn](#) - Frequency and tie-line flow control (AGC).

Bill [Tinney](#) - Sparse matrix technology.

John (Janos) [Zaborszky](#) - Control in emergencies.

Alcir [Monticelli](#) - State estimation in power systems.

Karl [Hasse](#), Felix [Blaschke](#) - Vector control of AC drives.

David [Middlebrook](#), Slobodan [Ćuk](#), Roger [Brockett](#) - Averaging for DC/DC converter control.

Lester [Fink](#) - DoE (actually ERDA - Energy Research and Development Agency).

History (2)

The vast networks of electrification are the greatest engineering achievement of the 20-th century.

US National Academy of Engineering

History (3)



World Trade Center (WTC) in New York - as a response to the '93 bombing, the primary distribution system in the buildings was improved (10 substations in the North tower, 11 in the South)

History (4)

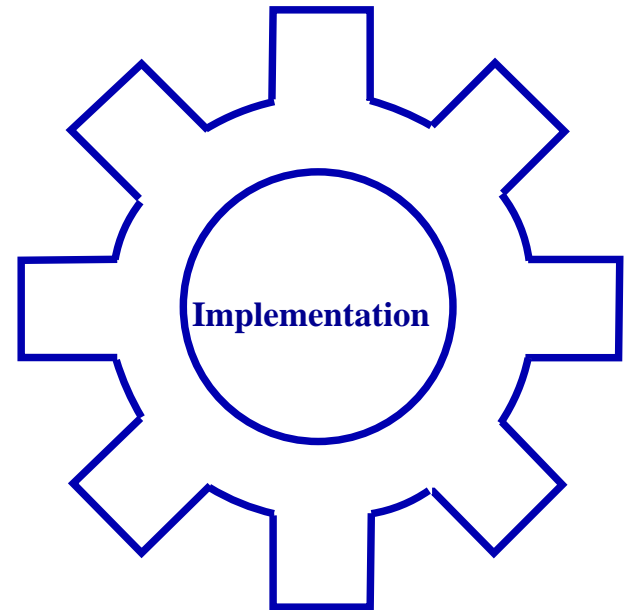
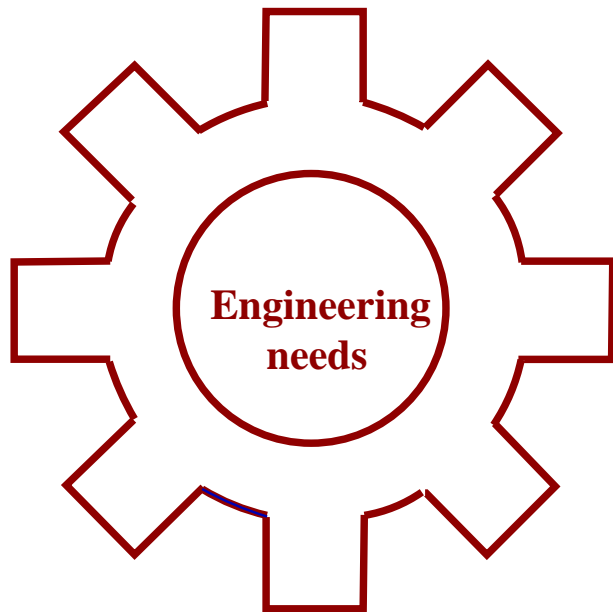


Power at WTC was kept for 102 minutes after the initial strike, and was the main factor in saving as many as 18,000 people who escaped from the towers before the collapse (G.T. Heydt).

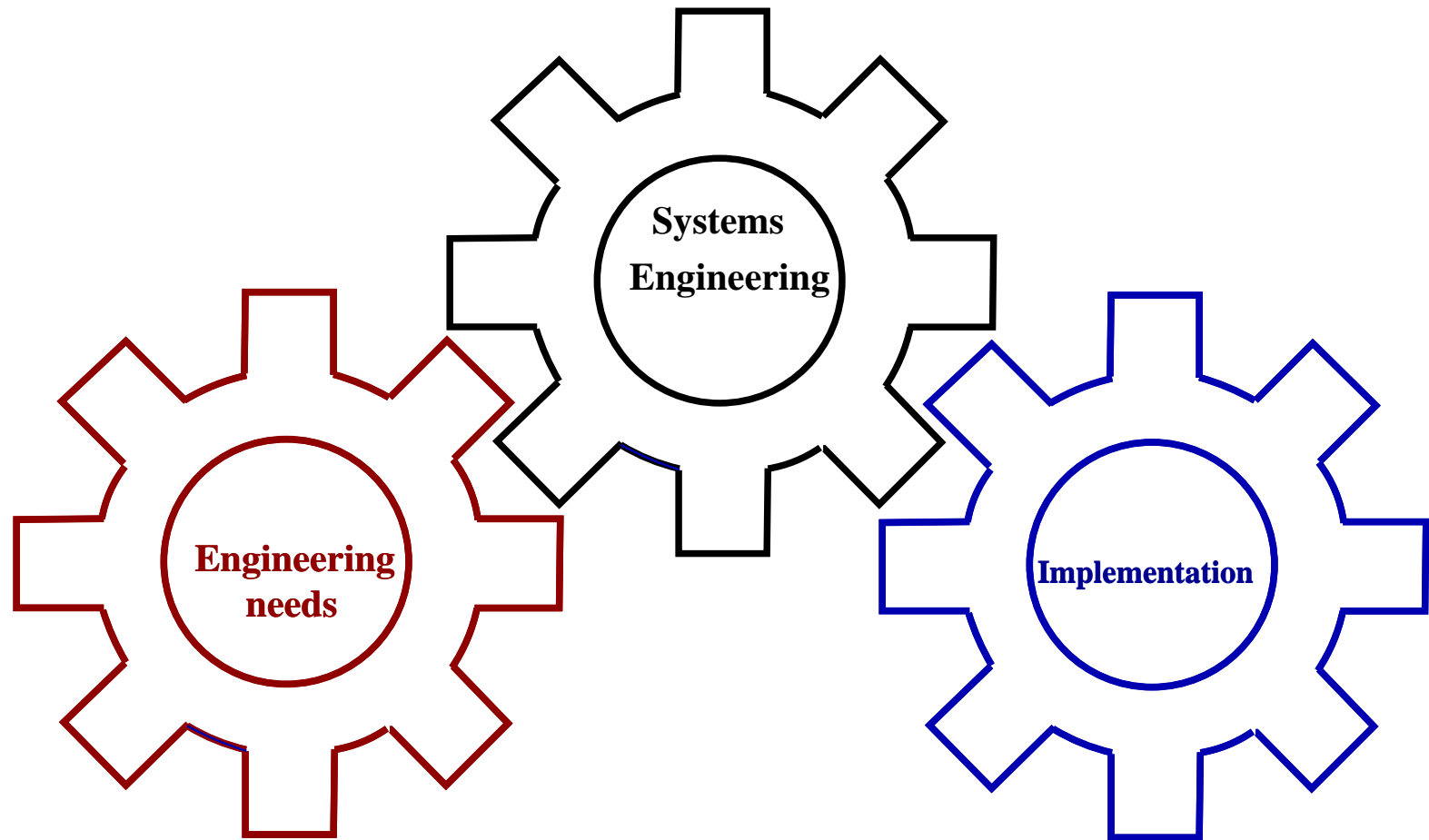
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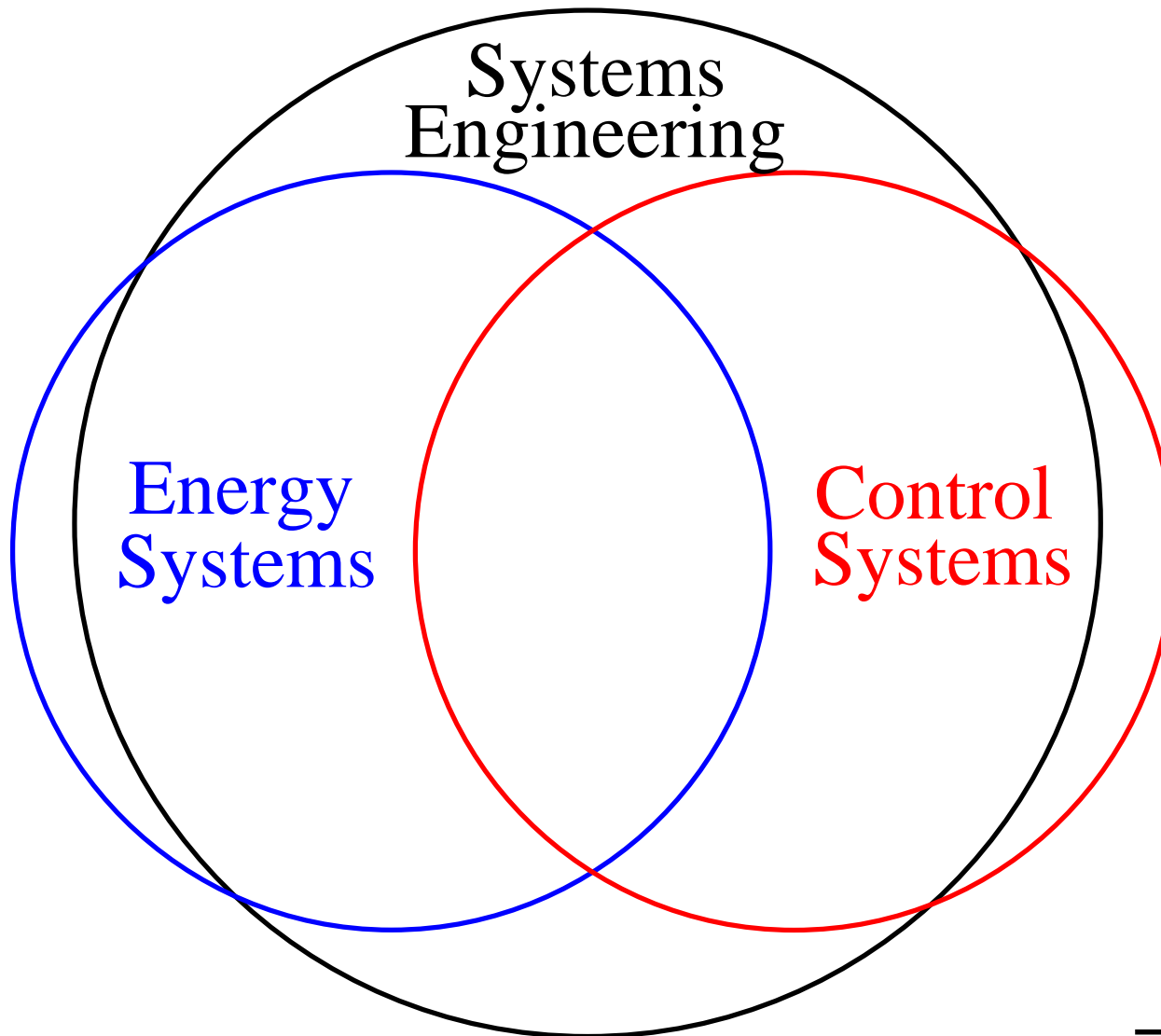
Energy and Control - Thematic Links



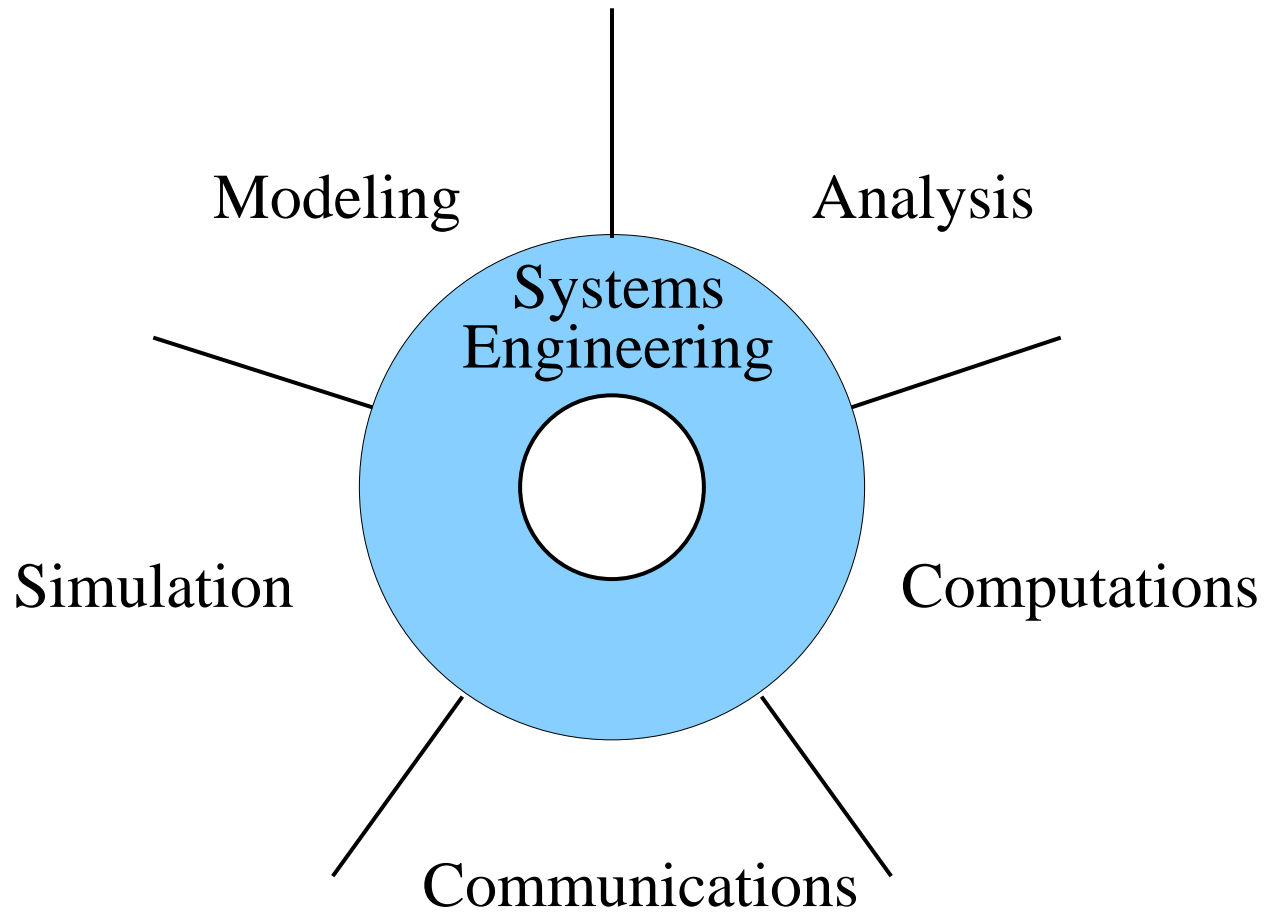
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Thematic Links (2)



Thematic Links (3)

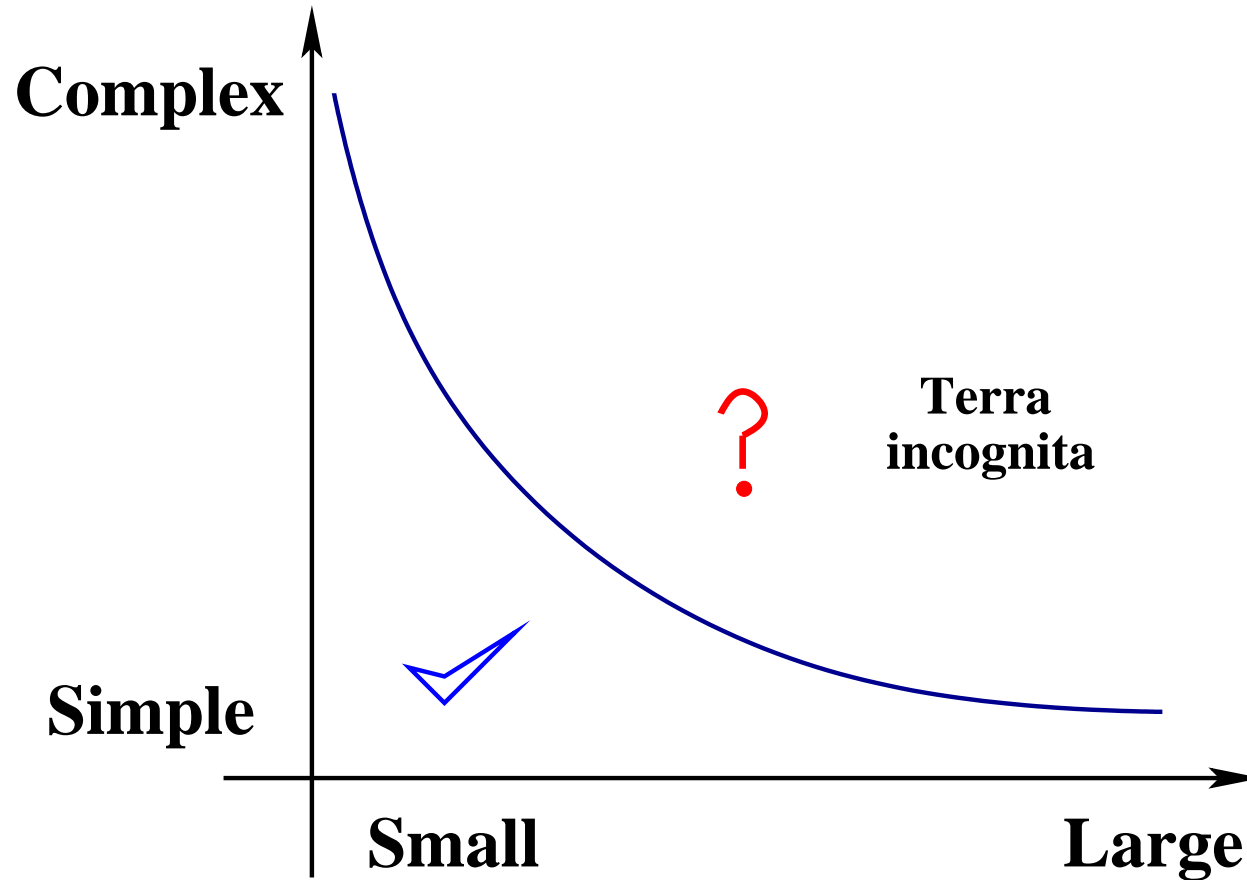


Grand Challenges in Power Engineering

IEEE Power Engineering Society, 2002:

- 1. Total control of power flow in networked systems.
- 2. Self-healing networks to achieve zero outages.
- 3. Zero-error state estimation.
- 10. Real time dynamic simulation of a 50 000 node, 2 000 generator, 500 000 MW system.

State of the Art - Controls



Present Mutual Perception

Control side:

- There is not much new in energy systems.
- Funding is intermittent at best.

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Energy side:

- Worshiping of fancy mathematics in controls,
- Increasingly dangerous control systems.

Characteristics of Energy Networks

- Built for **efficiency**.
- **Hybrid** - continuous and discrete acting components; discrete control actions perceived as key ones in preventing cascading blackouts.
- **Multi-scale** in time and space - microgrids that include distributed generation (DG) and load management.
- Sparse sensing ("information-starved"); new types sensors entering slowly - phasor measurements units (PMU).
- Limited actuation.
- **Uncertainty** (epistemic and aleatory) - closing a control loop around a system that handles high power, and whose dynamics are not always fully understood.
- Organization - multiple operators.

Energy Networks (2)

- Connectedness with other **national infrastructures** (gas, oil, transportation, telecom) and the continental scale - linked vulnerabilities.
- Complexity is fixed not by the designer, but by **economic considerations** and the natural scale of the problem.
- Input/Output characteristics are **regularized** by physics (conservation laws, symmetries and invariants - flows of energy and information).
- **Safety-critical** systems, controlled over networks.
- **Protective relays** are the first layer of control - discrete, distributed and loosely coordinated.
- Electromechanical control being replaced by electronic (software-controlled) - **embedded systems**.
- Limited experimental capability and few universally accepted benchmark examples.

Energy Networks (3)

Use of models:

- at component level control - detailed, "strong" use, e.g., in system full or partial inversion,
- at system level control - only basic, structural properties, "weak" use, e.g., only connection structure, graph properties and qualitative, physics-derived features).

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A *family* of models for a given physical component (e.g., generator, transformer or converter).

Will techniques **scale-up** gracefully - theorems go up fine, but computational tools?

Link with continuous analysis methods (control) and discrete analysis methods (computer science).

Energy Networks and Economics

Power system deregulation:

- Unclear what control structures are **viable**,
- Strong "invisible" hand of the National regulator (FERC in the US),
- Increases **uncertainty** and brings distributed decision making,
- How to assure symmetry of benefits for all participants, especially customers.
- Increases **fragility** - widespread data availability would greatly aid an entity seeking to intentionally create widespread disruption, without the constraint of maintaining acceptable operation within a portion, or being accepted as a market player in the future.

Cascading Faults in Energy Systems

Recent examples - US, Italy, Sweden, UK ... in 2003 (M. Amin):

US Blackouts	1991-1995	1996-2000
Over 100 MW	66	76
Over 50,000 customers	41	58

- US cost estimated at \$100 billion ($\$ 10^{11}$) per year,
- Often all controllers "performed as designed", but overall action inappropriate
- Better tools may give several minutes warning to operators(CA in '90s)

Cascading Faults (2)

- Defense should be **in depth** (voltage control design, switched caps, special protection schemes, direct load control).
- Analytical explanations - **optimization induced brittleness, criticality**.
- **No** comprehensive dynamic **analysis capability** exists today.
- "Next blackout will be different" - need predictive theory.

Decentralized Control of Energy Systems

- AGC is a **quintessential** example.
- Increases the number of decision makers, thus decreasing the sizes of problems to be solved by each - **if** successful, robustness \uparrow , computational complexity \downarrow , cost \downarrow .
- No technology** for effective design of decentralized schemes - coordination is heuristic.
- Interaction with the **physical layer** (environment) is larger than in other systems.
- Information structure constraints due to heterogeneous communication modes - **embedded, hybrid systems**, where "the model is the code".
- Some leads - decentralized feedback laws with a low-rank centralized correction, wide area measurement and control (WAMS and WACS).

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A voice from the past...

"Each n-dimensional "neuron" is represented by a generalized magnetohydrodynamic generator, equipped with parameters drawn from many regions and branches of modern physics. The geometry of the overall generation, transmission, and distribution network can be constantly modified and enlarged by any developments in algebraic and point-set topology ... That is, both the component units, as well as their interplay are so flexible that the complexity of the dynamic artificial brain can grow in step with the growth of the physical and geometrical sciences."

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G. Kron, "Power System Type Self-Organizing Automata", 1962.

The Bigger Picture

Destinations and technology drivers:

- Distributed generation,
- Power electronics - Flexible AC Transmission Systems (FACTS) and variants,
- Embedded systems - real-time communication, computation and control.

Action Items for Educators

- **Long term principles** over specifics of present technology, as root-cause understanding of phenomena helps establish fundamental limits of performance,
- **Compactify** and solidify the knowledge base (as it happened several times in the past),
- Maintain analytical rigor and the energy-control link (could have helped with the influx of economic concerns),
- Teach computational **large system dynamics**,
- Implement tools in software.

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- Feedback from observed data to modelling and control structures.
- Time to act - "we are responsible not only for what we do, but for what we don't do" - Moliere.

Spasibo Bol'shoe!