Pacific Institute *for the* Mathematical Sciences

Cognitive Systems Inc.

Challenges in Clean Energy and Opportunities for Mathematicians

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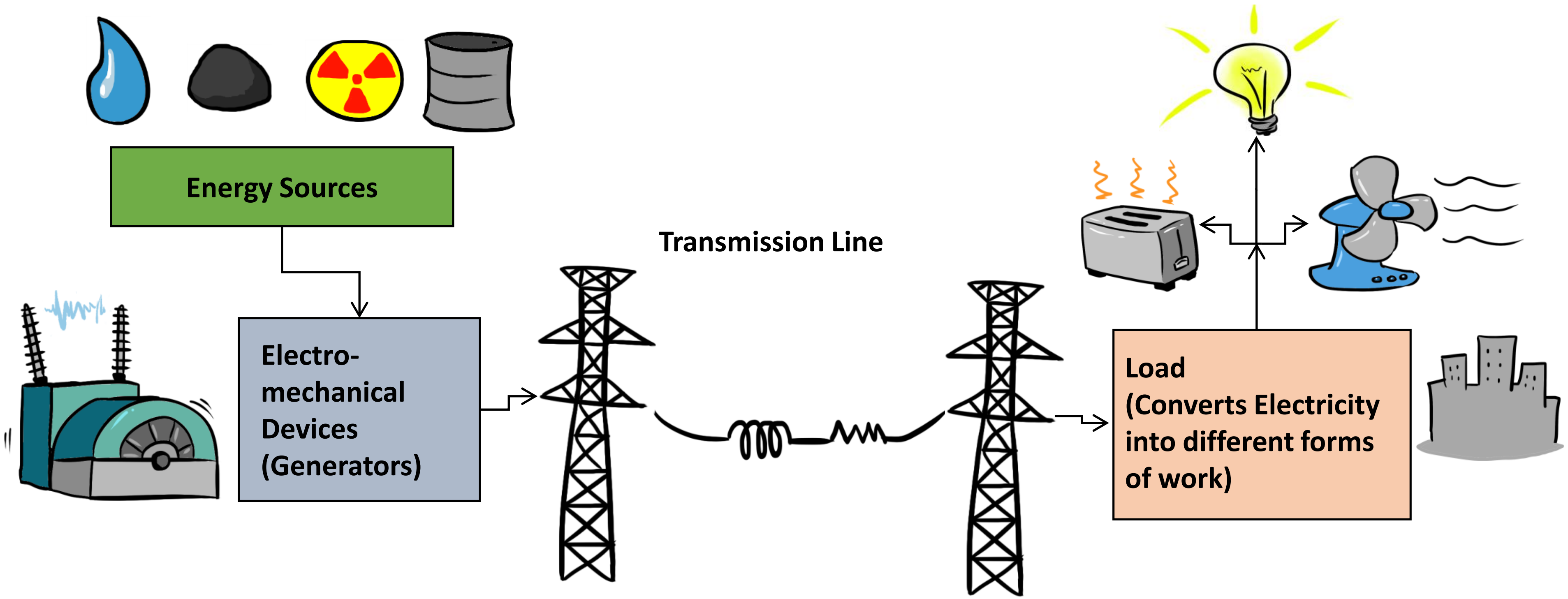
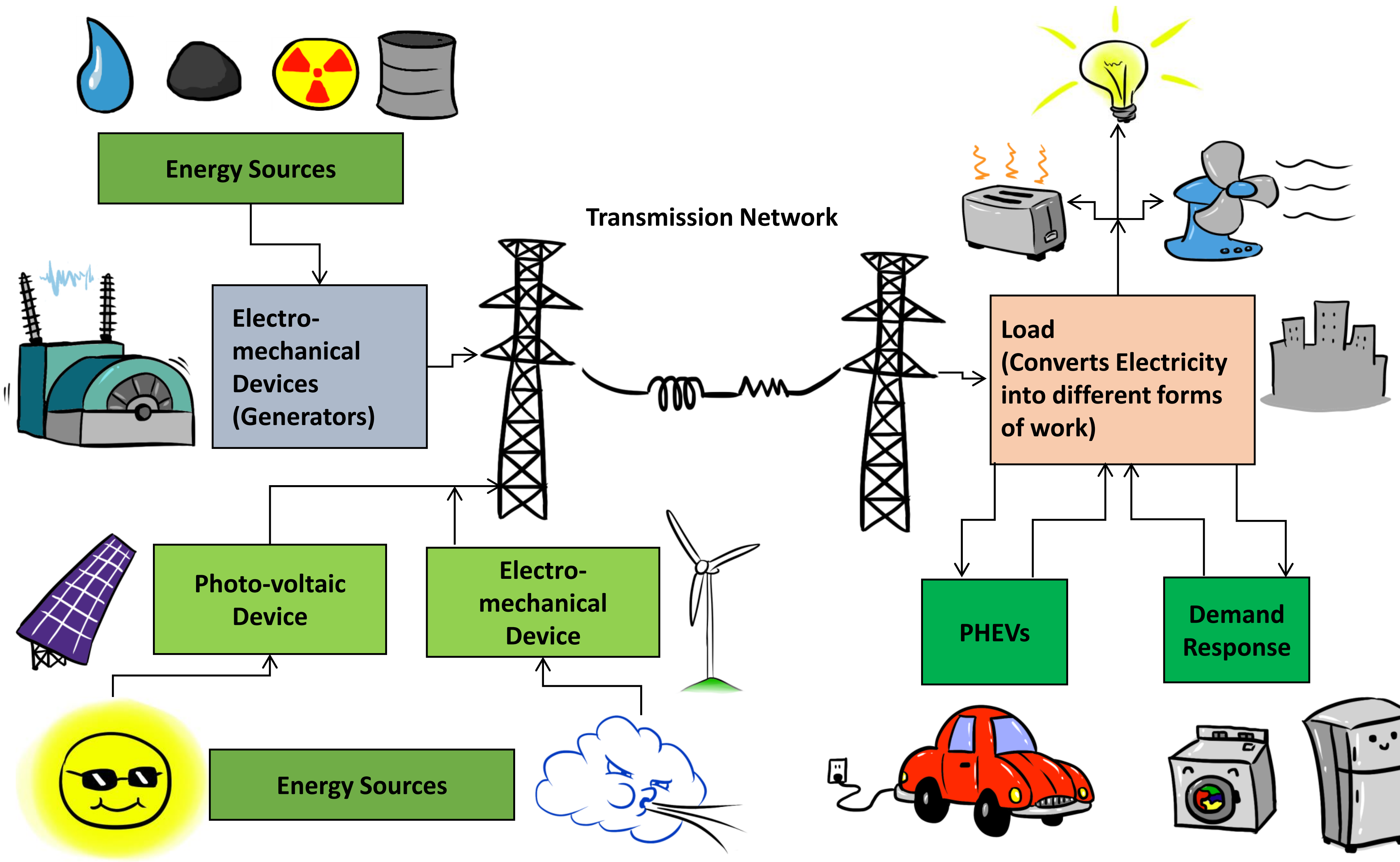
Outline:

- Technological and social drivers in the clean energy
- Smart Grid (moving from central to distributed energy systems),
- Decision making-Algorithm to improve efficiency,
- Improve Quality of Service,
- Safety concerns for equipment and system level,
- A non-intrusive condition monitoring,

Conventional Energy Systems:



Future Electric Energy Systems:



Technological and social drives in energy systems:

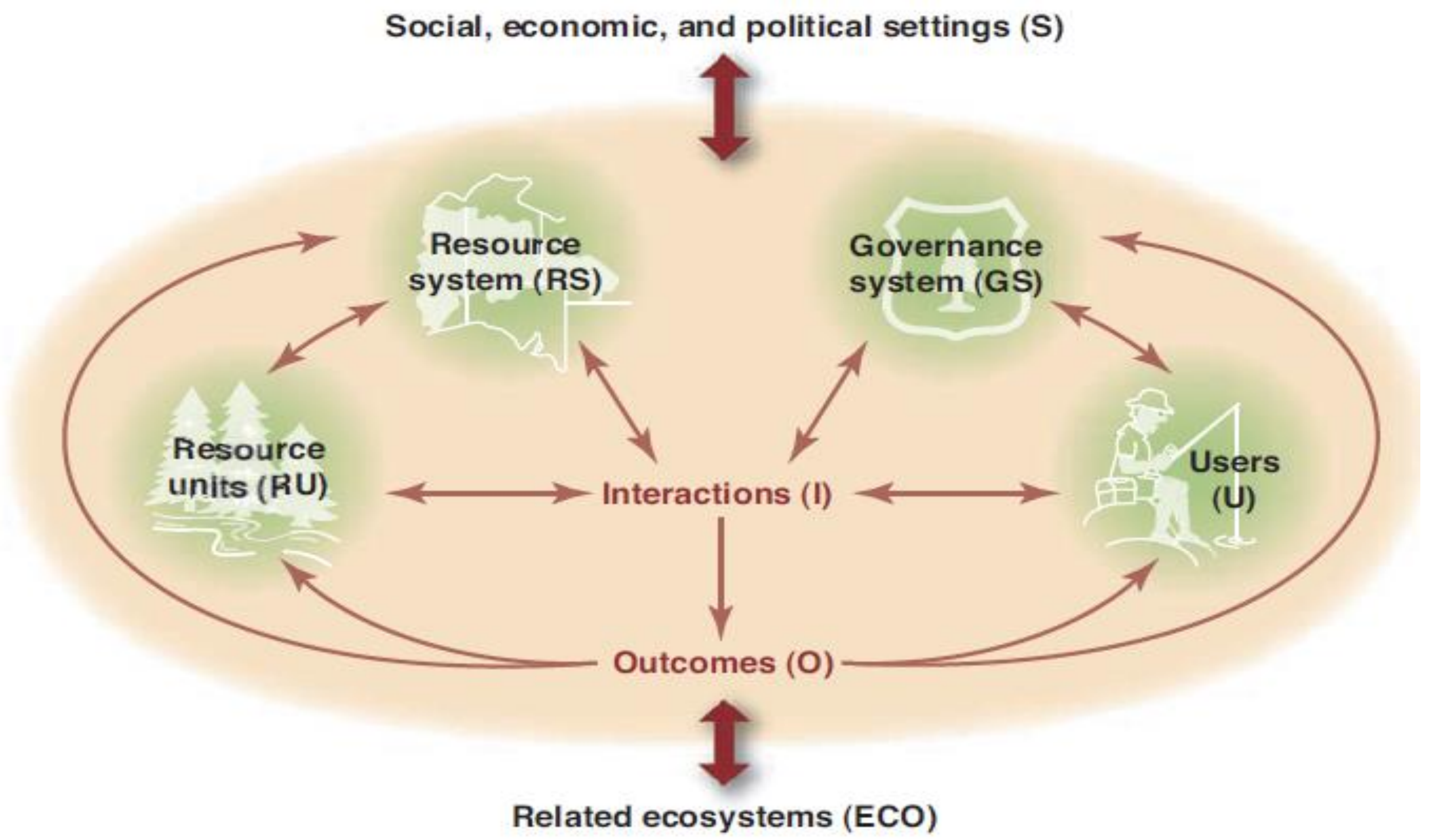
- Multiple objective (reliable, efficiency and environmental)
- Non-homogenous and non-utility-owned resources
- Renewable resources and demand response
- Technology drivers: Cost-effective ICT, GPS synchronized wide-area measurement systems (WAMS).
- Emergence of electricity market,
- Technologies for plug-&-play deployment

Clean Energy drives and concerns:

- Increasing presence of renewable energy resources which are **environmentally attractive** ☺ with **fast rate of response** ☺ but Intermittent ☹.

- 3 major questions for reliability and efficiency:
  1) **Better Prediction** of Intermittent Resources
  2) **More efficient utilization** of intermittent resources
  3) **More reliable operation** of intermittent resources

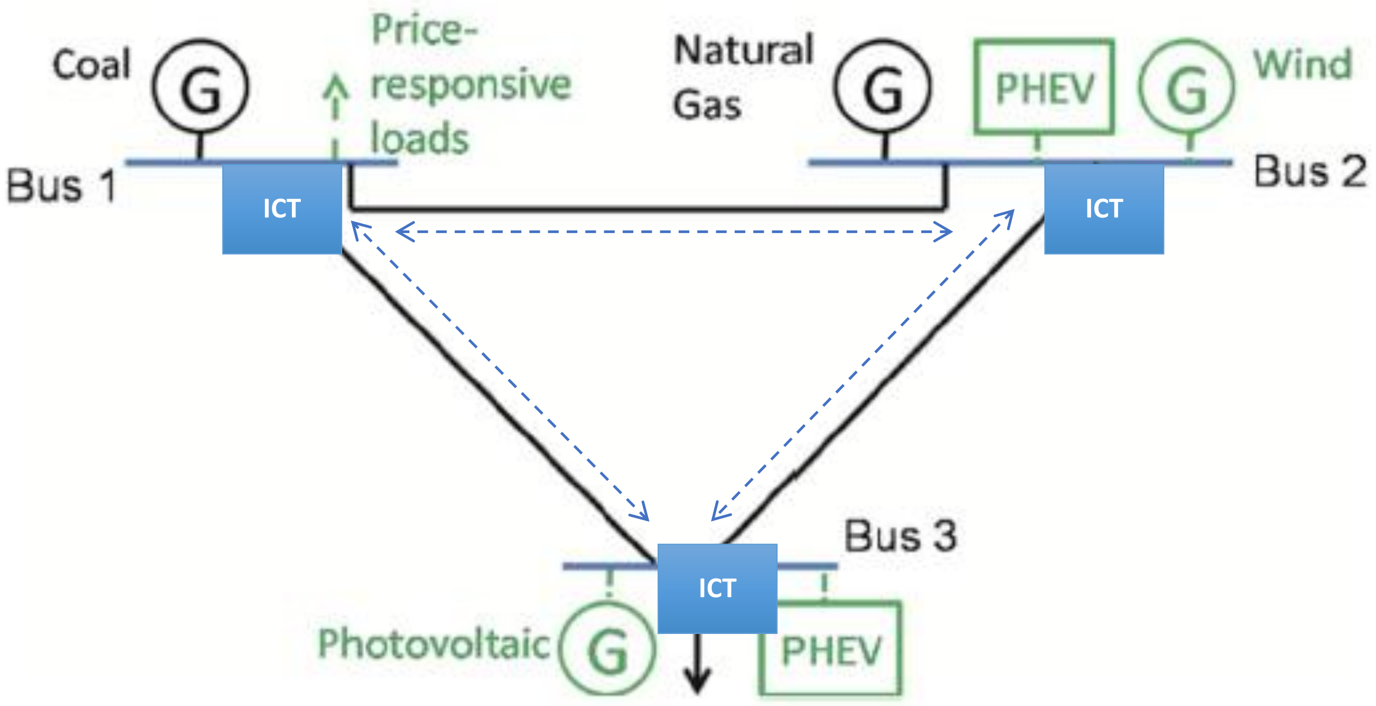
Moving from Central to Distributed Socio-Ecological Systems [1]:



The changing role of decision making:

Today's Power Grid (centralized objective subject to many constraints (externalities)	``Smart Grid" (multi-layered interactive coordination of objectives)
Deliver supply to meet given demand	Deliver power to support supply and demand schedules in which both supply and demand have costs assigned
Deliver power assuming a predefined tariff	Deliver electricity at QoS determined by the customers willingness to pay
Deliver power subject to predefined CO_2 constraint	Deliver power defined by users' willingness to pay for CO_2
Deliver supply and demand subject to transmission congestion	Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned); transmission at value
Use storage to balance fast varying supply and demand	Build storage according to customers willingness to pay for being connected to a stable grid
Build new transmission lines for forecast demand	Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service

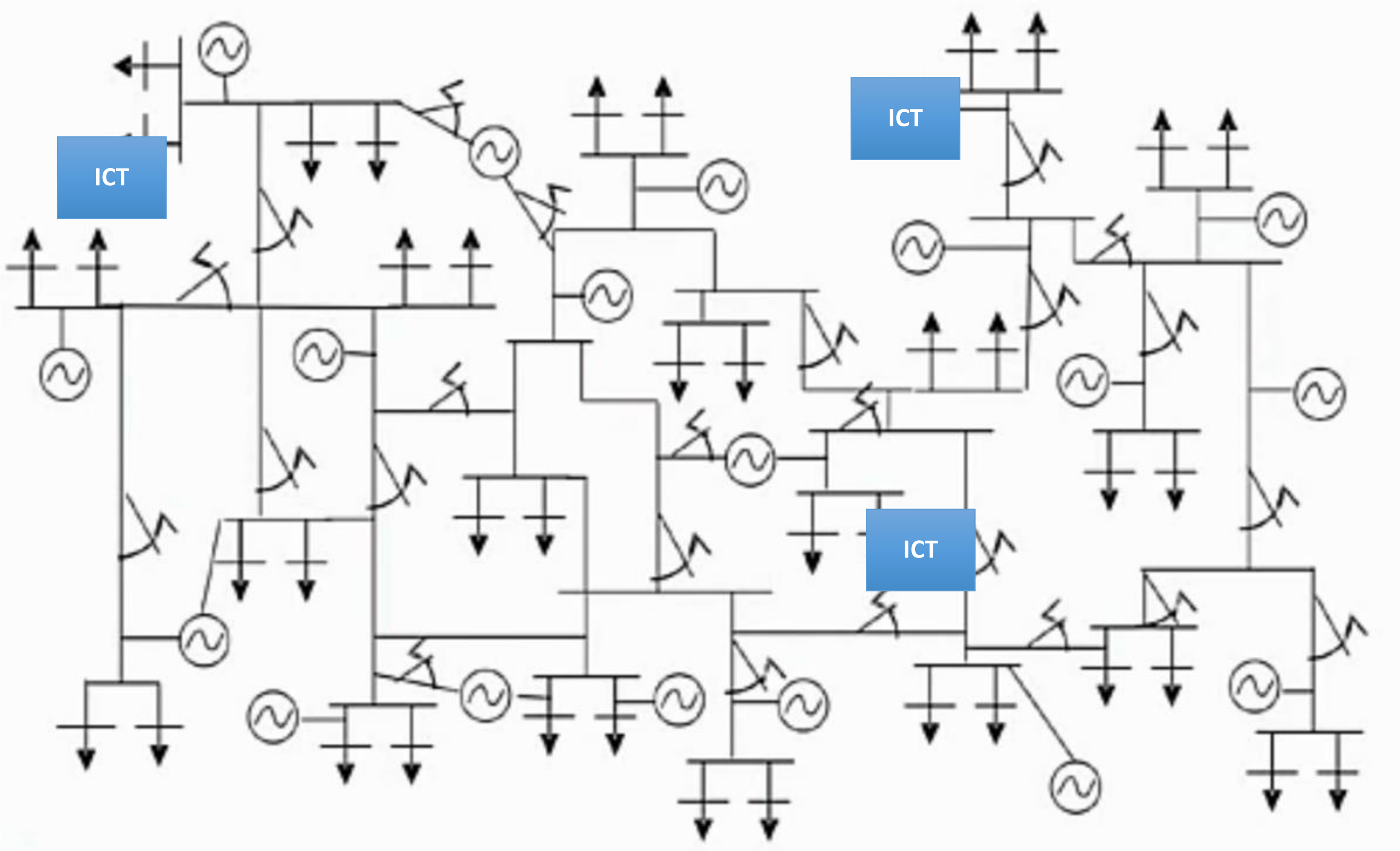
"Smart Grid" ←→ electric power grid



ICT (Sensors, Communications, Control & Decision)

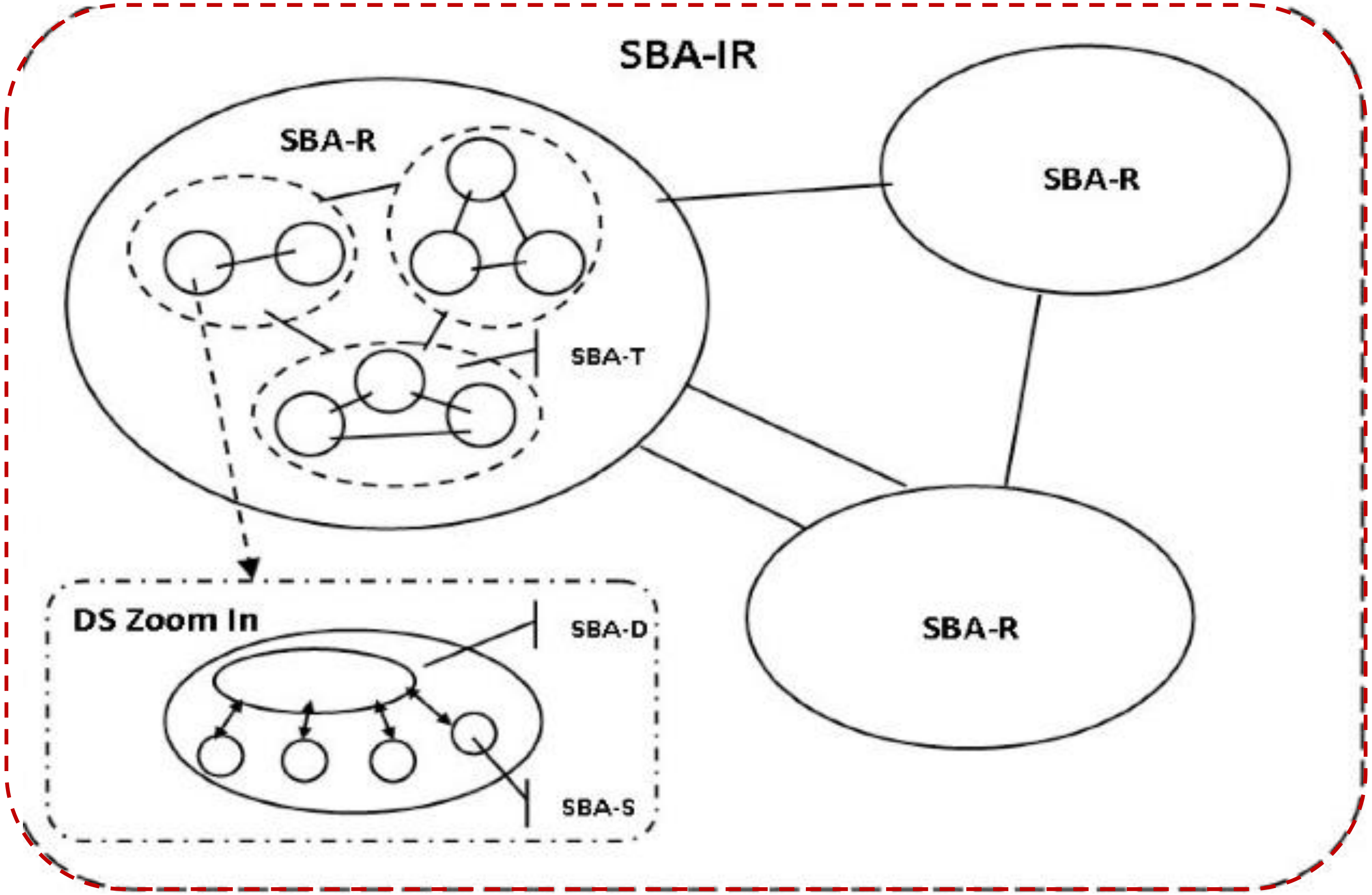
Measurement and Modelling:

What is the minimum number of measurement and a sufficient (accurate but not complex) model?



Interaction Variable:

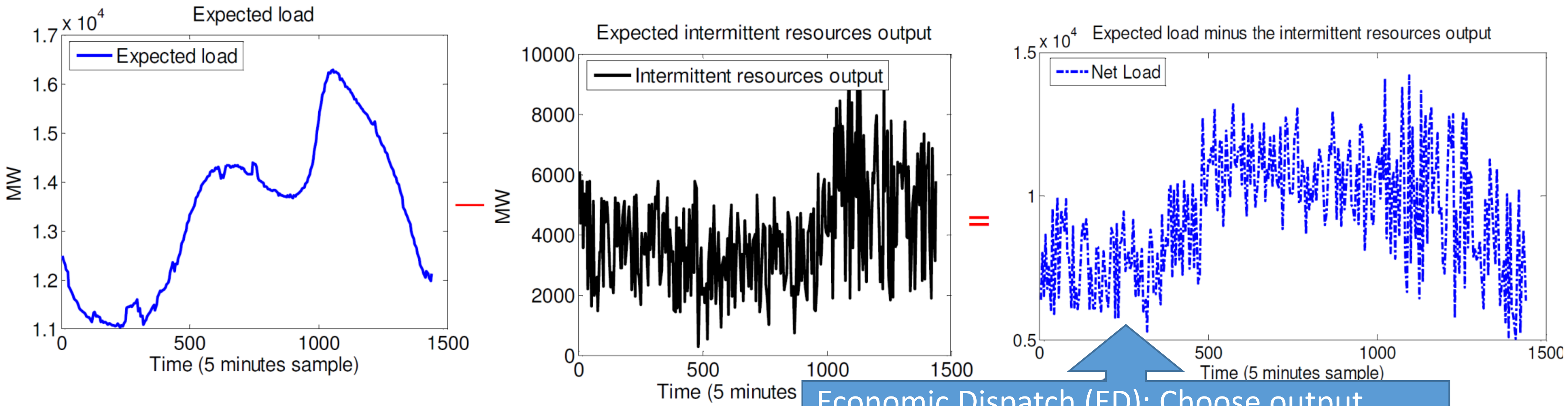
- ❑ A means of going from very coarse to granular model and back.
- ❑ framework for relating **engineering design**, **financial** & **environmental** objectives.



Decision-Making Algorithm: Efficient Utilization

Economic Dispatching (ED):

Given a mixture of energy resources, how to determine the output of individual energy resources so that:
(1) power supply always balances demand (2) total generation cost is minimized.

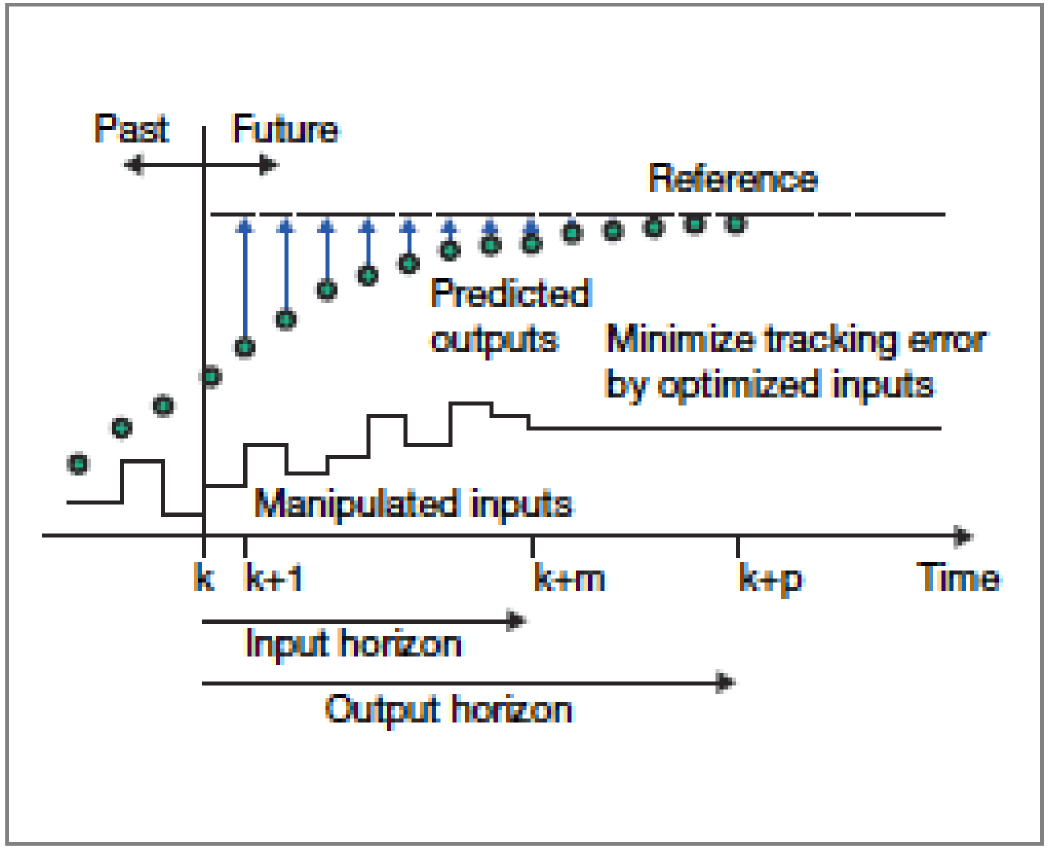


Economic Dispatch (ED): Choose output levels from conventional power plants to meet the "net load" at minimum cost [2].

Model Predictive Control (MPC)[2]:

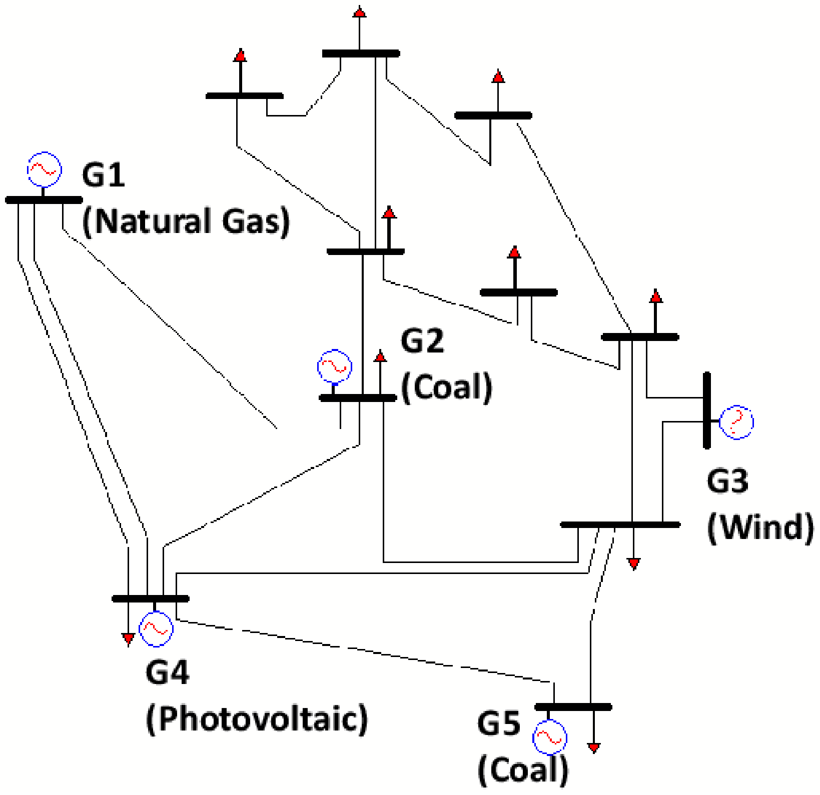
At each step, a finite-horizon optimal control problem is solved but only one step is implemented.

Markove Model to predict wind, ad demand).



Numerical Example (New):

Gen ID	Type	Capacity	Marginal Cost	Ramp Rate
1	Natural Gas	5000MW	1000$/MWh	100MW/5 min
2	Coal	9000MW	500$/MWh	1000MW/hour
3	Wind	3500MW	0$/MWh	150MW/5 min
4	Photovoltaic	1500MW	0$/MWh	100MW/5 min
5	Coal	8000MW	300$/MWh	800MW/hour



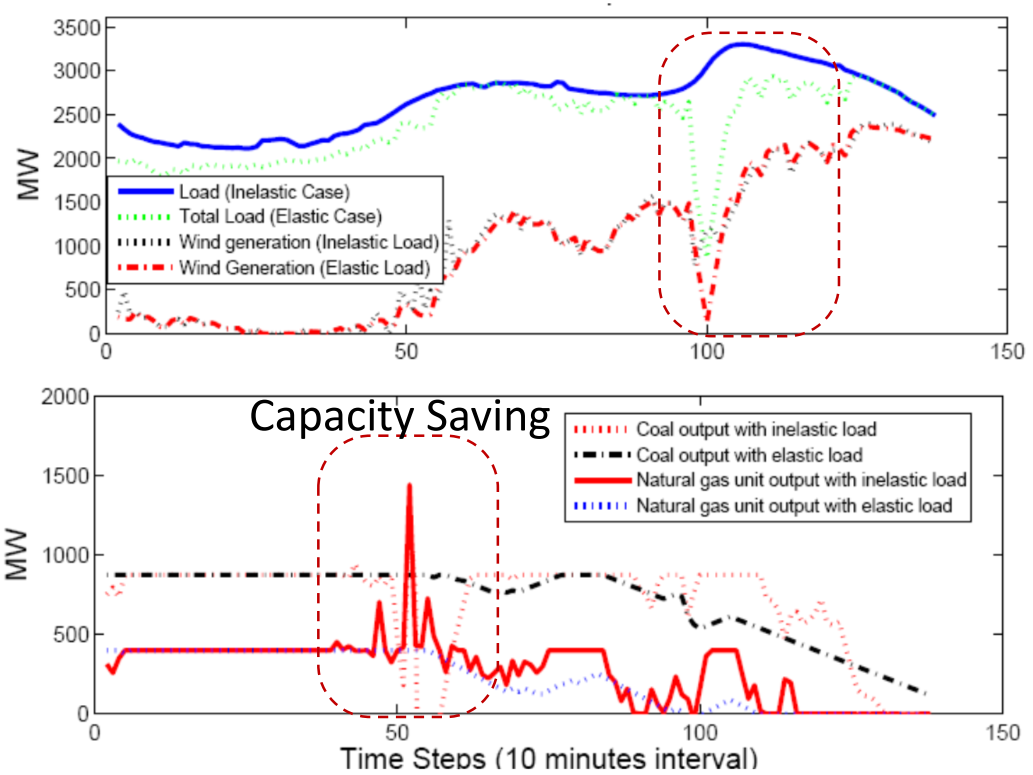
IEEE RT Model

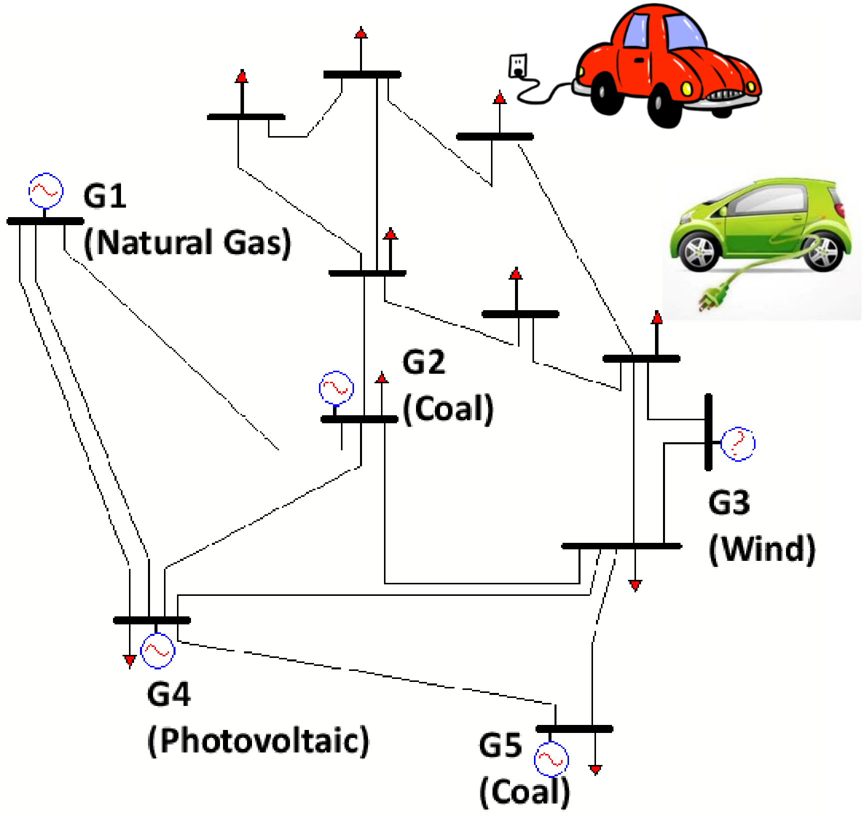
Conventional cost over 1 year *	Proposed cost over the year	Difference	Relative Saving
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%

load data from New York Independent System Operator, available online at http://www.nyiso.com/public/market_data/load_data.jsp

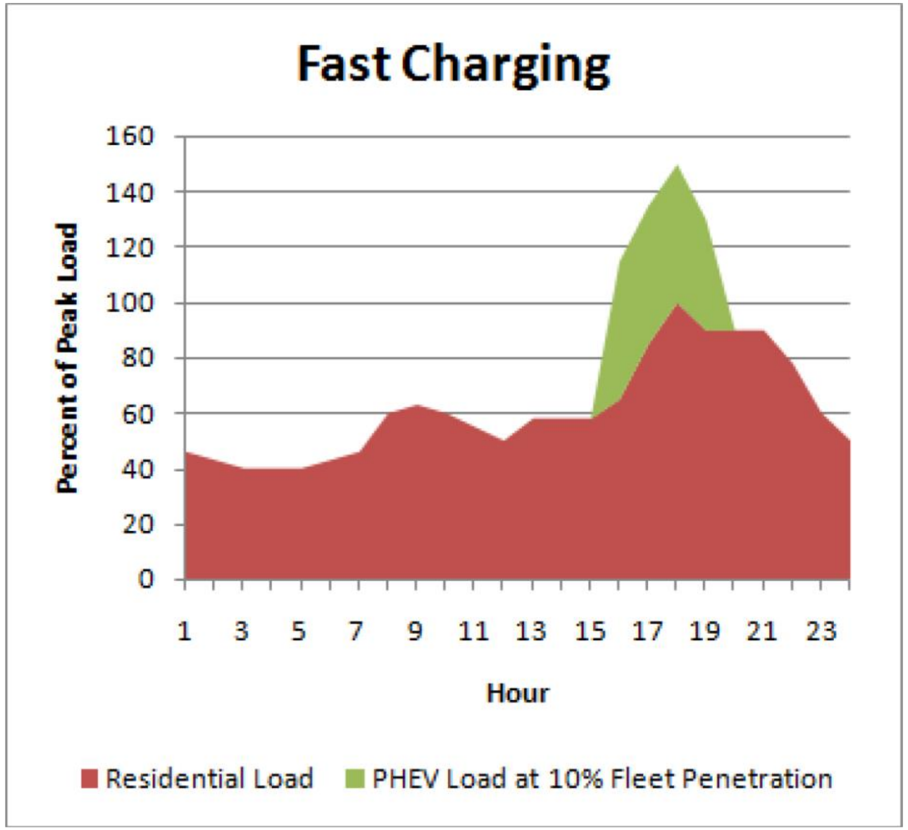
Numerical Example (New) [3,4]:

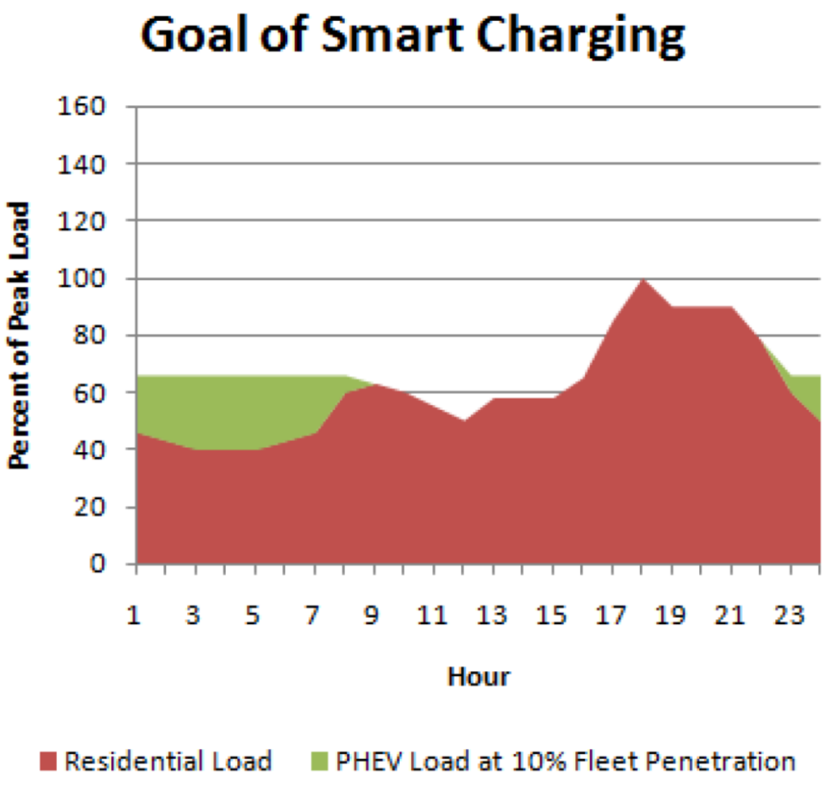
Elastic demand that respond to time-varying price.





Optimal Control of Plug-in –Electric Vehiles: Fast v.s. Smart Charging (Rotering, 2009)



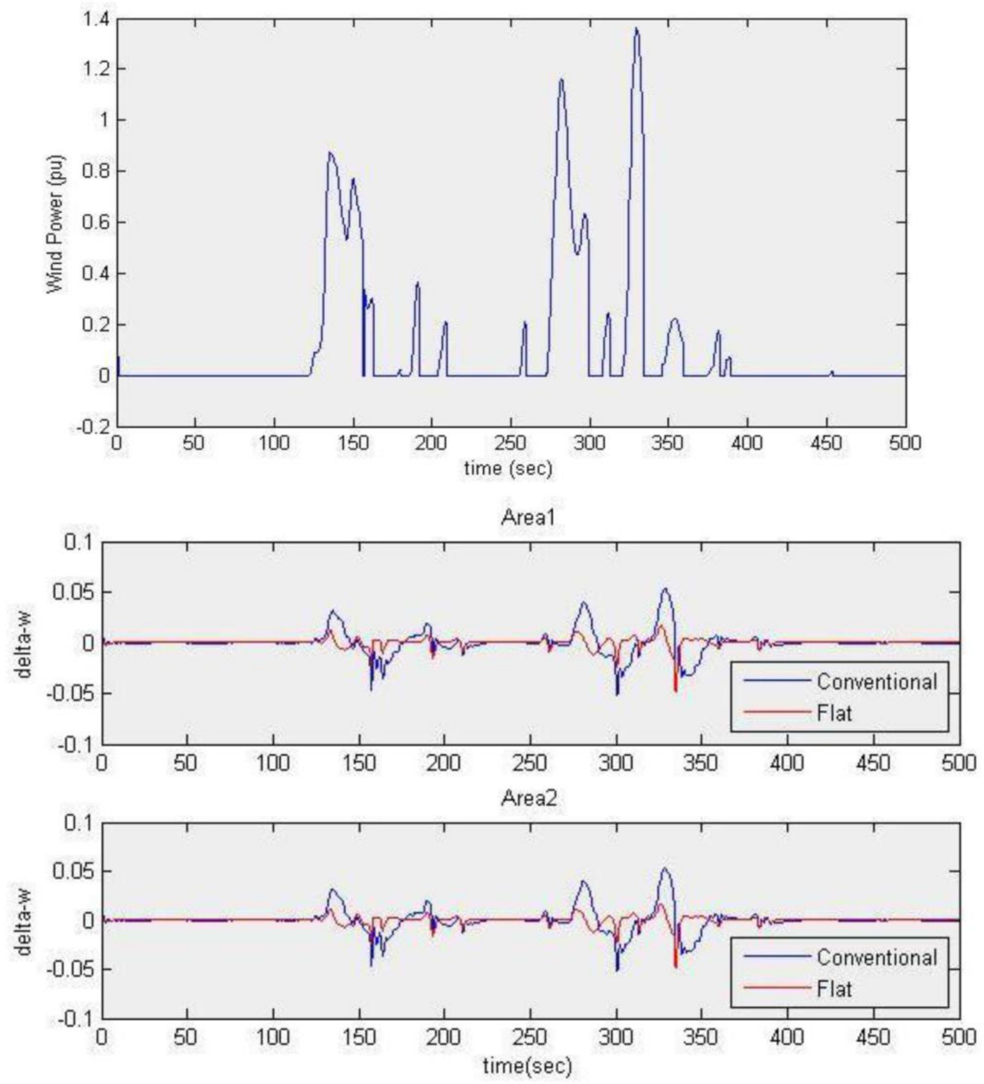


Decision-Making Algorithm:
Improve the Quality of Service (QoS)

Example: Flatness Systems for Automated Control Generation (AGC)

AGC is a system for adjusting the power output of multiple generators in response to changes in the load.

A system is **differential flat** if we can define the system *inputs* and *states* based on a so-called *“flat” output* and a finite number of its *differentiations*.
(A tool to transform a nonlinear system to linear control problem).



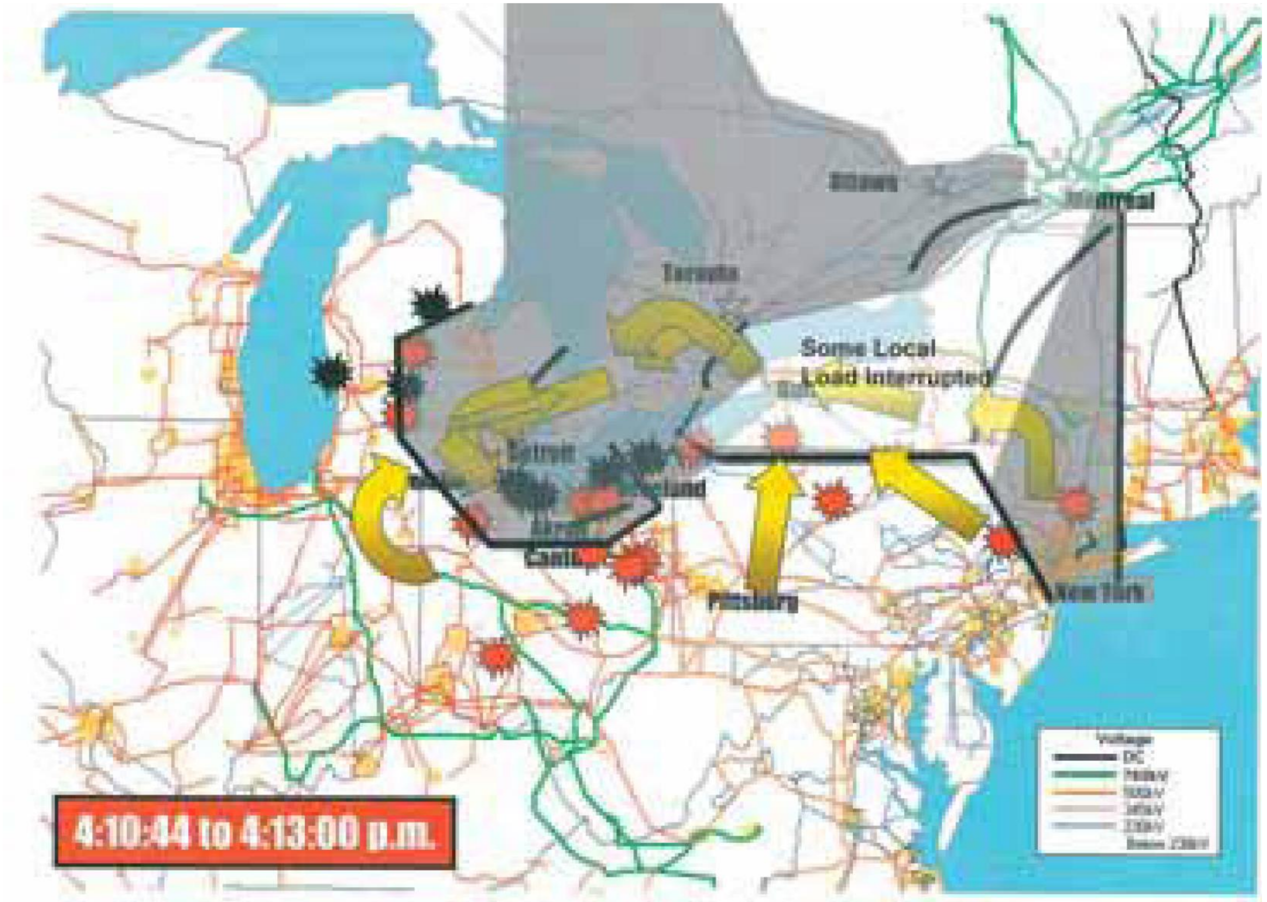
Frequency Deviations (pu)

Reliable Operation (Safety & Protection)

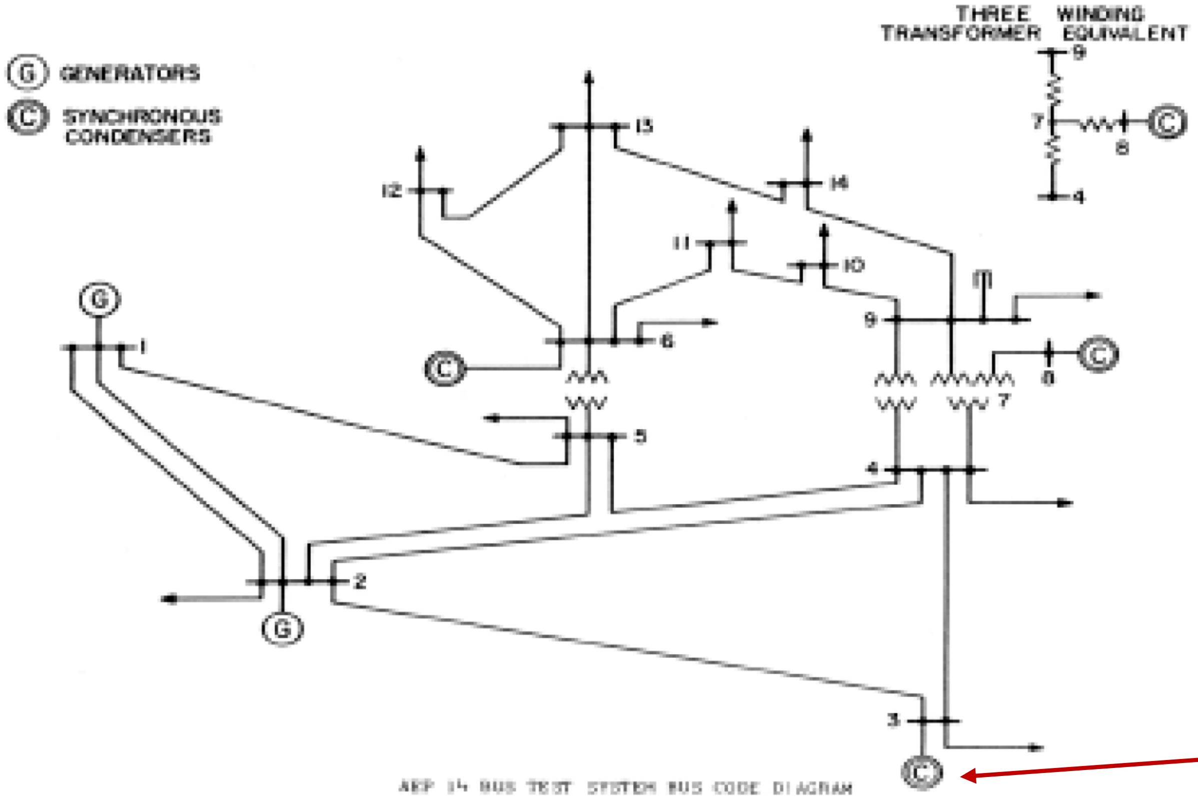
Harmonic Resonance & Su-Synchronous Harmonics

Peculiar safety challenges at the system level:

- **Harmonic resonance problem** (transformer destroyed by the resonance of specific harmonic);
- **Sub-synchronous resonance (SSR)** between turbine shafts and series capacitor banks (long transmission lines).

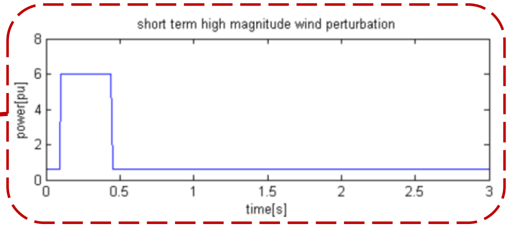


Safety Problem Caused by Harmonic Resonance [5,6]



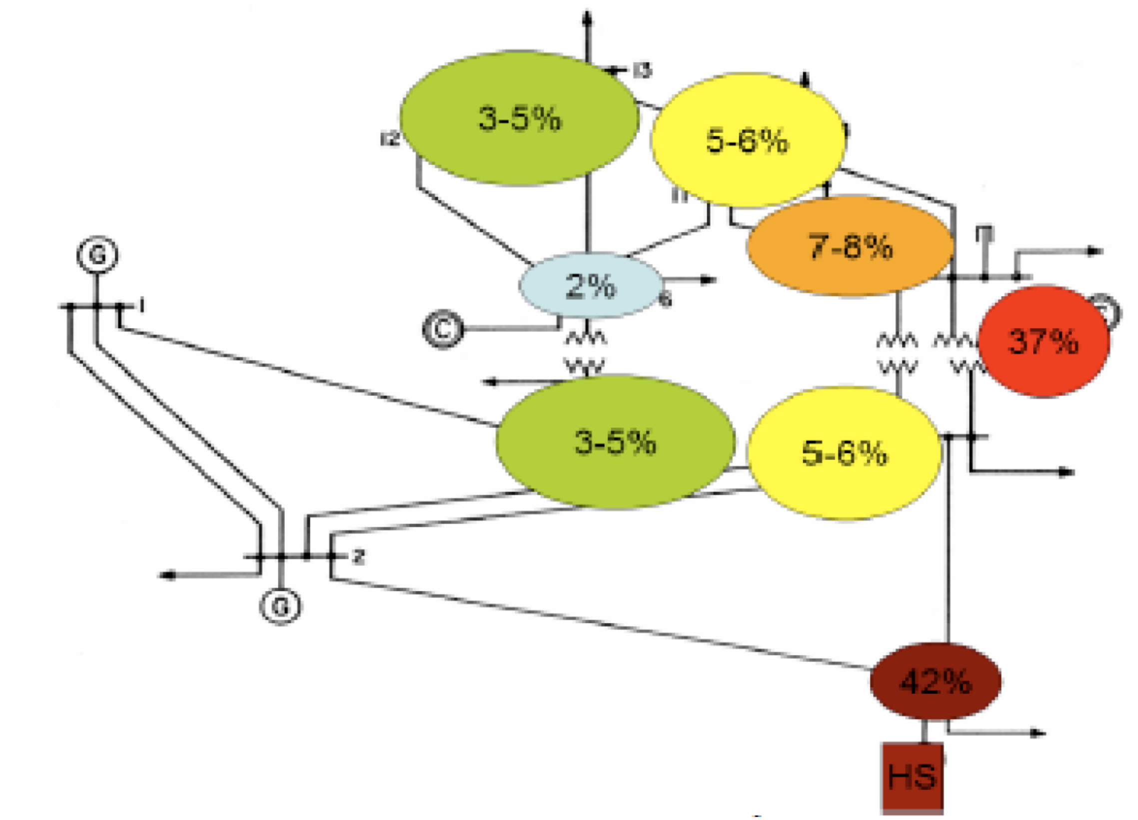
IEEE 14-Bus System

Wind Gust



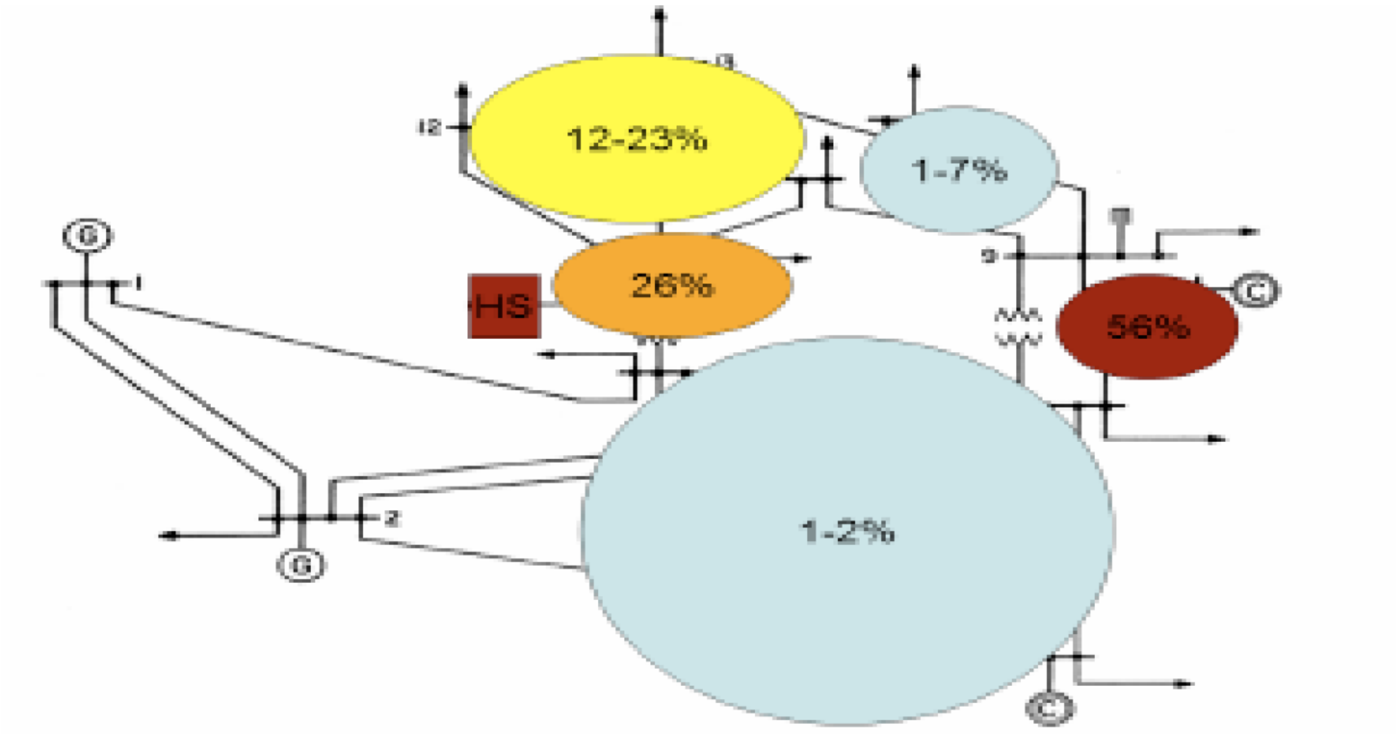
System-dependent;
disturbance-dependent

Nonlinear Load connected to Bus 3



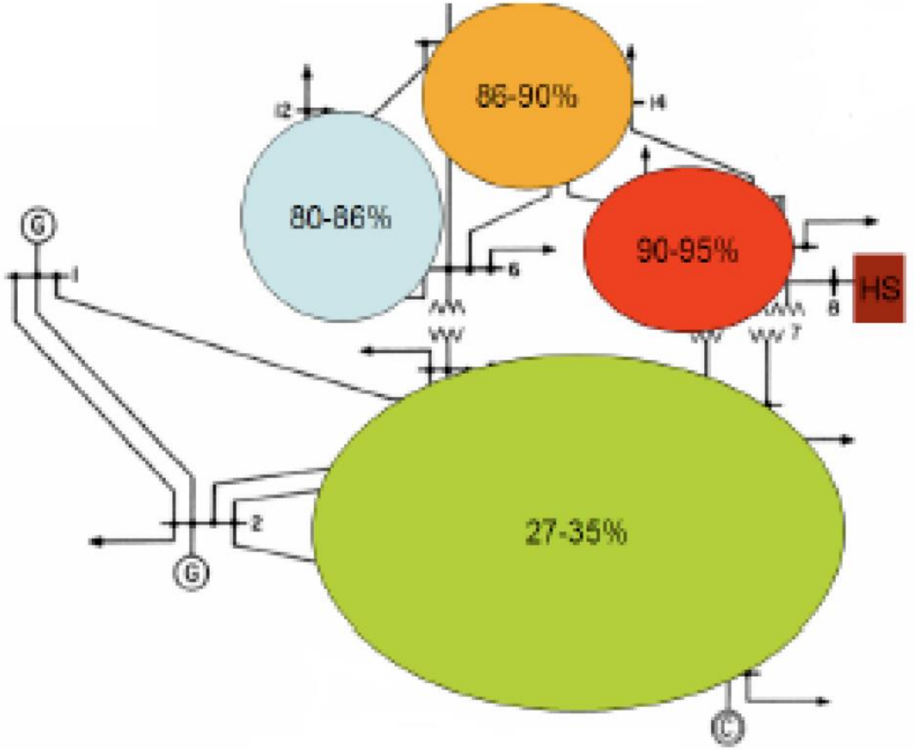
Harmonic Propagation for the 5th harmonics.
The Percentage of Harmonic Voltage to Normal Voltage at each Bus

Harmonic Source at Bus 6



Harmonic Propagation for the 5th harmonics.
The Percentage of Harmonic Voltage to Normal Voltage at each Bus

Harmonic Source at Bus 8



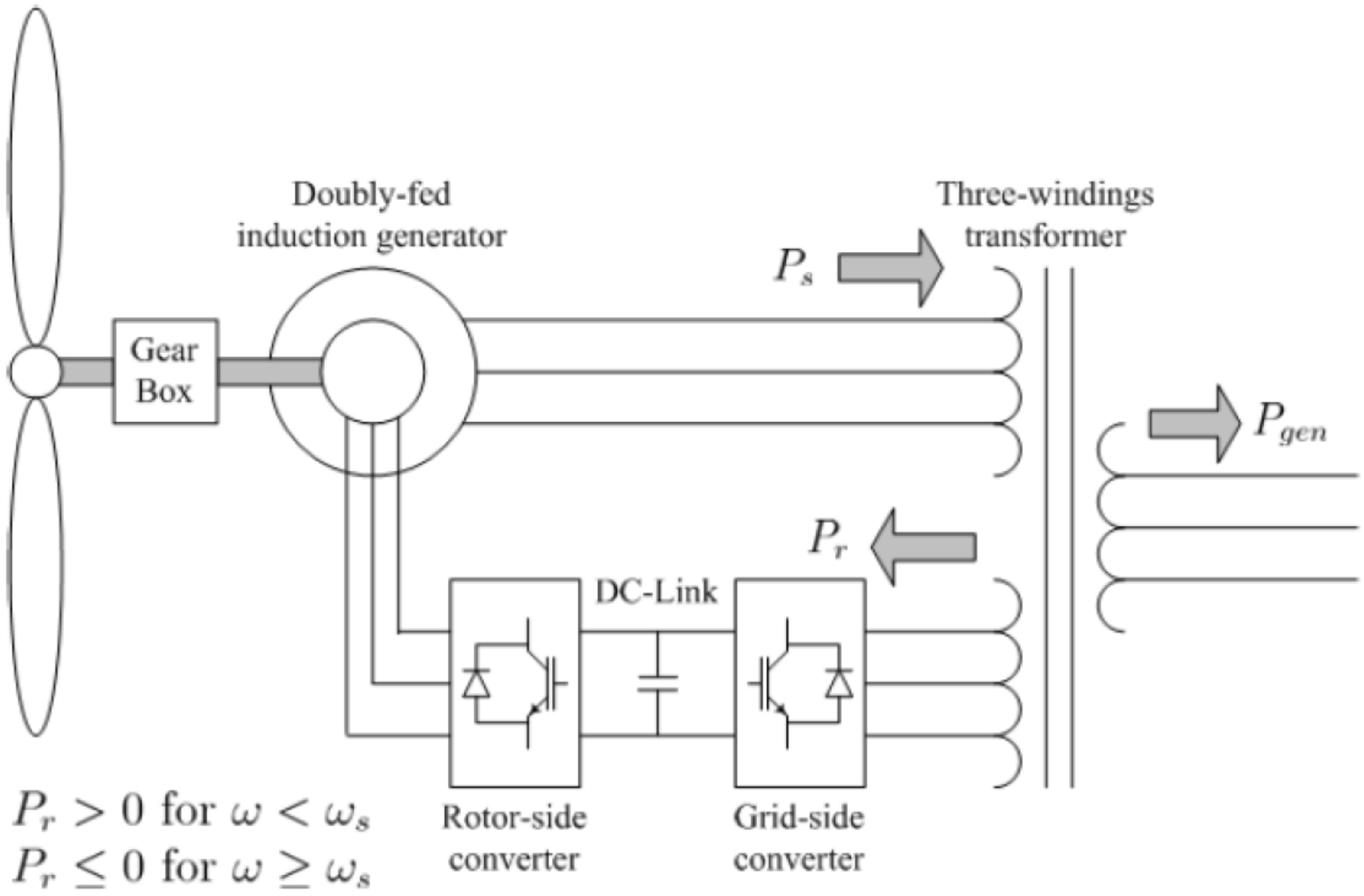
Harmonic Propagation for the 5th harmonics.
The Percentage of Harmonic Voltage to Normal Voltage at each Bus

Reliable Operation (Safety & Protection)

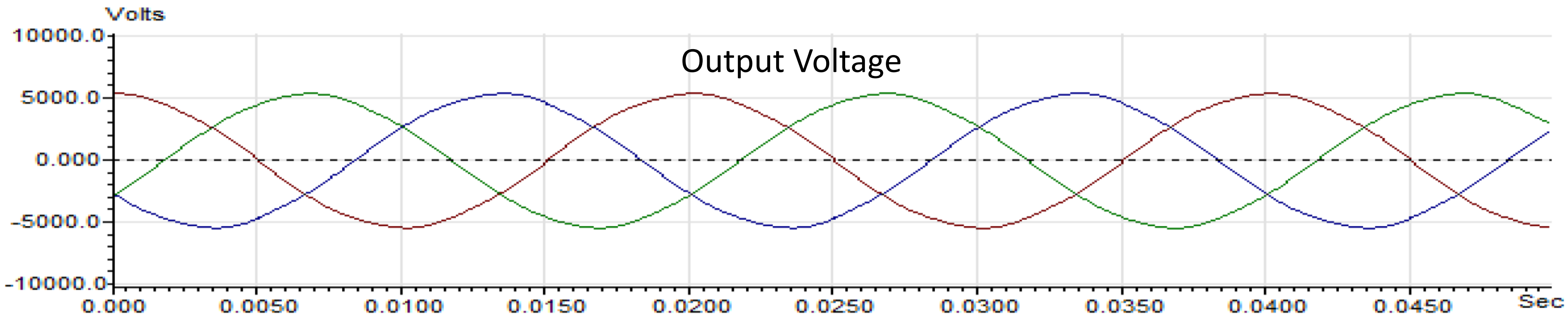
Fast Dynamics Matter!

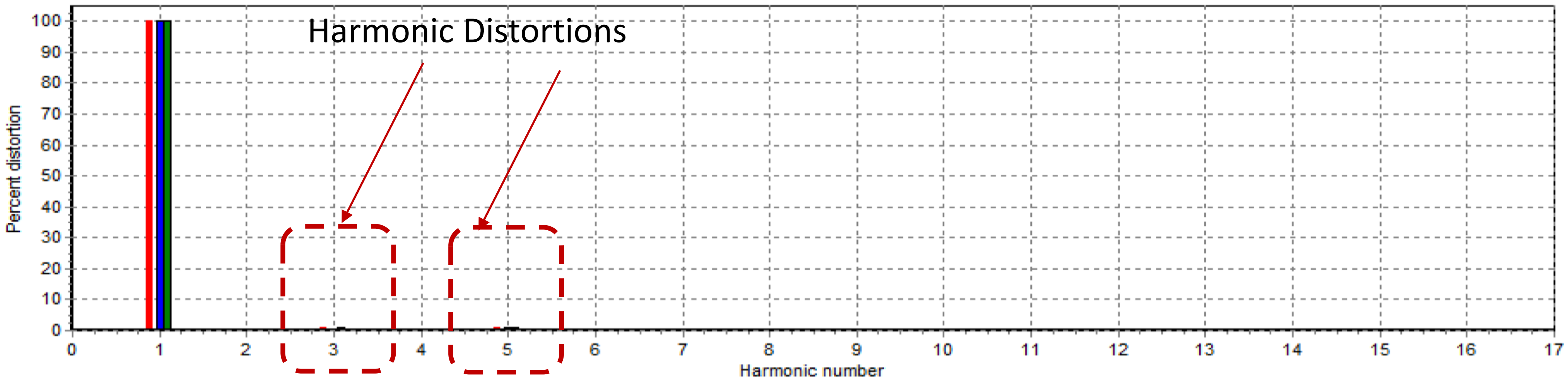
For more details contact info@cognitivesystems.ca

A Data-Driven Solution for Fast Dynamics:

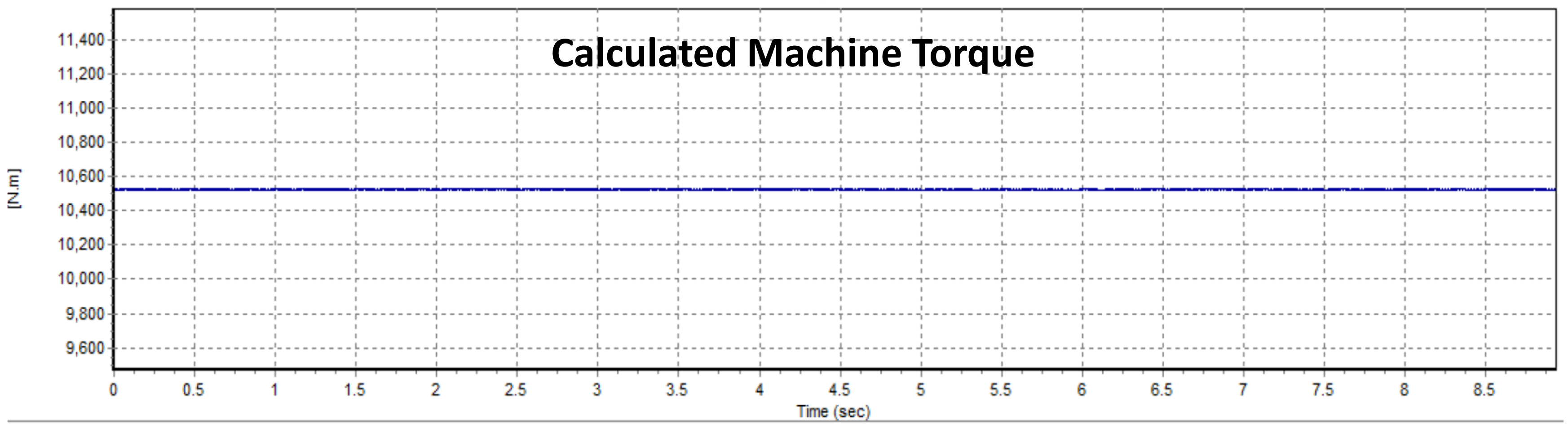


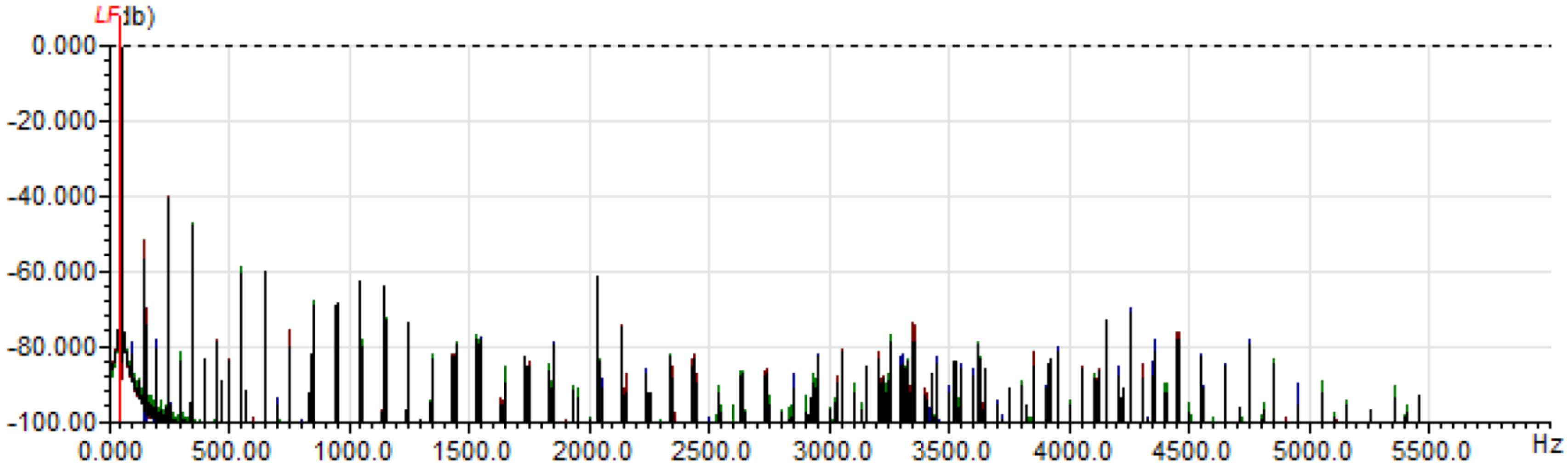
Non-Intrusive Harmonic Monitoring:



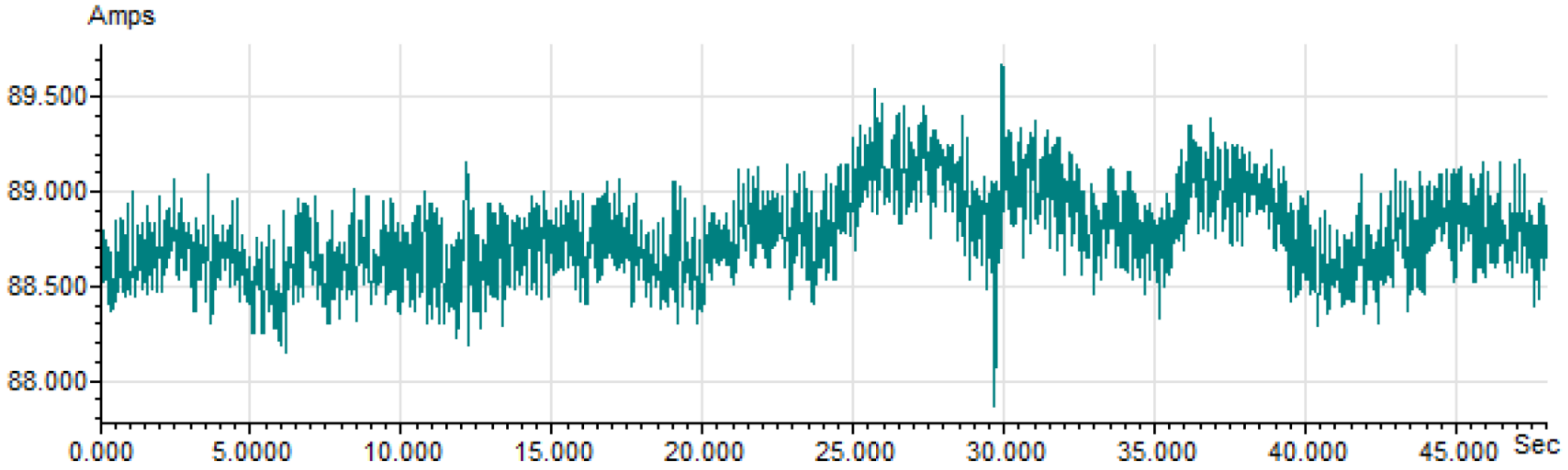


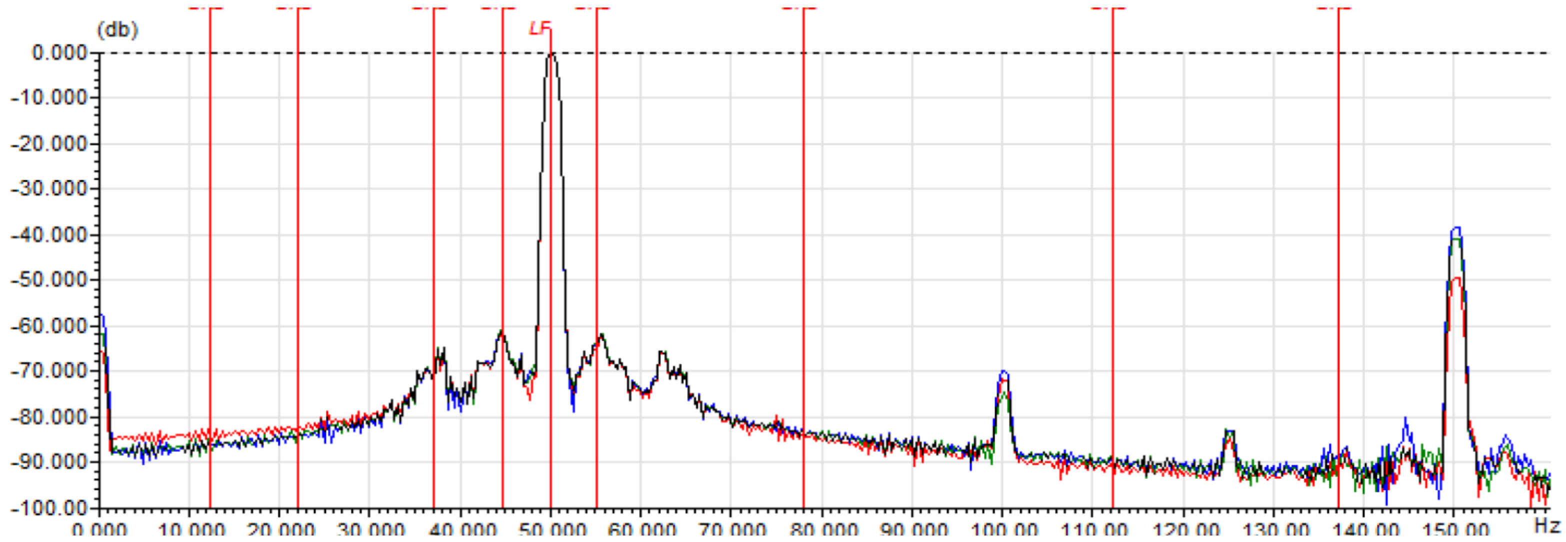
Non-Intrusive Health (Condition) Monitoring:





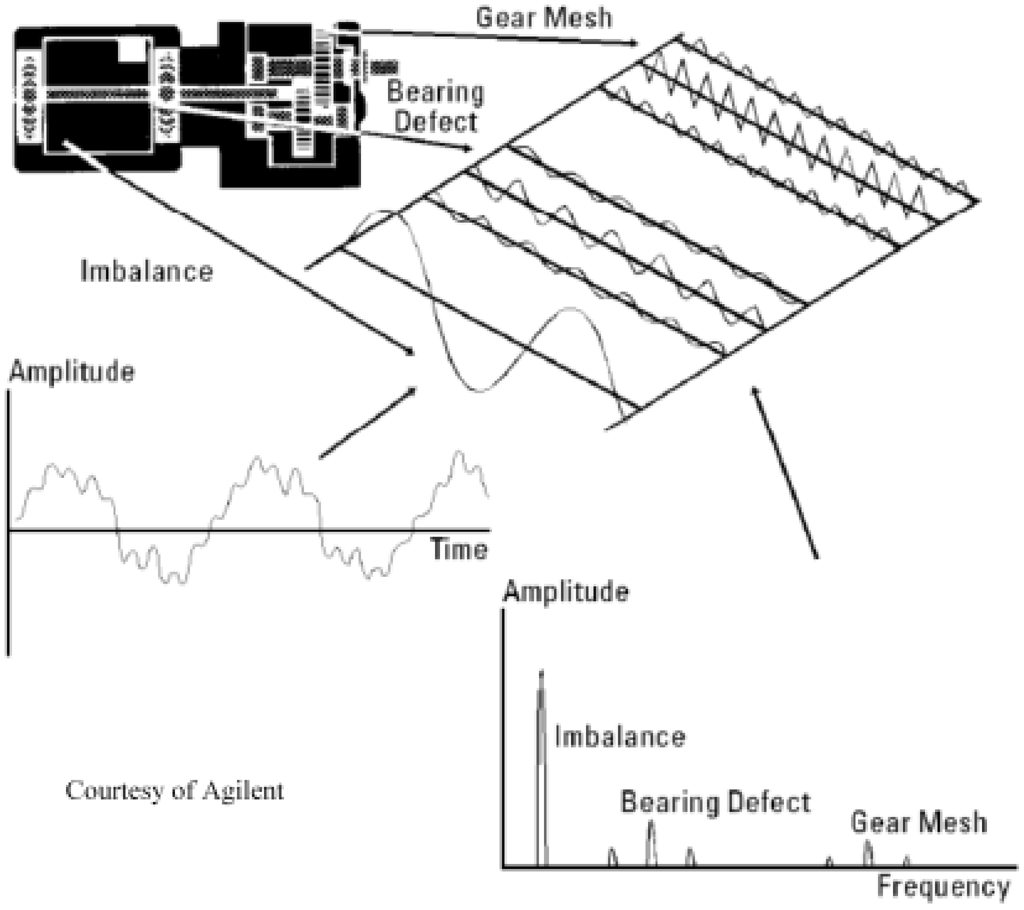
Non-Intrusive Health (Condition) Monitoring:





Non-Intrusive Health (Condition) Monitoring:

- Bearing faults;
- Blade problems;
- Low efficiency, heat effect;
- Gearbox/transmission problems;
- Unbalance/misalignment shaft;
- Rotor/stator faults like cracked rotor;
- Electrical (Distortions, Current imbalance);
- Loose windings, foundation, connections/contactors;
- Various Vibrations (e.g. cavitation, Stick-Slip, loos foundation, etc.).



Conclusion:

- Moving from a central system to a distributed systems,
- Challenges and Opportunities for Mathematicians (decision making),
- Peculiar case of sub-harmonics and the fast dynamics,
- Non-Intrusive Condition monition and data-driven modelling (as a part of servoc offered by Cognitive Systems to improve machinery reliability).

Thank You!

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Reference:

[1] Elinor Astrom, A General Framework for Analyzing Sustainability of Social-Ecological Systems, *Science* 24 Jul 2009.

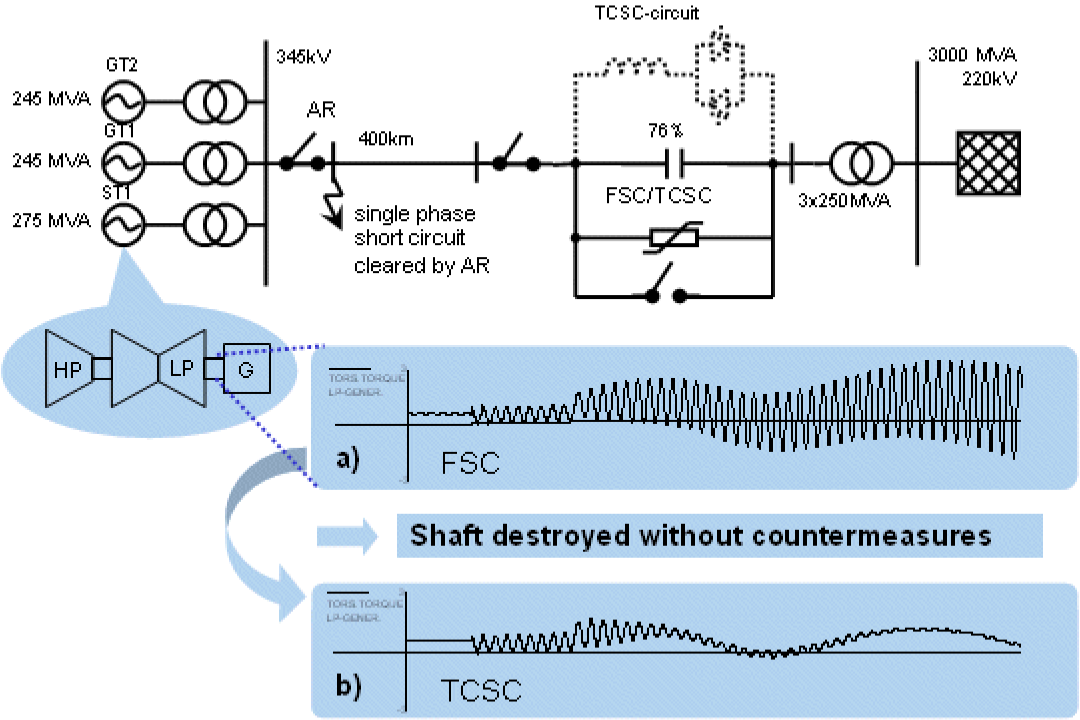
[2] L. Xe, M. Illic, Model Predictive Dispatch in Electric Energy Systems with Intermittent Resources, 2009.

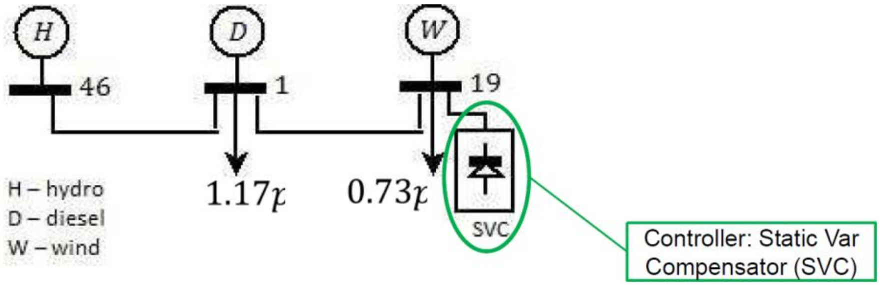
[3] N. Abdel-Karim and M. Ilic,"Short Term Wind Speed Prediction by Finite and Infinite Impulse Response Filters: A State
Space Model Representation Using Discrete Markov Process", IEEE PowerTech Conference, Romania June 2009
[4] J. Joo and M.D. Ilic, "A Multi-Layered Adaptive Load Management (ALM) system: information exchange between
market participants for efficient and reliable energy use," IEEE PES Transmission and Distribution Conference.

[5] E. Allen, et al., Effects of torsional dynamics on nonlinear generator control, IEEE Transactions on Control Systems Technology.

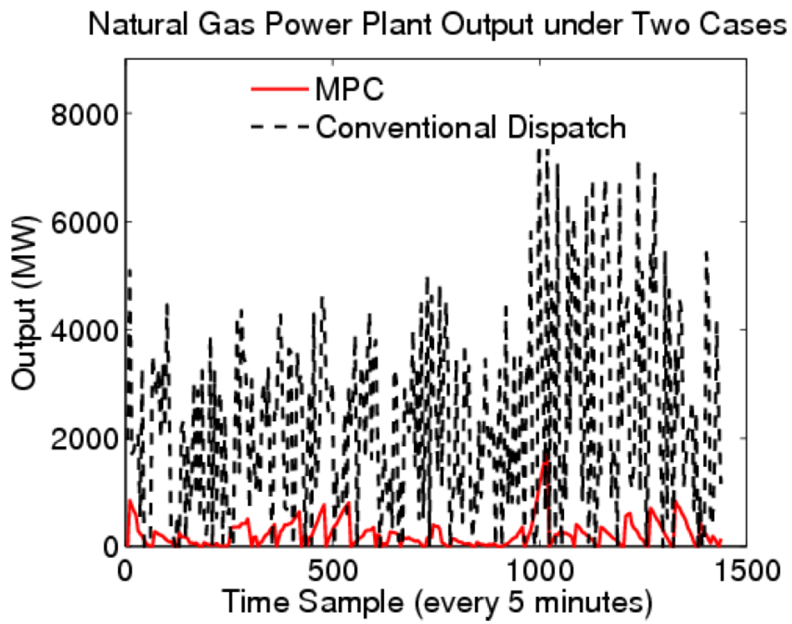
[6] D. Jeltsema, J.M.A. Scherpen, Multidomainmodeling of nonlinear network and systems, Control Systems Magazine, 2009.

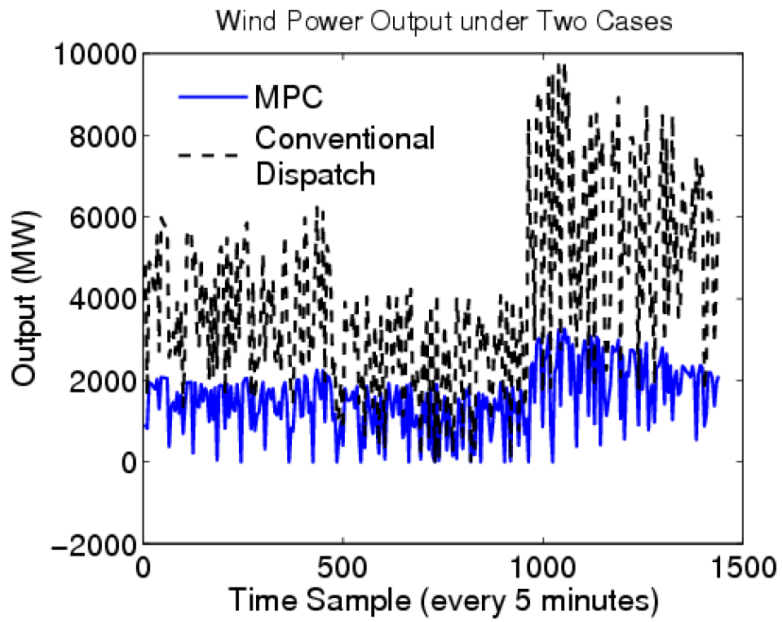
Harmonic Dampening:





Model Predictive Control:





New Technical Problems:

- The energy system, including its communication and control, does not readily enable choice and mulit-participant information exchange and processing for aligning [often] conflicting goals.
- It is essential to design intelligence for T&D operations to align these goals an concequently to make the most out of availbe resources while simultaneously offering robust and afforbale quality of service.
- New flexible energy processing equipment will also be needed to handle increasing variety and bandwith of many participants requests.