Coast to Coast Seminar (from Sydney), IRMACS Centre, Simon Fraser University, Canada, 3rd April 2012

Planning and control of massive networks

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NICTA

Outline

Motivation

Two applications
- Smart grids
- Traffic networks

Two techniques
- Feedback networks
- Dynamic learning

Many challenges

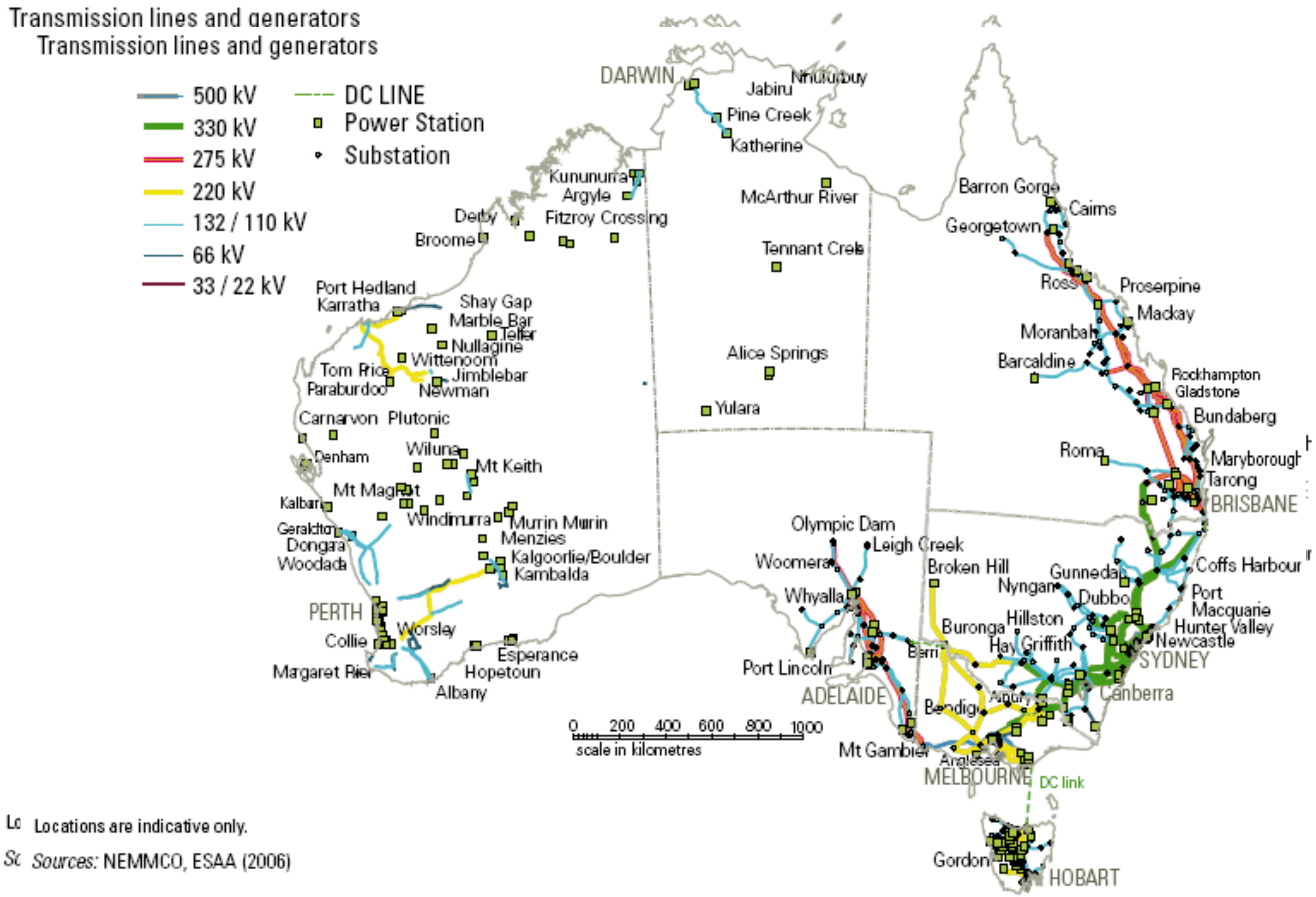
Conclusions

Traffic Flow

Problems in Sydney

- Long delays
- Congestions
- Tunnel decisions

Australian Transmission Network



Locations are indicative only.

Sources: NEMMCO, ESAA (2006)

Network of Life

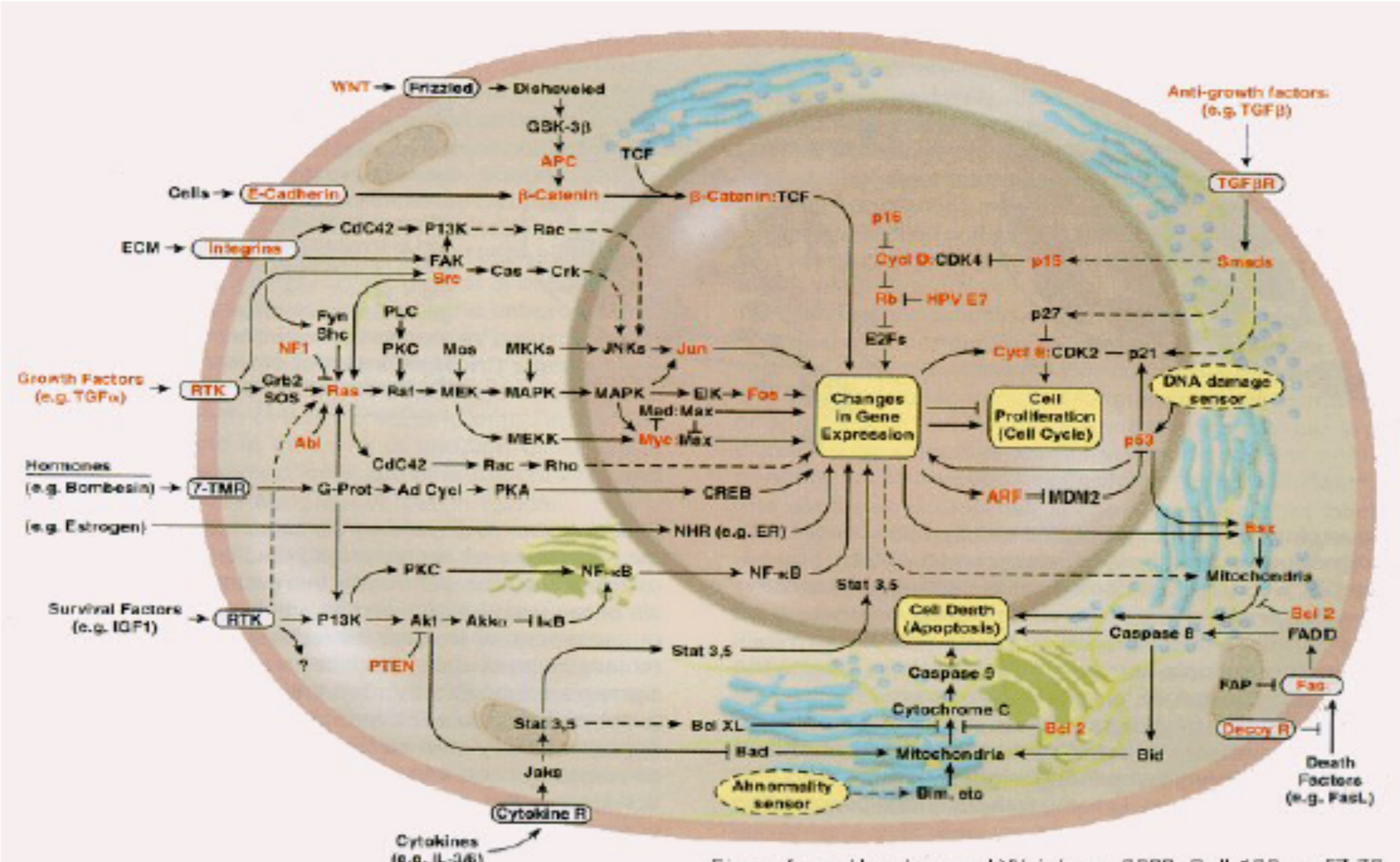


Figure from: Hanahan and Weinberg, 2000. Cell 100, p. 57-70

Challenges of Complexity

- Massive amounts of data
- Checking properties on such a scale – certificates?
- Optimizing on such a scale
- Planning vs self-organisation
- Local vs global control
- Security (cyber-physical)

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Future grids

Ref: European Technology Platform

Changes

› The existing grids typically do not have the right structure and capacities

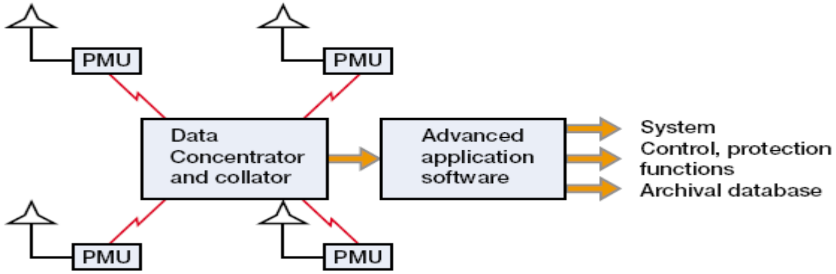
› Generation is much more volatile, i.e. now on both sides of the generation = load equation

› New loads, e.g. plug-in (hybrid) electric vehicles (PHEV)

➢ MUCH MORE UNCERTAINTY FOR THE GRID

➢ Need end-to-end control – ‘smart grids’

More new stuff



2 PMU utilization in a power system

Lots of new sensors and communication enabling of switchgear etc

Smart grids – what will they do?

› USA DOE NETL has identified the following features:

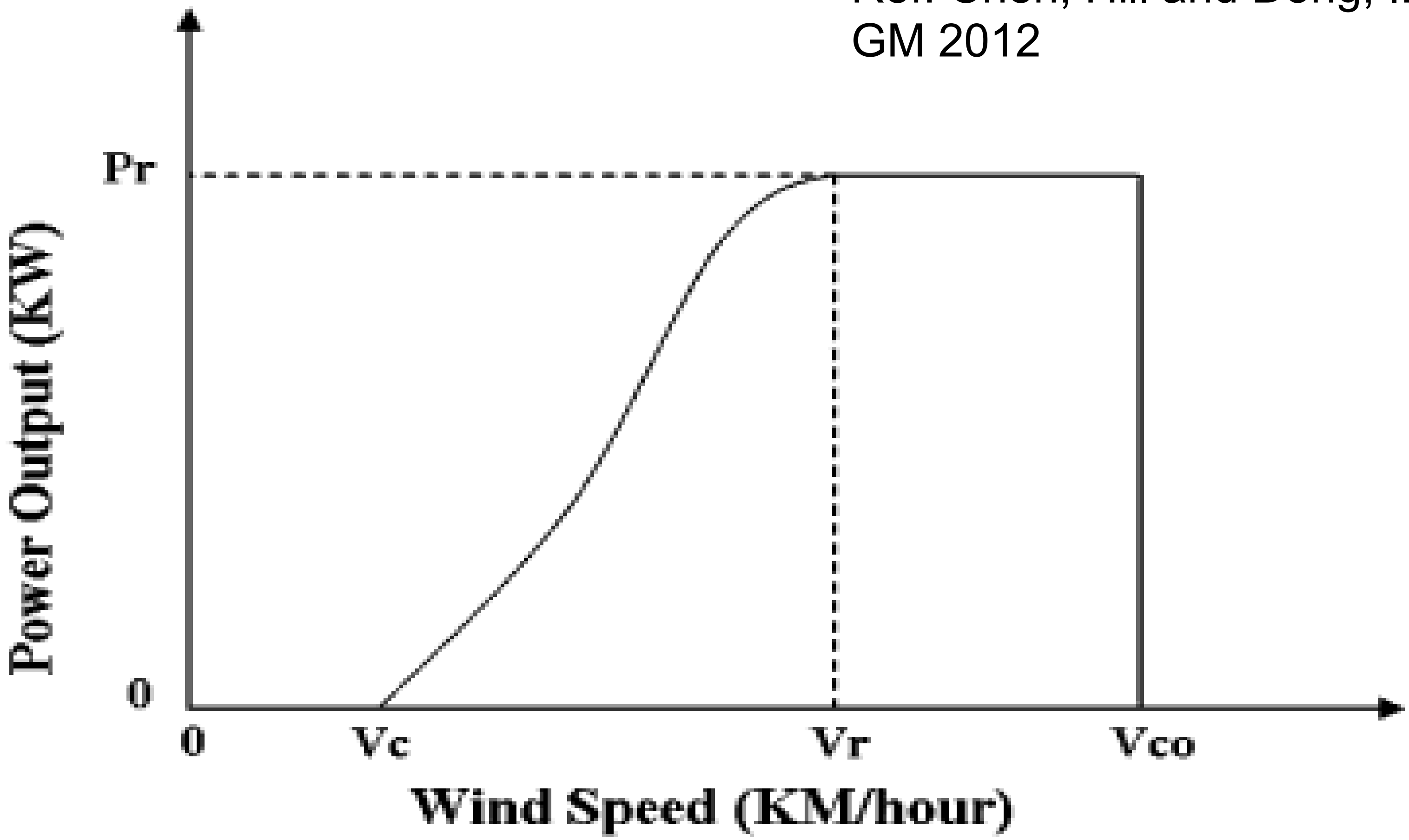
- Self-healing from power disturbance events
- Enabling active participation by consumers in demand response
- Operating resiliently against physical and cyber attack
- Providing power quality for 21st century needs
- Accommodating all generation and storage options
- Enabling new products, services and markets
- Optimizing assets and operating efficiently

Power grid basics

- PLAN – network, operations
- BALANCE – power, energy
- STABILITY – limits, dynamics
- PERFORMANCE – efficiency, effectiveness
- RECOVERY – from emergencies

Transmission network expansion planning

Ref: Chen, Hill and Dong, IEEE GM 2012



Transmission network expansion planning

$$\min \quad \sum_{(i,j)\in\Omega} c_{ij} n_{ij} + \alpha \sum_k r_k$$

$$\text{s.t.} \quad S^{\mathrm{T}} f + g + r = d$$

$$f_{ij} - b_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) = 0$$

$$\left|f_{ij}\right| \le (n_{ij}^0 + n_{ij})\bar{f}_{ij}$$

$$0 \le g \le \bar{g}$$

$$0 \le r \le d$$

$$0 \le n_{ij} \le \bar{n}_{ij}$$

$$n_{ij} \text{ is integer}, f_{ij} \text{ and } \theta_j \text{ are unbounded}$$

$$(i,j) \in \Omega$$

where here c_{ij}, b_{ij}, n_{ij}, $n^0{}_{ij}$ and f_{ij} represent the cost of a circuit to be added, the susceptance of that circuit, the number of circuits added, the number of circuits in the base case, the power flow on line. r is the vector of artificial generations (or load curtailment). α is a penalty parameter associated with loss of load caused by lack of transmission capacity.

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So what is a definition as a process?

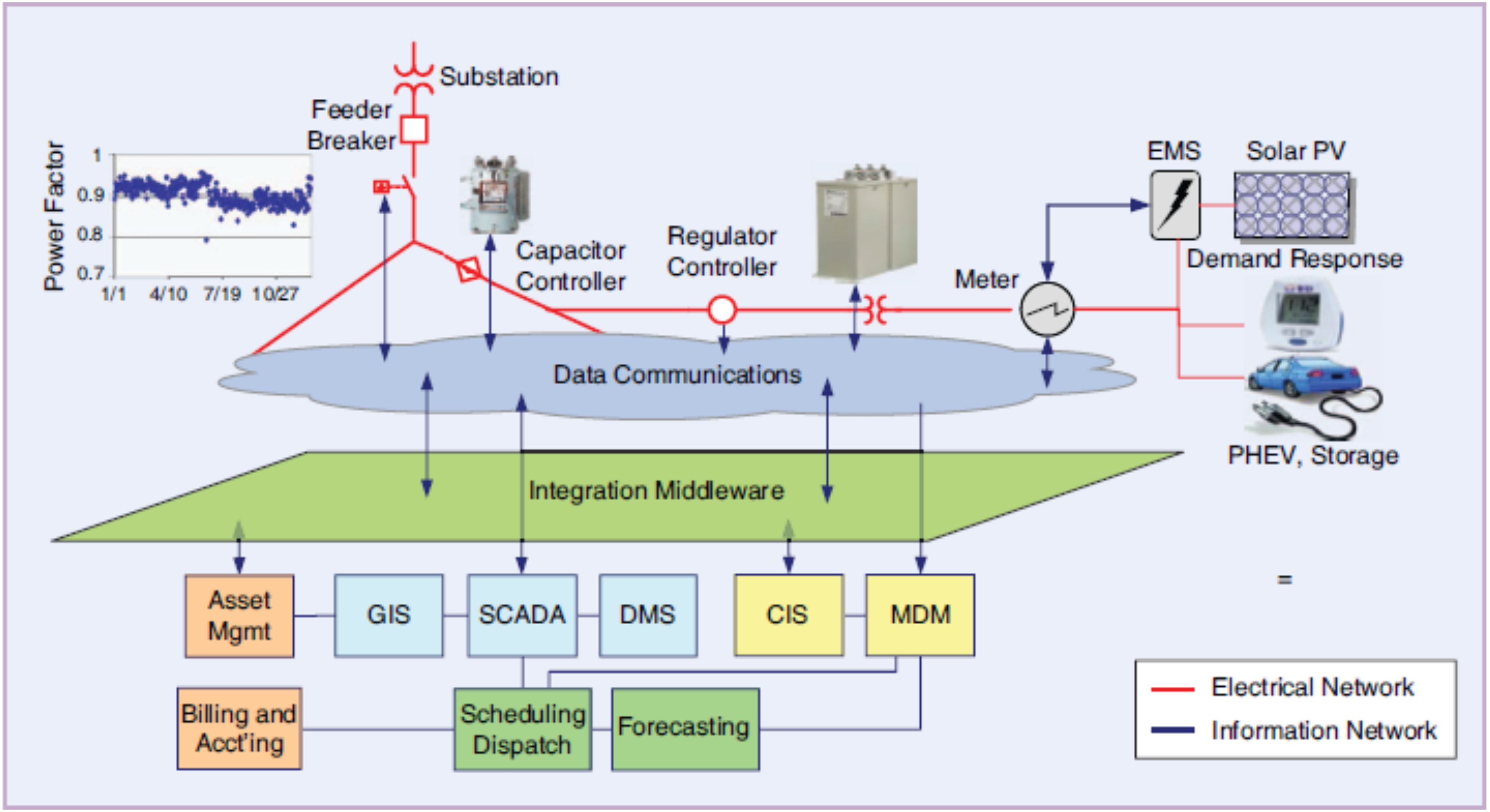
› A smart grid has in-built processes which ensure:

- Observability of all flows, voltages, currents, phases, frequency etc
- Inference to translate to knowledge about balance, stability, etc
- Distributed decision and control to ensure balancing, stability etc
- Emergency reconfiguration for recovery

New: adaptable to generation, load volatility

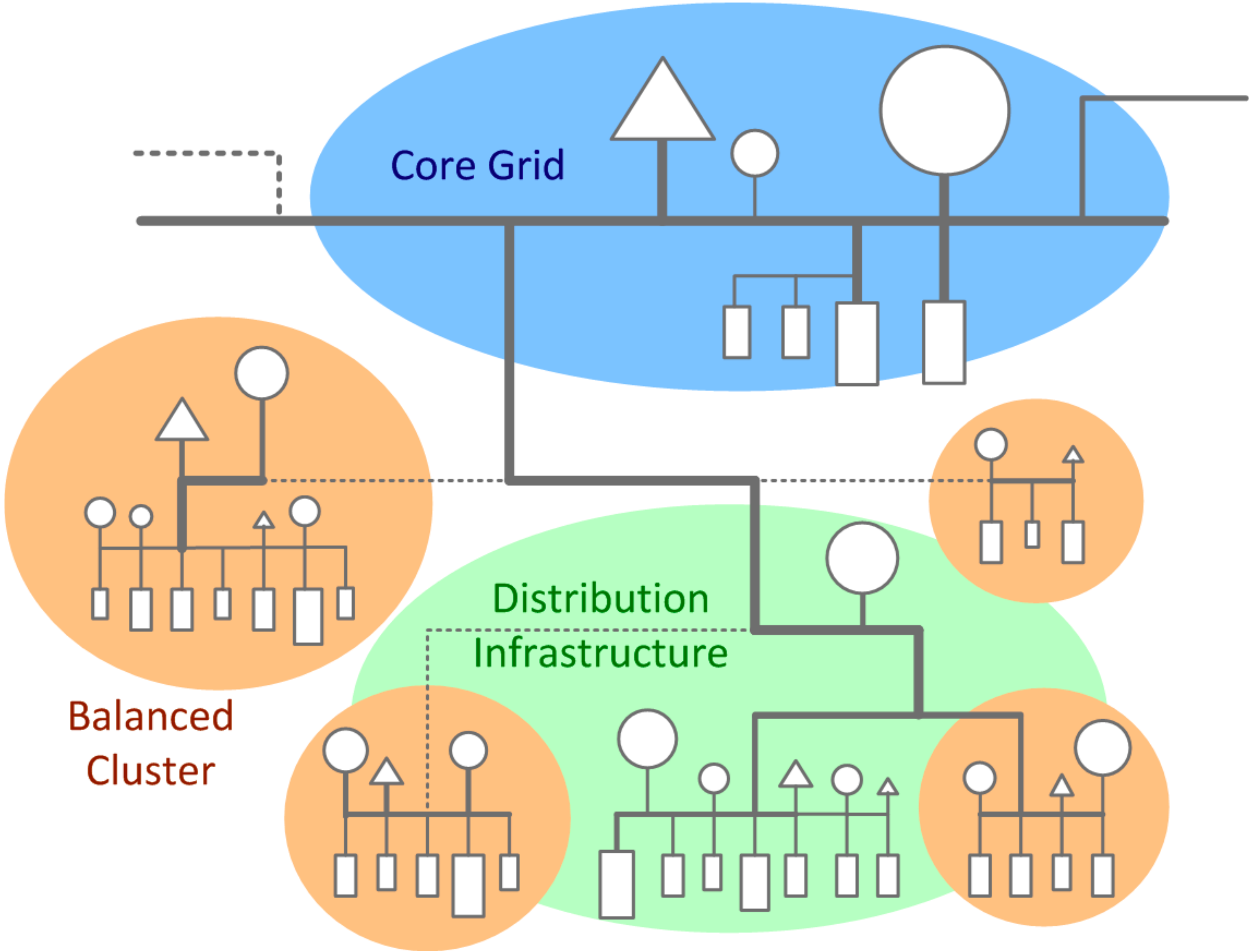
Clearly degrees here: full deal is 100% volatile generation

More monitoring, computing and control



Ref: A.Ipakchi and F.Albuyeh, *IEEE Power & Energy Magazine, Special Issue on the Next-Generation Grid*, Vol.7, No.2, 2009

Grid2050 Architecture (Bakken et al.)



Traffic Networks

› Problems in Sydney
  - Long delays
  - Congestions
  - Tunnel decisions

› Network view
  - Structure
  - Similar systems, e.g. Internet

› Traffic control
  - Flows and dynamics
  - Coordination (intersection, region, wide-area)

Planning Questions

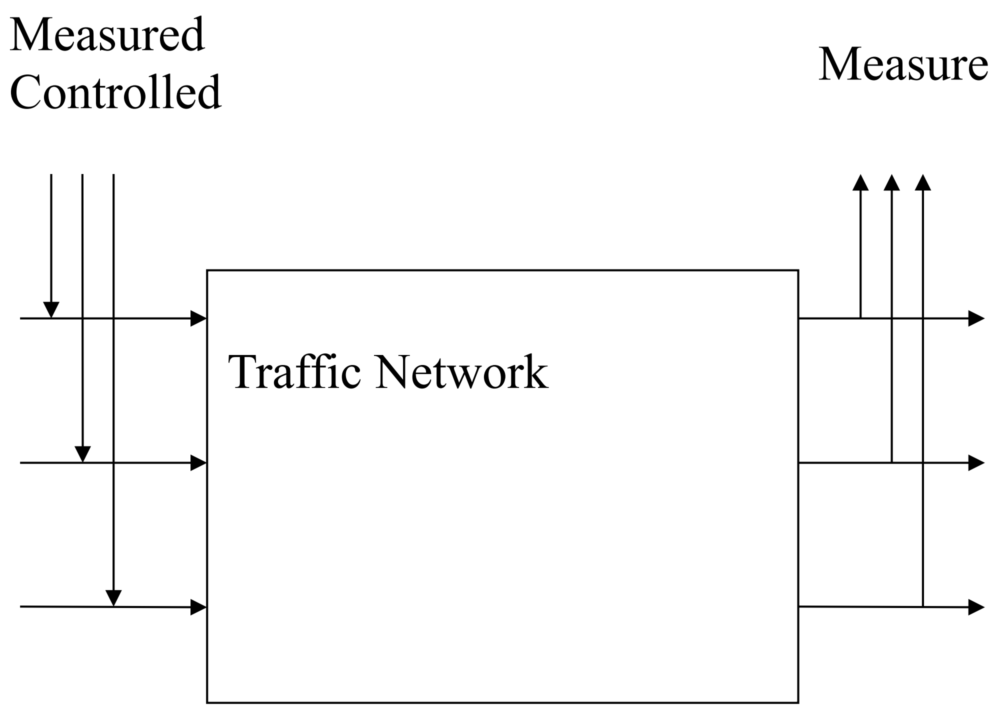
- Optimized expansion structure?
  - Performance
  - Security
  - Cost

- Braess's paradox
  - More links, less performance

- What communication links for wide-area control?

Control Questions

- Flow control: normal flow
- Dynamic control: transients
- Recovery control: failures, emergencies
- Hierarchy needed (global control)
- Coordination needed (beyond intersection)
- Types
  - Self-organise
  - Soft flow control, e.g. tariffs
  - Hard flow control, e.g., lights
  - Hard recovery, e.g. gating



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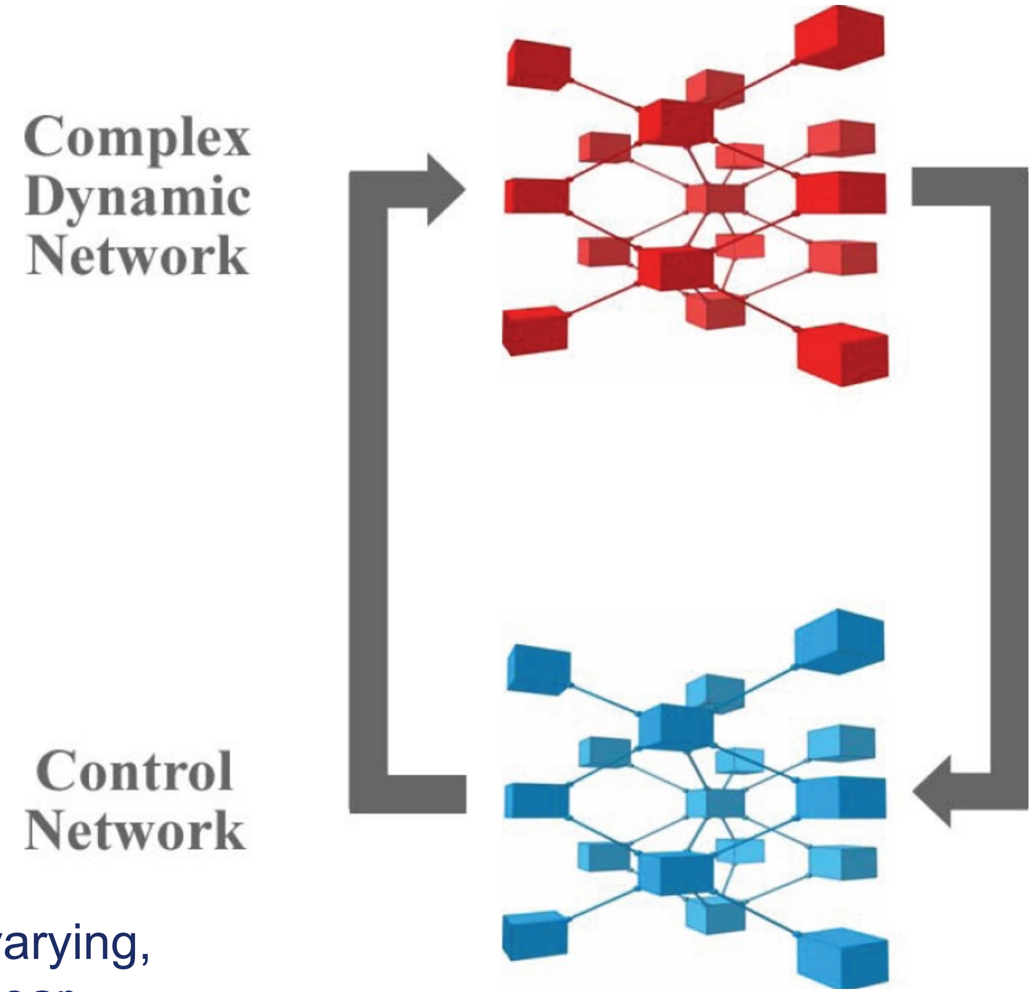
Feedback Networks



Network control of a network

Networks time-varying, switched, nonlinear

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Graphs of Control

The system is a large network (system graph)

- Cannot be controlled centrally

Controllers will need to communicate (control graph)

Sensing of data (sensor graph)

- Control designed around multiple graphs

General Network Model

We consider the general dynamic network consisting of:

- *diffusive coupling;*
- *massive numbers of nodes* modelled as n-dimensional systems

$$\dot{x}_i = f_i(x_i, p_i) + \sum_{\substack{j=1 \\ j \neq i}}^{N} a_{ij}\Gamma(x_j - x_i) + G_i u_i, \quad i = 1, \ldots, N;$$

Special case (Networks science): network with uniform coupling and linearly interconnected identical nodes

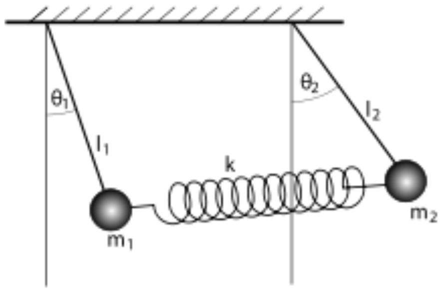
$$\dot{x}_i = f(x_i) + c\sum_{\substack{j=1 \\ j \neq i}}^{N} a_{ij}\Gamma(x_j - x_i) + u_i, \quad i = 1, \ldots, N.$$

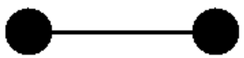
Pendulum Model

Coupled Pendulums are modelled by

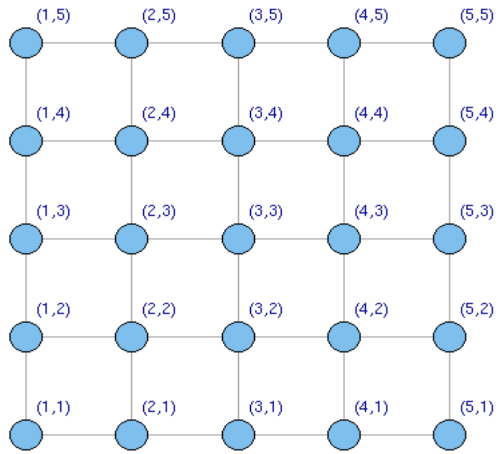
$$m_i\ddot{\theta}_i + \gamma_i\dot{\theta}_i + b_i \sin\theta_i = \tau_i^{'} + \tau_i \sin(\omega t + \varphi_i) + \sum_{\substack{j=1 \\ j\neq i}} b_{ij}(\theta_j - \theta_i)$$

2 coupled pendulums represented by a 2 node network with 1 link





Coupled pendulums can be arranged in network structure such as a 2-D Lattice



Laplacian Matrix -*A*

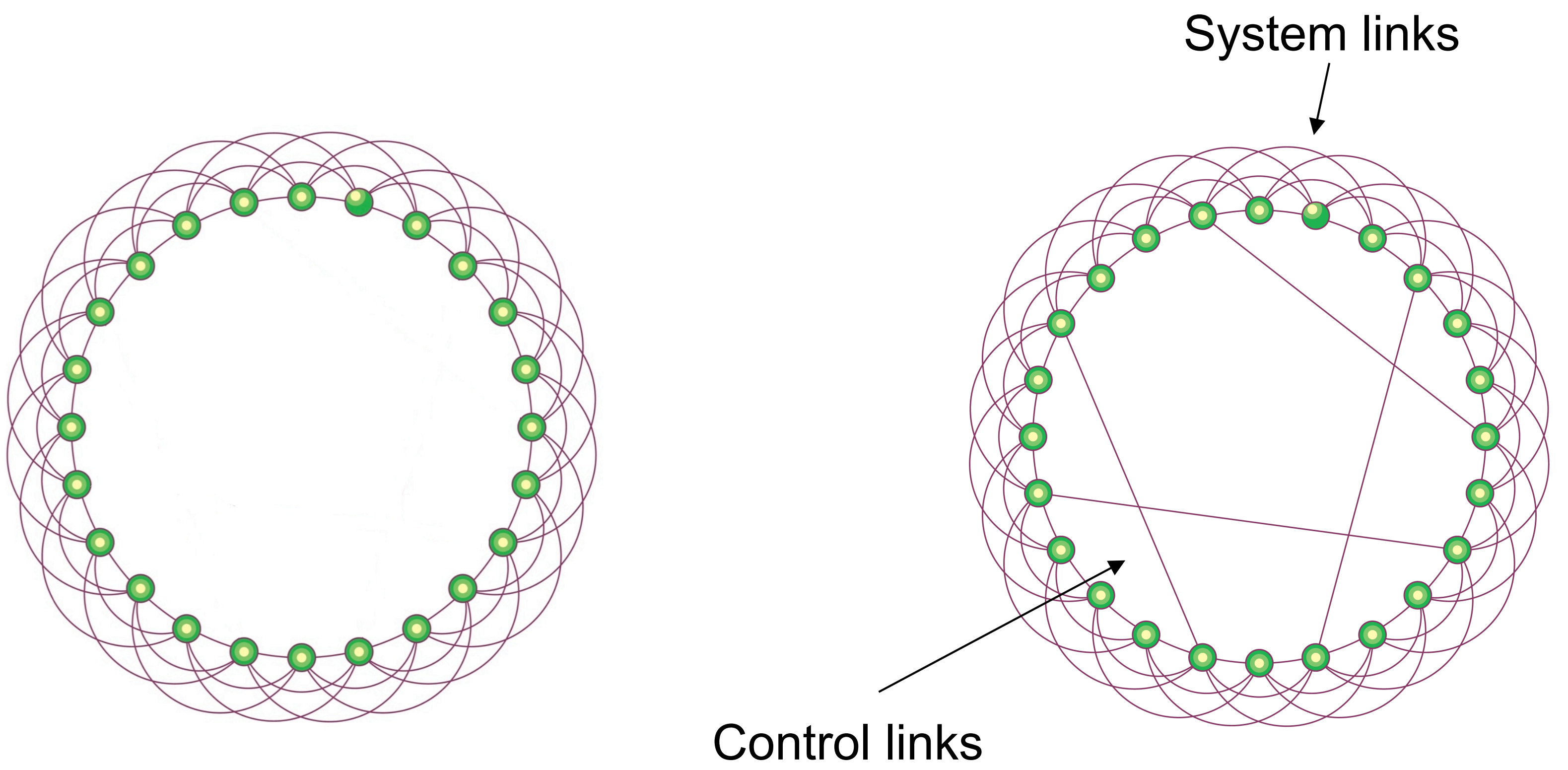
Outer coupling matrix A represents the topology of the network

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{pmatrix},$$

$$a_{ii} = -\sum_{\substack{j=1 \\ j \neq i}}^{N} a_{ij}$$

where $a_{ij} > 0,$ if there is a connection between nodes *i* and *j*, otherwise, $a_{ij} = 0,$

Control of Structure



Uncontrolled Locally connected

Controlled Small-world

Ref: S.H. Strogatz, “Exploring complex networks,” Nature, vol. 410, pp. 268-276, 2001

Design by Optimization (Liu, Hill and Zhao, IEEE TAC 2012)

$$\dot{x}_i(t) = f(x_i(t)) + c\sum_{j=1}^{N} a_{ij}\Gamma x_j(t) + u_i \quad i = 1,2,\ldots,N, \tag{5}$$

where $u_i \in R^n$ is the controller for the ith node with the following form

$$u_i = -\gamma \sum_{j=1}^{N} b_{ij}\Gamma x_j. \tag{6}$$

$\gamma > 0$ is the control gain, and $B \in R^{N\times N}$ is controller outer coupling matrix representing the topological structure of the network controller to be designed. Suppose B has the same properties as A excepted for the assumption of irreducibility.

Theorem 1. Consider the network. If there exists a solution d^* of the following mixed-integer nonlinear optimization problem satisfying $d^* \le \bar{d}$,

$$\min \quad d = \gamma \sum_{i=1}^{M^c} \bar{e}_i^c$$

$$\text{s.t.} \quad \lambda_2 (cA + \gamma \sum_{i=1}^{M^c} \bar{e}_i^c h_i^c h_i^{c\mathrm{T}}) \le \alpha_1$$

$$\bar{e}_i^c \in \{0,1\}, \quad i = 1,2,\ldots,M^c$$

$$\gamma > 0$$

then the control problem is solvable, and synchronization of the network (5) is achieved under the controller (6).

Sync by Switching Control

$$\dot{x}_i(t) = f(x_i(t)) + c\sum_{j=1}^{N} a_{ij}\Gamma x_j(t) + u_i^{\sigma(t)} \quad i = 1, 2, \ldots, N,$$

where $u_i^{\sigma(t)}$ is the switching controller with the following form

$$u_i^{\sigma(t)} = \gamma_{\sigma(t)} \sum_{j=1}^{N} b_{ij}^{\sigma(t)} \Gamma x_j(t), \quad i = 1, 2, \ldots, N,$$

Solved by convex combination and optimization approach.

Other Ideas

- Our view of control “is autistic”; for massive systems get “cognitive overload”
- Maybe just viewing the problem as computation reduction is inadequate
- Will need more than just using structure better
- In global control used ‘indicators’ and switching, c.f. economic control
- We also use learning from past experiences

Learning by doing

- Hewitt: I've been training extremely hard, putting in a lot of hours on the court …… (BBC Sports)

- An example of "Learning by doing"
- Fast responses needed

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Learning-based Control

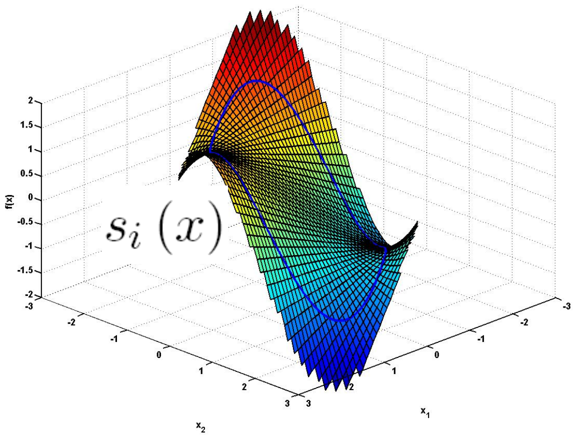
› Improves its performance based on past experiences (Fu, 1969; Farrell and Baker, 1993)

- Effectively recall and reuse the learned knowledge

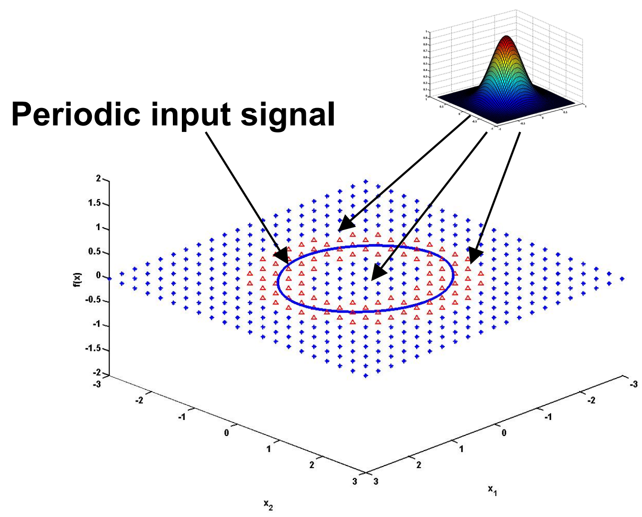
- Use stability robustness to handle mismatch

- Can be used to reduce space for optimization

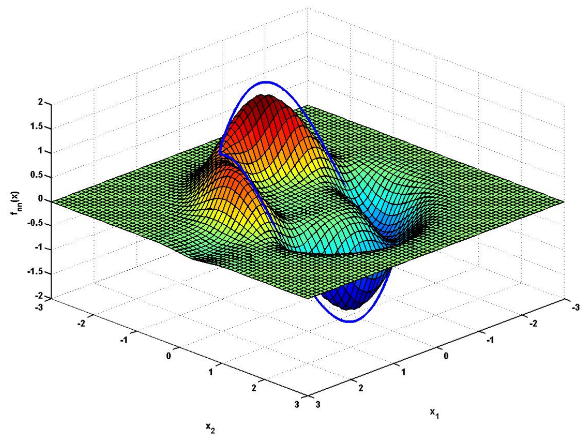
› Systems locally identified in state-space



Nonlinearity to be learned.



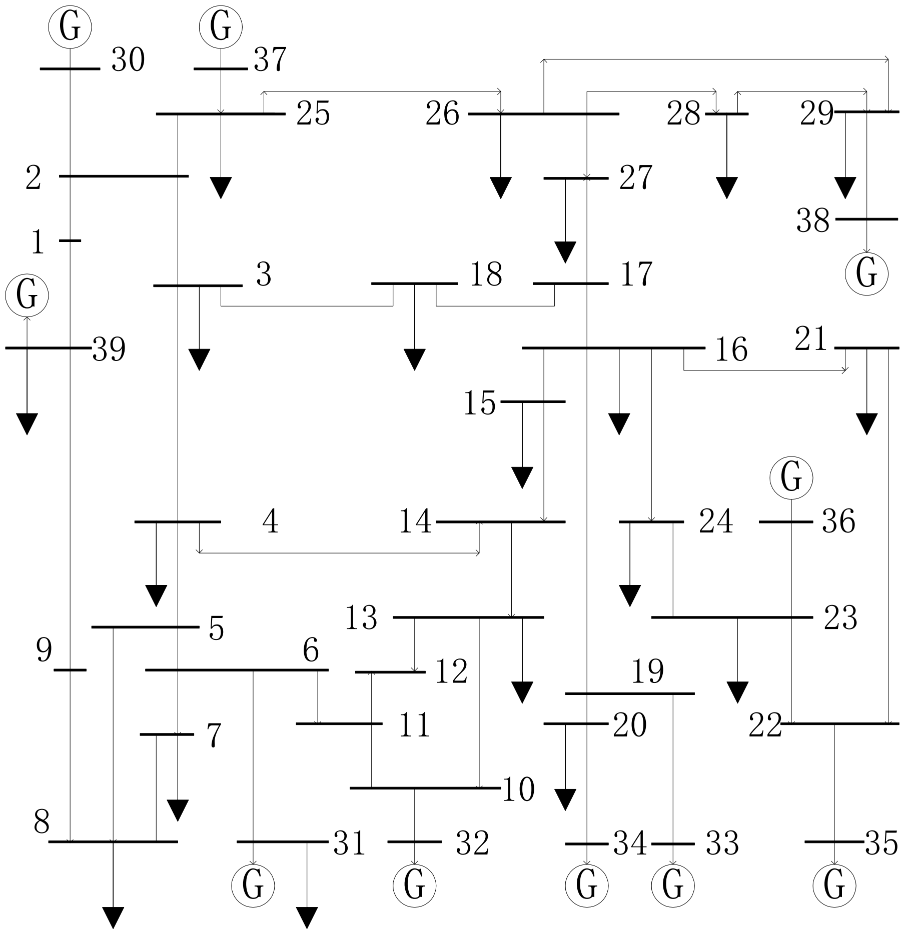
Nodes partially excited in a RBF network.



Local learning.

- Deterministic learning
  (Wang and Hill, IEEE TNN, 2006.)

Coordinated Voltage Control



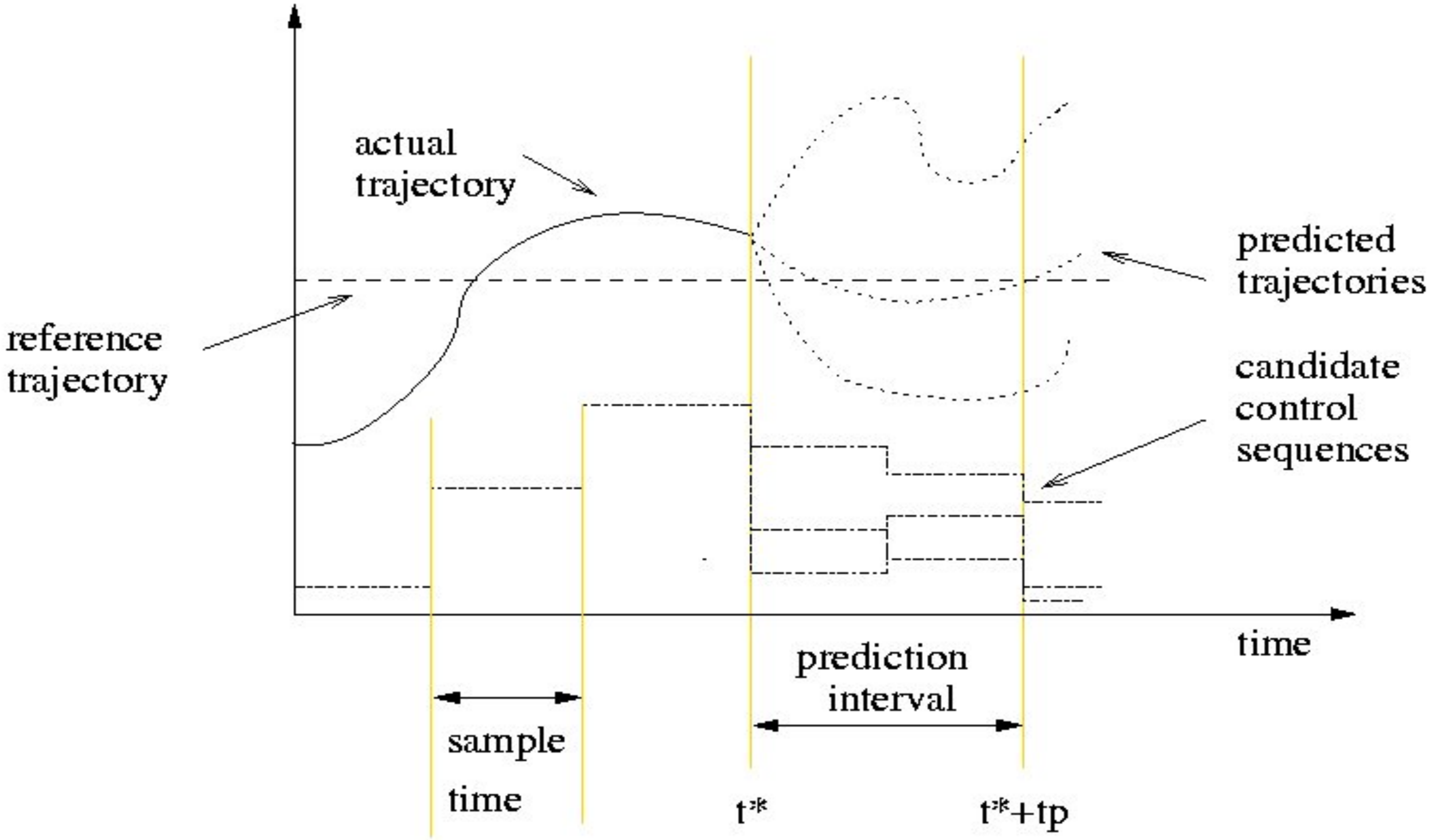
The New England 39-bus Power System

Voltage control

Aim: Maintain steady voltages at all buses.

Control devices: Tap changers, capacitors, load shedding

Coordinate via MPC



On-line Multi-Objective CVC System

MCVC System:

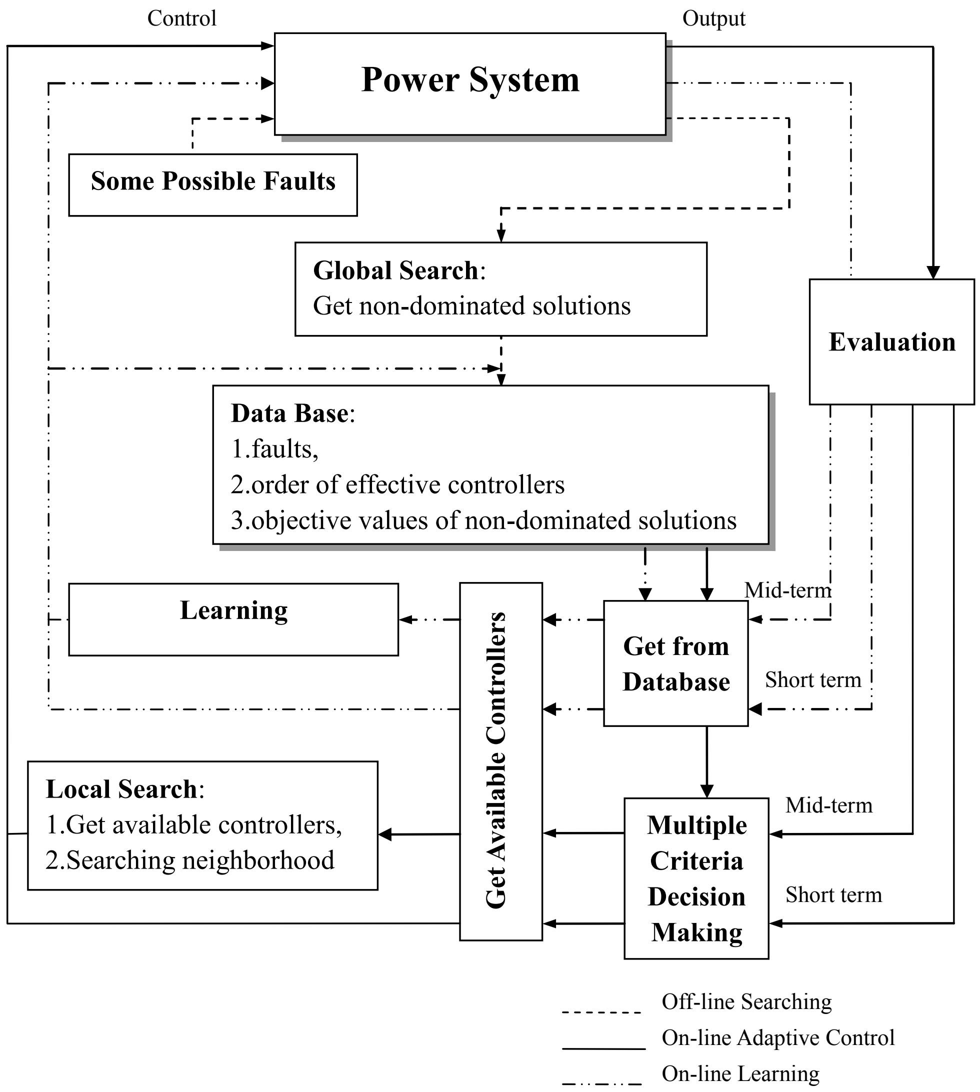
- Off-line global search
- On-line flexible control
- On-line learning

Objective functions:

$$J_{\sum vi} = \min \sum_i \sum_t \left| v_{it} - v_{iref} \right|$$

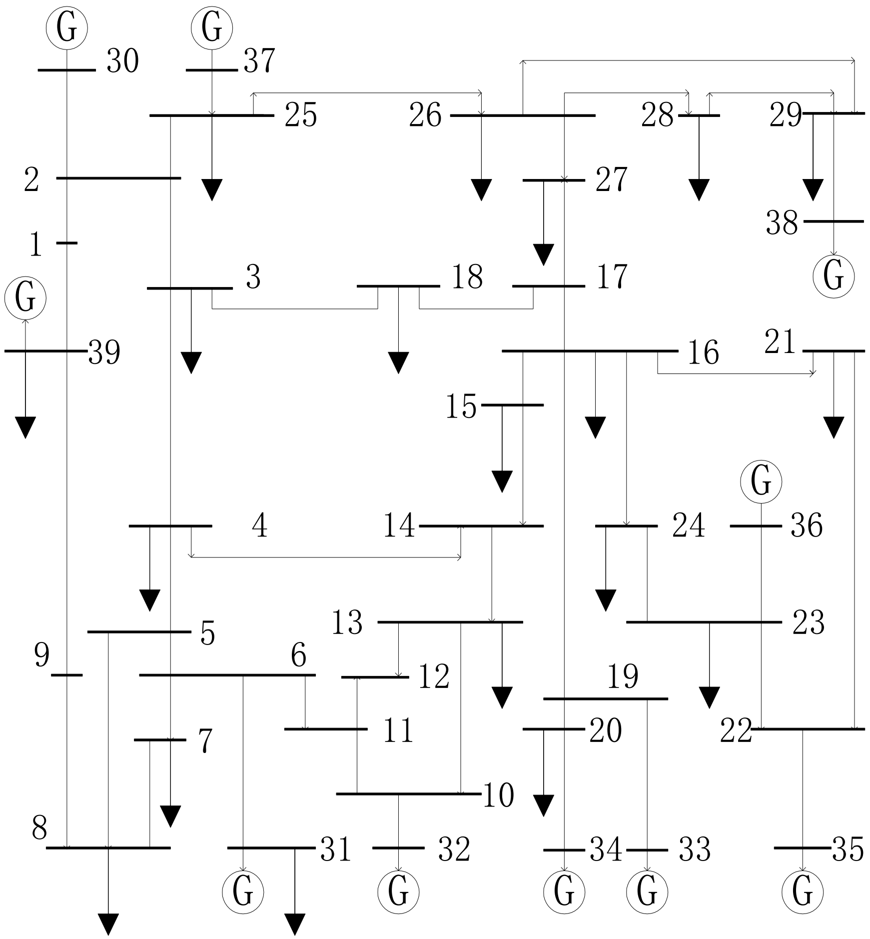
$$J_{act} = \min n_c$$

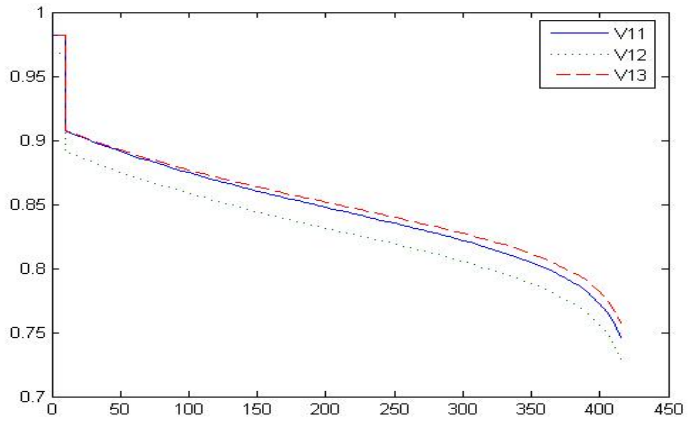
$$J_{load} = \min \sum_k n_{load_k}$$



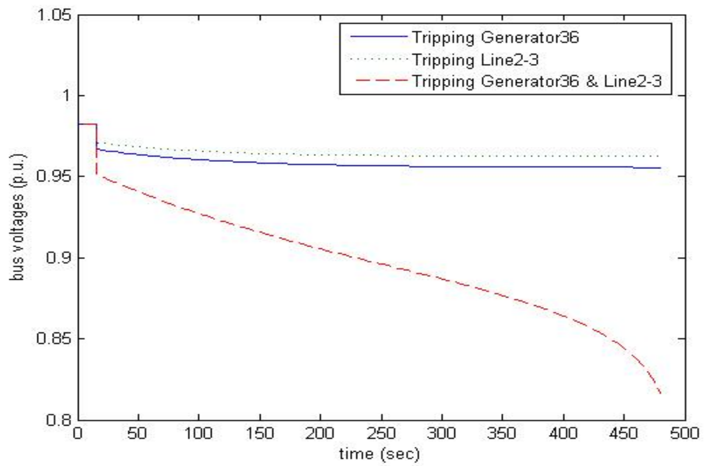
Case Study

Case1: Tripping Generator 32





Case1: Tripping Generator36 and Line2-3



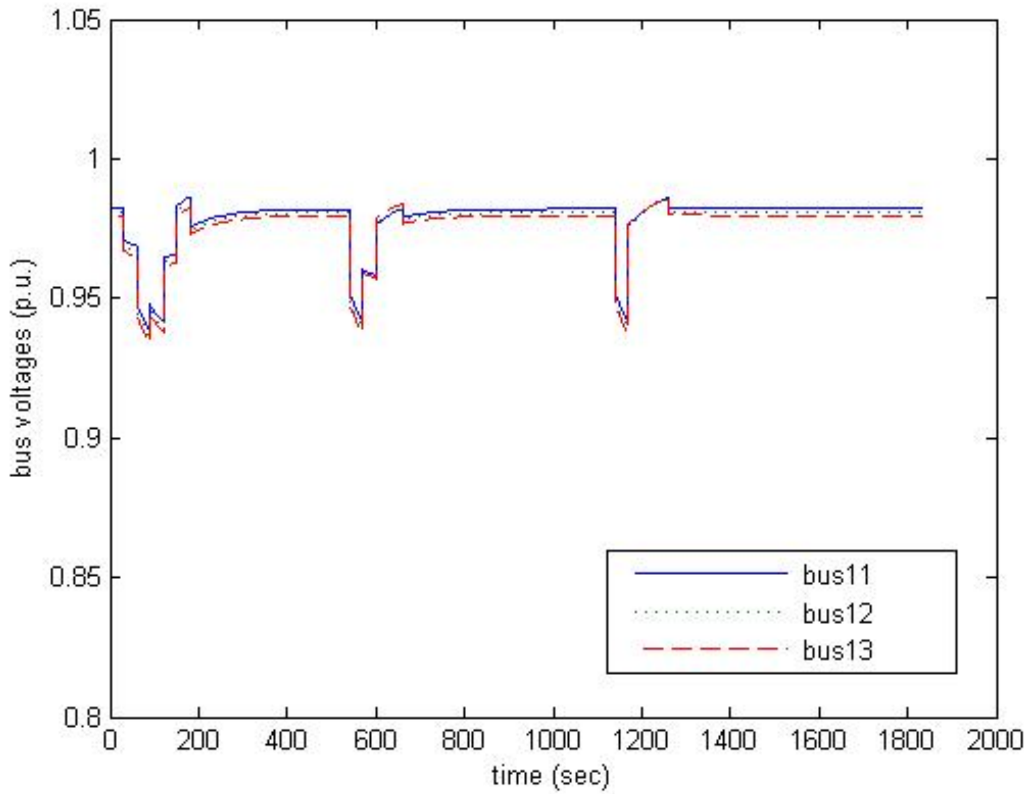
Case2: Tripping Generator 36 and Line 2-3

Case Study

Control Scenario

Time	Event
30s	Line3-2 tripping
60s	G36 tripping
180s	Line3-2 and G36 reconnection
540s	Line3-2 and G36 tripping together
660s	Line3-2 and G36 reconnection
1140s	Line3-2 and G36 tripping together

System performance:



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Two applications
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Challenges of Complexity

- Massive amounts of data
- Checking properties on such a scale – certificates
- Optimizing on such a scale
- Planning vs self-organisation
- Local vs global control
- Security (cyber-physical)

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But the data?

- Collecting lots of data, but: “We need to work out what to do with it” (Senior engineer in SGSC)

So need methods to manage ‘big data’, software on a large scale.

Steps

- Using graphical methods (Shvartzshnaider, NICTA)
- Learning in data mining

Ideas to compress hierarchially, turn into indicators etc

And the modelling

- Identify the graphs
- Taxonomies of nodes, links, ‘motifs’
- Metrics, indicators
- On-line vs off-line versions

Lots of work here before we can begin analysis!

Phase Angle Stability

Basic sync issue in AC systems

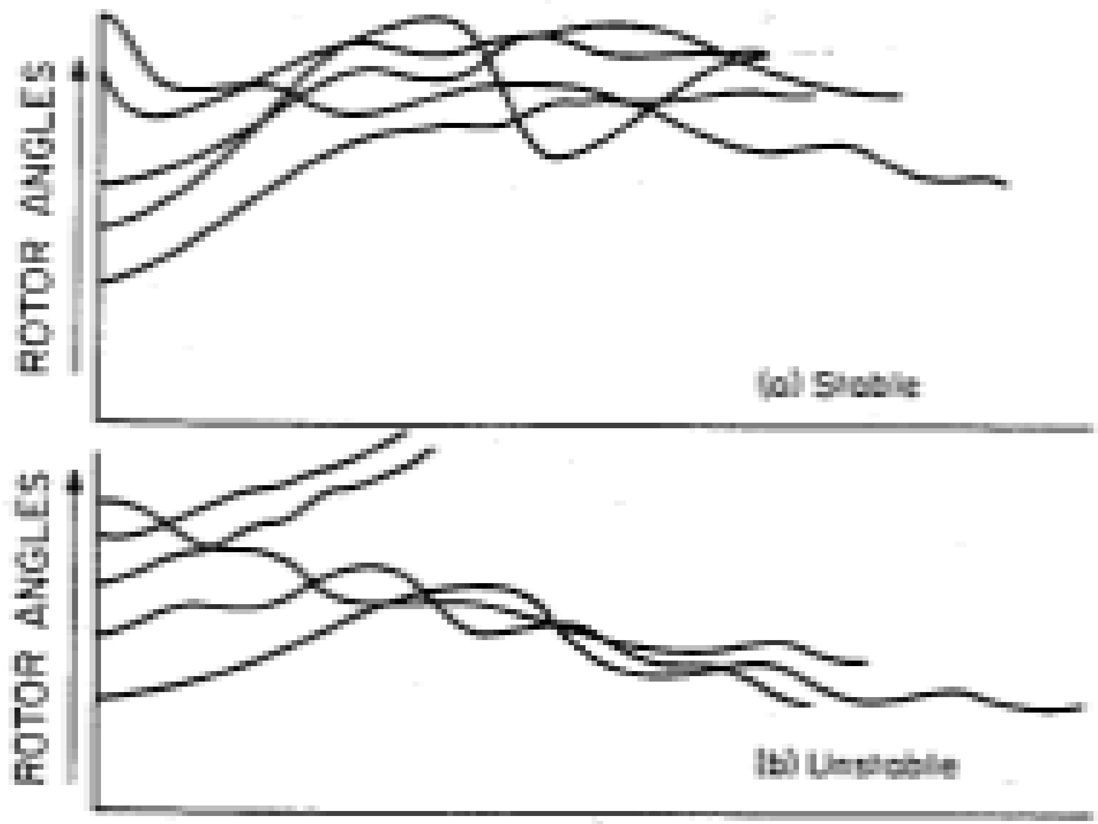

Fig. 1.1 Behavior of rotor angles for the stable and unstable case.

Ref: M.A.Pai, Energy Function Analysis for Power System Stability

Stability challenges

› Robustness to all the uncertainty

› Dependence on structure

- find the vulnerable points for collapse
- backbone networks vs weakly connected clusters for diverse generation

› How to guarantee stability from local checks

- certificates (with some exchange)

"Smart Grid" as control engineering

› Large network of sensors

› Massive amounts of data, i.e. measurements, availability etc

› Distributed control operating at many levels

› But for SGSC have 2 x 10^{12} possible links

› Architectures?

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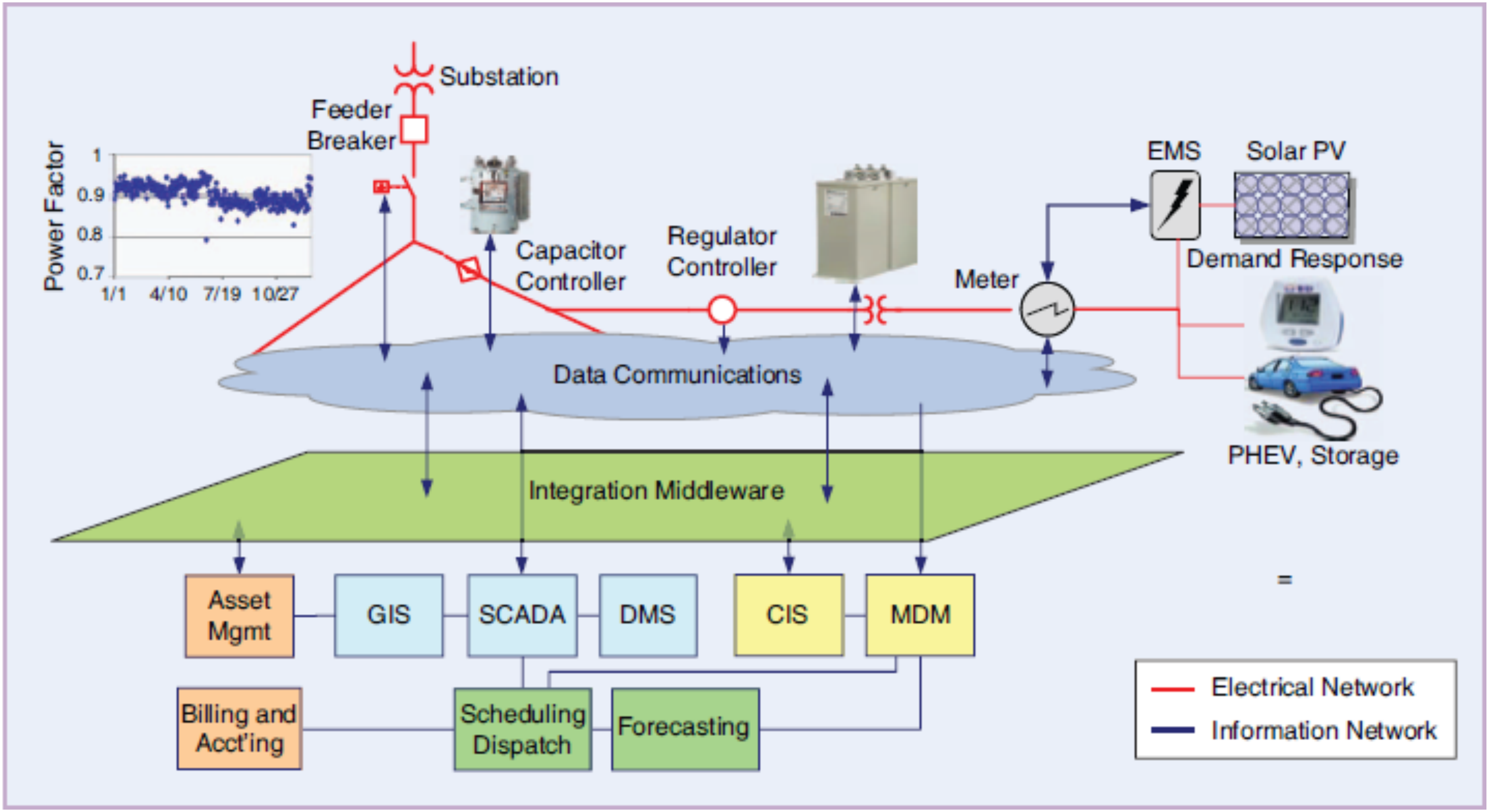
Control challenge

- Limitations of a centralised system

- Need distributed artificial intelligence
  - Avoids data overloads at critical places
  - Implements in-time control where needed
  - Robustness
  - Can achieve scaling (non-coop game ideas)
  - Question of granularity
  - Question of cyber security

- Anyway have an end-to-end optimal adaptive distributed control problem: a huge optimisation again

More monitoring, computing and control



Ref: A.Ipakchi and F.Albuyeh, *IEEE Power & Energy Magazine, Special Issue on the Next-Generation Grid*, Vol.7, No.2, 2009

Centralized vs decentralized

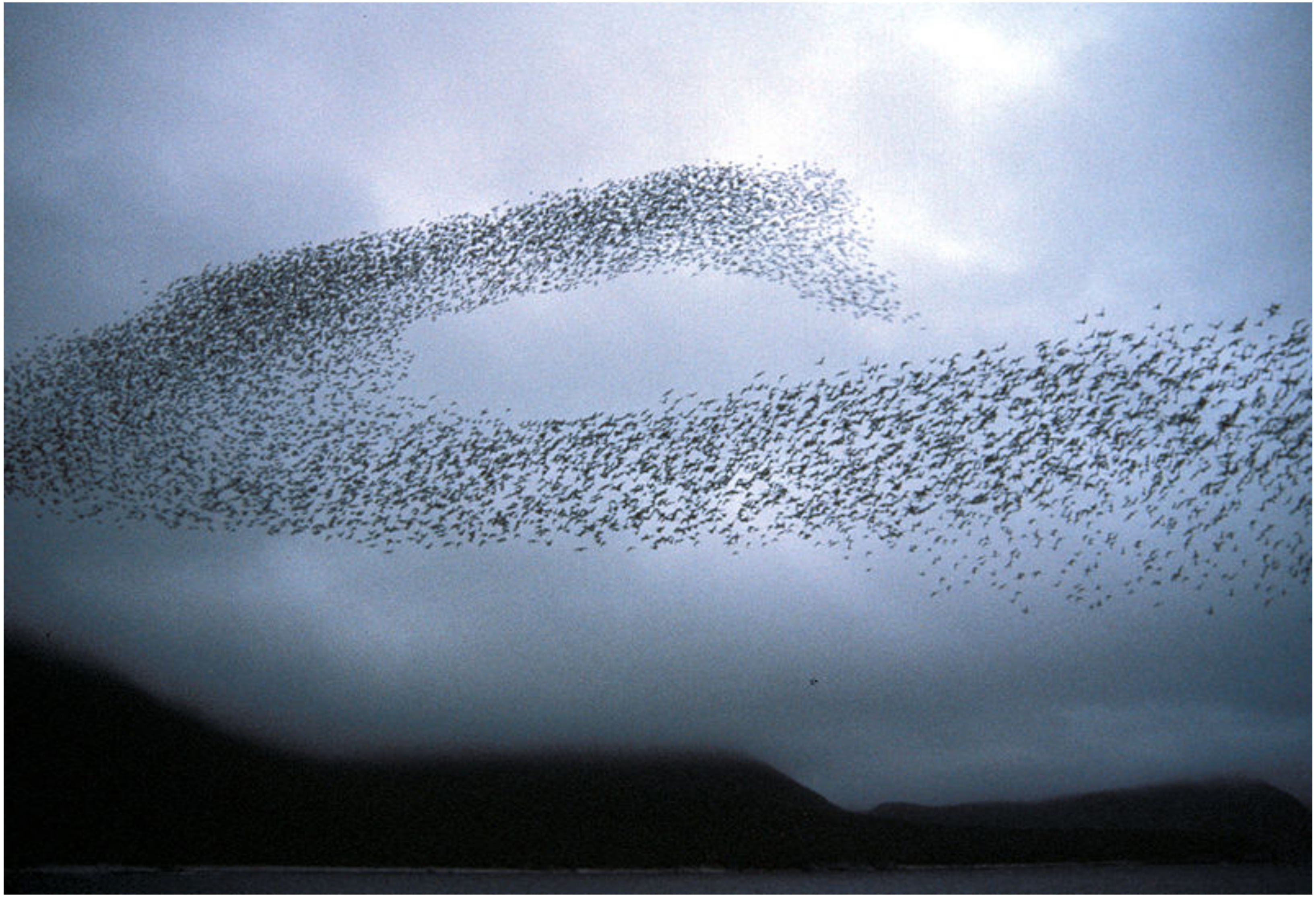
› Current power systems have a lot of decentralized control:
  - Voltage regulators
  - Power system stabilzers
  - AGC (frequency, line flows)
  - Sync

› For transmission, centralized monitoring via SCADA

› Centralized for balancing, i.e. dispatch, and advanced recovery

› Look for clever local controllers ’ talking to each other locally, e.g. STATCOMs, Ron Hui’s ‘electric springs

Swarming in nature



Mean-field type control

49th IEEE Conference on Decision and Control
December 15-17, 2010
Hilton Atlanta Hotel, Atlanta, GA, USA

Decentralized Charging Control for Large Populations of Plug-in Electric Vehicles

Zhongjing Ma Duncan Callaway Ian Hiskens

More specifically, subject to a collection of charging strategies $\mathbf{u}$, we suppose that the cost function of agent n, denoted by $J^n(\mathbf{u})$, is specified as,

$$J^n(\mathbf{u}) \triangleq \sum_{t=0}^{T-1} \left\{ p(r_t) u_t^n + \delta \left(u_t^n - \text{avg}(\mathbf{u}_t) \right)^2 \right\} \qquad (4)$$

where $r_t \equiv \frac{d_t + \text{avg}(\mathbf{u}_t)}{c}$ and the tracking parameter δ is a non-negative constant. It follows from (4) that each agent's optimal charging strategy must achieve a trade-off between the total electricity cost $p(.)u^n$ and the cost incurred in deviating from the average behavior of the PEV population $(u^n - \text{avg}(\mathbf{u}))^2$. The examples in Section IV illustrate that the small tracking costs are more than compensated by cost savings that arise from valley filling.

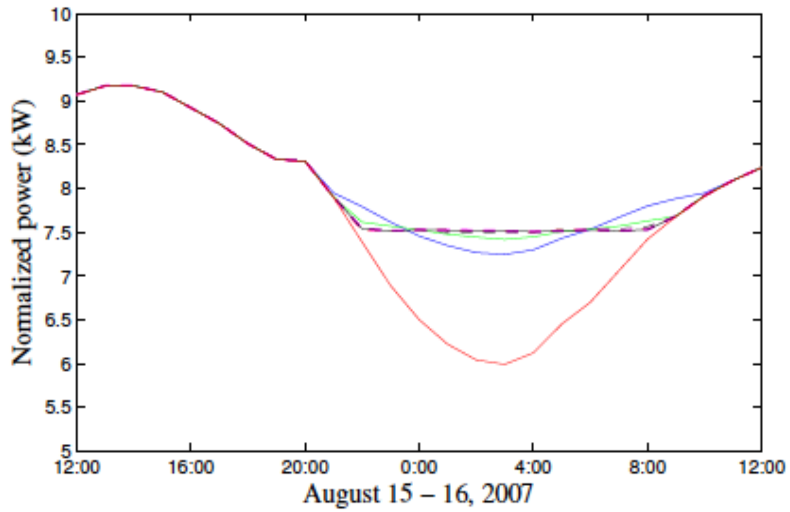


Fig. 4. Convergence of decentralized charging process for a homogeneous PEV population with $\delta = 0.015$.

Self-organising traffic control

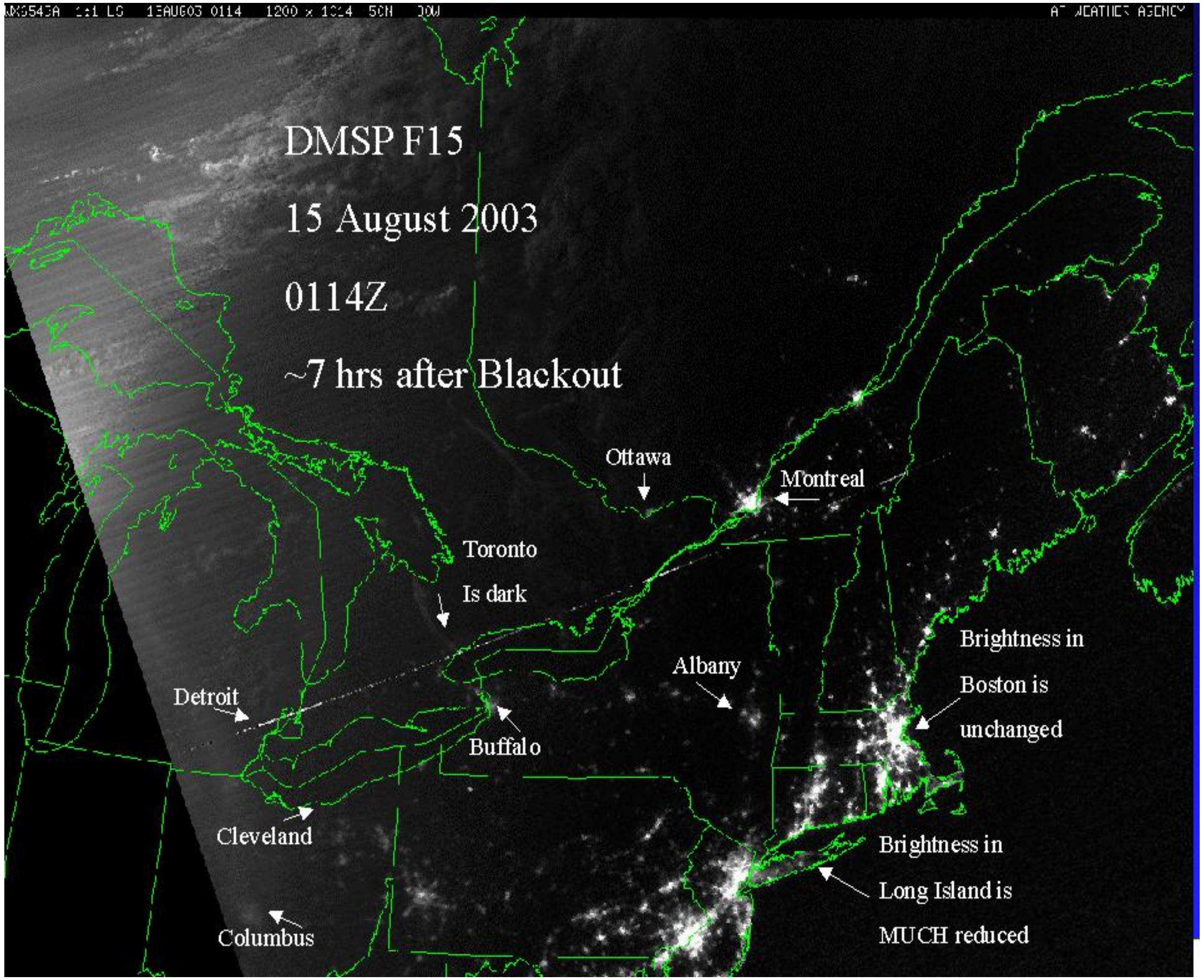
› Anecdotally: London cab drivers found traffic worked better sometimes when lights failed

› Study (Xia and Hill, 2009) shows using cellular automaton model (lattice, road segments) and rules for drivers for traffic lights and self-organising

› Results: Three phases of traffic flow:

1. Average travel time fixed, regardless of car density; SO best in most cases
2. Flow almost unchanged as density increases; traffic lights achieves higher flow
3. Flow degrades as traffic jams; both control strategies have similar results

Blackout 2003 USA-Canada



Network Security - planning

- Anticipated set of contingencies
- Anticipated set of operating conditions
- Given set of control actions
- System can achieve an acceptable state

Establish margins of security

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Security control

- Something has gone wrong, e.g. storm, failure
- Lots of data, e.g. alarms, phone calls
- Diagnose what state the system is in, e.g. locate fault, area of outage
- Assess security level, e.g. any potential problems
- Plan and schedule the response, e.g. restore, repair

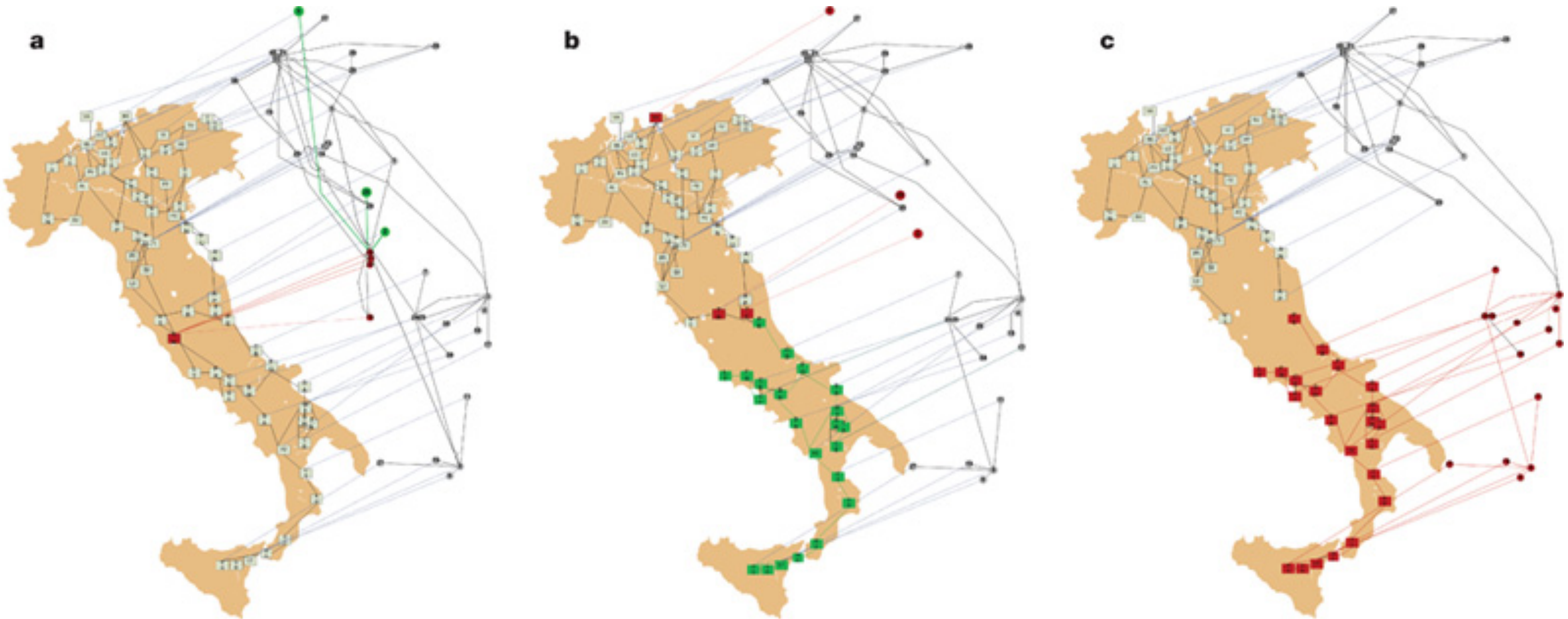
Questions – security

- Information architectures, i.e star vs mesh etc for control and cyber-security?

- Cyber-physical security –outsmart intruders? Remember Stuxnet

- Physical security was never completely solved, i.e. cascading collapse – put the two problems together!!???

Interdependent networks



SV Buldyrev *et al. Nature* **464**, 1025-1028 (2010) doi:10.1038/nature08932

Control Challenge

- A multi-level version of distributed adaptive control
- Attends to local and system control needs
- Reconfigurability plus tuning, i.e. can attack problems as they arise in staged response

Call it global control

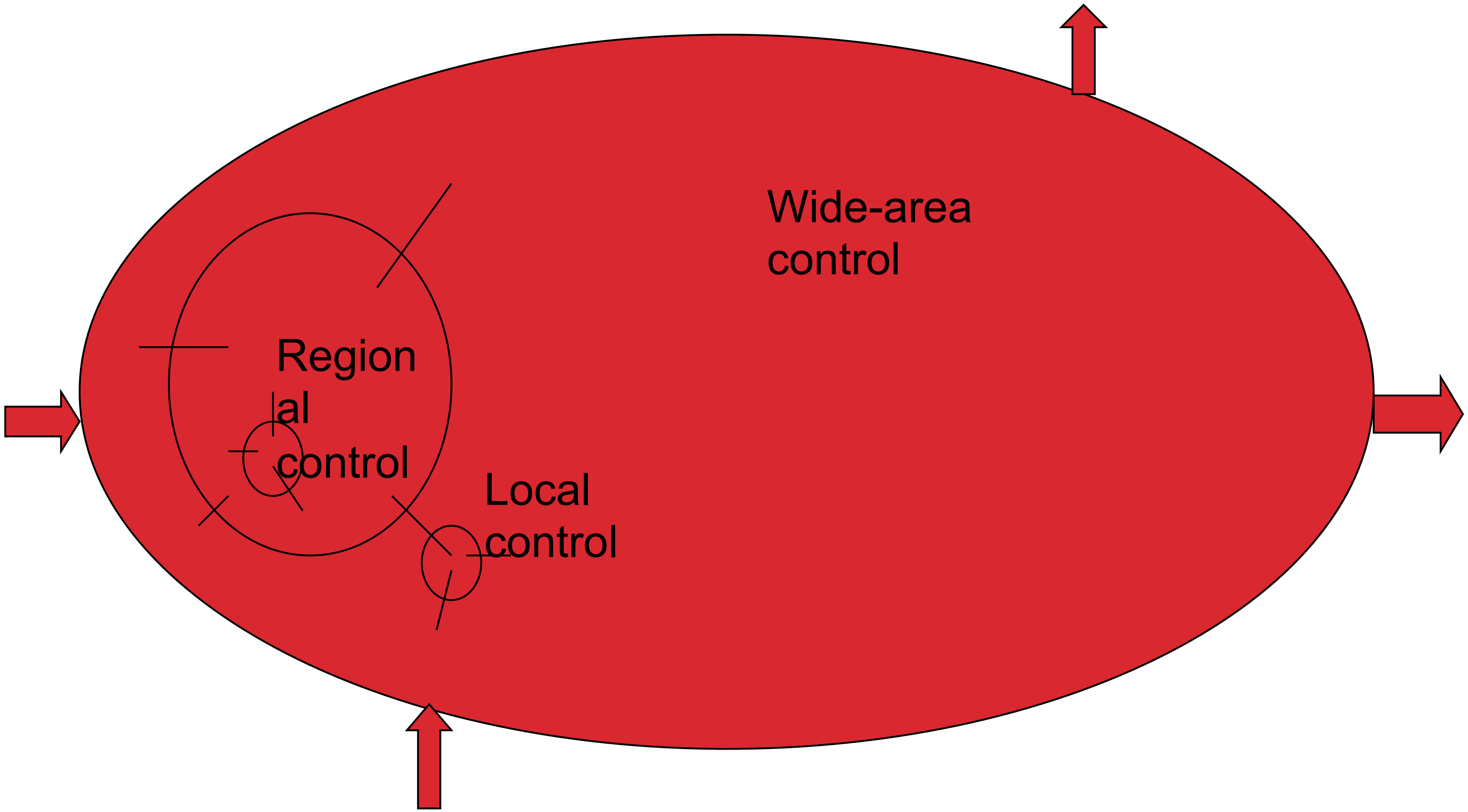
Basic idea

- Large numbers of local controllers act independently (non-cooperative games, Nash equilibria etc)
- Clusters which can cooperate
- Local controllers handle all routine things
- Higher levels handle slower loops and emergencies (swap local for system priorities)

All this has to be done dynamically.

Research needed.

Global Contro – traffic approach



Global Control Framework – power systems

(Leung, Hill and Zhang, 2009)

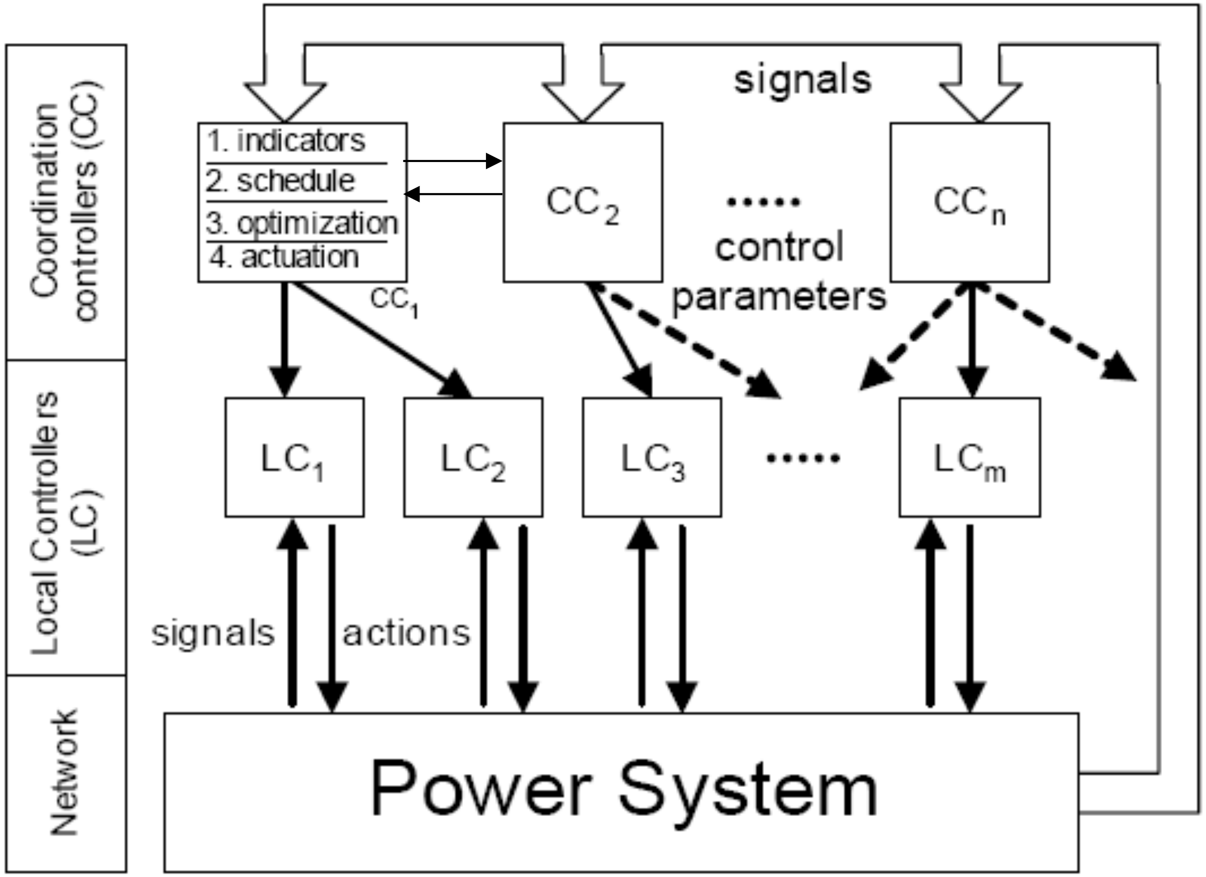


Fig.5.2: A generic global framework

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- Massive networks a new frontier for decision and control
- Network science ideas useful
- ‘Smart’ = cognitive ability (planning, awareness, attention, memory, action, learning)
- Problems of scaling solutions, granularity
- Merging control, computer , telecomms and network sciences
- How to KIS? New ideas

Convergence of Networks

Slide from Paul de Martini, CISCO – presented NICTA

Social Networks

- Individual & Organization
- Governments
- Communities & Markets

Cyber Networks

- Data, Voice & Video
- Protection & Controls
- Security

Physical Networks

- Electric Trans & Dist
- Water Trans & Dist
- Gas Trans & Dist