Automatic learning for advanced sensing, monitoring and control of electric power systems

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The message I would like to convey

Automatic learning has a lot of potential for advanced sensing, monitoring and control of electric power systems

- *But it is presently totally underused in power systems*
- *It needs much stronger implication from our industry*

What is Automatic Learning ?

- Supervised learning
- Reinforcement learning
- Unsupervised learning
- Automatic learning protocols
- Current stage of development

What kind of applications to electric power systems ?

- Types of problems
- Sources of data
- Example of a real-life application

Discussion/Conclusion

What is AL: 1. Supervised learning

- *Given a sample of observed (or simulated) input-output pairs define a model to compute output from inputs*

A sample of (x, y) pairs

	x_1	$\cdots$	x_n	y
z^1	x_1^1	$\cdots$	x_n^1	y^1
z^2	x_1^2	$\cdots$	x_n^2	y^2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
z^N	x_1^N	$\cdots$	x_n^N	y^N

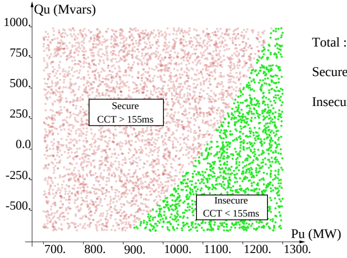
$\overset{SL}{\longrightarrow}$

How to compute y from x

Defun $\hat{y}(x_1, x_2, \ldots, x_n)$
(if $(x_1 < 23.4)$
(if (x_4 is high) (return $x_3 x_7$)
$\vdots$
. . .)
. . . (return 34.3))

- *Criteria: precision, scalability, interpretability*

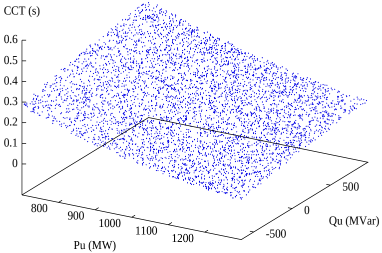
Supervised learning datasets: graphically

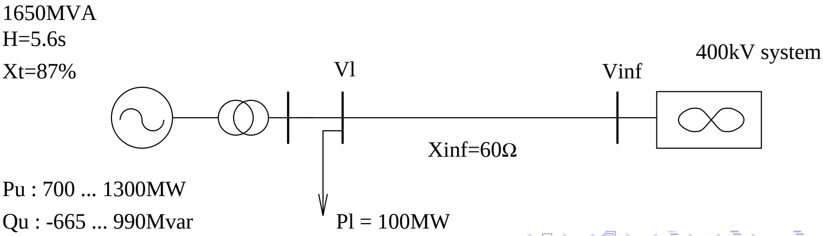


Total : 5000 states

Secure : 3510 states

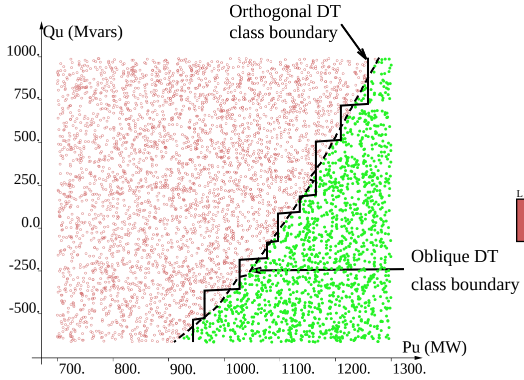
Insecure : 1490 states

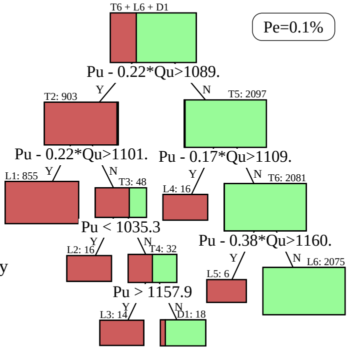




Supervised learning models: graphically

Models built by decision tree induction:





Supervised learning algorithms: milestones

- Before the computer age:
  - Linear regression and linear discriminants
- Around 1960:
  - Decision and regression trees
  - Nearest neighbor methods
- Around 1975:
  - Multilayer perceptrons
  - Other nonlinear methods
- During the nineties:
  - Kernel-based methods and Support vector machines
  - Ensemble methods (in particular of tree-based models)

What is AL: 2. Reinforcement learning

- Dynamical system: $x_{t+1} = f(x_t, d_t, w_t)$; $r_t = r(x_t, d_t, w_t)$
- *Given a sample of observed (or simulated) system trajectories compute an optimal decision strategy*

A sample of four-tuples

	x_t	d_t	r_t	x_{t+1}
z^1	x_t^1	d_t^1	r_t^1	x_{t+1}^1
z^2	x_t^2	d_t^2	r_t^2	x_{t+1}^2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
z^N	x_t^N	d_t^N	r_t^N	x_{t+1}^N

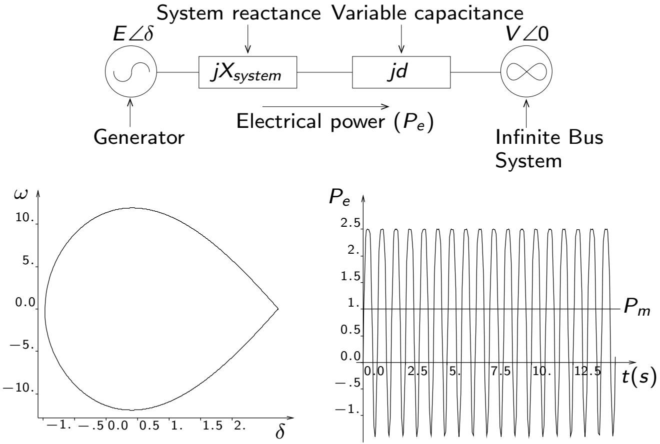
$\xrightarrow{RL}$

How to compute d_t^* from x_t

```
Defun d̂*(x, t)
(if (x < 3.4)
   (if (t = 1) (return +1)
⋮
...)
...(return -1) )
```

- *Optimal policy: maximizes* $E\{\sum_{t=0}^{h-1} \gamma^t r_t\}$

RL: Illustration: TCSC controller tuning (OMIB system)

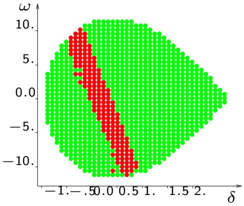


The sequential decision making problem

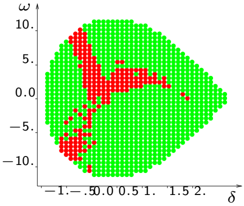
- Two state variables: $x = (\delta, \omega)$.
- Time discretization: time between t and $t+1$ equal to 50 ms
- Two possible decisions d: capacitance set to zero or capacitance set to its maximal value.
- $r(x_t, d_t) = -|P_{e\,t+1} - P_m|$ if $x_{t+1} \in$ *stability domain* and -100 otherwise ($\gamma = 0.98$)
- Sequential decision problem such that the optimal stationary policy damps the electrical power oscillations
- Sample generation: pick (x, d) at random and compute $f(x, d)$ and $r(x, d)$ to get a four-tuple (repeat N times)

Representation of $\hat{d}^*(x, t)$

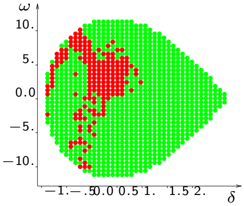
(10,000 four-tuples, $h = 200$, ie. 10s)



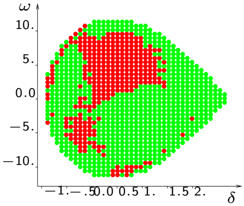
$\hat{d}^*(x, 200 - 1)$



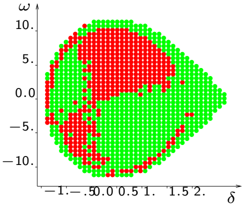
$\hat{d}^*(x, 200 - 5)$



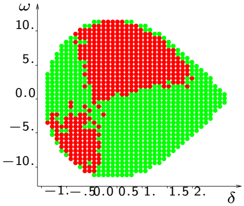
$\hat{d}^*(x, 200 - 10)$



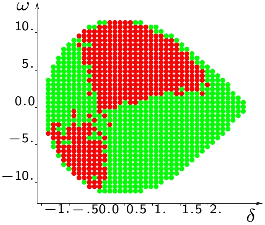
$\hat{d}^*(x, 200 - 20)$



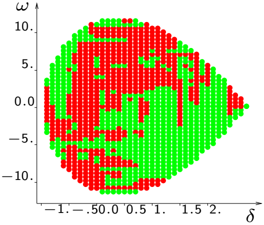
$\hat{d}^*(x, 200 - 50)$



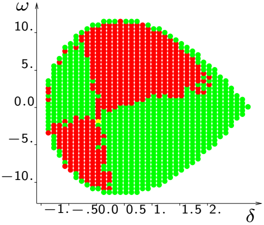
$\hat{d}^*(x, 0)$



$\hat{d}^*(x, 0)$
10,000 samples

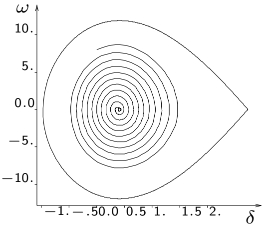


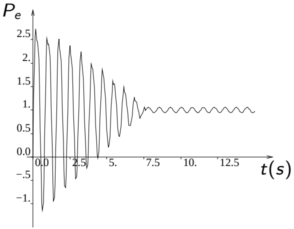
$\hat{d}^*(x, 0)$
1000 samples



$\hat{d}^*(x, 0)$
100,000 samples

$\hat{d}^*(x) = \hat{d}^*(x, 0)$
used to control the system
($h = 200$)
10,000 samples





Reinforcement learning algorithms: milestones

- Before the computer age:
  - (Nothing)
- Around 1960:
  - Dynamic programming principle
  - First approximate dynamic programming methods
- During the 80ies:
  - Temporal difference learning methods
  - Q-learning: parametric, incremental gradient descent
  - SARSA algorithm
- During the 90ies:
  - Neurodynamic programming
  - Q learning with function approximators
  - Model-based RL
- Today:
  - General supervised learning based Q learning
  - A lot of ongoing research...

What is AL: 3. Unsupervised learning

- *Given a sample of joint observations of several system measurements, identify (probabilistic) relationships among these measurements*

A sample of measurements

	y_1	y_2	$\dots$	y_n
z^1	y_1^1	y_2^1	$\dots$	y_n^1
z^2	y_1^2	y_2^2	$\dots$	y_n^2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
z^N	y_1^N	y_2^N	$\dots$	y_n^N

$\xrightarrow{USL}$

A set of relationships

Mixtures of Gaussians:
$$P(y) = \sum_j w_j \mathcal{N}(\mu_j, \Sigma_j)$$
ICA: $y_i = \sum_{j=1}^n \beta_{i,j} x_j$,
x_j independent sources
BN: $P(y_1, \dots, y_n) = \prod P(y_i | Pa(y_i))$
conditional independences
...

- Broad class of methods, numerous applications
- More general and more difficult than SL and RL

What is AL: various learning protocols

- Batch mode:
  - All samples are obtained beforehand
  - Like classical statistical inference
- On-line mode
  - Sample obtained one by one
  - Models refreshed incrementally, with bounded resources
  - Like adaptive model identification
- Active mode
  - Learning agent can influence sampling mechanism
  - Like sequential experiment design and dual control

What is AL: current stage of development

- Theoretical achievements:
  - Gap between AL and statistics has been bridged
  - Many "heuristic" algorithms are now well understood
- Practical achievements:
  - Scalable, parallel, and anytime algorithms
  - Bioinformatics, computer vision, process control...
  - Data mining in business and other fields
- Ongoing research:
  - Structured data: time-series, images, text, graphs...
  - Multi-agent learning systems and active learning
  - Learnability in non conventional settings

NB. There many other important things to say (e.g. ILP, Relational Learning, Semi-supervised learning, ...)

Application to electric power systems: *types of problems*

- Security assessment (academic proposal: 60ies; in practice: 1995)
  - Planning
  - Operation planning
- Forecasting (academic proposal: 70ies; in practice: 1990)
  - Long-term and short-term system load
  - Wheather
  - Market prices
- Automatic control (academic proposal: 80ies; in practice: ?)
  - Controller (re)tuning
  - Adaptive control systems design
- External equivalent models (academic proposal: 80ies; in practice: ?)
- Monitoring (academic proposal: 80ies; in practice: ?)
- Soft sensors (academic proposal: recent; in practice: ?)

Application to electric power systems: *sources of data*

- Data obtained from the field
  - Many sources: SCADA systems, EMS and DMS systems, substations, protections, OASIS, market management systems...
  - Difficulties: not enough data historians, mostly undocumented data, lack of uniform formats, heterogenous quality, access denial...
- Data generated by simulations
  - Generic approach: Monte-Carlo sampling and numerical tools (SE, OPF, SA, DSA...) to generate scenarios and compute inputs, outputs and performance indices for AL
  - Difficulties: complex methodology, needs careful experiment design and interpretation of results, requires large-scale computational infrastructure and tools (grids and DBMS)

Real-life application: wide area control (ULg, PEPITe, Hydro-Québec)

Problem

- Retune CH-F gen./ld. tripping syst.
- Reduce probability of false trip

Approach

- Collect 10,000 real-time snapshots
- Do a lot of time-domain simulations
- Learn decision rules to determine the amount of generation and load to trip as a function of pre-fault conditions

Outcomes

- New rules believed to enhance security
- Rules implemented in control center
- Methodology further applied at HQ

Discussion

(Personal observations and judgements)

- Research and development in automatic learning has increased a lot and gained its maturity during the last 20 years
- In principle, it has a huge potential of applications in electric power systems sensing, monitoring and control
- The electric power systems industry has been distracted from research and development due to the restructuring process
- Even before deregulation, this industry has been deceivingly slow to exploit the potentials of new developments of scientific research

Conclusion?

(Personal recommendation)

Rather than to to lunch new "futurist" research projects, research agencies should encourage the electric power systems industry to invest in what is needed to be able to exploit available technology:

- *Education of power system engineers to probabilistic and other non-conventional methods*
- *Investment into the development of the computational and data management infrastructures*

At the same time, they should fund fundamental research (mostly in Academia) to think about the next generation problems and methods.