

Analysis of electric power and energy systems

Lecture 9: Control of interconnected power systems and economic dispatch

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What will we learn today?

- Why do we need to control the voltage and frequency ?
- Control approaches of voltage and frequency in power systems
- Economic dispatch and optimal power flow methods
- Power systems security assessment

This lecture expands on Chapter 12 from the Ned Mohan's book.

Why and how to control voltage and frequency ?

- Technical requirements
 - Power system devices are designed so as to operate within well-defined 'tolerance regions' around nominal values V_n and f_n
 - Large/persistent deviations from nominal values could lead to cascading phenomena, service interruptions, and safety problems
- Exogenous threats
 - Sudden disturbances, such as line or generator tripping
 - Fast variations of net load (cf Duck curve)
- Control resources
 - Adjusting synchronous generators' field current and mechanical power
 - Changing transformer taps, or switching lines and/or shunt compensation
 - Fast start-up of generator units and/or in extremis load curtailment

Principle of Automatic Voltage Control

- The main tool: primary voltage control via Automatic Voltage Regulators (AVRs) of large synchronous generators and synchronous condensers
- Secondary voltage control and automatic switching of reactive compensation devices and transformer taps
- Tertiary voltage control and voltage profile optimization

Automatic voltage regulator of a synchronous machine

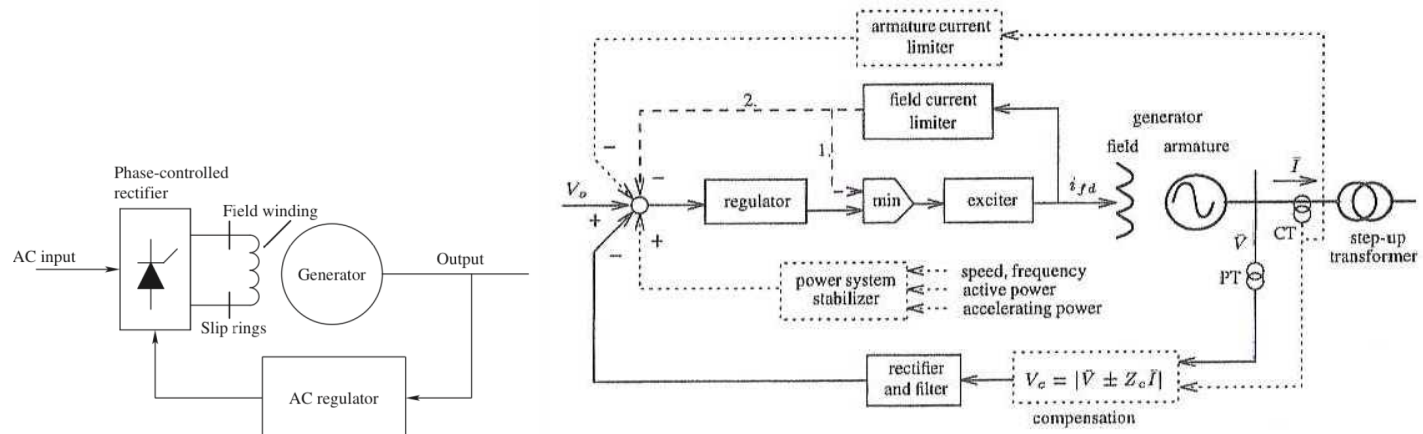


Figure on the right from: Voltage stability of electric power systems. T. Van Cutsem & C. Vournas, KAP 1998

- Notice that if several generators are connected in parallel (either at the MV or at the EHV bus), it is necessary to coordinate their AVRs so that they share the reactive power in an even way.
- The value of Z_c may be adjusted in order to ensure such a coordination.

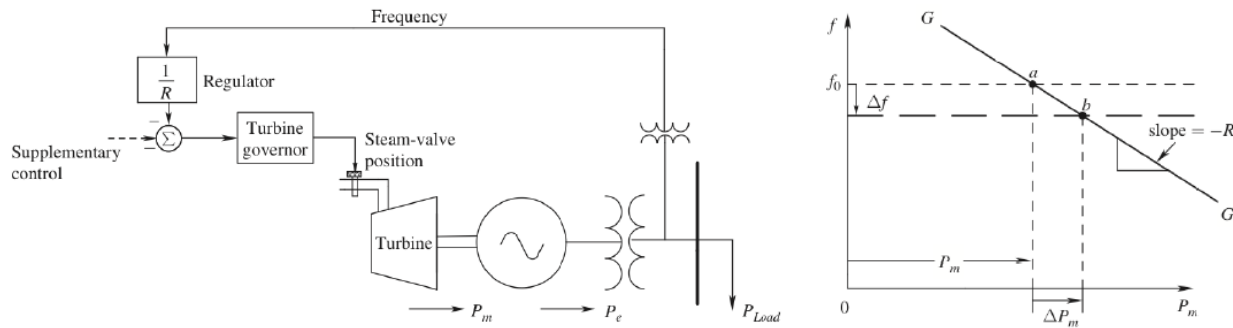
Primary, secondary and tertiary voltage control

- When a disturbance occurs, or subsequently to following the change in load (cf. 'duck curve'), the **primary** voltage control loops maintain suitable voltage levels close to the large power plants equipped with AVRs.
 - However voltages at other buses may move out of tolerance intervals (in either direction), and reactive power reserves may not be shared in an even way among generators.
- **Secondary** voltage control loops can be used at the zonal level, to adjust the set-points of AVRs so as to control the voltage at 'pilot nodes' in the network while distributing the required reactive power evenly among generators.
 - Secondary voltage control loops can also be used to switch shunt reactive compensation devices (capacitors/inductors) in order to increase reactive power generation margins in their zone (among a few large power plants).
- **Tertiary** voltage control uses OPF solvers to calculate set-points at pilot nodes and possibly adjust some transformer ratios, so as to minimize losses and maximize MVar reserves at the entire system level.
- Response times of different levels of voltage control
 - **Primary:** 1-3 seconds ; **Secondary:** 30 seconds -3 minutes ; **Tertiary:** 10-15 minutes

Principle of Automatic Frequency Control

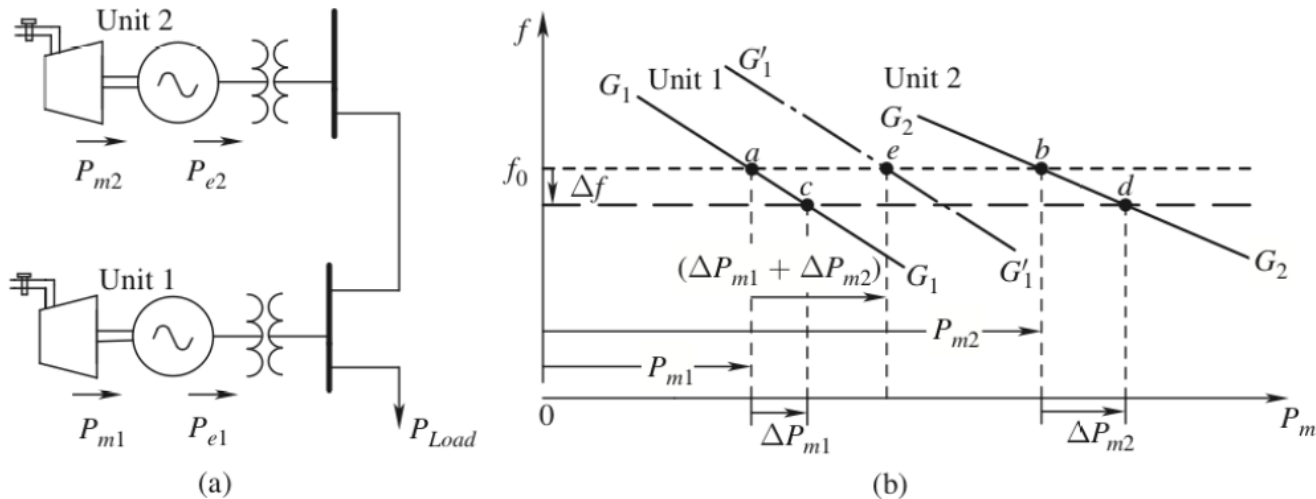
- **The main tool:** primary frequency control via **speed governors** of large synchronous generators
- Secondary frequency control (aka **Automatic Generation Control (AGC)**)
- Tertiary frequency control

Speed governor of a synchronous generator



- Measurement of rotor speed (or stator frequency as a proxy)
- If frequency (speed) is a bit below f_0 , the governor opens a bit more the valve to increase the mechanical power P_m
- In steady state, speed and mechanical power (or equivalently, frequency and electric power) are related by a linear relationship (see diagram on the right)
- This relationship allows to predict how the power generated by a certain generator would change when frequency changes
- It also shows that in order to have the generator adapt his power via this primary control loop, the frequency must change

The case of two generators helping out with a sudden increase of load



- Imagine that suddenly load power increases by ΔP_L : because of KL, total electric power of generators will also increase, hence they start to decelerate leading to a frequency drop. Both will react, according to the governor settings of their primary frequency control loop, to increase their mechanical power
- At steady state, Δf will be such that $\Delta P_1 + \Delta P_2 = \Delta P_L$; typical time to reach steady state: 10-20s
- Depending on mechanical inertia and speed of governor controls, frequency 'nadir' can be much lower than final $f_0 + \Delta f$ at steady state.

Primary frequency control in an interconnected system

- Goal: avoid too large frequency drop upon sudden loss of (the largest) generator connected to the system
 - Each area contributes in proportion to its load level,
 - Within each area, some generators are recruited to ensure area requirement,
 - There is a mutualisation of primary frequency control reserves.
 - If primary frequency control is unable to prevent a too large drop in frequency, more heroic emergency controls will act, e.g. under-frequency load shedding (see Movies)

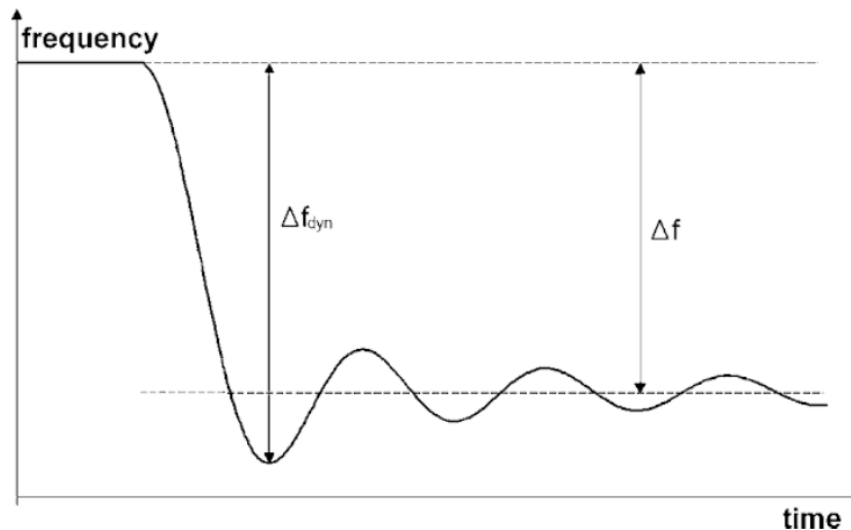
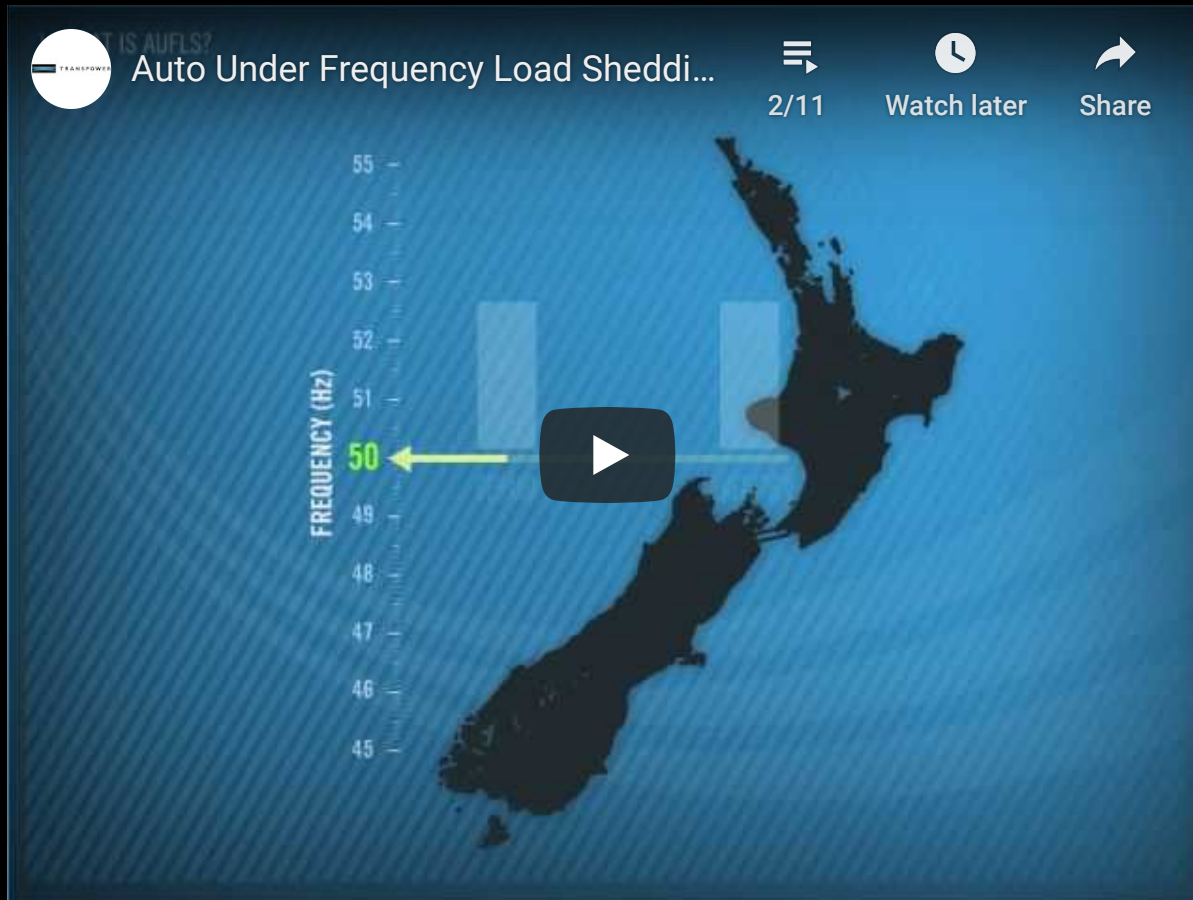


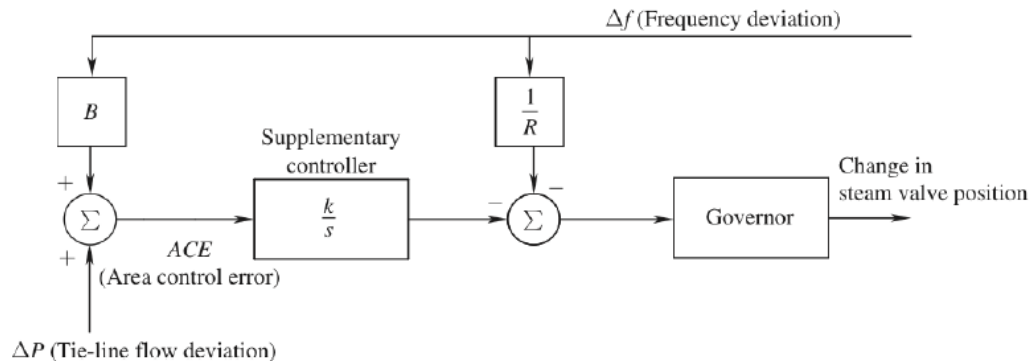
Fig from: <https://top10electrical.blogspot.com/2015/10/primary-secondary-and-tertiary.html>



Automatic under frequency load shedding

Secondary frequency control (aka AGC)

- After (gentle and successful) settlement of primary frequency control there are however some undesirable side effects:
 - Frequency has deviated from the nominal value
 - The exchanges between areas have deviated from their scheduled values
 - Part of the primary frequency control reserves have been depleted
- AGC (or secondary frequency control) aims at cancelling these side effects:



- Since AGC is an integral control, its steady state corresponds to zero Δf and zero ΔP (tie-line flows are also steered back to scheduled values)
- Once frequency is back to normal, primary control reserves are again fully available (takes 5-15 minutes)

Primary, secondary and tertiary frequency control

- **First**, primary control stabilizes frequency and power balance
 - response within 0-30s, fully local and fully automatic
- **Second**, frequency and power exchanges are brought back to nominal/contractual values, and primary control reserves are restored
 - response within 0.5-15 minutes, via area-control center (e.g. one country in Europe)
- **Third**, generation and exchange schedules are re-optimized, while restoring secondary frequency control reserves
 - response within 10-60 minutes, e.g. via intraday power exchange markets

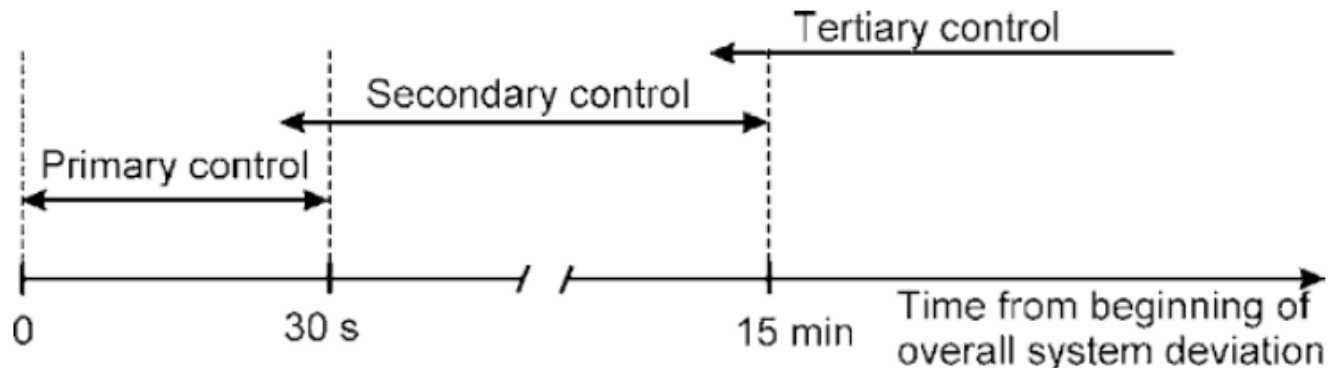


Fig from: <https://top10electrical.blogspot.com/2015/10/primary-secondary-and-tertiary.html>

Economic dispatch and optimal power flow

Two optimization problems

Economic dispatch problem statement (ED)

- Given a total load P_L to serve, and a set of candidate generators $i = 1 \dots n$, with P_i constrained to $\underline{P}_i \dots \overline{P}_i$, and a cost function $C_i(P_i)$,
- Find optimal values P_i such that $\sum_i^n C_i(P_i)$ is minimized
 - while ensuring $\sum_i^n P_i = P_L$ (+ a loss term, possibly).
- See 12.4.1 of ref. book for some intuition about the solution to this problem

Optimal power flow problem statement (OPF)

- As above, + network constraints
 - (given network topology, and electrical parameters of lines, cables, transformers, and shunt devices, as well as current flow limits of lines and transformers, and voltage tolerance intervals at buses)
- Determine the P_i such that $\sum_i^n C_i(P_i)$ is minimized
 - while modeling KLaWs and enforcing the above network-wise limits

Assessing the security/reliability of an electric power system

- General idea of security assessment
- Standard N-1 static security assessment
- Voltage stability assessment
- Transient stability assessment

General idea of security/reliability assessment

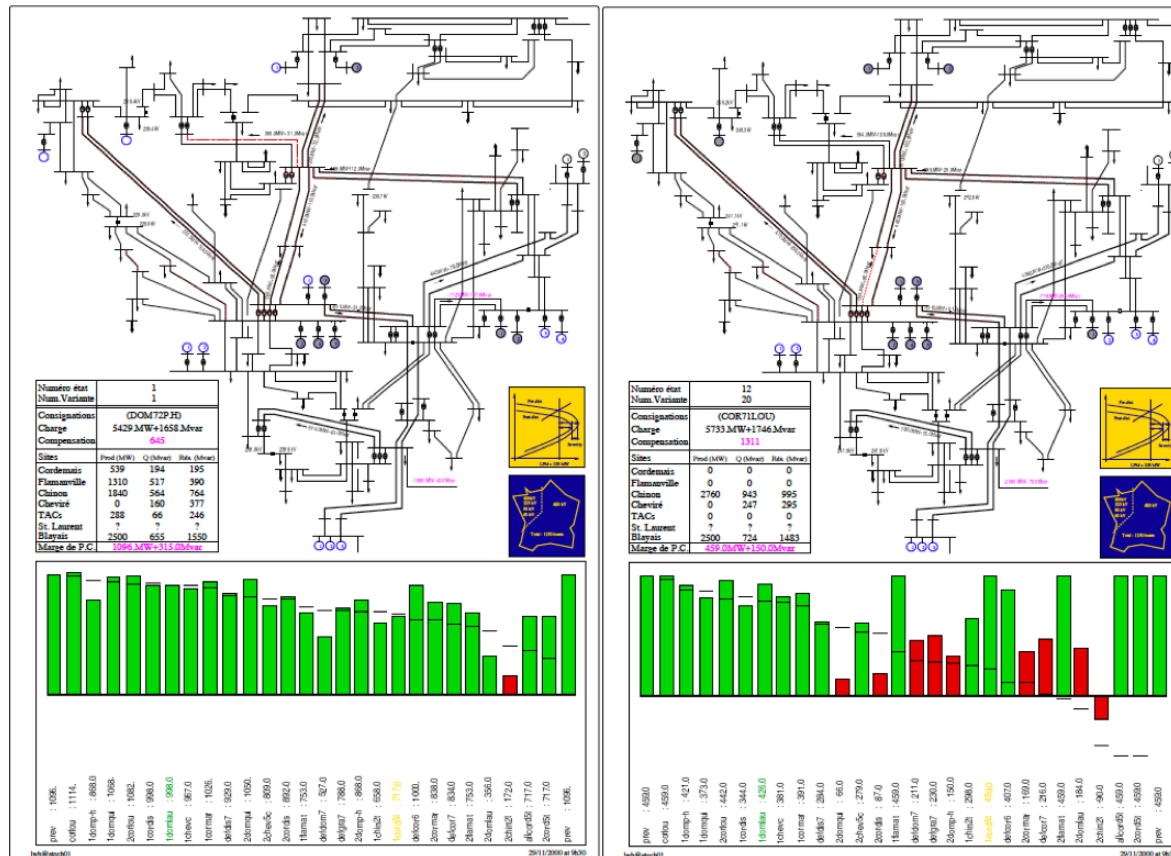
- General motivation:
 - Check the robustness of the system to a number of possible contingencies
 - NB: see examples of contingencies in subsequent slides
- Generic security assessment approach:
 - Given a list of contingencies and a steady-state base-case operating point of the system
 - Simulate the impact of each contingency if it is applied to the base case
 - For each simulation, check whether system response is acceptable
 - Summarize and display the results for all contingencies
 - If too many contingencies lead to unacceptable response, the base-case is insecure
- Remarks:
 - Such analyses can be carried out periodically, based on real-time measurements
 - They can also be applied in look-head mode, on a set of possible future system conditions
 - Such analyses are extensively carried out by TSOs, and when the conclusion is negative, the TSO has to decide preventive/corrective counter-measures

Standard N-1 static security assessment

- List of contingencies: all single-component outages
 - e.g. all single-line outages + all single-transformer outages
 - plus possibly all single-generator outages
- Procedure:
 - Run a power flow computation for the base case, and check pre-contingency limits
 - For each outage in the contingency list, run a power flow computation to determine post-contingency voltages and currents, and check post-contingency limits
- Precise limit values can depend on the context of security assessment:
 - e.g. in real-time operation, line/transformer permanent thermal limits and steady state voltage magnitude tolerance intervals are checked both for pre- and post-contingency
- Remarks/orders of magnitude:
 - e.g. for a system like the Belgian EHV transmission system (ELIA)
 - 1000-2000 contingencies
 - 2000-4000 limits to check for each contingency
 - Need to summarize in graphical form the results to be useful for a human operator

Voltage stability assessment (./...)

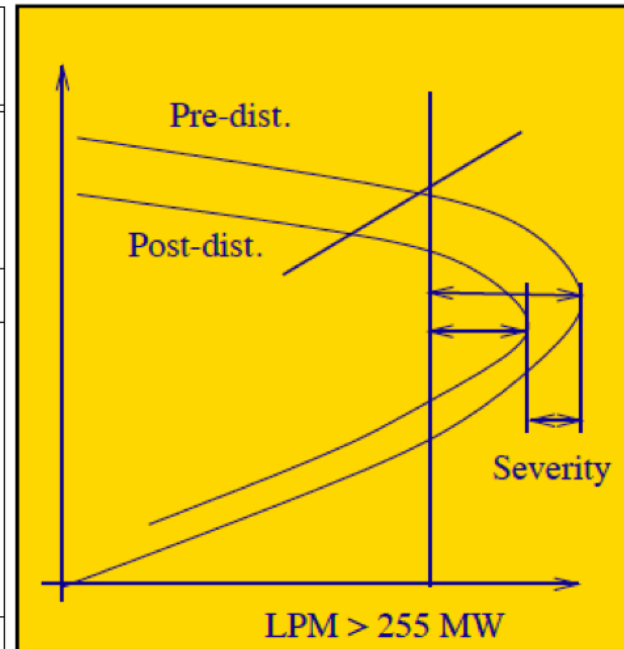
- Goal is to measure how far the system is from the voltage instability
- Distance: **Load power margin** i.e. how much load can be further increased until reaching the tip of the **nose-curve**



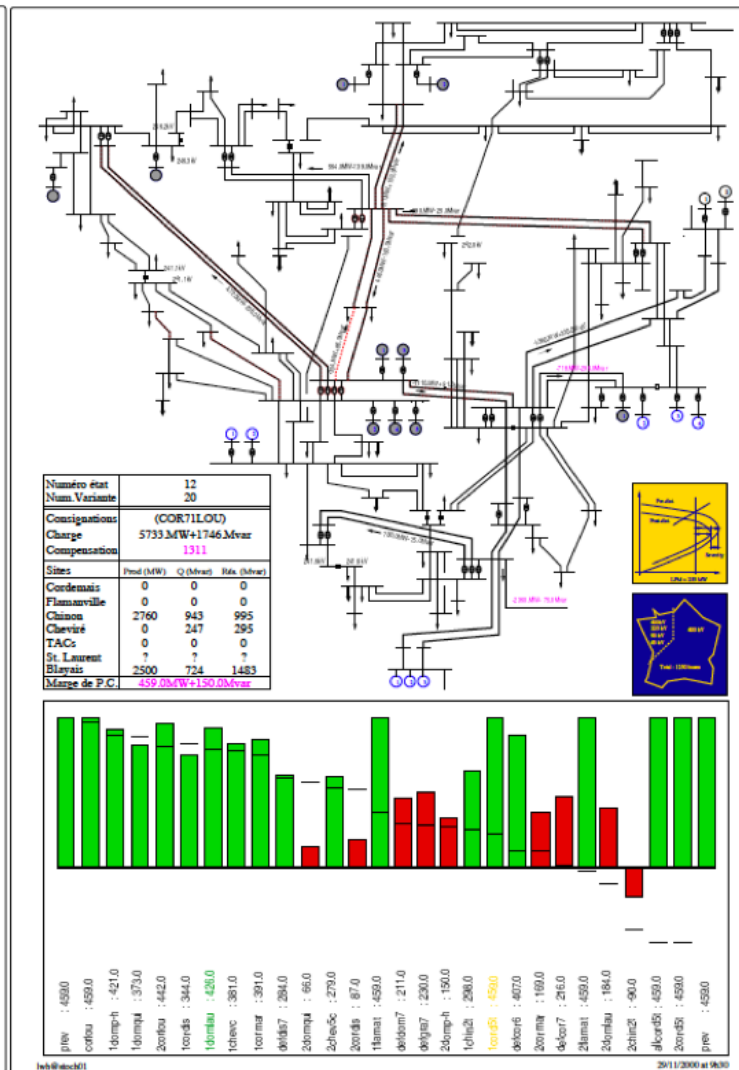
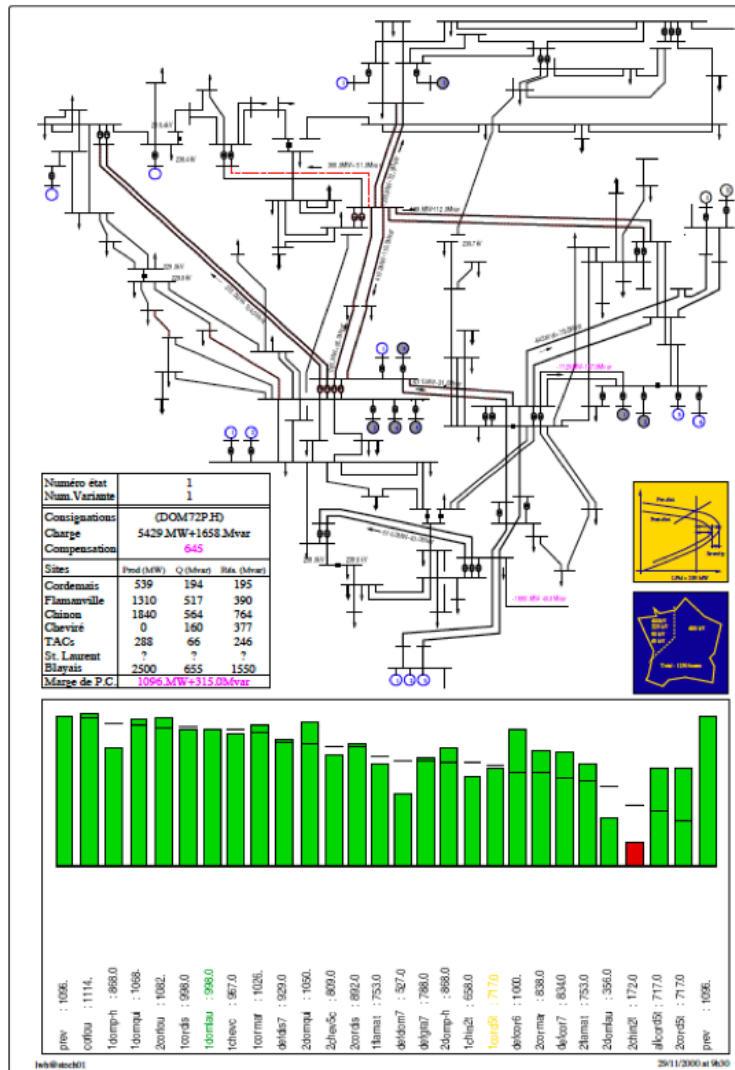
Voltage stability assessment (../...)

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Numéro état	4		
Num.Variante	6		
Consignations	(CHA61COR)		
Charge	4927.MW+1502.Mvar		
Compensation	285		
Sites	Prod (MW)	Q (Mvar)	Rés. (Mvar)
Cordemais	548	144	237
Flamanville	0	0	0
Chinon	1840	540	794
Chevire	0	125	414
TACs	0	0	0
St. Laurent	?	?	?
Blayais	2500	650	1558
Marge de P.C.	1002.MW+308.0Mvar		



Voltage stability assessment (.../...)



Transient stability assessment

- List of contingencies:
 - various 3-phase short-circuit locations and clearing schemes
 - e.g. at the EHV bus of each large power plant; on the different important lines connecting some power plants to the rest of the system
- Distance to instability:
 - compute CCT for each disturbance
 - compare with actual protection delays of the different types of faults
- Remarks:
 - Very time consuming computations, hardly possible in real-time
 - Need 'approximations' to speed up computations
 - Need to also determine suitable preventive or corrective countermeasures for the most dangerous contingencies

Transient stability limited systems

- Hydro-power dominated systems (e.g. Hydro-Québec)
- Longitudinal systems (e.g. Vietnam, Italy)
- Counter-measures: power flow limits; fast generation-tripping systems



Problem

- ▶ Improve emergency control scheme
 - ▶ Churchill-Falls power plant
- ▶ Reduce probability of blackout

Approach

- ▶ 10,000 real-time snapshots sampled (several years)
- ▶ Massive time-domain simulations
- ▶ Automatically learn decision rules to determine optimal amount of generation and load to trip
- ▶ Implement rules in real-time
- ▶ **New rules enhance security**

Likely impact of the energy transition

A think tank

- Less synchronous generators in operation at the transmission level results in reduced inertia and deeper frequency nadir, leading to more stringent requirements for (primary) frequency control
- Duck curve leads to higher variability of flows and more changes in flow-directions, making voltage control more complex/difficult
- Tech opportunities are provided by fast progress in IT and power electronics, leading to a lot of research and development opportunities

References

- Mohan, Ned. Electric power systems: a first course. John Wiley & Sons, 2012.

