Analysis of electric power and energy systems

Lecture 8: Transient and dynamic stability

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What will we learn today?

- Swing dynamics, loss of synchronism, and transient (in)stability
- Dynamic stability and interarea oscillations
- Cascading phenomena

This lecture expands on Chapter 11 from Ned Mohan's book.

First-swing transient (in)stability problem

One-Machine-Infinite-Bus system (OMIB)

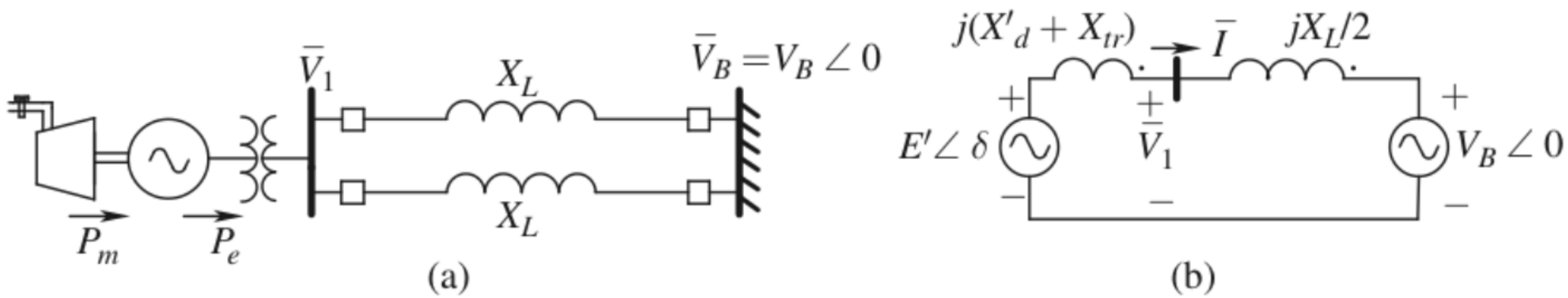


FIGURE 11.1 Simple one-generator system connected to an infinite bus.

See Figure (a):

- On the left, a synchronous generator driven by a turbine providing mechanical power P_m, and connected via a up-step transformer to the grid to deliver its electrical power P_e (it is called the machine).
- On the right of Fig (a), a very large system operating at synchronous frequency (it is called the infinite bus) and imposing the voltage $V_B \angle 0$.
- A double-circuit line (twice X_L in parallel) connecting the two parts.

Electric model of the OMIB system

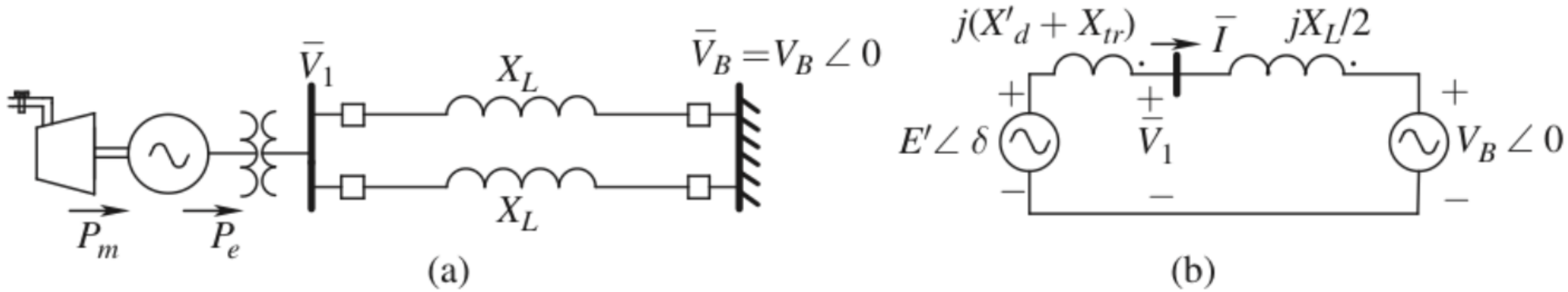
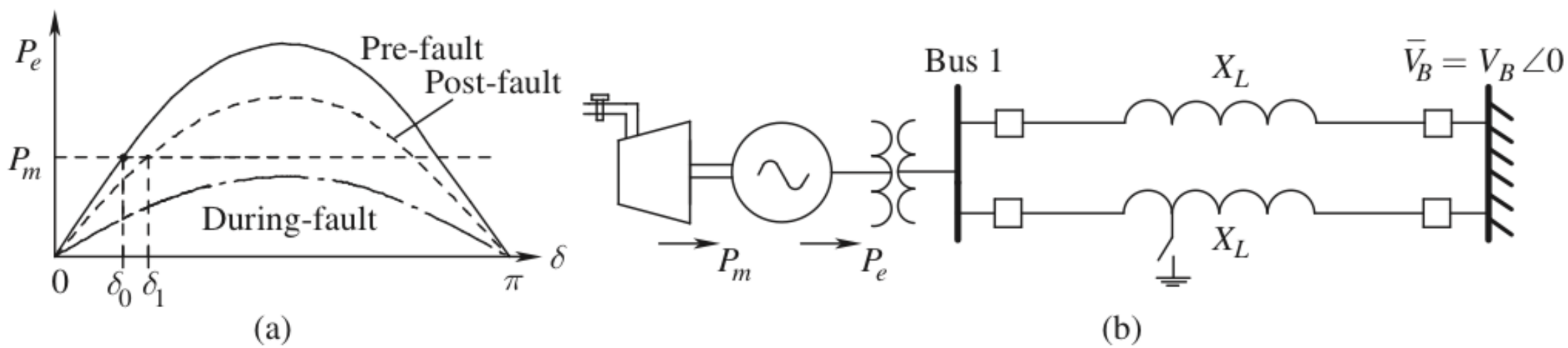


FIGURE 11.1 Simple one-generator system connected to an infinite bus.

See Figure (b):

- The machine is electrically represented as an ideal voltage source ($E' \angle \delta$) behind a transient reactance X'_d.
- Active power losses in the step-up transformer are neglected, and the transformer is simply modeled as a series reactance X_t.
- The two parallel circuits of the line are assumed of equal reactance X_L and their resistances and capacitances are neglected.
- The losses of the electro-mechanical conversion $P_m \to P_e$ are neglected.

The typical scenario of transient stability studies



- Initially the machine is operating in steady state corresponding to an angle δ_0 defined by the "Pre-fault" electric power characteristic.

- At t_0, a short-circuit appears on one of the two circuits of the line, resulting in a sudden decrease of the electric. power P_e delivered by the machine, according to the "During-fault" curve. The machine accelerates, because now $P_e < P_m$, hence its rotating speed ω_m and its angle δ start to increase.

- At $t_1 > t_0$, the short-circuit is cleared by breakers opening the circuit at its two ends, resulting in an increase of the electric power P_e, according to the "Post-fault" curve. This typically leads to a deceleration, but the speed ω_m is above the synhronous speed, the angle continues to increase.

Remarks and simplifying assumptions

- The (active) electrical power delivered by the machine is given by

$$P_e = \frac{E' V_B}{X_T} \sin \delta$$

  where X_T and V_B denote the reactance and voltage seen by $E' \angle \delta$.

- The machine is rotating at the mechanical speed ω_m (rad/s), and in the initial steady state this corresponds to the synchronous speed.

- A power flow solution assuming a PV or a PQ node at the generator HV bus, provides $\bar{V}_1$ from which we can compute E' and δ in steady state.

- P_m in steady state is set to the active power initially produced by the machine.

- Typically, a line-fault in EHV systems is cleared in less than 100ms, a study period of 1-2 seconds is often sufficient to check stability/instability.

- We assume here that P_m and E' can be considered as constant during the study period, but governor and excitation systems tend to improve stability.

Derivation of the swing equations

- Accelerating and decelerating torques acting on the mechanical speed

$$J_m \frac{d^2\delta_m}{dt^2} = T_m - T_e$$

where J_m is the moment of inertia.

- In terms of powers we have

$$\omega_m J_m \frac{d^2\delta_m}{dt^2} = P_m - P_e$$

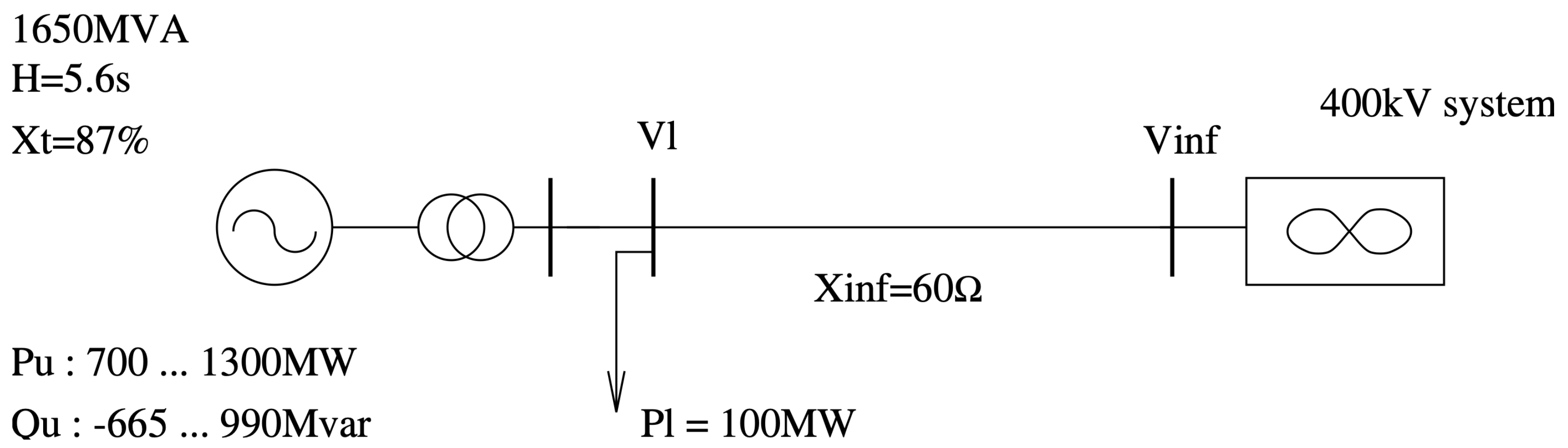
- Converting to electrical angles δ and electrical speeds ω, and observing that in practice $\omega \approx \omega_s$, we obtain

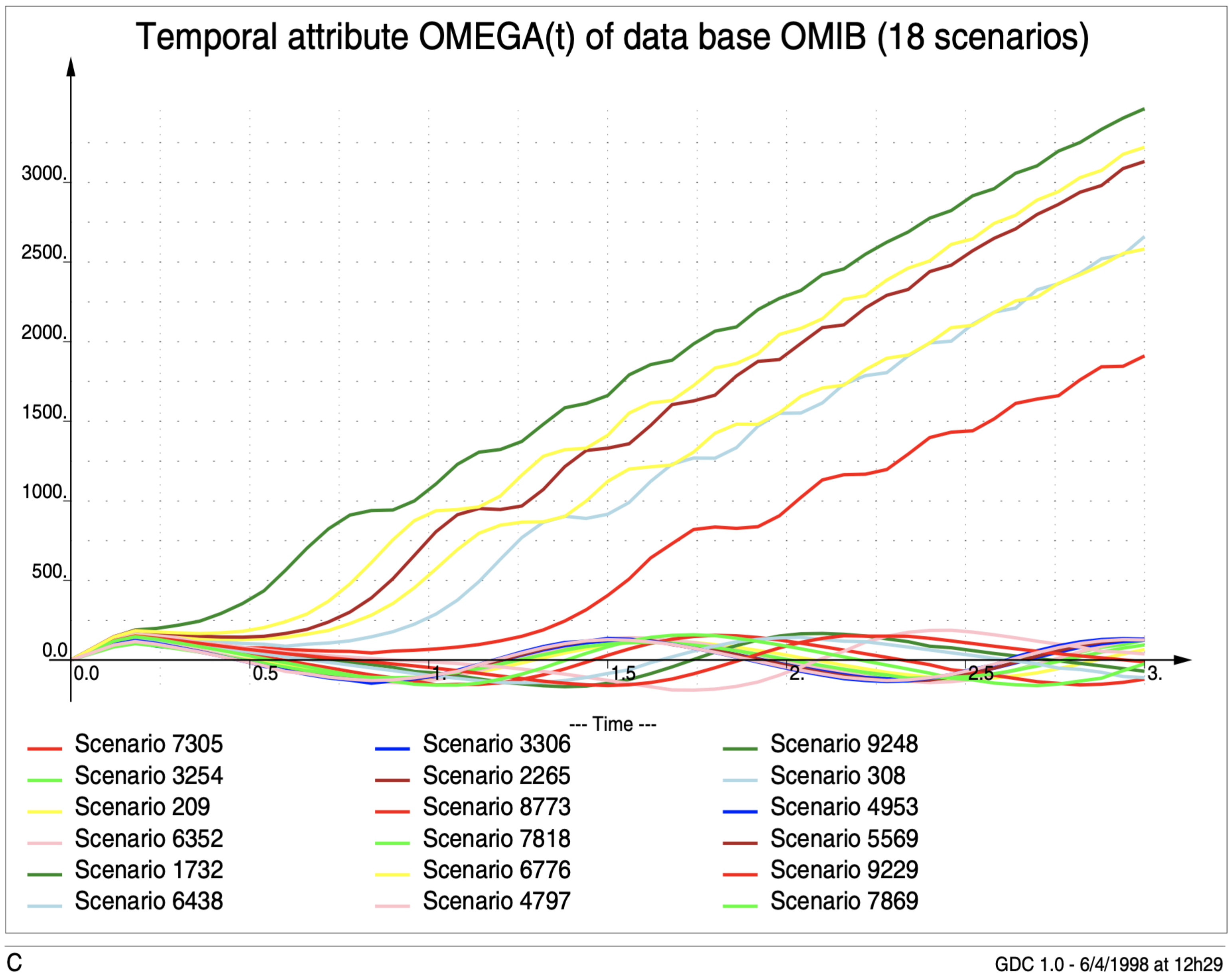
$$M \frac{d^2\delta}{dt^2} = P_m - P_e$$

(where $M = 2H/\omega_s$, see reference book for derivations).

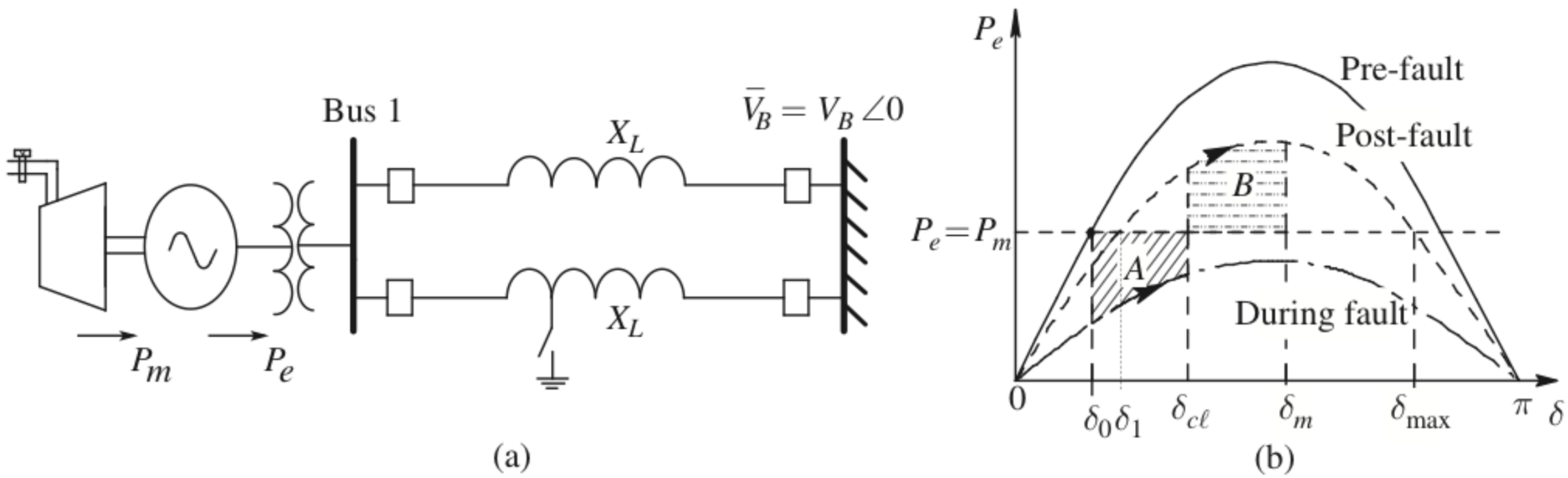
- NB: typically $H \in [1 - 10]$ seconds in machine MVA-base.

Typical swing-curves computed by time-domain simulation





The equal area criterion (forward swing)



- Kinetic energy gained in the 'During-fault' acceleration period

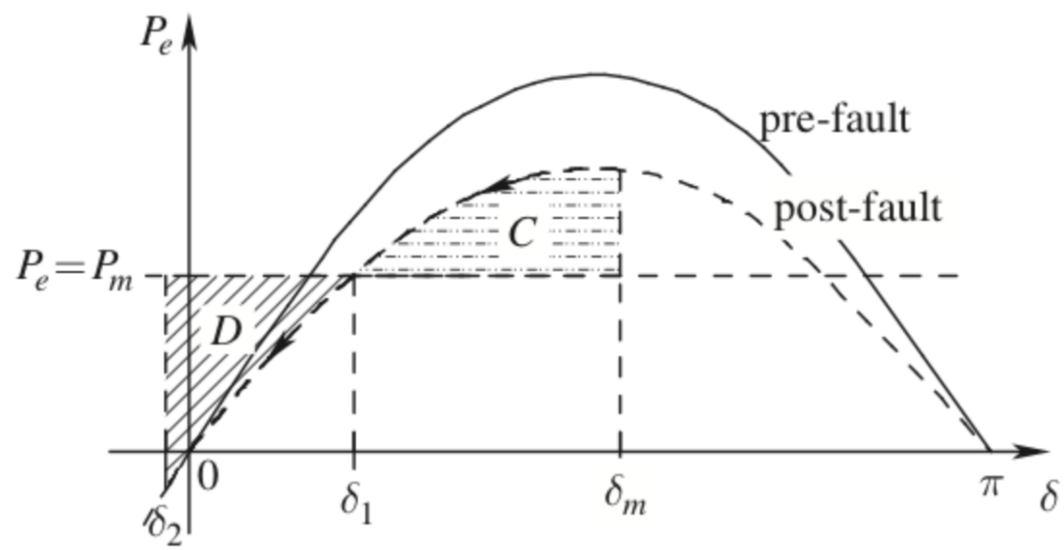
$$A = \int_{\delta_0}^{\delta_c} (P_m - P_e) d\delta$$

- The kinetic energy lost in the 'Post-fault' deceleration period

$$B = \int_{\delta_c}^{\delta_m} (P_e - P_m) d\delta$$

- Condition $A = B$, correponds to $\omega_m = \omega_s$ while $P_e(\delta_m) > P_m$: a maximum angle is reached, and subsequently the system swings-back.

The equal area criterion (back swing)



- Kinetic energy lost in the back-swing deceleration period

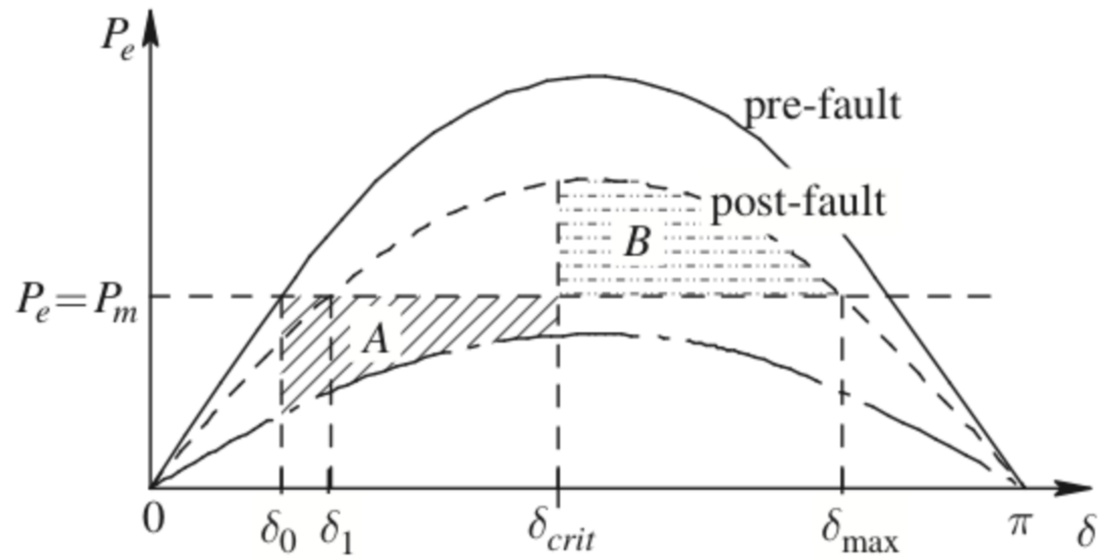
$$C = \int_{\delta_m}^{\delta_1} (P_m - P_e) d\delta$$

- The kinetic energy gained in the back-swing acceleration period

$$D = \int_{\delta_1}^{\delta_2} (P_e - P_m) d\delta$$

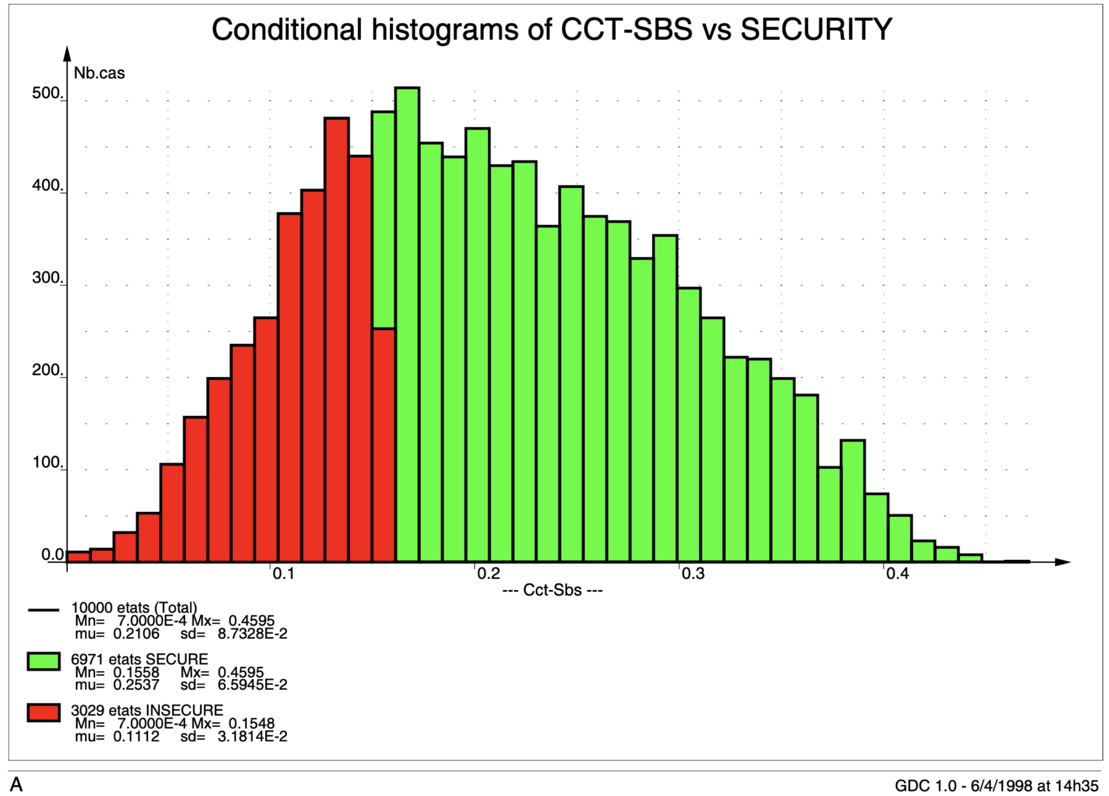
- There always exists a δ_2 such that $C = D$. After that, the angle increases again until δ_m, and decreases again until δ_2 etc. (There is no damping...)

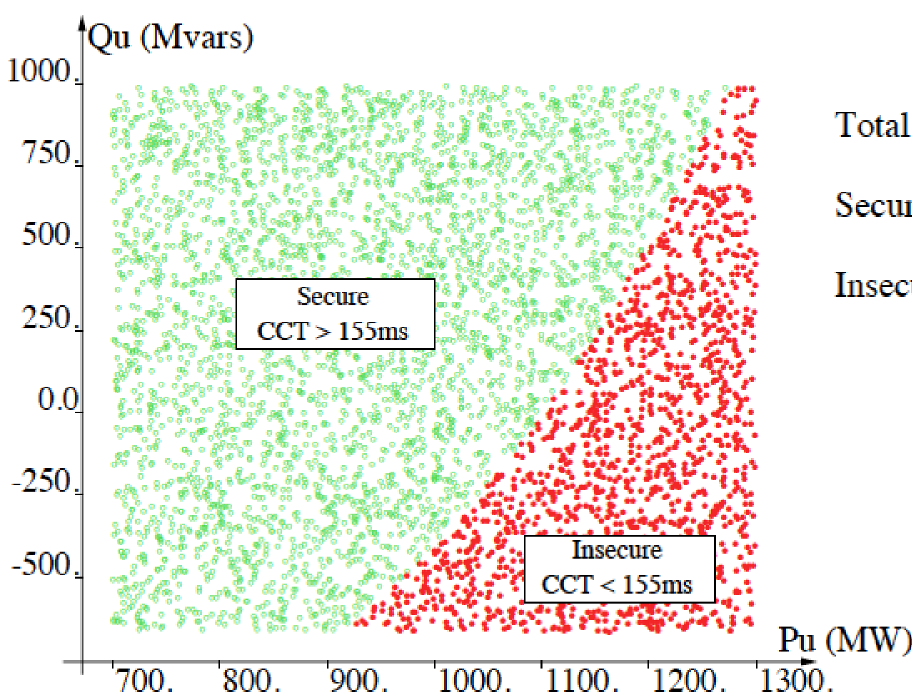
The notion of critical clearing time



- Increasing the time t_c to clear the fault increases the clearing angle δ_c and hence area A. Therefore δ_m will also increase to have area B increase as well so as to compensate the new value of A.
- Once $\delta_{\max}$ is reached, it is not possible to compensate for a further increase in δ_c. This corresponds to the critical fault-clearing angle.
- The time needed in the during-fault configuration to reach this critical clearing angle is called the Critical Clearing Time (CCT).
- One shows that with our simple model, if $t_1 - t_0 < CCT$ the system is stable, and otherwise unstable.
- In practice there are several sources of damping helping further out.

Illustration of CCT values (example of slide 7)

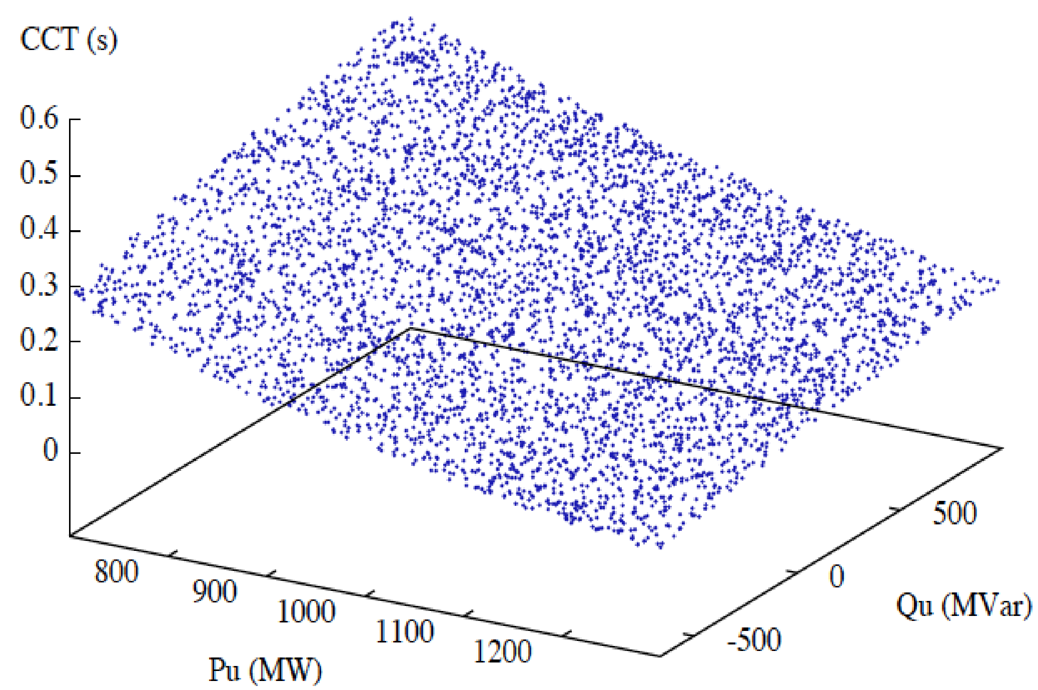




Total : 5000 states

Secure : 3510 states

Insecure : 1490 states



Discussion

- Multi-machine systems and load models
  - Machines that are located closer to the fault will accelerate more during the fault
  - Static loads as impedances, dynamic loads as induction motors, HVDC special models
- Effect of voltage and mechanical power controls and damping
  - Typically favorable, because they want voltage and speed to be close to nominal
- Effect of fault-type, location, and clearing scheme
  - The faster fault clearing, the better; fast line reclosing can be useful
  - Three-phase short-circuits worse than single phase, the closer to the generator the worse
- Effect of increasing the distance towards the rest of the system generators
  - The longer the distance of a power plant from the rest of the system, the more problematic from the viewpoint of transient instability.
  - Series compensation and/or shunt SVCs may help a lot
- Emergency control and other stability enhancements
  - Generator tripping
  - Fast mechanical power reduction, or electric braking

Transient instability is typcially much faster than voltage instabiliy

Inter-area instabilities and undamped oscillations

Read section 11.4 from reference book

Figures on the next slide are taken from: CIGRE 2000, Paper No 38-113, Analysis and Damping of Inter-Area Oscillations in the UCTE/CENTREL Power System, H. Breulmann, et al

CIGRE 2000, Paper No 38-113

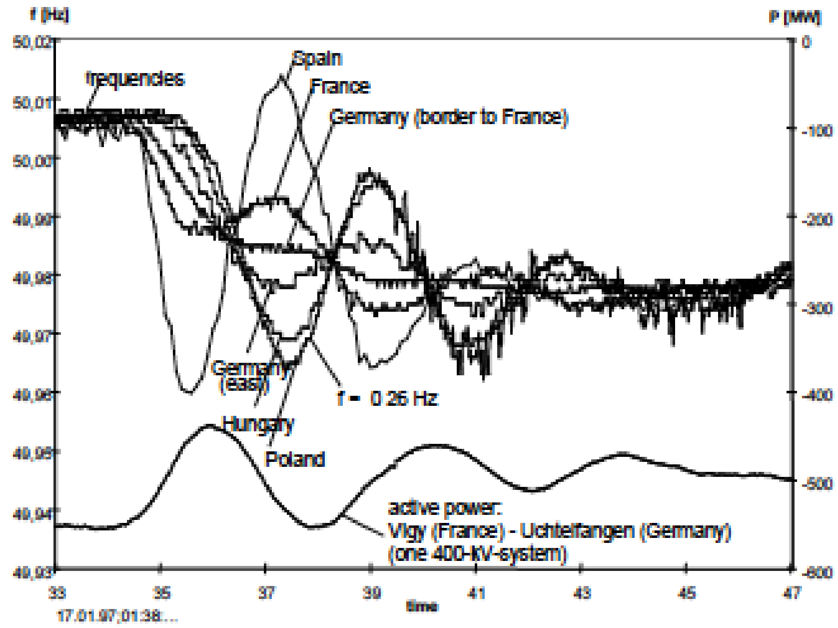


Fig. 2 Inter-Area Oscillation after Power Plant Outage in Spain, 900MW

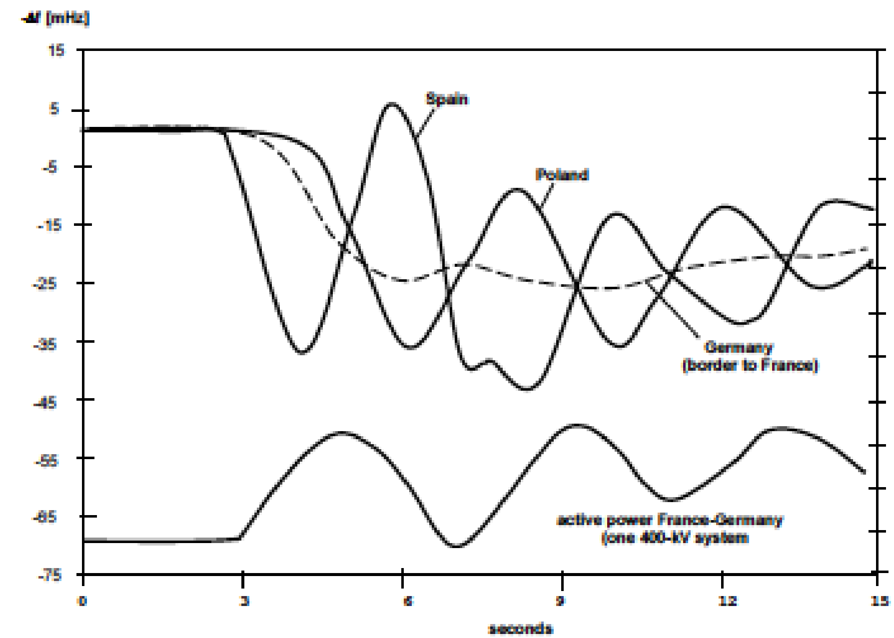


Fig. 4 Simulation of Power Plant Outage in Spain, 900 MW

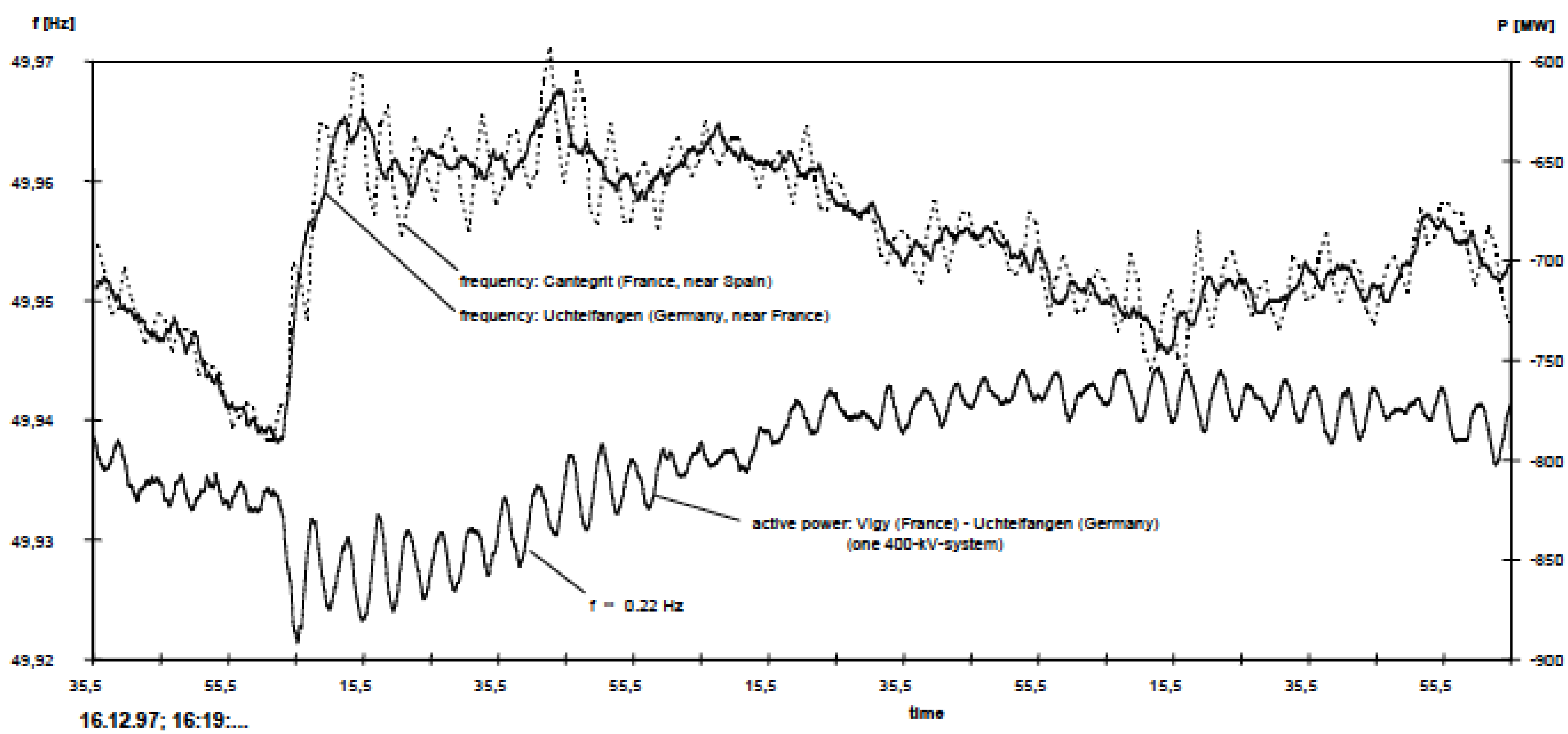


Fig. 3 Inter-Area Oscillation after Load Outage in Spain, 487 MW

Illustration of cascading phenomena

Example

At t=0s : Loss of a corridor of 400kV lines

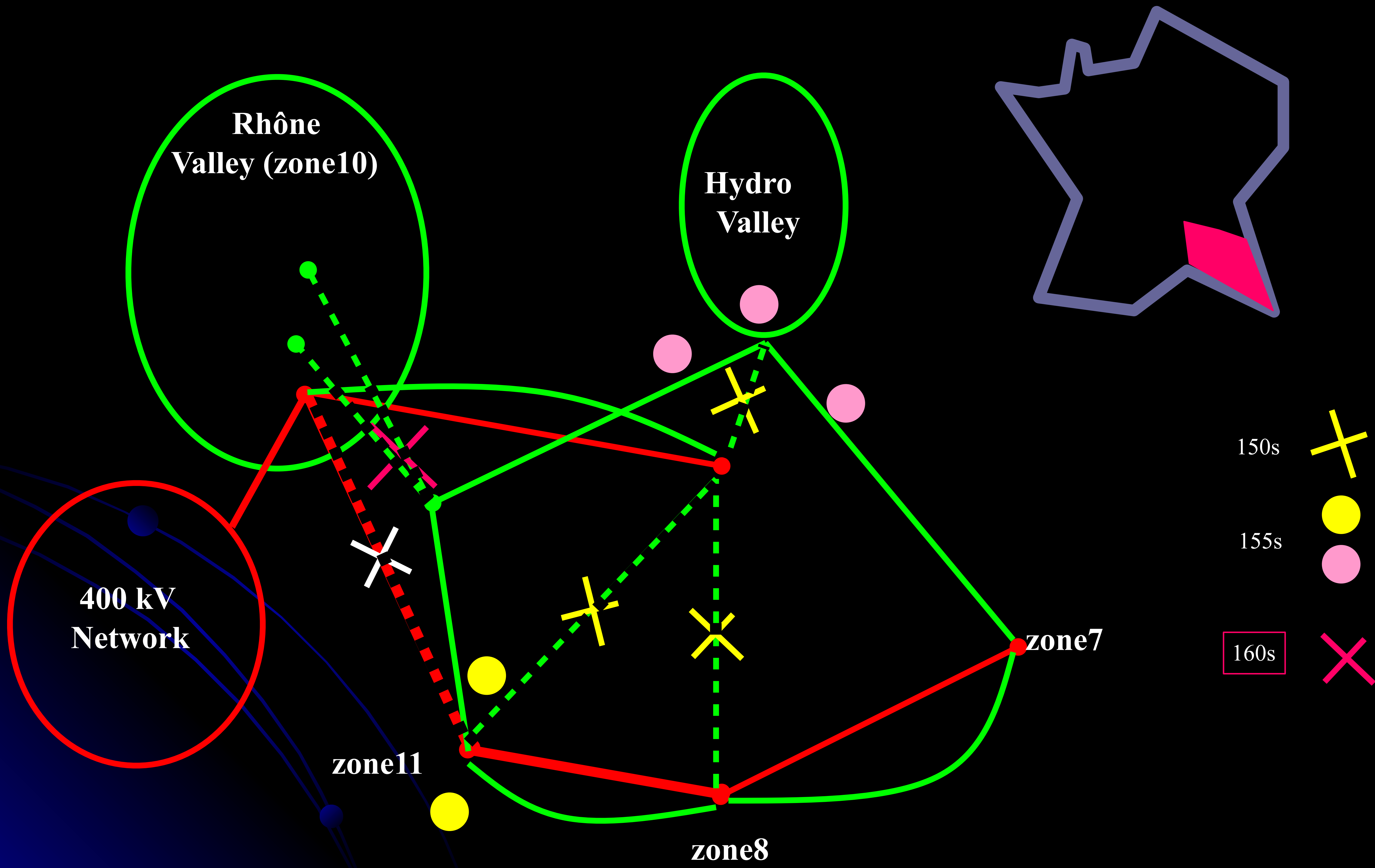
⇒ Overload, then tripping of three connexions :
- towards Zone 7 (225 kV) : 150 s
- towards Zone 8 (225 kV) : 150 s
- towards Zone 11 (225 kV) : 150 s

⇒ Loss of generators (total of 2500MVA lost):
- Two thermal plants on undervoltage protection : 155 s
- Three hydro plants on overspeed protection : 155 s

⇒ Overload, then tripping of the connexion towards Zone 10 (225 kV) : 160 s

⇒ Load shedding in zones 7, 8 and 11

Example (visual)



Likely impact of the energy transition

A think tank

- Less synchronous generators in operation at the transmission level
- Duck curve
- Higher variability of flows and flow-directions at the transmission level
- Tech opportunities

References

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

The end.