Test Case:
Power System Voltage Stability

Mats Larsson

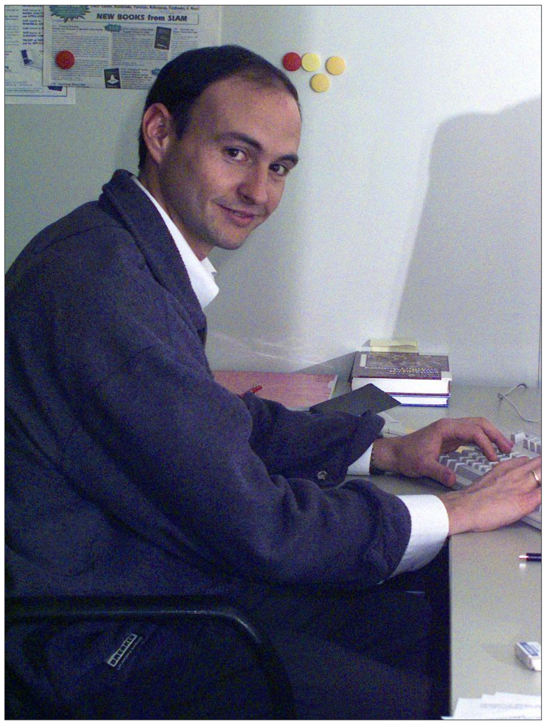
Preview

- The People from ABB
- Characteristics of Power Systems
- Voltage Stability
- Corrective Measures
- The ABB Platform for Corrective Control
- What do we need from CC ?

- The ABB Power Grid Test Case
- Conclusion

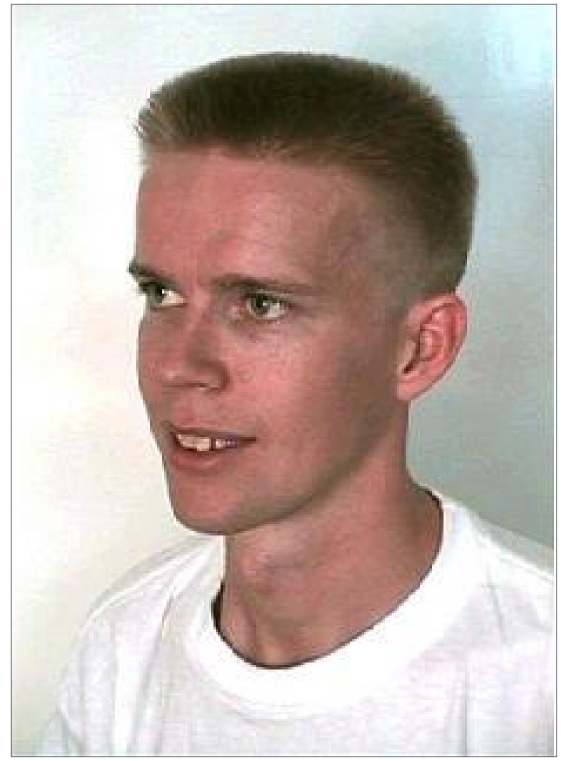
People Involved From ABB

- **Eduardo Gallestey**



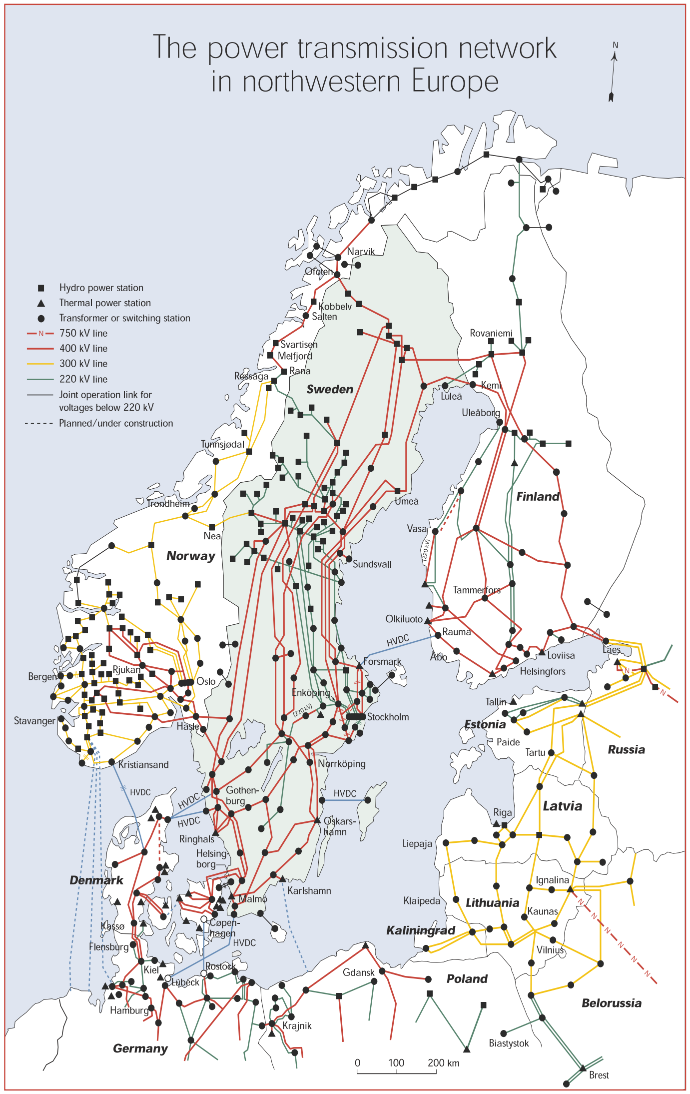
- **PhD in Mathemathics 1998**
  - **University of Bremen**
  - **Optimal and robust control, optimization etc.**

- **Mats Larsson**



- **PhD Industrial Automation 2001**
  - **Lund University**
  - **Control and stability of power systems**

Characteristics of Power Systems



- Large-scale
- Substantial nonlinearity
- Wide span of time-scales
- Uncertainty
- Changing operating point
- Mix of continuous and discrete control variables
- Embedded Controllers
- System model has differential-algebraic structure

- A good example of a ”complex” system !

Control of Power Systems

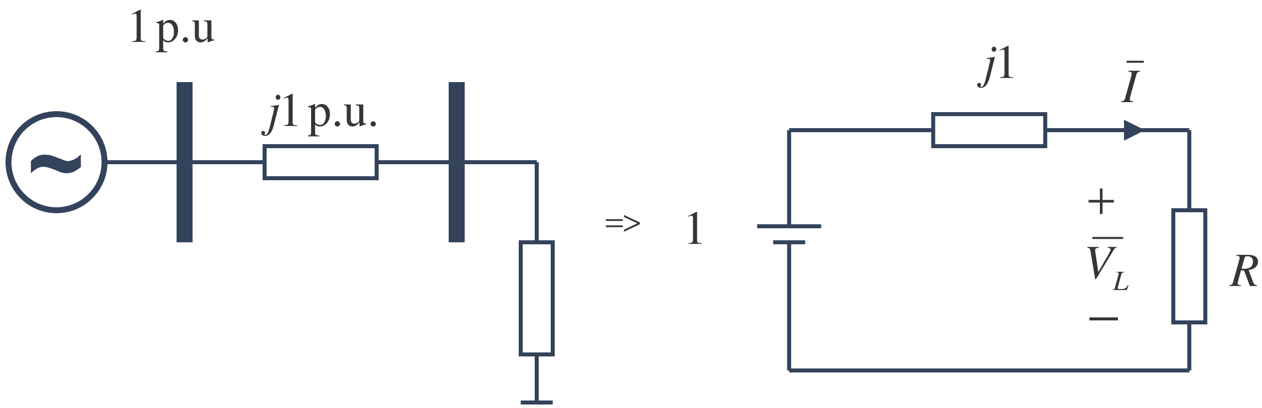
- Global control problem extremely difficult
- Decomposition, Controller hierarchies

- Some stability concerns in PS
  - Frequency stability – Simple linear decentralized control
  - Transient stability -- Energy functions, Lyapunov
  - Small-disturbance stability – Linear analysis, H_inf etc.
  - *Voltage stability – Model Predictive Control etc.*

System collapse due to Voltage Instability

Date	Location	Time to Collapse
860413	Winnipeg, Canada, Nelson River HVDC link	1 s
861130	SE Brazil, Paraguay, Itaipu HVDC link	2 s
850517	S Florida, USA	4 s
870822	W Tennessee, USA	10 s
960702	Western USA	35 s
831227	**Sweden**	55 s
820902	Florida, USA	1-3 min
821126	Florida, USA	1-3 min
821228	Florida, USA	1-3 min
821230	Florida, USA	1-3 min
770922	Jacksonville, Florida	minutes
820804	Belgium	4-5 min
870112	Western France	6-7 min
651209	Bretagne, France	minutes
761110	Bretagne, France	minutes
870723	Tokyo, Japan	20 min
781219	France	26 min
700822	Japan	30 min

Voltage Stability



$v =$ load voltage

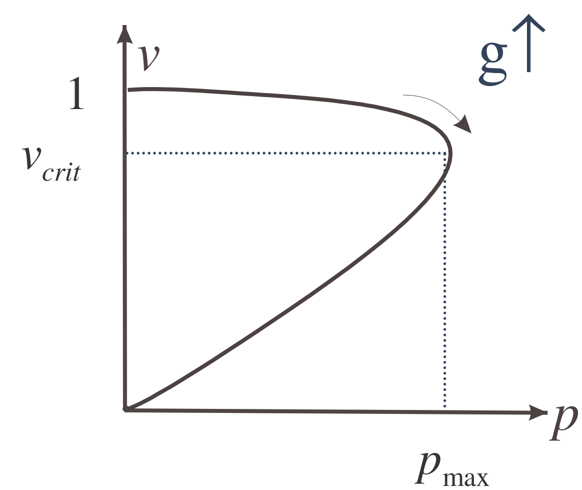
$\text{p} =$ load power

$\text{g} =$ load admittance

$$\bar{I} = \frac{1}{R + j1} \Rightarrow \bar{V}_L = R\bar{I} = \frac{R}{R + j1} = \frac{1}{1 + jg}$$

$$v = \left|\bar{V}_L\right| = \frac{1}{\sqrt{1 + g^2}}$$

$$p = gv^2$$



- **Maximum transfer:** $p = p_{\max}$ **at** $v = v_{crit}$

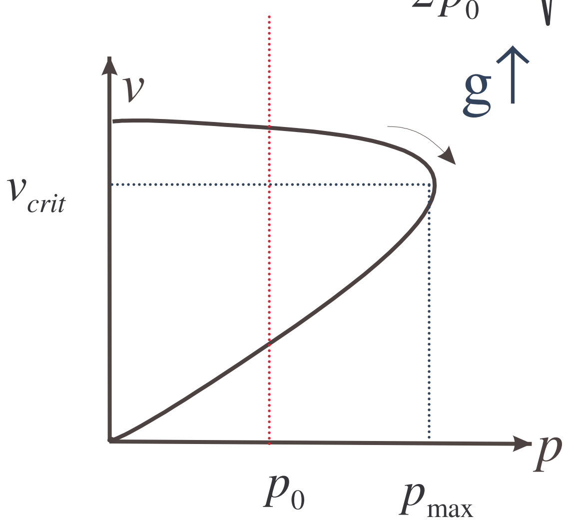
Stability analyis

- **Load constant power behavior:**

$$\begin{cases} T\dfrac{\mathrm{d}g}{\mathrm{d}t} = p_0 - gv^2 \quad \text{(increase } g \text{ if consumption too low)} \\ v = \dfrac{1}{\sqrt{1+g^2}} \end{cases} \quad => \quad f(g) = \frac{\mathrm{d}g}{\mathrm{d}t} = \frac{1}{T}\left(p_0 - \frac{g}{1+g^2}\right)$$

- **Stationary points given by:**

$$f(g) = 0 => g^* = \frac{1}{2p_0} \pm \sqrt{\frac{1}{4p_0^2} - 1}$$



$p_0 < 0.5$ - two equilibrium points

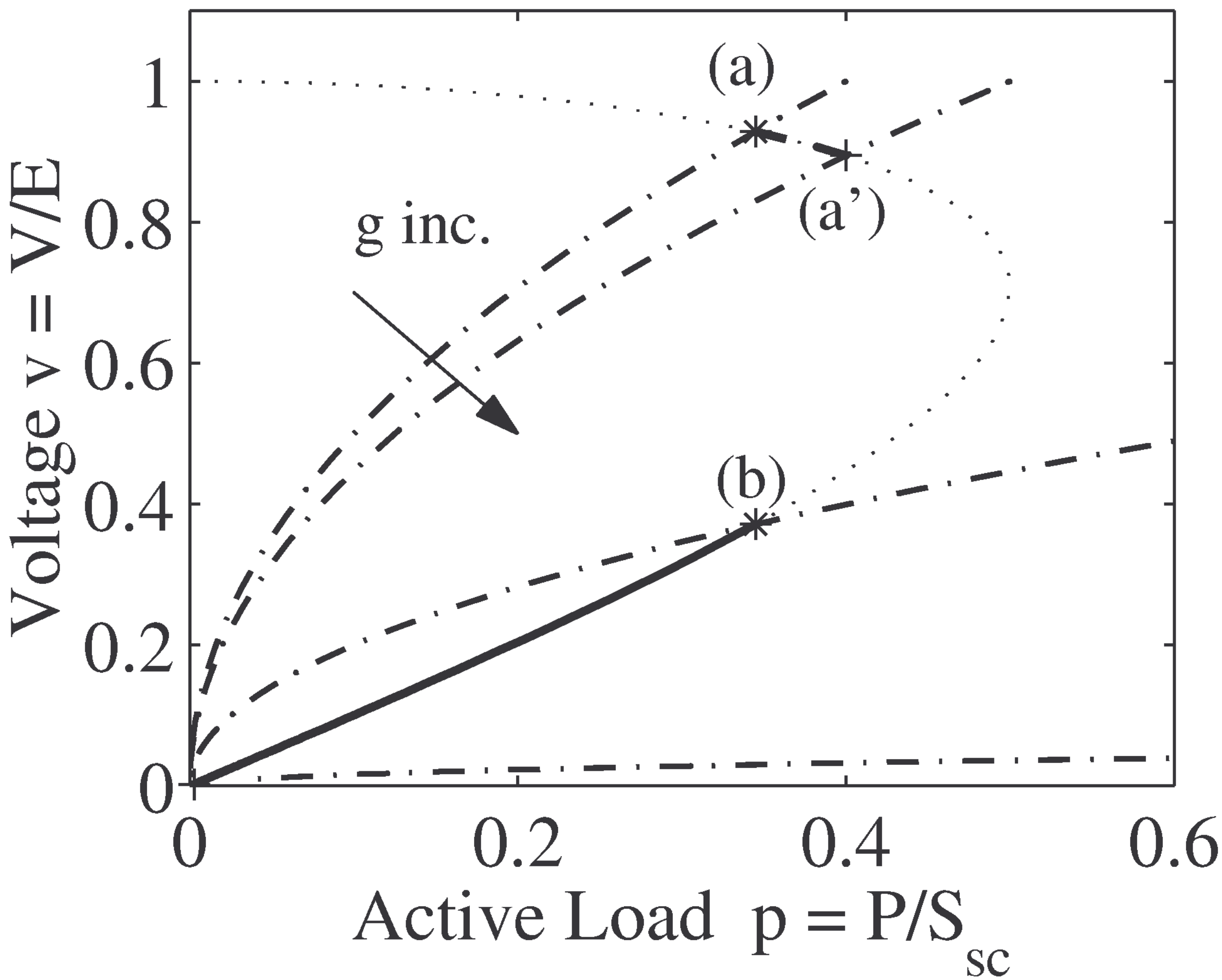
$p_0 = 0.5$ - the two equilibrium points coalesce

$p_0 > 0.5$ - no equilibrium points

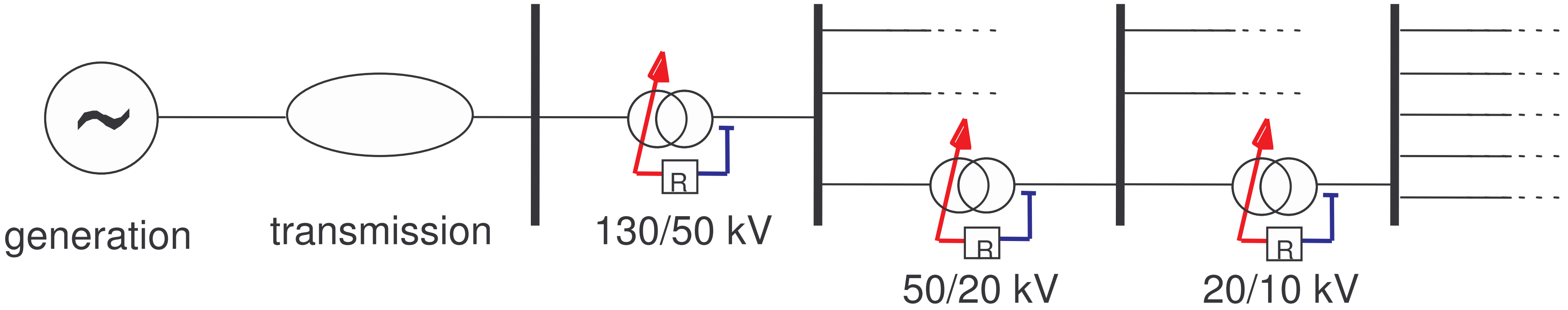
Unstable if: $p_0 > p_{\max}$ or $v < v_{crit}$

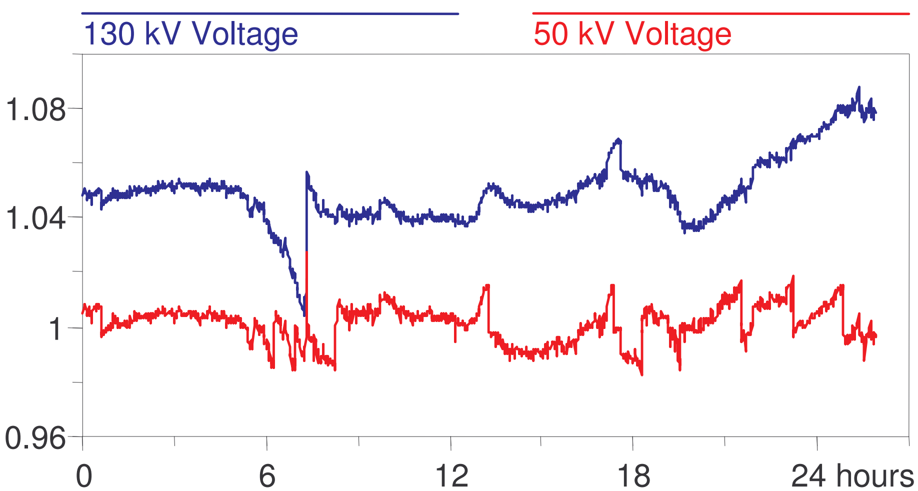
Simulation Results

- **Small Step in p0 (a) – stable case, (b) unstable case**



Tap Changer Control



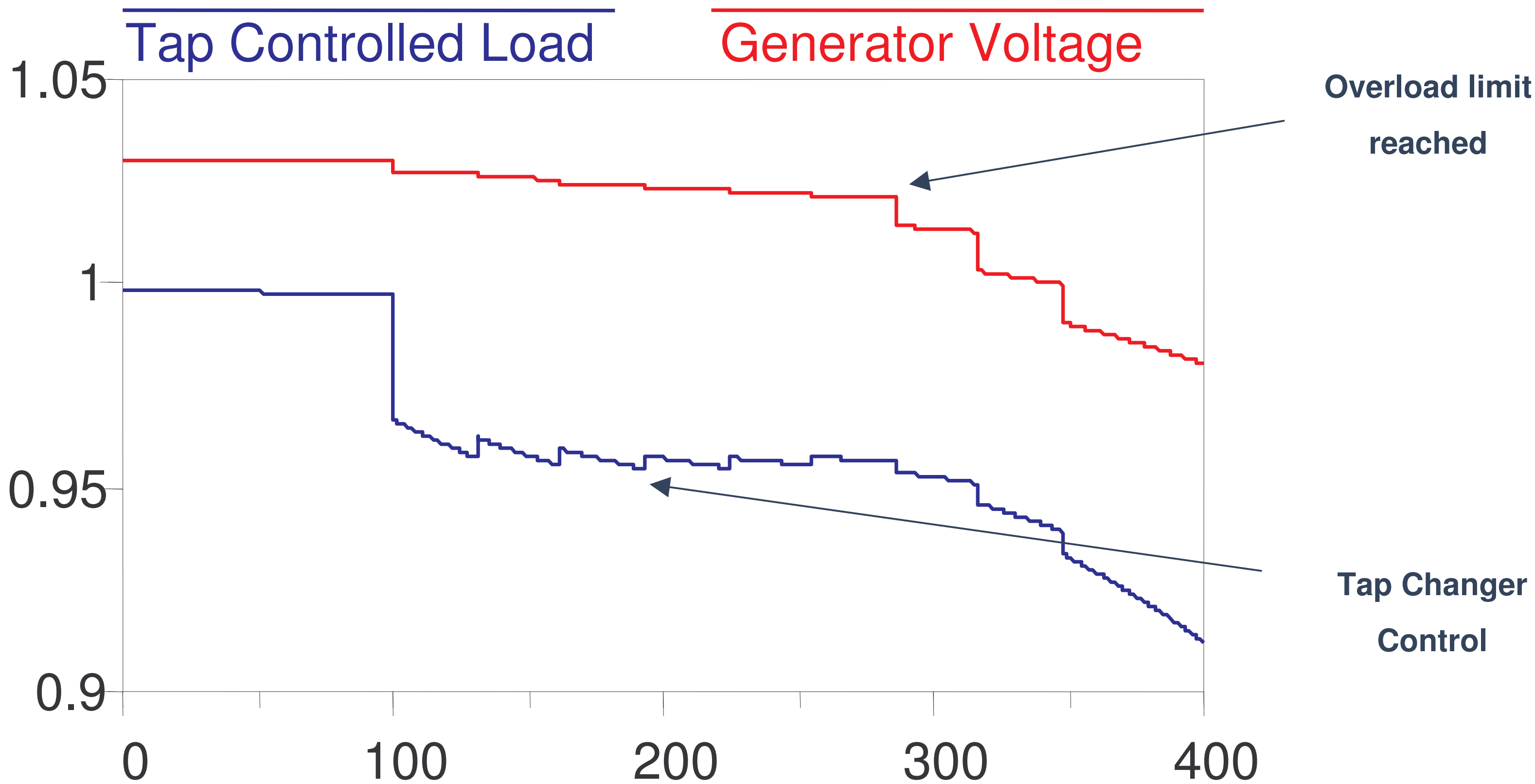


- **Used to control customer voltage**
- **Relay control**
- **Time delay + Deadband**

- **Uses a local viewpoint**
- **Bad for *System* Stability !**

Generator Overload Limits

- Generators normally under terminal voltage control
- If the generator is overloaded, voltage control is lost

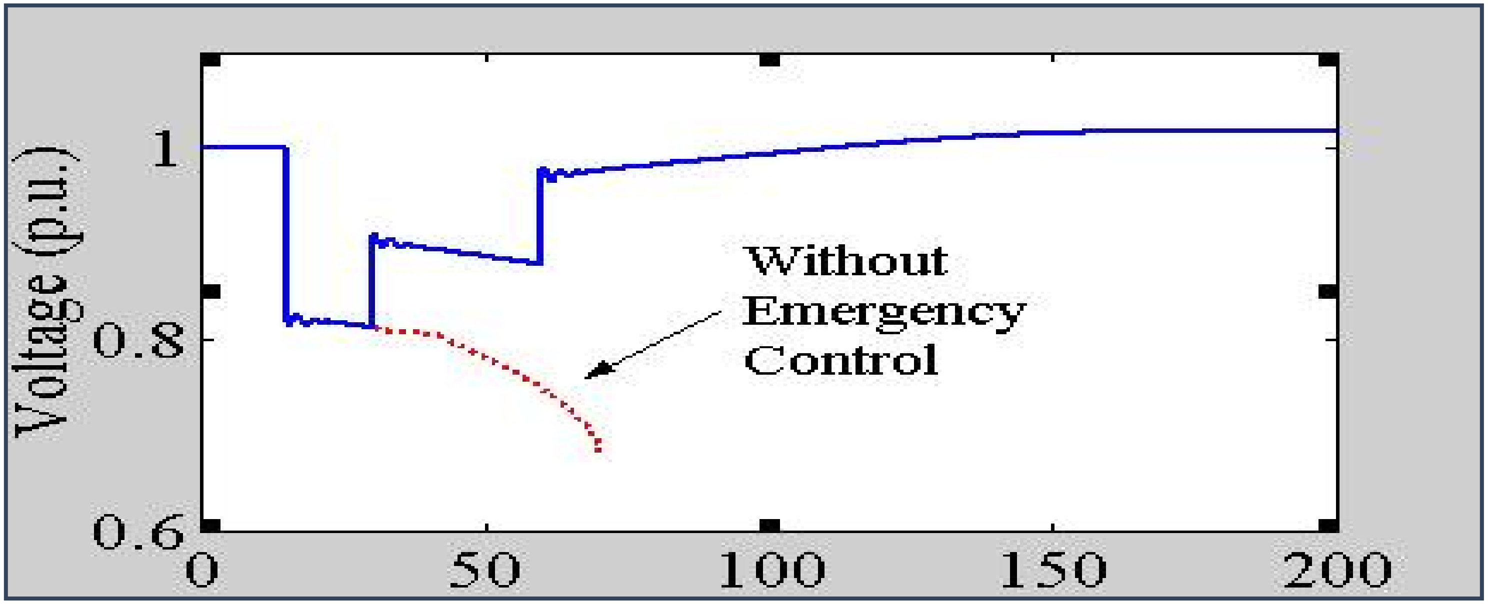


Typical Instability Scenario

1. Line or generator outage reduces the voltage in an area
2. Temporary load reduction
3. Transfer capacity to the area is reduced
4. Load demand recovers (distribution voltage control, inherent dynamics)
5. Voltage is further reduced
6. Generator overload protection activated
7. Collapse !

Time scale: seconds to several minutes

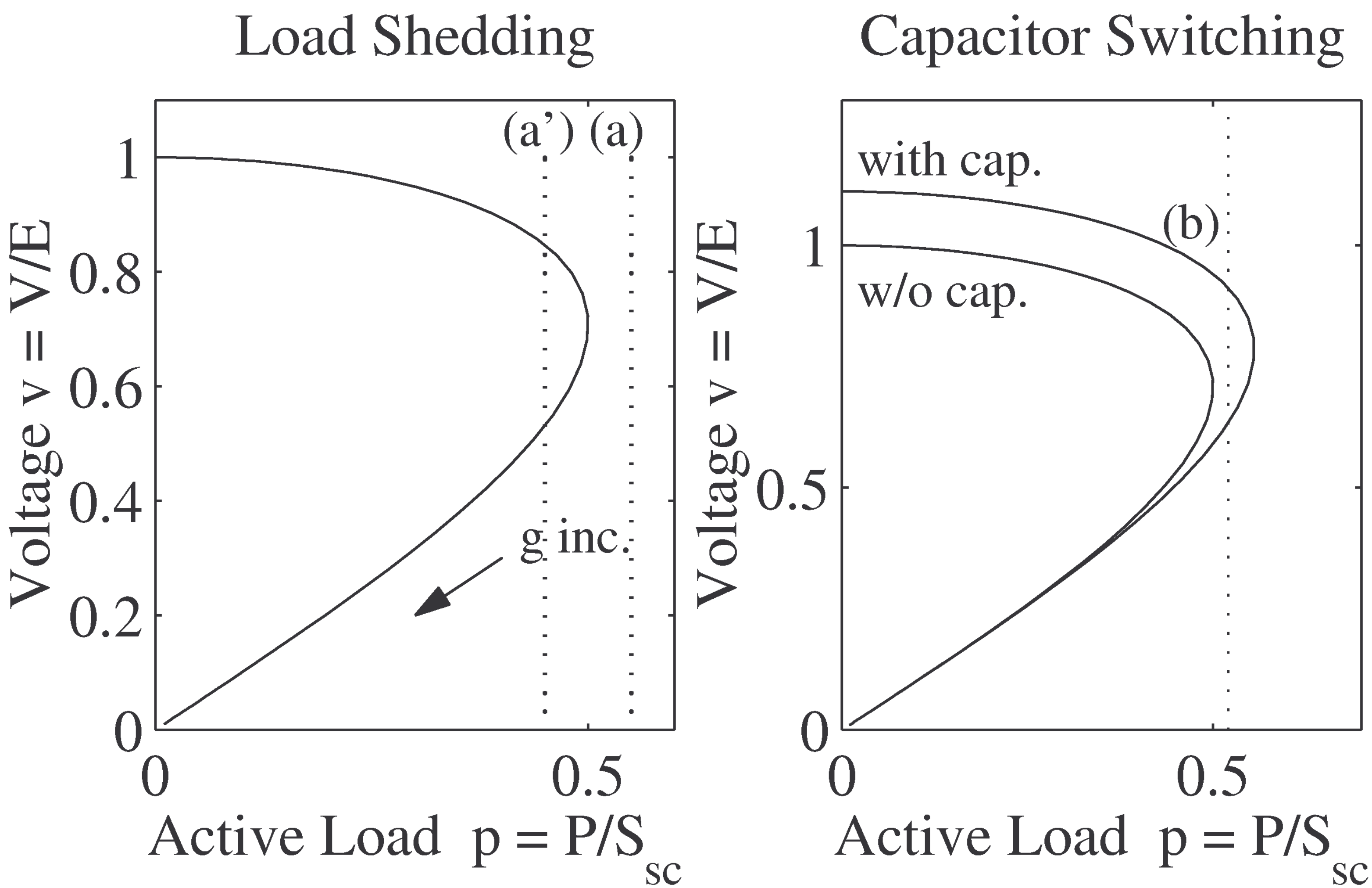
Countermeasures against Voltage Instability



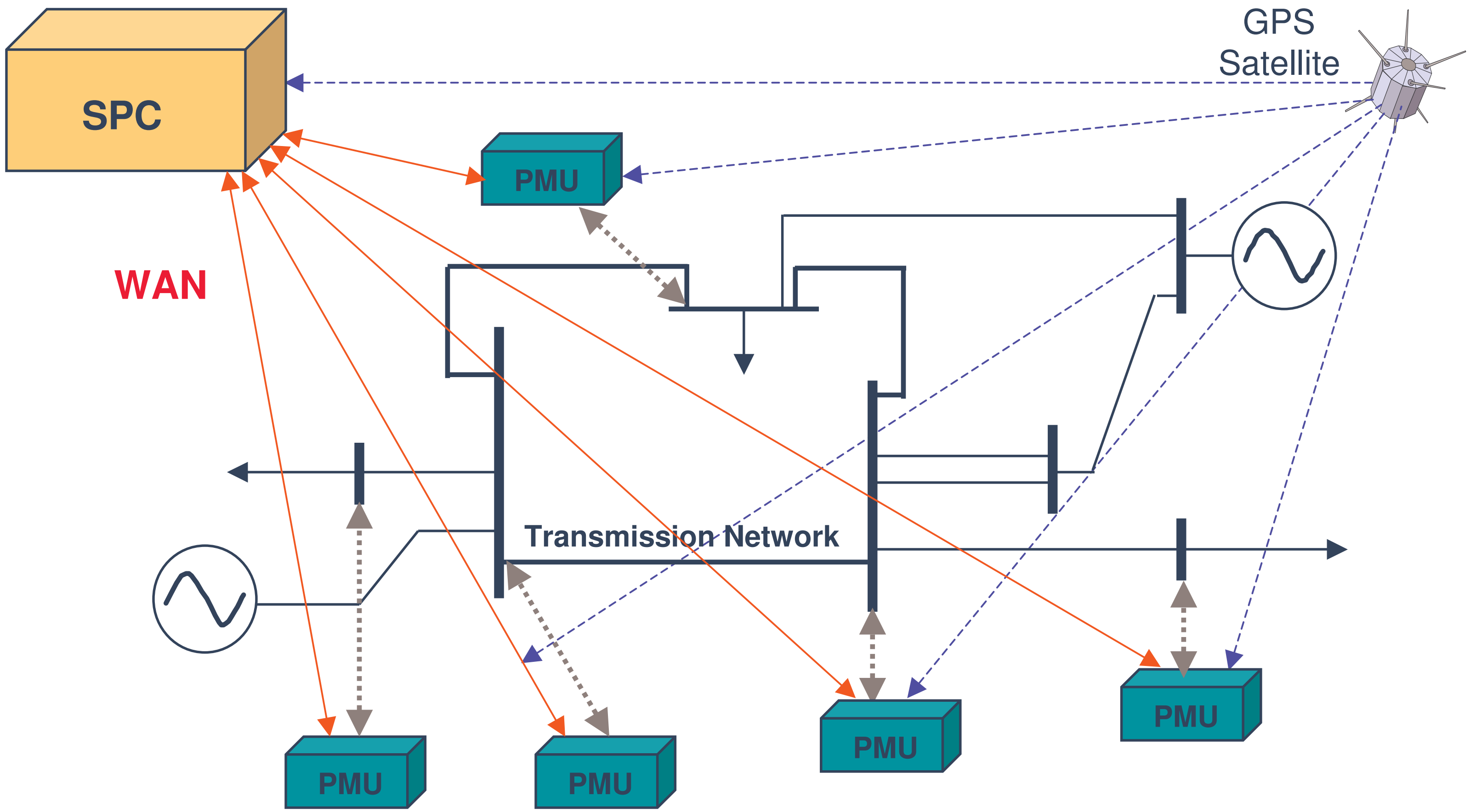
Time (seconds)

- Load shedding
- Tap locking
- Capacitor switching
- Generator voltage setpoints

Countermeasures (ctd.)

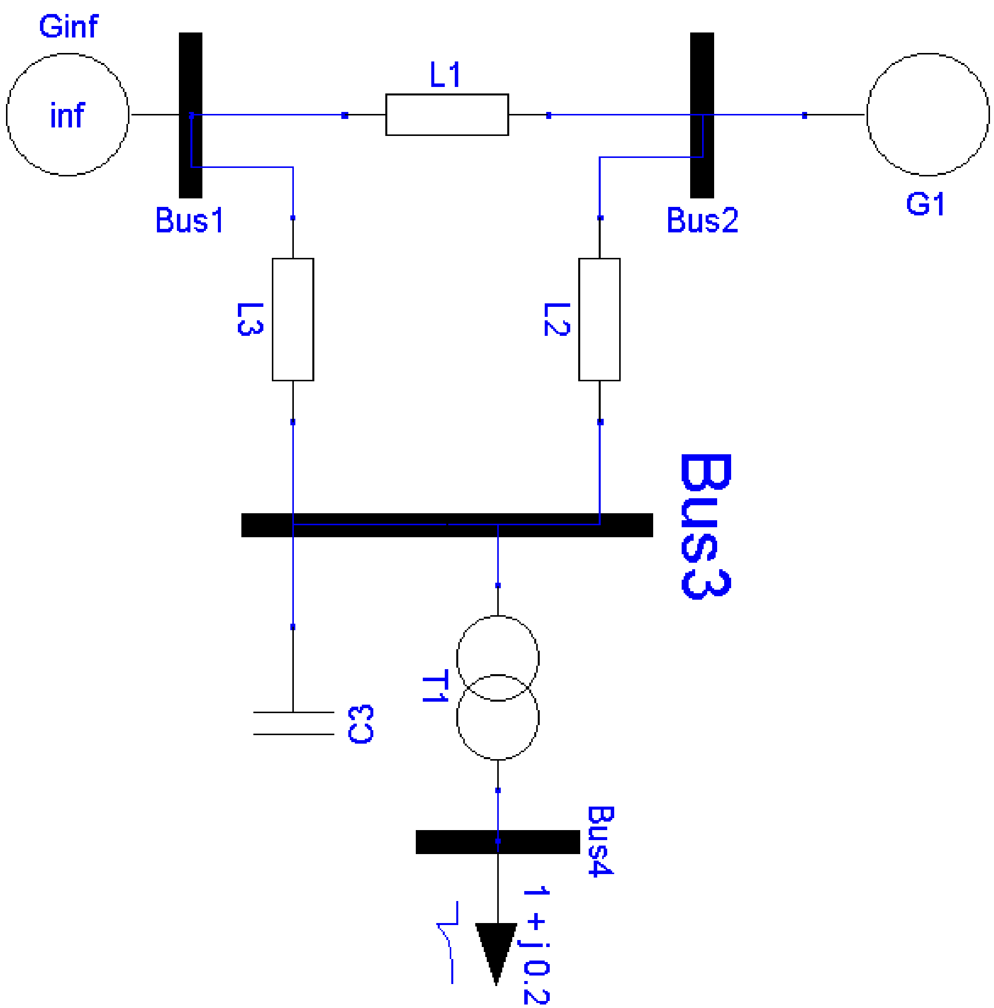


Wide-area Protection



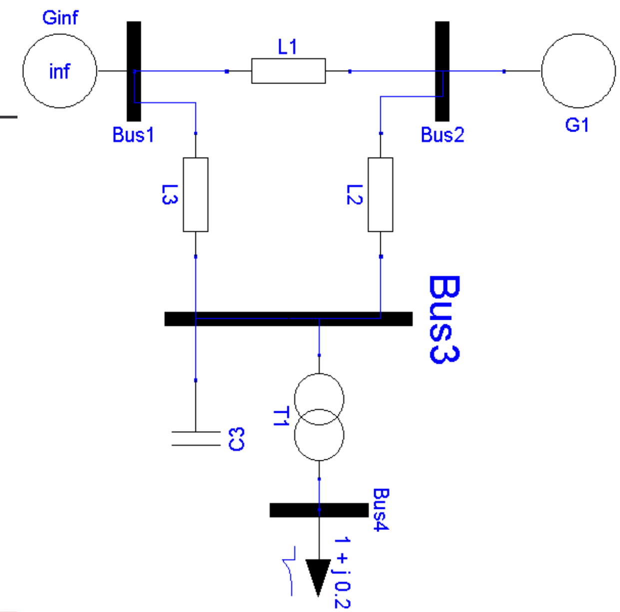
- Snapshot of power system *topology* and *state* every 50-250 ms
- Sophisticated control possible

The ABB Power Grid Test Case

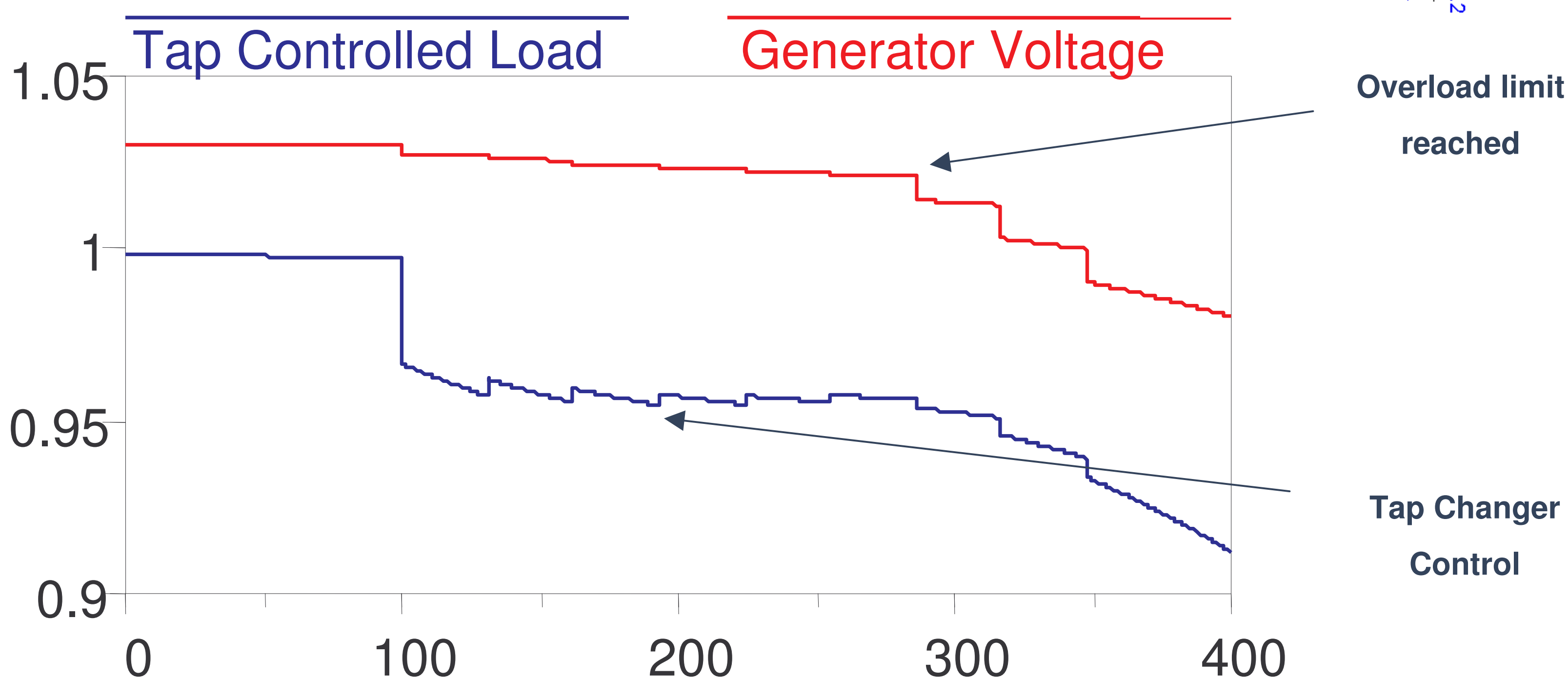


- Small-scale example
- Discrete Step Controls
  - Tap locking
  - Load Shedding
  - Capacitor Switching
- Hybrid Behaviour
  - Generator overload protection
  - Transformer Relay Control

Collapse Scenario



- Line tripping (L3) after 100 s
  - Inherent Load Recovery
  - Tap Changer Tries to Restore Voltage
  - Generator field limit activated at 286 s
  - Collapse



What Do We Need from CC ?

- Optimal Control Problem
  - Find optimal switching sequences for our controls
- Observability Analysis
  - Select a *minimum but sufficient* number of measurement points
- Controllability
  - Select a *minimum but sufficient* number of control points
- Reachability Analysis
  - Which are the *safe operating regions* ?
  - When is the *last time* to stabilize the system, given some set of available controls ?
- .... and other things ?

Conclusion

- Industrially highly relevant problem

- We are dealing with transmission – *not* distribution

- A challenging test case:
  - Nonlinearity
  - Load behaviour is uncertain
  - Hybrid behaviour
    - Embedded relay controls
    - Limiter logic
  - Large Scale

- Present Status
  - Now available in Modelica language, SIMULINK SimStruc
  - T. Geyer at ETH currently works on a PWA model

- Later on, medium and large scale examples will be available