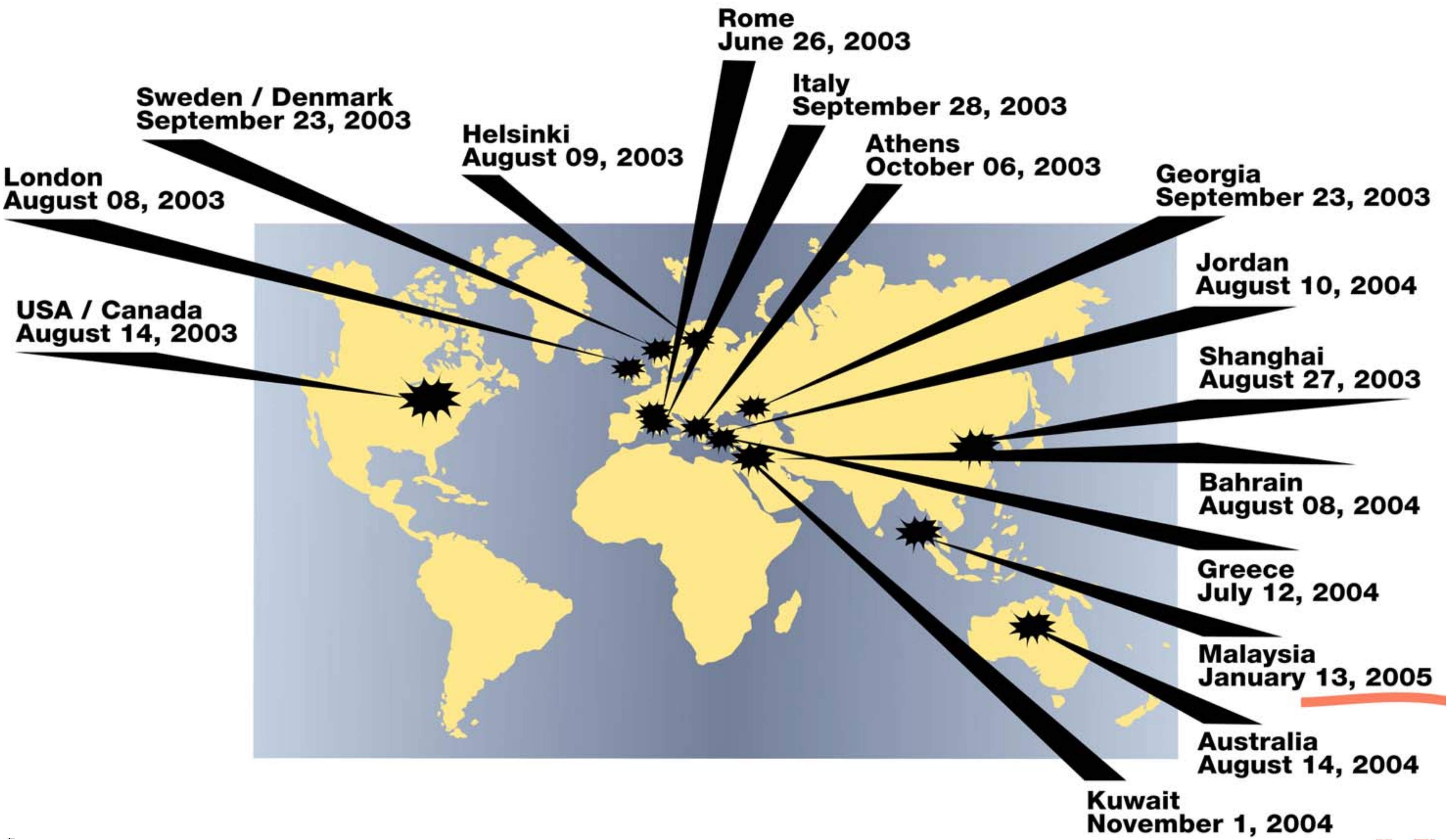
Progress on the Power Transmission Testcases

Summarized by
Mats Larsson

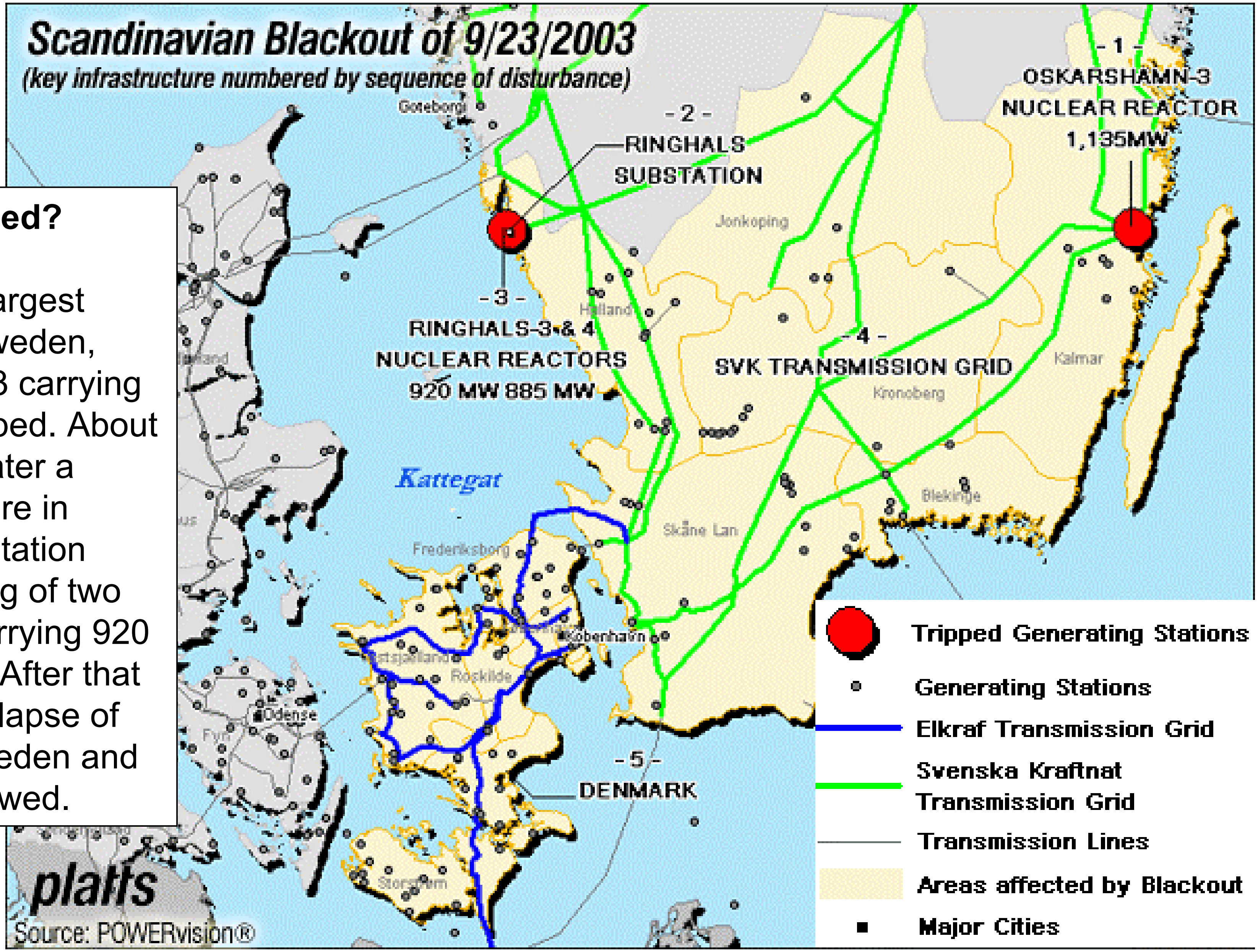
Outline

- Background
  - Recent blackouts in power systems
  - Voltage dynamics
  - Emergency voltage control
- The ABB Testcases
- Contributions by different Partners in EU CC
- A suggested Implementation Platform
- Conclusion

Recent Blackouts in Power Systems



Swedish Blackout Aug. 2003



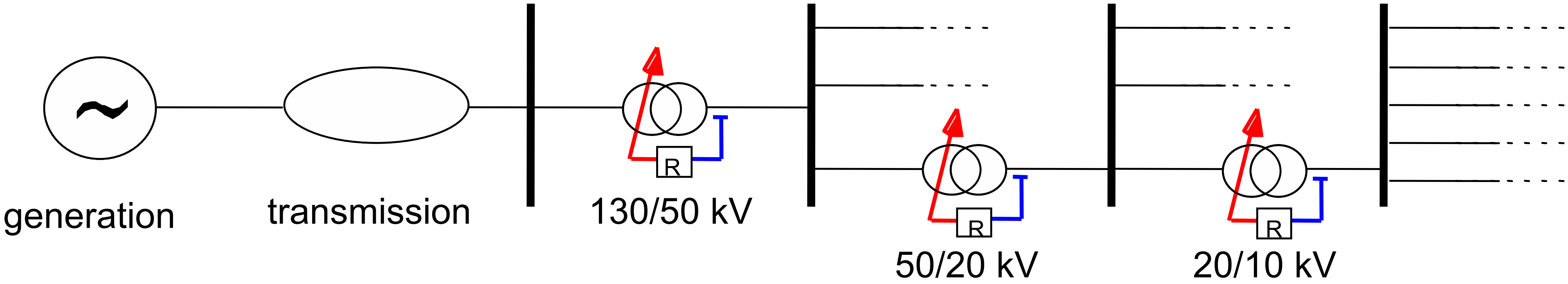
What happened?

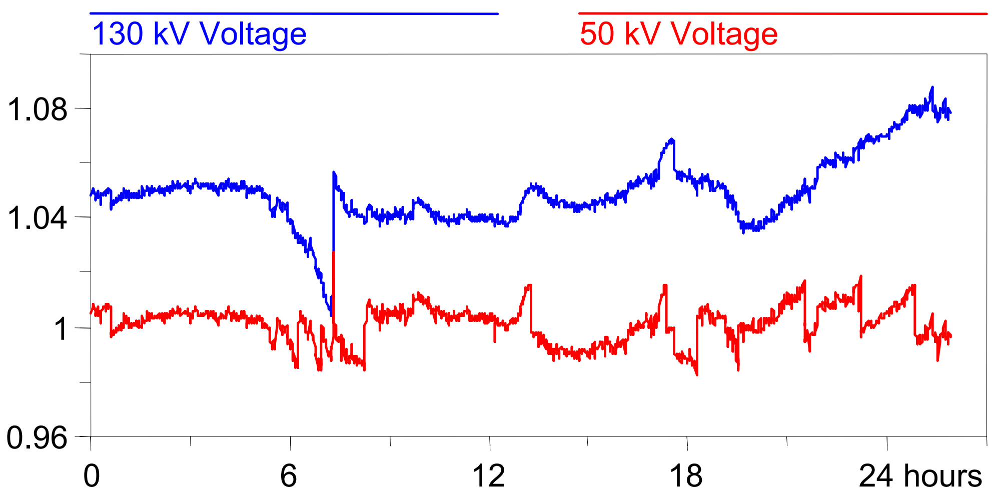
At 12:37 the largest generator I Sweden, Oskarshamn 3 carrying 1135 MW tripped. About five minutes later a unrelated failure in Ringhals substation caused tripping of two generators carrying 920 and 885 MW. After that a very fast collapse of the grid in Sweden and Denmark followed.

Failed Disconnector

Failed Disconnector

Source of instability - I - Tap Changer Control



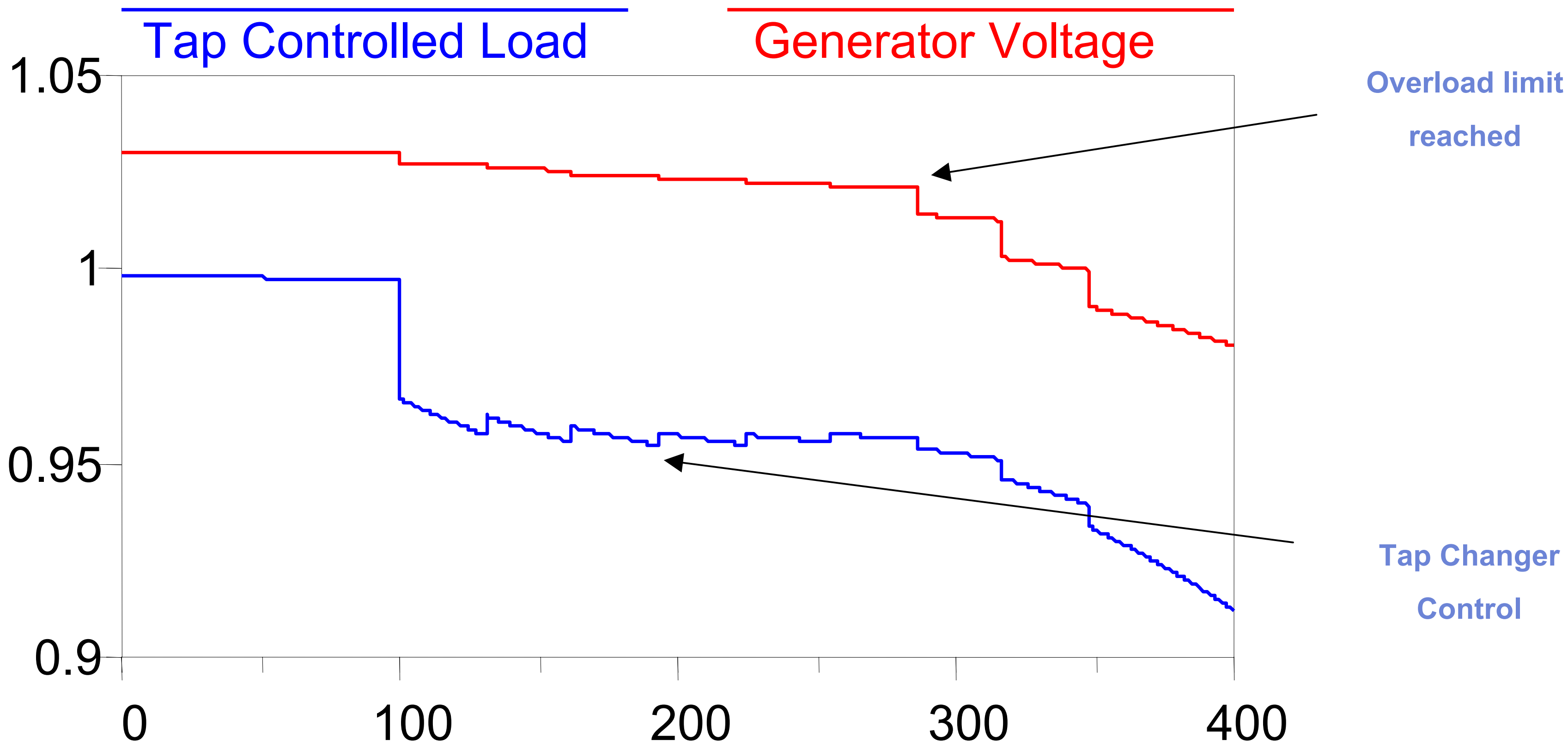


- Used to control customer voltage
- Relay control
- Time delay + Deadband

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

Source of instability - II - Generator Overload Limits

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



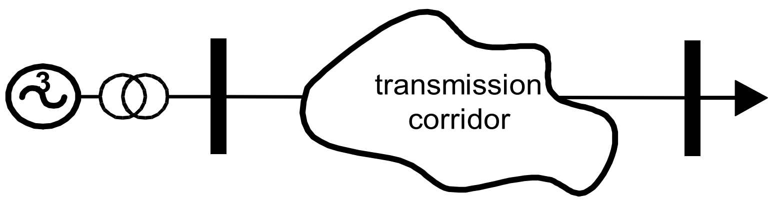
Typical Instability Scenario

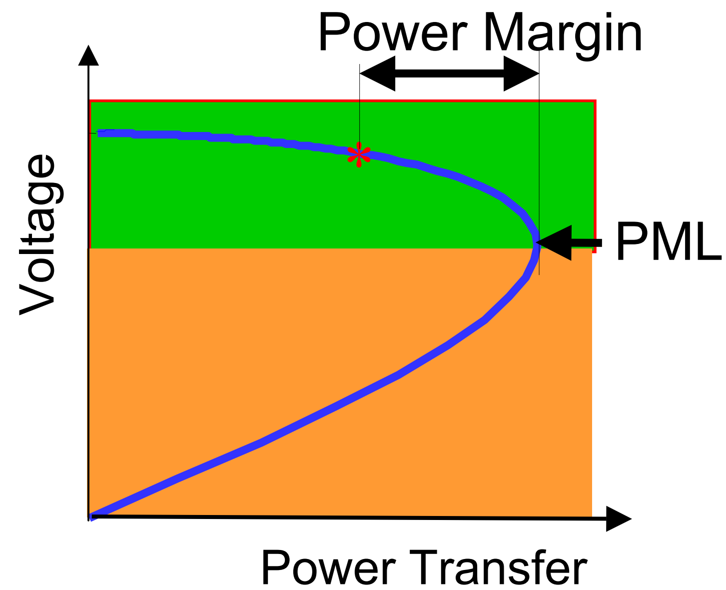
1. Line or generator outage reduces the voltage in an area
2. Temporary load reduction
3. Transfer capacity to the area is reduced
4. Load demand recovers (distribution voltage control, inherent dynamics)
5. Voltage is further reduced
6. Generator overload protection activated
7. Collapse !

Time scale: seconds to several minutes

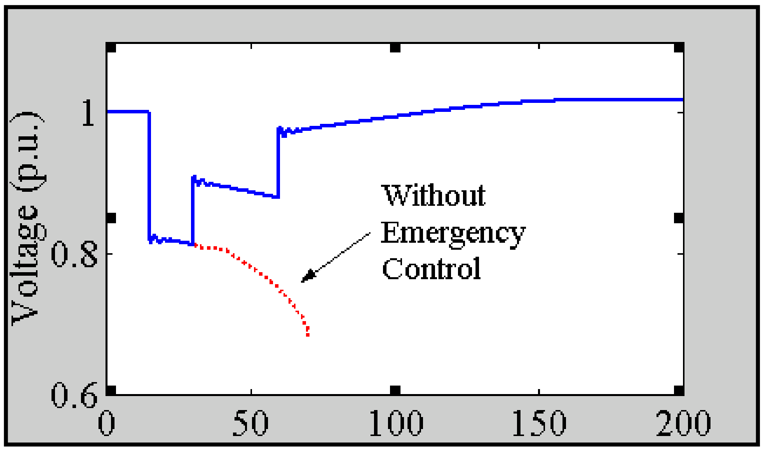
ABB

Emergency Voltage Control

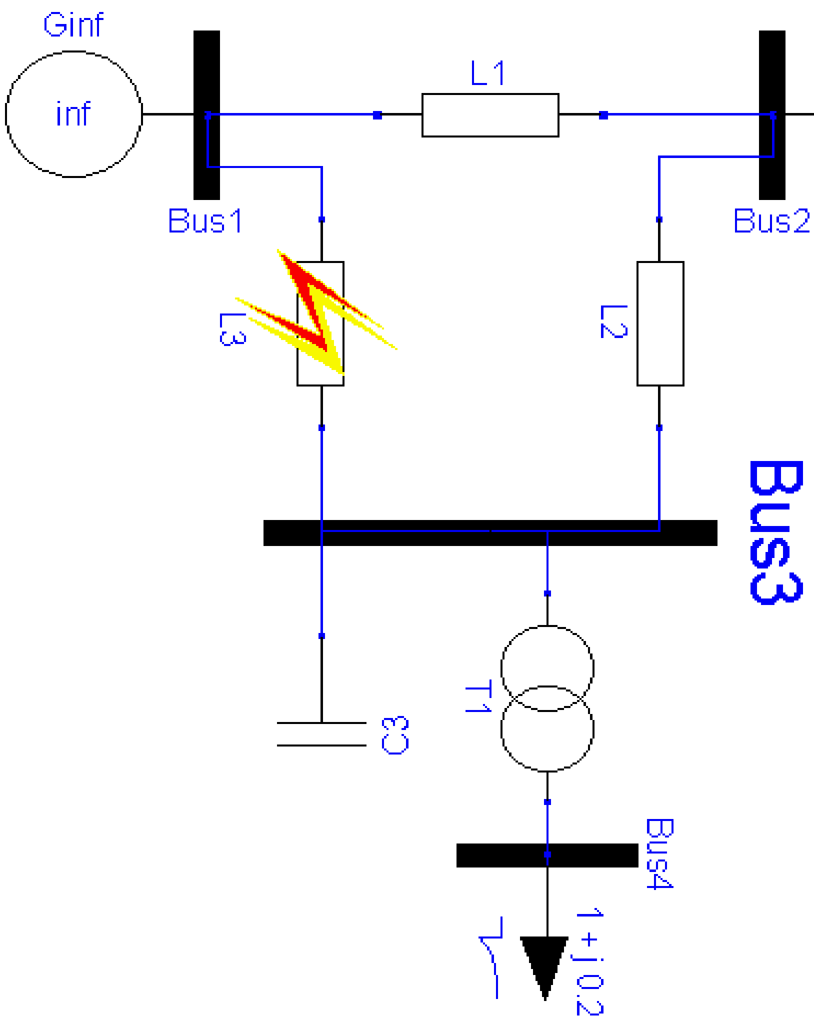




- Objectives
  - Stabilize unstable voltage dynamics
  - Switched controls
    - tap changers
    - capacitors
    - Load shedding



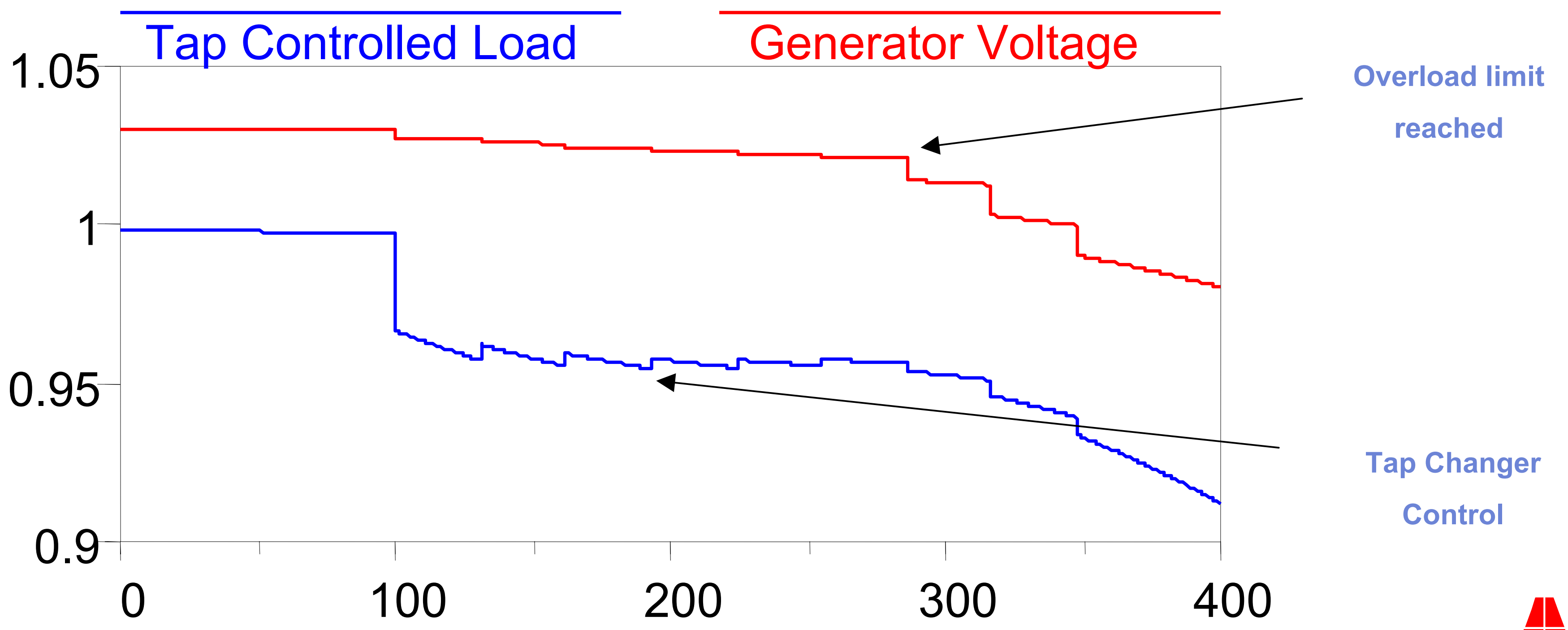
Original ”Small scale” benchmark



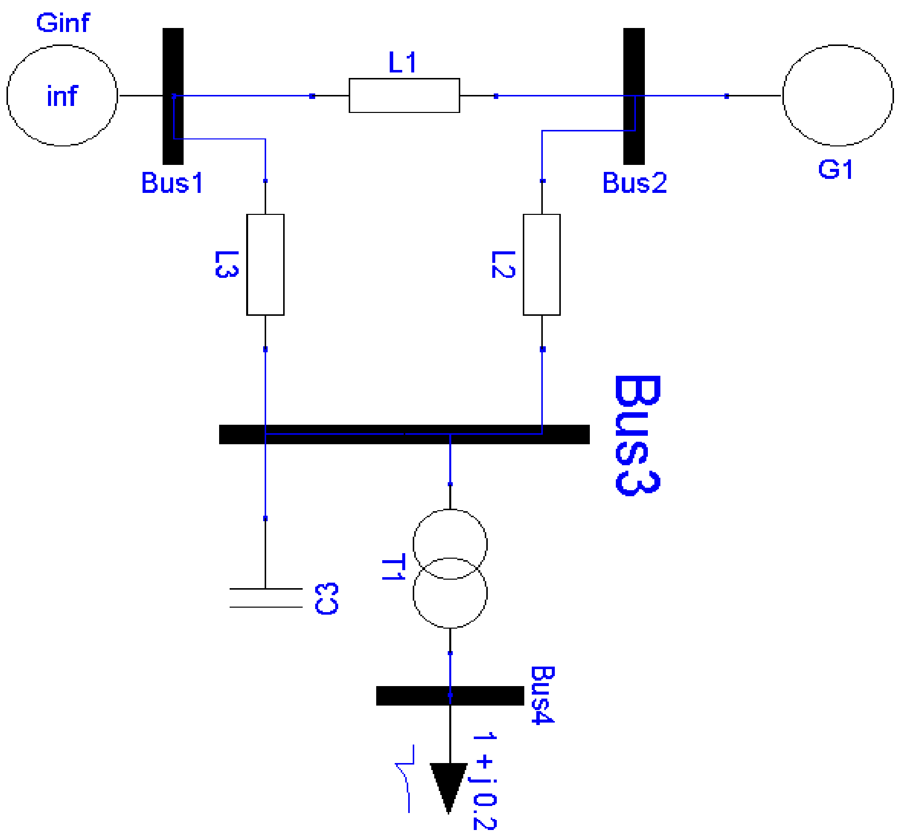
- Disturbance Input
  - Line trip
- Discrete Step Controls
  - Tap changer reference voltage
  - Load Shedding
  - Capacitor Switching
- Hybrid Behaviour
  - Generator overload protection
  - Transformer Relay Control
  - Discrete controls
- Nonlinearity
  - „sign change“ in tap changer control

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



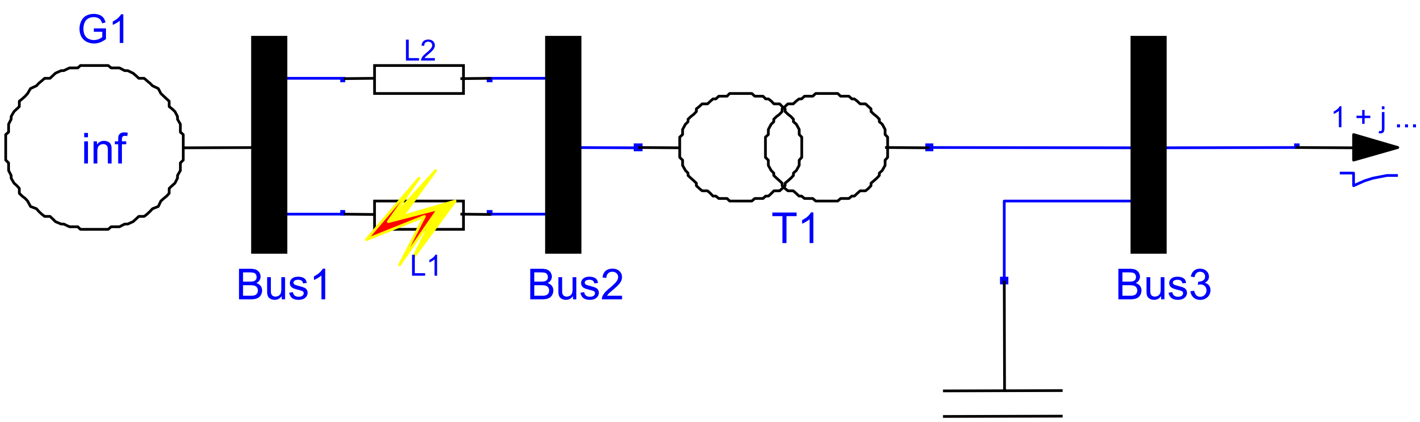
Control Objectives



- Stabilize all voltages within 0.9 - 1.1 p.u.
- Use minimal amount of load shedding

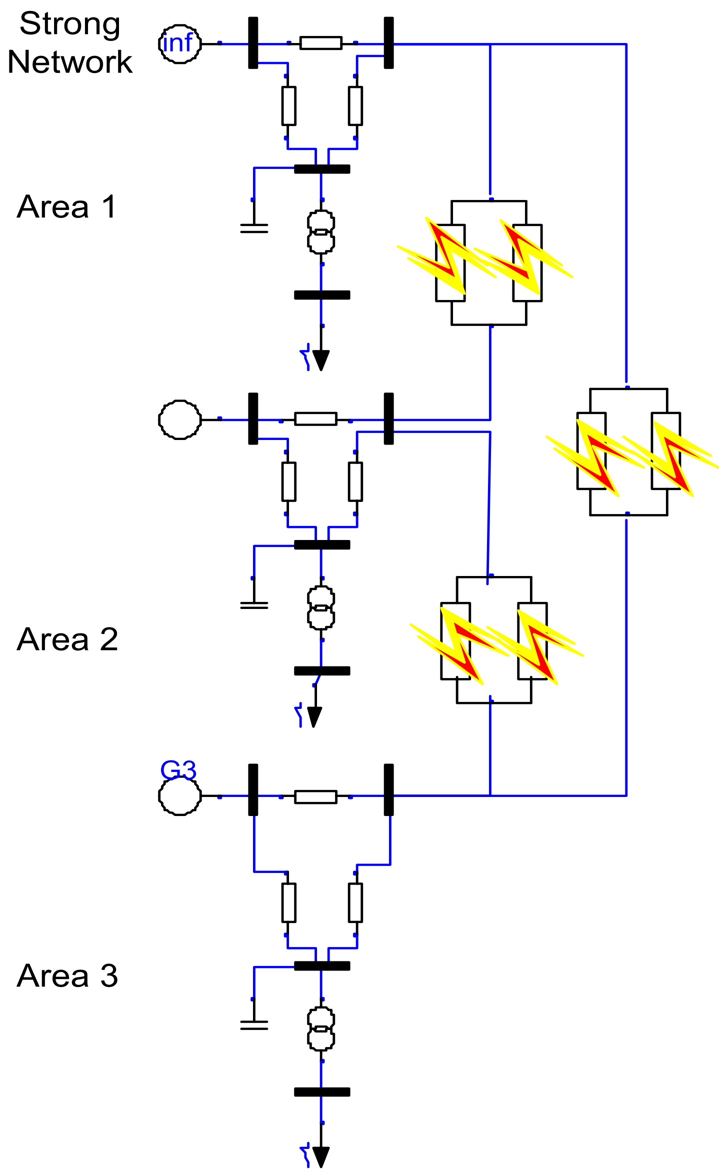
- Control voltage at bus 4 as close as possible to 1 p.u.
- Capacitor and tap changer control can be used freely

„Mini“ Testcase



- A simplified version of the small scale benchmarks
- Allows analytical modelling - crucial for understanding
- Still captures the essential hybrid behaviour

Overview – “Medium Scale” ABB Test Case



- Three copies of small case
- Similar control objectives
- Recovery dynamics in :
  - load (continuous)
  - Transformers (discrete) (optional)

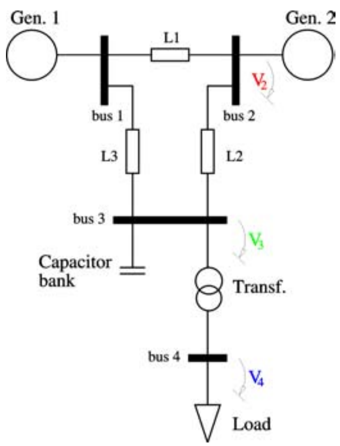
Inputs:
- Line impedances (fault)
- 3 Capacitors
- 3 Voltage Refs. Transformer (optional)
- 3 Load shedding

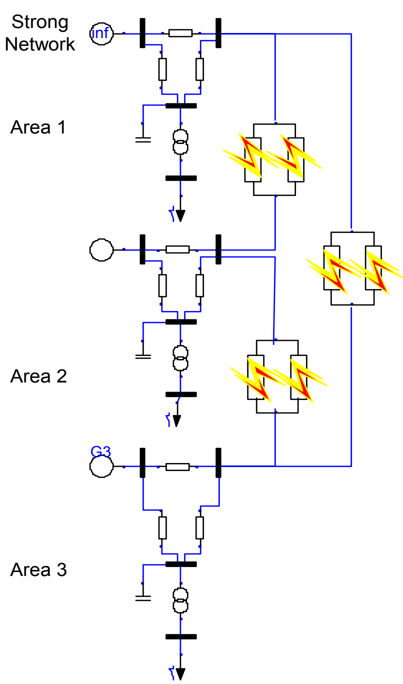
Outputs:
- 3 Load voltages
- 2 Generator field voltages

Contributions Through EU Control & Computation

- ETH Zürich
  - Predictive control based on Mixed-logical Dynamical (MLD) models
- Lund University
  - Feedback/Feedforward control laws for indvidual tap changers
- Grenoble / LAG
  - Nonlinear predictive controller with reduced order open-loop parameterization
  - Combined use of global control approach and local feedback strategies
- Grenoble / VERIMAG
  - Nonlinear predictive controller with search algorithm over branching tree
- ABB
  - Online equivalencing of complex networks
  - Predictive control

ETH Zürich - Modelling (1/2)





Small scale benchmark model:

- 4-bus network non-linearities accurately modelled with PWA model
- Full description of all logics involved (e.g. tap changer Finite State Machine)
- MLD framework captures PWA approximations and logics

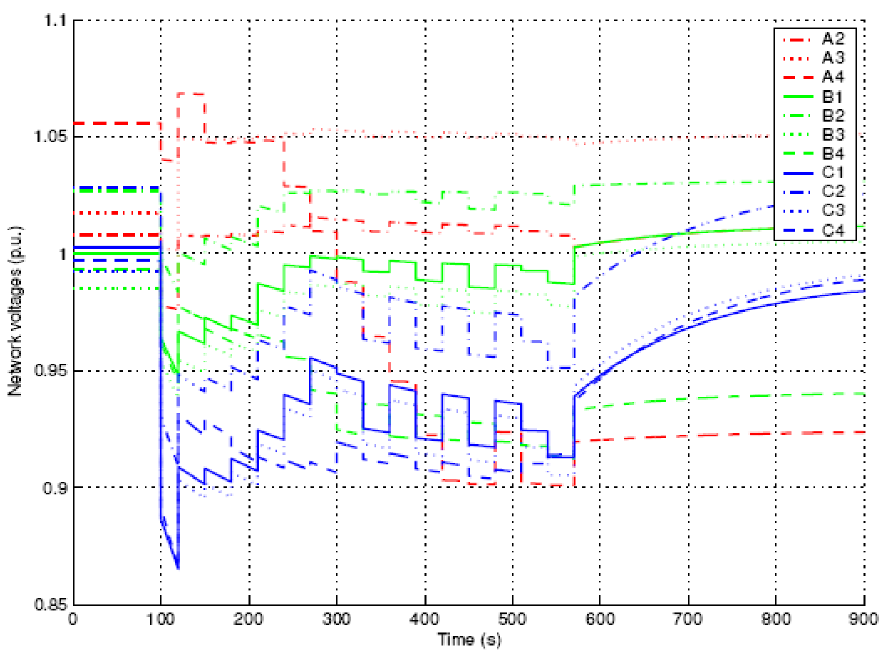
Medium scale benchmark model:

- Three area network equations linearized
- Considers four different linearizations according to state of generators
- Retains full description of logics
- System with PWA dynamics converted to MLD form

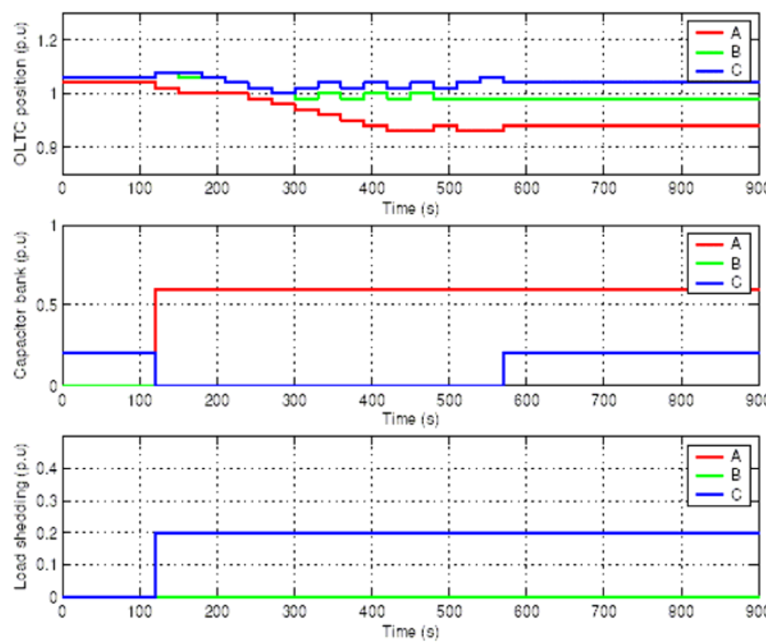
ETH Zürich - Model Predictive Control (2/2)

MPC approach:

- MPC explicitly takes into account constraints
- Tuning of cost function is straightforward
- Resulting MILP problem efficiently solved
- MPC effectively stabilizes voltages

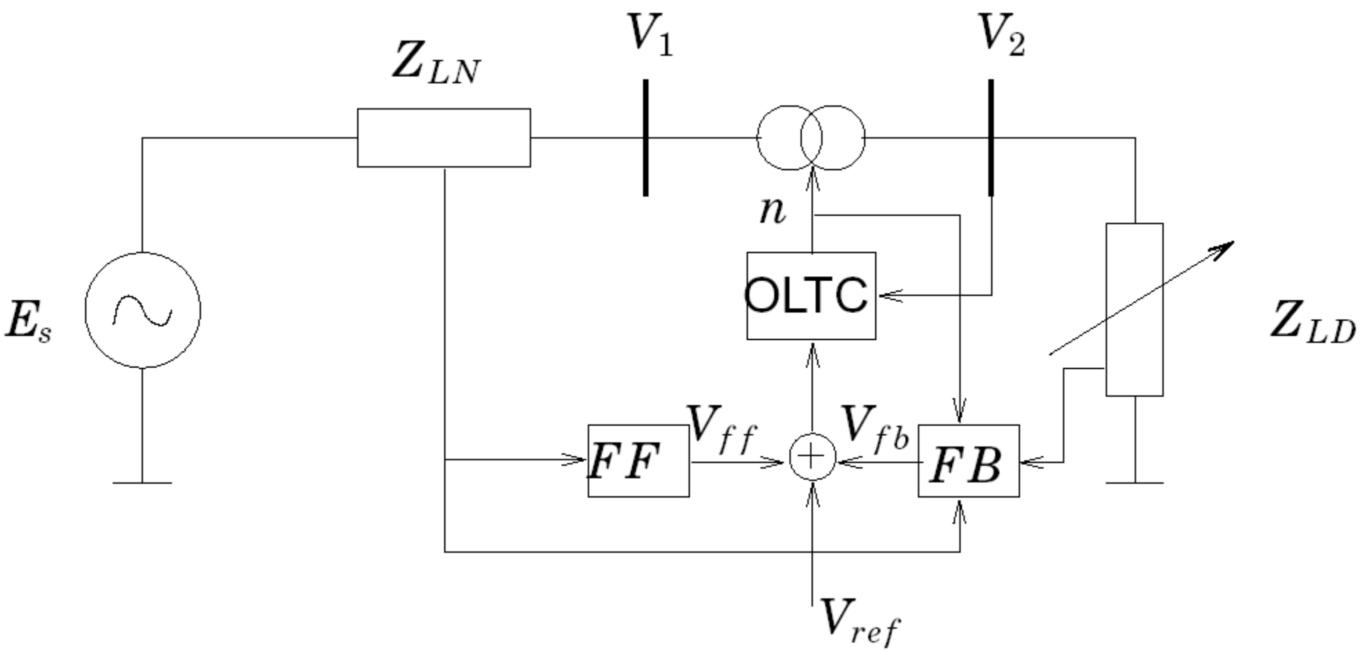


(a) Temporal evolution of network voltages



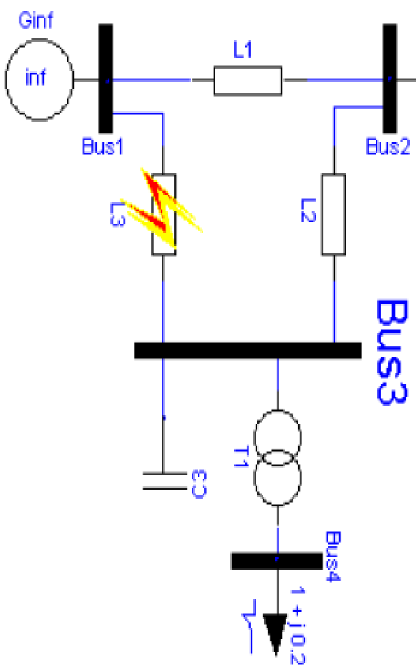
(b) Control input sequence

Transformer switching via impedance estimates

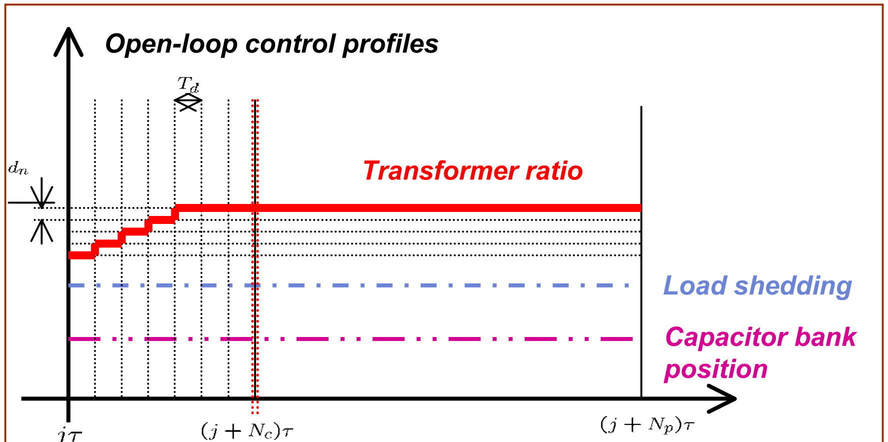


Using a simplified network model, feedback and feedforward loops from impedance estimates to switches in the transformer ratio have been analytically designed by the Lund node in close contact with ABB. A preliminary patent has been granted.

Grenoble / LAG: the small scale benchmark - (1/3)



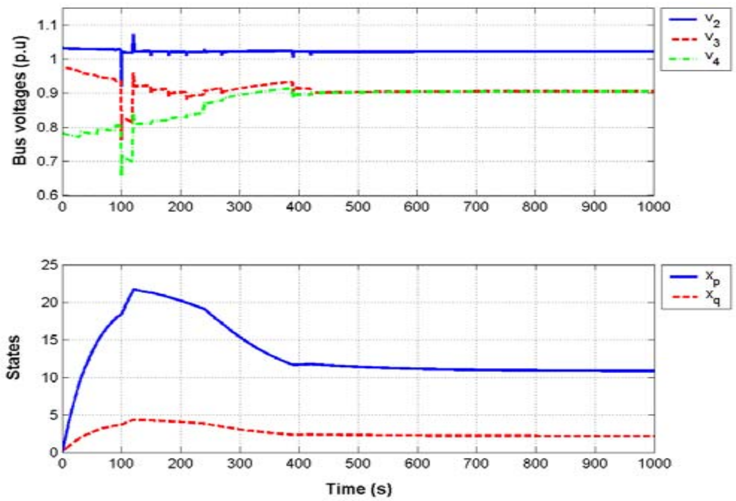
- Use of the nonlinear DAE model without any approximation
- Reduced order open-loop control parameterization
  - Constant capacitors
  - Constant load shedding
  - Monotonic transformer ratio dynamic.
- Using a virtual free-finite escape time behavior
- Handling priority in decision variables manipulation
  - (use of load shedding as a last resort)

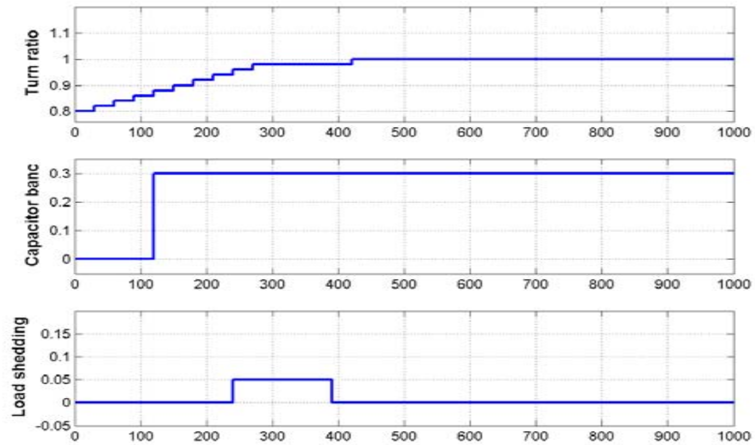


Reduced order parameterization of Open-loop control profiles

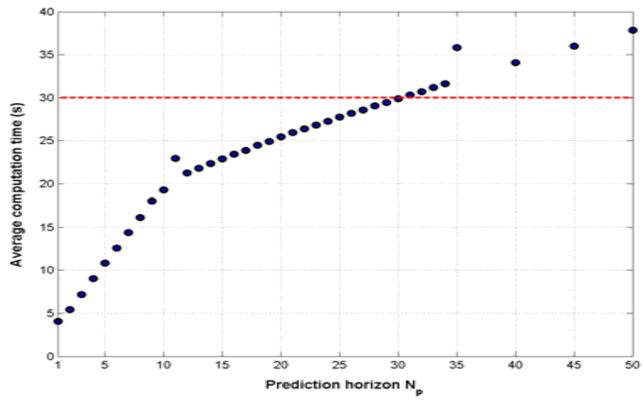
Open loop parameterization used in the Receding Horizon based controller

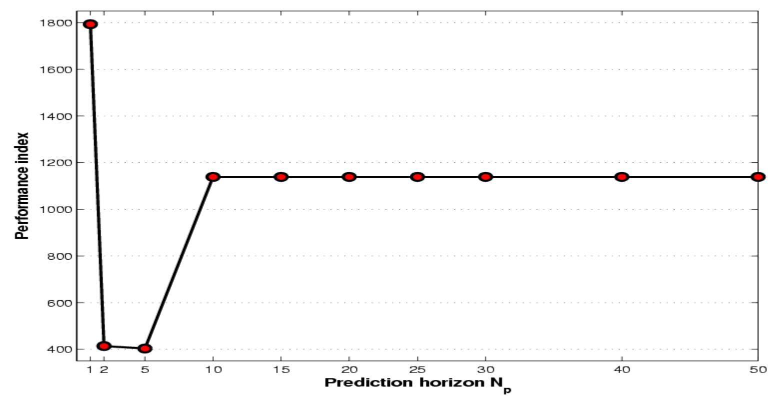
Grenoble / LAG : the small scale benchmark – (2/3)





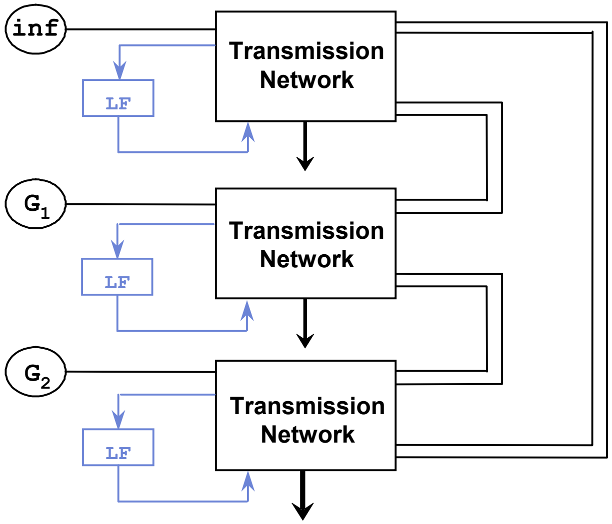
Case of a line outage at t=100 sec
Worst case (n(0) = 0.8)





Average computation and performance achieved as a function of The prediction horizon

Grenoble / LAG : the medium scale benchmark - (3/3)



Use of the nonlinear DAE model without any approximation

Use of Local feedback strategies to update the OLTC setpoints

Direct inversion of the state automata dynamics

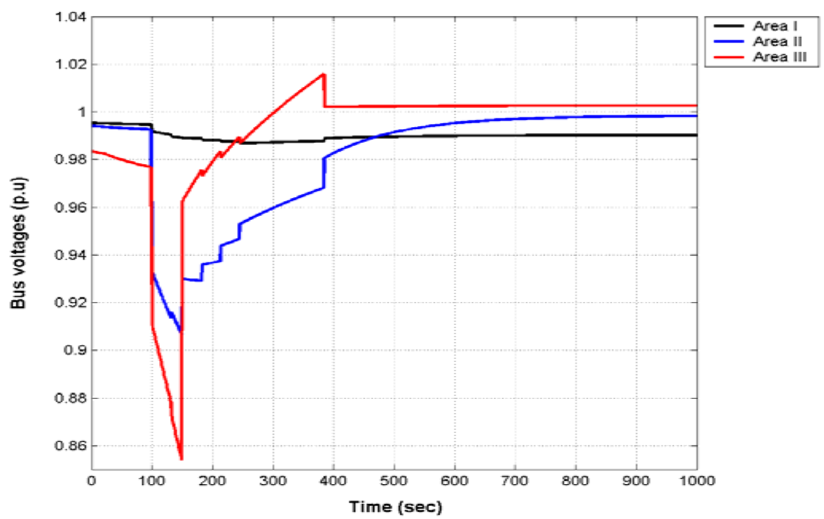
Use of a Global Nonlinear Predictive Control approach with a reduced order open−loop control parameterization

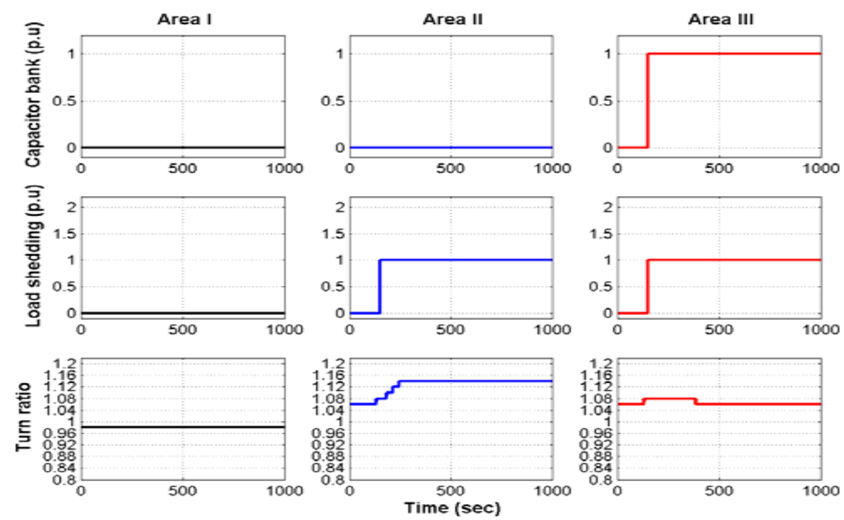
Constant capacitors

Constant load shedding

Handling priority in decision variables manipulation

Use of an efficient ordering technique





Case of a triple line outage at t=100 sec
Delay fault/action of 50 sec

Grenoble / VERIMAG

VERIMAG
Predictive control based on search

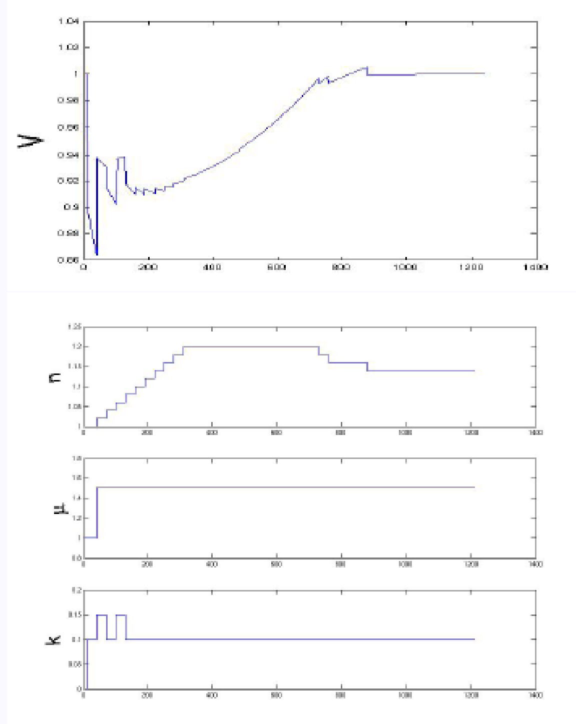
Mini testcase with

- Three inputs: tap ratio n, capacitance μ, load shedding k
- Cost function minimizing $|V - V_{\text{ref}}|$ and amount of use of k
- Nonlinear Model Predictive Controller with search over the $2 \times 5 \times 3$ branching tree

Size reduction of the search tree

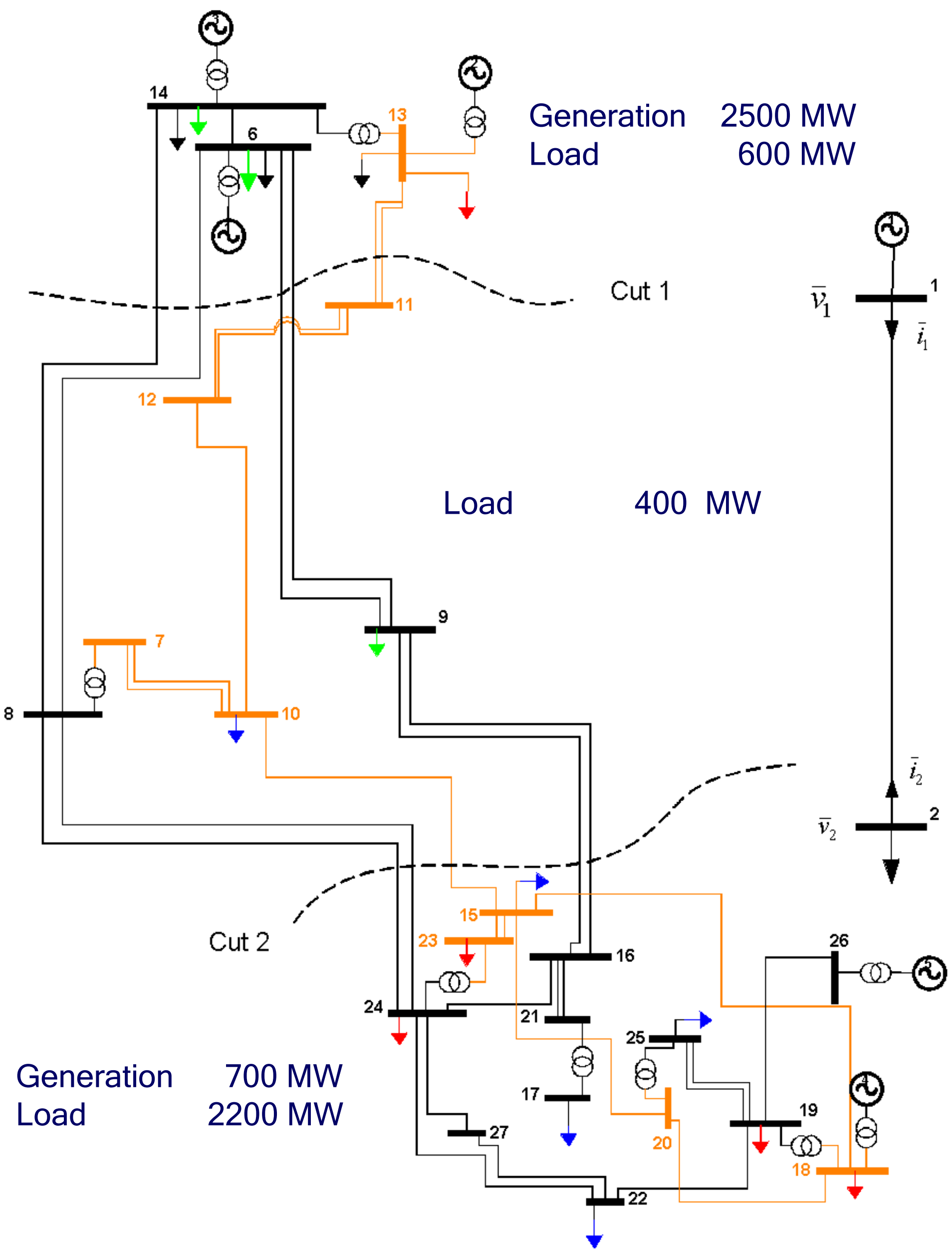
- Using caracteristics of the different inputs (monotonicity, response amplitude)
- Using long term worst case estimations analytically derived and computed from expression of DAE
- Search methods: best-first search, branch-and-bound method

Ex. Impedance X jumps from .25 to .6



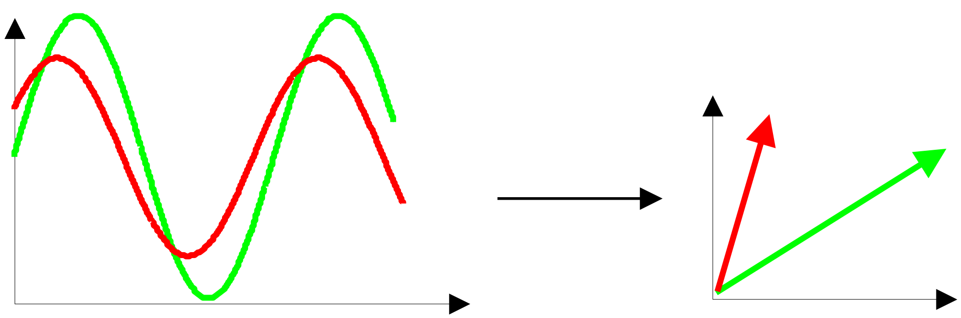
Preliminary work engaged on Medium Scale Test Case

ABB - Network Equivalencing



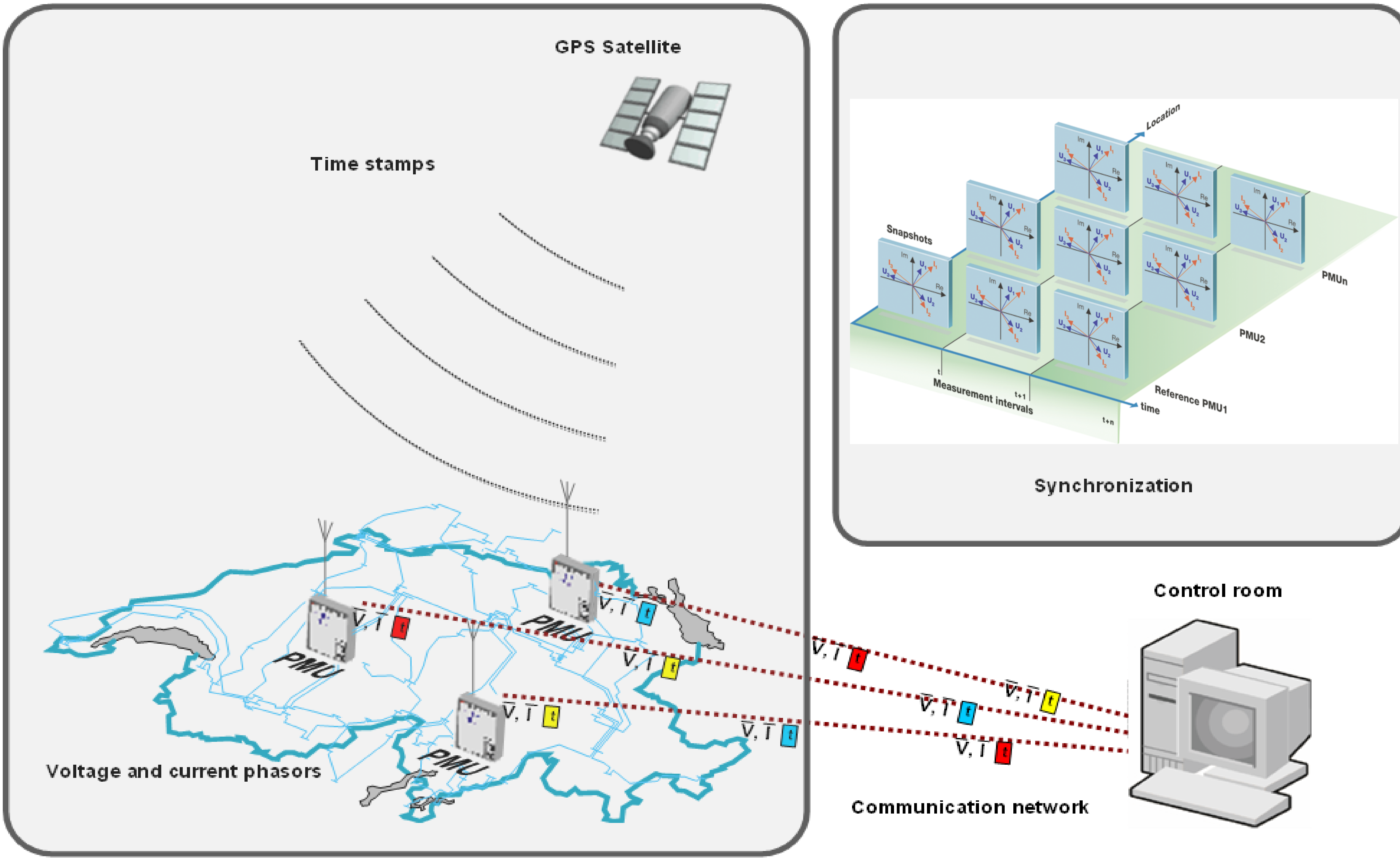
- On-line computation of reduced simplified equivalents
- In many cases, resulting models can be as simple as the EU CC benchmark problems
- Can vastly reduce computational requirements

Implementation Platform I - New Measurement Technology



- Phasor Measurement Units (PMU)
- Synchronization by GPS clock
- Timestamp accuracy < 1 microsecond
- Angle accuracy < 0.1 degree
- Allows monitoring of voltage dynamics

Implementation platform II - Wide-area Monitoring and Control



Conclusion

- Substantial and industrially relevant contributions have been made through the EU CC project
  - Predictive Control
  - Analytical Methods

- Computational complexity is a major issue
  - Efficient solution techniques
  - Reduced network models

- Not only Control & Computation – Analysis and Engineering is also required

- Technology is available now
  - ABB has already offered a voltage stability control system based on predictive control to a customer (no order yet)

ABB