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Voltage Security Assessment and Protection against Voltage Collapse

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Overview

- Introduction to Voltage Stability
- Voltage Security Assessment
- Contingency analysis
- Computation of loadability limits
  - Determination of available transfer capabilities (ATC)
- The Hellenic power system
- On-line VSA application
- Early identification of voltage instability
- Protection measures

Power System Stability

- Classification of power system dynamics:
  - Electromagnetic transients and Power Electronic converters
    - Sub-period (ms) – EMTP
  - Synchronous and induction machine electrical and mechanical transients (short-term)
    - Usually 1 to 10 s – stability simulation programs
  - Load and other slow dynamics (long-term)
    - Several seconds to minutes – frequency and voltage stability
- Multiple time scales

IEEE/CIGRE stability classification

POWER SYSTEM STABILITY

ability to regain equilibrium after disturbance

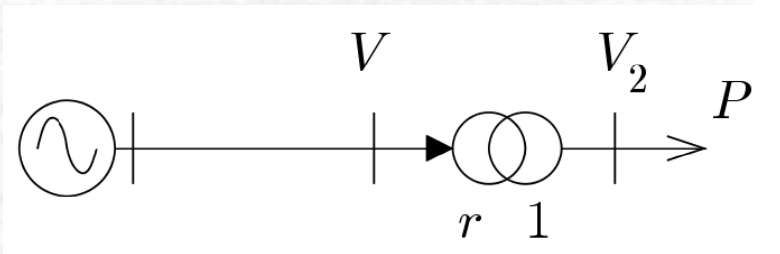
- **(ROTOR) ANGLE STABILITY**
  - ability to maintain synchronism between generators
  - balance between mechanical and electromagnetic torques acting on each rotor
  - short-term dynamics (up to 10-20 s)
    - small-signal angle stability
    - transient (angle) stability
- **FREQUENCY STABILITY**
  - ability to maintain frequency close to nominal value
  - global balance between active power generation and active power load
  - “single-bus”
  - long term
- **VOLTAGE STABILITY**
  - ability to maintain voltages near their nominal values
  - ability of combined transmission - generation system to deliver the power requested by loads
  - load-driven
    - short term
      - induction machines
    - long term
      - slow load dynamics

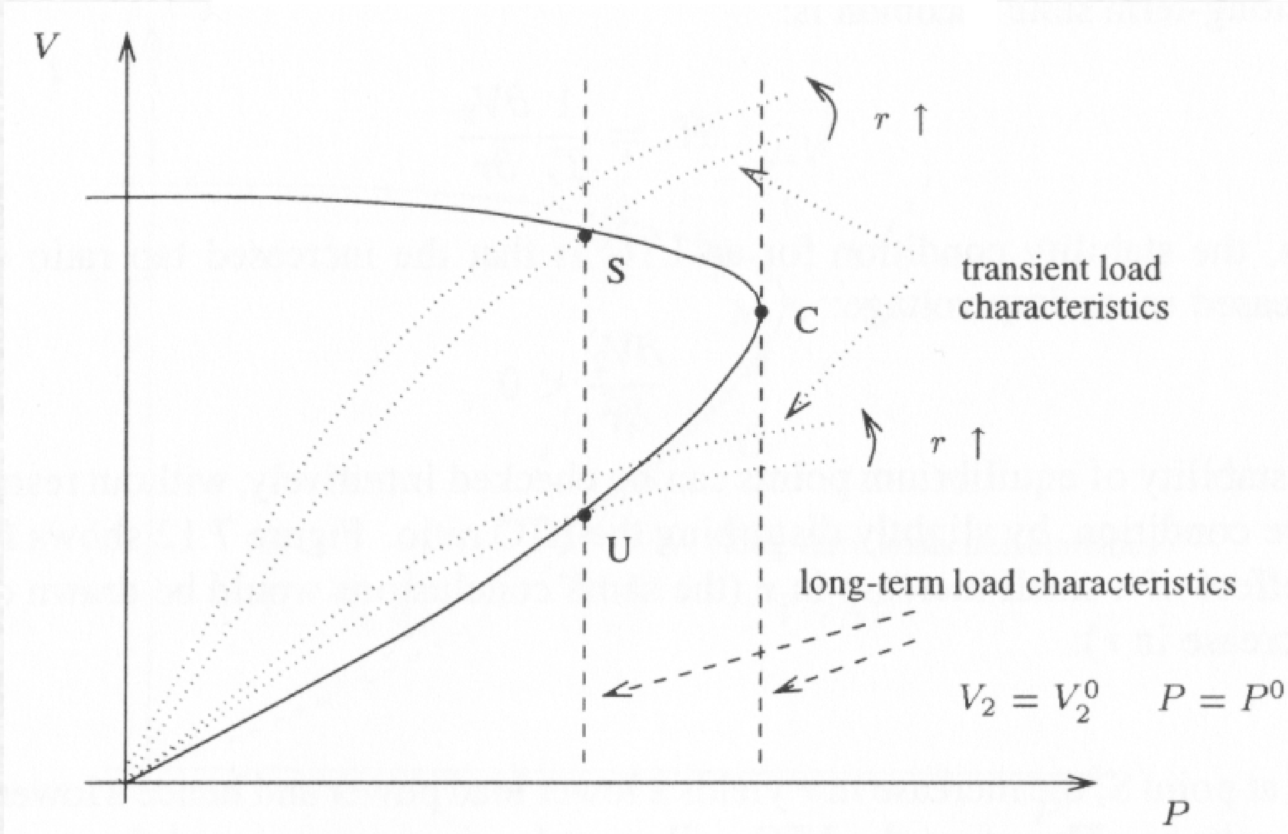
Load power restoration

- Induction motor
  - Time frame ~1 second
  - State variable: motor speed (slip)
  - Mechanical and Electrical torque equilibrium
- Load Tap Changer (LTC)
  - Time frame: several seconds to few minutes
  - State variable: transformer ratio
  - Equilibrium: secondary voltage within deadband
- Thermostatically controlled load
  - Time frame: tens of minutes
  - State variable: amount of connected load
  - Equilibrium when temperature within deadband

Long-term voltage stability

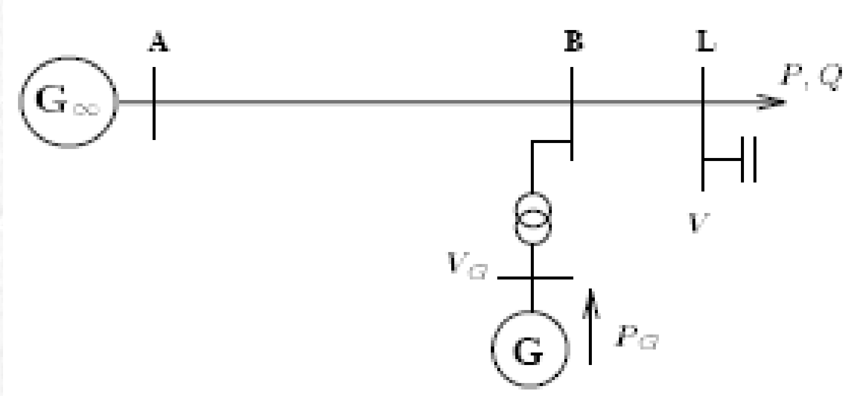
- An LTC restoring load from voltage-sensitive to constant power
- Representation in PV plane
  - Maximum power C
- Network and load characteristics
  - Steady State (S-T)
  - Transient (L-T)

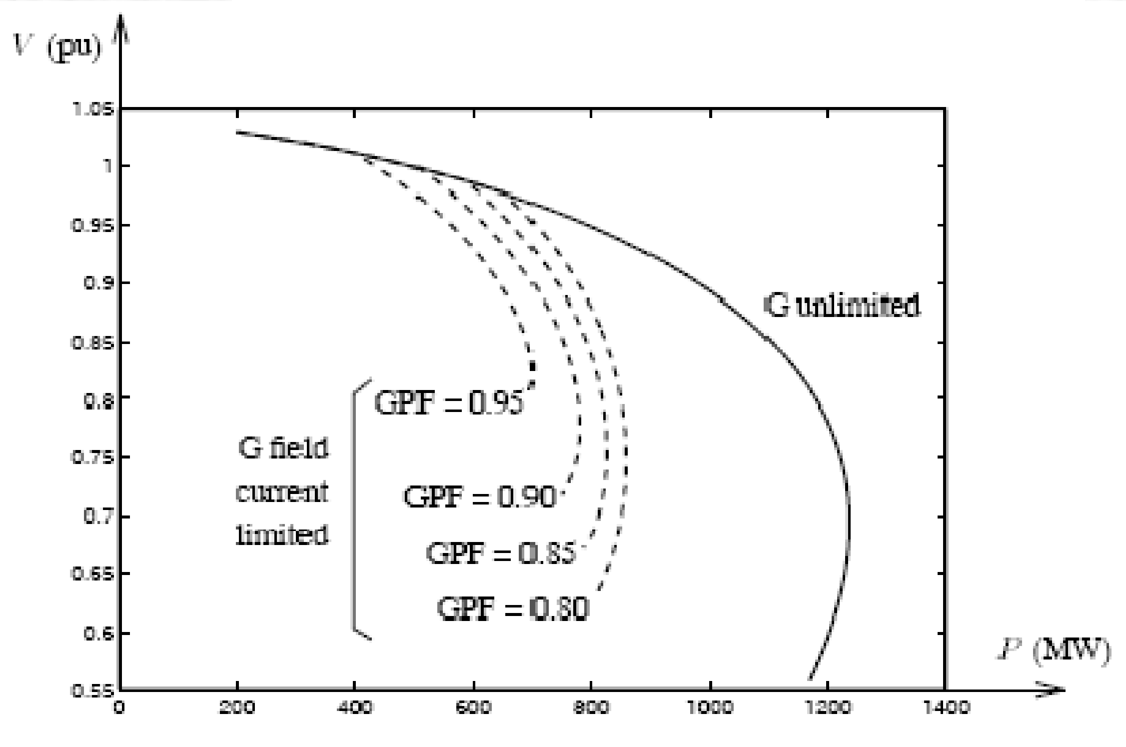




Effect of generator reactive limits

- Role of local generator
  - Reduce power transfer
  - Provide reactive support
- Maximum power depends upon generator reactive power limits
- Strong P-Q coupling
- Low power factor generators near load centers





Power System Security

- Security Monitoring
  - important aspect for preventing instability and minimizing blackout risks
- Analysis of a long list of contingencies
  - N-1 (all simple failures)
  - selected N-2 (credible multiple failures)
- Determination of security margins
  - Distance to instability (preferably in MW of load)
- Can be performed
  - On-line during operation
  - Off-line (planning or system studies)

Security Assessment

- A system is secure when
  - can withstand successfully a list of contingencies
- Post-contingency controls *not affecting loads* allowed after N-1 contingencies:
  - shunt compensation switching
  - increase in generator/compensator voltages
  - secondary voltage control
- Controls affecting loads are considered for more severe (multiple) disturbances
  - Typically N-2

VSA vs. Static Security

- Static security assessment checks for post-contingency:
  - voltage levels (e.g. V>0.9)
  - line overloads (thermal limits)
    - danger of cascaded line tripping
  - both determined by standard load flow
- Voltage Stability
  - dynamic phenomenon
  - proper models required
    - Generators (not PV/PQ buses)
    - Load restoration processes (not always constant P or G)
    - Time dependent controls (e.g. generator OEL)

Time scale decomposition

- Long-term dynamics (10s of seconds – minutes)
  - Continuous
    - Load self-restoration
    - Prime movers, Secondary voltage regulation etc.

$$\dot{\mathbf{z}}_c = \mathbf{h}_c(\mathbf{x}, \mathbf{y}, \mathbf{z}_c, \mathbf{z}_d)$$

  - Discrete
    - Load tap changers
    - Generator over-excitation limiters (OEL)
    - Automatic device switching (capacitors, reactors)

$$\mathbf{z}_d(k+1) = \mathbf{h}_d(\mathbf{x}, \mathbf{y}, \mathbf{z}_c, \mathbf{z}_d(k))$$

- Short-term dynamics (few seconds)
    - Generators, motors, SVCs, etc.

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{z}_c, \mathbf{z}_d)$$

- Network (instantaneous)

$$\mathbf{0} = \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{z}_c, \mathbf{z}_d)$$

Quasi-steady-state (QSS) approximation

- Short-term dynamics replaced by equilibrium conditions $\mathbf{0} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{z}_c, \mathbf{z}_d)$
  - Algebraic eq. solved together with network (extended set of power flow equations)
- Conditions for QSS to be valid:
  - Short-term dynamics must
    - be fast
    - have a stable equilibrium
    - initial conditions within region of attraction
- Greatly simplifies system representation

Static vs. time-domain methods

- Static methods
  - based on algebraic equations (equilibrium conditions of long-term dynamics)
    - extended power flow equations
  - cannot account for time-dependent controls
- Time domain methods
  - higher modeling accuracy (benchmark)
  - reveal instability mechanisms
  - richer in information
    - time sequence of events
    - assessment of remedial actions (countermeasures)

Contingency Analysis Methods

- Post-contingency load flow
- Non-divergent power flow
- VQ curves
- Full (multi-time scale) simulation
- QSS simulation

Load flow vs. long-term equilibrium

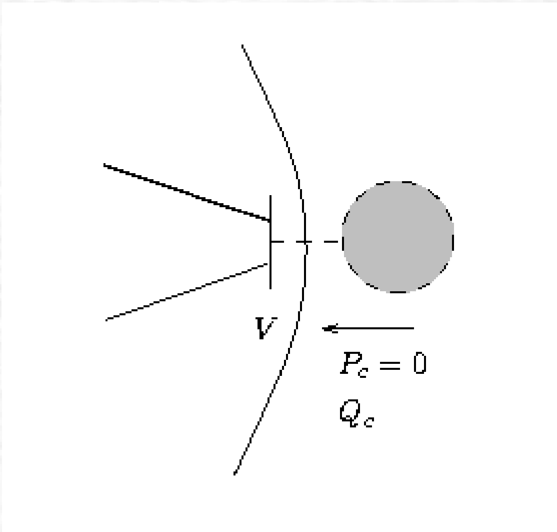
<table>
<tr><th></th><th>STANDARD LOAD FLOW</th><th>TRUE LONG-TERM EQUILIBRIUM CALCULATION</th></tr>
<tr><td>LOADS</td><td>constant power</td><td>if controlled by LTC and LTC not limited :
$\simeq$ constant power in steady state
(neglecting the deadband)
all other cases :
loads are voltage dependent</td></tr>
<tr><td rowspan="4">GENERATORS</td><td>constant voltage (PV bus)</td><td>under voltage control :
there is a voltage droop effect</td></tr>
<tr><td>constant reactive power (PQ bus)</td><td>under rotor current limit :
reactive power varies with voltage
(for saturated machines increases at low voltage)</td></tr>
<tr><td colspan="2">active power imbalances must be compensated by generators
according to frequency control</td></tr>
<tr><td colspan="2">reactive power capabilities must be updated with active power output</td></tr>
</table>

Non-divergent power flow

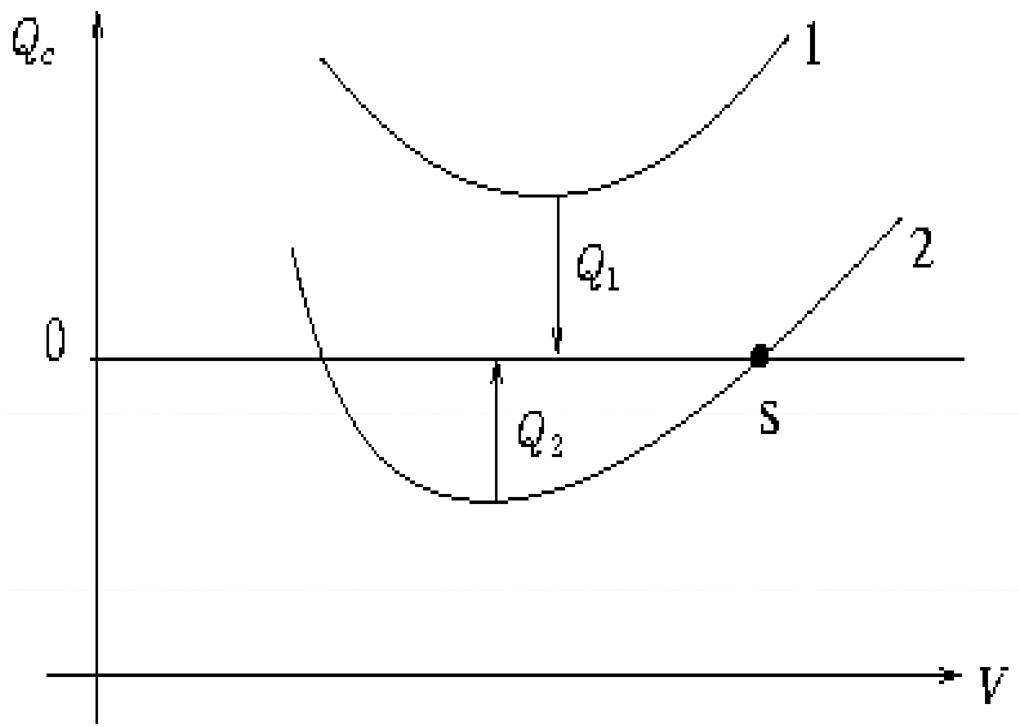
- Instead of solving $\mathbf{g}(\mathbf{y}) = \mathbf{0}$
  minimize squared mismatch $\sum_i g_i^2$
- Helps convergence of Newton-Raphson method
- Provides the area responsible for infeasibility in unsolvable cases
  - Buses with largest $|g_i|$
- Limitations :
  - enforcing a generator limit may be difficult
  - works only for mild infeasibility

VQ curves

- Relationship between the reactive power Q_c injected at a bus and the voltage V at this bus.
- Obtained by adding a fictitious synchronous condenser and solving repeated load flows for decreasing values of V

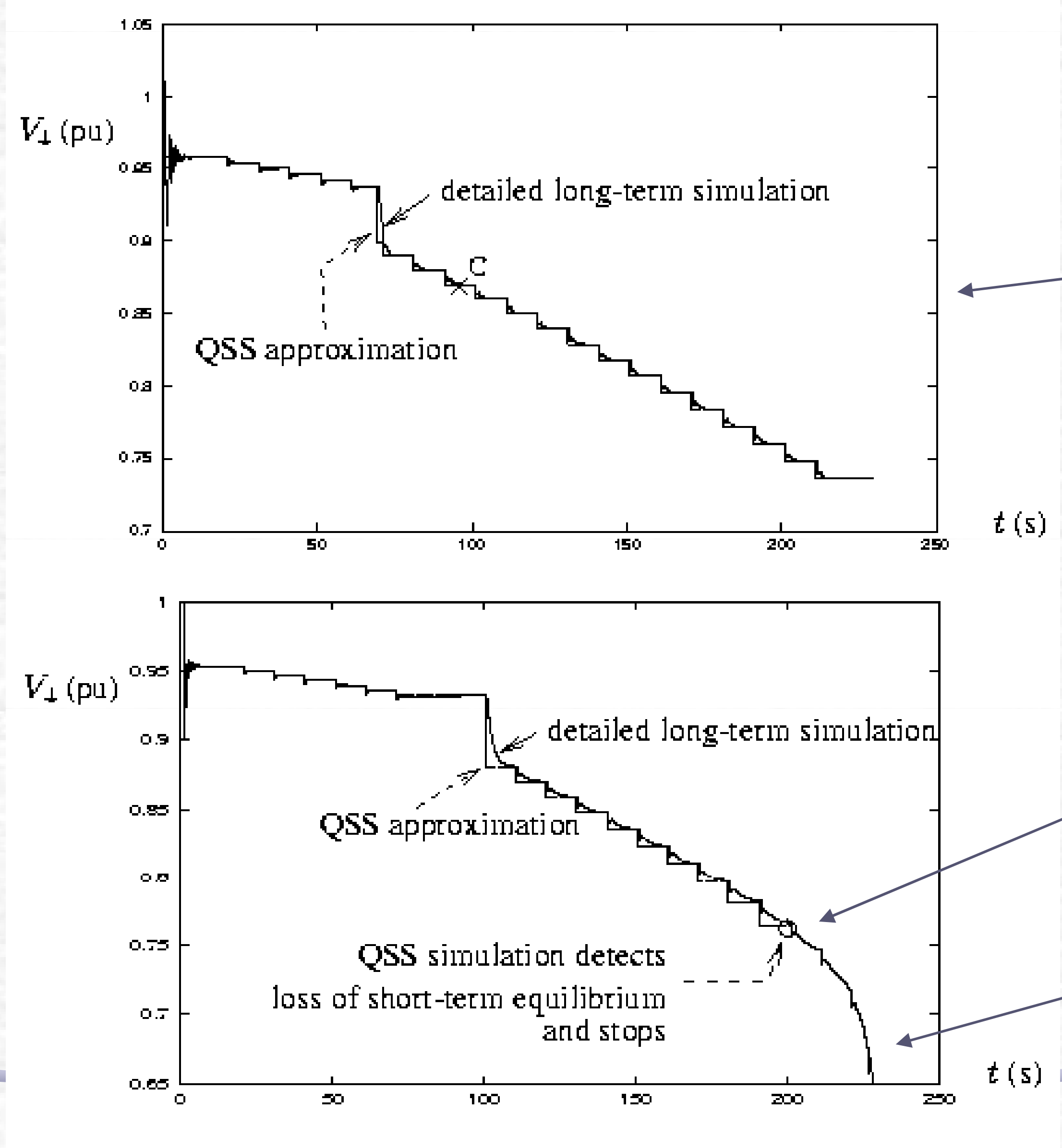


Stable and unstable cases



- Curve 1 (unstable)
  - provides a solution when the original load flow problem is infeasible
  - indicates the minimal reactive power to inject at the chosen bus in order to stabilize the system (minimum required compensation Q_1)
- Curve 2 (stable operating point S)
  - provides a reactive power margin to instability Q_2
  - by increasing a single reactive load, the resulting mode of instability is unrealistic

Full vs. QSS simulation



- Stable case
- Unstable case
- Time scale decomposition stops being valid
  - Short-term instability

QSS simulation pros and cons

- Compromise between
  - efficiency of static methods and
  - advantages of time-domain methods
- Accurate for voltage security analysis
- Well suited to real-time
  - >1000 times faster than multi-time-scale simulation
- Limitations: cannot deal with
  - instability of short-term dynamics
    - loss of short-term equilibrium detected by QSS divergence
  - severe disturbances
    - leading to instability or
    - triggering emergency controls in the short-term

Available Transfer Capability (ATC)

- ATC: measure of system ability to further transfer power from a set of sources to a set of sinks
  - stress direction
- ATC = TTC - TRM - existing transmission commitments
  - TTC: Total Transfer Capability = total power that can be securely transmitted
    - min (thermal limit, voltage stability limit, transient angle stability limit)
  - TRM: Transmission Reliability Margin
    - Includes all types of reserves
- Focus on TTC in terms of voltage security

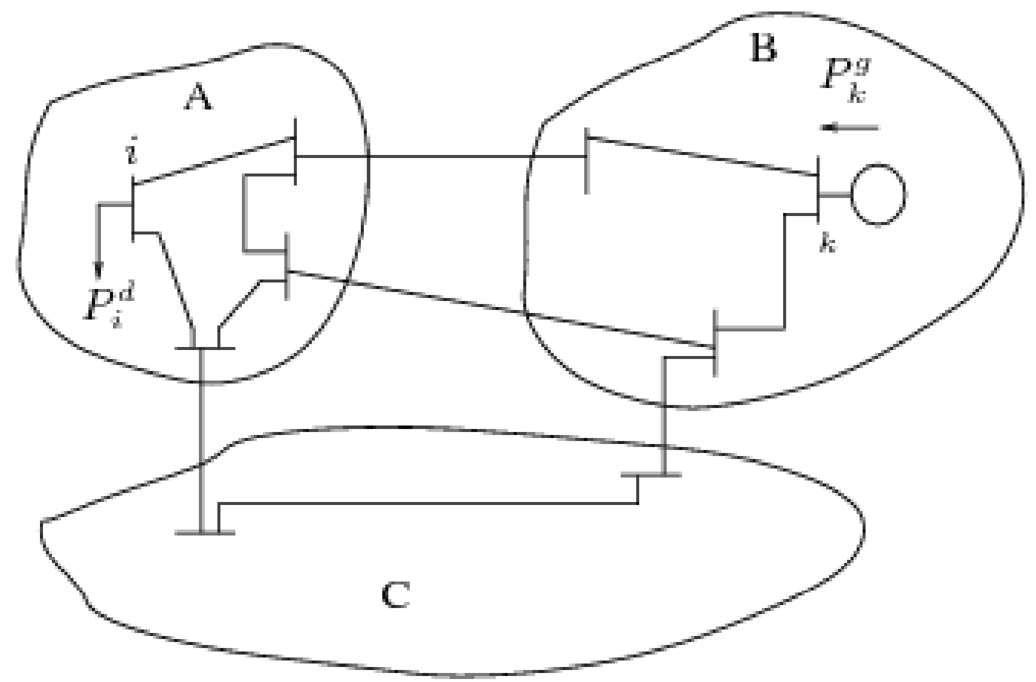
Stress definition

- Active loads: $P_{\ell i} \; = \; P^o_{\ell i} + S\,\lambda_{\ell i}$ with $\sum_i \lambda_{\ell i} = 1$
- Reactive loads: $Q_{\ell i} \; = \; Q^o_{\ell i} + S\,\mu_{\ell i}$ with $\sum_i \mu_{\ell i} = \tan\phi$
- Generation: $P_{gi} \; = \; P^o_{gi} + S\,\lambda_{gi}$ with $\sum_i \lambda_{gi} = 1 + \delta$
- Long-term equilibrium conditions:

$$\mathbf{f}(\mathbf{y},\mathbf{p}) = \mathbf{0} \qquad \text{with} \qquad \mathbf{p} = \mathbf{p}^o + S\,\mathbf{d}$$

  - S: level of stress
  - $\mathbf{d}$: direction of stress
  - $\mathbf{p}$: vector of load and generating powers
  - $\mathbf{p}^o$: reference operating point

Example of different stresses



$$P_{\ell i} = P^o_{\ell i} + S\,\lambda_{\ell i}$$
$$Q_{\ell i} = Q^o_{\ell i} + S\,\mu_{\ell i}$$
$$P_{gi} = P^o_{gi} + S\,\lambda_{gi}$$

- TTC from B to A (all λ_C=0, all μ according to PF)
  - λ_{gB}>0, λ_{lA}>0 (typical for voltage security even in the same system) or
  - λ_{gB}>0, λ_{gA}<0 (preferred by UCTE for TTC between countries)

Loadability limits and security margins

- Define maximum permissible stress level S
- Computational methods include:
  - Continuation power flow
  - Optimization formulation
  - QSS simulation with sensitivity analysis
- Types of limits:
  - No-contingency or post-contingency loadability limits (PCLL)
  - Secure Operation Limits (SOL)

Optimization formulation

- Define the loadability limit as the solution of optimization problem: $\max_{y,S} \; S$
  - Subject to $\mathbf{f}(\mathbf{y}, \mathbf{p}^0 + S\,\mathbf{d}) = \mathbf{0}$
  - and inequalities constraints corresponding to limits
- 1st order necessary optimality conditions

$$\frac{\partial \mathcal{L}}{\partial \mathbf{y}} = \mathbf{0} \quad \Leftrightarrow \quad \mathbf{f}_{\mathbf{y}}^T \mathbf{w} = \mathbf{0}$$

$$\frac{\partial \mathcal{L}}{\partial \mathbf{w}} = \mathbf{0} \quad \Leftrightarrow \quad \mathbf{f}(\mathbf{y}, \mathbf{p}^0 + S\mathbf{d}) = \mathbf{0}$$

$$\frac{\partial \mathcal{L}}{\partial S} = 0 \quad \Leftrightarrow \quad 1 + \mathbf{w}^T \mathbf{f}_{\mathbf{p}^o} \mathbf{d} = 0$$

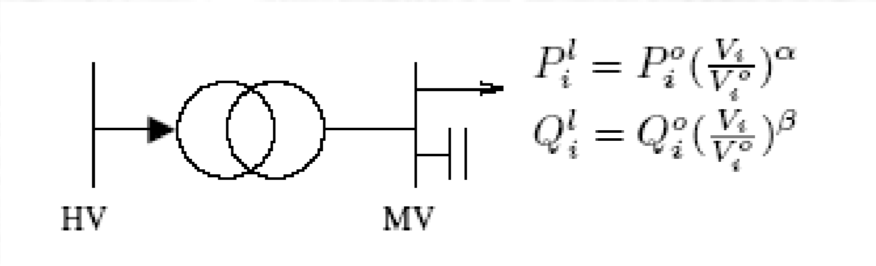
  - Jacobian of equilibrium equations singular at optimum (without inequality constraints)
  - $\mathbf{w}$ (vector of Lagrange multipliers) left eigenvector of the zero eigenvalue of Jacobian
    - Used to compute sensitivity of margin S

Solution of optimization problem

- Directly by solving optimality conditions
  - Newton method (involves Hessian of f)
  - Handling of generator reactive limits:
    - guessing which generators are limited at the maximum load point
- Optimal Power Flow (OPF)
  - Explicitly include inequalities
  - Interior point method (logarithmic barrier)
- Simulate the stress with constant power loads up to the maximum
  - problems with divergence near the maximum

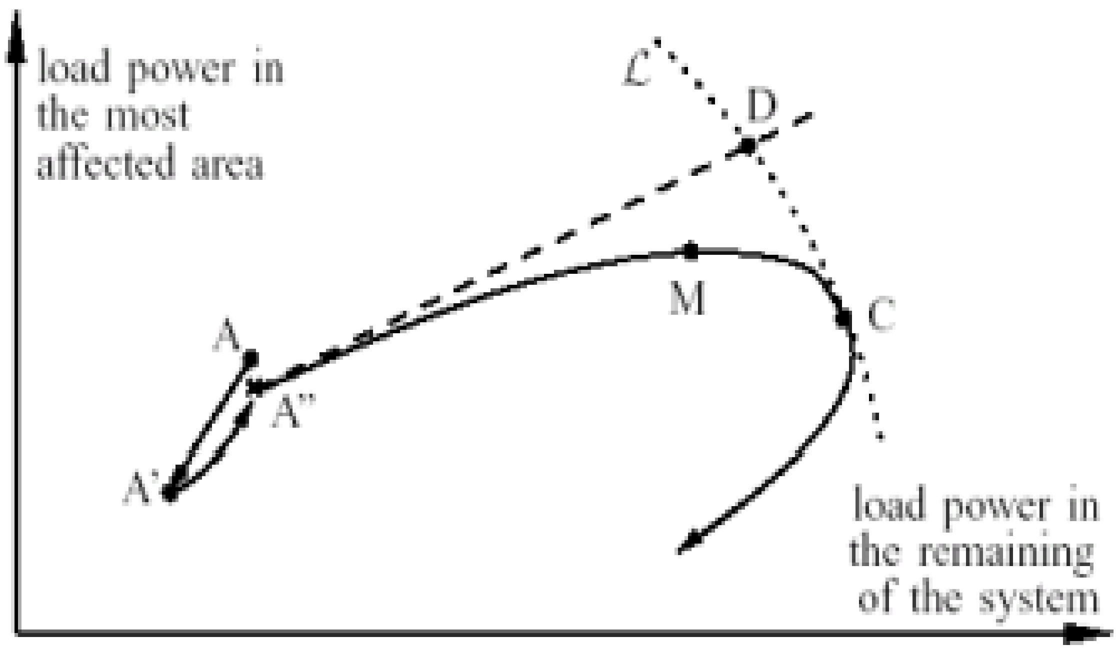
QSS simulation coupled with sensitivity analysis

- Use voltage dependent load behind real or assumed LTC transformers



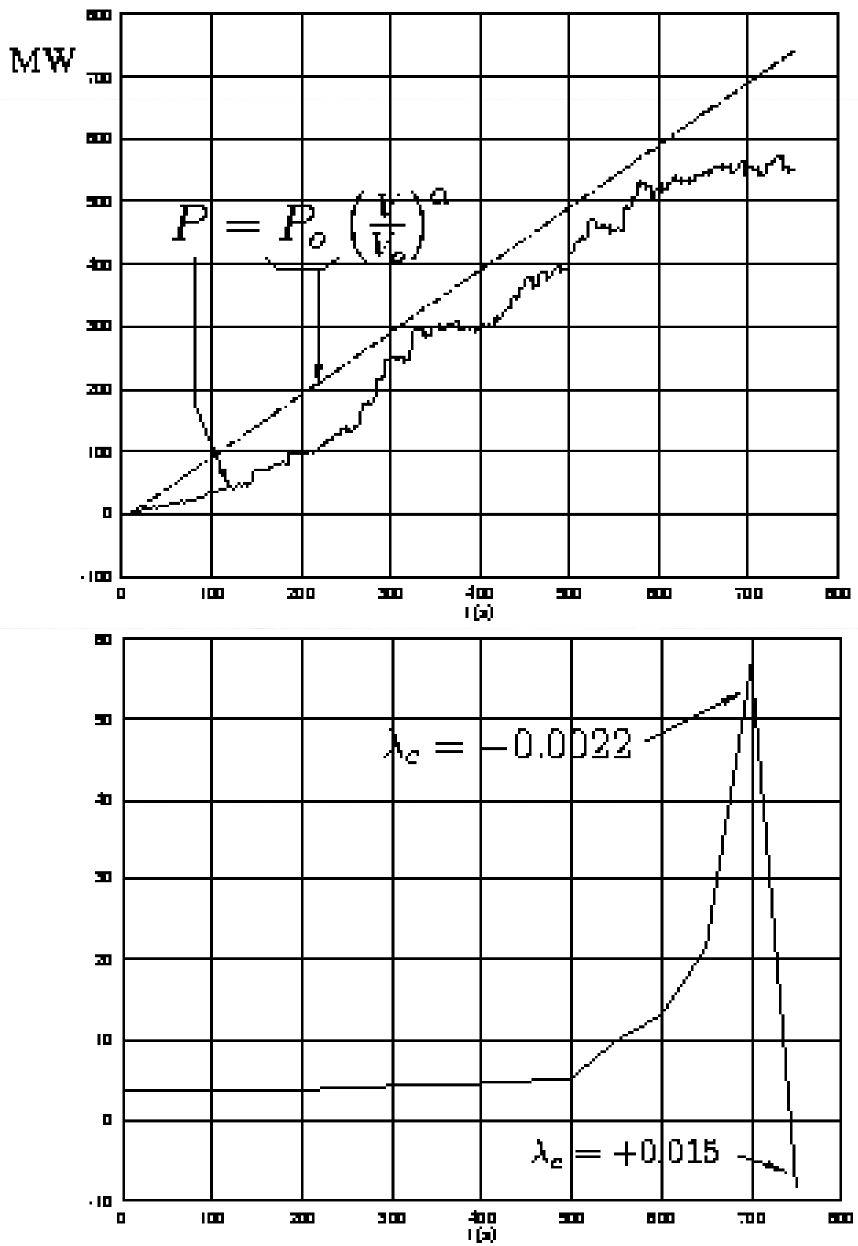
- Simulate a ramp increase in demand P^o
- Enforce all limits during simulation
- Track smallest eigenvalue (and/or a sensitivity index)
  - When sign changes a loadability limit is reached

Critical Point and Maximum Loadability



- Loadability surface
  - Load power space
- Simulate unstable scenario
- Stress direction AD
- Critical Point C
  - On the loadability surface
  - Sensitivities change sign
- Point M
  - Not a Loadability Limit
  - LTCs unable to restore V in affected area

Example of QSS simulation

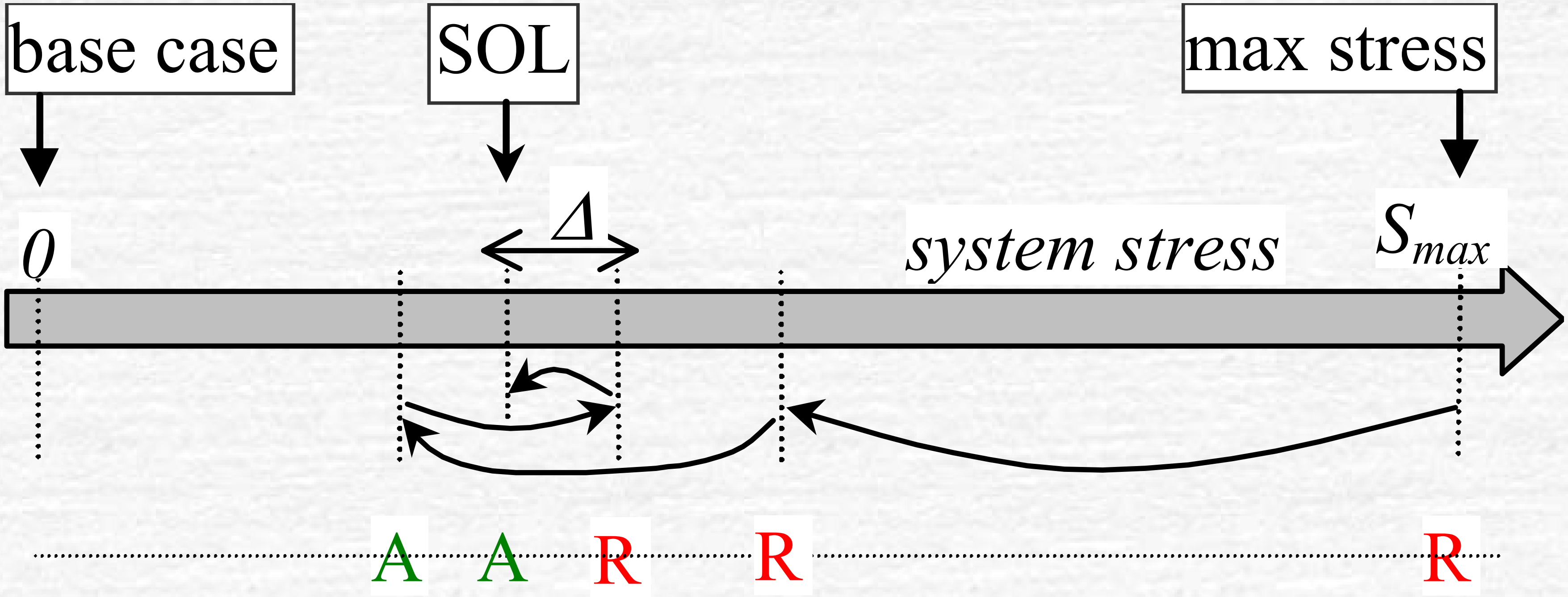


- Increase in demand vs. actual consumption
- Maximum P not necessarily loadability limit
  - Maximum consumption limited by LTC limits and other load increase
- Change of sensitivity sign
  - through infinity
  - coincides with eigenvalue sign change through zero

Types of loadability limits

- No-contingency or post-contingency loadability limits (PCLL):
  - First apply contingency, then stress the system
  - Apply a method for loadability limit computation to post-contingency situation
- Secure Operation Limits (SOL)
  - Stress the pre-contingency system, until it can withstand all contingencies
  - clear distinction between
    - pre-contingency configuration (control by operators)
    - post-contingency configuration (only automatic controls)
  - meaningful for system operators:
    - security in terms of pre-contingency parameters (load)

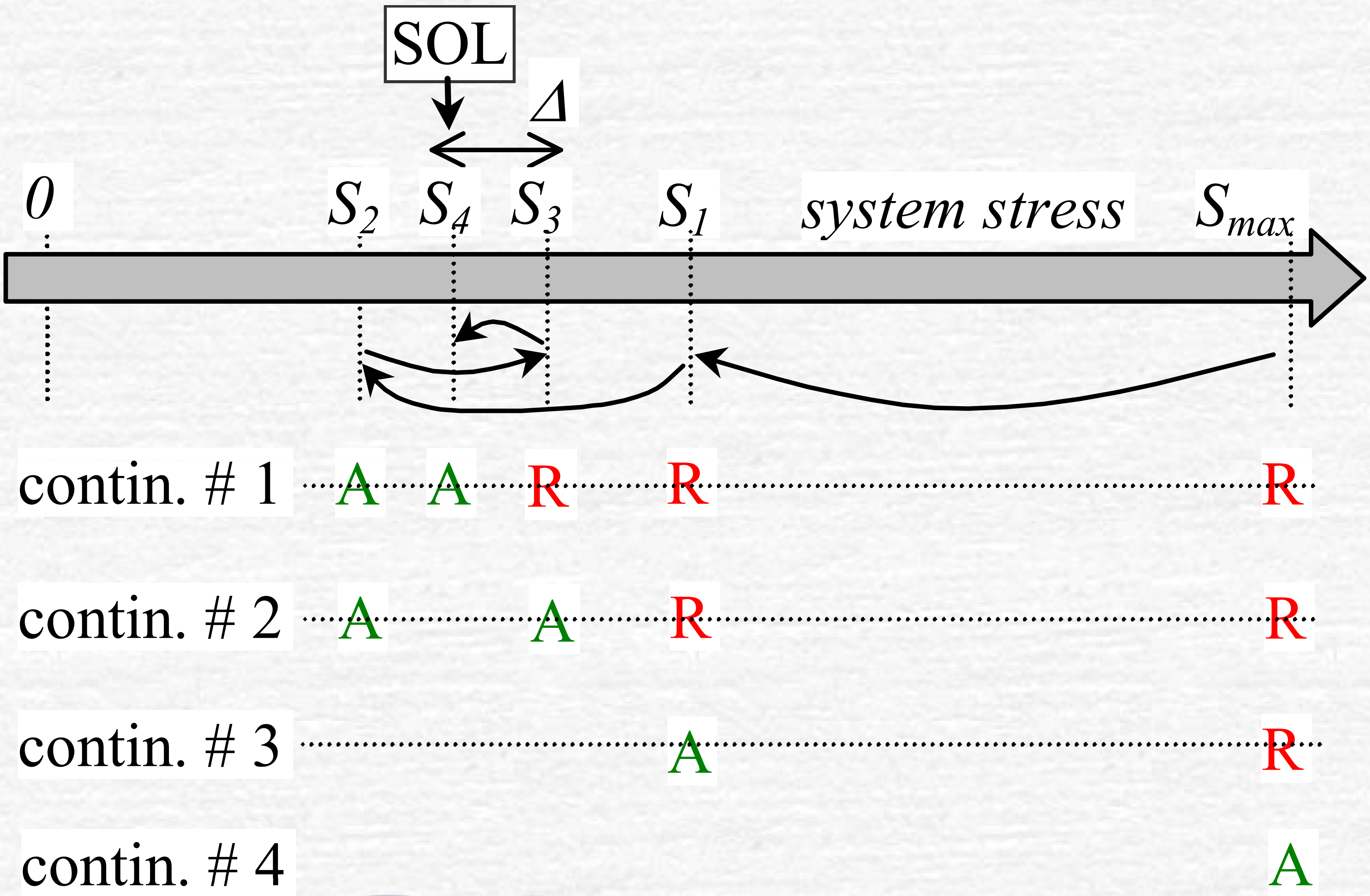
Binary search of an SOL



A : post-contingency evolution Accepted

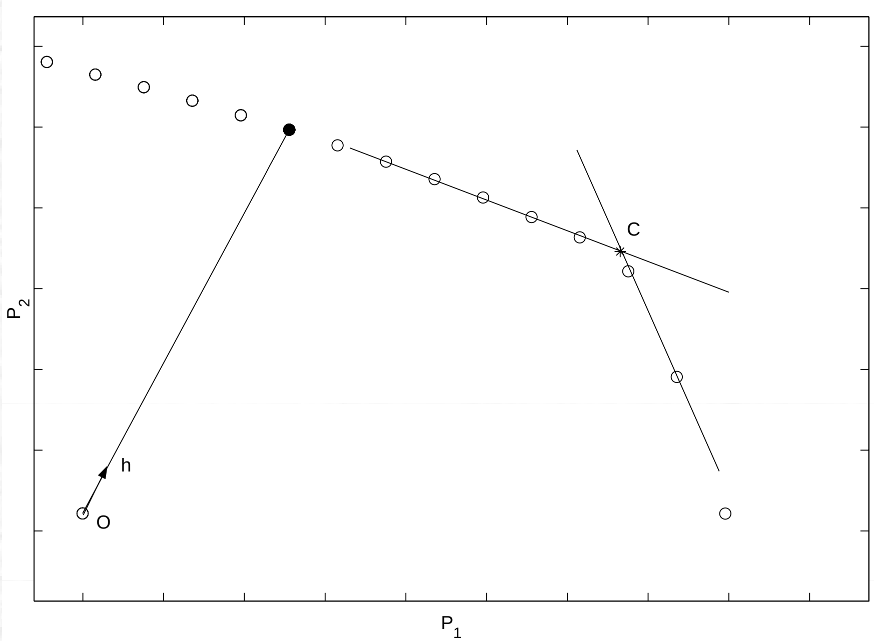
R : post-contingency evolution Rejected

Simultaneous binary search



Loadability limit visualization - Nomograms

- 2-D image of loadability limits in parameter space
- Group load parameters in two sets, e.g.
  - two major regions
  - other parameters, e.g. power transfers
- Off-line calculation of security limits
  - Post contingency or SOL
  - Used by operators on-line when DSA too slow to run in real time



P_1: total load area 1

P_2: key power transfer

Off-line vs. on-line VSA

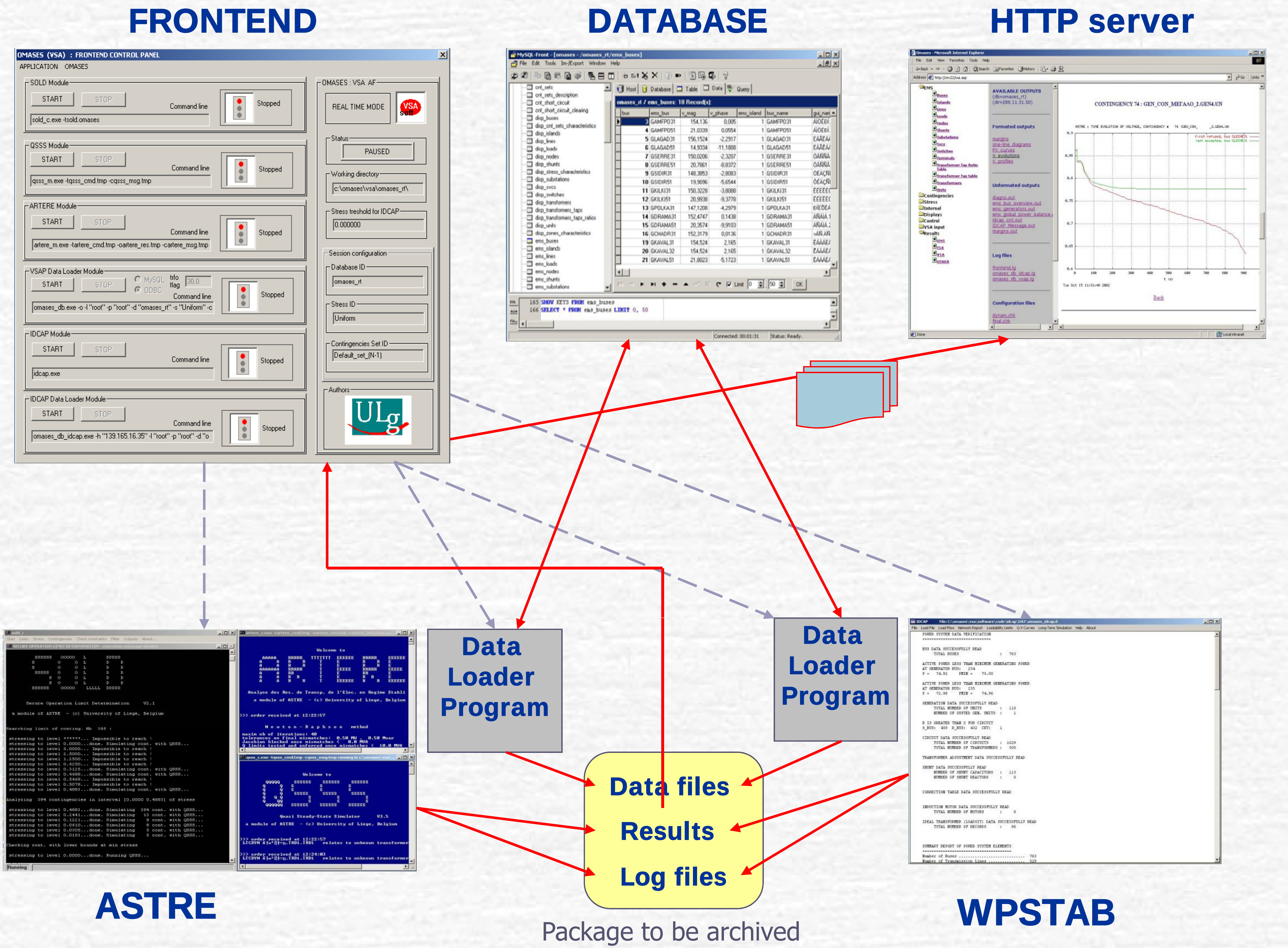
- Off-line voltage security assessment:
  - projected data and system conditions (multiple studies)
  - worst-case assumptions
  - uncertainty of system topology and actual loads introduces need for additional security margin
- On-line VSA starts from actual system conditions
- No uncertainty of topology and base case loads
- Strict requirements
  - Limited time to run
  - Need to tune off-line tools to meet the challenge

On-Line VSA in the Hellenic Interconnected System

- In operation at HTSO National Control Center
- Developed during EU OMASES project
  - ALSTOM, Tractebel, HTSO, CESI, U of Liege, NTUA, U of Genova, U of Strathclyde
- Trial operation 2002-2003
- Continuous operation since Fall 2004
  - after July 2004 blackout
- Runs every hour
- Training sessions for operators

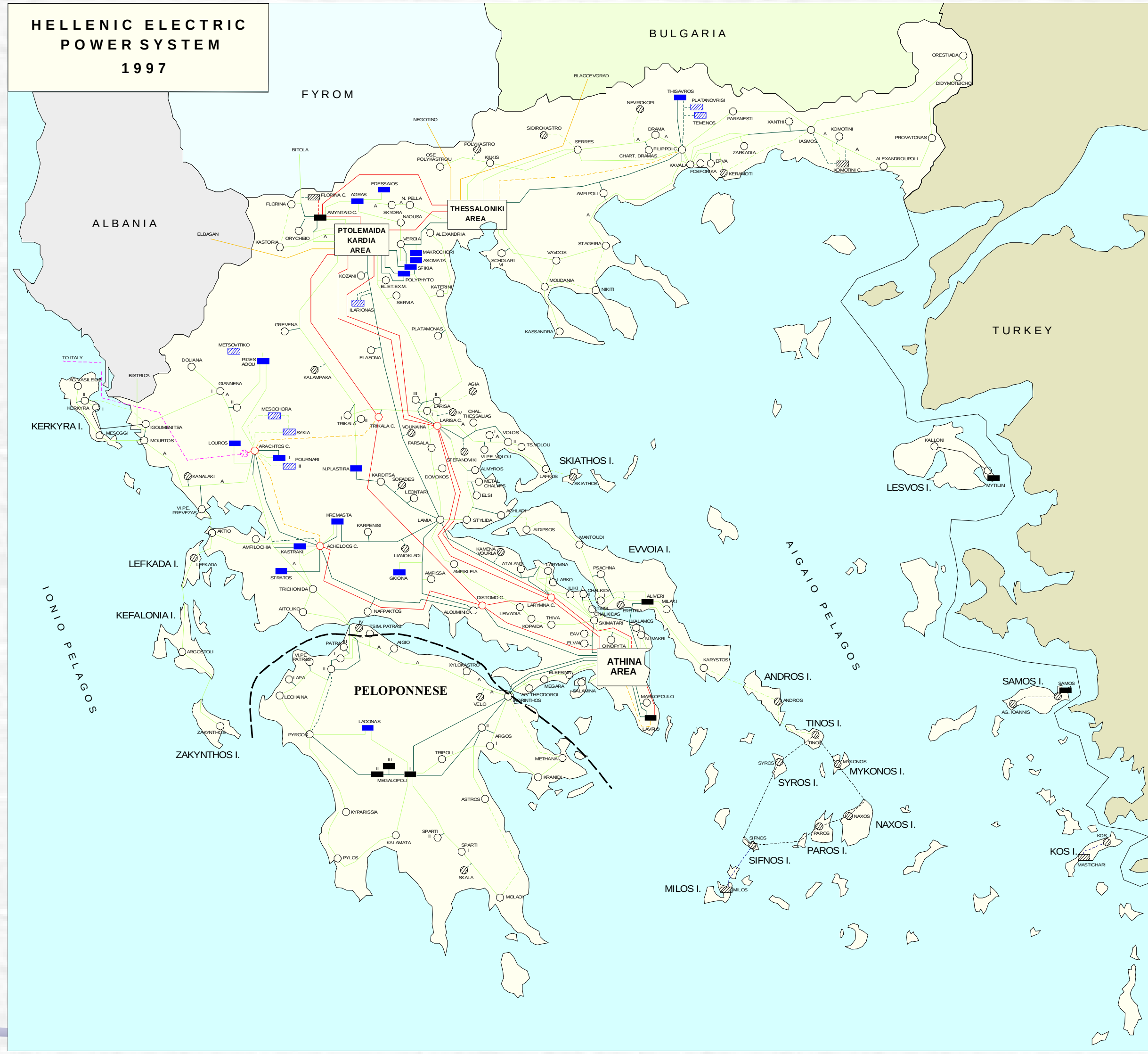
OMASES VSA Function

- ASTRE software (ULg)
  - SOL (Secure operation limit)
  - contingency filtering
  - analysis of instability mode:
    - low voltage vs. instability, area affected, involved generators and reserves, etc.
- WPSTAB software (NTUA)
  - Post-contingency Loadability Limits
  - National and regional PV curves
    - for critical contingencies identified by SOL
    - Produced with QSS simulation
  - Qualitative analysis of voltage instability


FRONTEND
DATABASE
HTTP server
Data Loader Program
Data Loader Program
Data files
Results
Log files
ASTRE
WPSTAB
Package to be archived

The Hellenic Interconnected Power System

- Main generation in the north and west
- Main consumption in Athens (south)
- International connections in the north (UCTE-2nd zone)
- Severe voltage stability problems



Peak load development

- Summer 1996: 7000 MW
- Summer 2001: 8500 MW
- Summer 2003: 9100 MW (*trial on-line VSA*)
- Summer 2004: 9400 MW (blackout)
- Summer 2005: 9800 MW (*on-line VSA restored)*
- Summer 2006: 9960 MW
- Summer 2007:10700 MW
- Summer 2008:10550 MW
- Summer2009: 9830 MW (recession…)

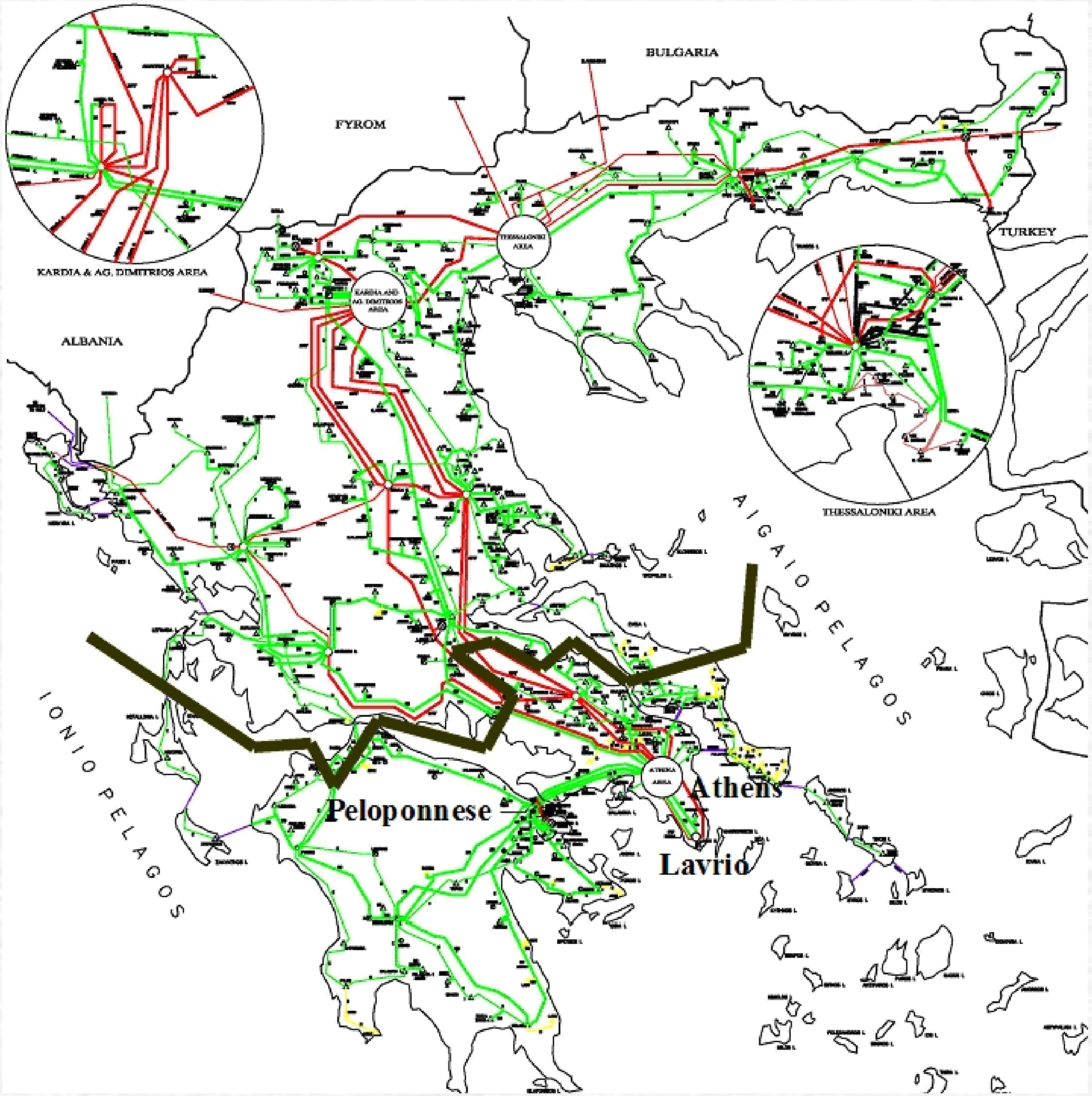
Long history of voltage instability

- Summer 1996
  - 580 MW generation missing in the South
  - Voltages dropped to 0.80 pu
  - Without collapse
- Significant system upgrades 1996-2000
  - Increase of loadability into Athens
  - New voltage instability mode in Peloponnese
- Further reinforcements (2000-2003)
  - Upgrade of the connection to Peloponnese
  - Local instability of Peloponnese eliminated
  - Weakest point in Central Greece

Athens Blackout July 2004

- Further network upgrades planned for the Athens Olympics not yet in place
- Lavrio Unit 2 (300 MW) lost, synchronized but lost again
- Manual load shedding requested
  - 80 MW manually tripped
- Unit Aliveri 3 in the weakest area tripped
- Cascade of generator trips
  - Undervoltage, auxiliaries overcurrent
- System split – South system blacked out

2004 system split



Sample on-line VSA results

Hellenic Interconnected System

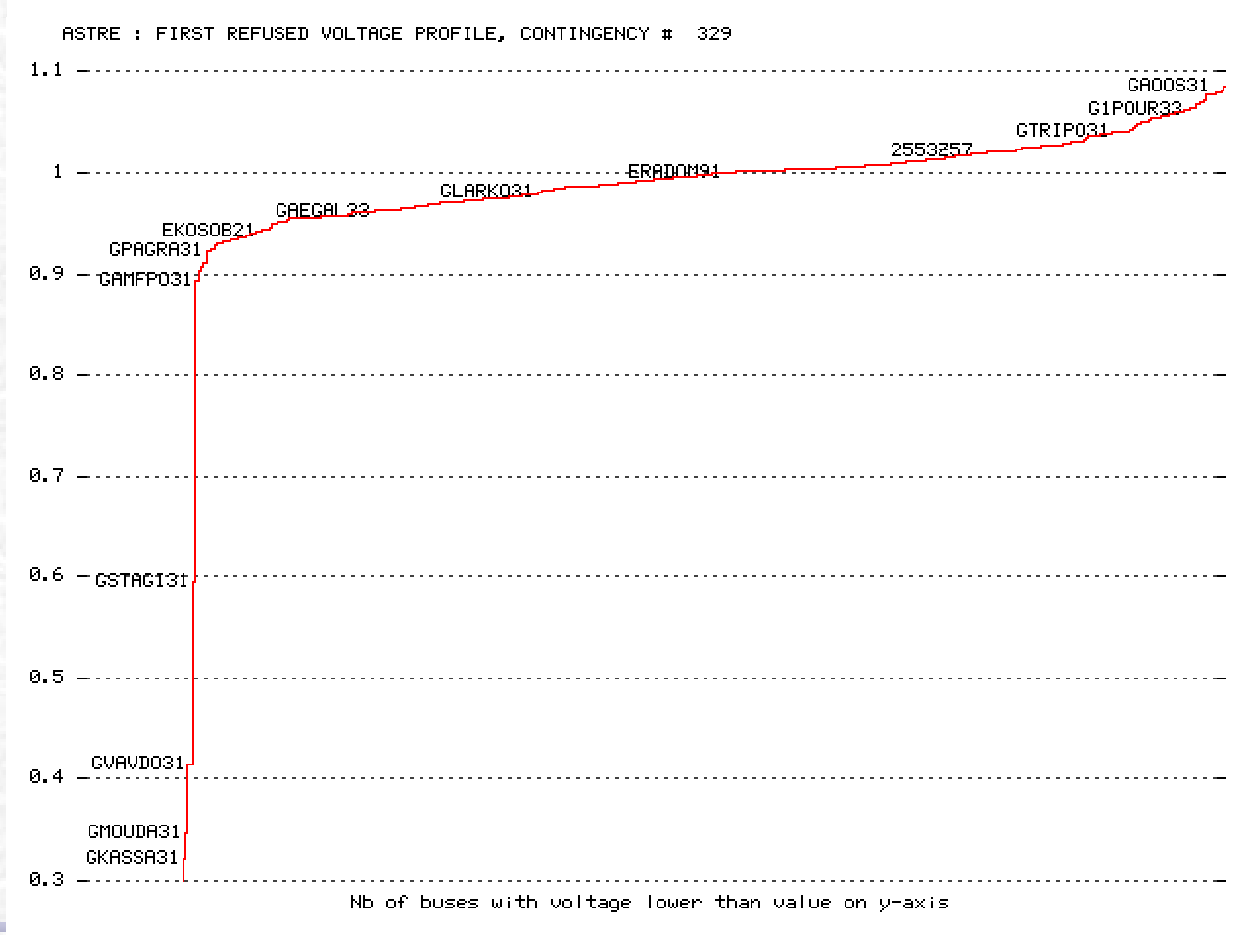
Trial operation: Summer 2002
Secure Operation Limits (SOL) in MW

329	LINE_CON_ΤΜΟΥΔΑΝ-ΜΟΥΔ.1		0
296	LINE_CON_ΜΟΥΡΤ-ΜΕΣΟΓ.1		0
228	LINE_CON_ΚΘΕΣ-ΣΧΟΛΑΡ.1		0
312	LINE_CON_ΜΕΣΟΓΓ-ΚΕΡΚ2.1		0
109	LINE_CON_ΑΡΓ2-ΑΡΓ1.1		73
347	LINE_CON_ΣΧΗΜ-ΘΗΒΑ.1		94
69	**GEN_CON_Κ_ΛΑΥΡΙΟ.GFIC.UN**		**146**
58	GEN_CON_ΛΑΥΡΙΟ.GFIC.GEN2.UN		167
90	LINE_CON_ΑΓΡΑΣ-ΣΚΥΔΡΑ.1		292
388	LINE_CON_ΦΙΛΙΠ-ΑΜΦΙΠΟ.1		324
22	GEN_CON_ΑΓ.ΓΕΩΡΓ.GEN9.UN		470
	all other contingencies	>	668

Only local problems (id. by voltage profiles)

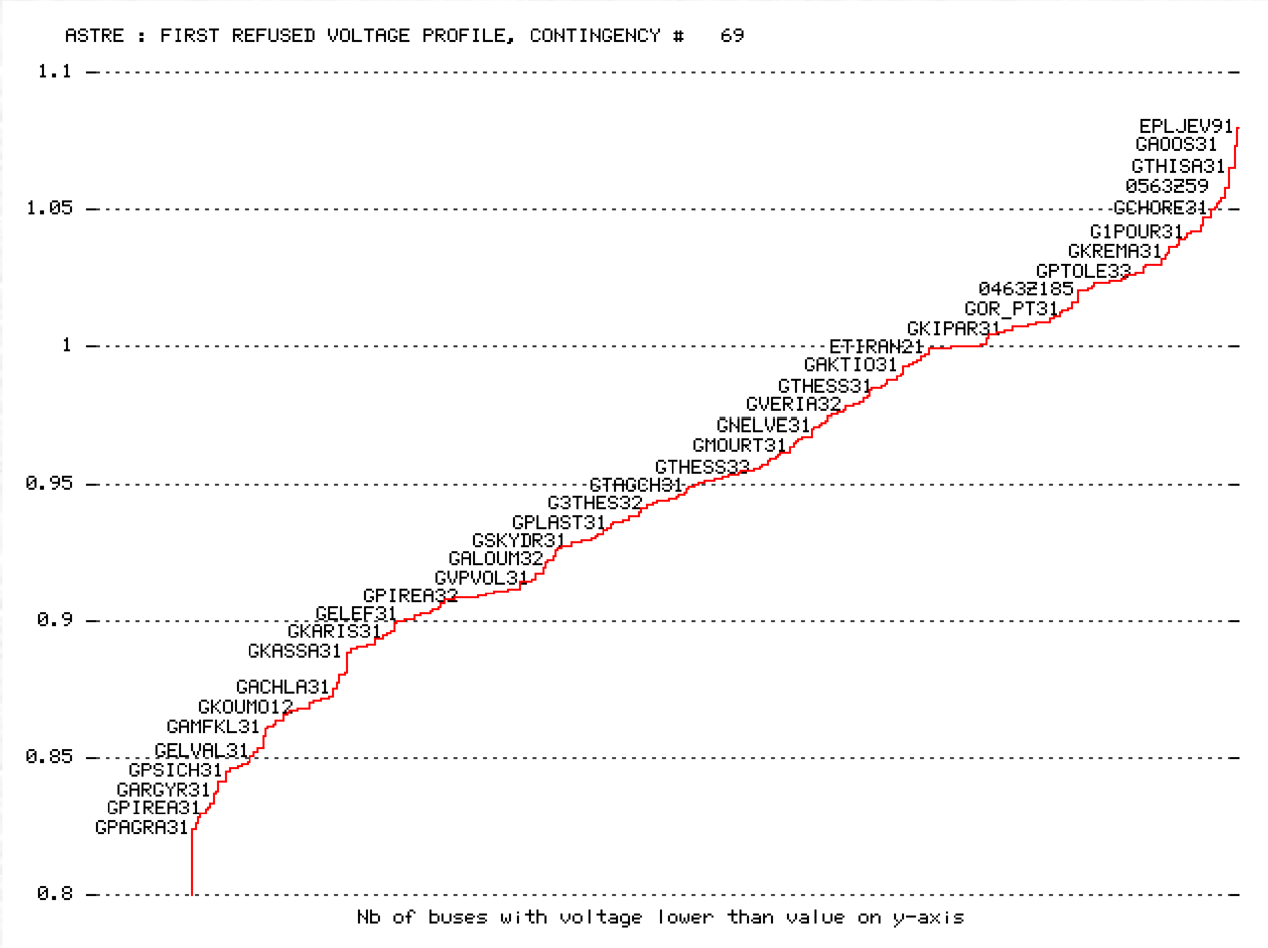
Voltage profile results

- Number of buses below a certain voltage
- Voltage profile for first contingency
  - Very few buses below 0.9
  - Localized impact



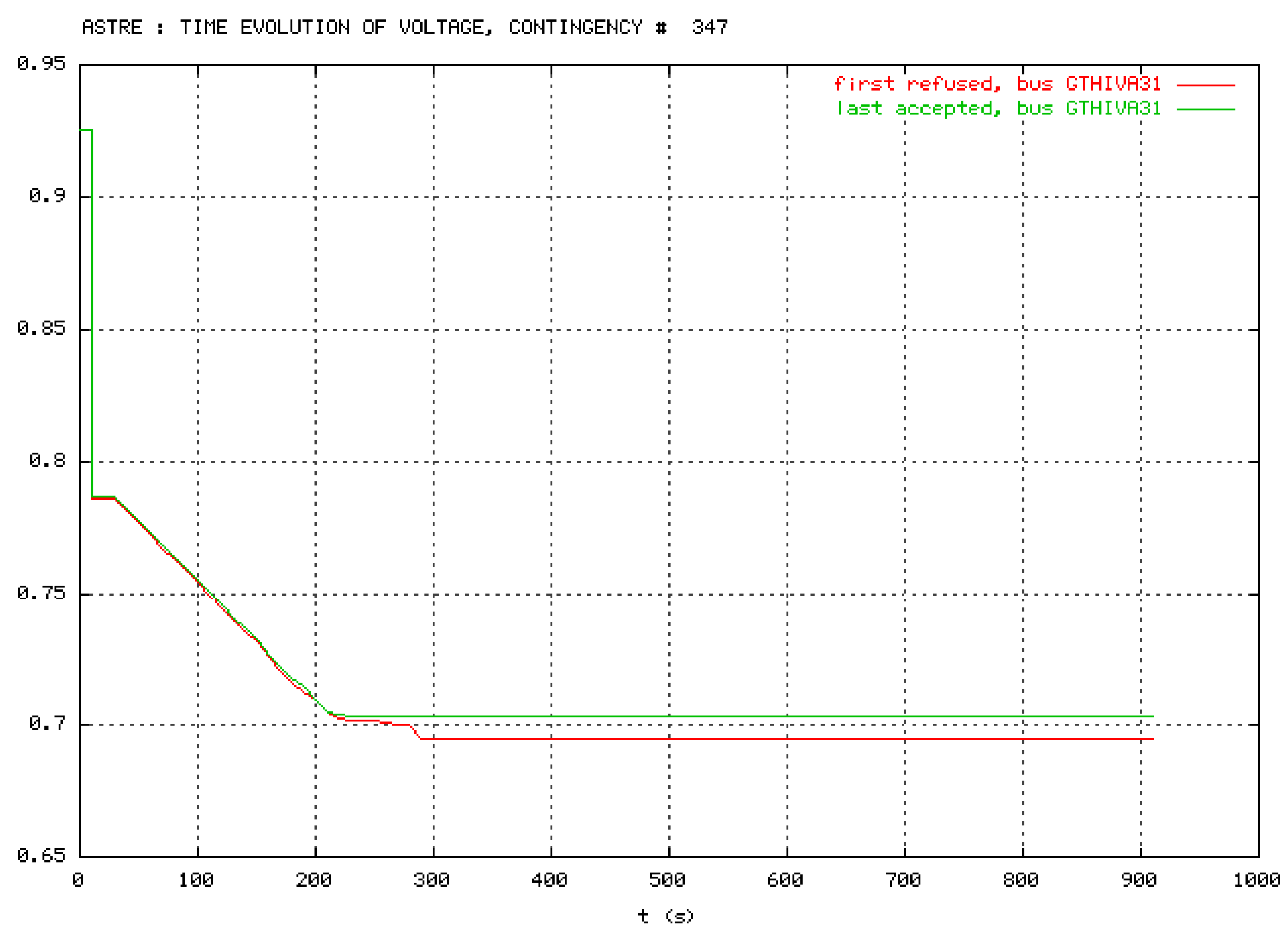
Voltage profile results

- First contingency with system-wide impact
- Uniform distribution of low voltages



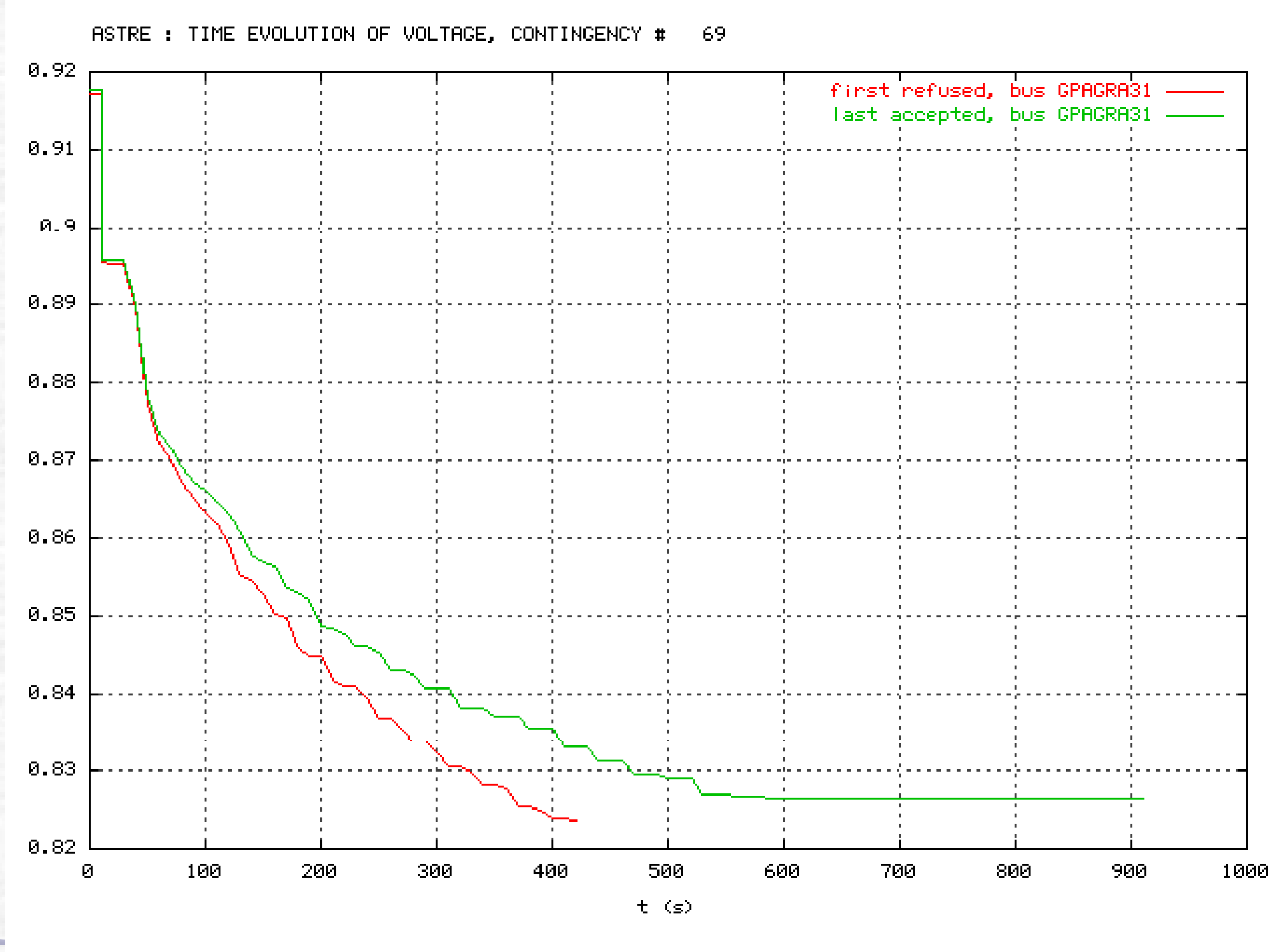
Sample voltage evolution results

- Lowest post-contingency voltage simulation
- Acceptance criterion 0.7 pu
- Case of low but stable voltages



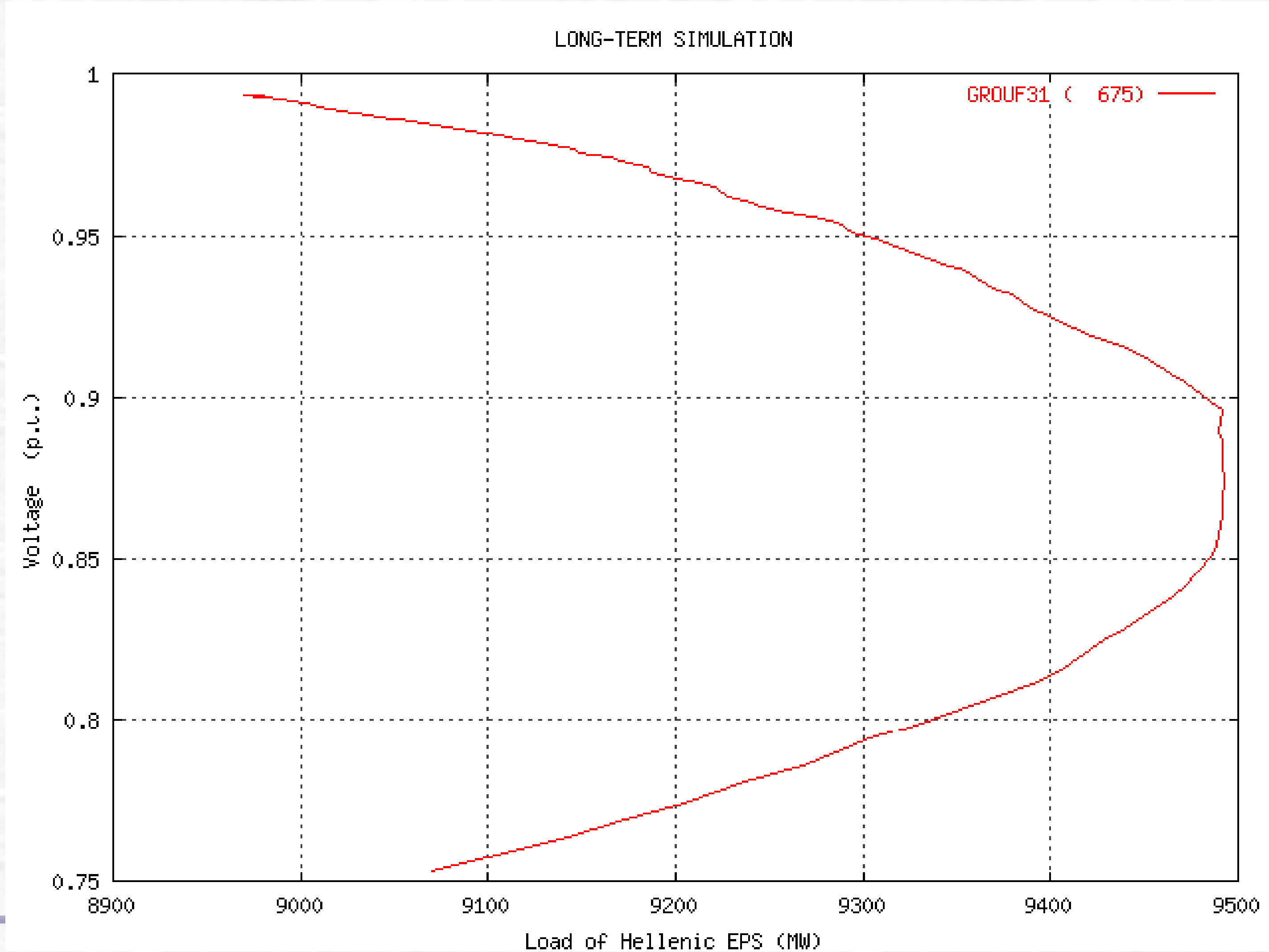
Sample voltage evolution results

- Voltage instability and collapse
- No QSS solution at end of simulation



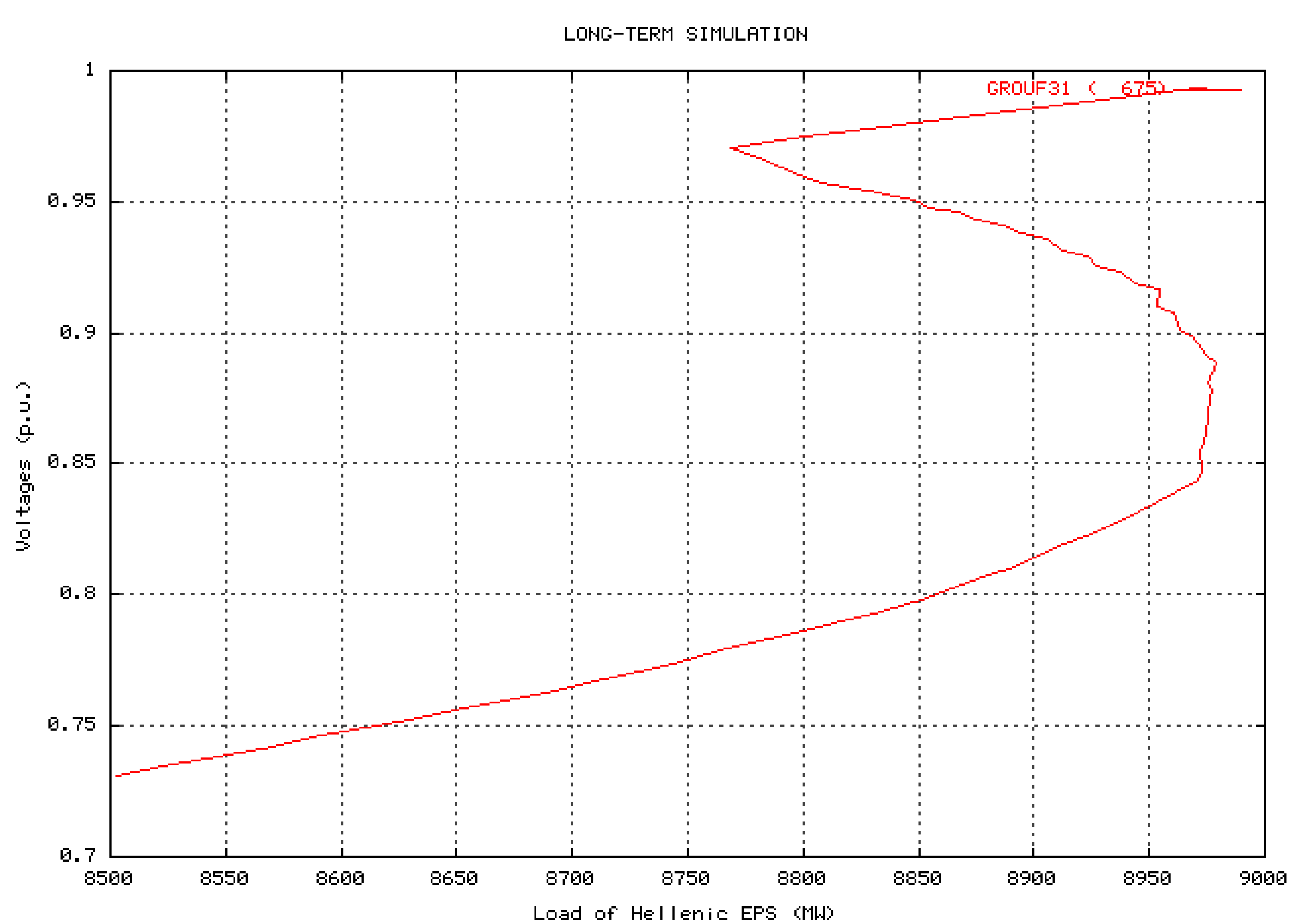
Sample VSA results (2002)

- National PV curve: no contingency



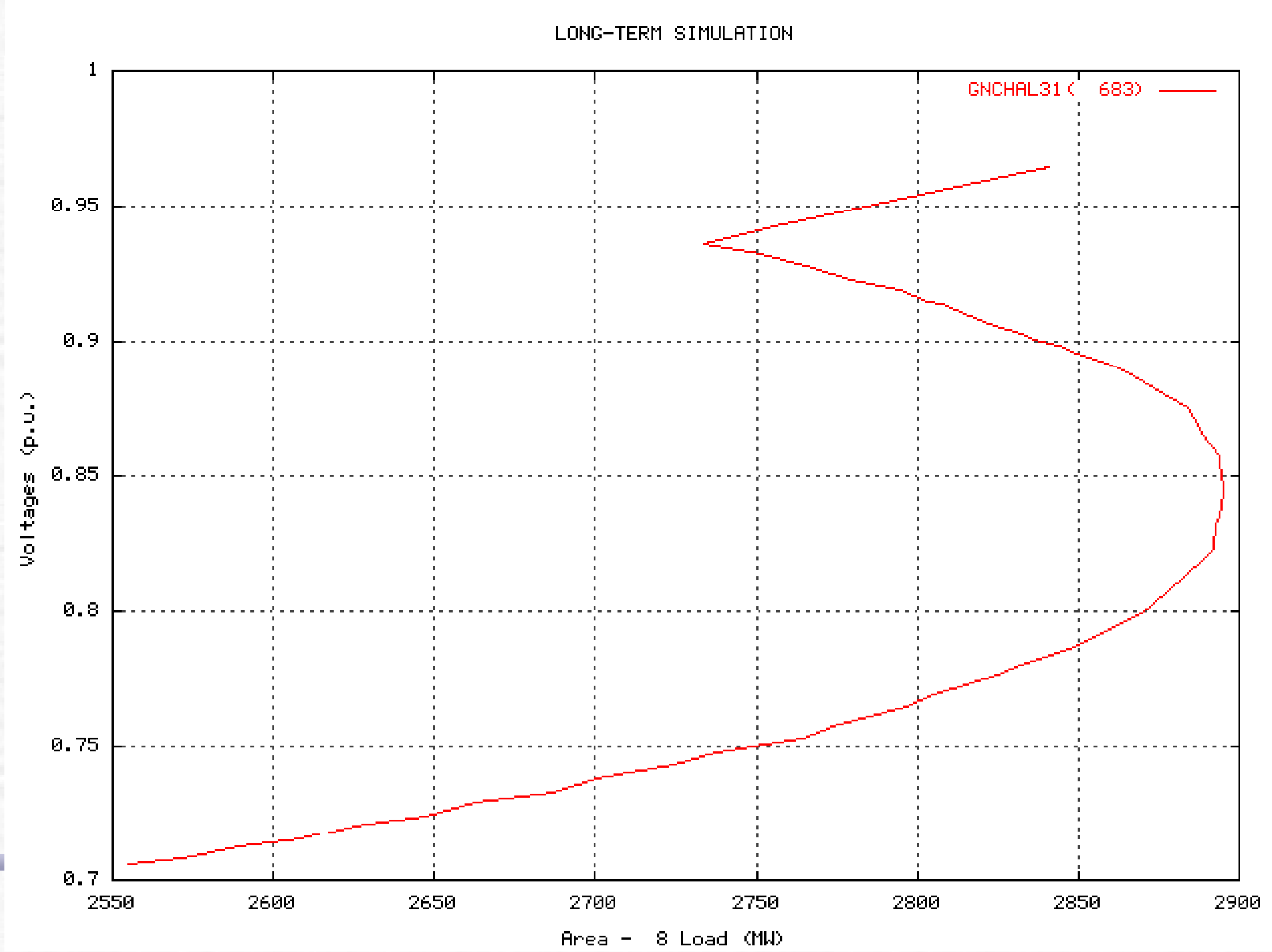
Sample VSA results (Summer 2002)

- National PV curve: critical contingency



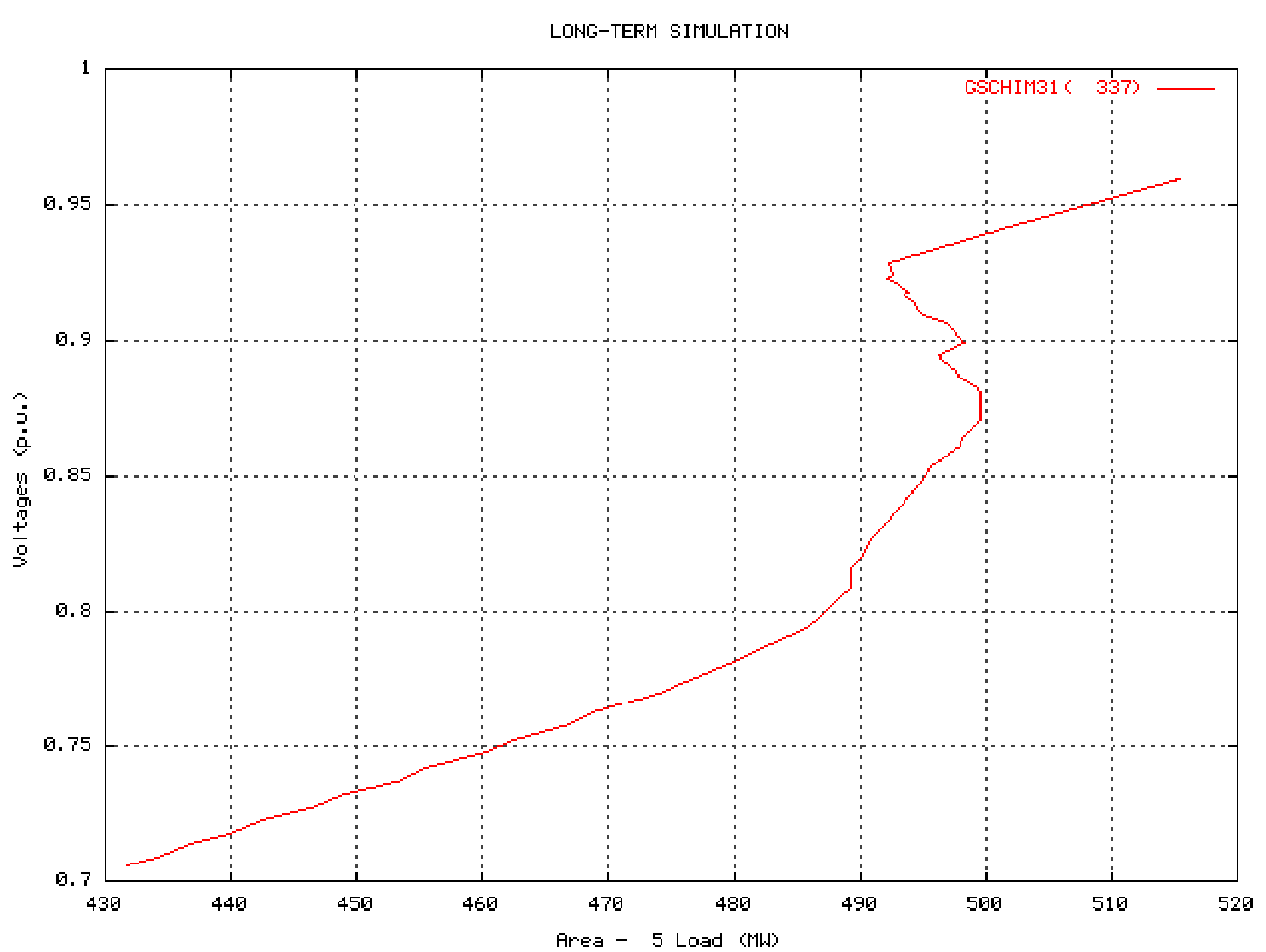
Sample VSA results

- Athens region PV curve: critical contingency
- Affected but not critical area



Sample VSA results

- Central Greece regional PV curve
- Critical area unable to restore load



On-line VSA Summary

- On-line VSA critical for monitoring system condition and avoiding blackout
- QSS simulation can face on-line VSA challenge
  - Margin determination within 5 minutes
  - Accurate representation of components
  - By-product: helpful analysis tools
- Upgrades allow increased transfer limit
  - but peak load keeps growing…
- What if security margin unacceptable?
  - Need to propose countermeasures…

Load Shedding Protection Schemes

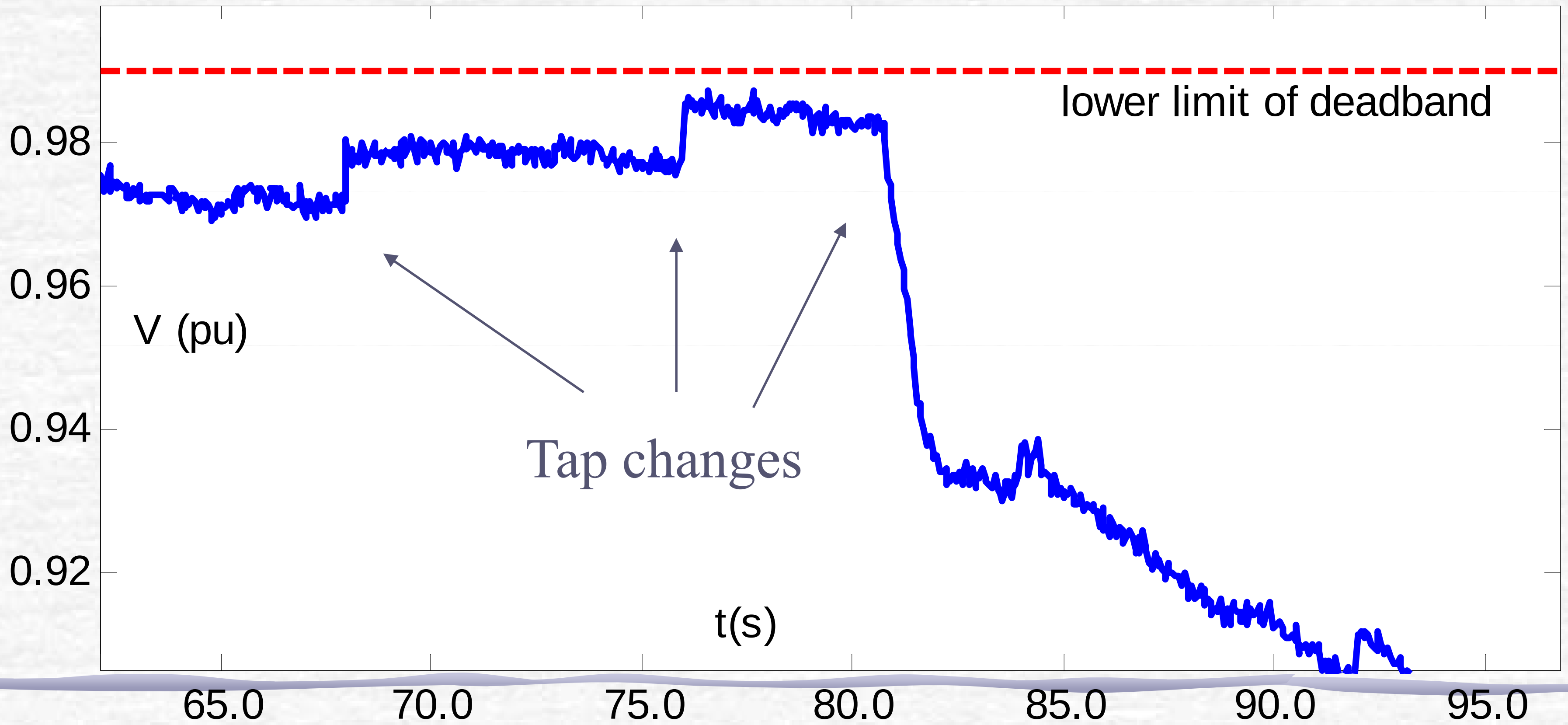
- Last resort countermeasure, when a critical situation arises
- Manual load shedding not effective
  - imposes heavy responsibility on the operators
  - induces undesired delays
  - difficult to coordinate with other controls
- Response-based vs. event-driven
- Undervoltage load shedding requires:
  - Design and tuning for a large number of contingencies
  - Extensive off-line studies

Local Identification of Voltage Emergency Situations (LIVES)

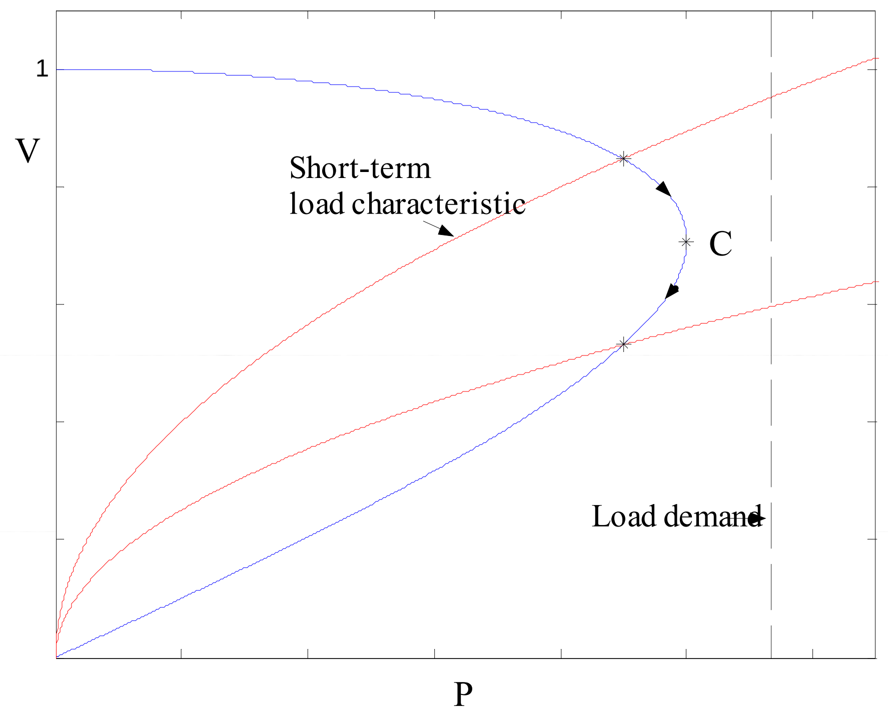
- Monitor Maximum Loadability conditions during system operation
- Desired properties of an indicator
  - Local (no communication necessary)
  - Dependable (always detect instability)
  - Secure (avoid false alarm)
  - Predictive (for emergency control to be effective)
- Voltage Stability Relay?

Key observation

- Typical simulation of voltage instability
- Before collapse LTC-controlled load voltage (and power) reach a maximum

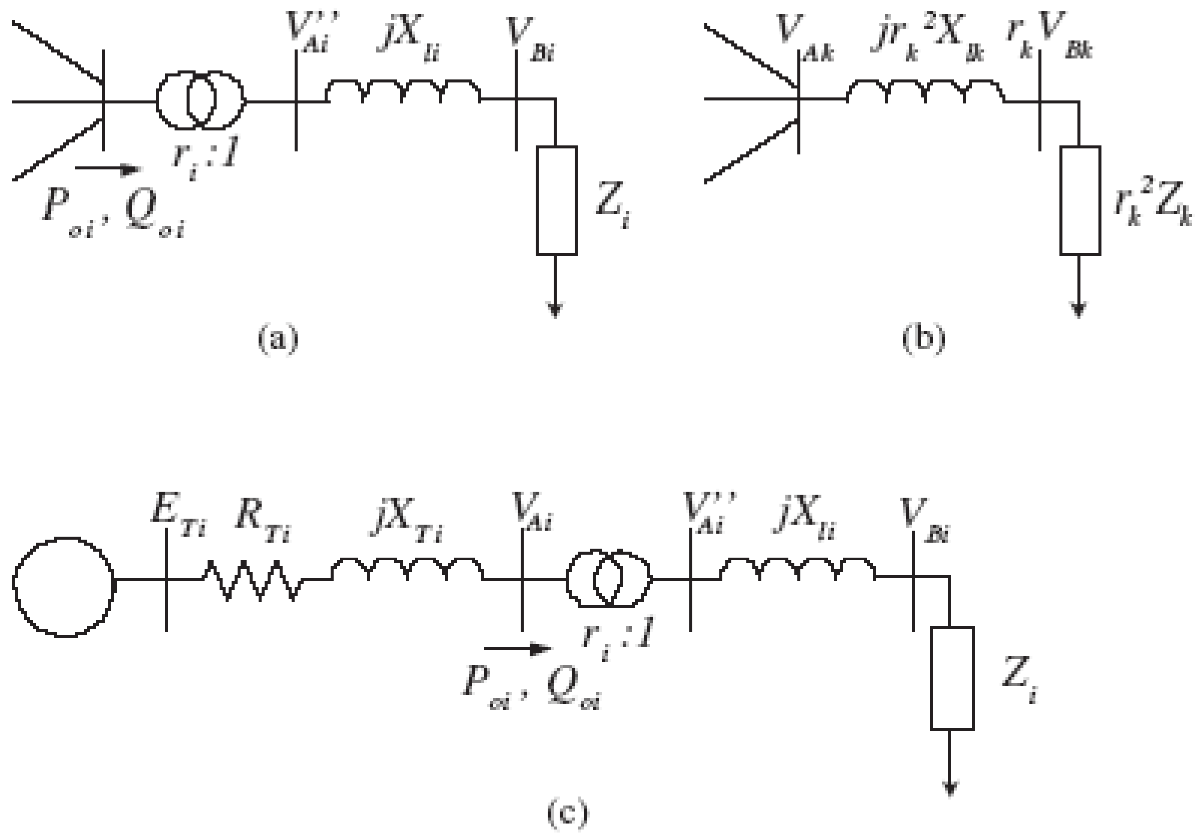


Single load case (PV curve)



- Long-term load demand infeasible
- Point C
  - Tip of the curve (bifurcation point)
  - Switching loadability limits not considered
  - Impedance Matching condition
- Extend to multi-load?

Multi-load system



- Thevenin theorem assumptions
  - Linear loads (admittances)
  - Generators are voltage sources (infinite bus)
- Load restoration through LTCs
  - Discrete or continuous
- Each load 2nd order equilibrium equation

Secondary (load) voltage to tap ratio sensitivity matrix

- Jacobian (state) matrix

$$\mathbf{A} = \left[\partial V_i / \partial r_j \right]$$

- Secondary voltage change

$$\Delta \mathbf{V}^k = \mathbf{A}\, \Delta \mathbf{r}^k$$

- LTC sufficient stability condition
  - Discrete system
    - Medanic et al.
  - Continuous system
    - Gershgorin theorem

$$a_{ii} + \sum_{j \neq i} \left| a_{ij} \right| < 0 \qquad i, j = 1,..,m$$

- After severe contingency we can assume
  - if all tap steps equal

$$\Delta V_i^k = -\Delta s \sum_j a_{ij} = -\Delta s (a_{ii} + \sum_{j \neq i} a_{ij})$$

Sufficient Stability Conditions

- For non-capacitive loads a_{ij} positive
  - assuming low voltages all taps reduce simultaneously
- Absolute can be dropped from sufficient stability condition

$$a_{ii} + \sum_{i \neq j}^{m} |a_{ij}| < 0 \ \text{for}\, \mathrm{i} = 1, \ldots, \mathrm{m}$$

- Impedance matching
  - $a_{ii}=0$ Maximum power for constant taps r_j , $j \neq i$
  - Occurs after instability (necessary instability condition)

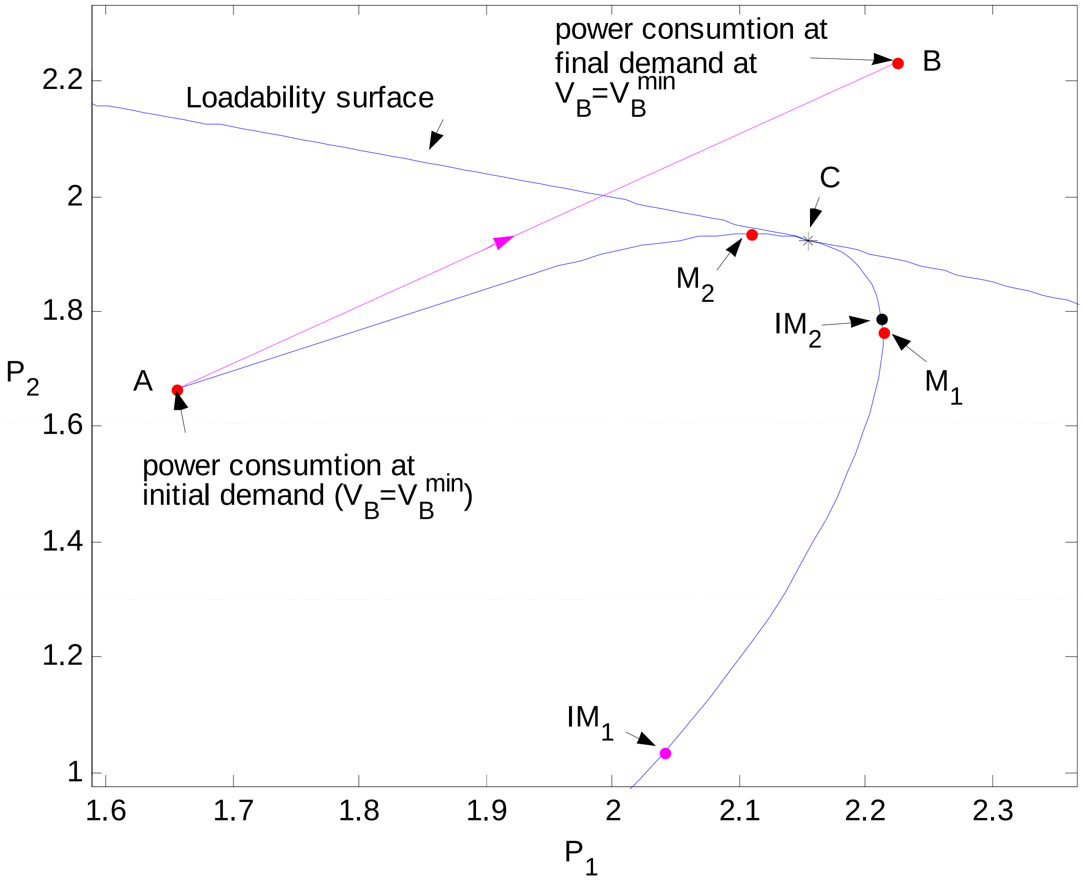
Monitoring sufficient stability condition through V_{Bi}

- Emergency detected when V_{Bi} starts decreasing

$$a_{ii} + \sum_{j \neq i} a_{ij} = -\frac{\Delta V_i^k}{\Delta s} < 0 \quad \Leftrightarrow \quad \Delta V_i^k > 0$$

  - Sufficient stability condition violated
  - When all LTCs (in an area) have acted
- Maximum power delivered to bus i along system trajectory
  - Maximum V_{Bi} along trajectory
  - Point M

Two-load system
Severe instability case



- Load power space
- Step demand increase beyond loadability limit
  - Discrete LTC simulation
- Point M_2 (maximum V_{B2}) encountered before C
- IM condition is met after C

Emergency Detection (max V_B)

- Starts when V_{Bi} remains below deadband after tap change (V_{Bi}^{o})
- Define

$$\Delta V_i^k = V_{Bi}^k - V_{Bi}^{k-1}$$

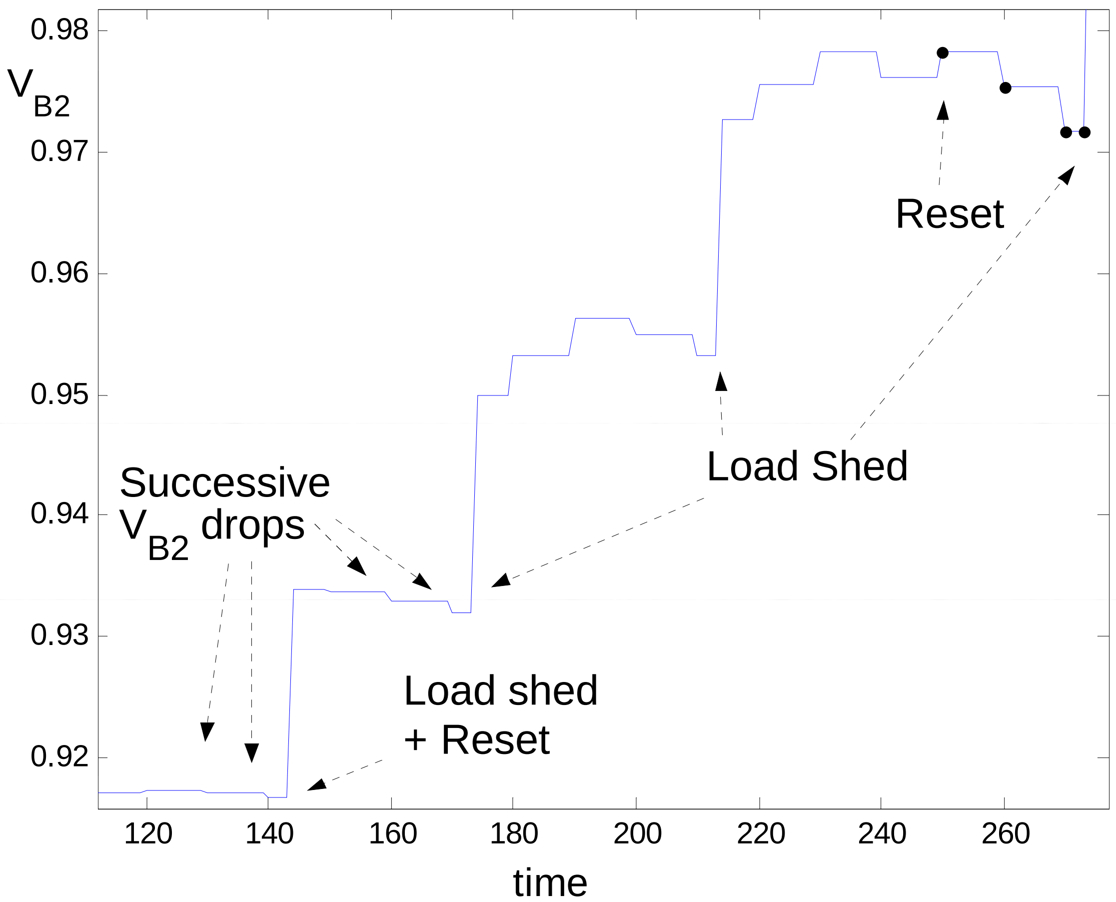
  - Measured after each LTC_i tap change
  - Assuming all LTCs have operated (same cycle)
- If ΔV_i remains negative for two cycles
  - Voltage emergency detection
- As an example 5% load is shed after detection
  - From corresponding bus (locally)

LIVES algorithm

$$\Delta V_i^k = V_i(kT) - V_i[(k-1)T]$$

```
IF  V_i>V_i^min  THEN
    detection := off ; V_r:=0
ELSE
    IF  detection=OFF  THEN
        detection := ON ; V_r:=V_i; count:=1
    ELSE
        IF  V_i<V_r  THEN
            IF  count=1  THEN
                V_r:=V_i ; count:=2
            ELSE
                alarm issued on this LTC
            ENDIF
        ELSE
            detection := OFF
        ENDIF
    ENDIF
ENDIF
```

Case 1 Emergency Detection and Load Shedding



- Detection immediately after M_1
- Load shedding resets detection process
- 4 load shedding operations (20%)
  - Only from bus 2

Conclusions

- LIVES: easy implementation of a local indicator of voltage emergency
  - locally at each LTC
- Becomes inactive when LTC limits are hit
  - Need to restore LTC operation
- Combined protection control
  - Setpoint reduction when tap limited and voltage is low
  - Load shedding after LIVES alarm
- Successful implementation so far in test systems
- Real system application remains a challenge

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