

Real-time, Measurement-based Identification of Voltage Stability



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Overview

- Introduction to Voltage Stability
- Stability monitoring vs. Security Assessment
- Voltage Instability Indices
 - NLI and RLI
- Simulation of NLI performance in a real event simulation
- On-line Application at National Control Center of IPTO in Greece
- Indicative results for the AC interconnection to Crete
 - following an actual incident (loss of generation) on the island

Voltage Stability features

- Voltage Stability is load driven
 - Unlike rotor angle (generation driven) and converter driven
- Voltage Stability associated with network
 - Maximum Power Transfer
 - Unlike frequency stability (single bus assumption)
- Usually, short-term voltage instability initiated by large disturbances
 - Short circuit, Motor stalling, also HVDC link disturbances
- Both large and small disturbances can initiate long-term voltage instability
- Effect of CIG on Voltage Stability
 - Voltage/reactive power controls interfere with load recovery and PQ injections to transmission buses
 - Modeling: Maximum current and active power constraints, FRT (LVRT)

A few remarks on voltage stability

- In some cases, static tools are used for long-term voltage stability
 - Based on exact algebraic equilibrium equations
 - This does not mean that the problem is of static nature
- Relation to angle and converter-related stability
 - Rotor angle instability or GFL converter loss of synchronism may result from degraded operating conditions caused by voltage instability
- Short-term voltage stability
 - same time frame and modeling requirements as transient angle stability
 - after a fault “fault induced delayed voltage recovery”
- Maximum power transfer conditions associated with converters give stability limits similar to those of voltage stability

What is Voltage Instability?

- Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system
 - T. Van Cutsem, C. Vournas, *Voltage Stability of Electric Power Systems*
- Key aspects
 - Maximum Power Transfer set by Transmission and Generation
 - Voltage instability is load driven
 - Dynamic phenomenon, but can be studied by steady state (equilibrium) conditions
 - Reactive power has an influence but at stability limit both active and reactive power are significant

Voltage Security Assessment vs. Stability Monitoring

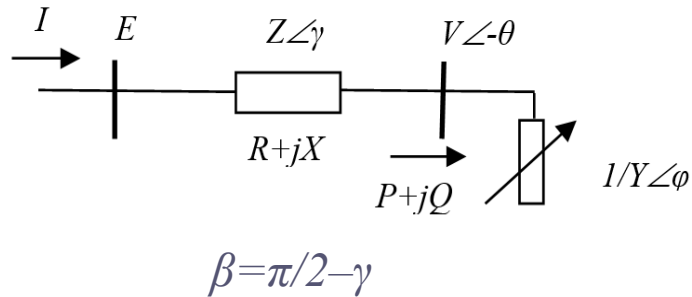
- Voltage Security Assessment checks sufficient security margins against plausible contingencies, but
 - The unexpected can always happen
- Stochasticity in system operation grows and affects both power flows and system strength
- Unforeseen stress conditions cannot be included in security analysis
- As a result, system may come close and even overstep voltage stability limit after an unforeseen event
- Need for a safety net!!!

On-line Voltage Stability Monitoring

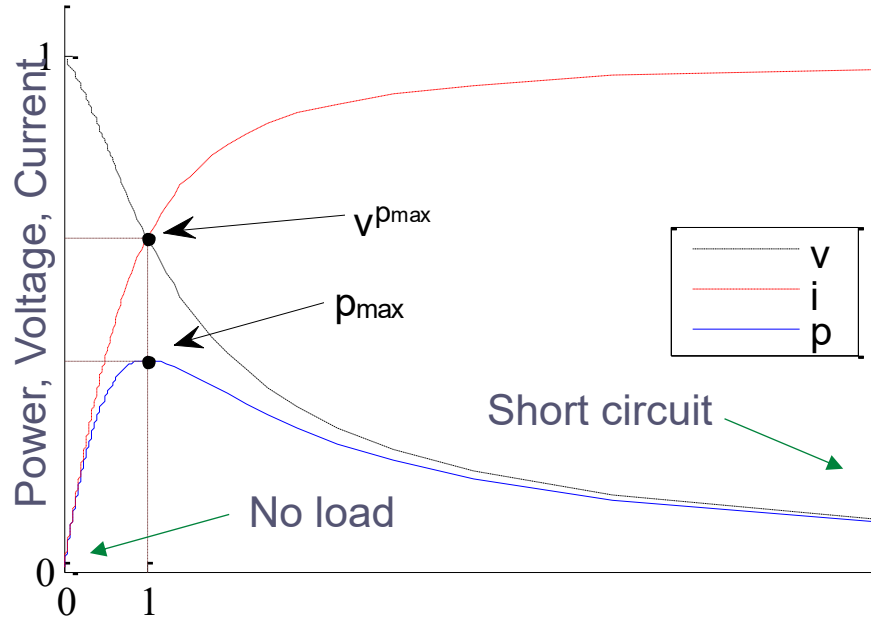
- Indirect Monitoring
 - Transmission Voltage Magnitude
 - Not sufficient as stability indicator
 - UVLS only after extensive system-specific off-line studies
 - Not applicable when instability occurs close to nominal voltage
 - Impedance Matching based on measurements
 - Both upstream and downstream networks needed for matching condition
 - Applies only to radial system
 - Requires constant load PF at measurement point (not valid far from load)
- Direct Stability Monitoring (response based)
 - LTC failure to Regulate Distribution Voltage
 - LIVES (Local Identification of Voltage Emergency Situations)
 - Power Transfer Maximization
 - NLI (PMU based) and RLI (Relay based, GR Pat Reg 1009503)
 - Power transfer maximized in affected corridor before instability is met

Impedance Matching and MPT

Radial system, constant
PF load



- Impedance matching (IM) condition $Y=1/Z$ results in maximum power transfer



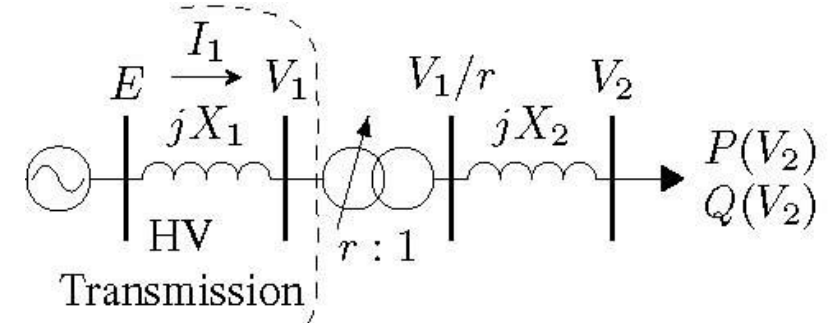
- P_{max} : Voltage Stability Limit
 - After this point
 - More admittance/less power
- IM theorem does not hold:
 - If not at constant PF bus
 - For variable E (changing with load)
 - For parallel loads

Voltage Stability Monitoring Methods

- Centralized On-line Voltage Stability Monitoring
 - Requires system-wide information and analysis in real-time
 - Monitors exact instability conditions (known system state)
 - Requires system observability with phasor information
- Currently EMS better suited for Voltage Security Assessment
 - “what if” scenarios (N-k)
 - Low-cost corrective measures (e.g. rescheduling), when insecure
- Local stability monitoring reliable for system protection
 - Measurement based (transmission bus PMU or line relays)
 - Minimal processing (filtering, G and P calculation)
 - Identifies locally a system-wide instability
 - Alarm issued for protective actions when close to instability

New LIVES Index (NLI)

- Stability condition: V_2 increases after tap decrease ($\Delta V_2 / \Delta r < 0$)
- Equivalently:



$\Delta r < 0$ $\longrightarrow$ Increase of apparent conductance seen from HV ($\Delta G_1 > 0$)

$\Delta V_2 > 0$ $\longrightarrow$ Increase of active power transfer ($\Delta P(V_2) > 0$)

- Thus, stability condition becomes:

$$\text{NLI} = \frac{\Delta P}{\Delta G_1} > 0$$

- and can be monitored using current and voltage measurements in transmission buses upstream from the LTC

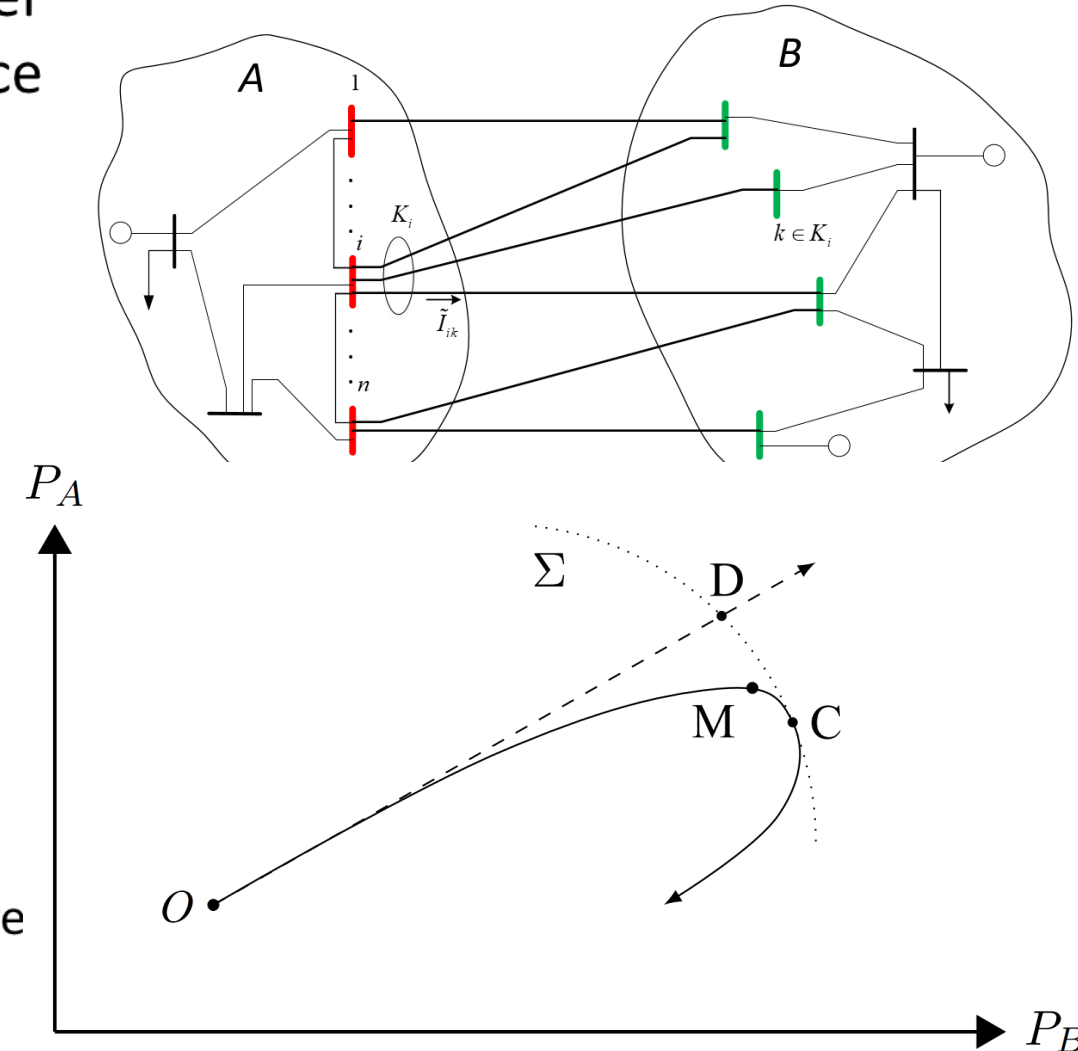
In summary (so far)

- Voltage Instability stems from load demand exceeding maximum power
 - Maximum power transfer set by transmission/generation
 - Load demand can be estimated by increasing admittance
 - If increased demand (conductance G) results in increased consumption (P)
 - system stable
 - If increased demand fails to increase consumption,
 - load restoration becomes unstable
 - load demand increase results in less transmitted power
- Indices NLI and RLI based on local $\hat{V}$ and $\hat{I}$ measurements
 - At transmission system level
 - Bus PMUs or Digital Relays
 - Identify necessary condition for voltage instability

NLI implementation

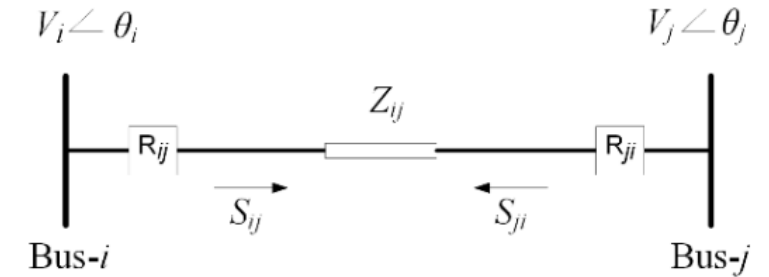
NLI calculates sensitivity of transmitted active power over apparent downstream conductance

- PMU measurements on stressed corridor (boundary buses)
- Total current inflow $\hat{I}_i = -\sum_{k \in K_i} \hat{I}_{ik}$ from K_i set of connected external buses to bus i
- Received active power $P_{r,i} = \text{Re}\{\tilde{V}_i \tilde{I}_{r,i}^*\}$
- Apparent conductance $G_i = \text{Re}\left\{\frac{\tilde{I}_{r,i}}{\tilde{V}_i}\right\}$
- Index based on successive changes:
- $NLI_i = \frac{\Delta P_{r,i}}{\Delta G_i}$
- Assuming a stress direction from O to D (beyond max power transfer)
- Power consumption trajectory will reach point M before point C (stability limit)



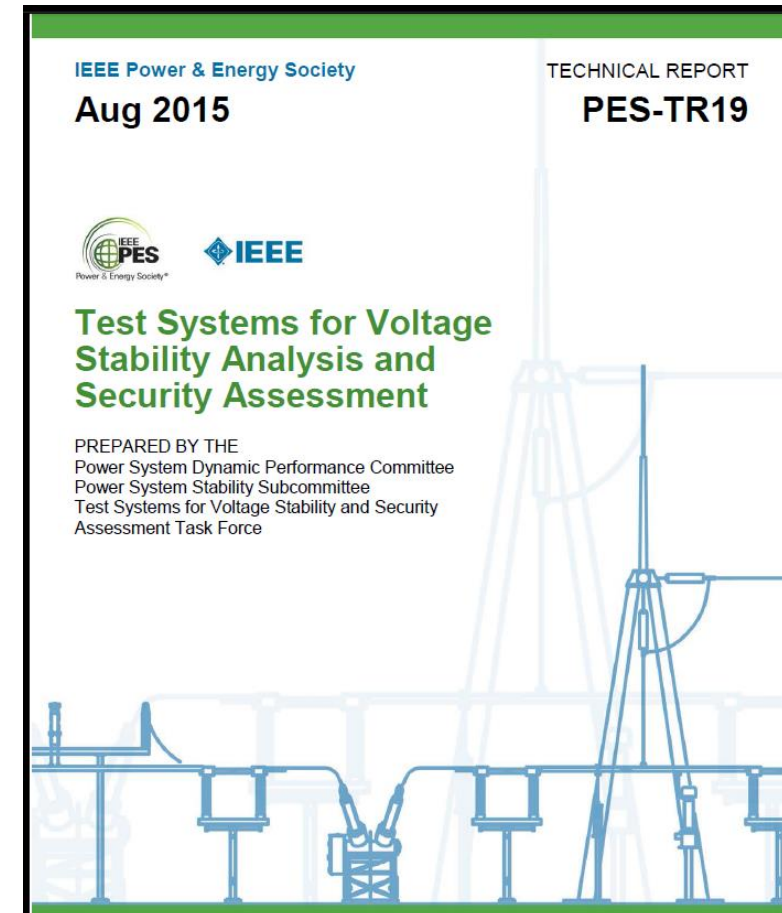
Relay-based Local Index (RLI)

- Same approach can be followed for individual transmission lines (at both ends)
 - Along a power transfer corridor
 - Using digital relay measurements at each end
- RLI calculation and averaging similar to NLI
- Can be used to avoid undesired 3rd zone trip during voltage instability incidents
- Patent GR Pat Reg 1009503 issued April 4, 2019
 - Held by spin-off Power Systems ARTS PC (Analysis, Monitoring, Control and Simulation)

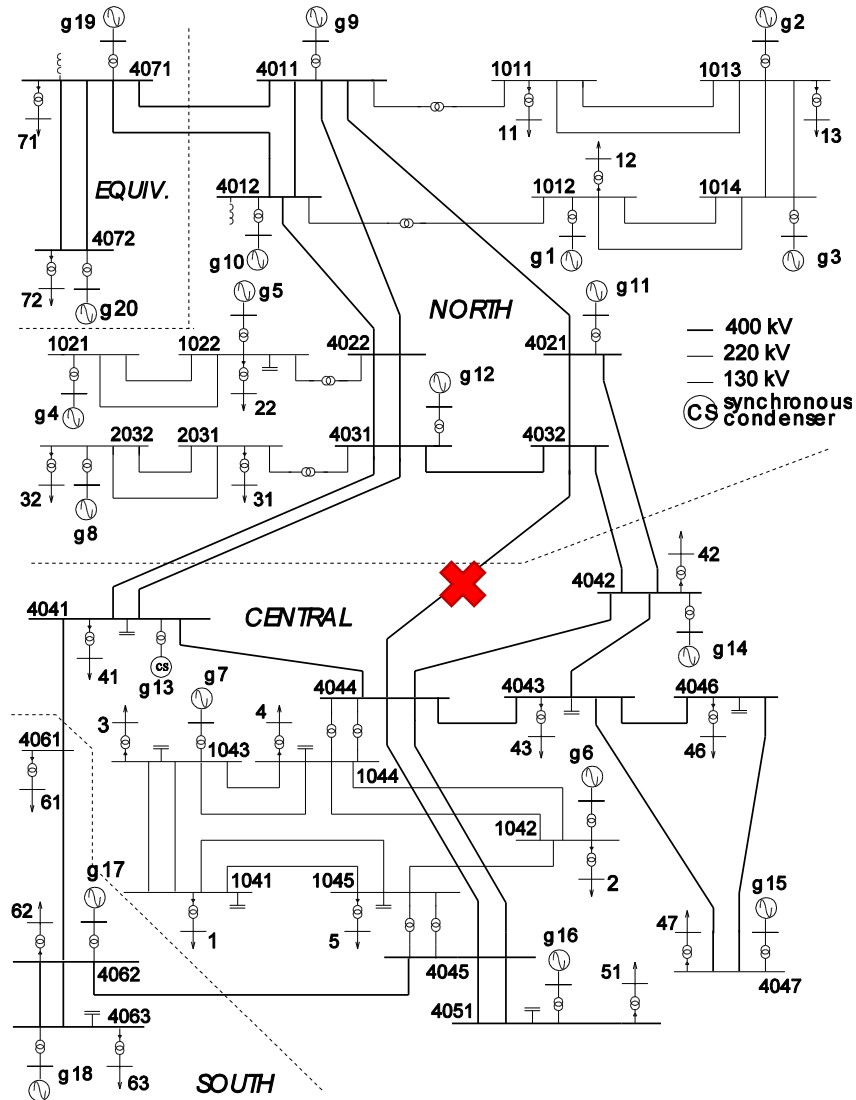


Applications to test and real systems

- IEEE “Nordic” test system
- All data included in report and on-line (PSDP Committee web page)

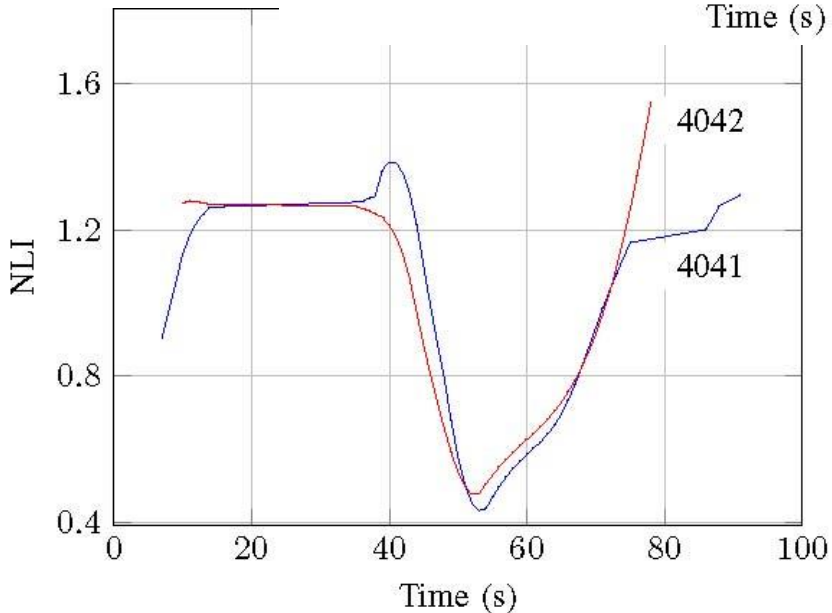
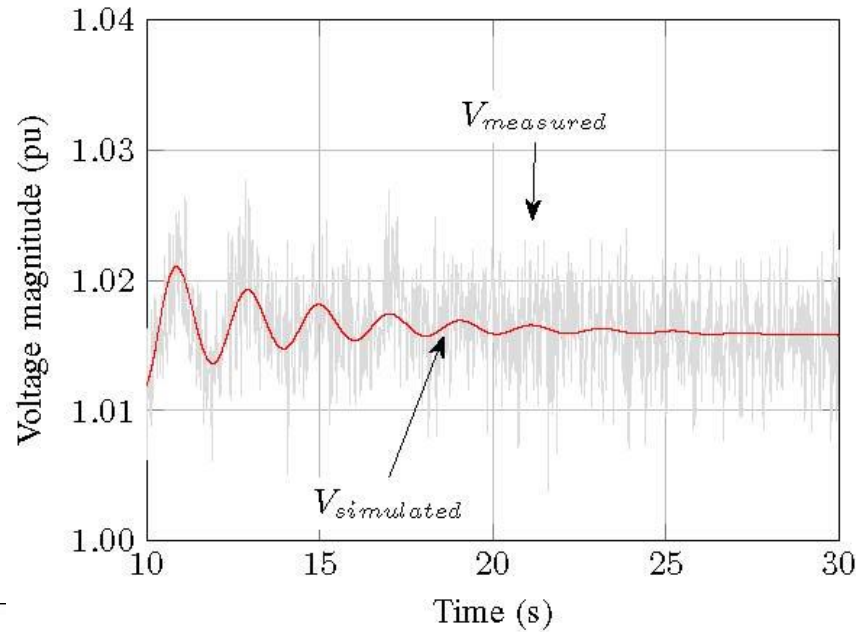


IEEE Nordic Test System



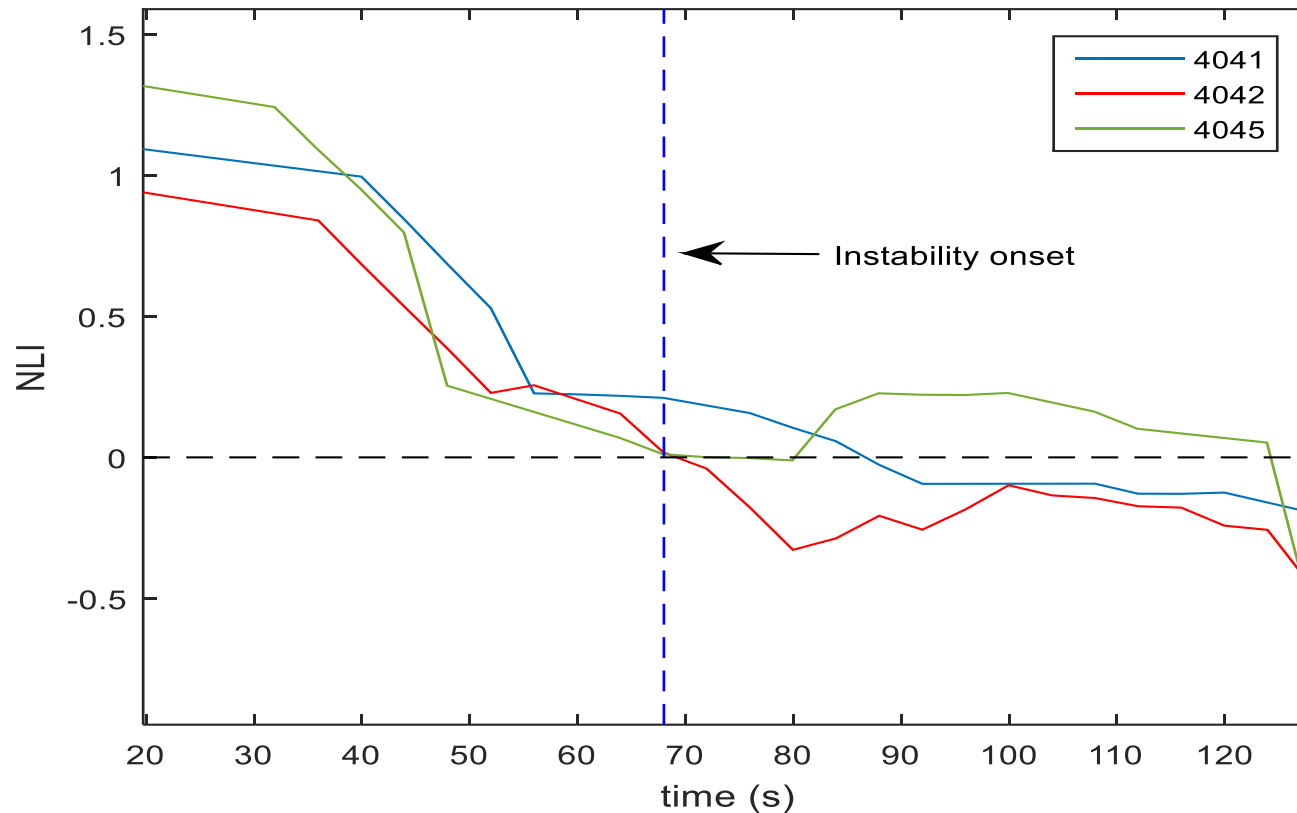
- Task Force on VSA test systems
 - Weak central area
 - Transfer corridor
- Operating points A, B
- Short circuit at $t=1s$ cleared by tripping 4032-4044
 - Point A Unstable
 - Point B Stable
- Boundary buses for NLI test
 - 4041, 4042, 4044
- Full time simulation with noise for measurement
- QSS locates exact instability onset

Full time Simulation – Stable scenario



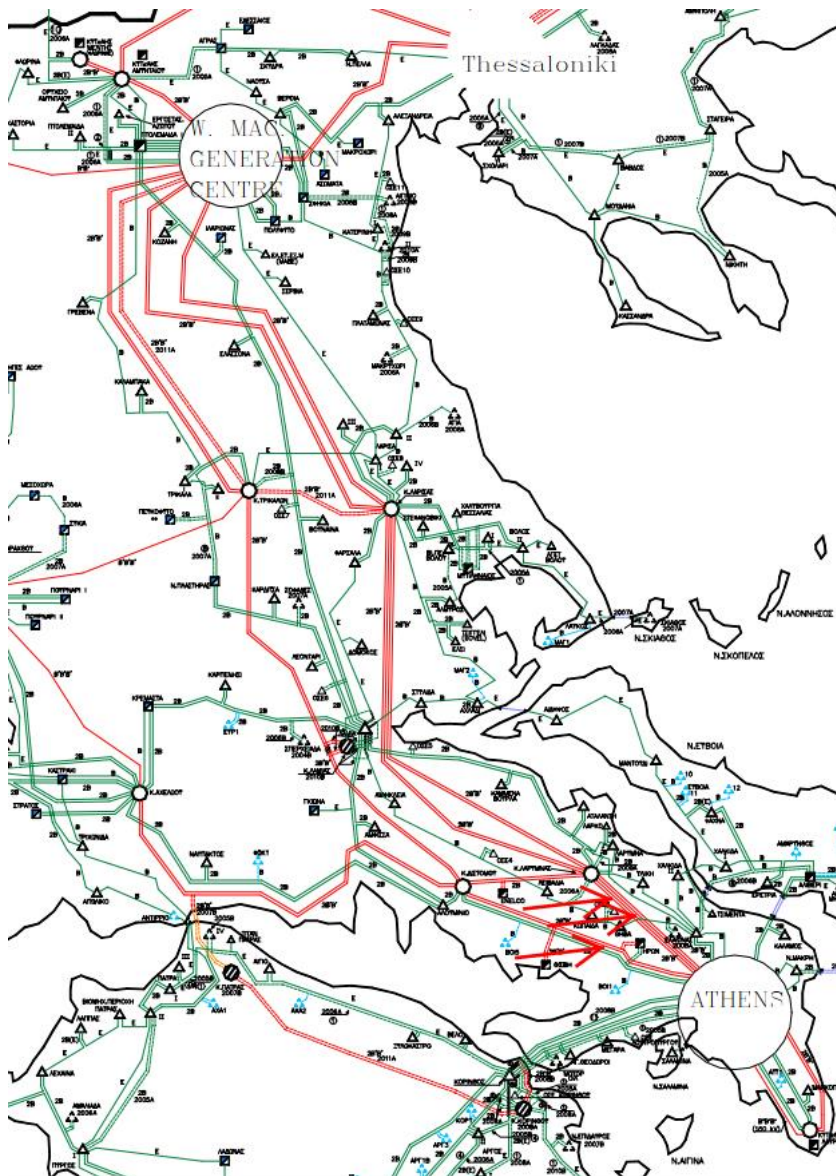
- Added measurement noise on top of short-term transients
- Short-circuit and trip of line 4032-4044
- No false alarm
- Initial low NLI values due to electromechanical oscillations

Unstable scenario: NLI at boundary buses



- At 2/3 boundary buses NLI identifies the instability exactly at its onset
- The third NLI crosses 0 with 20s delay (still not critical for automatic protection)
- The same with RLI

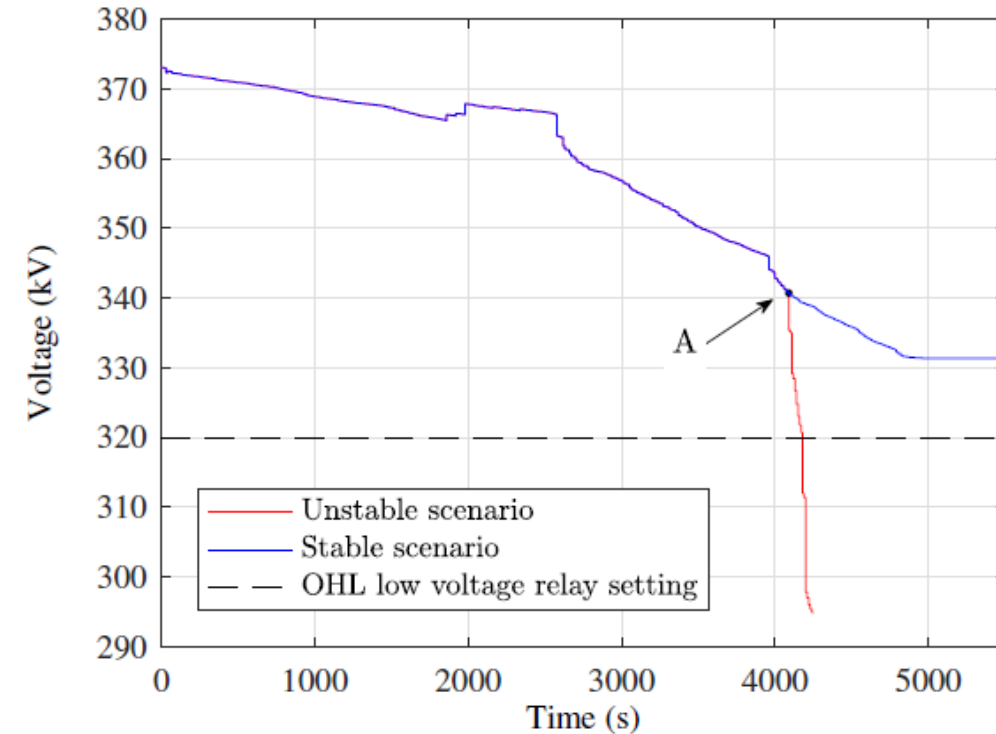
NLI simulation for 2004 Hellenic blackout



- North-South large power transfer mainly through EHV (400 kV network)
- The July 2004 blackout involved long-term voltage instability and subsequent generator disconnection due to low voltage
- Historic event simulations are repeated assuming NLI (RLI) computations in the EHV corridor leading to metropolitan Athens area

Simulation of instability incident

- Replay of 2004 Athens blackout in QSS long-term simulation with QSS long-term simulation
 - Starting at 11:30 am from converged State Estimator solution
- Critical event
 - Trip of Aliveri 3 unit, operating under stress
- Red line: trip at point A leading to EHV line trips
 - set at 0.8pu or 320kV
 - Collapse at 4200s simulation time
- Blue line without Aliveri unit 3 trip
 - System settles down at low voltages
 - Not low enough to activate protection of EHV lines

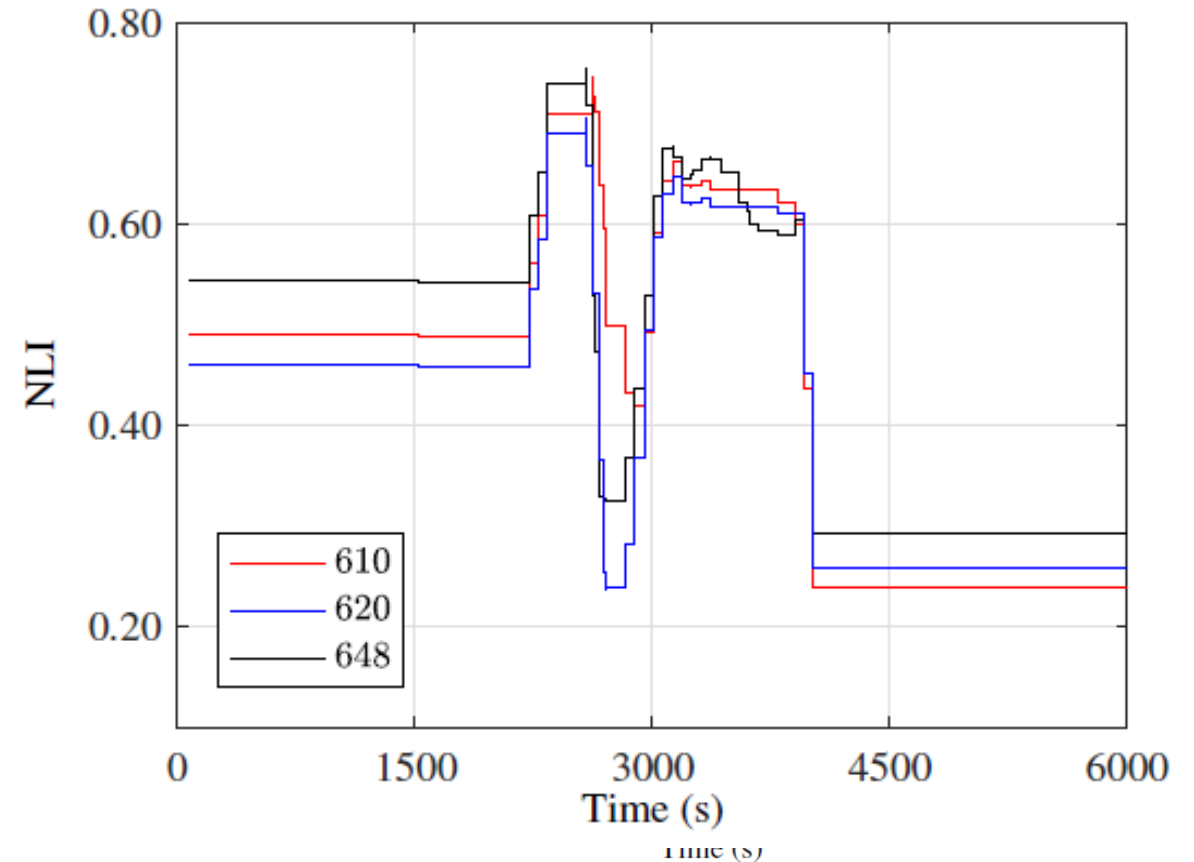


Simulation Monitoring Assumptions

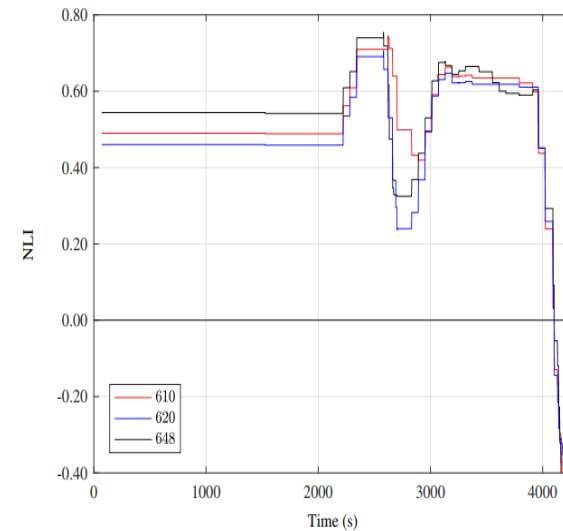
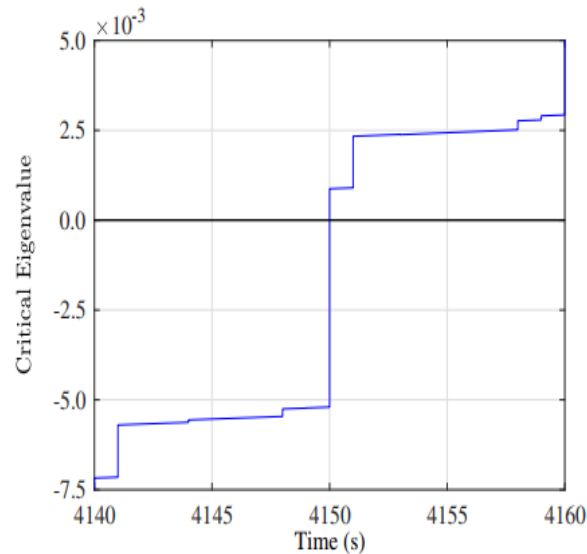
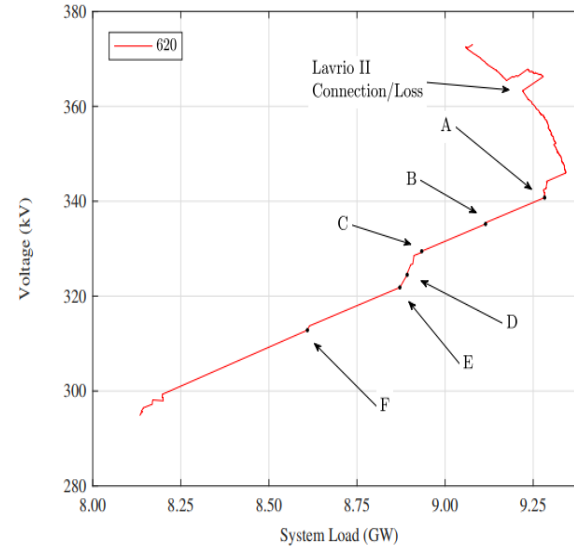
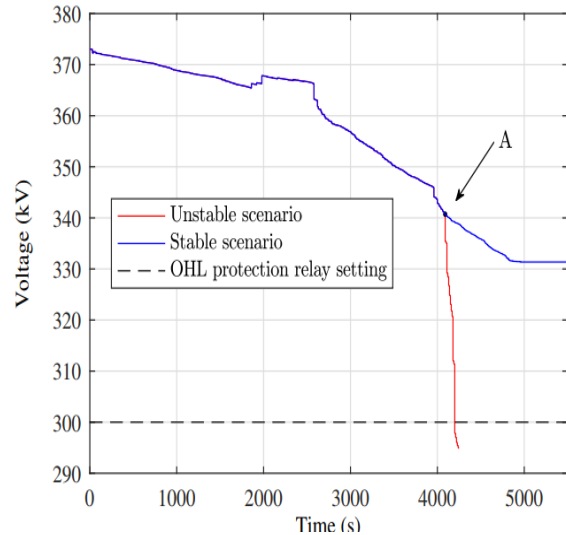
- PMUs assumed in three EHV/HV substations in Athens
- Both unstable and stable scenarios are tested
- Starting point at 11:30, 12 July (SE solution of EMS)
- Total System Load: 9084 MW
 - 1374 MW is industrial
 - 7710 MW end-user load participating in ramp
- Constant uniform load increase is assumed with $r=0.0038\%$ per second from $t=10s$ until $t=4800s$.
- Unstable scenario is close to the actual blackout simulation
- Stable scenario: Aliveri power plant remains in operation (final stage before blackout)

Simulation of NLI index performance

- Monitored at 3 EHV/HV
- Unstable scenario (actual events)
 - Warning $NLI < 0.5$ issued from the simulation start (one hour before collapse)
 - Alarm ($NLI < 0.2$) 2 min before collapse
 - Zero-crossing 1 min before collapse
- Stable scenario
 - NLI remains above 0.2 (alarm setpoint)

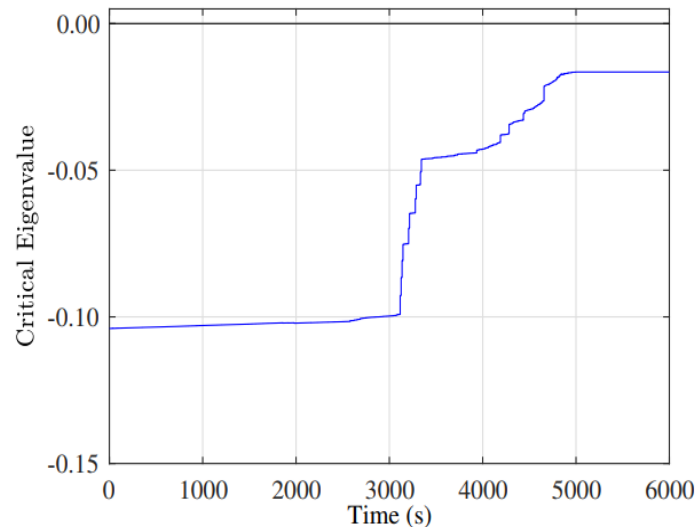
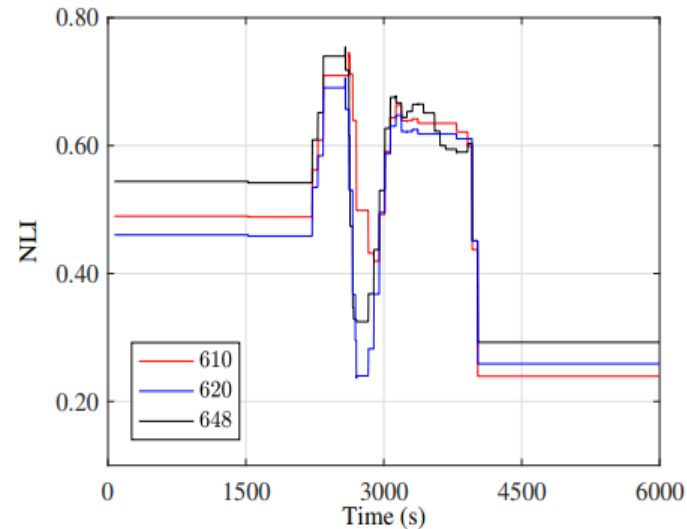
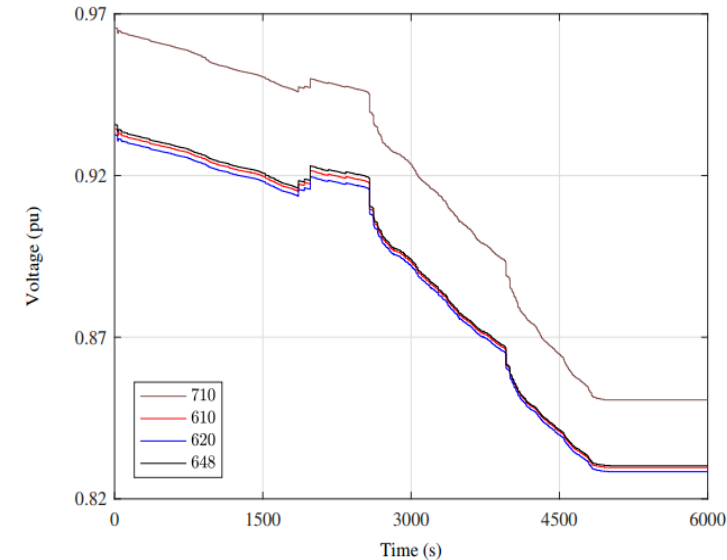


Unstable scenario simulation



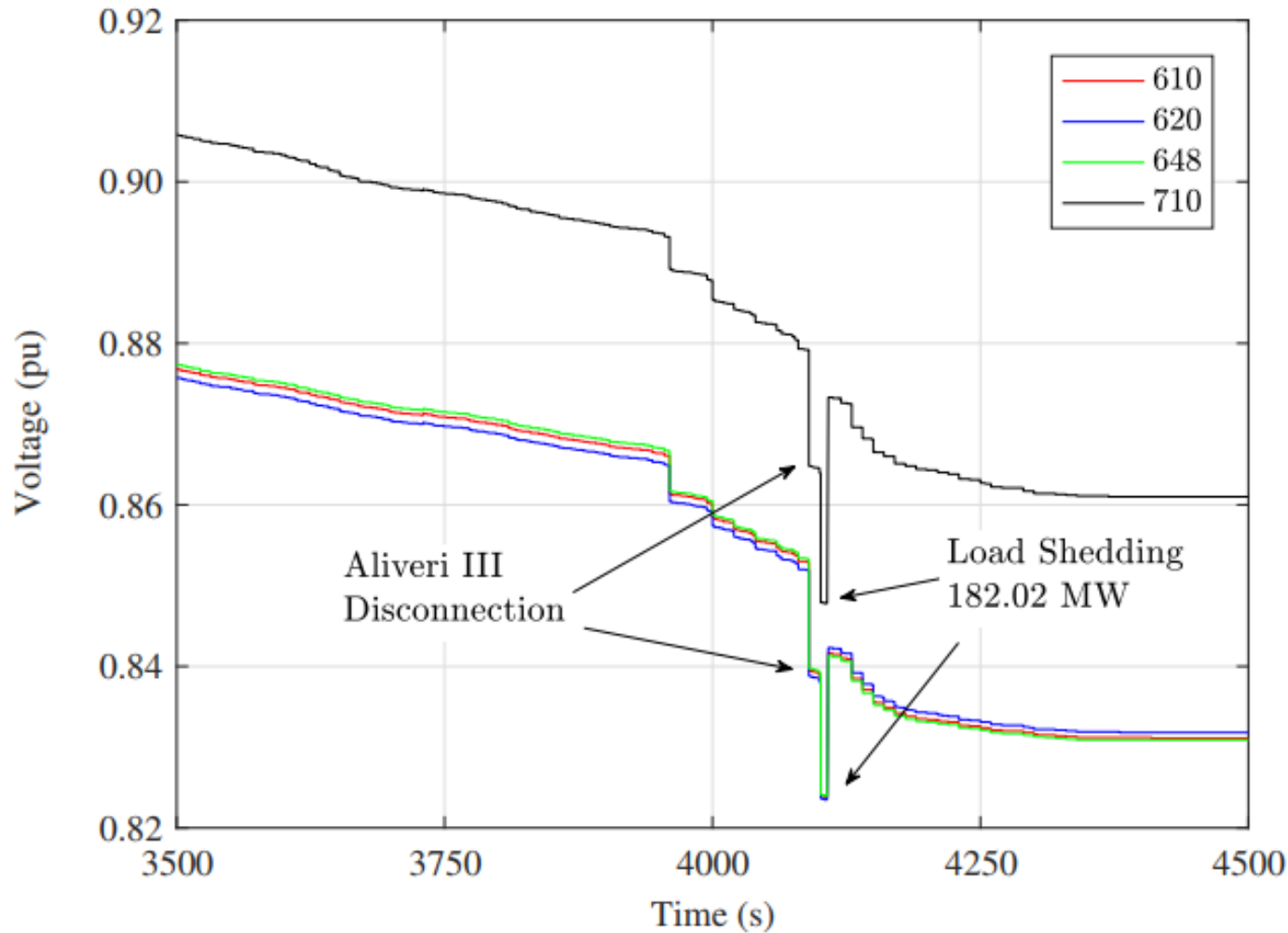
- Successive generator overexcitation limitations
- At point A Aliveri unit trips
 - Followed by UV Gen trip
 - Immediate loss of stability
- Critical eigenvalue and NLI simulated values
- Timely NLI alarms
 - Very close to actual voltage
 - Instability time

Stable scenario simulation



- System stabilizes, even at low voltages
 - LTCs exhausted
 - Eigenvalue close to 0
- Voltage instability is marginally avoided
- No NLI/RLI false alarms issued in this case
- Selectivity
- Reliability
- Dependability

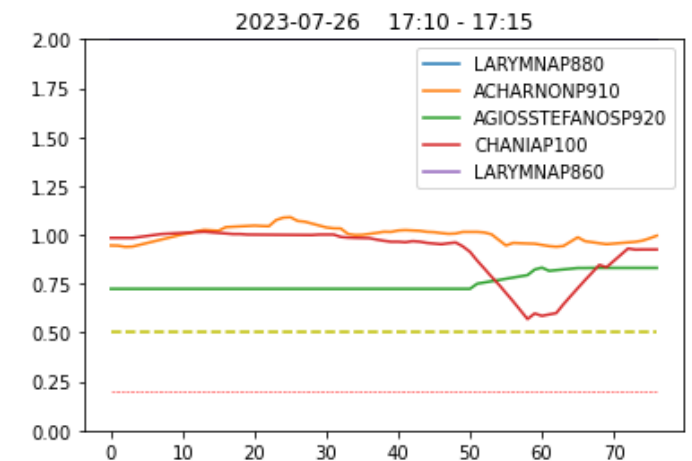
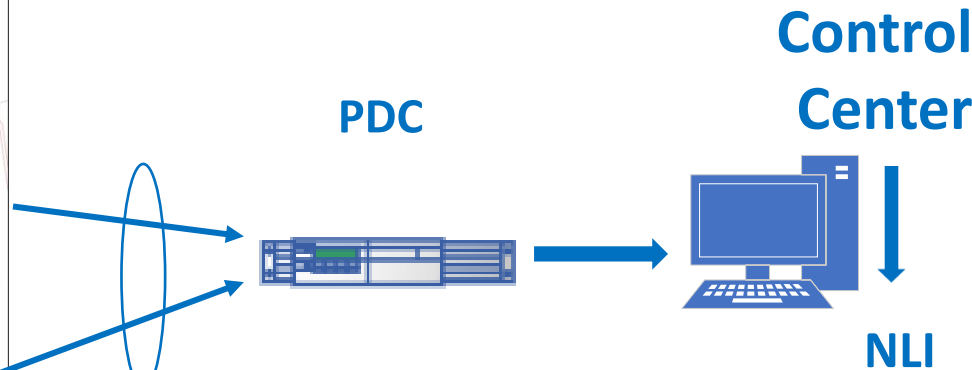
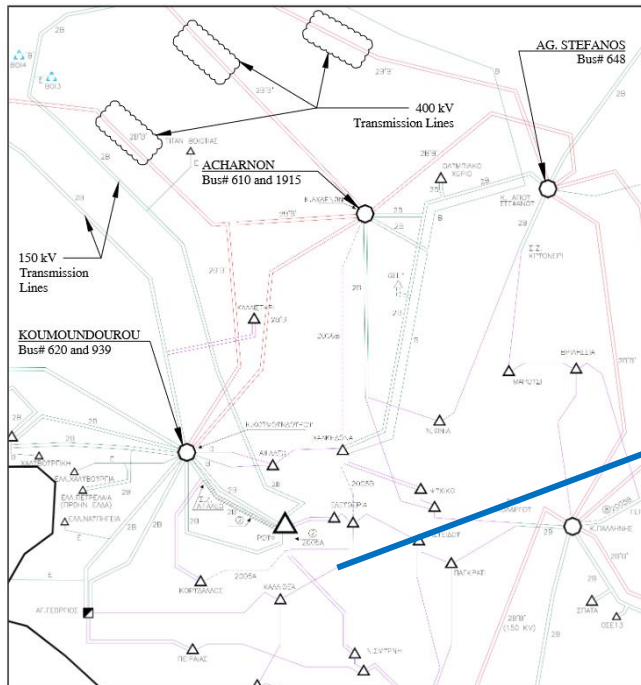
Controlling instability following NLI alarm



- Special Protection Scheme (SPS assumed)
 - Direct load shedding
 - applied after NLI (RLI) alarm
 - to pre-specified substations
- Unstable scenario is stabilized with 182 MW of curtailed load
- instead of 2000 MW
- Low voltages remain still

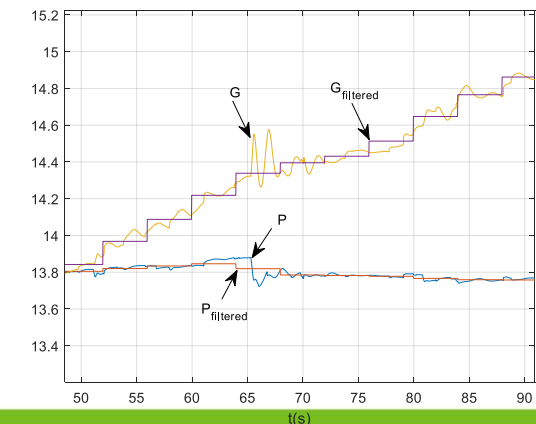
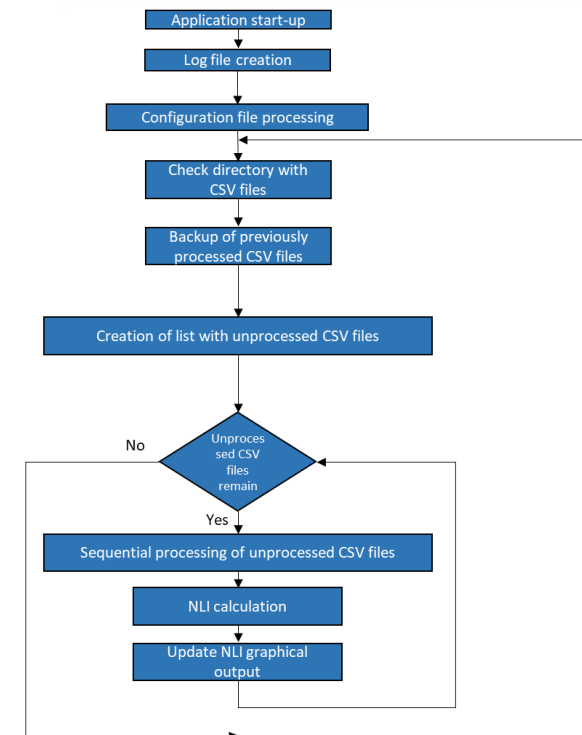
On-line Implementation at IPTO NCC

- Independent Power Transmission Operator is TSO of Greece
- On-line application of NLI in selected PMU measurements



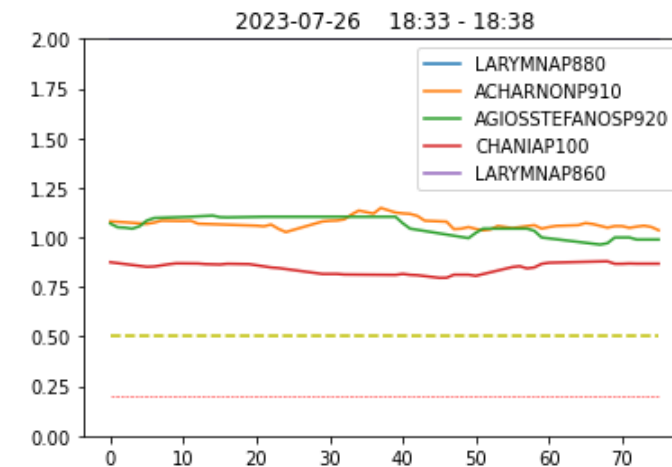
On-line Application structure

- PMU data available from PDC
- Measurements stored in csv files every 60''
 - $\hat{V}$, $\hat{I}$ and frequency measurements every 20 ms
- 5 out of 22 installed PMUs selected for voltage stability monitoring
- Short-term Fourier Transform and filtering
 - 400 sample window (8 second data frame)
 - 50% data frame overlap → recalculation every 4 seconds
 - Index calculated only for positive ΔG and with adjusted threshold for avoiding random variations
 - Final averaging of NLI for further smoothing



NLI Performance for an Incident in Crete

- AC cable interconnection with mainland (400 MVA capacity).
 - 1GW DC interconnection in trial operation (expected commissioning Sept 2025)
 - Sequence of events (July 26, 2023):
 - Gen ST8 (26 MW) tripped at 17:13
 - Gen GT5 (24 MW) tripped at 17:36
 - Gen GT7 (30 MW) tripped at 18:21
- 5 min window displayed at NCC
- Yellow line warning
 - Red line alarm
 - Temporary NLI drop at Chania PMU after ST8 trip
 - Final Chania NLI stabilization at relatively low 0.8 value
 - System remains stable, but the interconnection to Crete weakened



Next steps

- Application of voltage stability monitoring in streaming mode
 - No intermediate data files
 - Communication with IEEE Std. C37.118
- Off-line voltage stability analysis of Crete AC interconnection
 - In parallel with double DC submarine cable with two GFM converters (2x500 MW)
- Investigation of overvoltage stability issues
 - Alternate implementation of NLI/RLI (ΔP , ΔG sign reversal)

Conclusions

- On-line stability monitoring a must
 - Due to changing flows and conditions
- NLI index using PMU measurements
 - based on consumption/demand sensitivity
 - Extensively tested in test systems and a real blackout of 2004
- Monitoring application installed in the IPTO NCC
 - NLI index performed well for a severe incident in Crete
 - Stability maintained, but system weakened
- Application may be utilized for arming and activating wide-area protection schemes
- Streaming data application in preparation

Related papers and patent

- C. Vournas, P. Mandoulidis, O. Darmis, S. Chountasis, S. Tsakiris, G. Korres, “PMU Applications for Voltage Stability monitoring and Oscillation analysis”, to appear in Cigre Paris Session 2024, August 2024
- P. Mandoulidis, V. Nikolaidis and C. Vournas, “Implementation of Real-Time, PMU-Based, Long-Term Voltage Stability Monitoring”, PAC World Conference, Athens, Greece, June 2024.
- C Lambrou, P Mandoulidis, C Vournas, “Validation of voltage instability detection and control using a real power system incident”, Energies, 14 (21), 7165, 2021
- P Mandoulidis, C Vournas, “A PMU-based real-time estimation of voltage stability and margin”, Electric Power Systems Research 178, 106008, 2020.
- V Nikolaidis, P Mandoulidis, C Vournas, “Combining Transmission Line Protection with Voltage Stability Monitoring”, 2018 Power Systems Computation Conference (PSCC), 1-7, 2018.
- C Vournas, C Lambrou, P Mandoulidis, “Voltage stability monitoring from a transmission bus PMU”, IEEE Transactions on Power Systems 32 (4), 3266-3274, 2016.
- RLI protected by patent GR Pat Reg 1009503, awarded by Hellenic Industrial Property Organization, owned by Power Systems ARTS, PC.