



Implementation of Real-Time, PMU-Based, Long-Term Voltage Stability Monitoring

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Presentation overview

- Voltage Stability Monitoring
 - Necessity, background and main principles
 - Voltage Instability Indices NLI and RLI
- VSM application at Hellenic NCC
 - Application structure, interface, filtering
- Indicative results following an actual incident
- Future outlook and further research directions

Long-term Voltage Instability Monitoring

- Why necessary?
 - Voltage Security Assessment checks sufficient security margins against plausible contingencies
 - in principle, but
 - The unexpected can always happen
 - Stochasticity in system operation grows and affects
 - both power flows and system strength
 - As a result, system may come close and even overstep its *voltage stability limit* after an unforeseen event
- Voltage stability monitoring more necessary than ever!

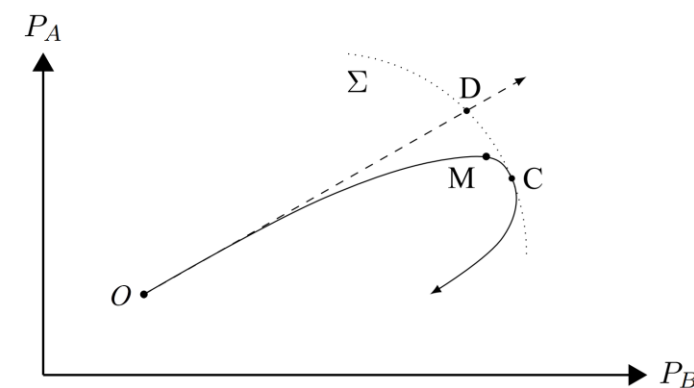
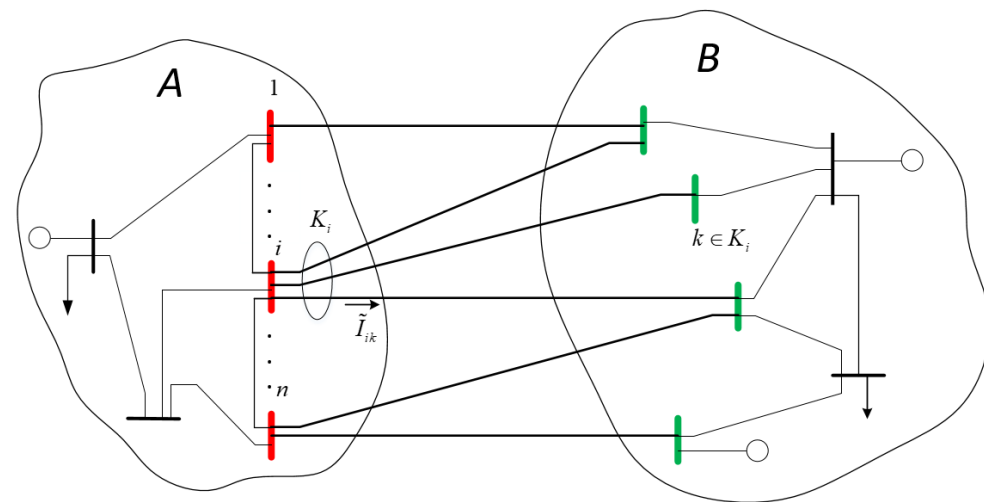


Local Voltage Stability Monitoring

- Maximum power transfer
 - Maximum power transfer sets voltage stability limit
 - If reached, further load demand increase results in less provided active power
 - Load restoration becomes unstable
- Measurement-based indices NLI and RLI base their results on local $\hat{V}$ and $\hat{I}$ measurements gathered from
 - PMUs or Digital Relays
 - Identify necessary condition for voltage instability

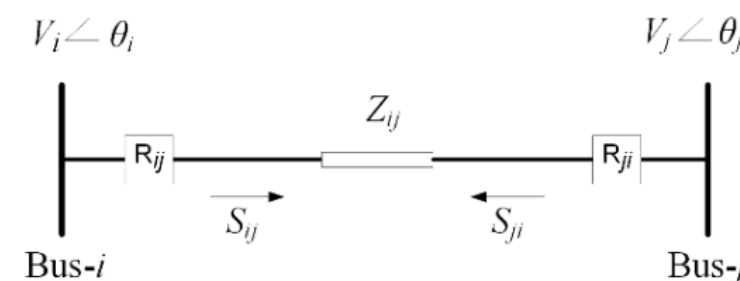
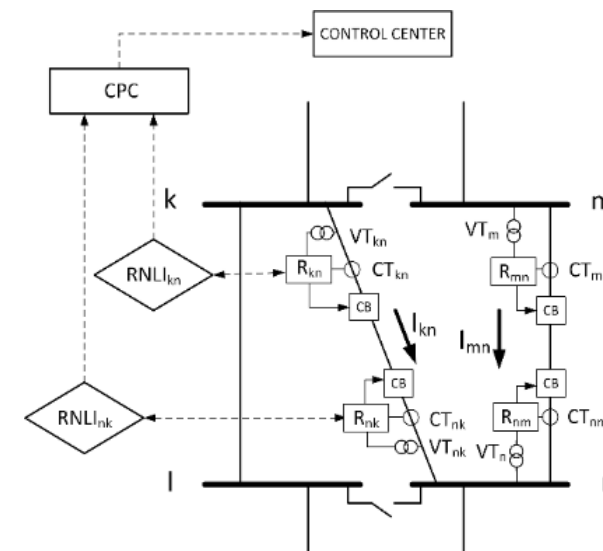
NLI concept

- 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 $P_{r,i} = Re\{\tilde{V}_i \tilde{I}_{r,i}^*\}$
 - Apparent conductance $G_i = Re\left\{\frac{\tilde{I}_{r,i}}{\tilde{V}_i}\right\}$
 - 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)



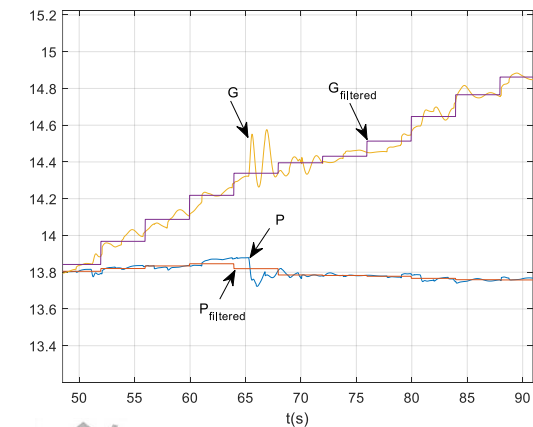
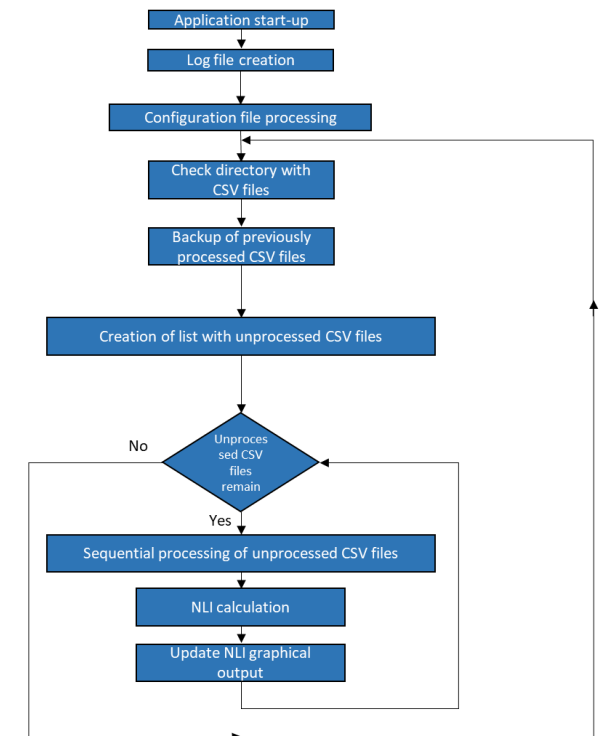
RLI concept

- Voltage stability monitoring at individual transmission line
 - Works at both ends of a transmission corridor line
 - Available measurements from relays
 - $RLI_{ij} = \frac{\Delta P_{ij}}{\Delta G_{ij}}$
 - Before instability point, at least one line power transfer is maximized
 - May be used to avoid undesired 3rd zone trip during voltage instability incidents
 - Greek patent owned by spinoff company Power Systems ARTS PC



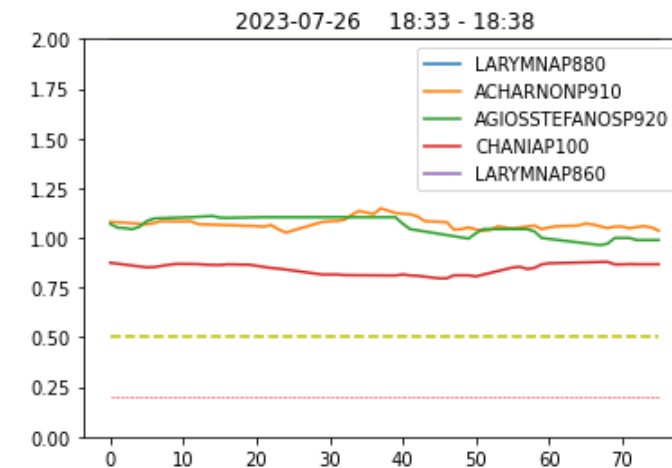
Voltage Stability Monitoring Application at NCC of Hellenic System

- Implemented in Python 3 language
- PMU data available from local PDC
- Measurements stored in csv files every 60''
 - $\hat{V}$, $\hat{I}$ and frequency measurements every 20 ms
- 5/22 installed PMUs selected for voltage stability monitoring
- Short-term Fourier Transform and filtering
 - 400 sample window (8 second data frame)
 - 50% data frame overlap $\rightarrow$ 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



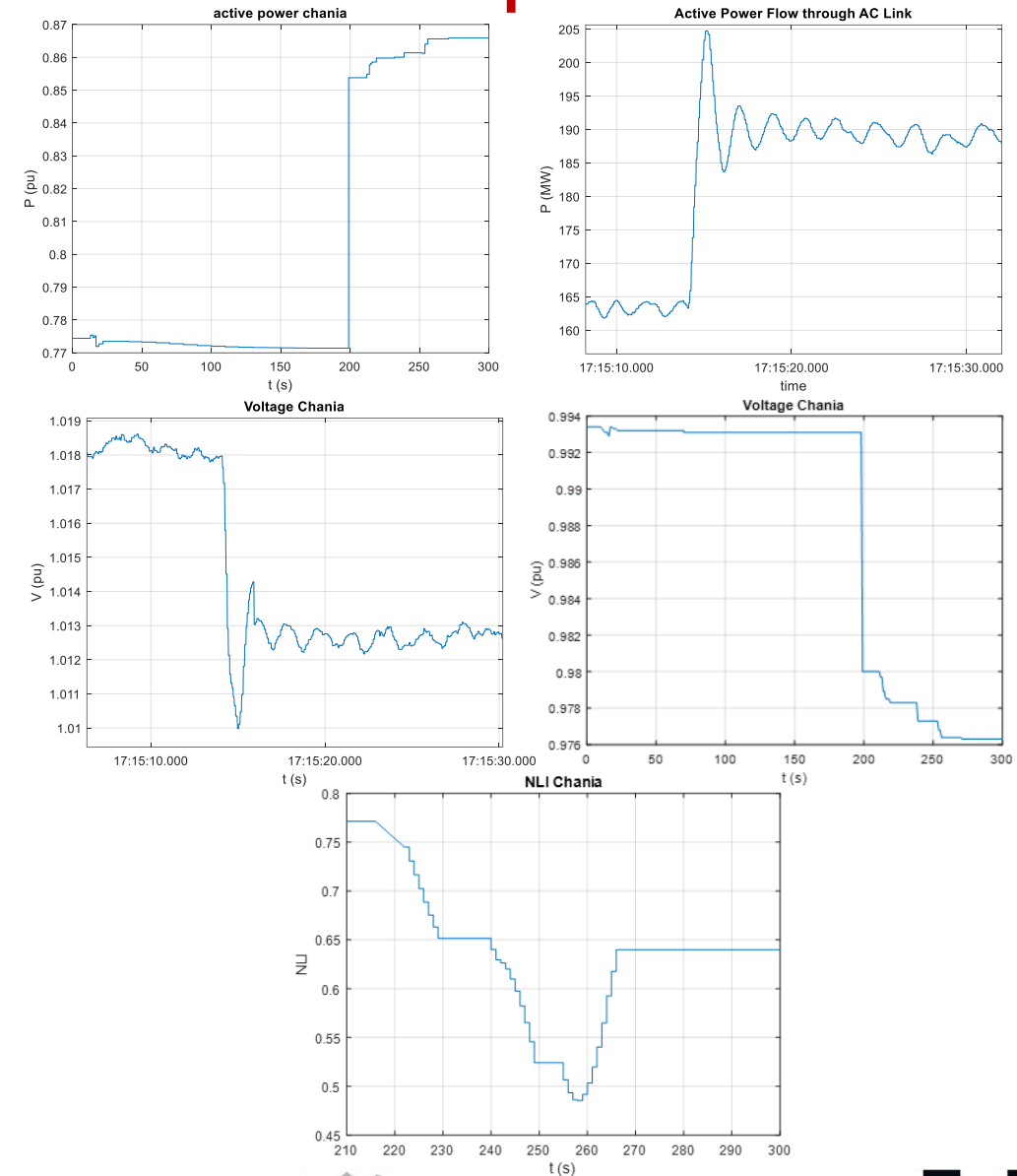
NLI Performance for an Incident in Crete

- AC interconnection with mainland (400 MVA capacity)
- Sequence of events (July 26, 2023):
 - Gen ST8 (26 MW) tripped at 17:15
 - 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



QSS Simulation of first generation trip

- Simulation of incident with quasi-steady state simulation software
 - Accounts for long-term LTC dynamics
 - Equilibrium algebraic equations for short-term dynamics.
- Initialization load-flow from available EMS snapshot at 16:31
- Generation of local units adjusted according to SCADA measurements
- Similar voltage and tie-line flow responses achieved
- NLI trend could be approximated when several units in Crete were set to manual (constant excitation)



Conclusions and further research

- Real-time voltage stability monitoring installed
 - at Hellenic NCC
- Application may be utilized for arming and activating a wide-area load-shedding scheme
 - to protect against instability
- Further refinement is possible by directly using PMU data instead of csv files
- NLI index performed well for a severe incident in Crete
 - Showed that stability was maintained, but system was weakened
- Additional investigation of 26th July incident in Crete is required, to identify root-causes of temporary NLI drop
 - And possible voltage stability implications

NLI and RLI 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
- 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, P Mandoulidis, "On-line voltage stability monitoring", 2018 IEEE International Symposium on Circuits and Systems (ISCAS), 1-5, 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.

Thank you for your attention!