

Long-term Voltage Stability Wide-Area Control using PMU Measurements



Costas Vournas, Professor Emeritus NTUA
Partner, Power Systems ARTS P.C.

Presentation credits: Prof. Vassilis Nikolaidis and Dr. Panos Mandoulidis
Power Systems ARTS PC

On-line Voltage Instability Indices: PMU based NLI and relay-based RLI

Related Papers and Patent

- 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 concept is protected by a patent (GR Pat Reg 1009503), awarded by Hellenic Industrial Property Organisation.

Long-Term Voltage Instability

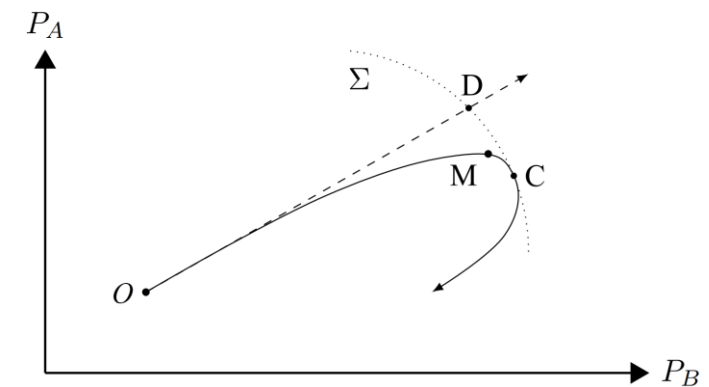
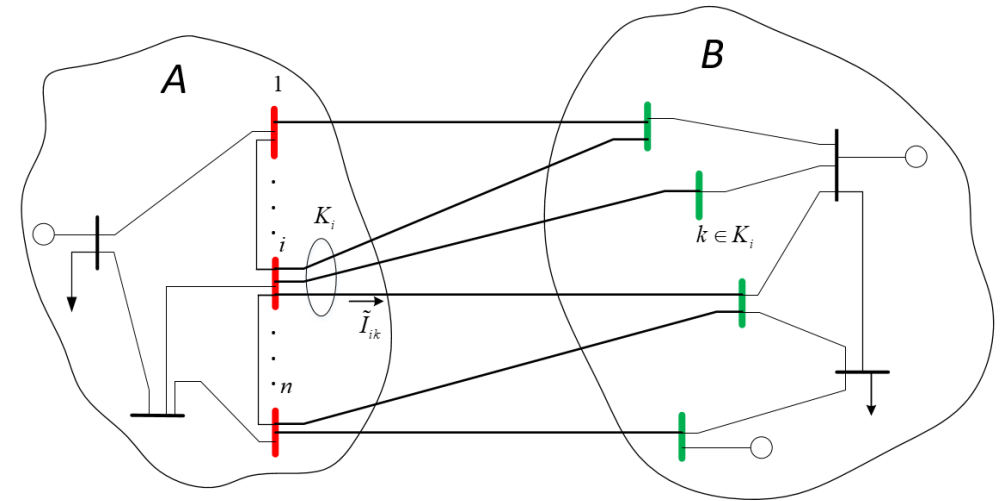
Still a concern in bulk power system operation...

- Instability mechanisms well understood
- Renewables raise concerns in terms of providing sufficient and efficient voltage support, when required
- Conventional power plants phase-out complicates system operation
- New perspectives for real-time system monitoring are available with PMUs
- Intelligent & adaptive SPS (RAS, SIPS) are necessary for operating safely transmission systems close to margins

Concept of New LIVES Index (NLI)

Two-area system

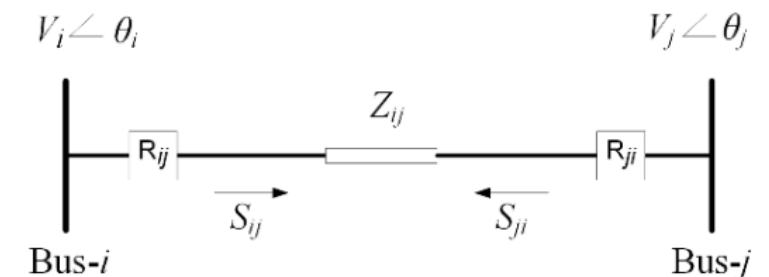
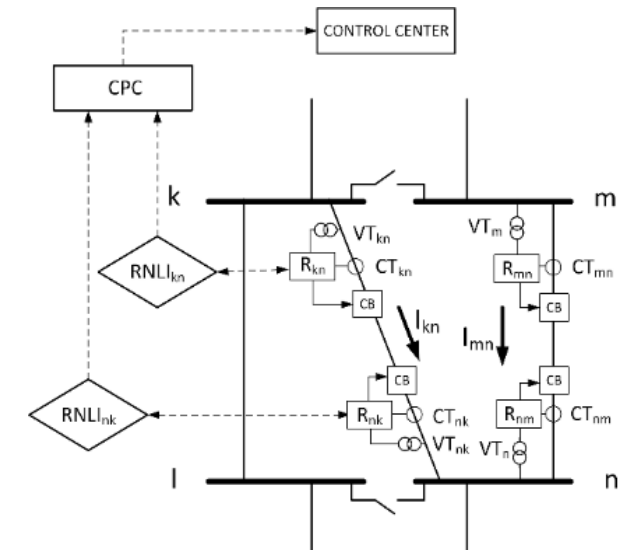
- Area A imports power from area B
 - through corridor B-A
- PMU measurements in receiving corridor buses (red)
- Total current inflow $\tilde{I}_{r,i} = -\sum_{j \in K_i} \tilde{I}_{ij}$
- Received active power $P_{r,i} = \text{Re}\{\tilde{V}_i \tilde{I}_{r,i}^*\}$
- Apparent conductance $G_i = \text{Re}\left\{\frac{\tilde{I}_{r,i}}{\tilde{V}_i}\right\}$
- Index based on successive steps $NLI_i = \frac{\Delta P_{r,i}}{\Delta G_i}$
- Typical representation in load power space
- Loadability surface Σ
- Point M expected before bifurcation point C



Concept of Relay based Index (RLI)

Voltage stability monitoring at transmission line level

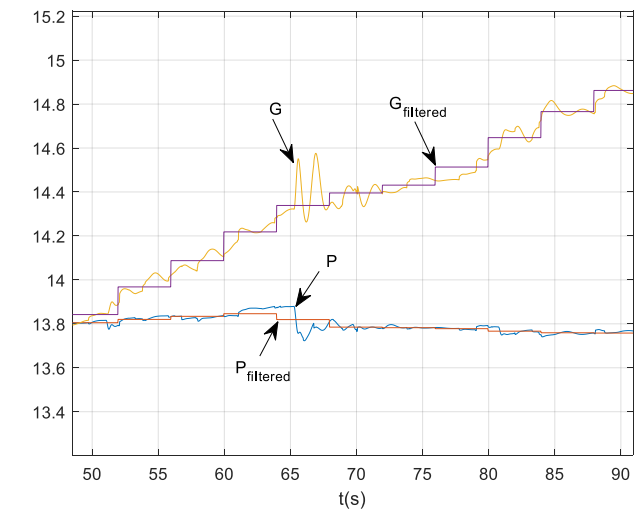
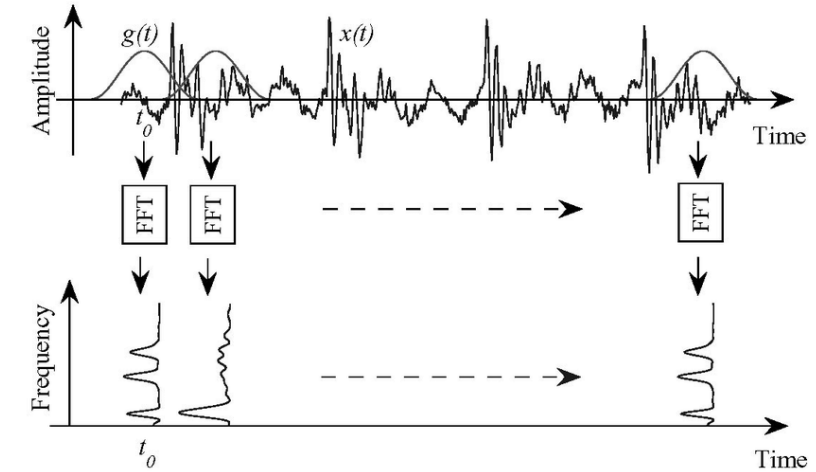
- At both ends of transmission corridor lines
- Uses measurements available at relay
- Similar concept to NLI
- $$RLI_{ij} = \frac{\Delta P_{ij}}{\Delta G_{ij}}$$
- Before bifurcation point, at least one line power transfer becomes maximum (Grijalva)
- If set, avoids undesired 3rd zone trip during voltage instability (PSCC 2018 paper)
- Greek patent owned by PSARTS PC



Implementation

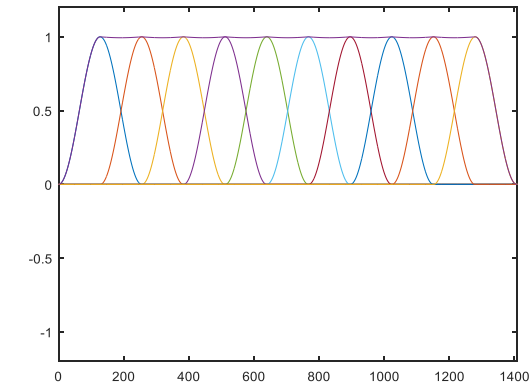
Real-life concerns...

- Important pre-filter: Only apply when demand increases ($\Delta G > \epsilon > 0$)
- Not computed for very small (noise) and very large (faults) variations
- Need for suppressing effectively
 - Measurement noise
 - Short-term system dynamics (electromagnetic and electromechanical system dynamics)
- Short-Term Fourier Transform (STFT)
 - Construct G_f, P_f filtered signals
 - Focusing on filtered signals long-term trends (DC Fourier component)



Going deeper into filtering calculations...

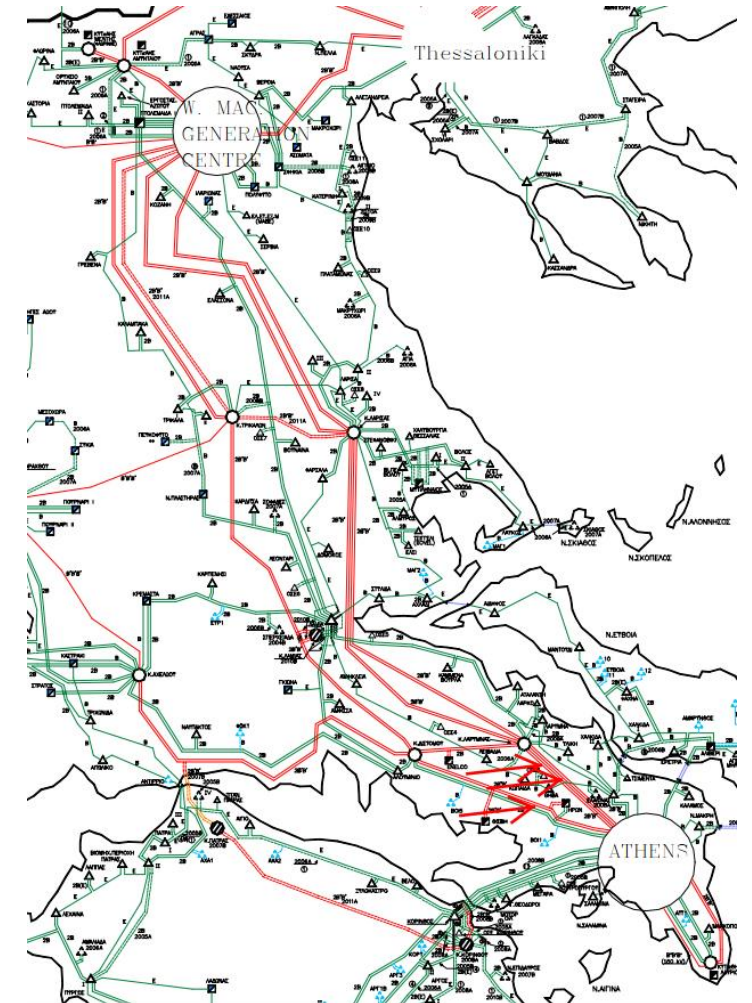
- Measurements are centered at every time step
 - (e.g. $t \pm 4s$) creating a time window shift (4s)
- Continuous process
 - Select a proper window size (e.g. $\pm 4s$) for the window function w
 - $X_m[m, k] = \sum_{n=0}^{N-1} x[n]w[n - mR]e^{-j\frac{2\pi}{N}kn}$, $k = 0..N - 1$
 - Focus on the DC component $\Rightarrow X(m, 0) = \sum_{n=0}^{N-1} x[n]w[n - mR] \Rightarrow$,
 - Reconstruct the filtered signal $\Rightarrow x_f = \frac{1}{N} X(m, 0)$
 - Final averaging for security $\Rightarrow \overline{NLI}_{k,i} = \frac{1}{q} \sum_{k=1}^q \frac{\Delta P_{f,i}(t_k)}{\Delta G_{f,i}(t_k)}$
 - Parameter q should not produce big delays



Historical simulation results

On the Hellenic Power System

- Main generation is located in the northern system, main load is in the south
- Large power transfers 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



Simulations on Hellenic Power System

Scenarios and characteristics

- PMUs assumed in three EHV/HV substations in Athens area
- Unstable and stable scenarios are tested
- System loading at 11:30, 12 July
 - total system load: 9084 MW
 - 1374 is industrial
 - 7710 MW end-user load
- 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
- Stable scenario: Aliveri power plant remains in operation (final stage before blackout)

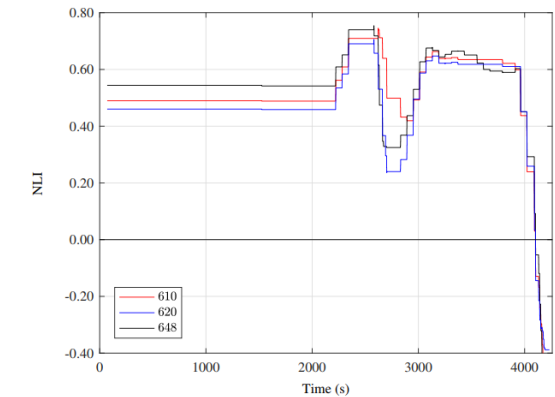
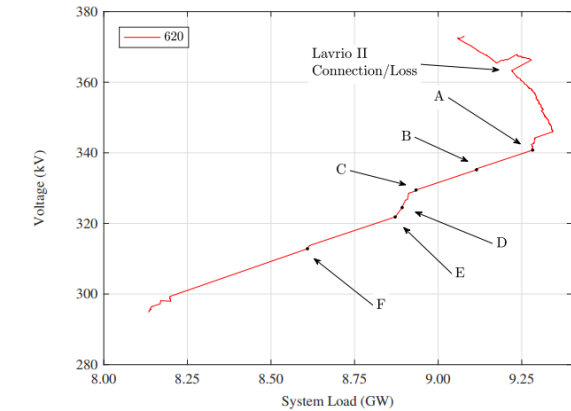
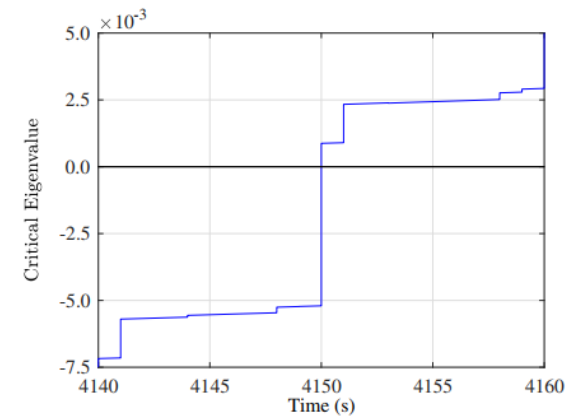
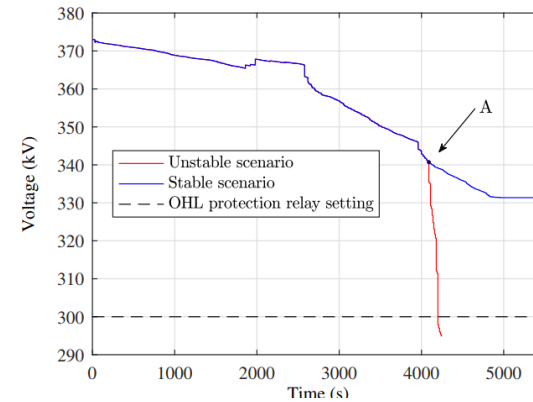
Arrival Boundary Bus	Departure Boundary Bus
620 (Koumoundourou)	404 (Distomou)
939 (Koumoundourou)	404 (Distomou)
610 (Acharnon)	395 (Larymnas)
1915 (Acharnon)	395 (Larymnas)
648 (Ag. Stefanou)	395 (Larymnas)
648 (Ag. Stefanou)	395 (Larymnas)

Simulations on Hellenic Power System

Unstable scenario results

- At point A Aliveri unit trips.
- Cascade OEL activations
- Timely NLI alarms close to the actual stability limit

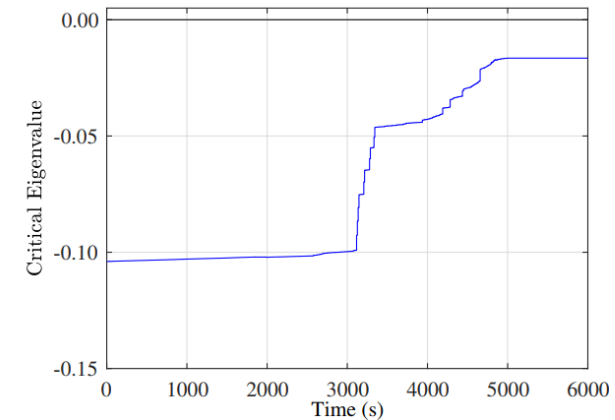
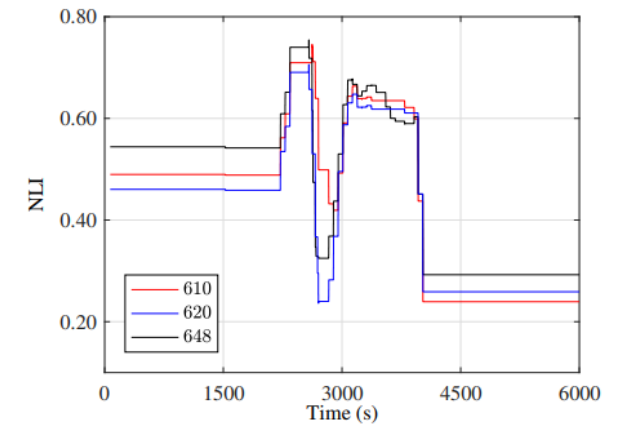
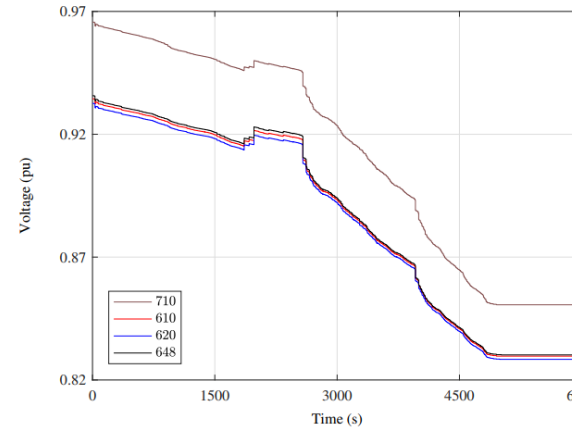
t (s)	Unit	Bus	Event	Point in Figure 5
20	Aliveri IV	338	OEL	
30	Lavrio 4	667	OEL	
60	Aliveri III	337	OEL	
1649	Lavrio I	664	OEL	
1860	Lavrio II	660	Load pick up	
2498	Lavrio I	664	OEL	
2580	Lavrio II	660	Unit loss	
2610	Megalopoli III	569	OEL	
2930	Ag. Georgios 9	675	OEL	
3468	Ag. Georgios 8	674	OEL	
4090	Aliveri III	337	Disconnection	A
4101	Aliveri IV	338	UV trip	B
4102		620	NLI < 0 Alarm	C
		610	NLI < 0	
4103		648	NLI < 0	
4120	Megalopoli IV	575	OEL	
	Ladonas II	583	OEL	
4150	Ladonas I	582	OEL	
			Stability limit	D
4162	Ag. Georgios 9	675	UV trip	E
4173	Lavrio I	664	UV trip	F
	Ag. Georgios 8	674	UV trip	
4200	Megalopoli II	573	OEL	
4233	Megalopoli III	569	UV trip	
			Collapse	



Simulations on Hellenic Power System

Stable scenario results

- System stabilizes, albeit at low voltages
- Voltage instability is marginally avoided
- No NLI/RLI false alarms issued
- Operator actions are still required for bringing system to secure operation



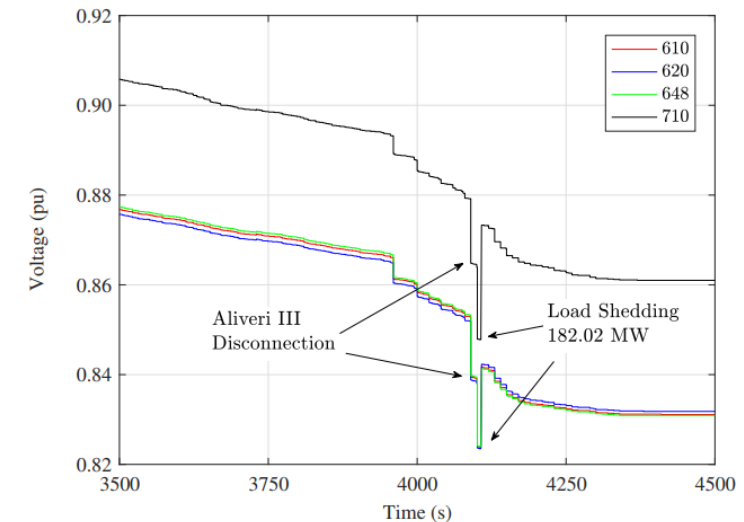
t (s)	Unit	Bus	Event
4166	Ladonas II	583	OEL
4190	Megalopoli IV	575	OEL
4449	Ladonas I	582	OEL
4800	End of load increase		

Simulations on Hellenic Power System

Controlling instability by an SPS (direct load shedding)

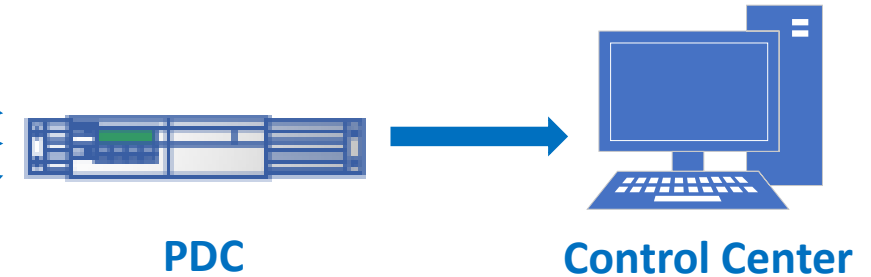
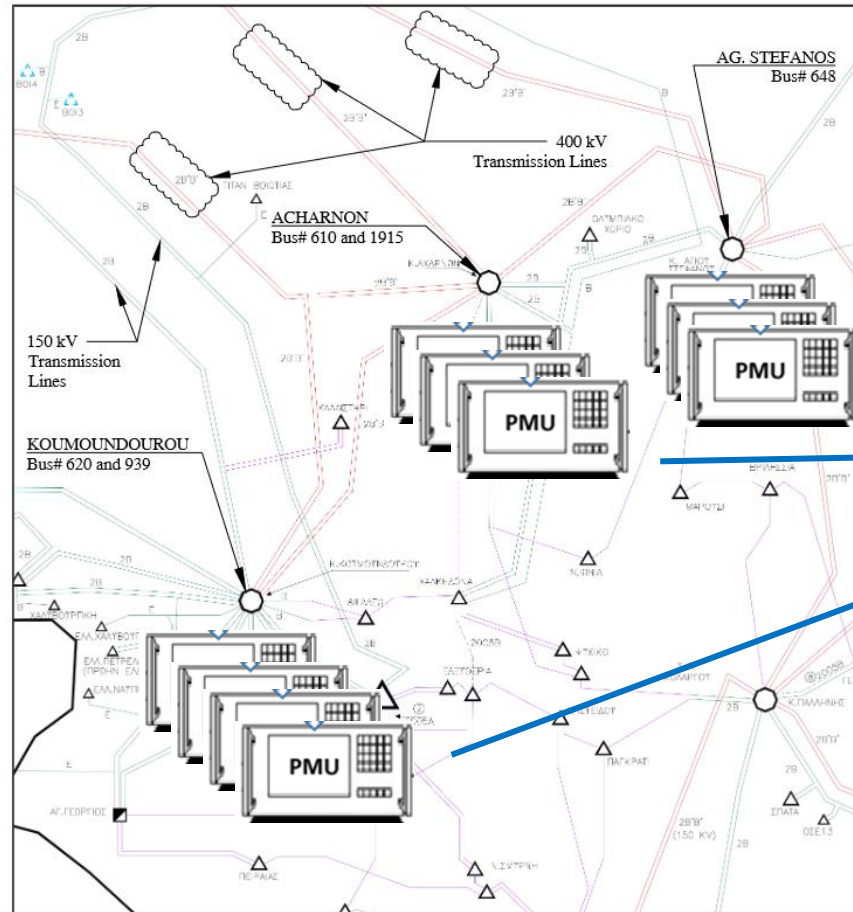
- Load shedding scheme applied after NLI (or RLI) alarm
- Refers to pre-specified substations in the greater area of Athens
- Unstable scenario is stabilized with 182 MW curtailed load

Substation	Bus	P_{nom} (MW)	Q_{nom} (MVar)	ΔP_{nom} (MW)	ΔQ_{nom} (MVar)
MEGARA	709	14.8354	7.7040	7.418	3.852
MEGARA	950	14.31149	15.5524	7.157	7.776
ELEFSINA	687	36.1574	28.7276	18.079	14.364
ELEFSINA	688	39.0019	29.6629	19.501	14.831
AEGALEO	730	184.3492	67.7878	92.175	33.894
AEGALEO	953	75.0891	24.3724	37.545	12.186
AEGALEO	954	0.2977	-2.2234	0.149	1.117
Total		364.0455	171.5735	182.023	85.787



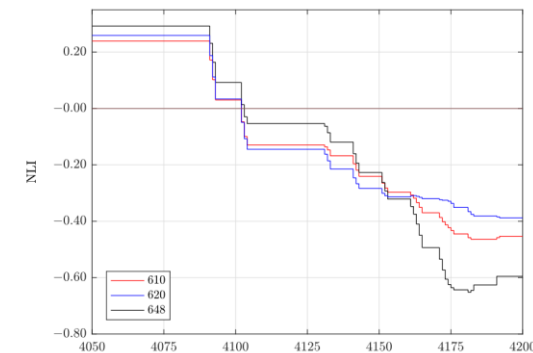
Running Project

Independent Power Transmission Operator – National Technical University of Athens



PDC

Control Center



NLI

Conclusions

LT Voltage Instability can be monitored and controlled

- From PMUs at selected substations or transmission line relays
- Early instability detection can save the system by appropriate control actions
 - Needs to be automatic and fast
- Demonstration with a historic severe instability incident
- Pilot implementation in progress at IPTO of Greece
 - Even though Hellenic System is much more robust now due to upgrades and solar PV during Summer peak
 - Particular interest on the AC interconnection of the island of Crete

Thank you

