Real-Time Voltage Stability Margin Monitoring using Synchronized Measurements

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Introduction

- We present a simple model-free procedure to visualize voltage stability power margins in real-time,
- The margins are visualized in P-Q plane (bus, corridor, or load center),
- Underlying concept is Voltage Instability Predictor (VIP),
- Both voltage instability and FIDVR are analyzed
- A real-time prototype implemented and tested at SCE.

Background

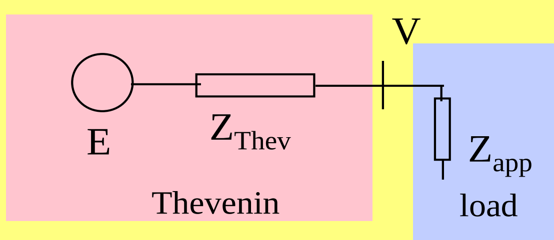
- Voltage instability is linked to the inability of the combined generation-transmission system to provide the power requested by loads

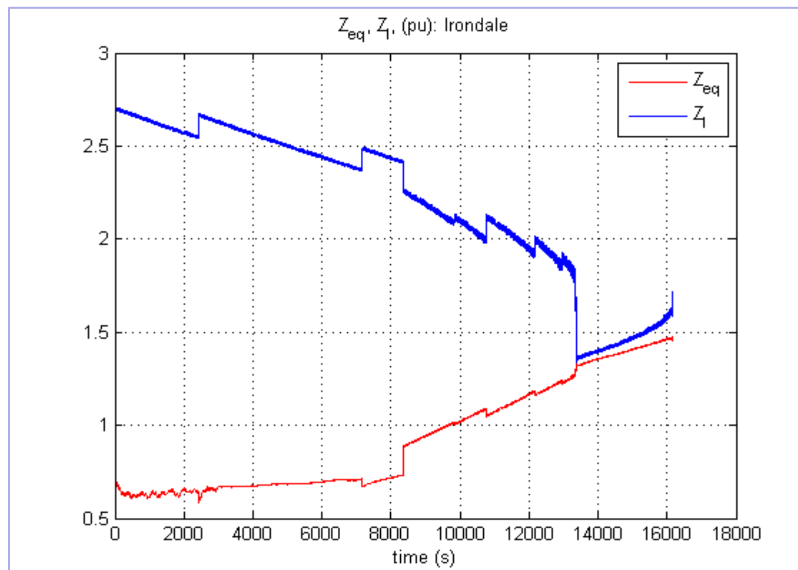
- Notion of MAXIMUM DELIVERABLE POWER
Simple two-bus system:

Maximum power transfer ⇔

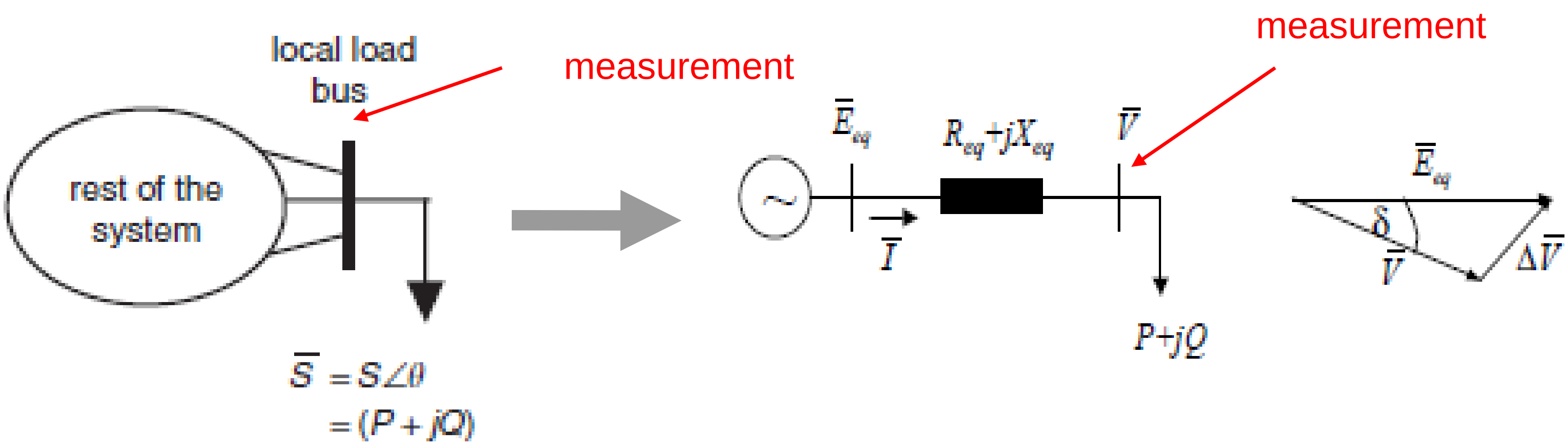
$$|Z_{app}| = |Z_{Thev}|$$

Point of collapse





VIP Concept (Original)



Idea from basic circuit theory of simple 2-bus system

$$|\bar{Z}_{eq}| = |\bar{Z}|$$

$$ISI = \frac{|Z_{eq}|}{|Z|}$$

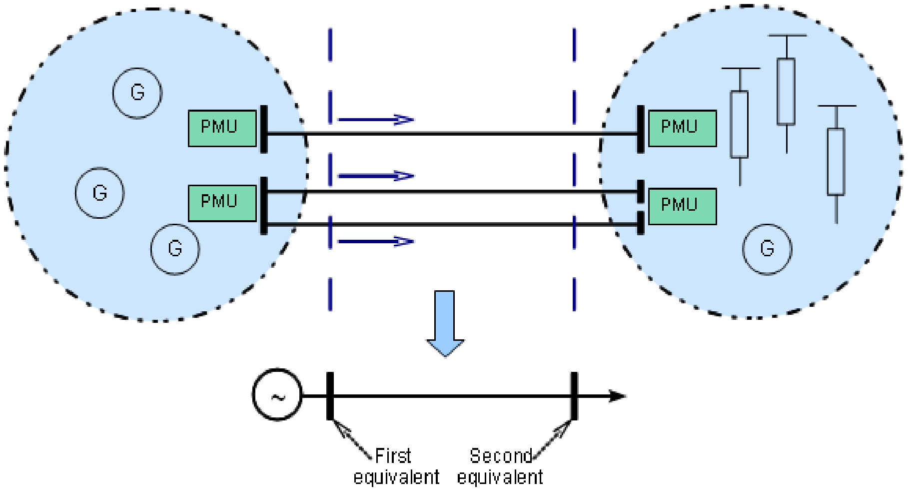
$$VSI = \frac{|V|}{|\Delta V|}$$

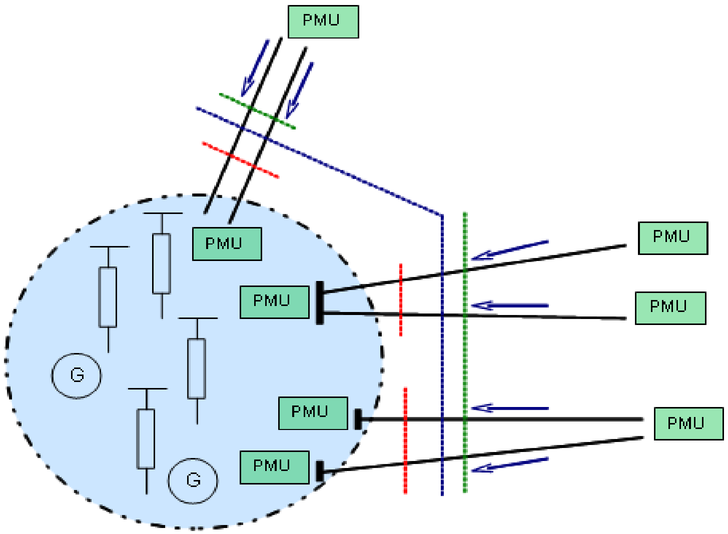
$$S = |Z|I^2 - |Z_{eq}|I^2$$

$$ISI_k = min_{i\in\alpha PQ}\{ISI_{i,k}\}$$

$$VSI_k = min_{i\in\alpha PQ}\{VSI_{i,k}\}$$

Extensions and Improvements





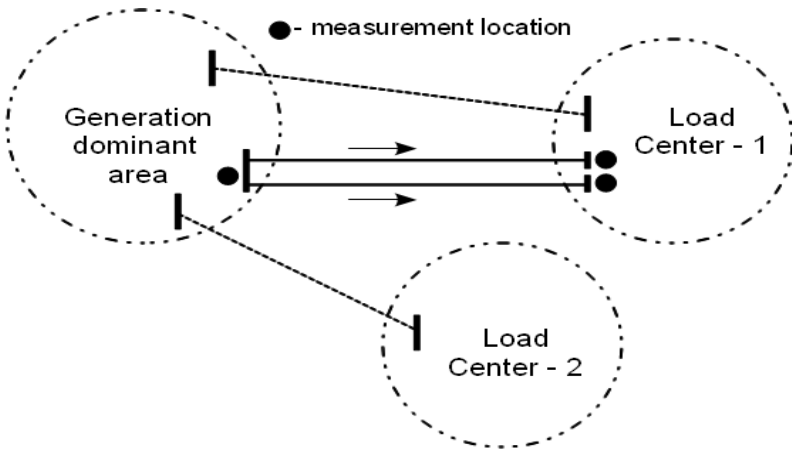
Corridor Power Margin Monitoring:

- Based on sending end measurements identify sending end equivalent first, then
- Append corridor parameters, then
- Repeat identification at receiving end.

Load Center Power Margin Monitoring:

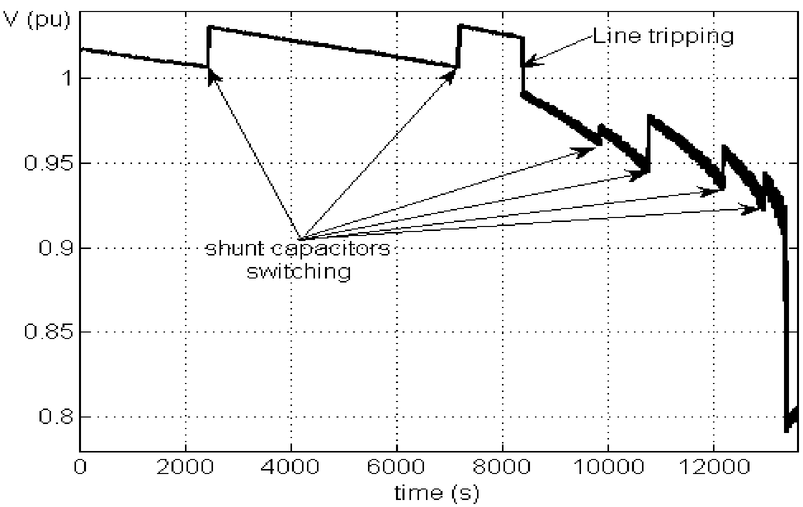
- Closely related to Corridor VIP
- Apply corridor VIP (with updates at both ends)
- Consider each physical corridor separately (to avoid masking effect).

Results using a part of NW USA system

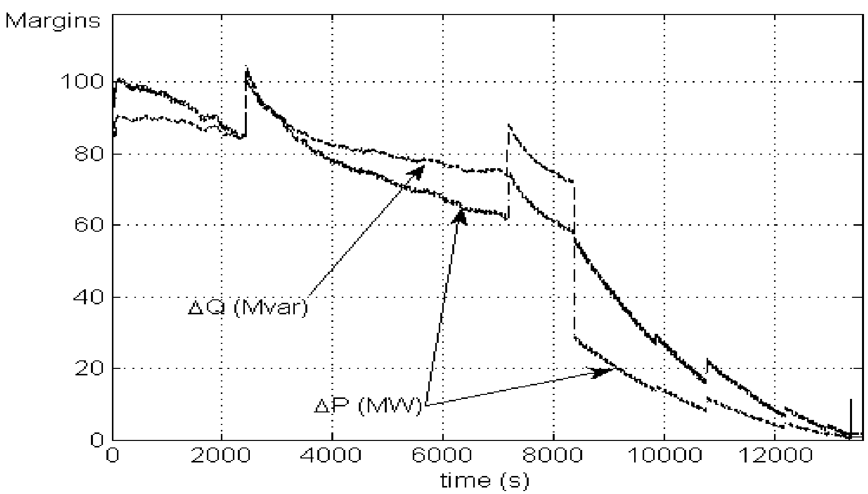


Scenario

- The load ramping,
- A shunt capacitor switched at t=2200 (s),
- Further load ramping followed by another shunt capacitor switching at t=7000 (s)
- A line tripped at approx. t=8000 (s)



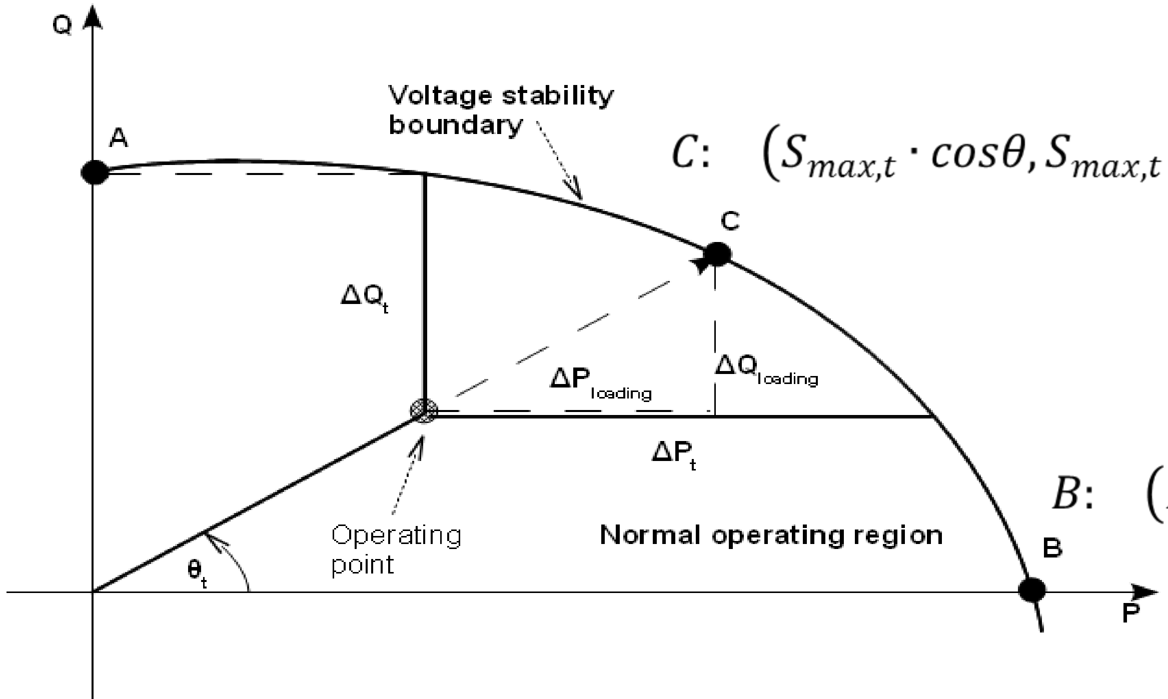
Voltage at a receiving end



Power margins (time evolution)

Power Margin Visualization

$A: \quad (0, Q_{max,t})$



$C: \quad (S_{max,t} \cdot cos\theta, S_{max,t} \cdot sin\theta)$

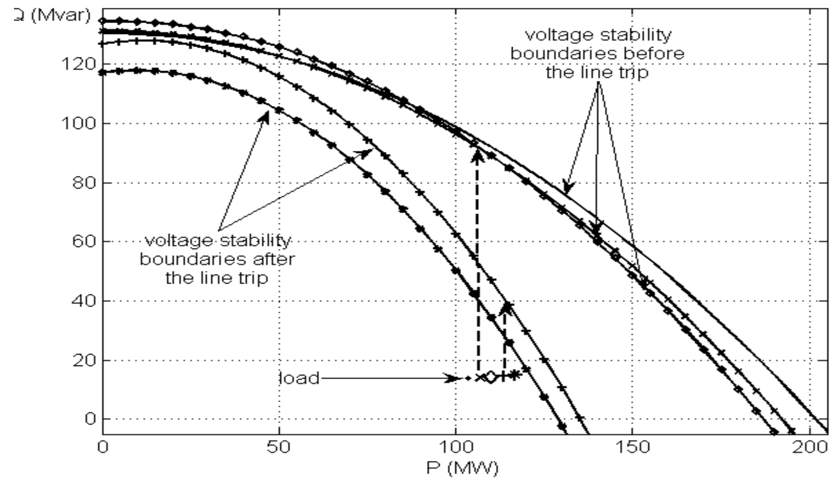
$B: \quad (P_{max,t}, 0)$

$$S_{max,t} = \frac{|\overline{E}|^2_{eq,t}\sqrt{1+tan^2\theta_t}}{2\left(R_{eq,t}+X_{eq,t}\cdot tan\theta_t \mp \sqrt{(R^2_{eq,t}+X^2_{eq,t})(1+tan^2\theta_t)}\right)}$$

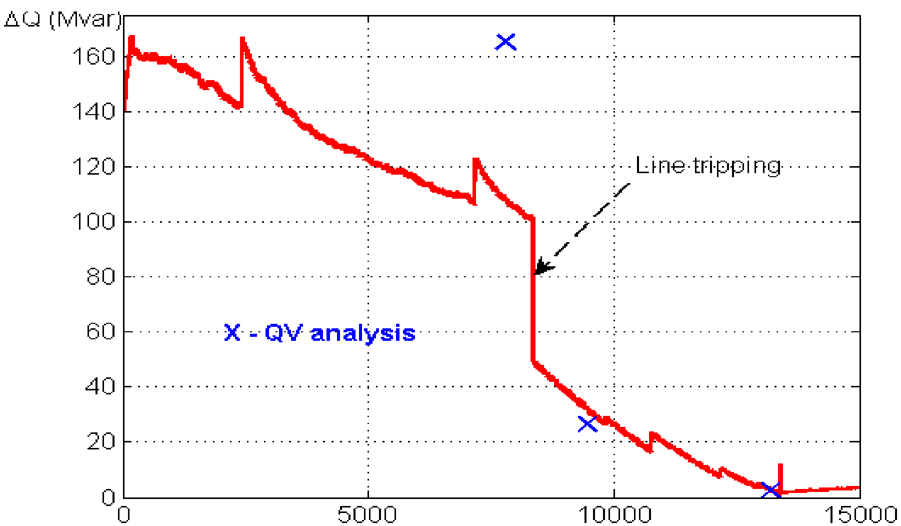
$$P_{max,t} = \frac{E^2_{eq,t}}{2(R_{eq,t}+|Z_{eq,t}|)},$$

$$Q_{max,t} = \frac{E^2_{eq,t}}{2(X_{eq,t}+|Z_{eq,t}|)}$$

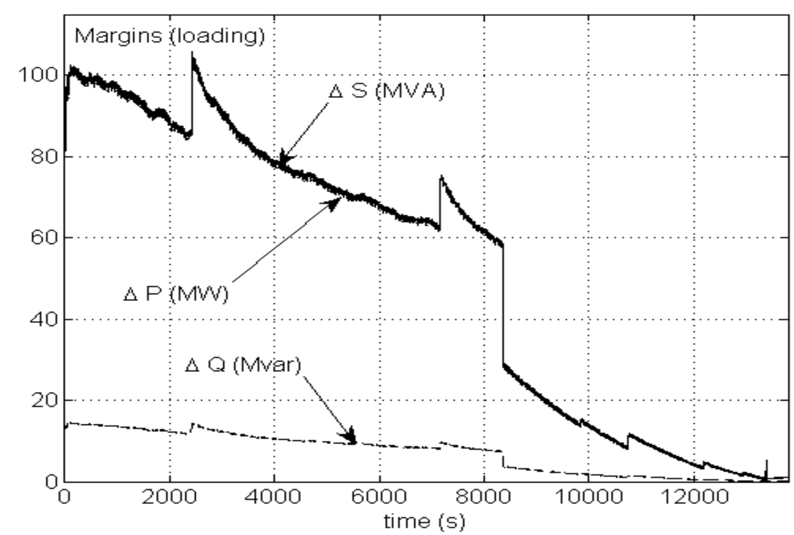
Results using a part of NW USA system



- Loading margins can still be computed,
- Comparison with off-line VQ analysis (good accuracy close to system stability boundary)



Comparison with VQ analysis



Loading margins (time evolutions)

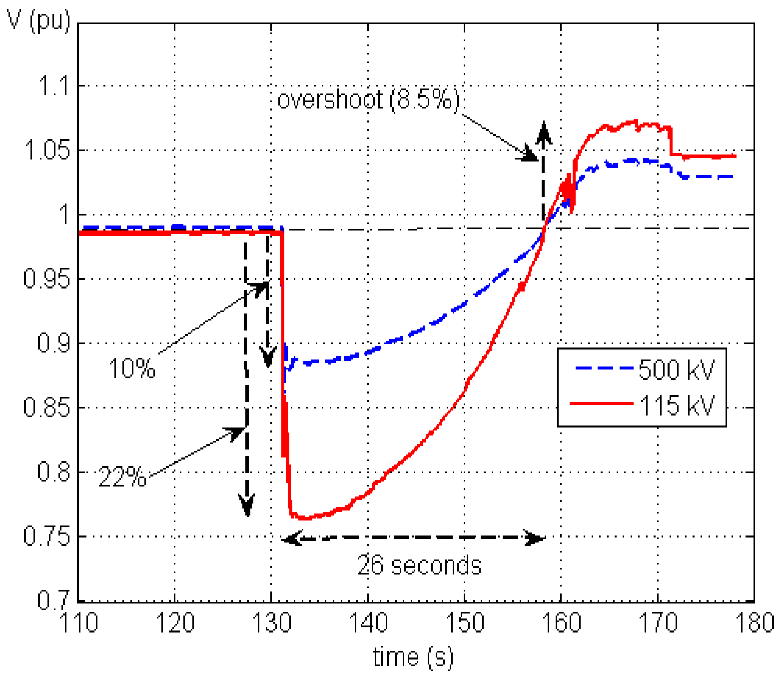
Test Results - BPA and SCE Networks

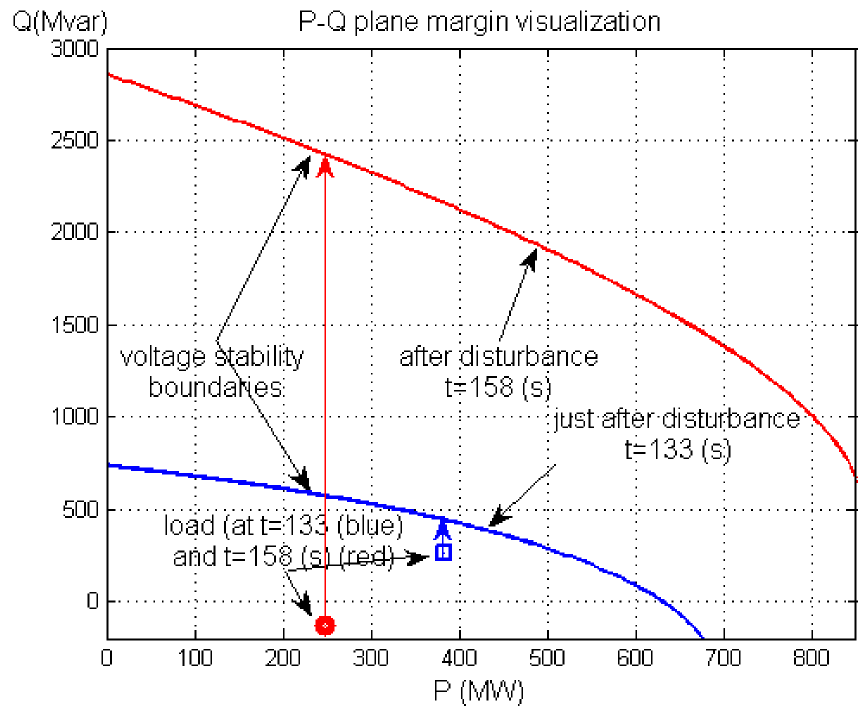
Comprehensive tests using real-life PMU and SCADA measurements and off-line system simulations

- ***Bus:*** Malin - COI, Devers, Valley, Kramer; ***Corridor:*** Jones Canyon; ***Load centers:*** West of Cascades, Fairmont/Bremerton, Portland/Vancouver
- For all cases new methodology works correctly
  - Ability to detect instability even if voltage close to nominal
  - Results comparable to detailed, model-based off-line QV analysis; very accurate closer to instability boundary
  - No false alarms
- Discriminates between FIDVR and fast voltage instability
  - FIDVR cases (no voltage collapse) are accurately detected despite the fact the voltage is low for some time

SCE Example: P-Q Plane and Margins

Valley substation, 115 kV

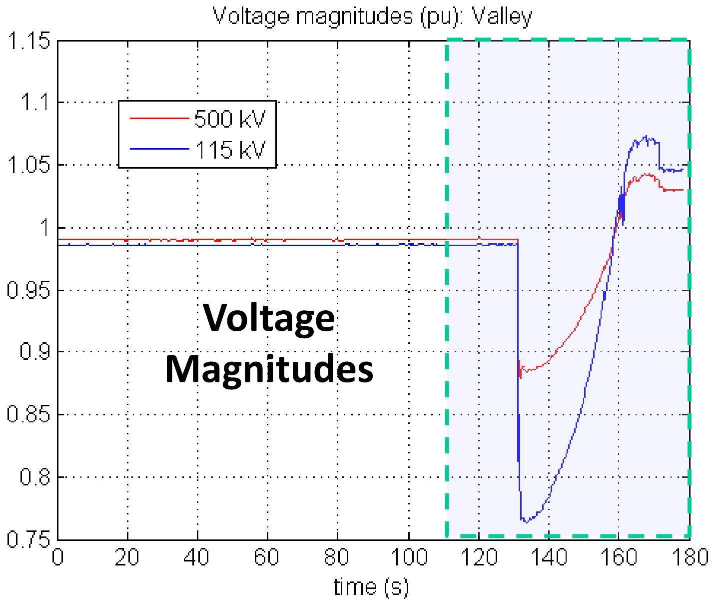


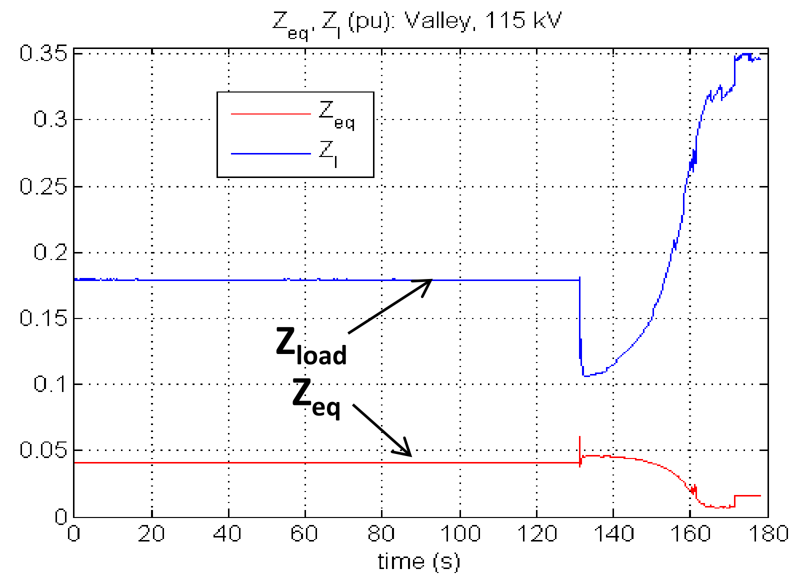


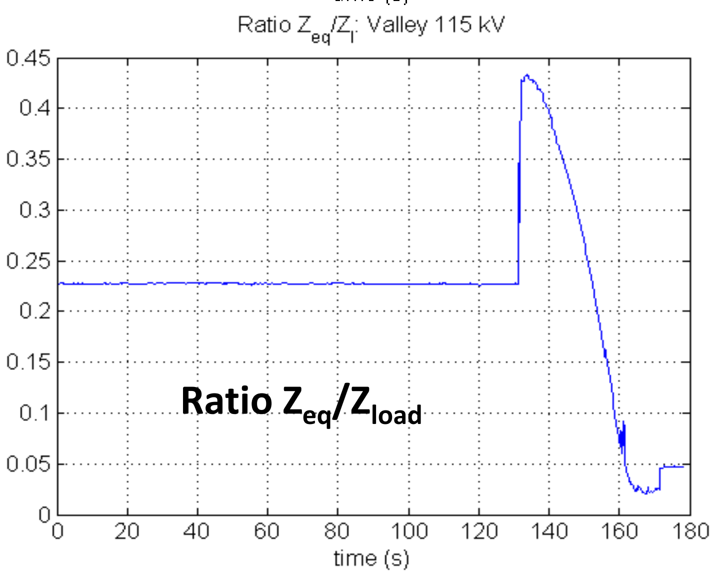
Fault Induced Delayed Voltage Recovery (FIDVR)

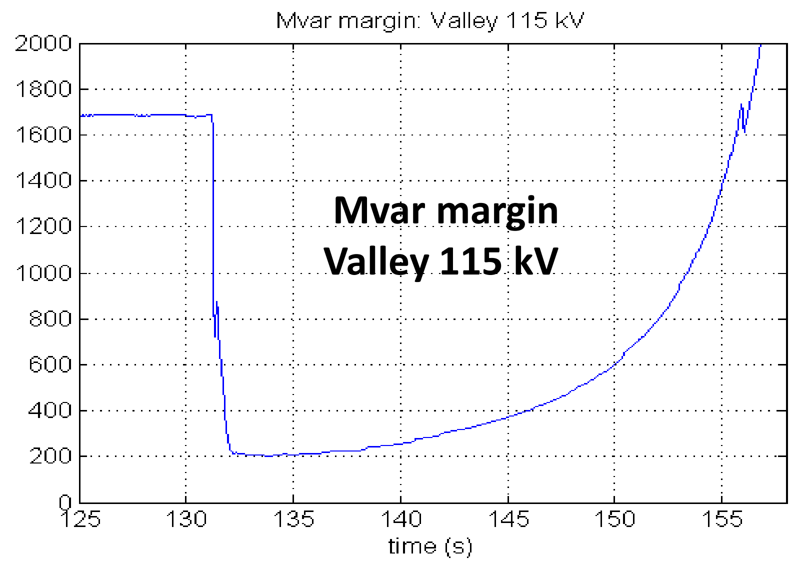
P-Q visualization of FIDVR

SCE Example – Substation Valley 115 kV





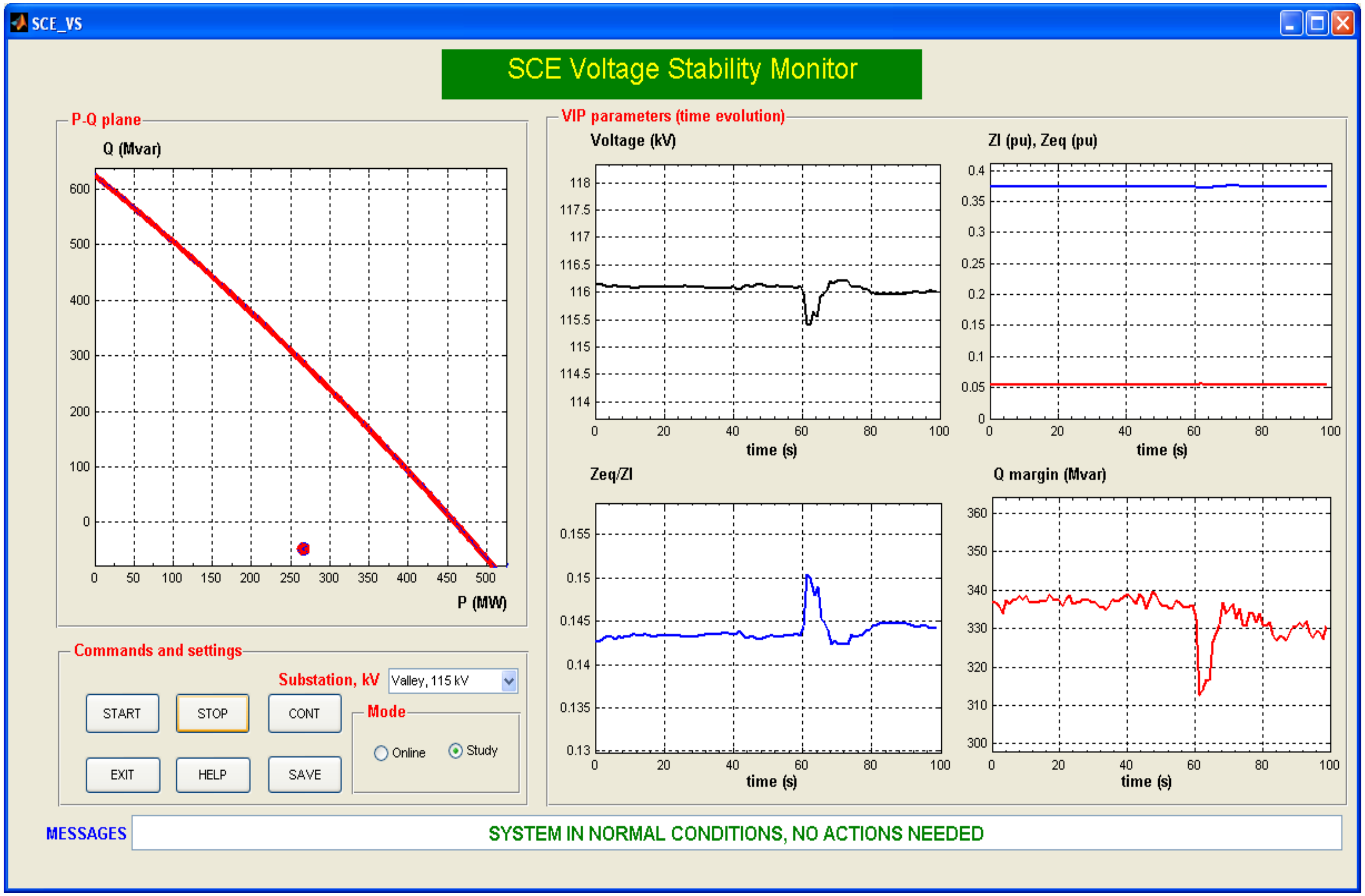




Recent Developments at SCE

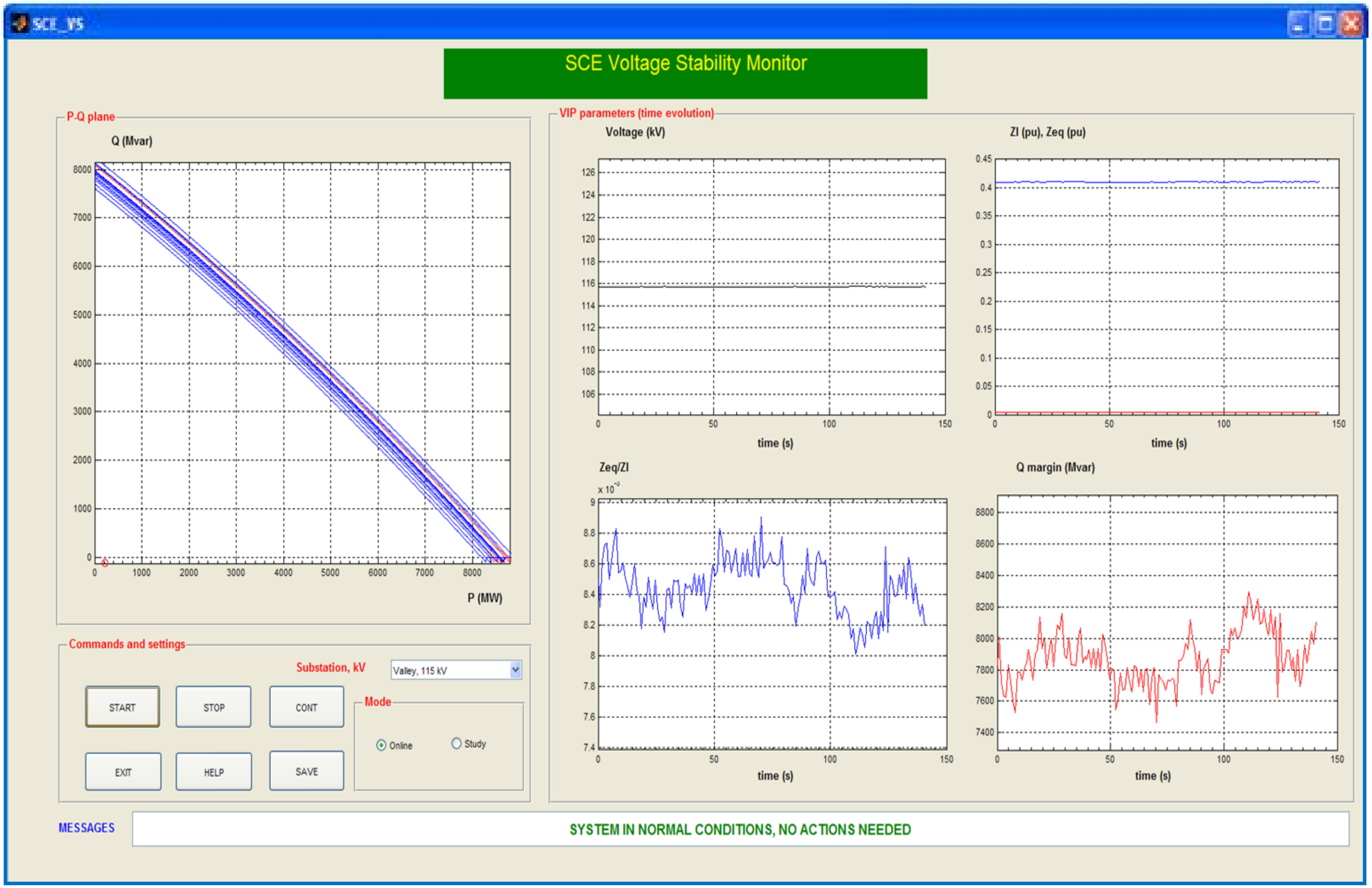
- A simple visualization tool developed based on the presented method
- The following stations are considered (with PMU measurements):
  - Valley 115 kV, Valley 500 kV,
  - Devers 115 kV, Devers 230 kV, Devers 500 kV,
  - Antelope 66 kV, Antelope 230 kV
  - Kramer 115 kV
  - Rector 230 kV,
- The tool has been tested in real-time environment (using phasor data streams),
- User Datagram Protocol (UDP) is used for sending phasor data streams from Phasor Data Concentrator (PDC).
- Proposed method also tested in cases of FIDVR (Fault-Induced Delayed Voltage Recovery)

GUI - Study Mode Example



GUI working in study mode, Valley 115 kV station

GUI - Online Mode Example



GUI working in on-line mode, Valley 115 kV station

Conclusions

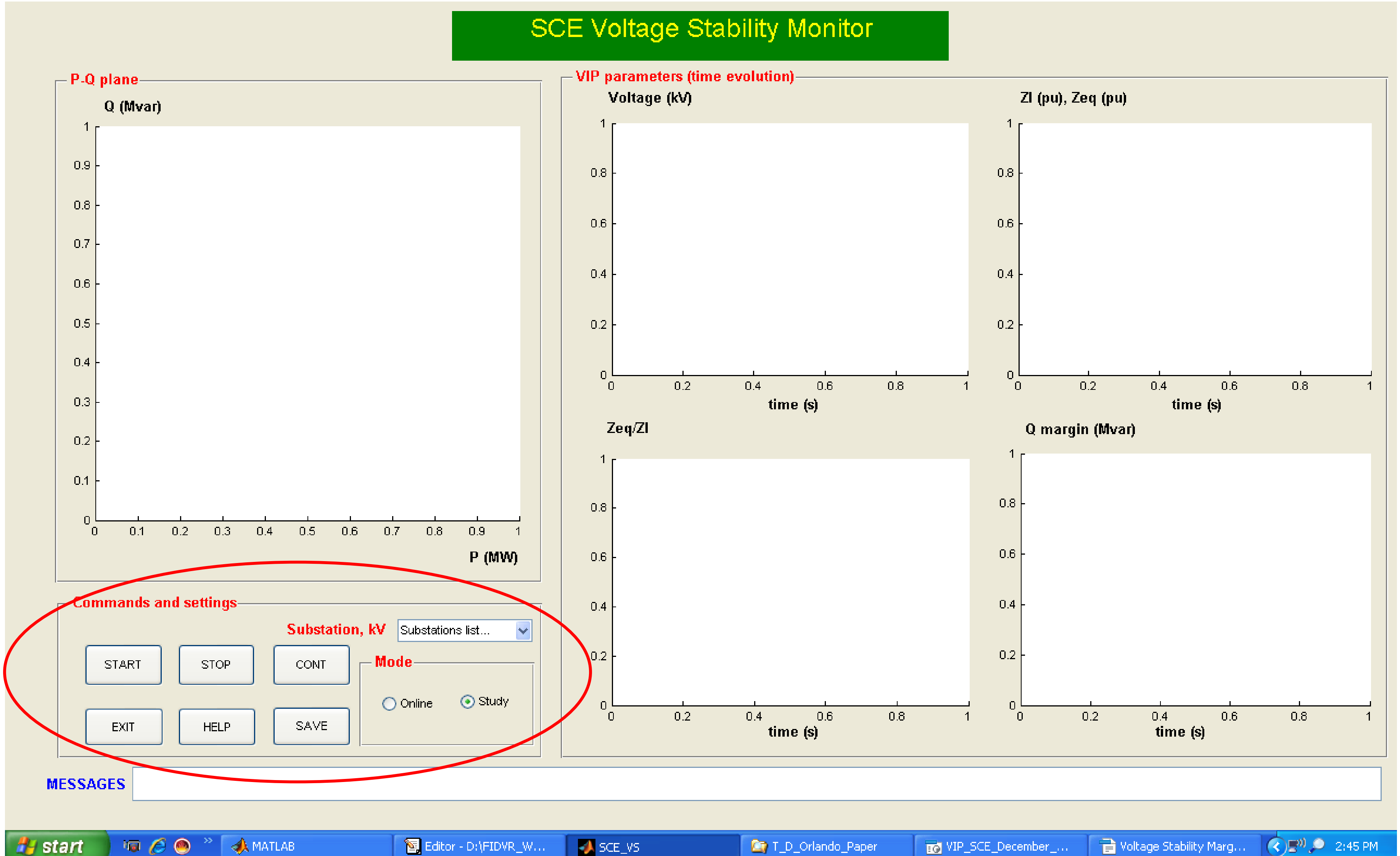
- Proposed method is easy to implement and interpret,
- Power margins derived easily visualized in P-Q plane and refreshed at high rates, in real-time
- Preferred margin monitoring derived indices:
  - Q margin particularly suitable for FIDVR (motors pulling reactive power)
  - Ratio of impedances
- New Power Margin Monitoring (PMM) Method works very well with loads centers and transmission corridors regardless of the voltage level.
- ‘Nodal PMM’ method works very well with stations of 115 kV and lower (radial network)
- Sometimes not as accurate for highly meshed topologies at 230 and 500 kV:
  - Not all measurements (especially currents) were taken into account
  - It requires careful consideration of PMU placement (improvements being considered)

Conclusions (FIDVR)

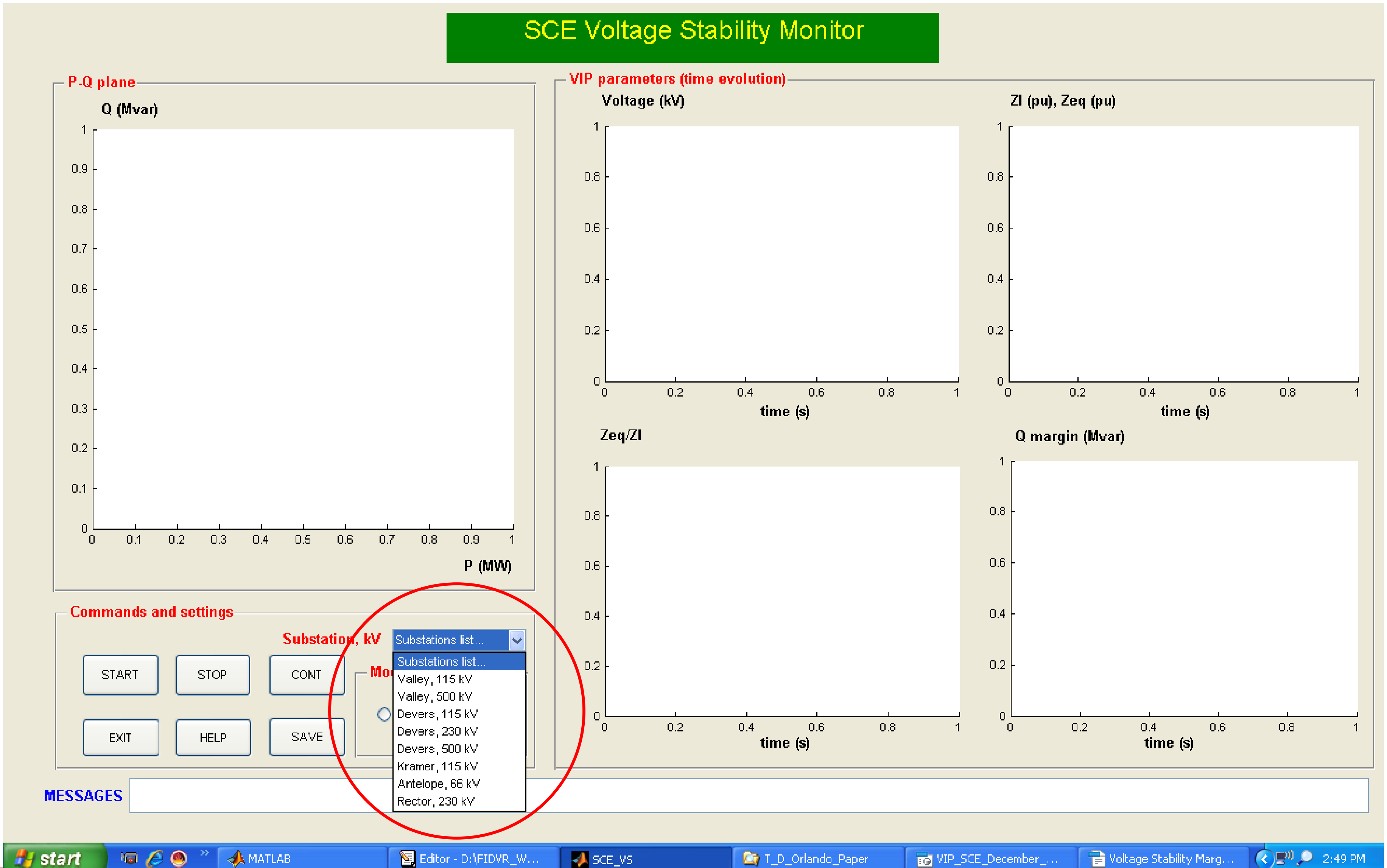
- PMM method was not originally developed for FIDVR but results suggest that it could be a useful indicator to distinguish between FIDVR and voltage instability cases
- In all eight provided FIDVR cases NO false alarm issued by VIP despite the fact the voltage magnitudes may go below 0.8
  - No crossing between the two equivalent impedances (R_{load}/R_{eq} ratio stayed >1)
  - Q margin never reached 0

Backup

Graphical User Interface - 1



Graphical User Interface - 2



Graphical User Interface - 3