REAL TIME DIGITAL SIMULATION

RTDS® Southern Africa Users' Group Meeting

25th January, 2016

Real-Time Simulations Using a Synchrophasor-Based Wide Area Monitoring, Protection, and Control (WAMPAC) Testbed

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Cape Peninsula University of Technology

PRESENTATION OUTLINE

- Background
- Objectives
- Methodology
- Experimental Results
- Conclusion
- Bibliography

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BACKGROUND

Power System Operations

- Provide reliable supply of electricity
- Efficient and secure operation

- **Current trend**
  - Large/complex interconnections
  - Loads continue to increase
  - Long distance between gens. & loads
  - Lack of new power stations

- **Implications**
  - Power systems are stressed
  - Systems are operating closer to their stability limit

- Power System Stability

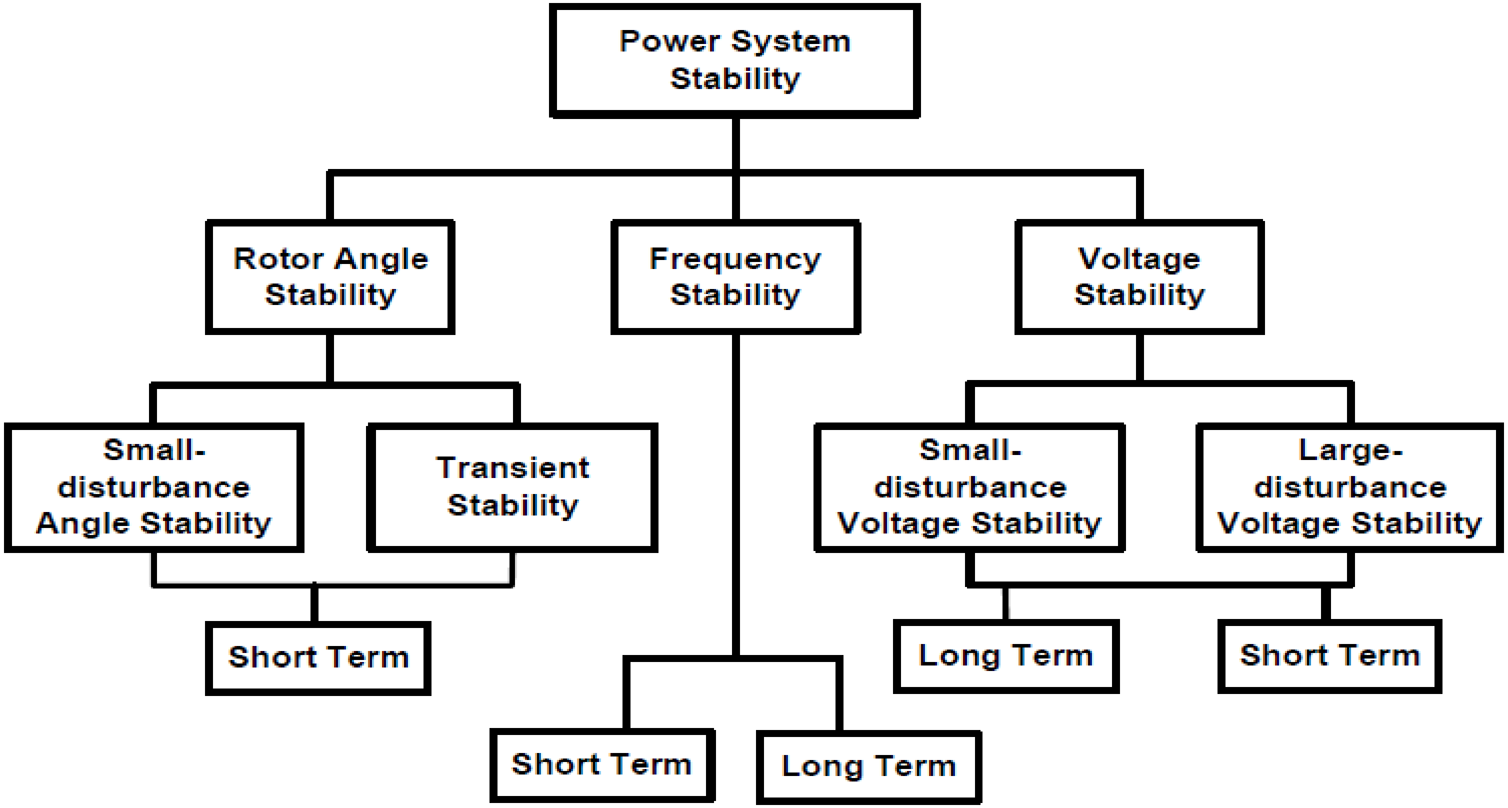

Figure 1: Power system stability (Kundur, 1994)

BACKGROUND

Voltage Stability Assessment (VSA)

Ability to maintain acceptable voltage profile during steady state conditions & after a disturbance

Causes of voltage instability:

- Small disturbances: Gradual increase in system loading
- Large disturbances: Loss of lines/generators, faults, transformer and generator controls (OLTCs/OXLs)
  - Lack of reactive power support
  - Loss of voltage control

Analysis:

- The proximity of the system to voltage collapse
- Mechanism of voltage collapse (how?, why?, what, where the voltage weak areas are? effectives RAS.

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System Integrity Protection Schemes for VSA

(RAS, SPS, SIPS)

Functions

- Monitor
- Detect abnormal system conditions
- Initiate remedial action(s)
- Preserve system integrity

SIPS Elements

- System monitoring element
- System protection element
- Execution element

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System Integrity Protection Schemes for VSA (RAS, SPS, SIPS)

Table 1: Remedial actions for power system instability

SIPS/RAS/SPS	Transient instability	Small-signal instability	Frequency instability	Voltage instability
Generation rejection	×	×	×	×
Remote load shedding	×	×		
HVDC controls	×	×	×	
Braking resistor	×	×		
Under-frequency load shedding			×	
Turbine fast valving	×	×	×	
Automatic shunt switching	×	×		×
Under-voltage load shedding				×
Tap-changer blocking			×	×
AGC controls		×		×
Gas turbine start-up			×	×

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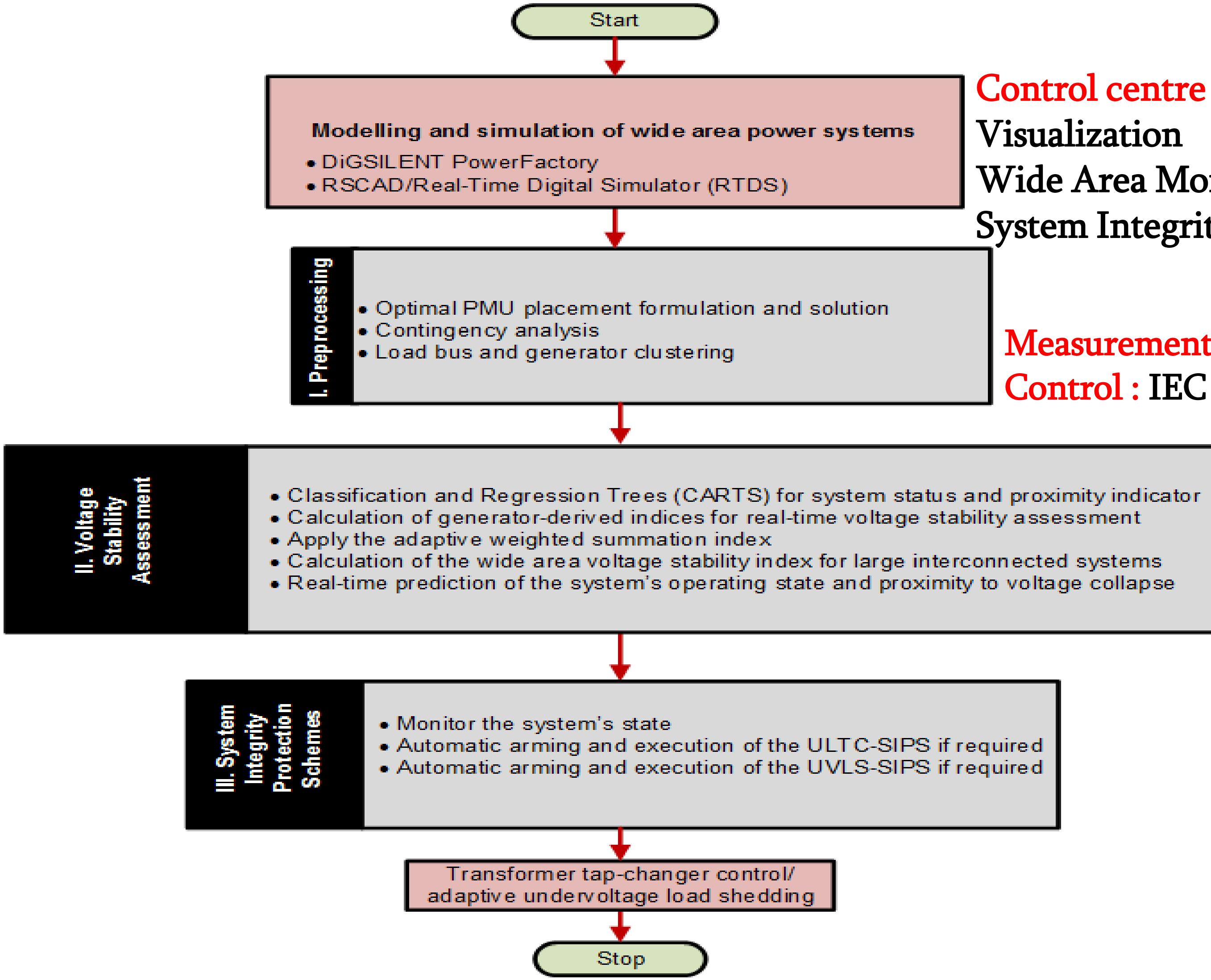
OBJECTIVES

Proposed algorithms and methods for WAMPAC



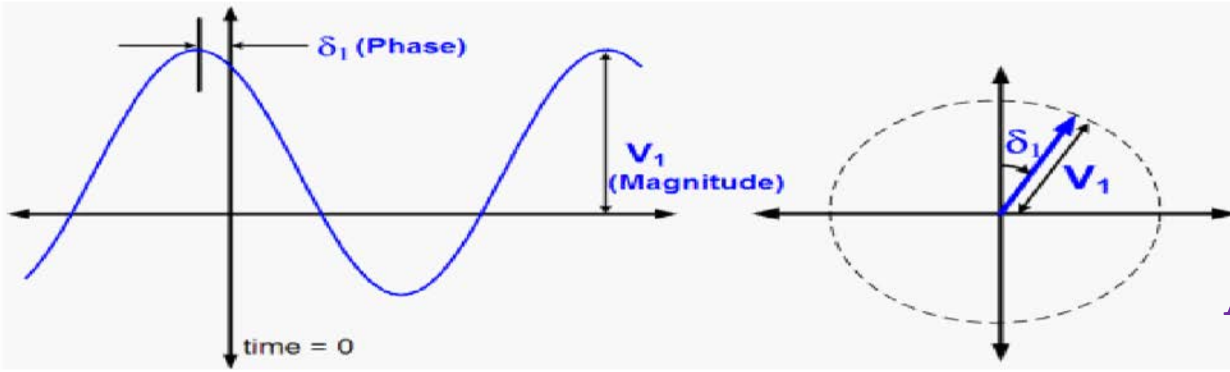
Control centre applications for:
Visualization
Wide Area Monitoring System
System Integrity Protection Schemes

Measurements: IEEE C37.118 PMUs
Control : IEC 61850 GOOSE

Figure 2: Proposed methods and algorithms for Wide Area Monitoring, Protection, and Control (WAMPAC)

OBJECTIVES

- What are synchrophasors?



Voltage phasors
Current phasors
Sequence components
Frequency
ROCOF
Analogue measurements
Digital statuses

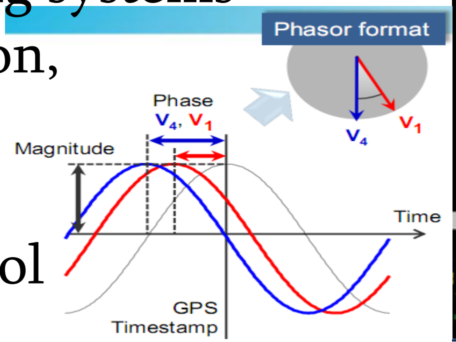
Features

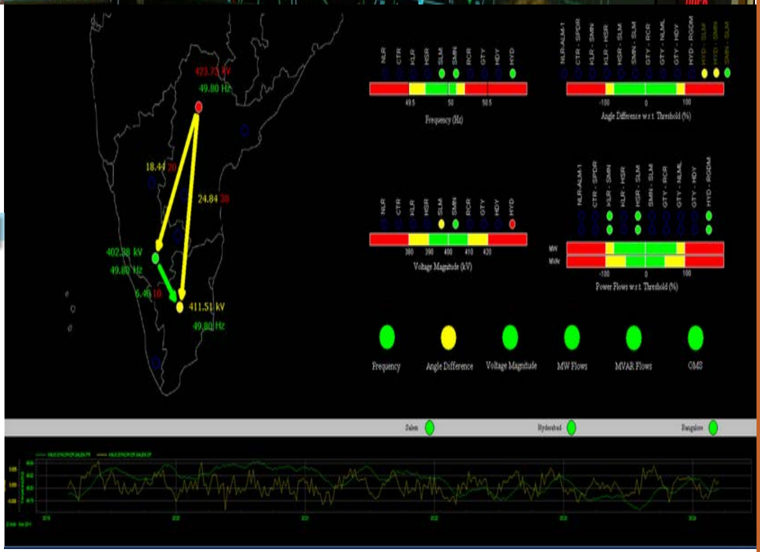
- 1μs synchronization to the GPS,
- Reporting rates up to 200 fps for 50 Hz systems
- Accuracy of 1% TVE
- Compliance with IEEE C37.118 Std.

OBJECTIVES

Applications of synchrophasors

- Situational awareness
- Wide area monitoring systems
- Linear state estimation,
- Decision support
- Real-time analysis
- Protection and control
- Model validation





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OBJECTIVES

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Table 2: Comparison with existing technology

Existing Technology	Emerging Technology
SCADA Data	Phasor Measurement -PMU
Refresh rate = 2-10 seconds	Refresh rate = 200 samples per second (50 Hz)
Magnitude only	Magnitude & phase angle
Measurements are not time synchronized	Measurements are time synchronized
Legacy communication technology	Modern communication technology
Not suitable for rapidly changing system conditions	Suitable for capturing dynamic changes
X-ray	MRI

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METHODOLOGY

- Derivations of real-time voltage stability indices
  - Generator reactive power reserve

- Derivation for centralized SIPS (undervoltage load shedding scheme)
  - MVAR mismatch, Voltage Control Areas (VCA), volt deviation

- Development of a 'proof-of-concept' testbed

- Modelling of the test system
  - New England 39-bus test system

- Real-time hardware-in-the-loop simulations of case studies
  - Case studies: Load increase, generator contingencies, line contingencies

METHODOLOGY

Proposed Real-Time Voltage Stability Indices (RVSA) indices

- Derivation from generator maximum reactive power reserve

$$Q_{g\max} = -\frac{V_g^2}{X_s} + \sqrt{\frac{V_g^2 I_{fd\max}^2}{X_s^2} - P_{g\max}^2} \qquad RVSA_{Q,i} = \left(1 - \frac{Q_{gki}}{Q_{g\max i}^c}\right) \times 100\% \qquad (1)$$

- Generator field current derivation from $Q_{g\max}$

$$-\frac{V_g^2}{X_s} + \sqrt{\frac{V_g^2 I_{fd\max}^2}{X_s^2} - P_{g\max}^2} = -\frac{V_g^2}{X_s} + \sqrt{\frac{V_g^2 I_{fdk}^2}{X_s^2} - P_{gk}^2} \qquad RVSA_{Ifd,i} = \left(1 - \frac{I_{fdki}}{I_{fd\max i}^c}\right) \times 100\% \qquad (2)$$

- Generator stator current derivation

$$Q_{ga\max} = \sqrt{V_g^2 I_{a\max}^2 - P_{ga\max}^2} \qquad RVSA_{Ia,i} = \left(1 - \frac{I_{aki}}{I_{a\max i}^c}\right) \times 100\% \qquad (3)$$

Proposed RVSA indices for large interconnected power system

- Reactive power reserve on system generators

$$RVSA_{Q,sys} = \min_{i \in sys}\left\{RVSA_{Q,i}\right\} = \min_{i \in sys}\left\{\left(1 - \frac{Q_{gki}}{Q^{c}_{g\max i}}\right) \times 100\,\%\right\} \qquad (4)$$

- Field current reserves on system generators

$$RVSA_{Ifd,sys} = \min_{i \in sys}\left\{RVSA_{Ifd,i}\right\} = \min_{i \in sys}\left\{\left(1 - \frac{I_{fdki}}{I^{c}_{fd\max i}}\right) \times 100\,\%\right\} \qquad (5)$$

- Stator current reserves on system generators

$$RVSA_{Ia,sys} = \min_{i \in sys}\left\{RVSA_{Ia,i}\right\} = \min_{i \in sys}\left\{\left(1 - \frac{I_{aki}}{I^{c}_{a\max i}}\right) \times 100\,\%\right\} \qquad (6)$$

METHODOLOGY

Derivations for undervoltage load shedding scheme

- Total reactive power mismatch

$$\Delta Q_{gik} = Q_{gik} - Q_{gi0}, \quad i = \overline{1, N_g}, \quad k = 0, 1, 2, \ldots \qquad (7)$$

- Total load to shed

$$Q_{shed,k} = \beta_K \cdot \sum_{i=1}^{N_g} \Delta Q_{gik}, \quad k = 0, 1, 2, \ldots \qquad (8)$$

- Total load to shed per VCA

$$\Delta Q_{shed,VCA_{jk}} = \left(\frac{100 - vcaRVSA_{jk}}{100n - \left(\sum_{j=1}^{n} vcaRVSA_{jk} \right)} \right) \times Q_{shed,k} \qquad j = \overline{1, n}, \quad k = 0, 1, 2, \ldots \qquad (9)$$

- Total load to shed per VCA per load bus

$$\Delta Q_{shed,\,jBp} = w_{j\Delta VBp} \times \Delta Q_{shed,VCAjk} \qquad (10)$$

METHODOLOGY

SIPS elements for undervoltage load shedding

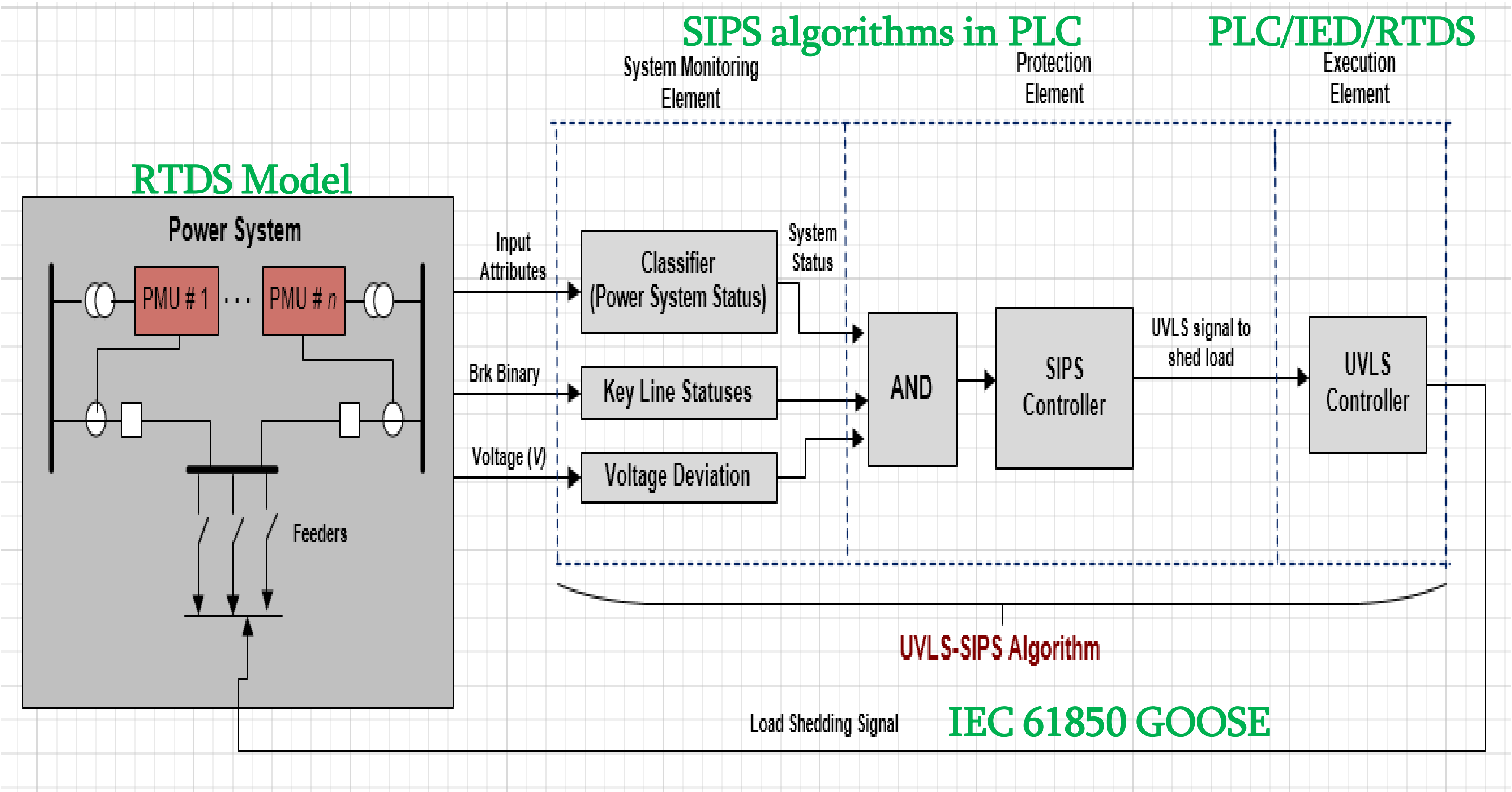

Figure 3: System Integrity Protection Scheme (SIPS)

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METHODOLOGY

Testbed used at CSAEMS-CPUT

- RTDS, PMUs, PDCs, IEDs, GPS Clocks, PLC, Network Switches

Figure 4: Implemented WAMPAC testbed

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METHODOLOGY

Table 3: RTDS Resources at CPUT (4 Racks)

S/N	RTDS Card	Function	Nr.
1	PB5	Processor card	6
2	GPC	Processor card	3
3	GTWIF	Work station interface	4
4	GTNET	Communication protocols (PMU, GSE, SV, DNP3)	5
5	GTNET X2	Communication protocol X2 (GSE, SKT)	1
6	GYSYNC	Time synchronization	2
7	GTAO	Analogue output card	2
8	GTAI	Analogue input card	1

METHODOLOGY

Test System Model

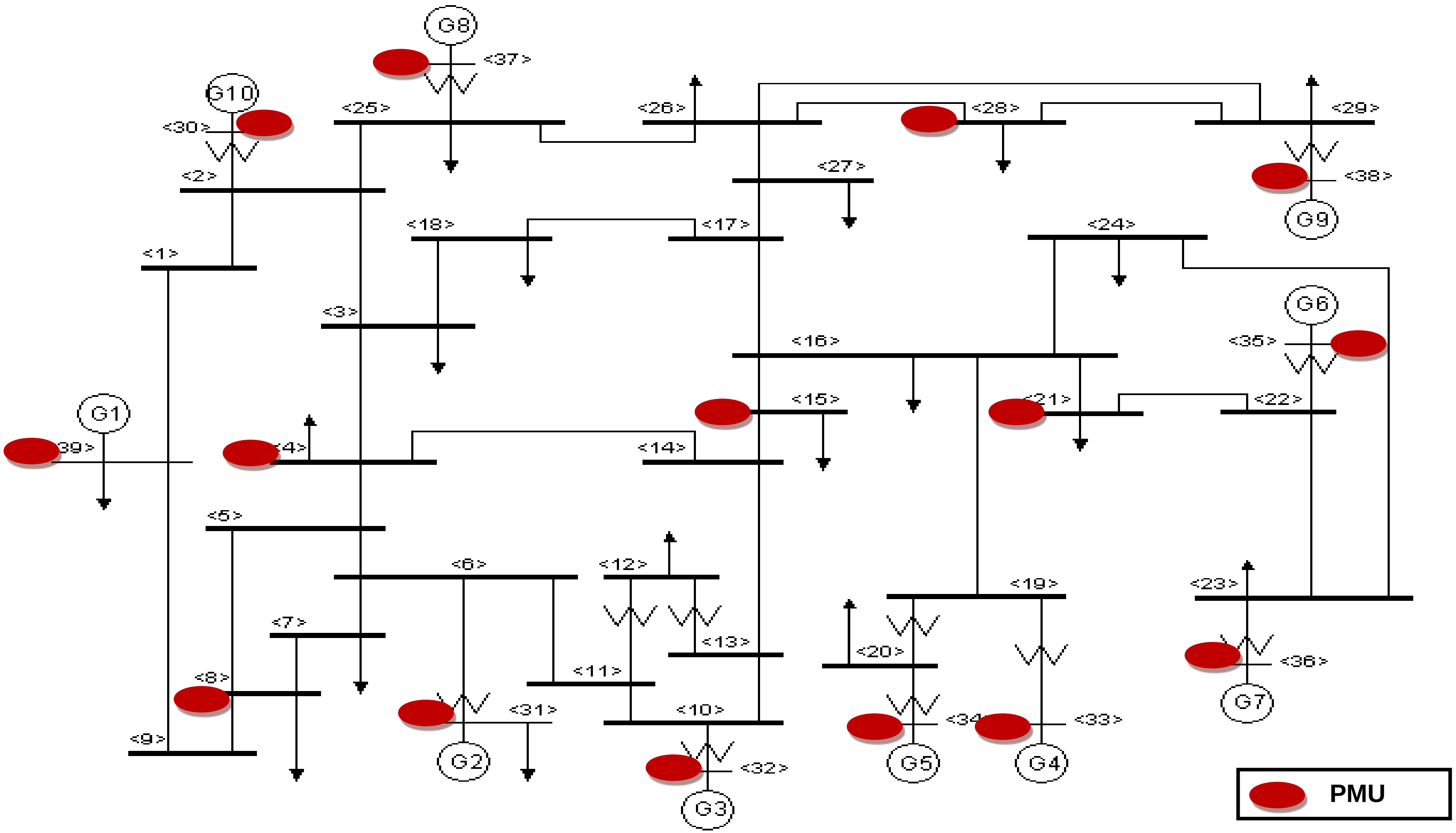

Figure 5: New England 39-bus test system

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METHODOLOGY

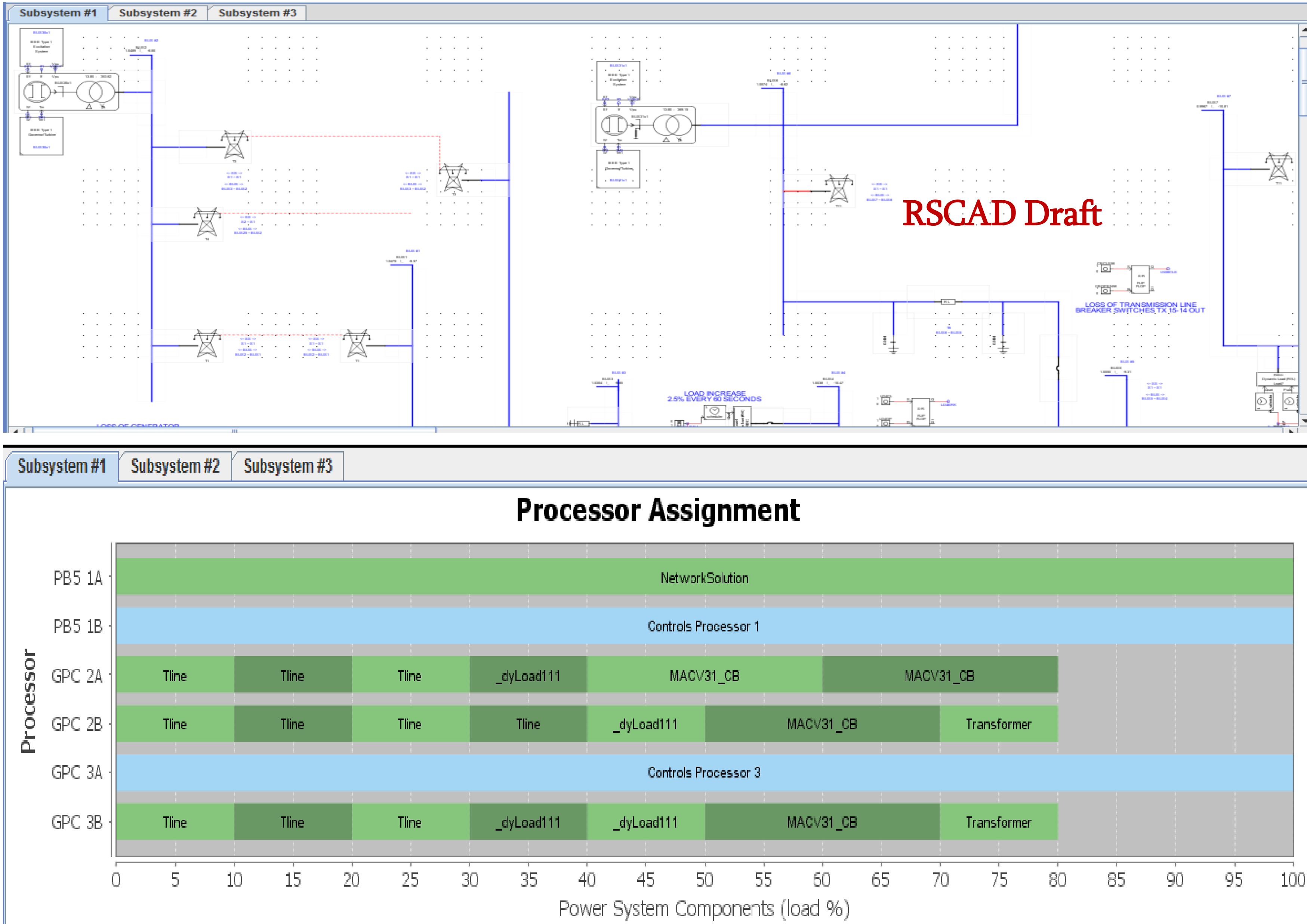

Figure 6: (a) RSCAD draft; (b) processor assignment

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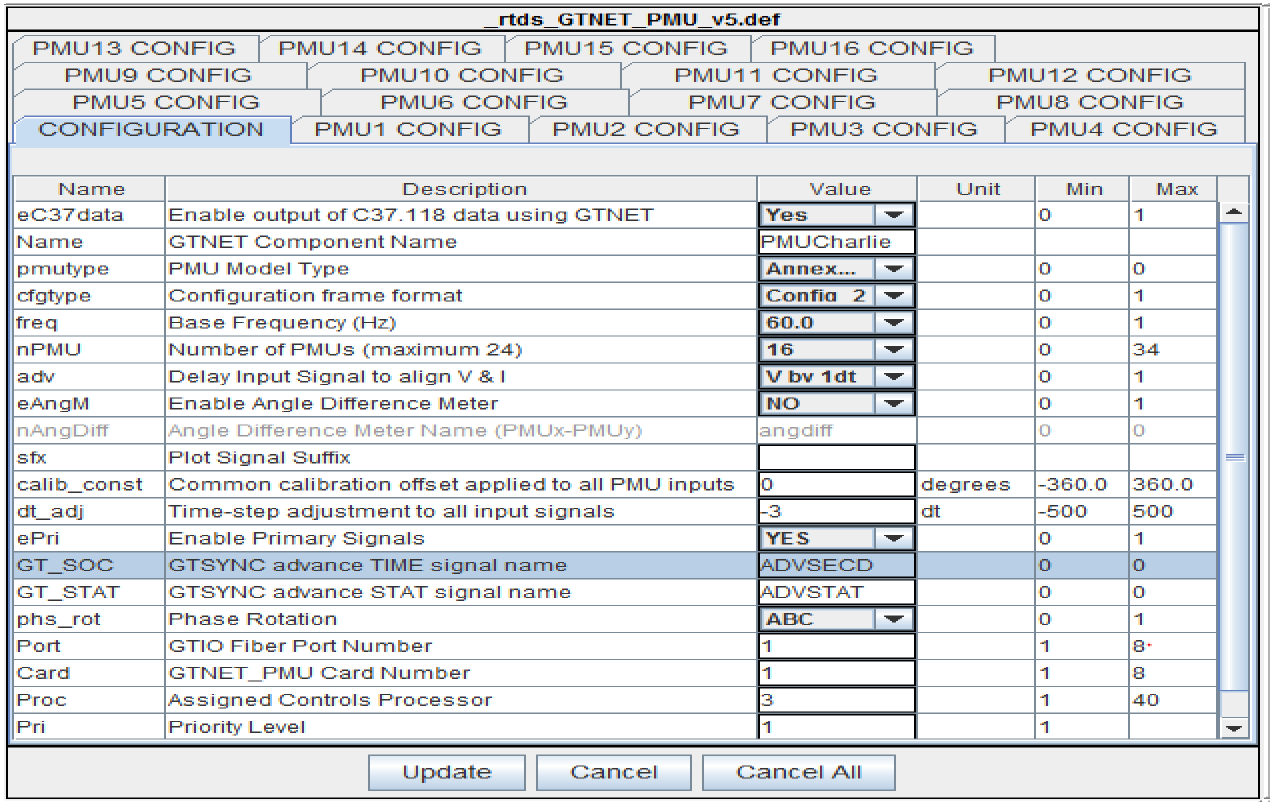
METHODOLOGY



_rtds_GTNET_PMU_v5.def

PMU13 CONFIG | PMU14 CONFIG | PMU15 CONFIG | PMU16 CONFIG
PMU9 CONFIG | PMU10 CONFIG | PMU11 CONFIG | PMU12 CONFIG
PMU5 CONFIG | PMU6 CONFIG | PMU7 CONFIG | PMU8 CONFIG
CONFIGURATION | PMU1 CONFIG | PMU2 CONFIG | PMU3 CONFIG | PMU4 CONFIG

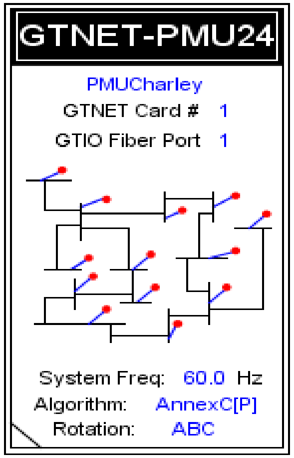
Name	Description	Value	Unit	Min	Max
eC37data	Enable output of C37.118 data using GTNET	Yes		0	1
Name	GTNET Component Name	PMUCharlie			
pmutype	PMU Model Type	Annex...		0	0
cfgtype	Configuration frame format	Config 2		0	1
freq	Base Frequency (Hz)	60.0		0	1
nPMU	Number of PMUs (maximum 24)	16		0	34
adv	Delay Input Signal to align V & I	V by 1dt		0	1
eAngM	Enable Angle Difference Meter	NO		0	1
nAngDiff	Angle Difference Meter Name (PMUx-PMUy)	angdiff		0	0
sfx	Plot Signal Suffix				
calib_const	Common calibration offset applied to all PMU inputs	0	degrees	-360.0	360.0
dt_adj	Time-step adjustment to all input signals	-3	dt	-500	500
ePri	Enable Primary Signals	YES		0	1
GT_SOC	GTSYNC advance TIME signal name	ADVSECD		0	0
GT_STAT	GTSYNC advance STAT signal name	ADVSTAT		0	0
phs_rot	Phase Rotation	ABC		0	1
Port	GTIO Fiber Port Number	1		1	8
Card	GTNET_PMU Card Number	1		1	8
Proc	Assigned Controls Processor	3		1	40
Pri	Priority Level	1		1	

Update | Cancel | Cancel All

Figure 7: RSCAD-PMU component

PMU

RSCAD Draft GTNET-PMU Component



PMU Parameters:

- IEEE C37.118.1-2011
- P-Class
- Positive sequence phasors V_1 & I_1
- Analogue measurement and digital word
- Polar format, real values, 60 fps, CFG-2
- IRIG-B time sync from the GTSYNC card

GTNET-PMU Card

METHODOLOGY

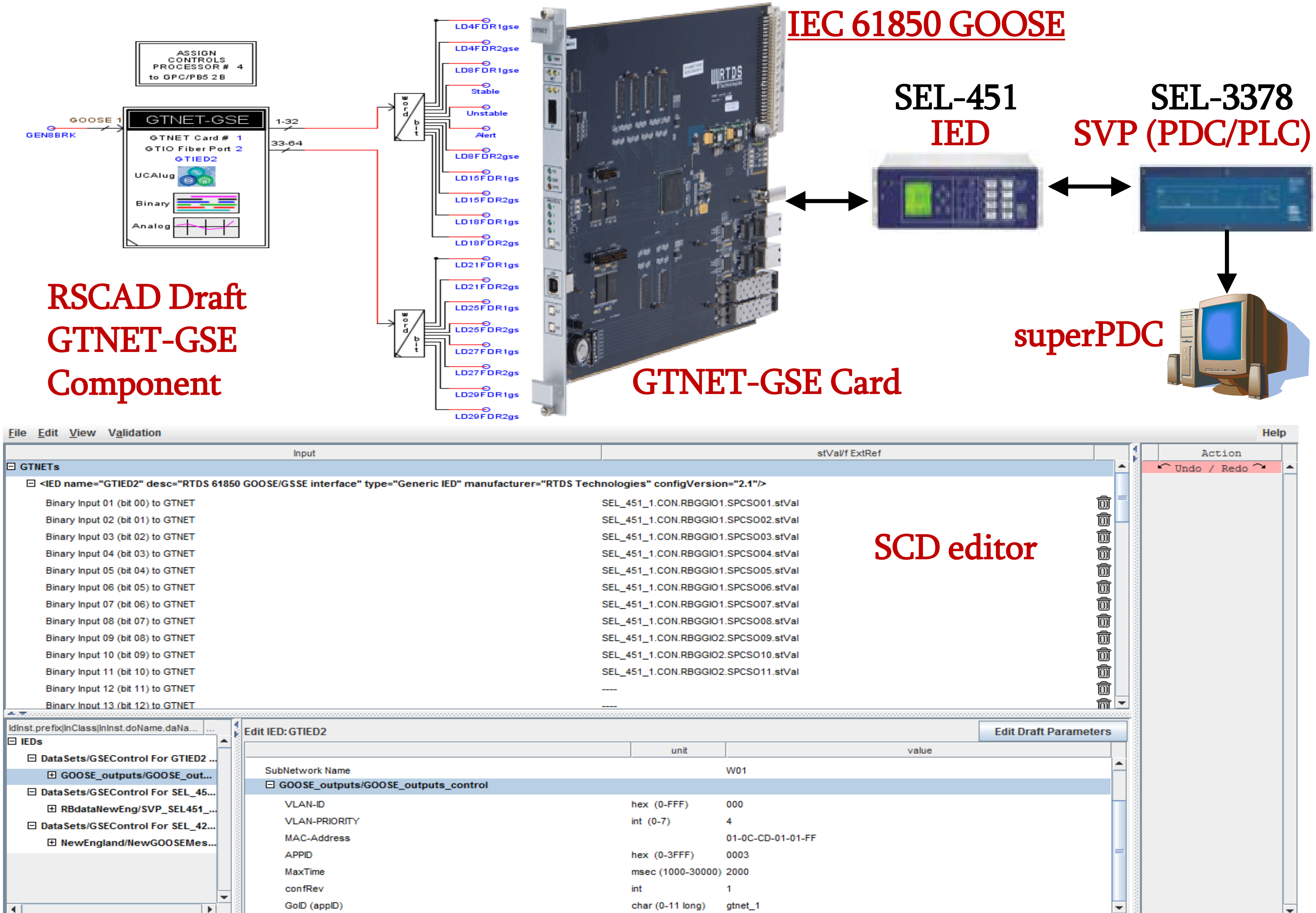


Figure 8: (a) RSCAD-GSE component; (b) RSACD SCD editor

METHODOLOGY

RSCAD Runtime

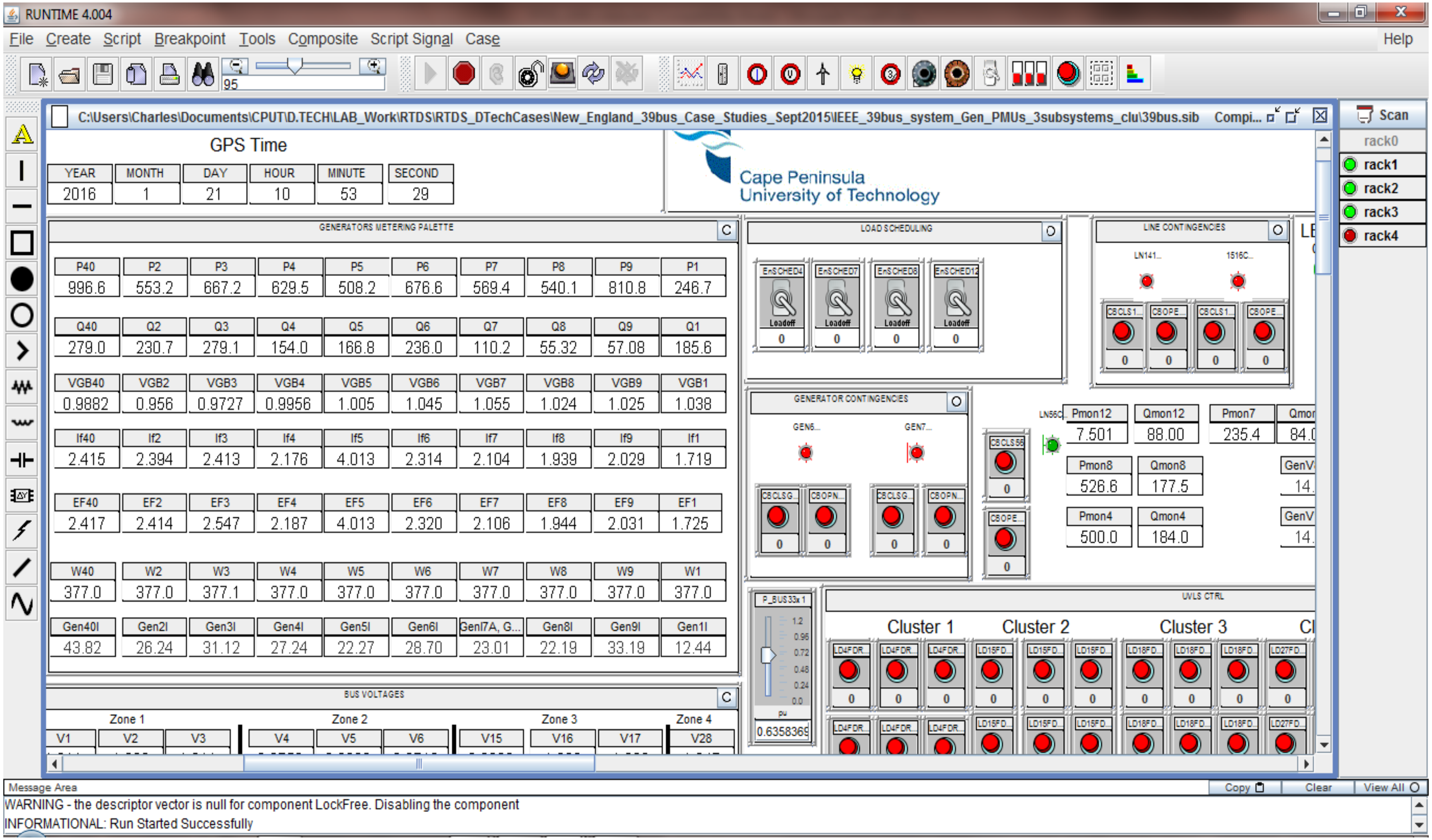


Figure 9: Runtime module with meters and controls

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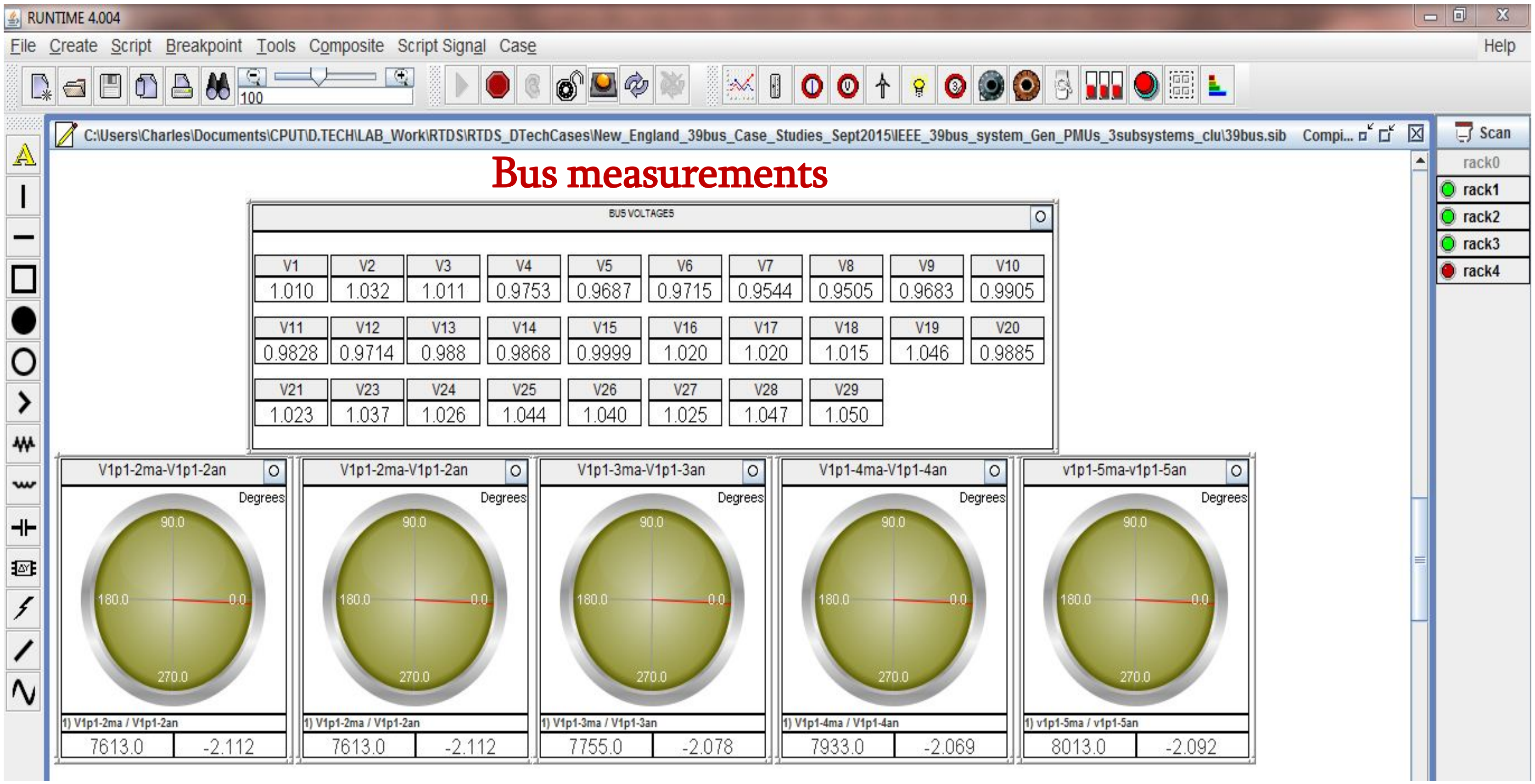
METHODOLOGY

RSCAD Runtime



PMU vector plots

Figure 10: Runtime module with meters and PMU vector plots

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EXPERIMENTAL RESULTS

Simulation: Dynamic Analyses using the RTDS

Combinations of small disturbances & large disturbances

Case Studies:

- Case Study 1: Increased system loading
- Case Study 2: *N-2* line contingencies + load increase
- Case Study 3: *N-2* generator contingencies + load increase
- Case Study 4: Load increase + transformer ULTC & Generator OXL dynamics

Dynamic Load Scheduling

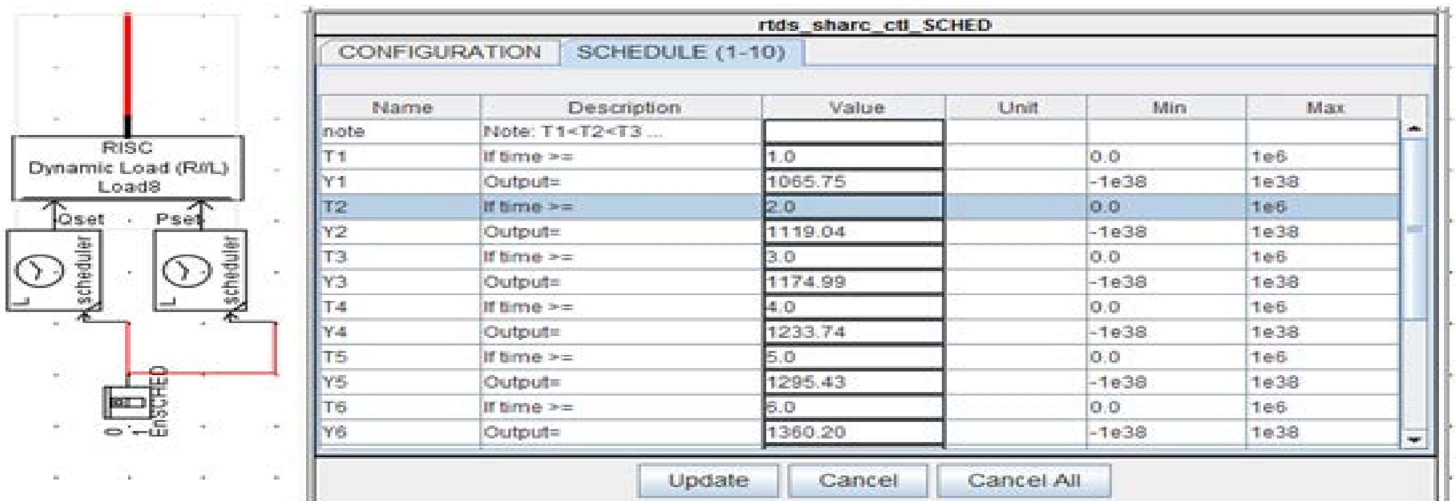

Figure 11: Real-time dynamic load scheduling

EXPERIMENTAL RESULTS

Testing with PMU Connection Tester

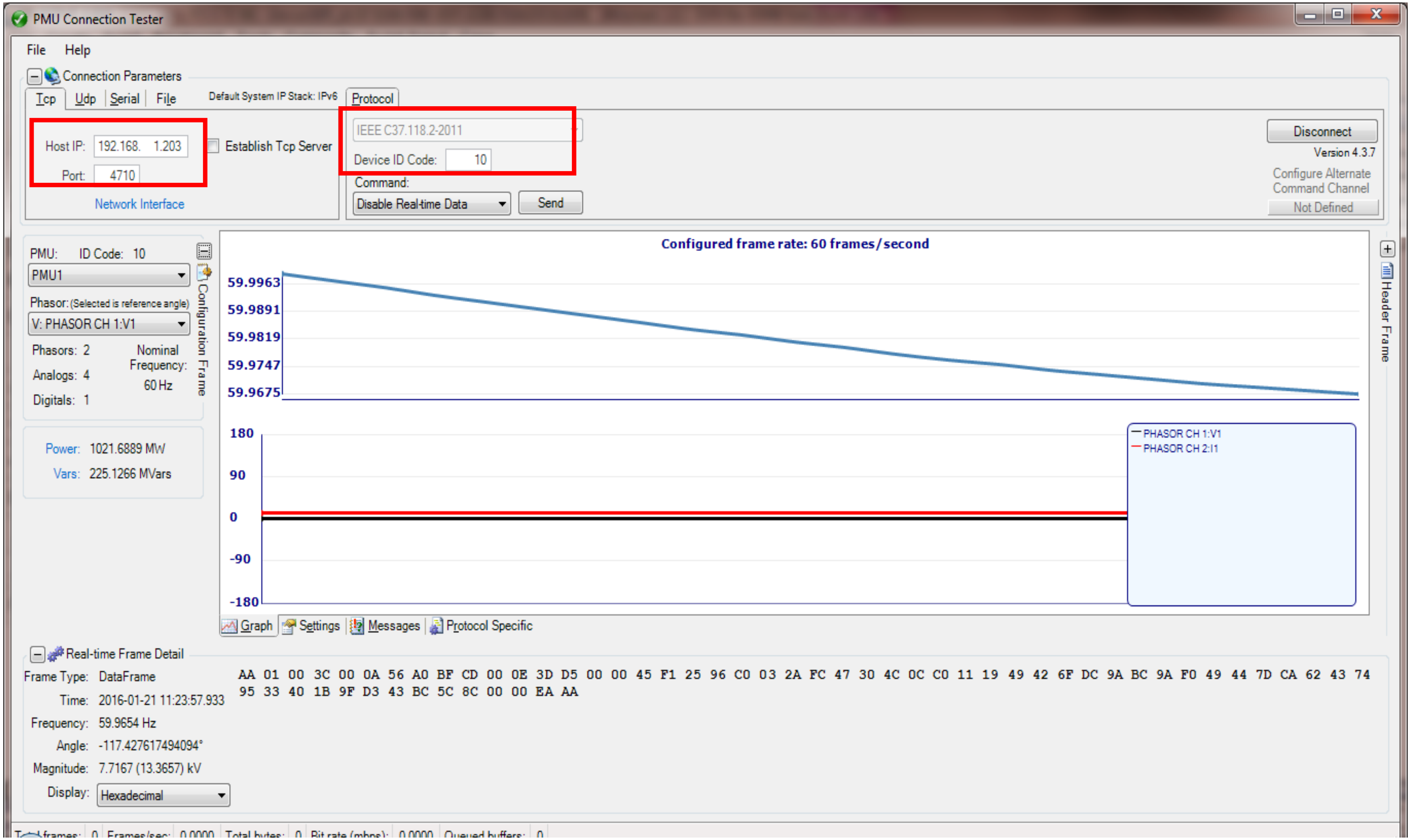

Figure 12: PMU connection testing

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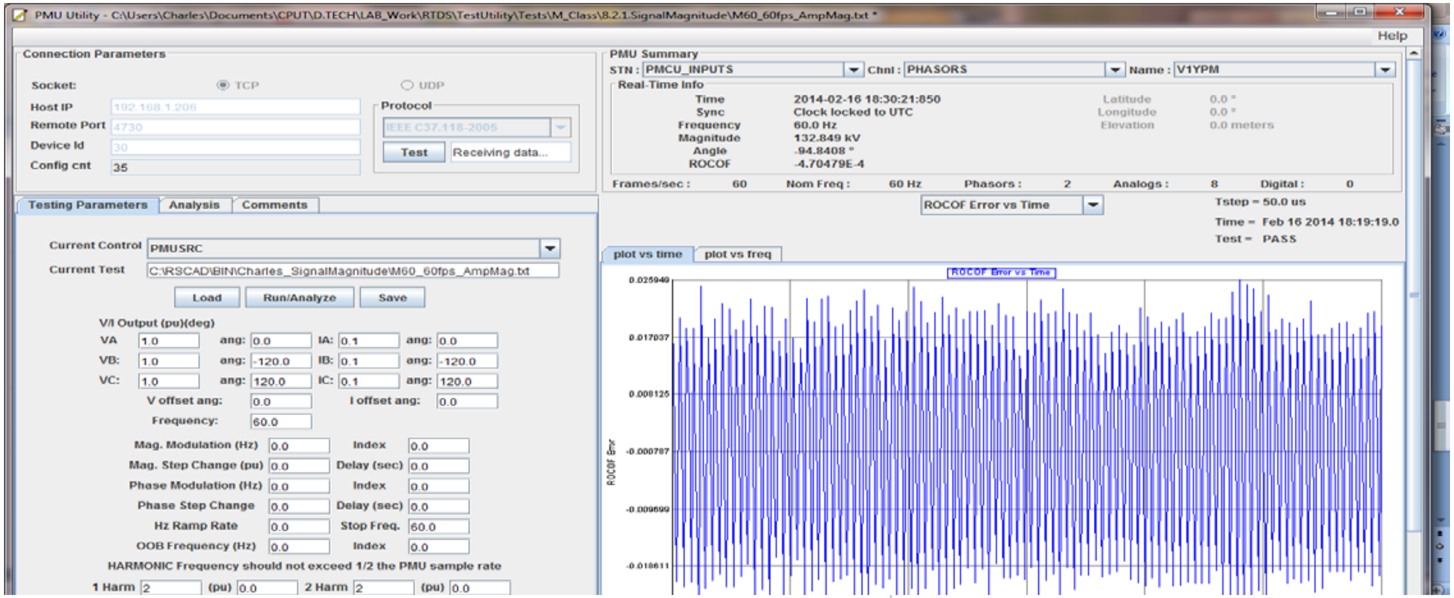
EXPERIMENTAL RESULTS

Testing with RTDS PMU Utility



TVE: 1%
FE: 0.005 Hz
RFE: 0.01 Hz/s

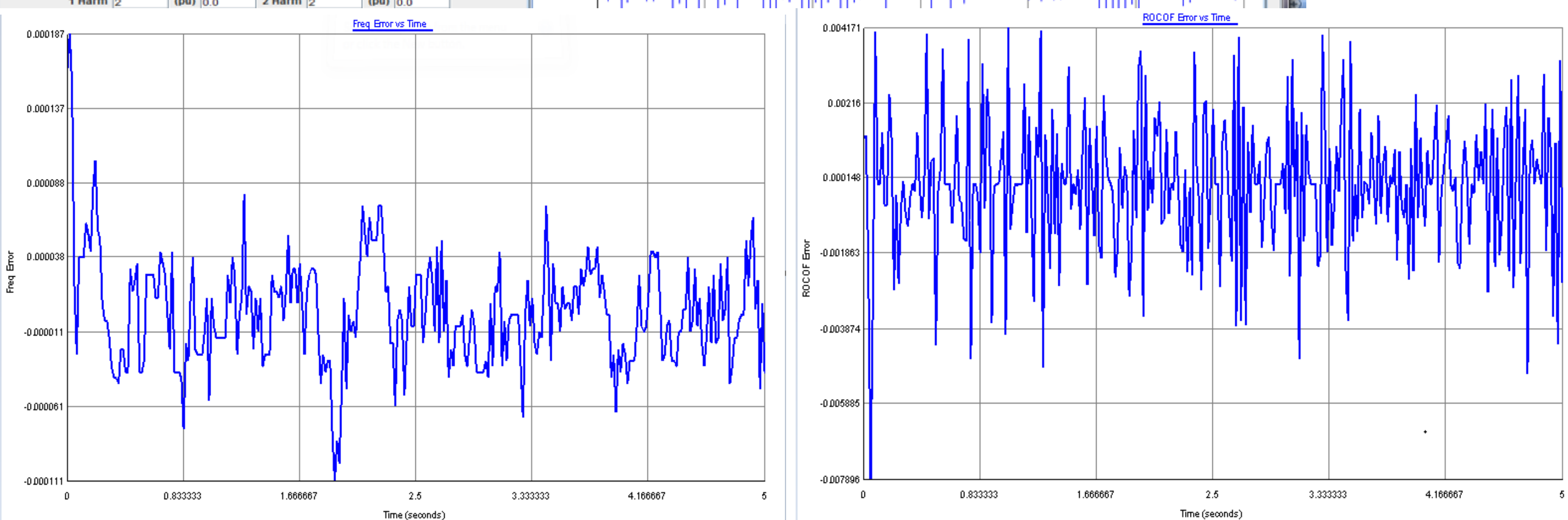


Figure 12: PMU connection testing

EXPERIMENTAL RESULTS

Ethernet Capture using Wireshark Network analyzer

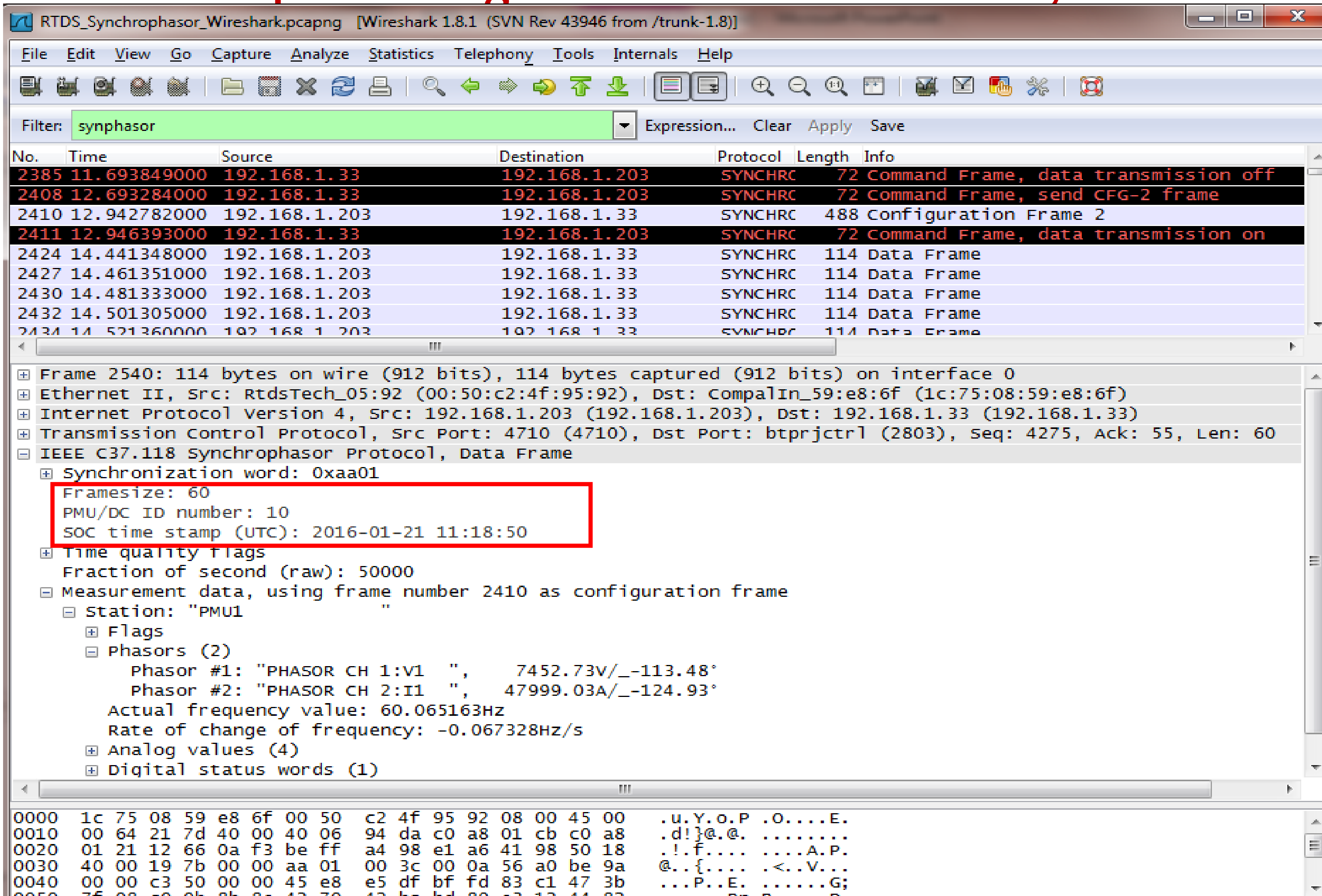


Figure 13: Synchrophasor packet sniffing using Wireshark

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EXPERIMENTAL RESULTS

Aggregation using the SEL-5070 PDC

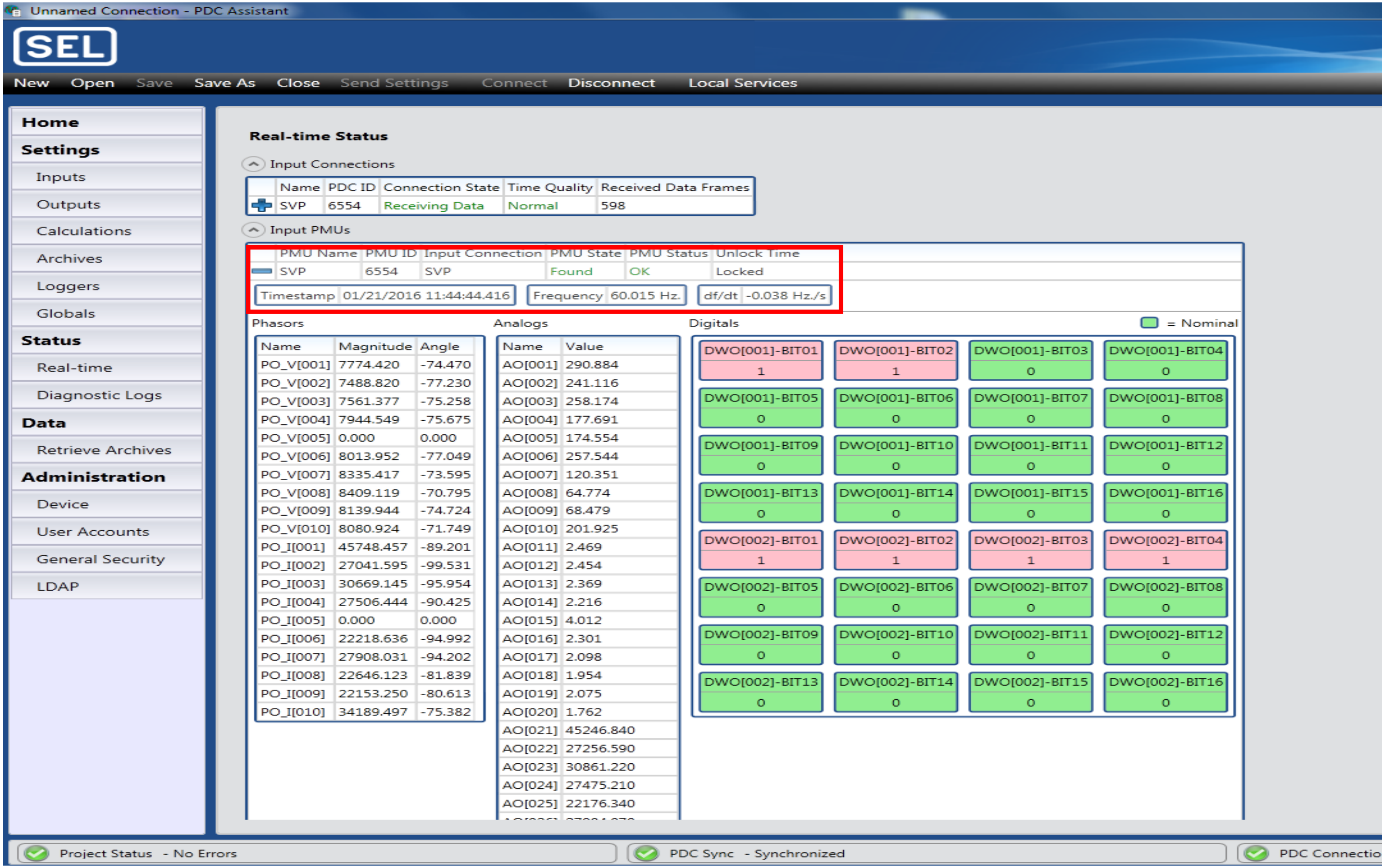

Figure 14: Aggregation of PMU measurements using the PDC

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EXPERIMENTAL RESULTS

Case Study 1

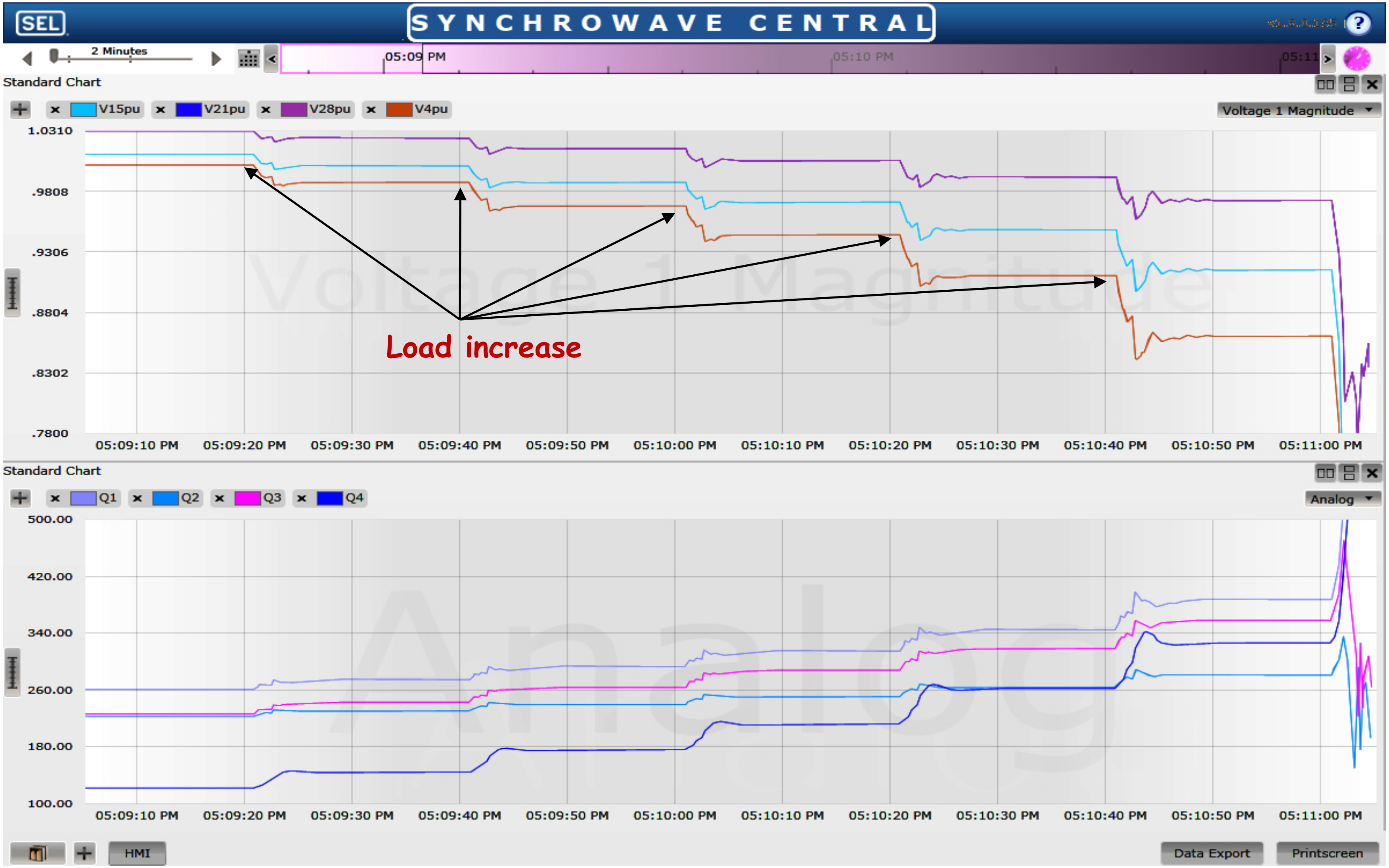

Figure 15: Case Study 1: Real-time plots of voltage phasors and generator MVAr for increased system loading

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EXPERIMENTAL RESULTS

Case Study 2

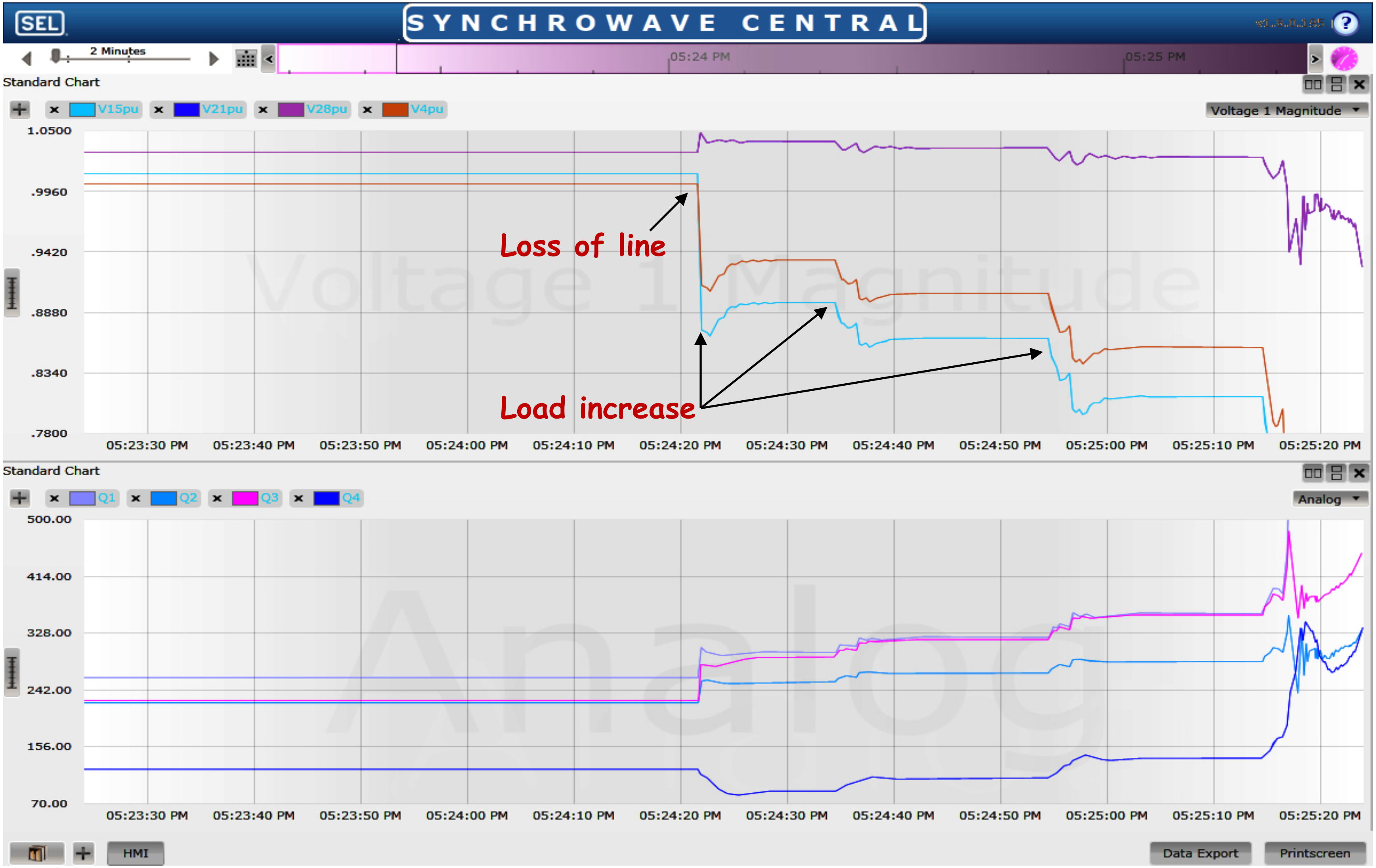

Figure 16: Case Study 2: : Real-time plots of voltage phasors and generator MVAr for *N-2* Line contingency and increased system loading

EXPERIMENTAL RESULTS

Case Study 3

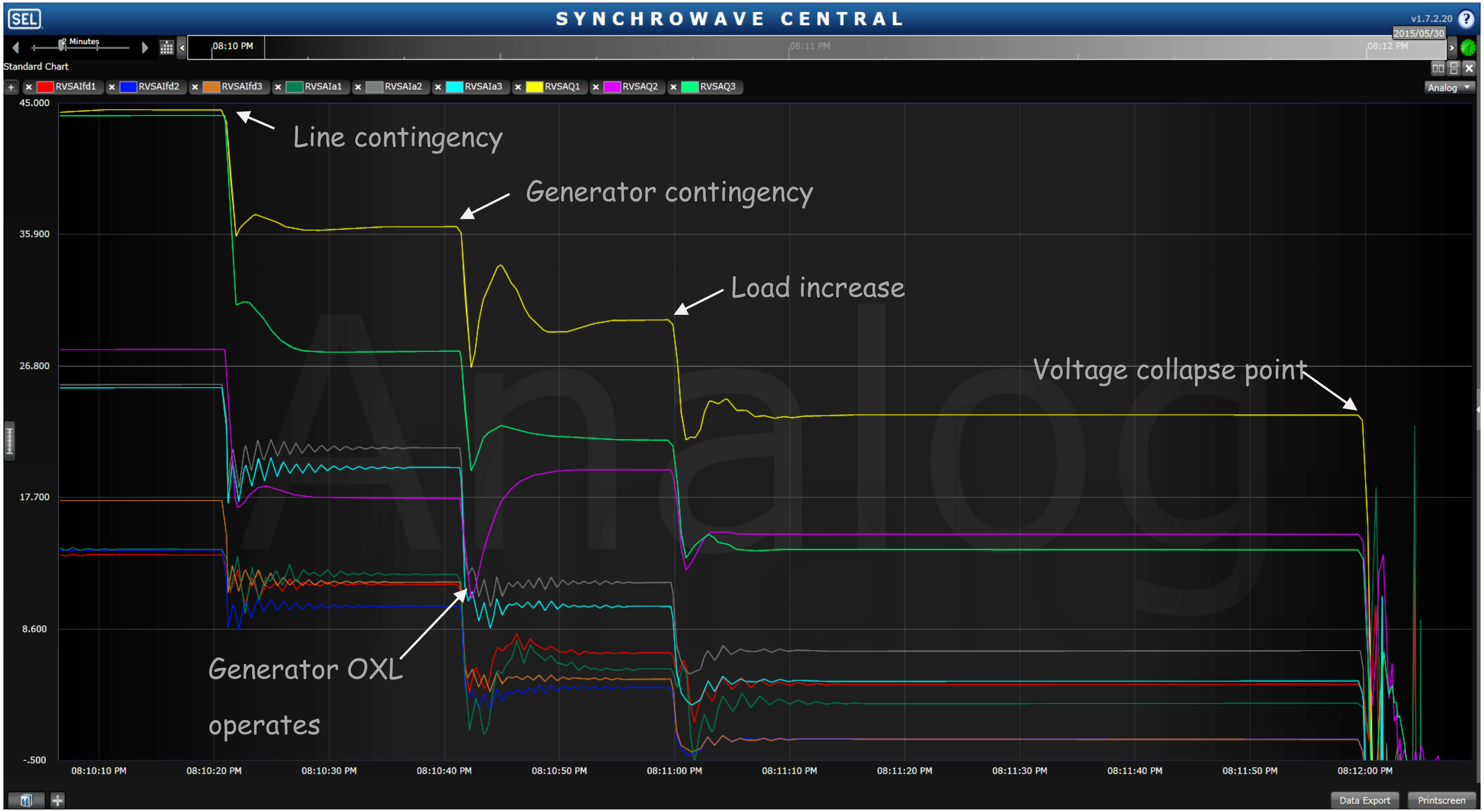

Figure 17: Case Study 3: Real-time plots of generator-derived indices for increased loading conditions, line - generator contingencies, and OXL operation

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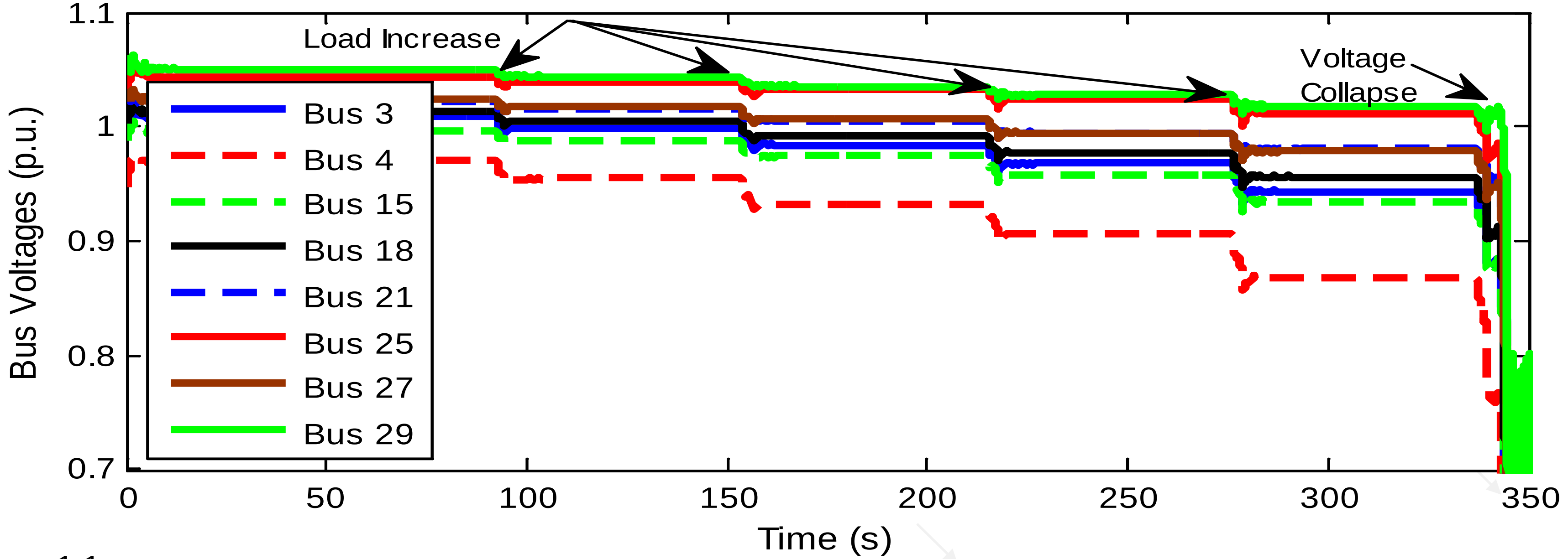
EXPERIMENTAL RESULTS



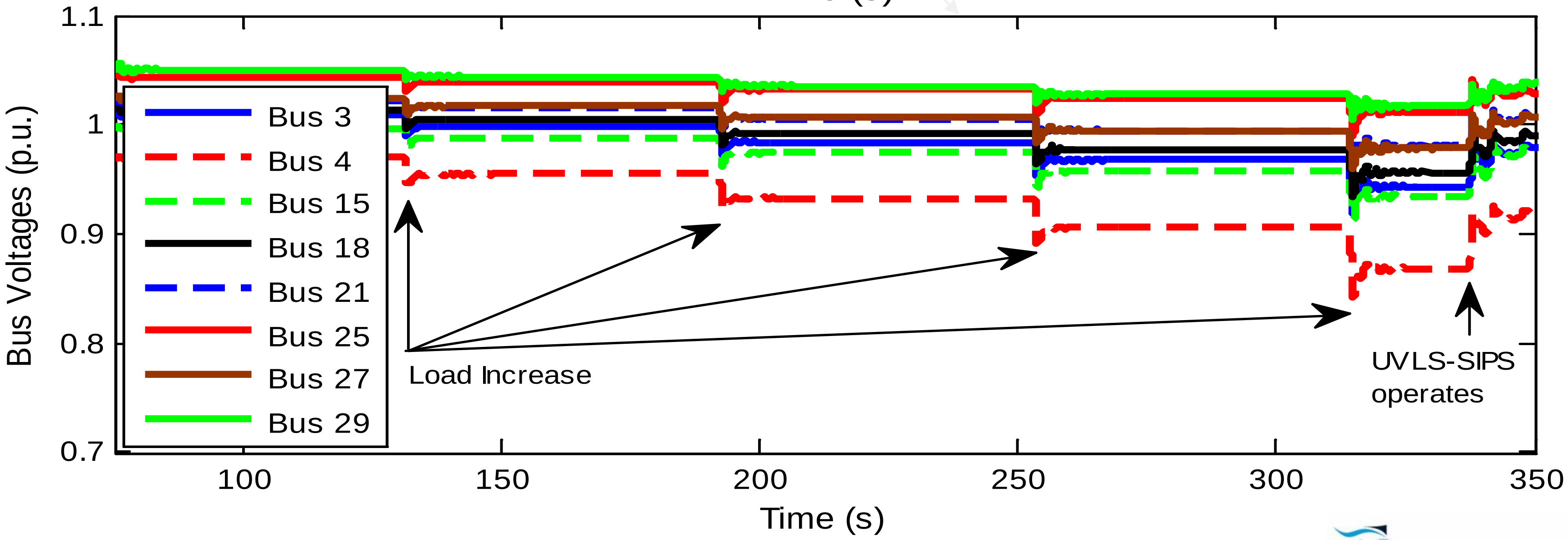
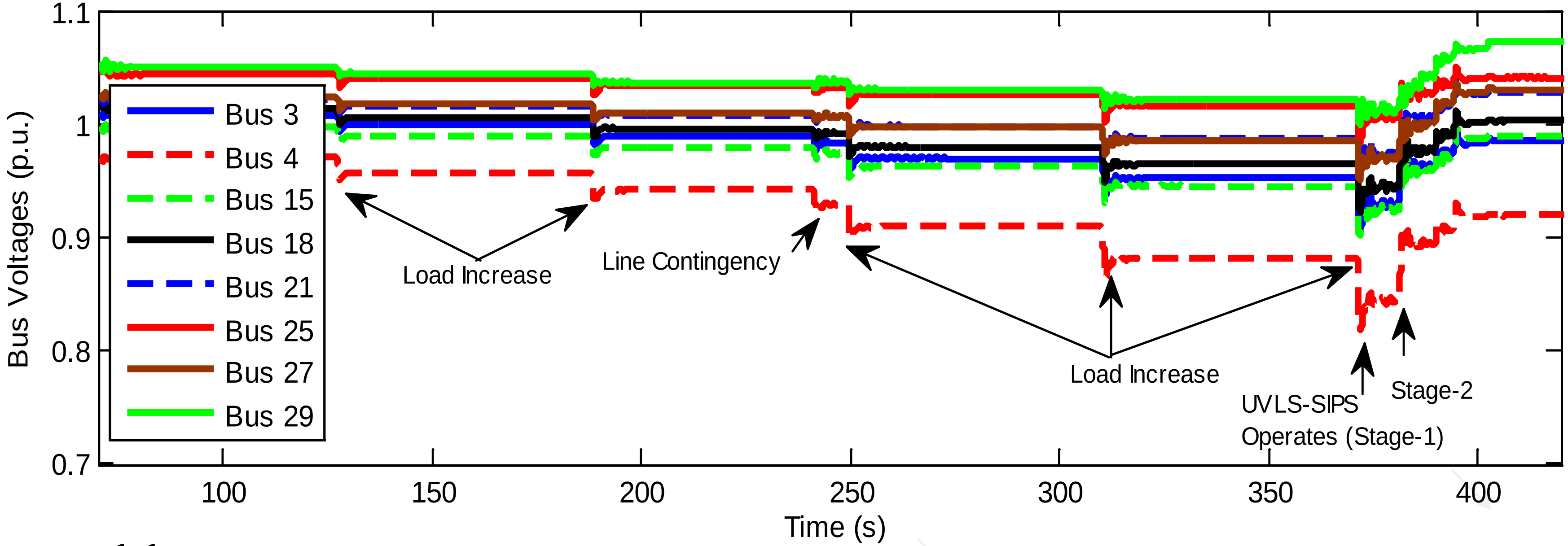


Figure 18: Increased loading (a) Without SIPS; and (b) with SIPS

EXPERIMENTAL RESULTS



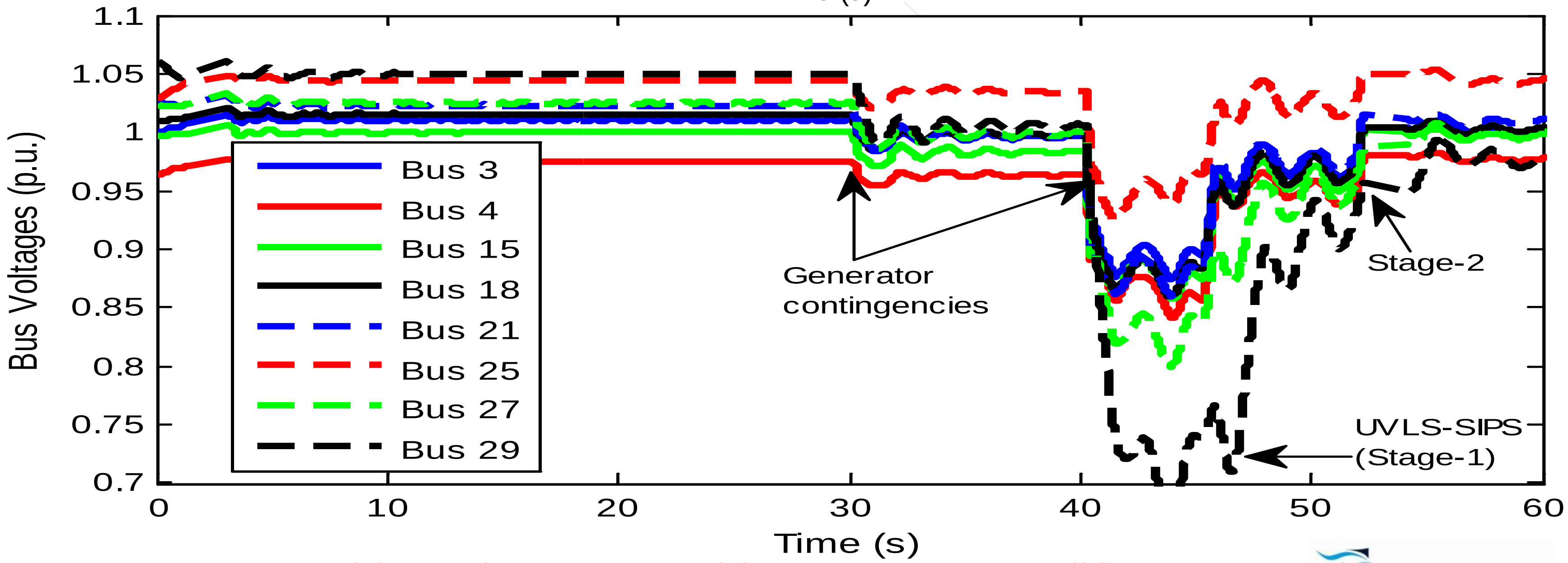


Figure 19: (a) Load increase and line contingency; (b) generator contingencies

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Department: Science and Technology
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CONCLUSION

- Three generator-derived RVSA indices based on PMU measurements
- Comparison of the various RVSA indices.
  - EGSCR index gave the best performance
  - Less sensors, less measurements,
  - ease of practical implementation

- SIPS using undervoltage load shedding
- A real-time ‘proof-of-concept’ testbed was implemented
- Future work: Impact of pervasive network conditions and cyber security in wide area applications

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Thank you

Questions?