Eastern Interconnection Phasor Project

at

Entergy

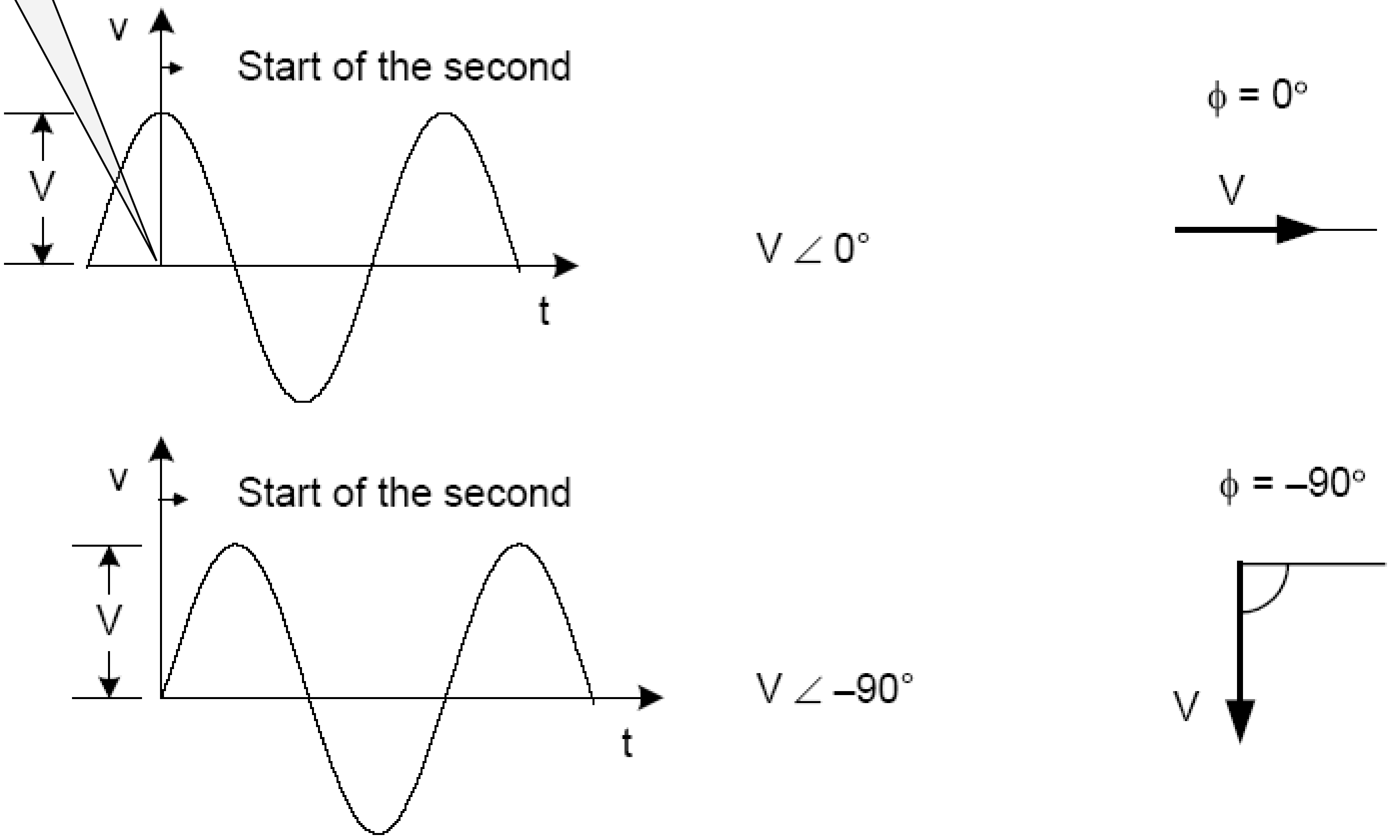
C. Wells, OSIsoft
F. Galvan, Entergy

Outline

- Phasors
- Eastern Interconnection Phasors
- Entergy's participation
- Suggested architecture

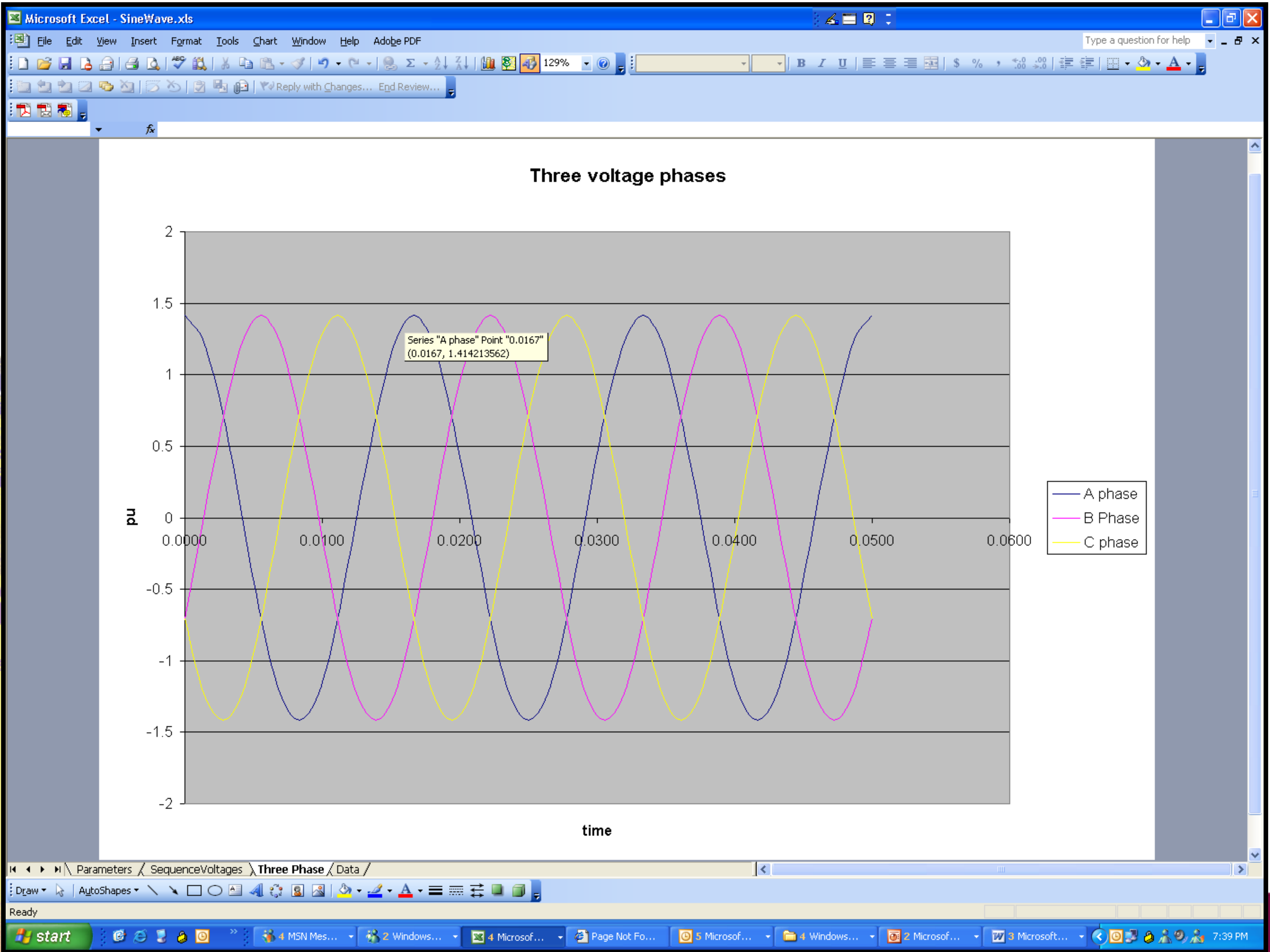
What is a Phasor(*)?

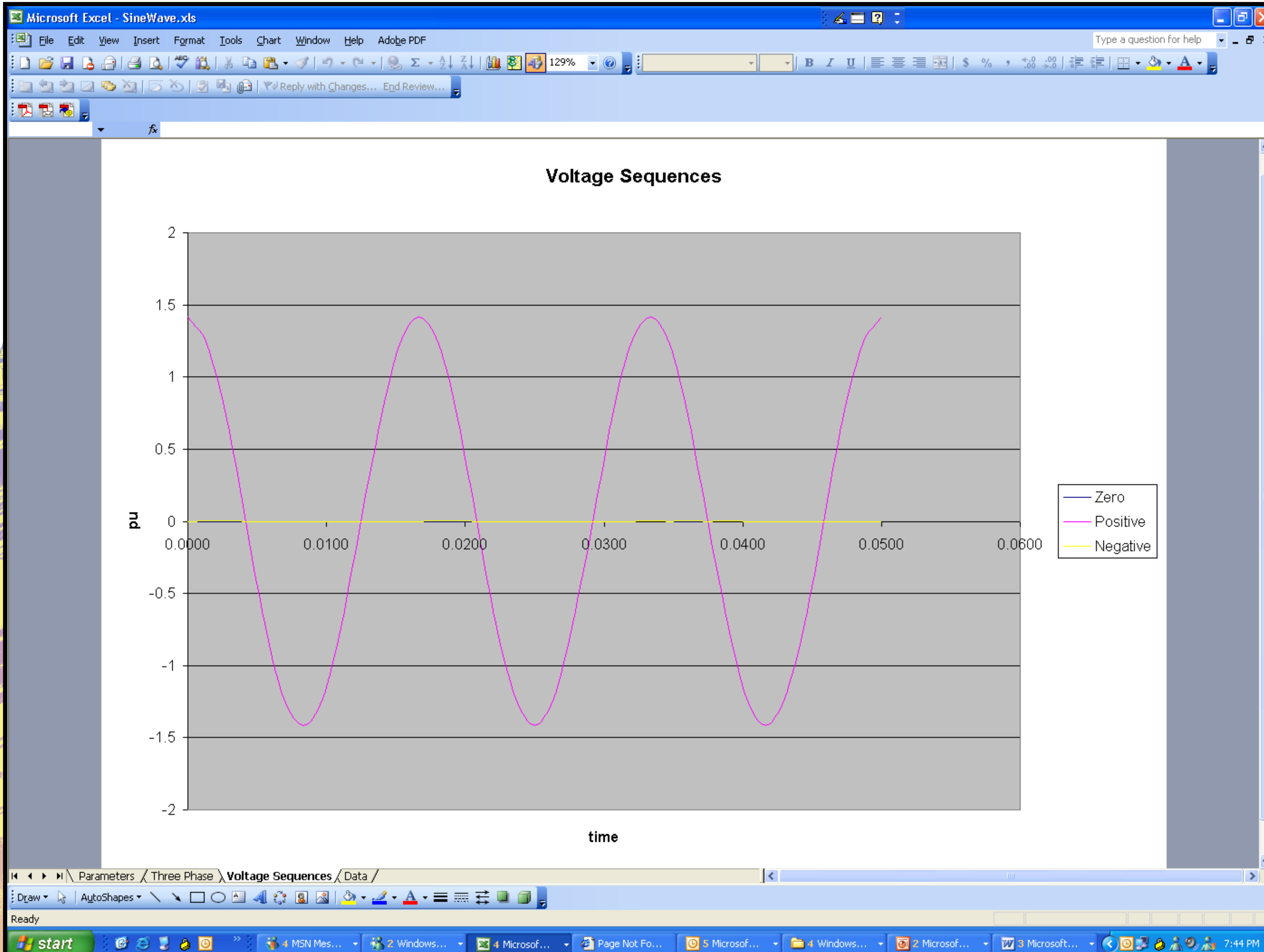
$$v = V \cdot \cos(\omega \cdot t + \phi)$$



(*) IEEE Standard 1344-1995

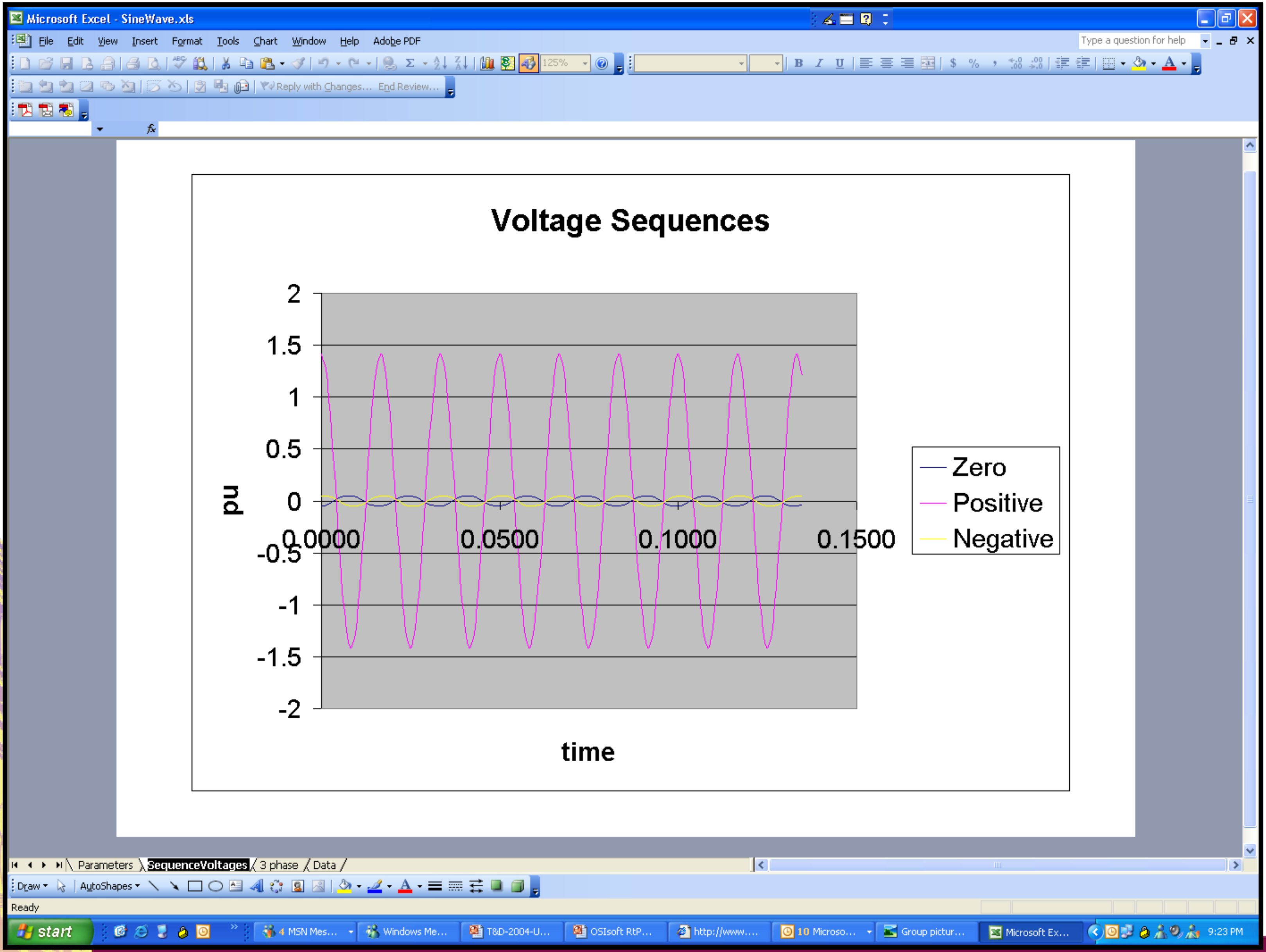
3 Phase volts





Microsoft Excel - SineWave.xls
Voltage Sequences
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
pu
0.0000
0.0100
0.0200
0.0300
0.0400
0.0500
0.0600
time
Zero
Positive
Negative
Parameters
Three Phase
Voltage Sequences
Data
Ready

B leads, C lags, 5 degrees



PMU/PDC

- Phasor Measurement Unit
  - Six inputs (3 current, 3 voltage)
  - Sample rates: 20, 30, 50, 60 Hz
  - Up to 110 output variables
- Phasor Data Concentrator
  - Handles multiple data streams
  - From multiple PMUs

History

- 1981 A. Phadke
  – Virginia Tech
- Bonneville Power
  – 1993 John Hauer, Ken Martin
- First Standard
  – 1995 IEEE 1344, reaffirmed 2001
- Next Standard
  – IEEE 37.118, soon

Father of PMUs

Prof. A. Phadke

Accuracy (Arbiter)

- Frequency ± 1 mHz (0.006 %)
- Angle ± 0.01 degrees
- Magnitudes (V,I) 0.025 %

Manufacturers

- ABB (2002)
- Arbiter (2000)
- SEL(2004?)
- Macrodyne (1995)
- Siemens
- GE

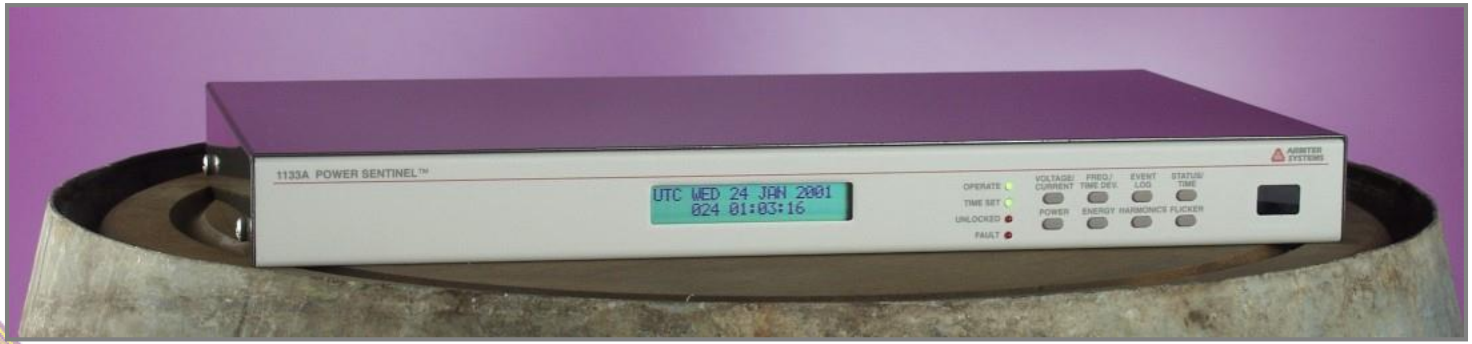
Macrodyne 1690

ABB 521

SEL 421


SEL-421
PROTECTION
AUTOMATION
CONTROL
SEL
413.8
403.8
411.4
ESC
ENT
CLOSE
TRIP

A PMU (phasor measurement unit)



Interoperablility

- All claim IEEE 1344 compatibility, but
  - Check sums not defined
  - Byte order in messages not defined
  - …

Not all are equal

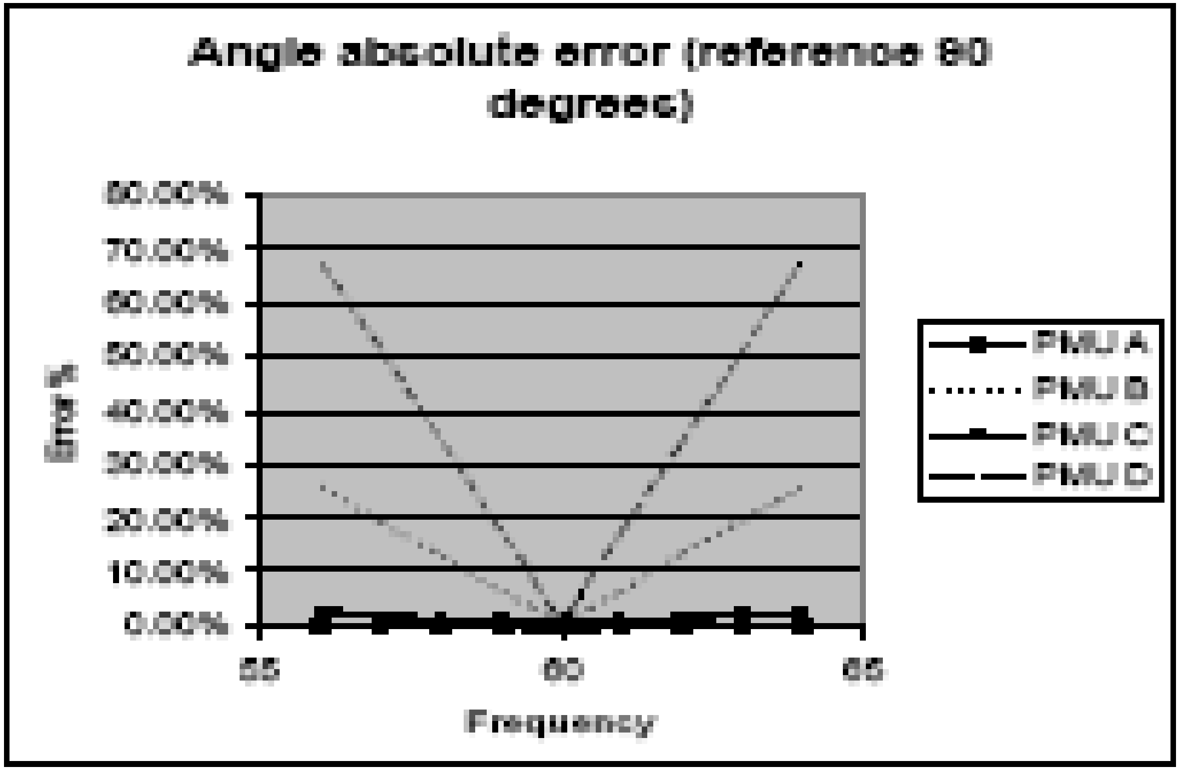
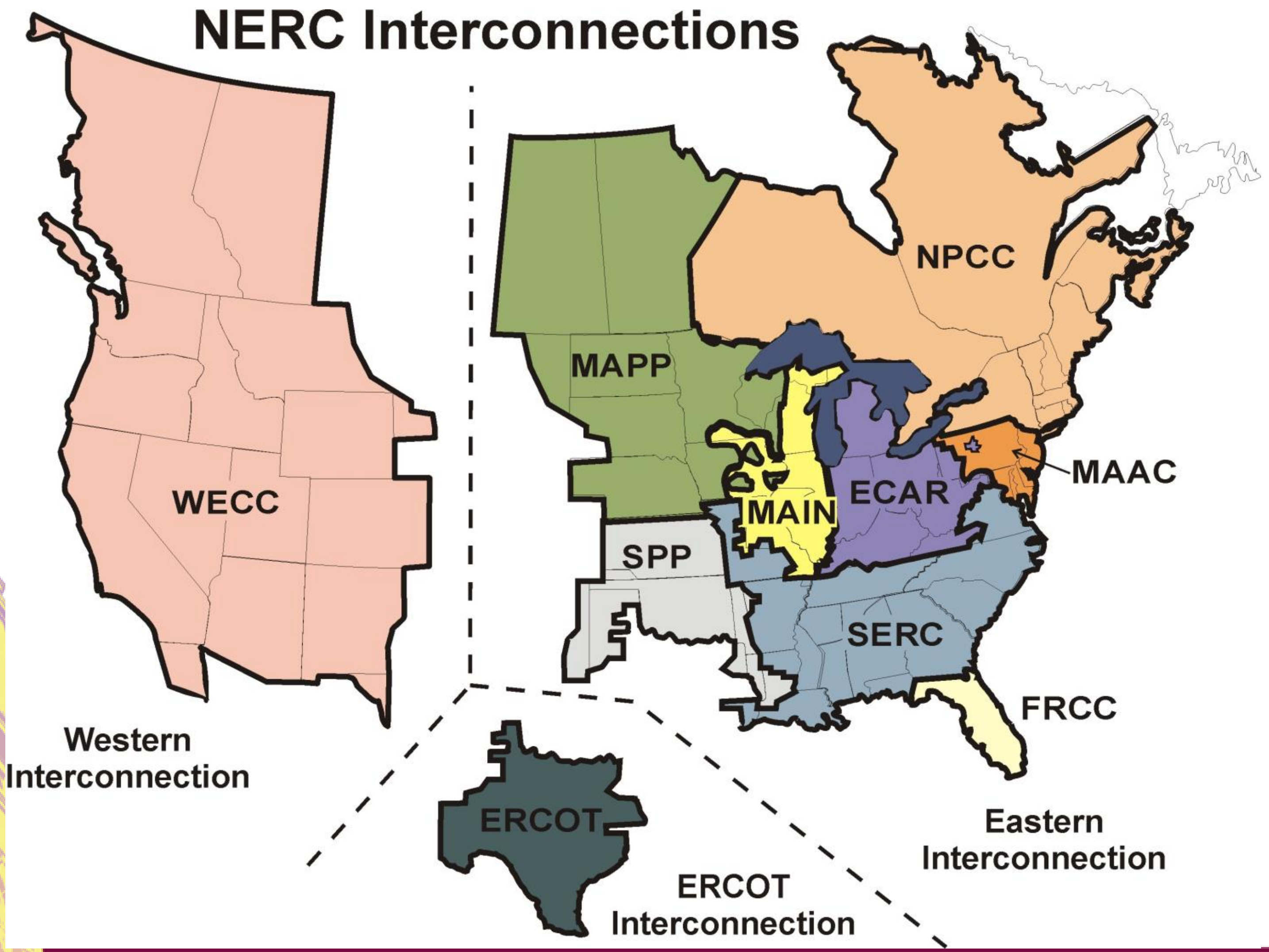


Figure 9: Variation of the Phase angle absolute error with respect to the frequency.

Quote from Summer Power Conference Paper

- "The above results reveal that even the units with proper magnitude correction algorithms yield different phase measurements at off-nominal frequencies."

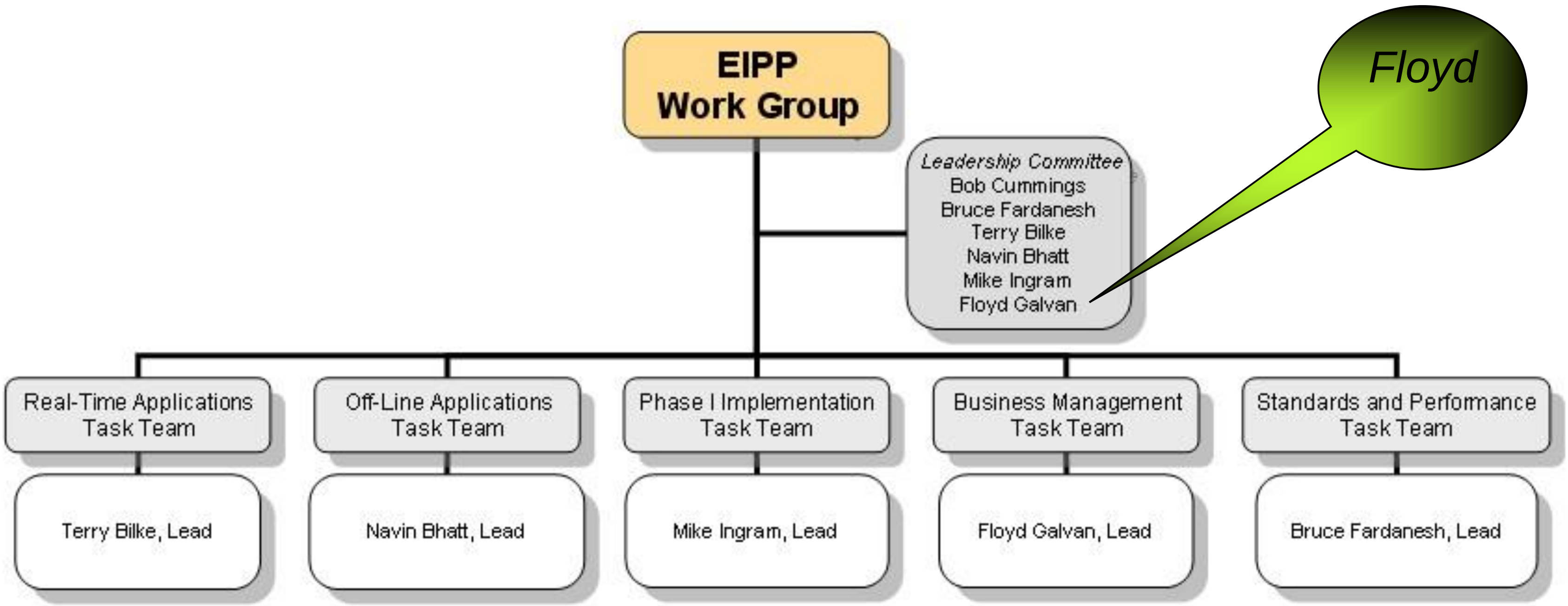
Eastern Interconnection



Eastern Interconnection Phasor Project

- **Vision Statement**
- The vision of the EIPP Work Group is to improve power system reliability through wide area measurement, monitoring and control.
- **Mission Statement**
- The Work Group's mission is to create a robust, widely available and secure synchronized data measurement infrastructure over the eastern interconnection with associated analysis and monitoring tools for better planning and operation, and improved reliability.
-

EIPP Organization



Benefits

- More comprehensive wide-area view of system
- Rapid assessment of system conditions
- Improved system models for steady-state and dynamic analysis
- Enhanced post-disturbance analysis
  - *sequence of events*
  - *what happened first*
- Power swing detection by on-line angle difference monitoring
- Increased power system performance
- Higher utilization of existing investments
- Reduced outage costs

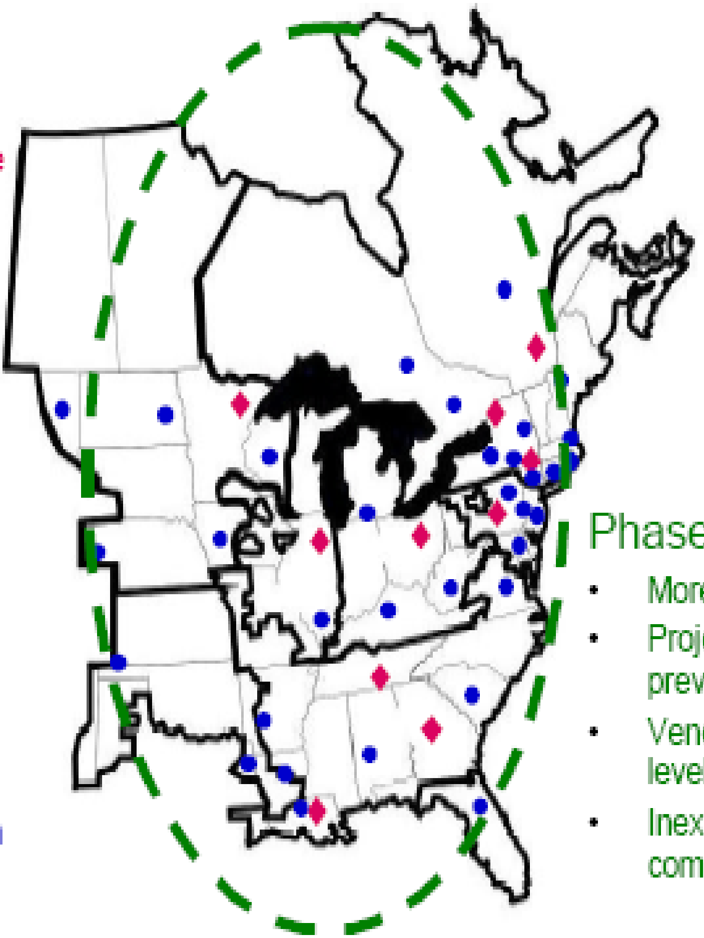
Current Plan

Phase I (2003-2004)

- 10-12 Instruments, most are already installed but not connected
- Work out communications issues
- Transfer software tools to users
- Establish relationships

Phase II (2004-2005)

- ~50 Instruments
- Immediate benefits from previous slide realized
- All major corridors covered
- Data available to research community to begin work on projected benefits



Phase III (2006-)

- More than 350 Instruments
- Projected benefits from previous slide realized
- Vendors participating at all levels
- Inexpensive instruments and communications available

Oscillations before Blackout

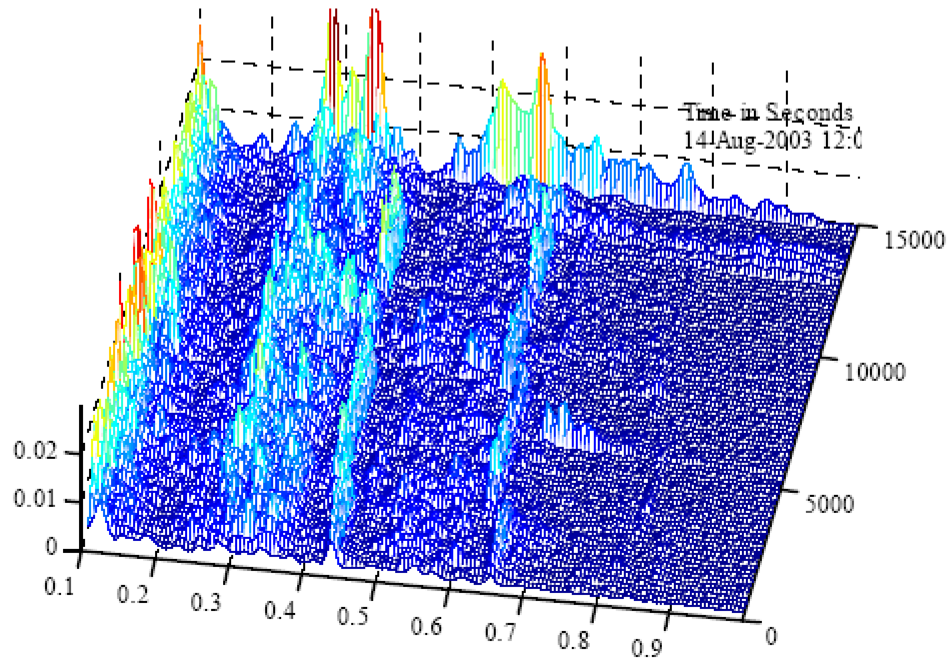


Fig. 12. Spectral history of AEP Kanawha River bus frequency for August 14 Blackout. 12:00-16:10 EDT

Oscillations before Blackout

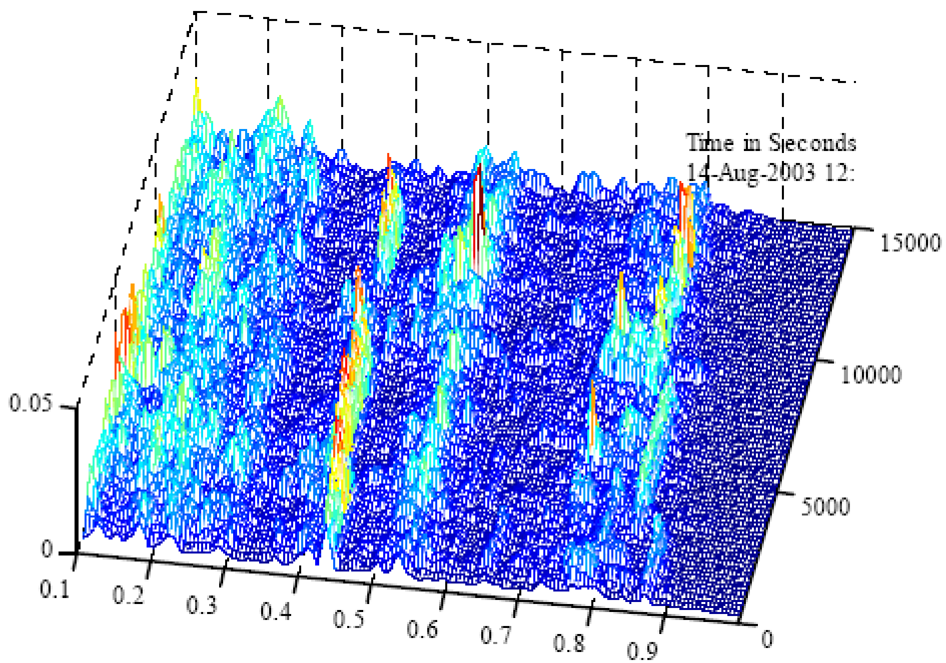
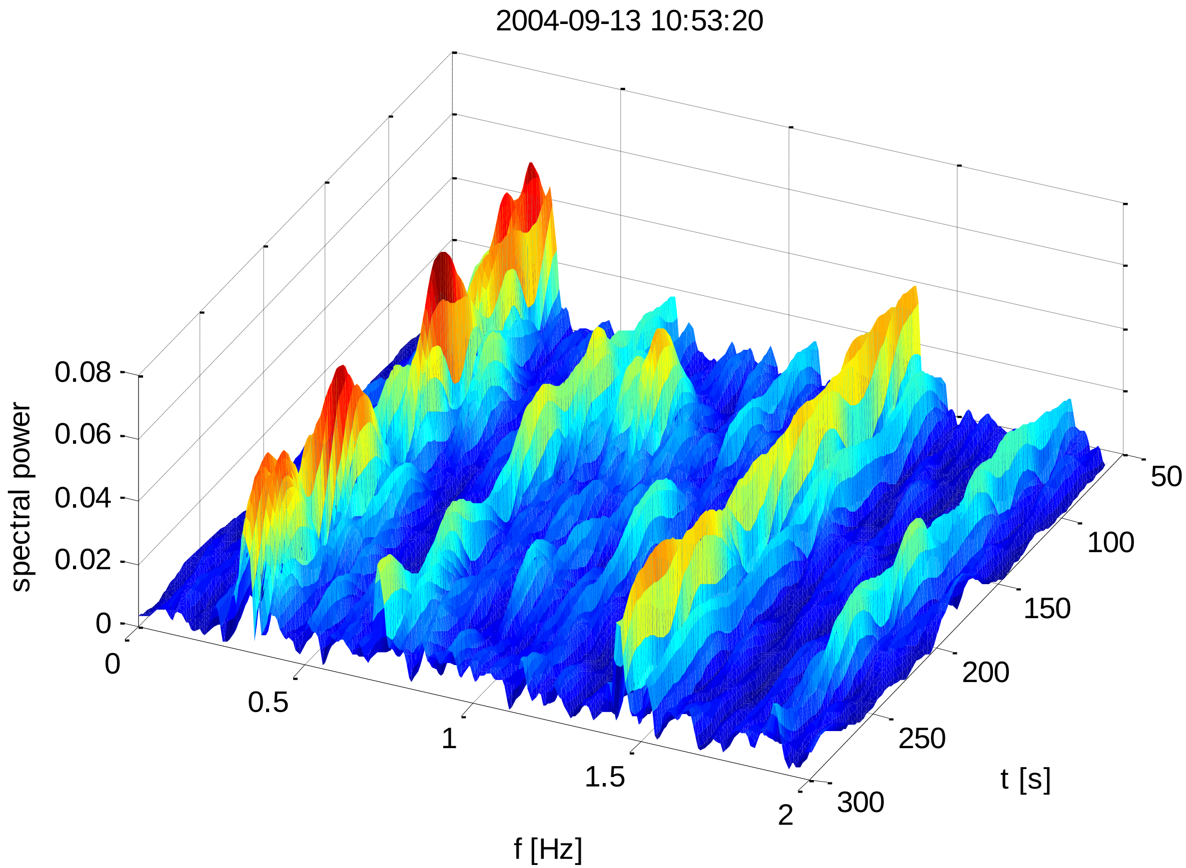


Fig. 13. Spectral history of Ameren Rush Island bus frequency for August 14 Blackout. 12:00-16:10 EDT

Oscillations in Sweden



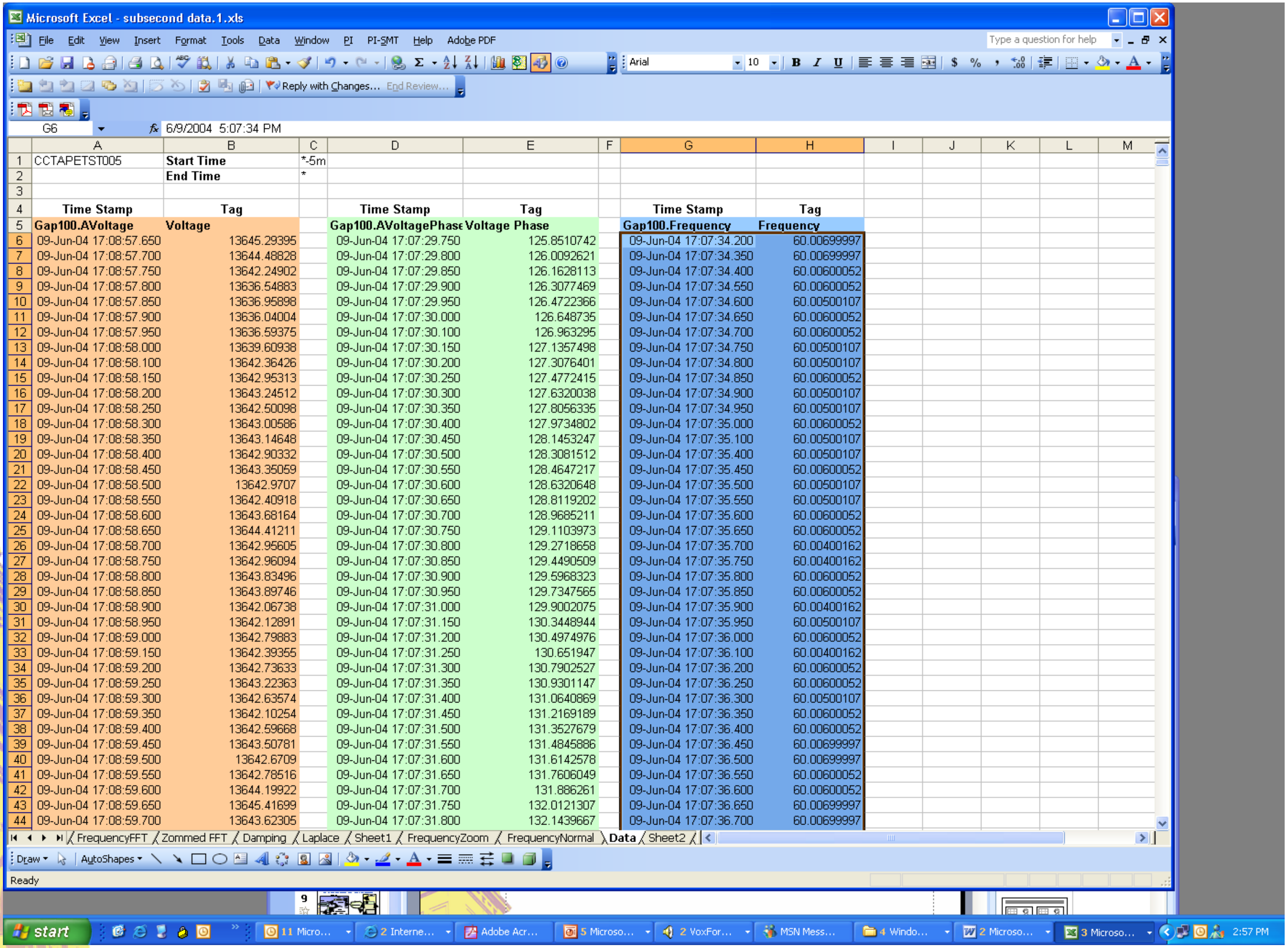
EIPP
at Entergy

- 10 PMU (Phasor Measurement Unit)
- 1 PDC (Phasor Data Concentrator)
- 10 PMU (Black start generators)

Phasor Measurements

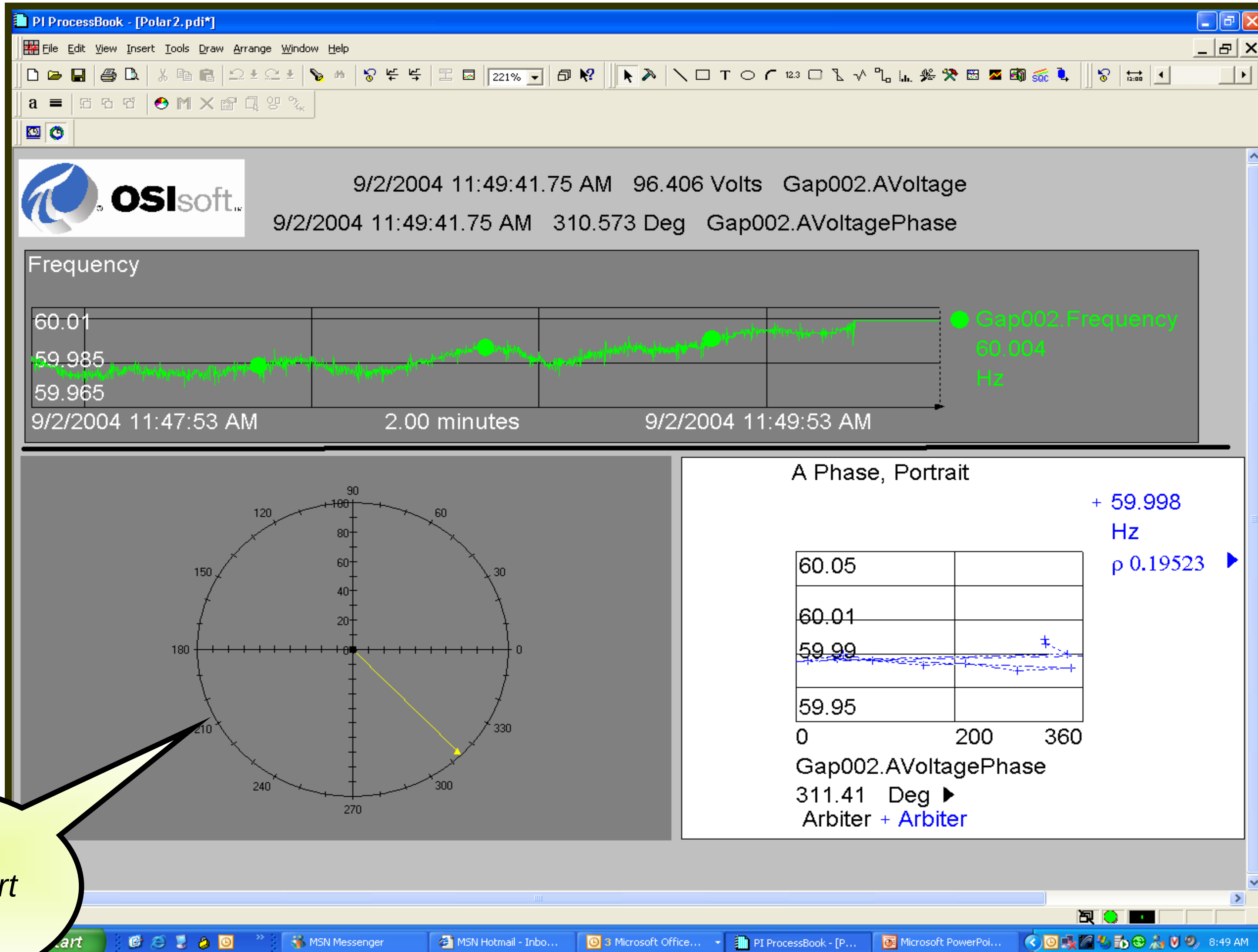
[Link]

Datalink



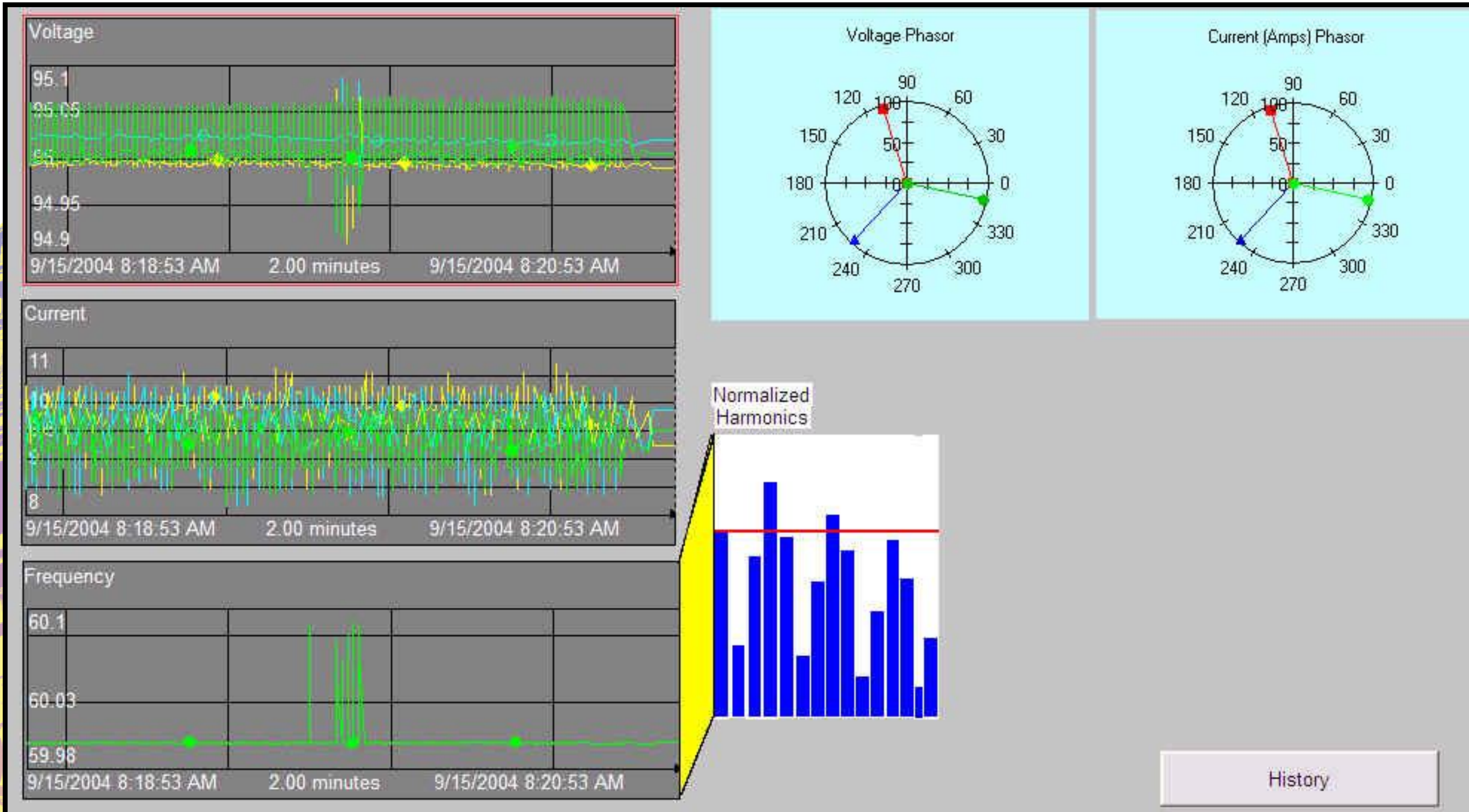
	A	B	C	D	E	F	G	H
1	CCTAPETST005	Start Time	*-5m					
2		End Time	*					
3								
4	Time Stamp	Tag		Time Stamp	Tag		Time Stamp	Tag
5	Gap100.AVoltage	Voltage		Gap100.AVoltagePhase	Voltage Phase		Gap100.Frequency	Frequency
6	09-Jun-04 17:08:57.650	13645.29395		09-Jun-04 17:07:29.750	125.8510742		09-Jun-04 17:07:34.200	60.00699997
7	09-Jun-04 17:08:57.700	13644.48828		09-Jun-04 17:07:29.800	126.0092621		09-Jun-04 17:07:34.350	60.00699997
8	09-Jun-04 17:08:57.750	13642.24902		09-Jun-04 17:07:29.850	126.1628113		09-Jun-04 17:07:34.400	60.00600052
9	09-Jun-04 17:08:57.800	13636.54883		09-Jun-04 17:07:29.900	126.3077469		09-Jun-04 17:07:34.550	60.00600052
10	09-Jun-04 17:08:57.850	13636.95898		09-Jun-04 17:07:29.950	126.4722366		09-Jun-04 17:07:34.600	60.00500107
11	09-Jun-04 17:08:57.900	13636.04004		09-Jun-04 17:07:30.000	126.648735		09-Jun-04 17:07:34.650	60.00600052
12	09-Jun-04 17:08:57.950	13636.59375		09-Jun-04 17:07:30.100	126.963295		09-Jun-04 17:07:34.700	60.00600052
13	09-Jun-04 17:08:58.000	13639.60938		09-Jun-04 17:07:30.150	127.1357498		09-Jun-04 17:07:34.750	60.00500107
14	09-Jun-04 17:08:58.100	13642.36426		09-Jun-04 17:07:30.200	127.3076401		09-Jun-04 17:07:34.800	60.00500107
15	09-Jun-04 17:08:58.150	13642.95313		09-Jun-04 17:07:30.250	127.4772415		09-Jun-04 17:07:34.850	60.00600052
16	09-Jun-04 17:08:58.200	13643.24512		09-Jun-04 17:07:30.300	127.6320038		09-Jun-04 17:07:34.900	60.00500107
17	09-Jun-04 17:08:58.250	13642.50098		09-Jun-04 17:07:30.350	127.8056335		09-Jun-04 17:07:34.950	60.00500107
18	09-Jun-04 17:08:58.300	13643.00586		09-Jun-04 17:07:30.400	127.9734802		09-Jun-04 17:07:35.000	60.00600052
19	09-Jun-04 17:08:58.350	13643.14648		09-Jun-04 17:07:30.450	128.1453247		09-Jun-04 17:07:35.100	60.00500107
20	09-Jun-04 17:08:58.400	13642.90332		09-Jun-04 17:07:30.500	128.3081512		09-Jun-04 17:07:35.400	60.00500107
21	09-Jun-04 17:08:58.450	13643.35059		09-Jun-04 17:07:30.550	128.4647217		09-Jun-04 17:07:35.450	60.00600052
22	09-Jun-04 17:08:58.500	13642.9707		09-Jun-04 17:07:30.600	128.6320648		09-Jun-04 17:07:35.500	60.00500107
23	09-Jun-04 17:08:58.550	13642.40918		09-Jun-04 17:07:30.650	128.8119202		09-Jun-04 17:07:35.550	60.00500107
24	09-Jun-04 17:08:58.600	13643.68164		09-Jun-04 17:07:30.700	128.9685211		09-Jun-04 17:07:35.600	60.00600052
25	09-Jun-04 17:08:58.650	13644.41211		09-Jun-04 17:07:30.750	129.1103973		09-Jun-04 17:07:35.650	60.00600052
26	09-Jun-04 17:08:58.700	13642.95605		09-Jun-04 17:07:30.800	129.2718658		09-Jun-04 17:07:35.700	60.00400162
27	09-Jun-04 17:08:58.750	13642.96094		09-Jun-04 17:07:30.850	129.4490509		09-Jun-04 17:07:35.750	60.00400162
28	09-Jun-04 17:08:58.800	13643.83496		09-Jun-04 17:07:30.900	129.5968323		09-Jun-04 17:07:35.800	60.00600052
29	09-Jun-04 17:08:58.850	13643.89746		09-Jun-04 17:07:30.950	129.7347565		09-Jun-04 17:07:35.850	60.00600052
30	09-Jun-04 17:08:58.900	13642.06738		09-Jun-04 17:07:31.000	129.9002075		09-Jun-04 17:07:35.900	60.00400162
31	09-Jun-04 17:08:58.950	13642.12891		09-Jun-04 17:07:31.150	130.3448944		09-Jun-04 17:07:35.950	60.00500107
32	09-Jun-04 17:08:59.000	13642.79883		09-Jun-04 17:07:31.200	130.4974976		09-Jun-04 17:07:36.000	60.00600052
33	09-Jun-04 17:08:59.150	13642.39355		09-Jun-04 17:07:31.250	130.651947		09-Jun-04 17:07:36.100	60.00400162
34	09-Jun-04 17:08:59.200	13642.73633		09-Jun-04 17:07:31.300	130.7902527		09-Jun-04 17:07:36.200	60.00600052
35	09-Jun-04 17:08:59.250	13643.22363		09-Jun-04 17:07:31.350	130.9301147		09-Jun-04 17:07:36.250	60.00600052
36	09-Jun-04 17:08:59.300	13642.63574		09-Jun-04 17:07:31.400	131.0640869		09-Jun-04 17:07:36.300	60.00500107
37	09-Jun-04 17:08:59.350	13642.10254		09-Jun-04 17:07:31.450	131.2169189		09-Jun-04 17:07:36.350	60.00600052
38	09-Jun-04 17:08:59.400	13642.59668		09-Jun-04 17:07:31.500	131.3527679		09-Jun-04 17:07:36.400	60.00600052
39	09-Jun-04 17:08:59.450	13643.50781		09-Jun-04 17:07:31.550	131.4845886		09-Jun-04 17:07:36.450	60.00699997
40	09-Jun-04 17:08:59.500	13642.6709		09-Jun-04 17:07:31.600	131.6142578		09-Jun-04 17:07:36.500	60.00699997
41	09-Jun-04 17:08:59.550	13642.78516		09-Jun-04 17:07:31.650	131.7606049		09-Jun-04 17:07:36.550	60.00600052
42	09-Jun-04 17:08:59.600	13644.19922		09-Jun-04 17:07:31.700	131.886261		09-Jun-04 17:07:36.600	60.00600052
43	09-Jun-04 17:08:59.650	13645.41699		09-Jun-04 17:07:31.750	132.0121307		09-Jun-04 17:07:36.650	60.00699997
44	09-Jun-04 17:08:59.700	13643.62305		09-Jun-04 17:07:31.800	132.1439667		09-Jun-04 17:07:36.700	60.00699997

Typical ProcessBook display

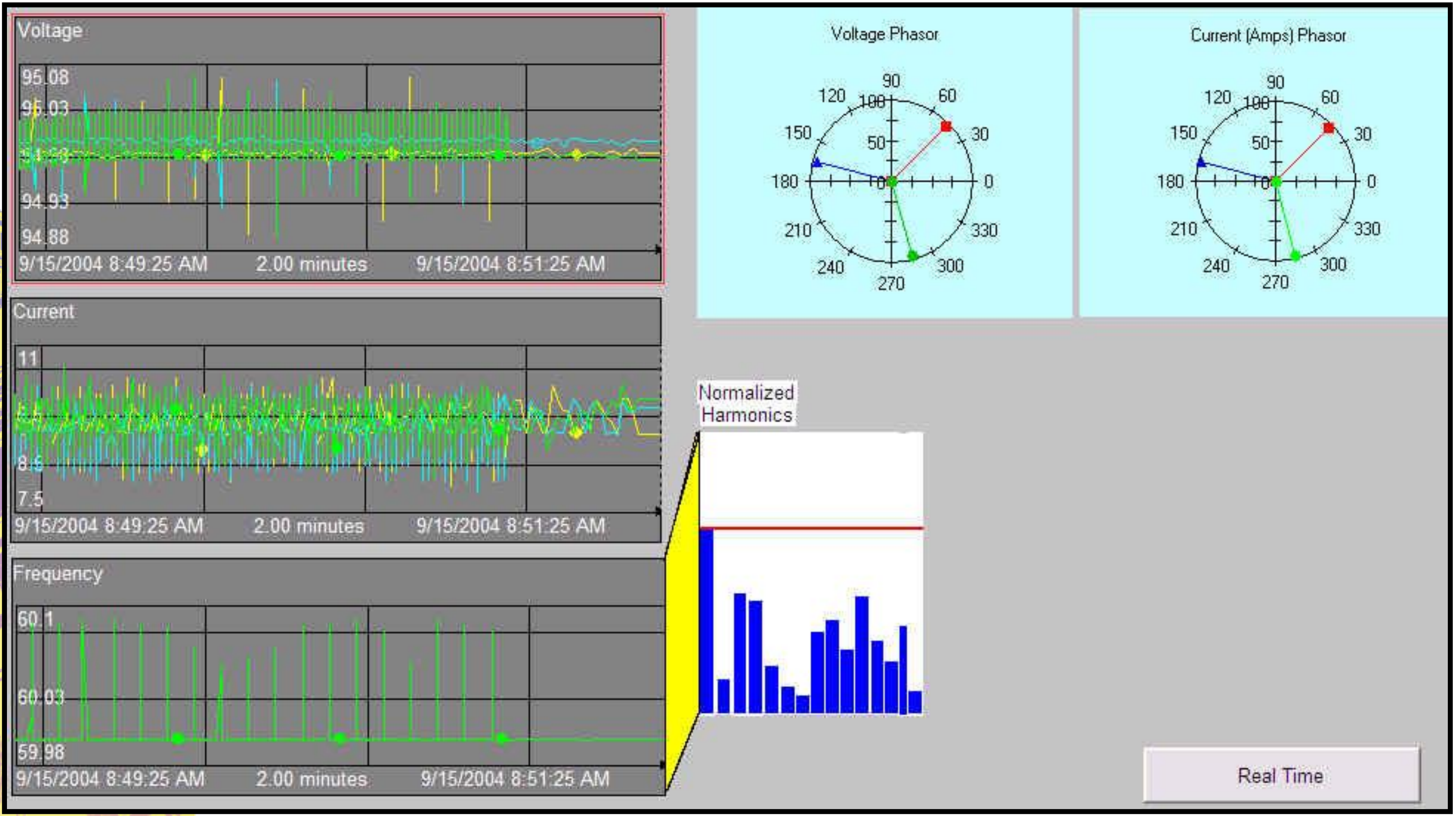


SISCO
Polar Chart
OCX

SISCO – GAP Displays

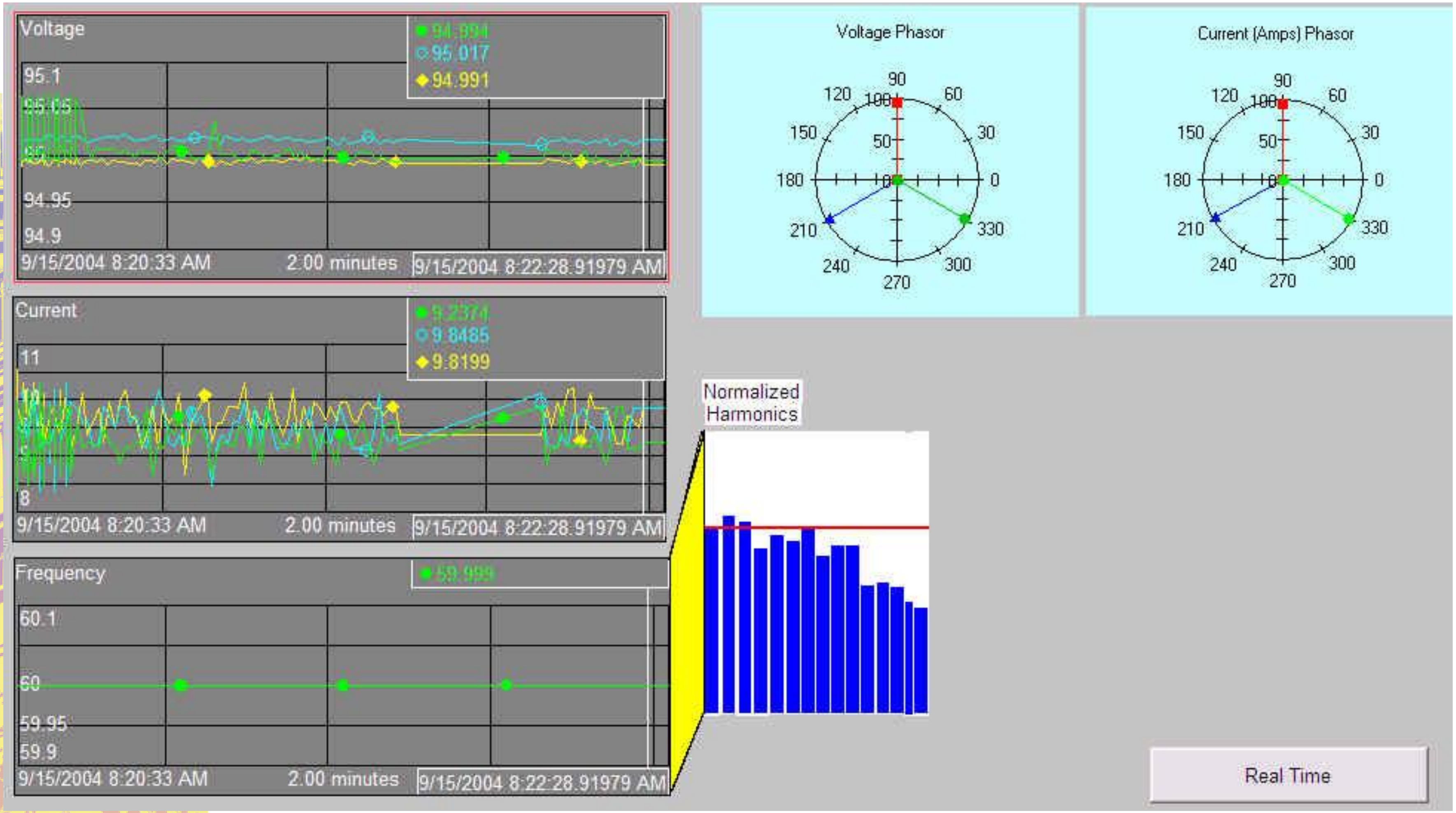


SISCO-GAP



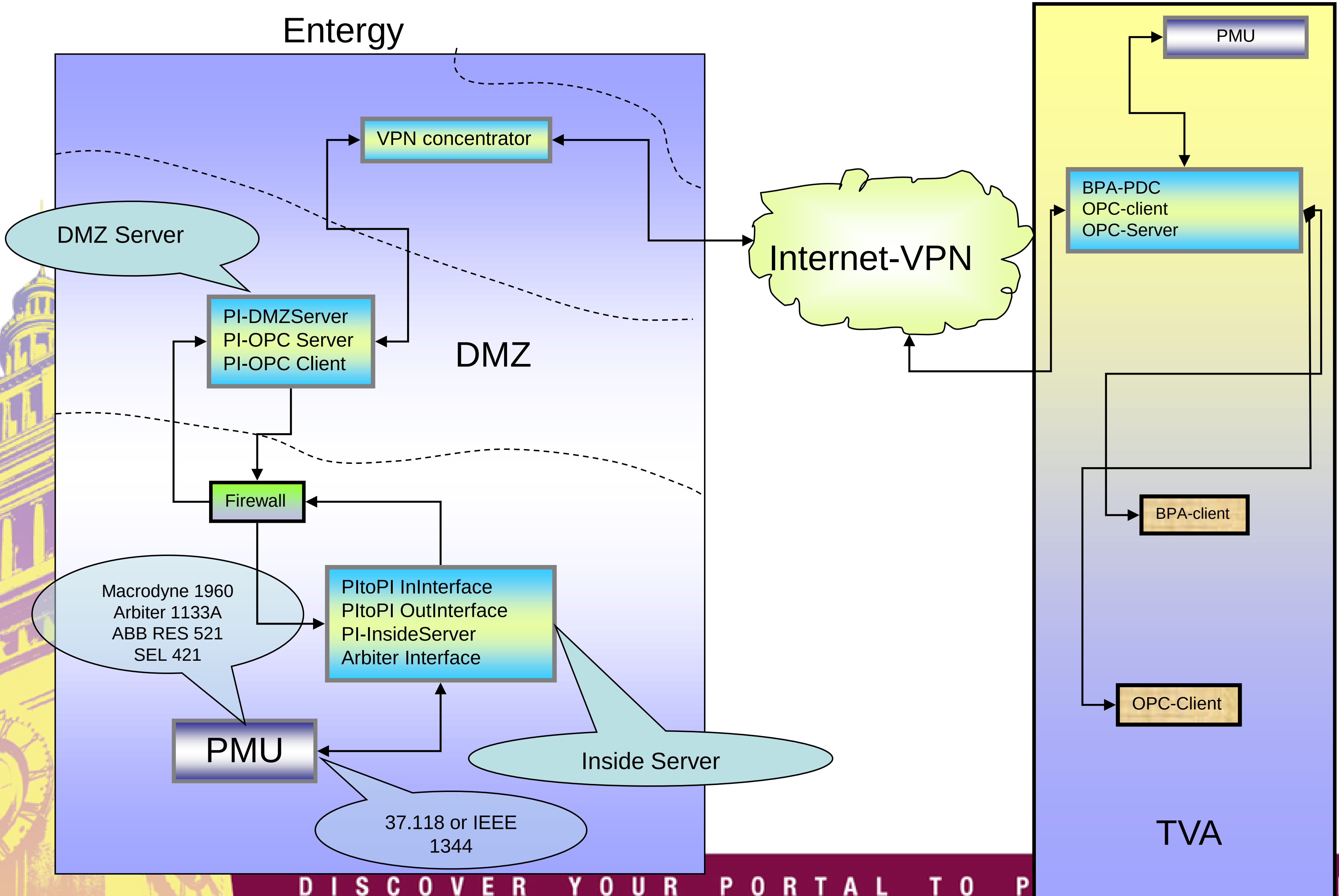
Voltage
95.08
95.03
94.93
94.88
9/15/2004 8:49:25 AM
2.00 minutes
9/15/2004 8:51:25 AM
Current
11
8.6
7.5
9/15/2004 8:49:25 AM
2.00 minutes
9/15/2004 8:51:25 AM
Frequency
60.1
60.03
59.98
9/15/2004 8:49:25 AM
2.00 minutes
9/15/2004 8:51:25 AM
Voltage Phasor
Current (Amps) Phasor
Normalized Harmonics
Real Time

SISCO-GAP Displays



D I S C O V E R   Y O U R   P O R T A L   T O   P E R F O R M A N C E

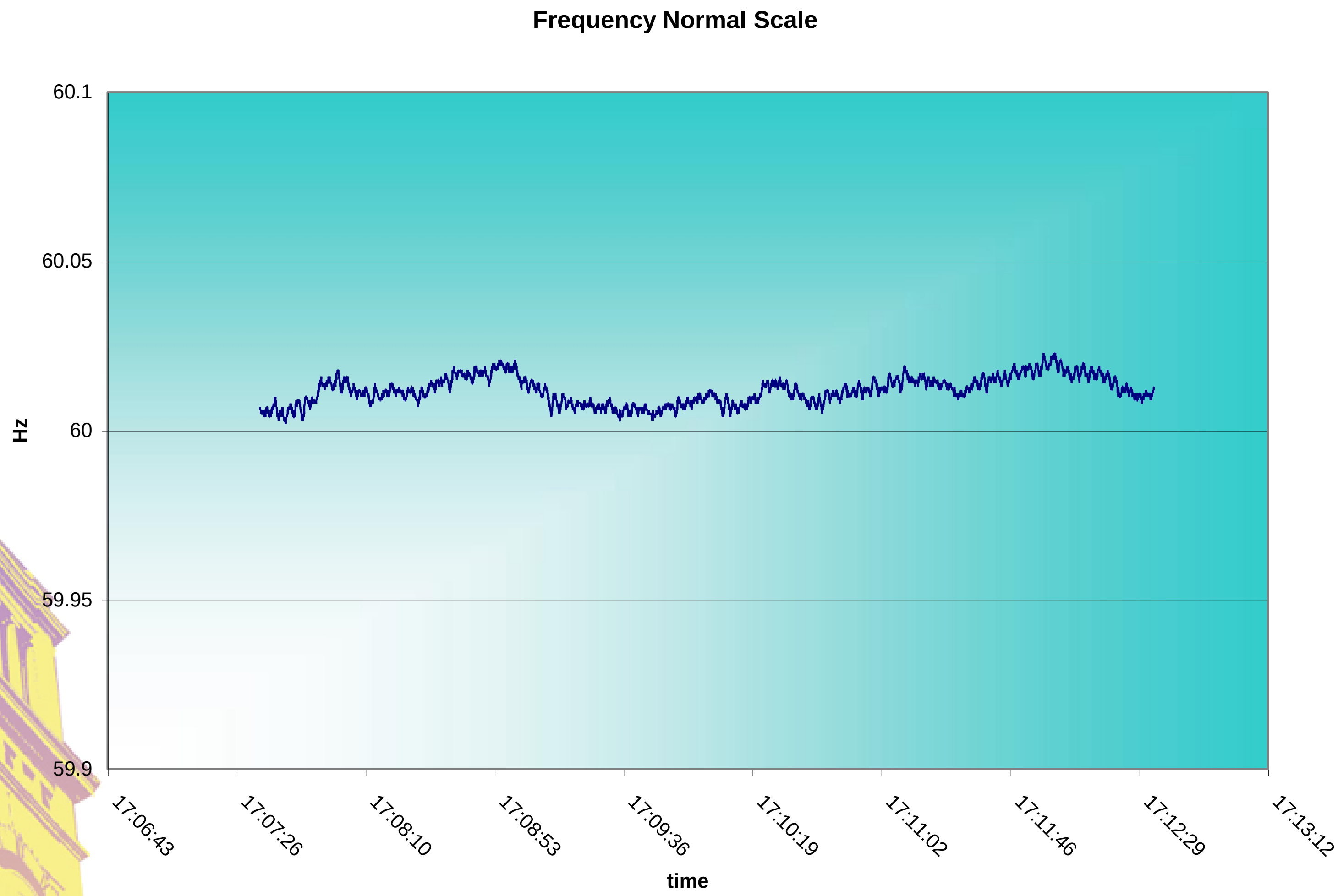
June 18th Eastern Interconnection Phasor Project – Open Architecture



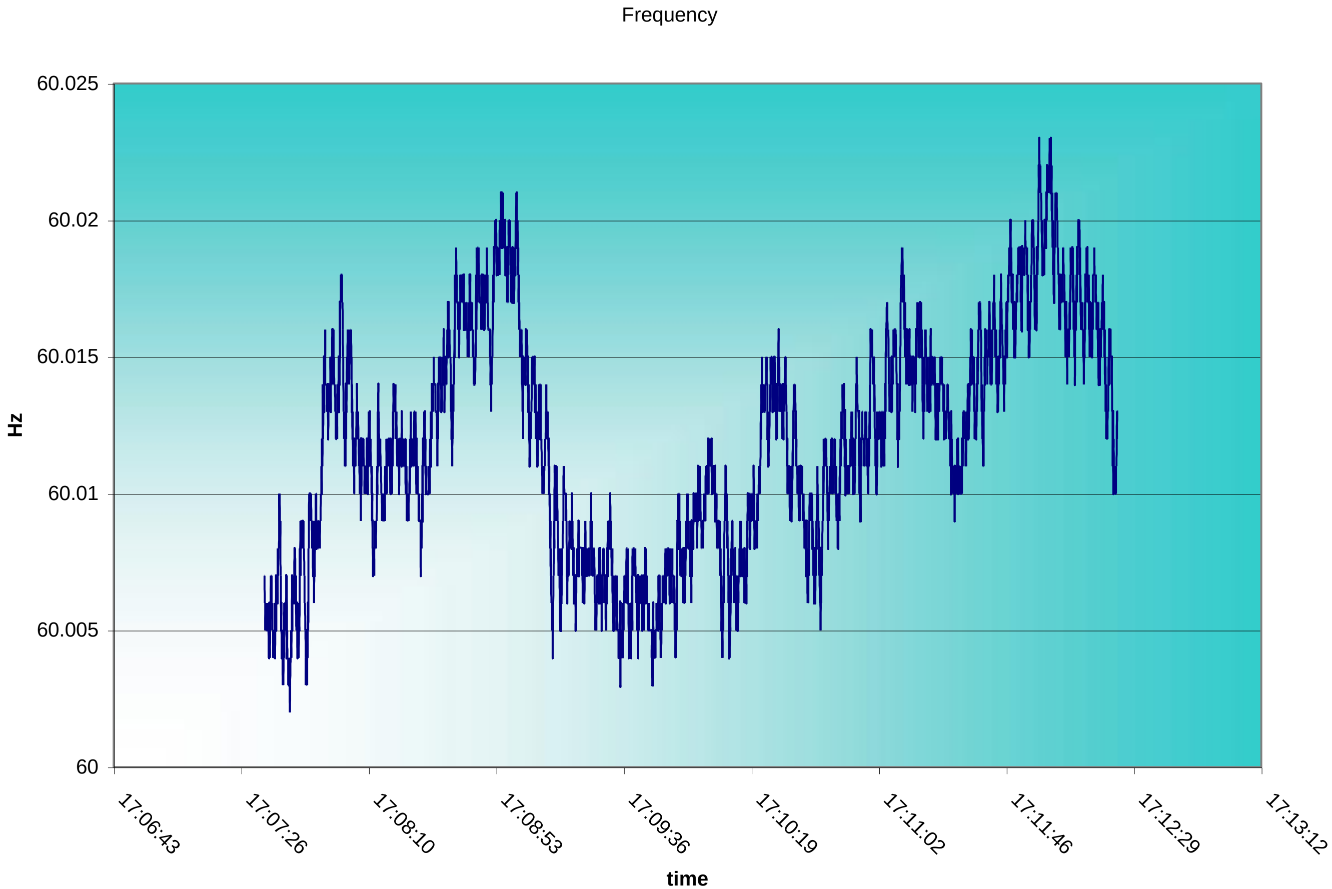
Interoperability tests

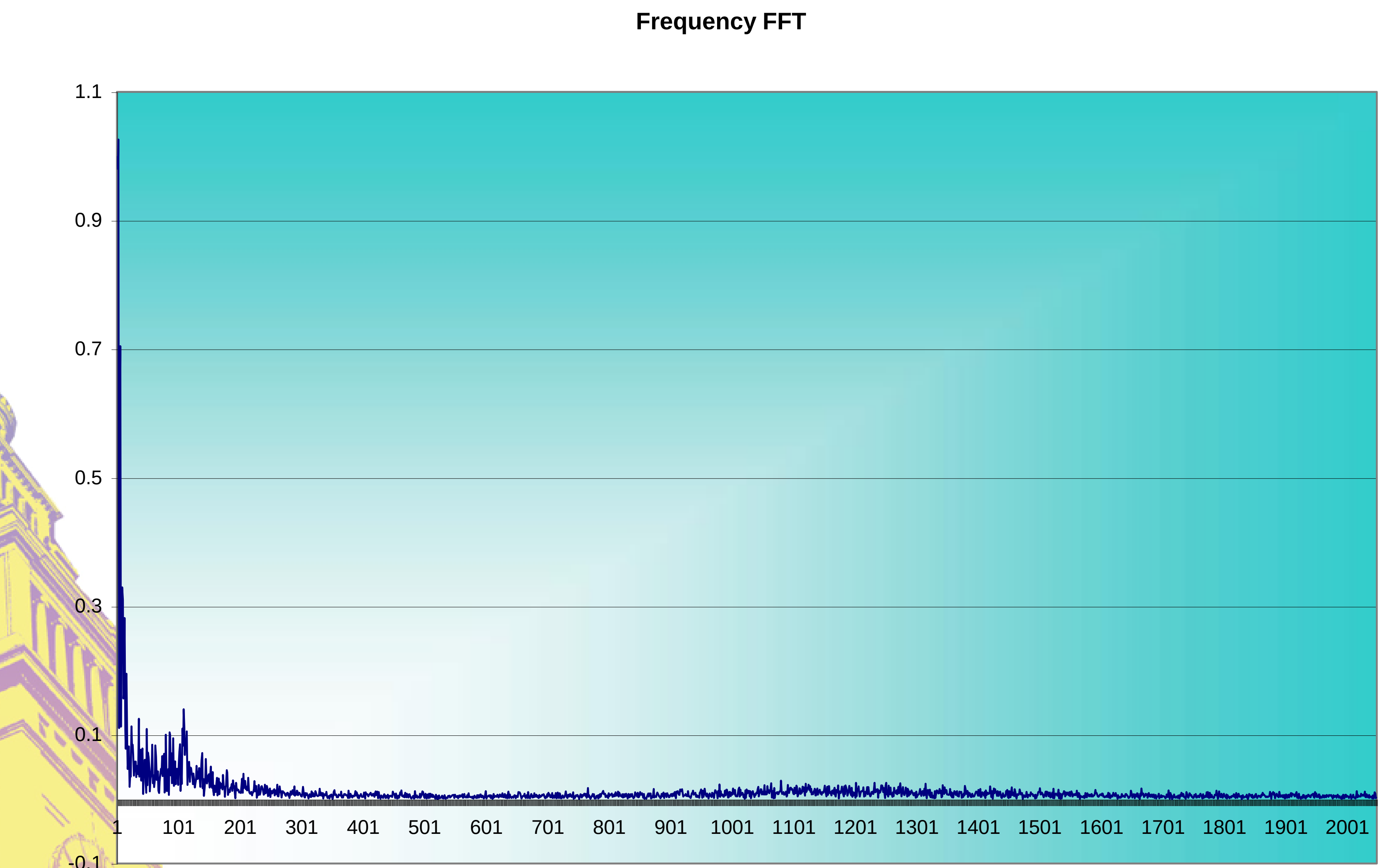
- Pass data in real time between
  - Entergy
  - TVA

Frequency at Patterson

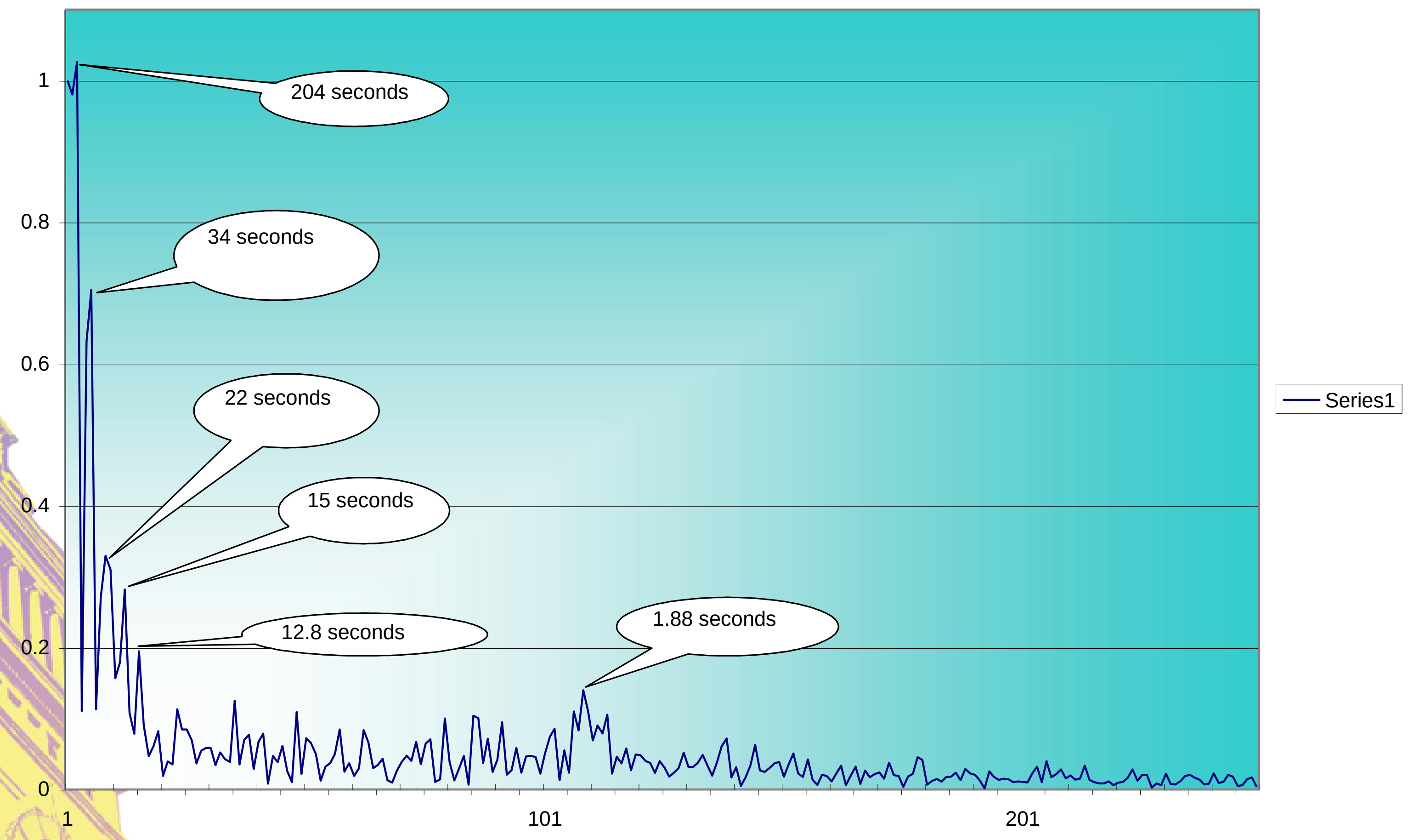


Rescaled view

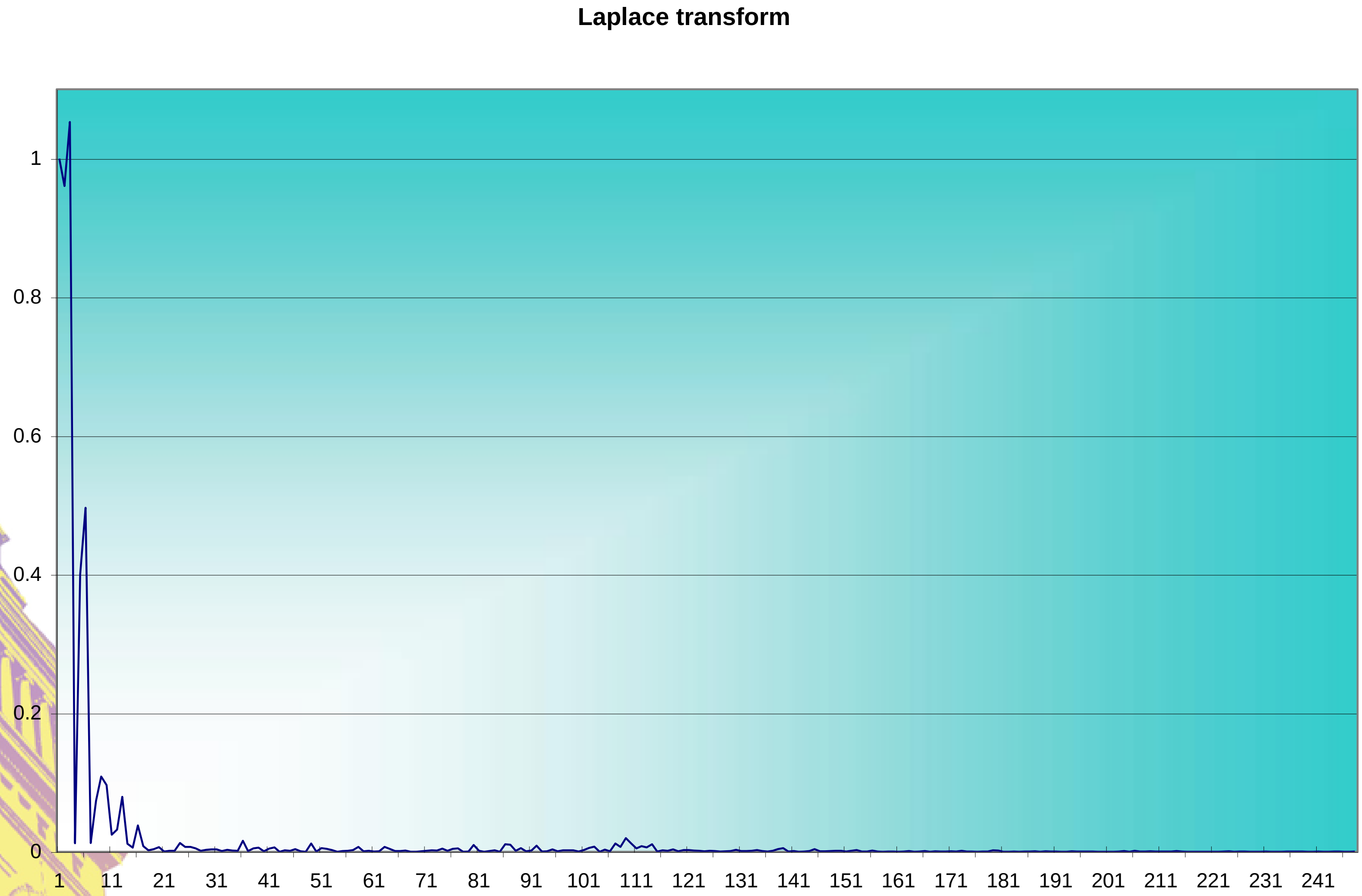



Frequency FFT
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
1
101
201
301
401
501
601
701
801
901
1001
1101
1201
1301
1401
1501
1601
1701
1801
1901
2001

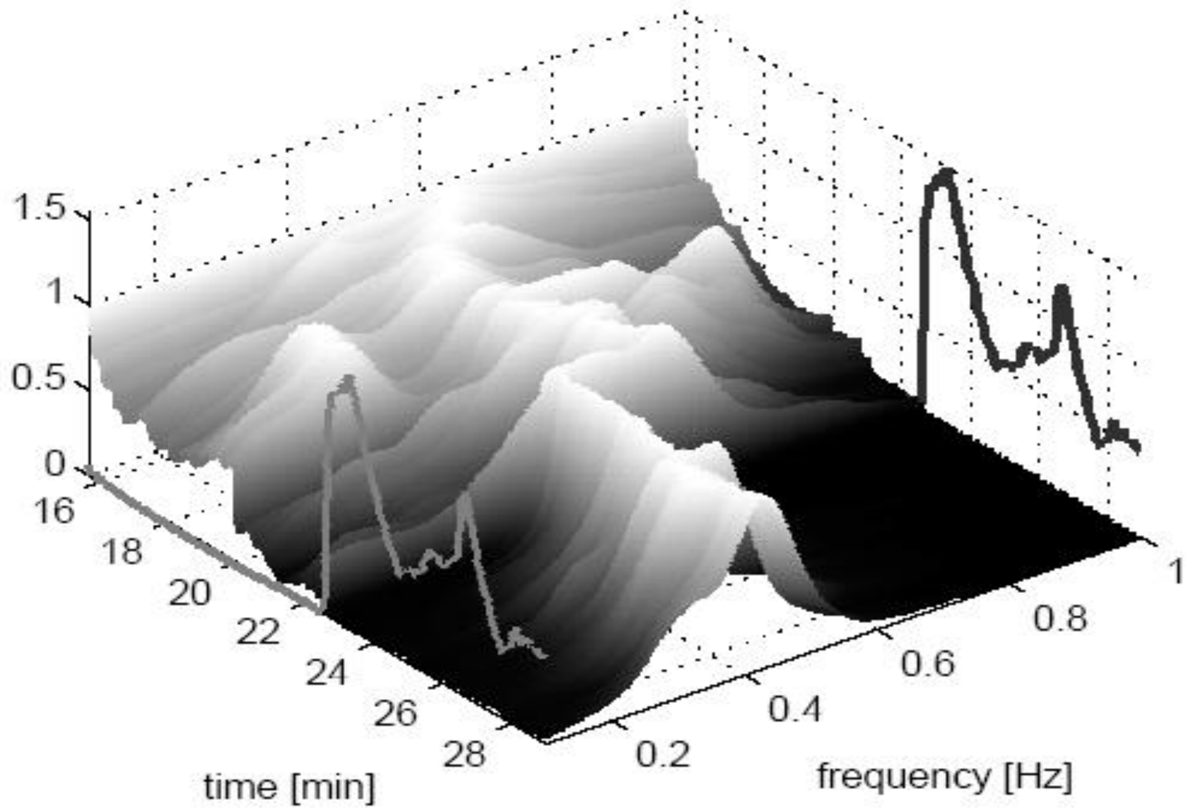
Zoomed FFT



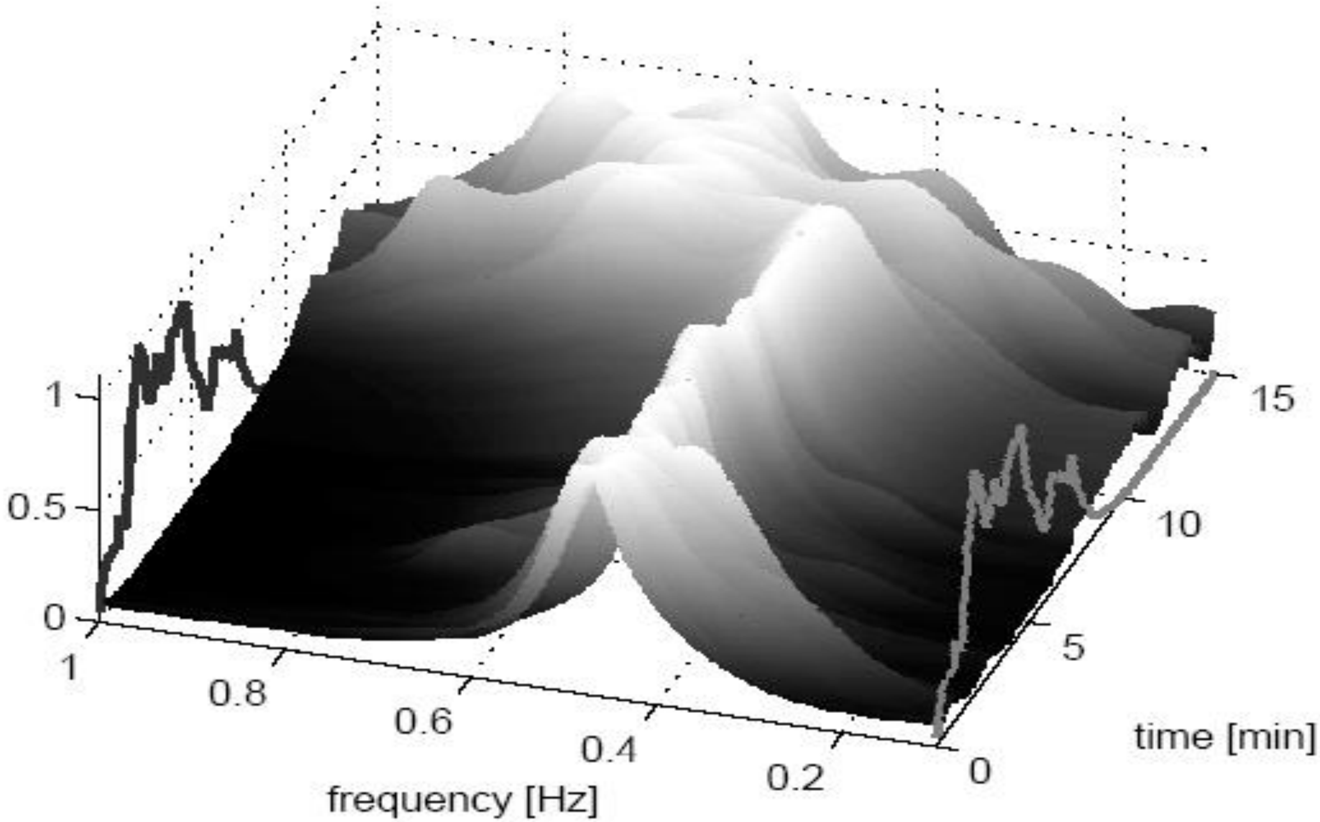
1
0.8
0.6
0.4
0.2
0
1
101
201
204 seconds
34 seconds
22 seconds
15 seconds
12.8 seconds
1.88 seconds
Series1


Laplace transform
1
0.8
0.6
0.4
0.2
0
1
11
21
31
41
51
61
71
81
91
101
111
121
131
141
151
161
171
181
191
201
211
221
231
241

Phasor toolbox



Frequency FFT



Phasor Applications

- Grid stability
- Transient stability
- Small signal stability
- Real time Security and Reliability
- State estimator
- Distance protection relaying
- Adaptive Relaying
- System protection
- PSS (damping control)
- Maximum transmission capacity

Grid damping

$$\ddot{x} + 2\zeta\omega_0\dot{x} + \omega_0^2 x = 0$$

$$\alpha = \frac{IM}{RE} = \frac{\sqrt{(1-\zeta^2)}}{\zeta}$$

$$\zeta = \sqrt{\frac{1}{(\alpha^2 + 1)}}$$

Instability test

- If ζ < 0.7 for more than X seconds
- For any peak ζ
- Advise transmission operator

Distance protection relay

http://www.selinc.com/techpprs/6139.pdf

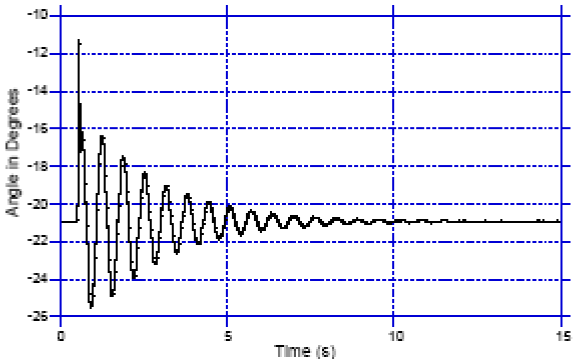


Figure 18 PSV phasors phase angle difference between buses for a 50 ms fault

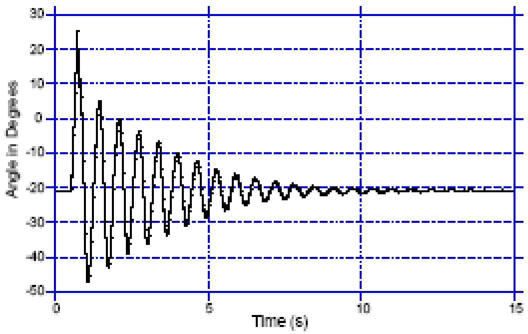


Figure 20 PSV phasors phase angle difference between buses for a 200 ms fault

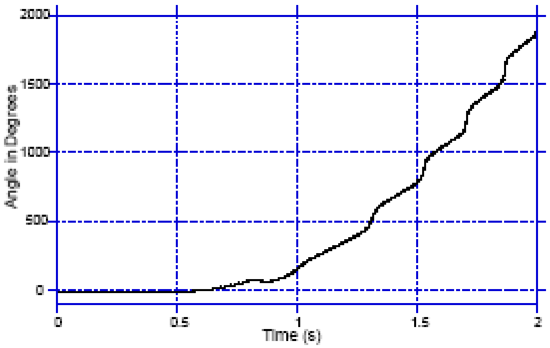


Figure 22 PSV phasors phase angle difference between buses for a 300 ms fault

State Estimation

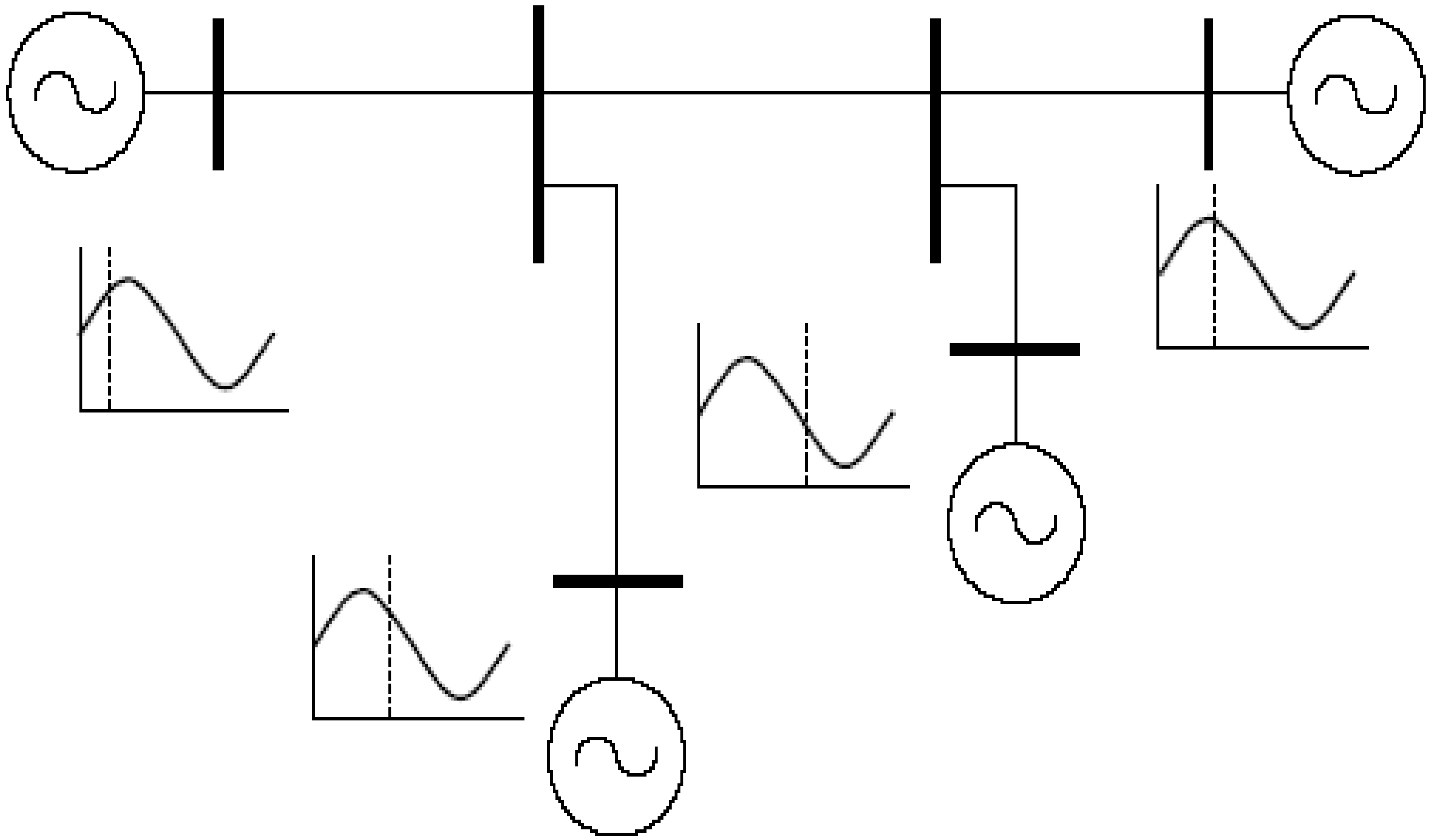
$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \delta_{12} \\ V_1 \\ V_2 \end{bmatrix}$$

$$z = \begin{bmatrix} \delta_{12} \\ V_1 \\ V_2 \\ P_{12} \\ Q_{12} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \end{bmatrix}$$

$$z = h(x) + \varepsilon = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \dfrac{x_2 \bullet x_3 \bullet \sin x_1}{X_{12}} \\ \dfrac{x_2^2 - x_2 \bullet x_3 \bullet \cos x_1}{X_{12}} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \end{bmatrix}$$

$$x^{k+1} = x^k + \left[H(x^k)^T \bullet R^{-1} \bullet H(x^k)\right]^{-1} H(x^k) \bullet R^{-1} \left[z - h(x^k)\right]$$

System wide control and protection



Current status at Entergy

- Operating 4 Arbiter 1133As
- Loading data into PI at 20 Hz, 2000 events per second
- Using PB 3.0 to view real time data
- Running since early June
- In a few weeks, 10,000 events per second

Suggested Architecture