



Advanced analytics and visualization of PMU data

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OSIsoft and Duke Energy

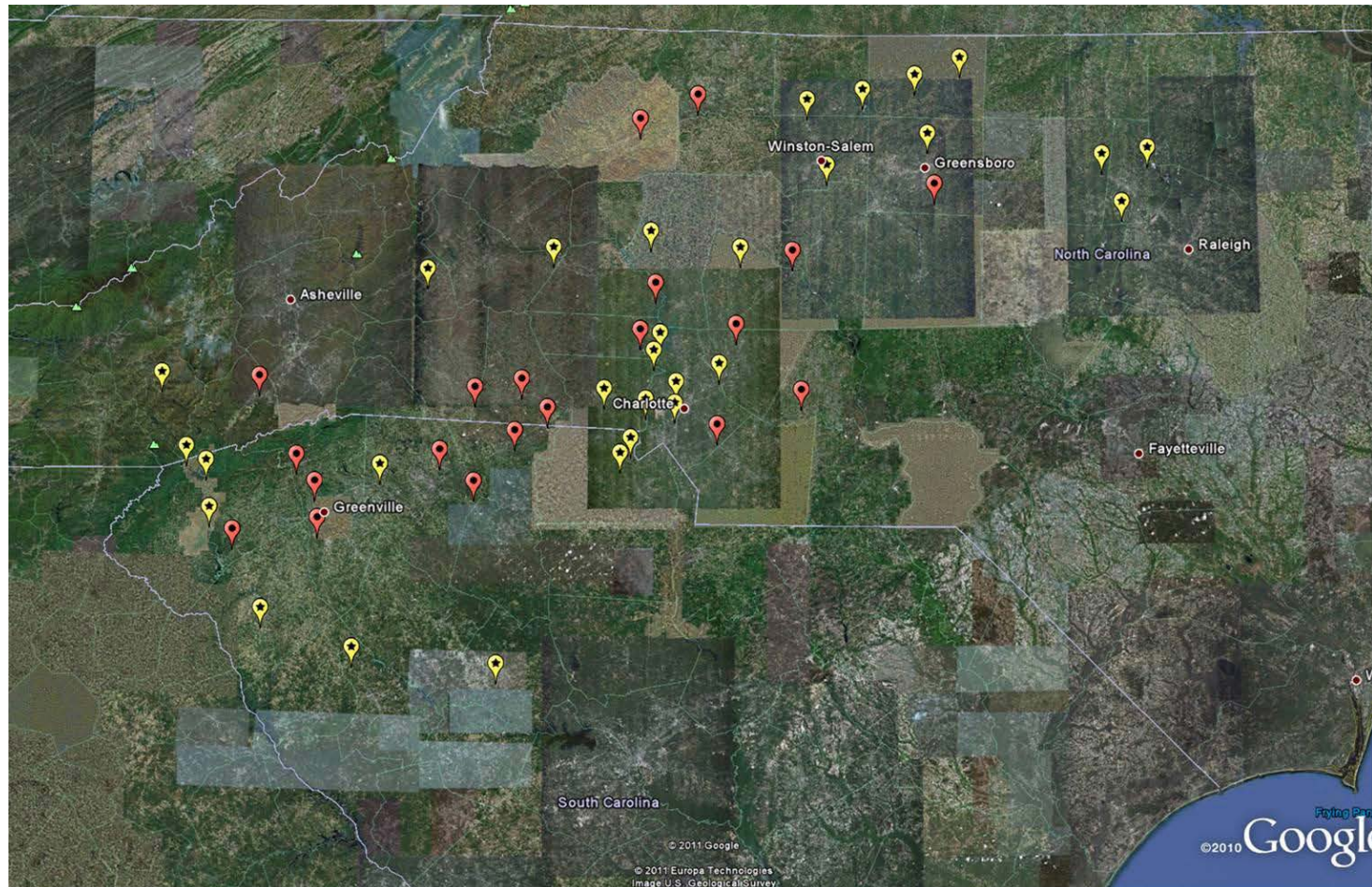
March 30, 2011



Outline

- Summary of Duke Energy's SGIG project
- Importance of time accuracy in PMUs
- Review of selected phase angle data at Duke
 - Importance of unwrapping and order dependence
- Effects of compression on disk storage
- Visualization Examples
 - WECC, Entergy, EIPP, FNET

Duke's SGIG Project



Project SCOPE

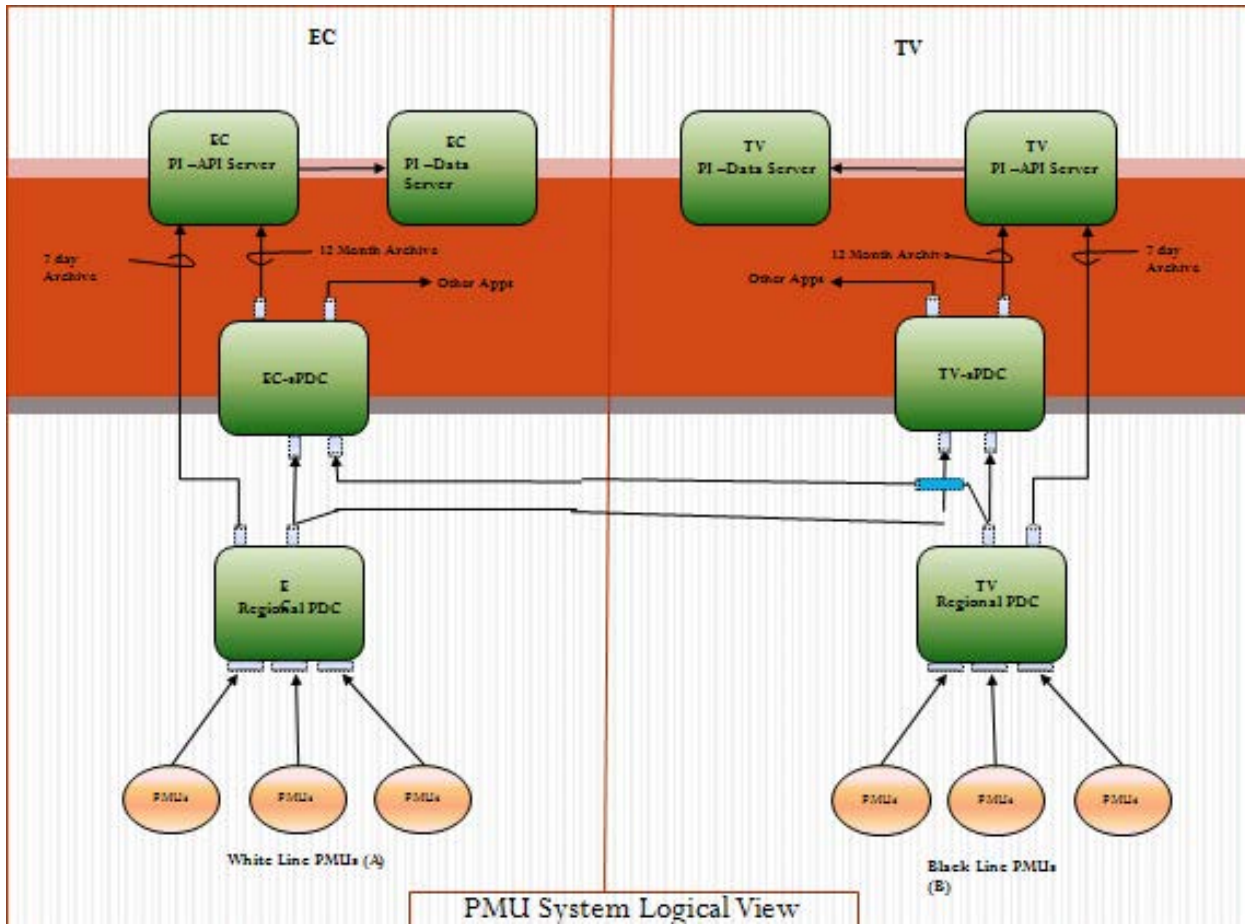
- •Single transmission owner in project and 104 PMUs
- •Transmission elements monitored by PMUs
 - 12 elements >345 kV (500 kV)
 - 92 elements $\geq 230 - 345$ kV (230 kV)
- •100% of regional footprint monitored by PMUs (based on load)
- •52 substations with PMUs
 - 2 PMUs/substation monitoring different elements
- •30 Samples/second
- •Stand Alone SEL 351A
- •PMU installation rate (stations)
 - # installed: 36 total as of 5/30/2012
- # installed: 52 total, 49 new, 3 replacement by May 2013

PMU structure

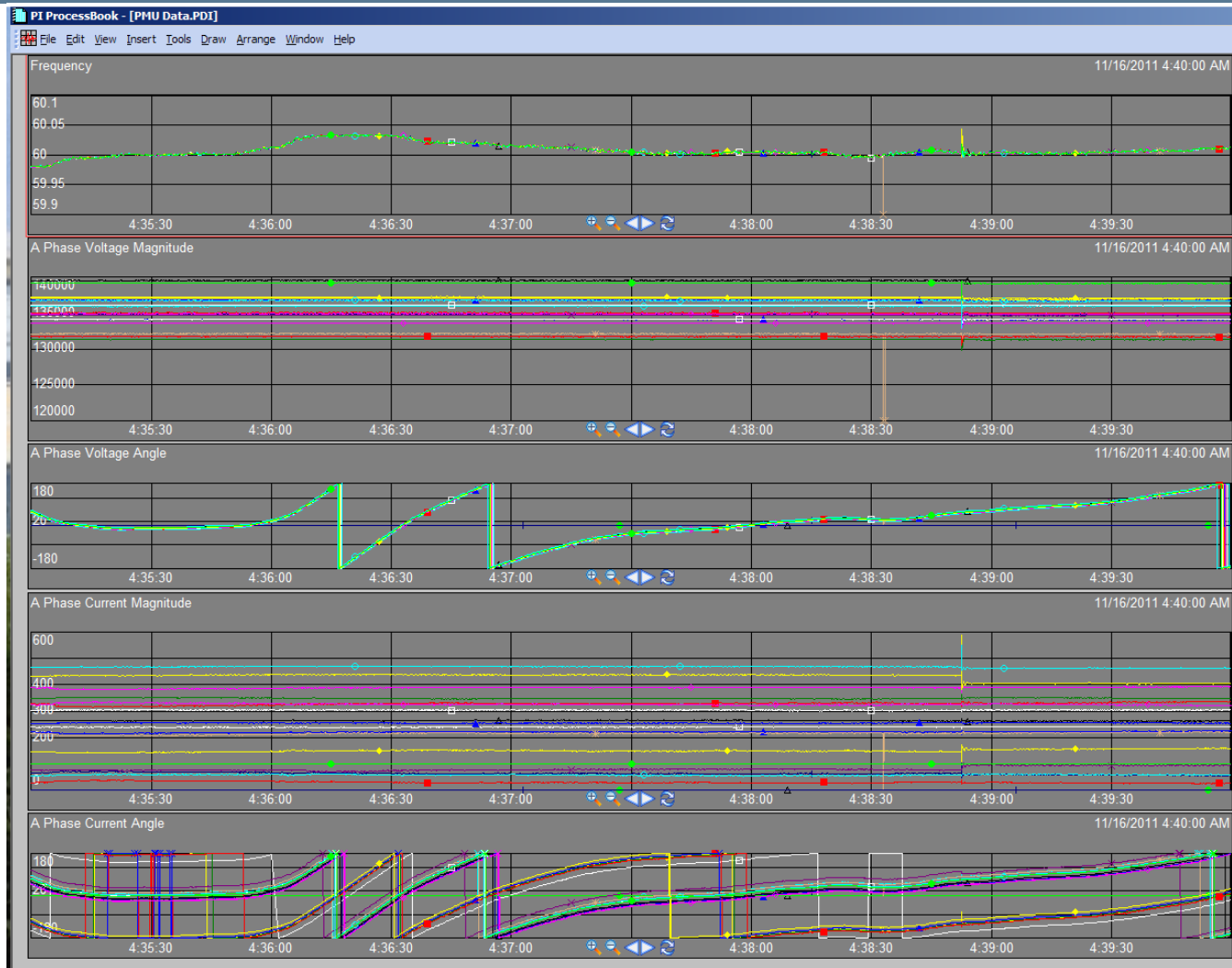
- PDCs
- –2 BA/TO control centers with PDCs (using *openPDC*); each center has 1 primary and 2 regional clusters (see next slide)
- –Archive/database status
 - •70 terrabyte
 - •12 months of data to be readily accessible
 - •Communications system
- –Communication across TO's private network
- –Utilize IP Network

Primarily owned by TO with some leased circuits

PDC Stacking



Current PI Displays



Pros and Cons of Unwrapping

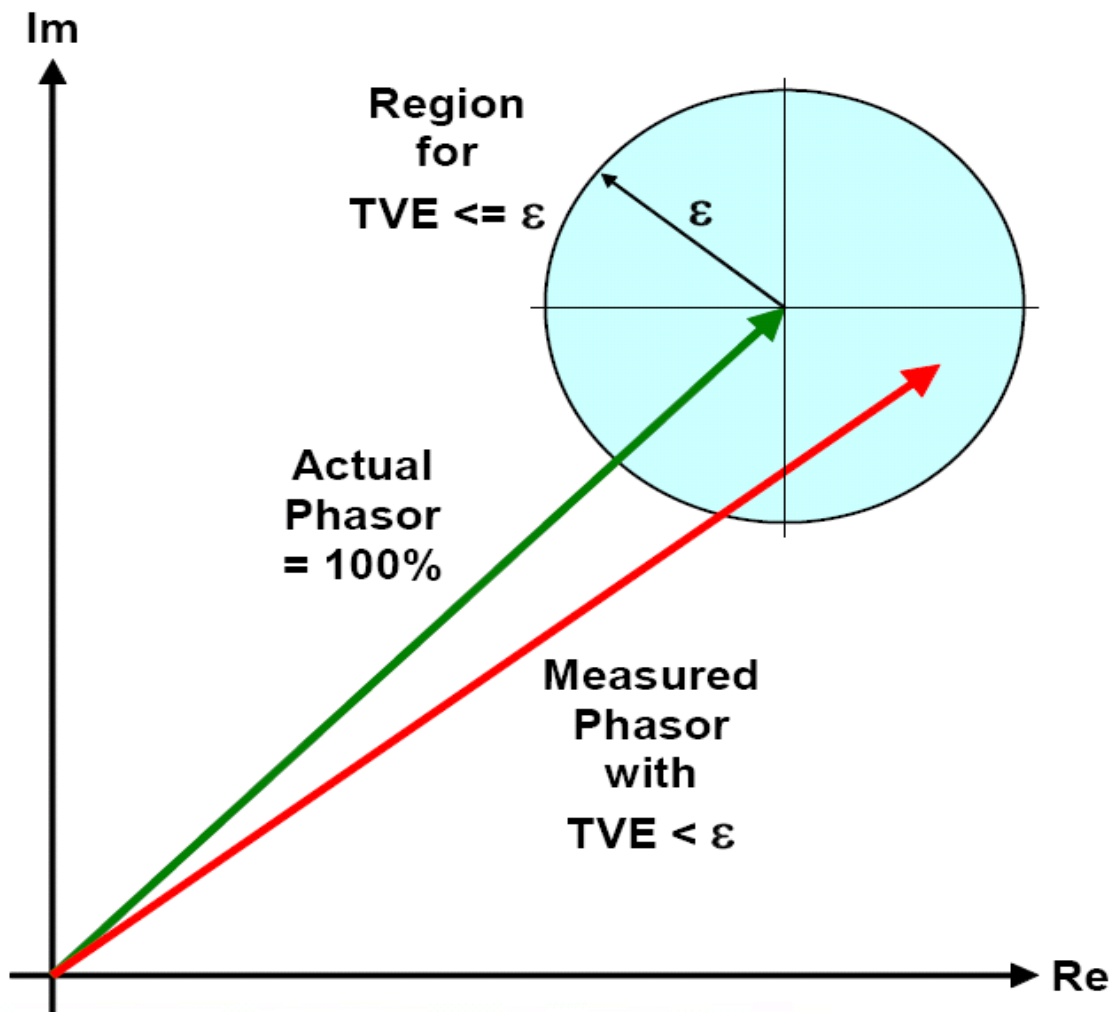
■ Pros

- Eliminate 360 swings that occur when angles wrap at different times
- Can easily see which way frequency is trending
- Eliminates sawtooth waveform
- Can still compute angle differences easily

■ Cons

- Unbounded angle is not intuitive and can be confusing
- If PMU data is lost can look like event

PMU accuracy

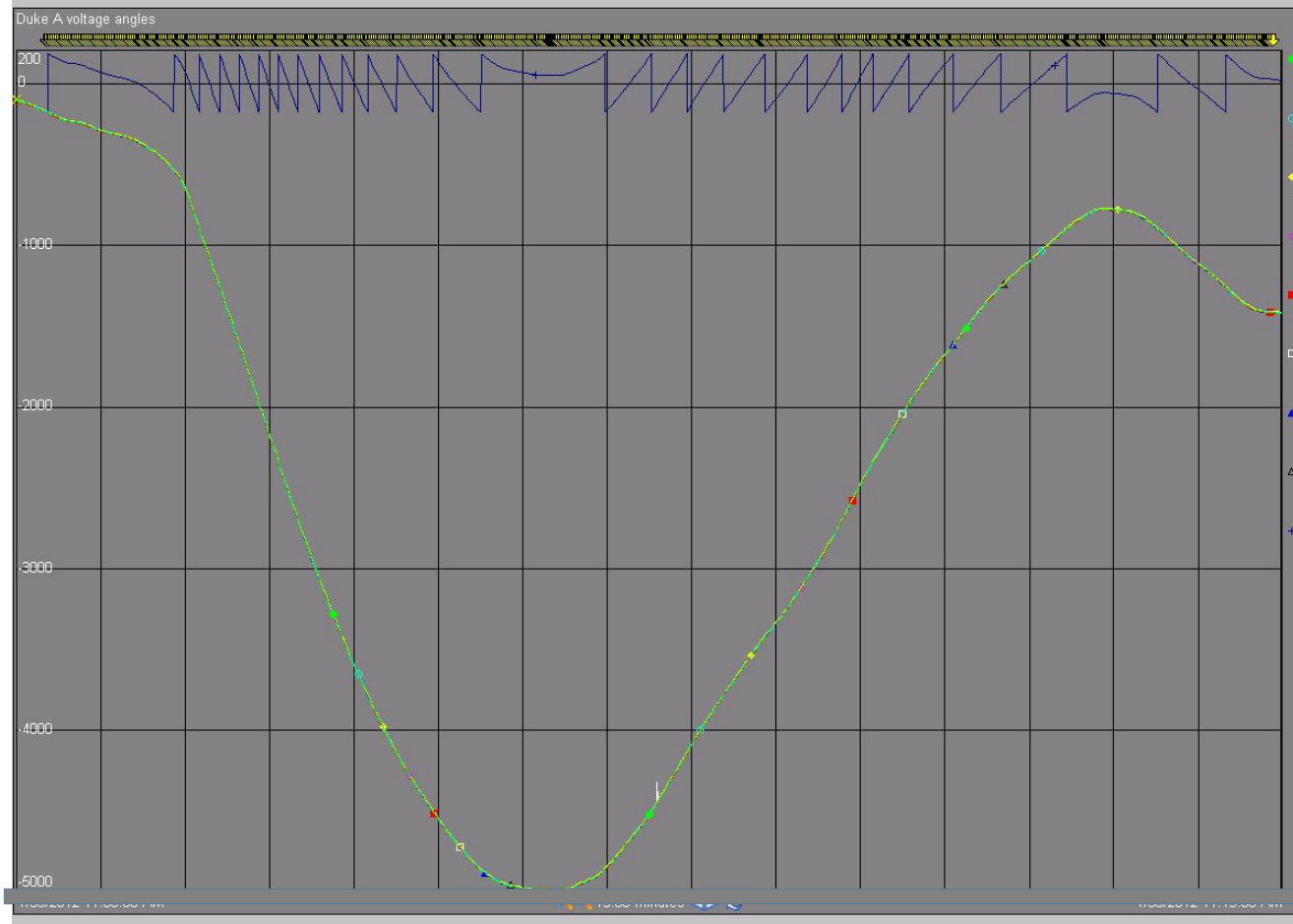


- One percent total vector error
- $\pm 26 \mu \text{ sec}$

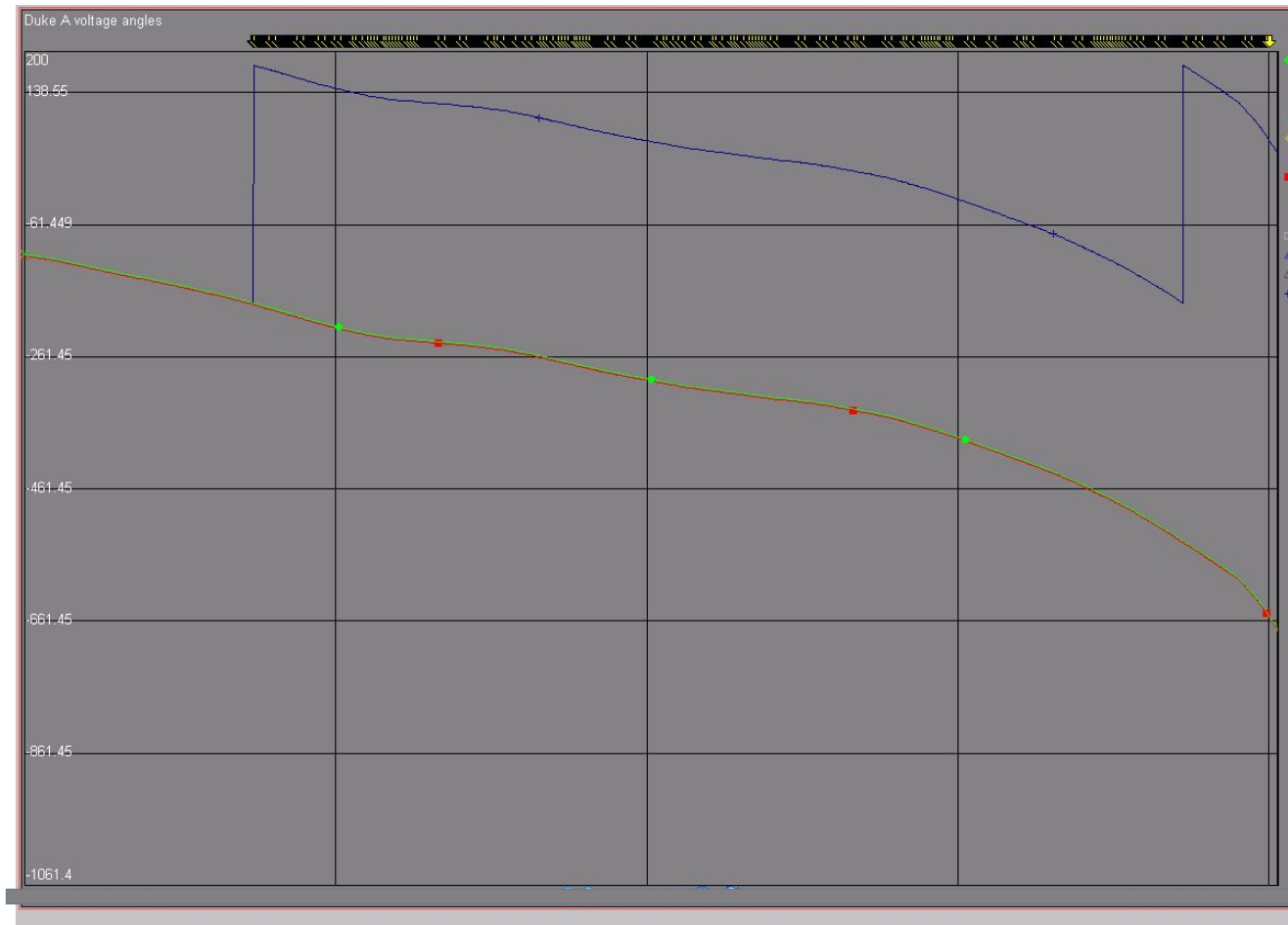
Suggested basic analytics

- Unwrap each voltage and current angle
 - C37.118 angles are discontinuous (± 180)
- Compute angle differences from the unwrapped angles
- Compute frequency differences
- Compute FFT of frequency differences
 - Several window widths are required to pick up events of interest
- Compute damping coefficients at each mode.

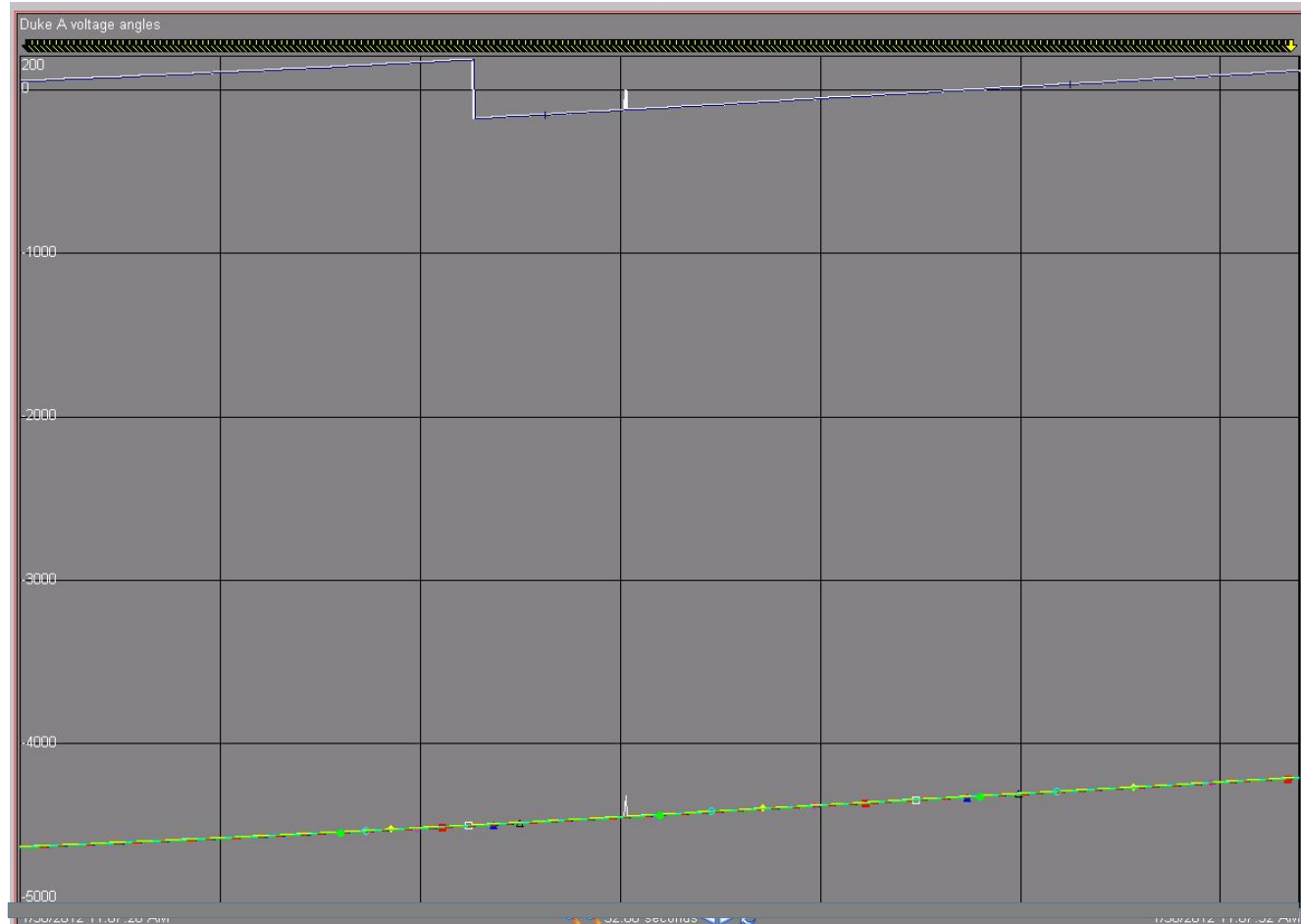
Examples: Nine unwrapped angles and one wrapped



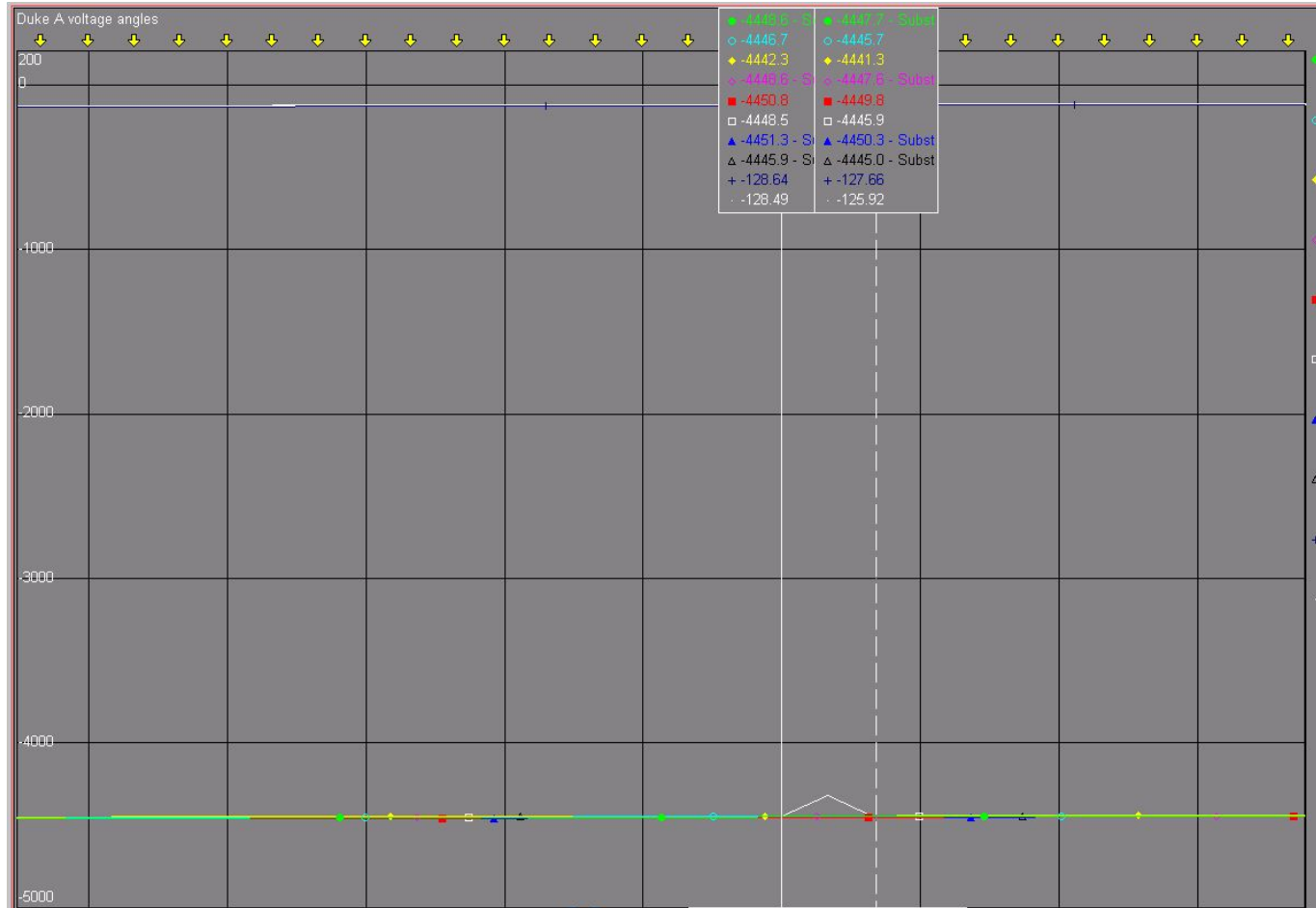
Zoom



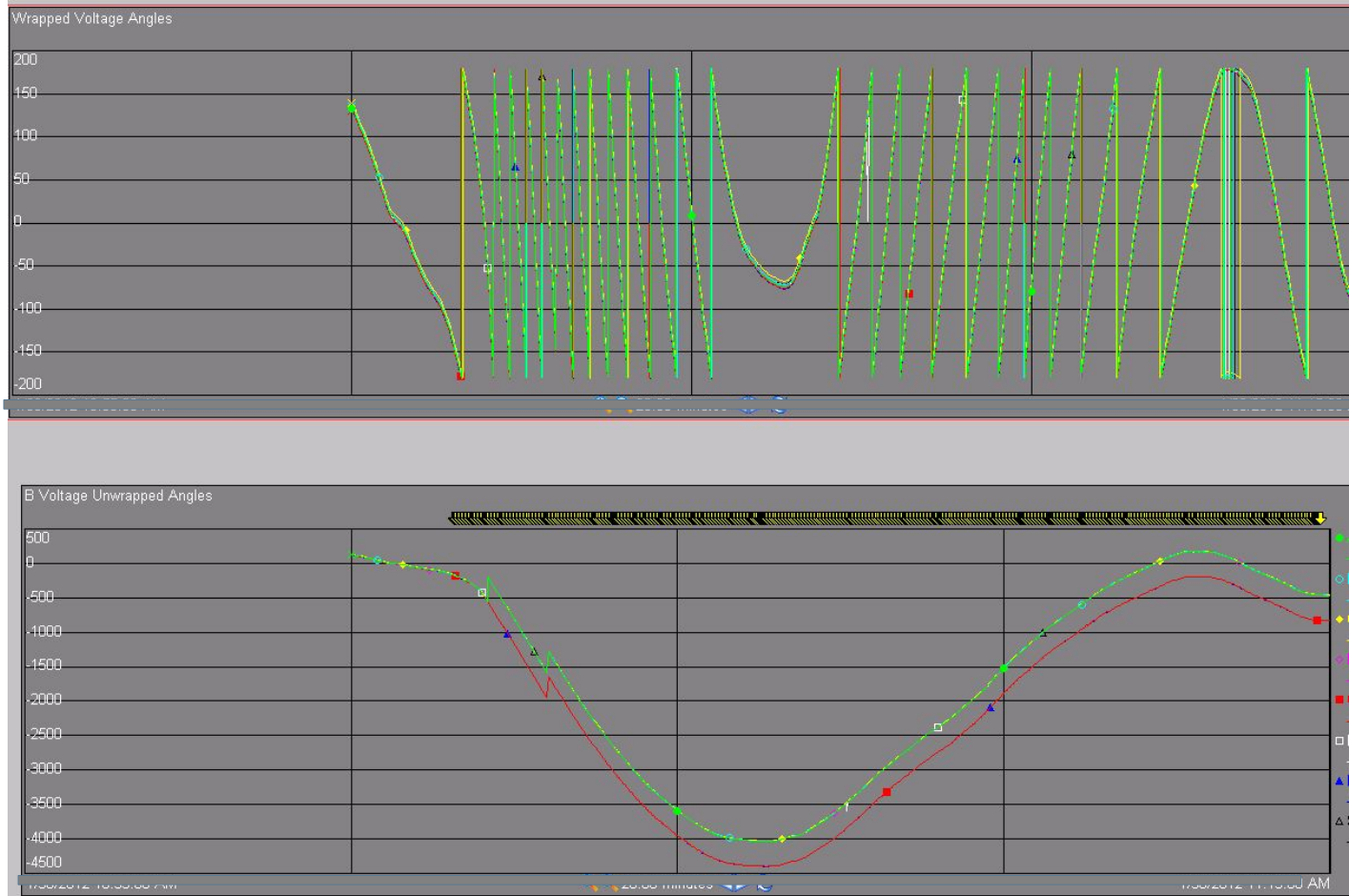
disturbance



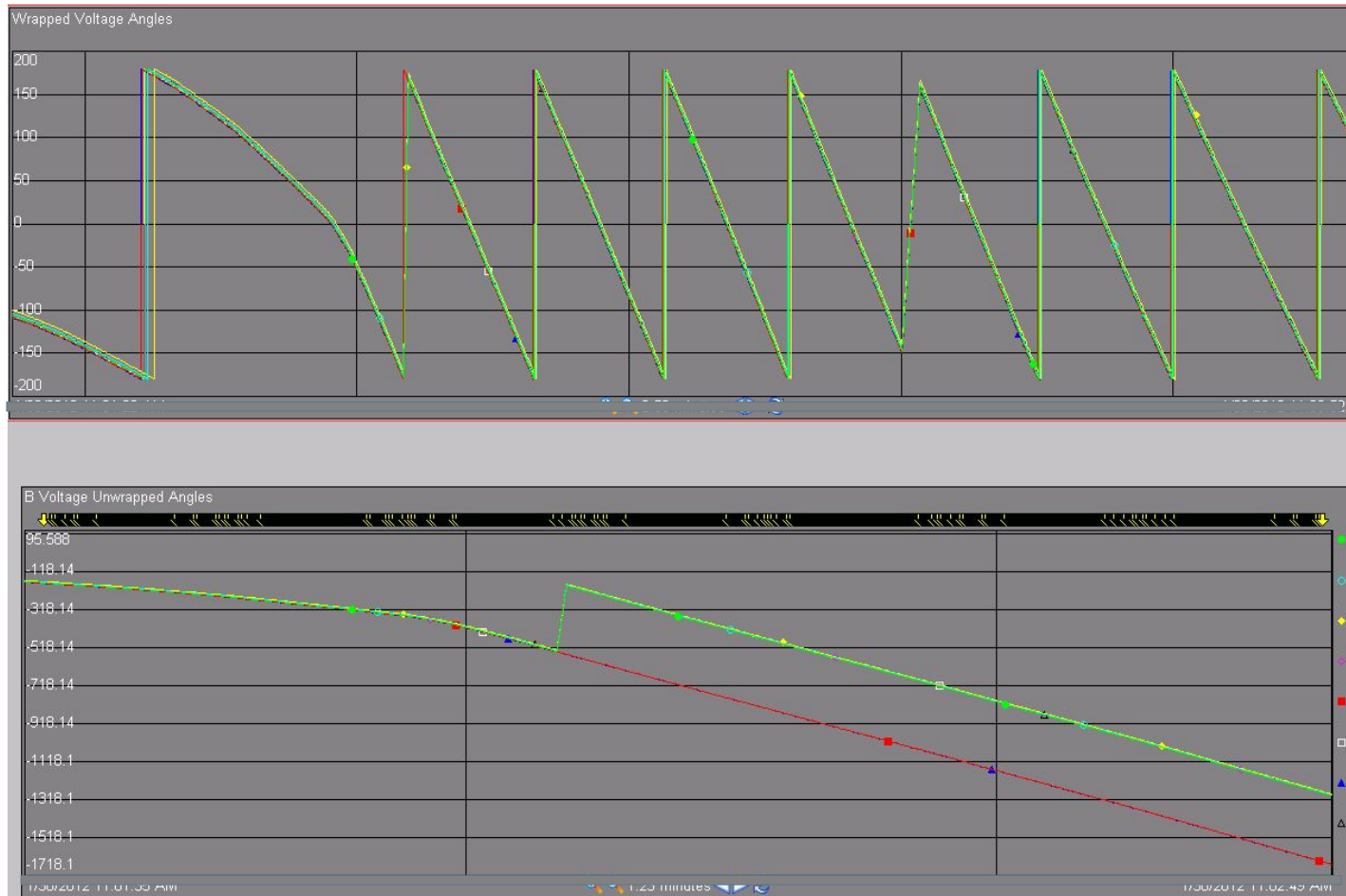
Deeper zoom



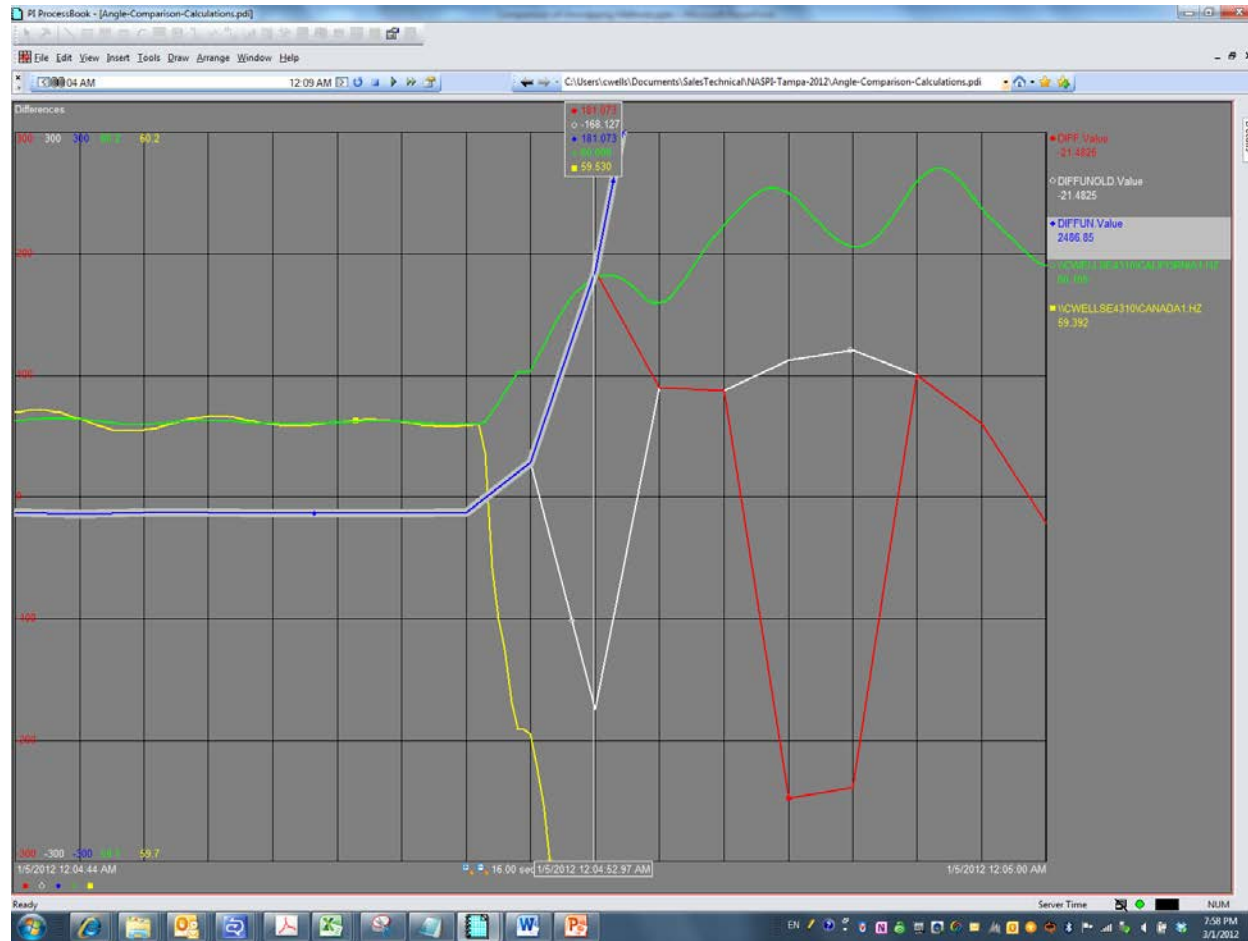
B phase voltage angles



Zoomed in view



Unwrapping comparison



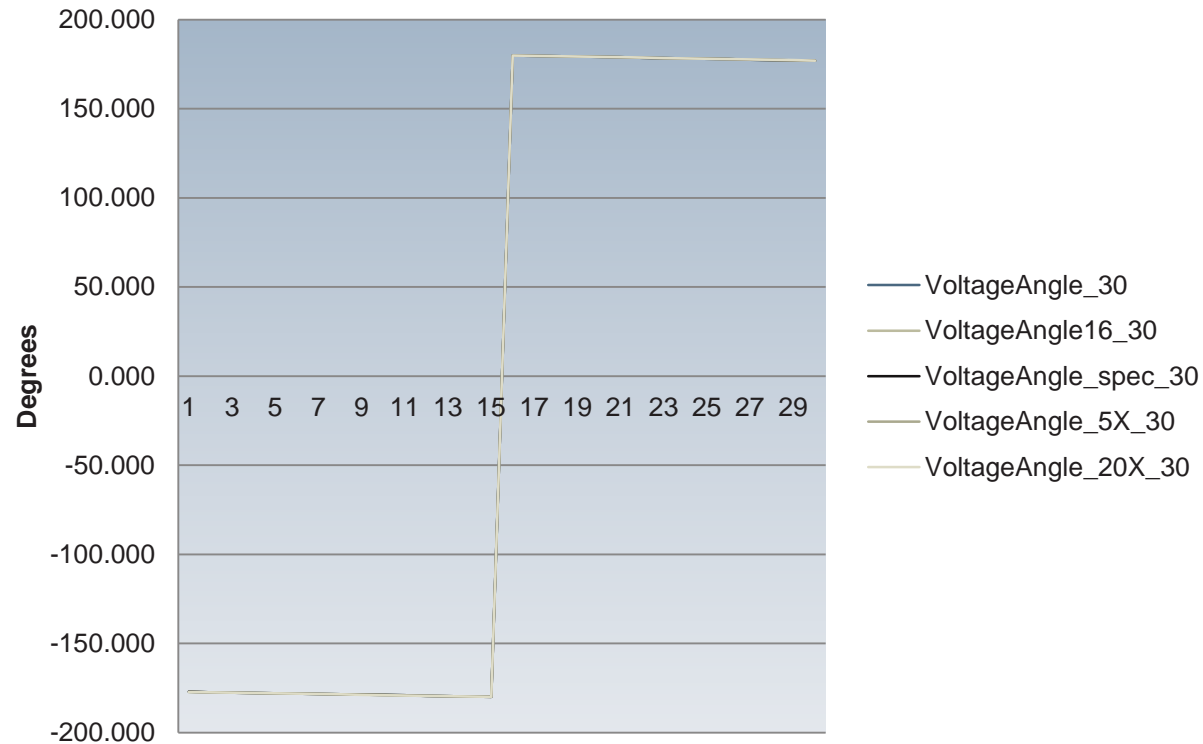
Compression of Voltage Angle

| | A | B | C | D | E | F | G | H | I | J |
|-------|-----------------|-----------------|-------------------|--------|----------------------|--------|--------------------|--------|---------------------|--------|
| 1 | | VoltageAngle_30 | VoltageAngle16_30 | Delta | VoltageAngle_spec_30 | Delta | VoltageAngle_5X_30 | Delta | VoltageAngle_20X_30 | Delta |
| 54004 | Average | -23.777 | -23.777 | 0.000 | -23.777 | 0.000 | -23.777 | 0.000 | -23.775 | -0.002 |
| 54005 | Variance | 10364.174 | 10364.170 | 0.000 | 10364.177 | 0.000 | 10364.381 | 0.001 | 10365.345 | 0.014 |
| 54006 | Maximum | 179.990 | 179.989 | 0.005 | 179.990 | 0.010 | 179.990 | 0.050 | 179.990 | 0.200 |
| 54007 | Minimum | -179.998 | -180.000 | -0.005 | -179.998 | -0.010 | -179.998 | -0.050 | -179.998 | -0.200 |
| 54008 | Compdev | | | | | 0.010 | | 0.050 | | 0.200 |
| 54009 | Archived events | 54001 | 54001 | | 14813 | | 1979 | | 766 | |
| 54010 | % Compression | 0 | 0 | | 72.6% | | 96.3% | | 98.6% | |

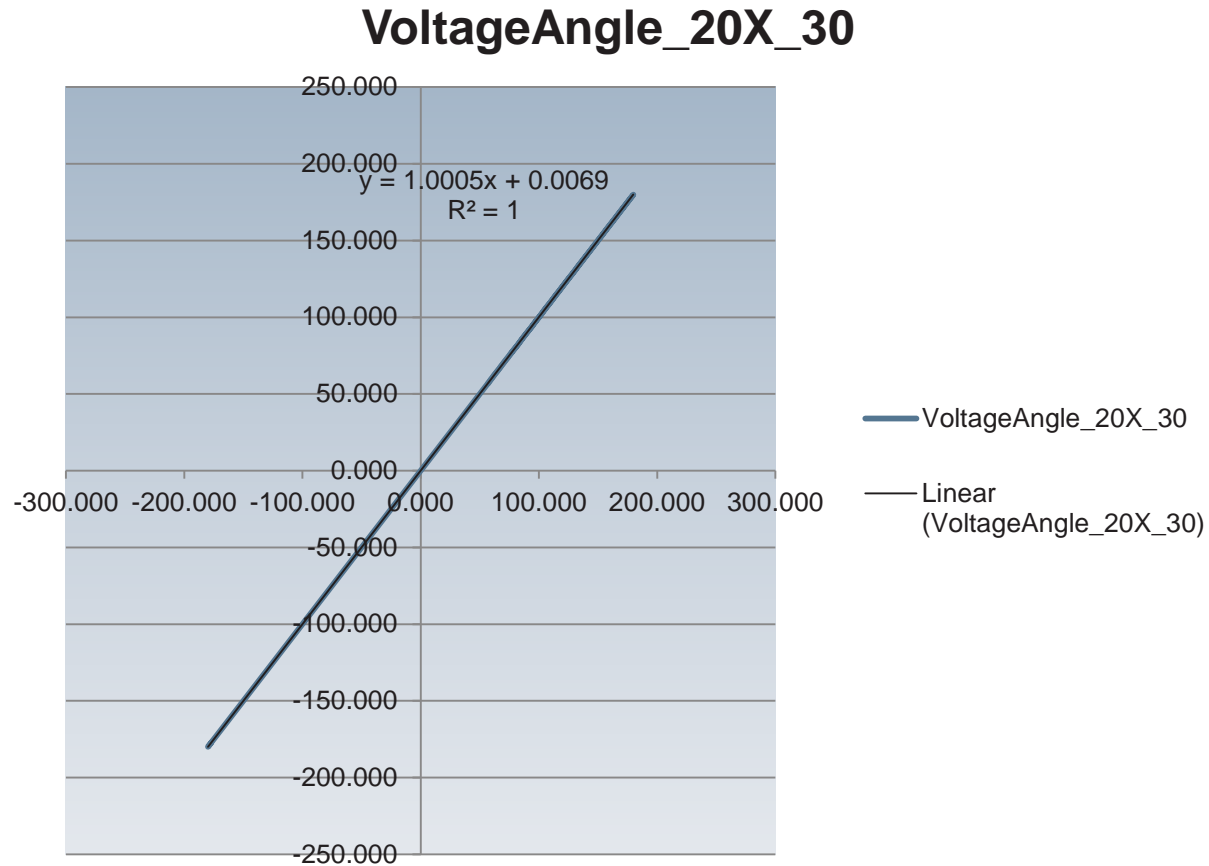
Table 1 Comparison of three levels of compression

Angle compression results

Voltage Angle versus time (30 samples per second)

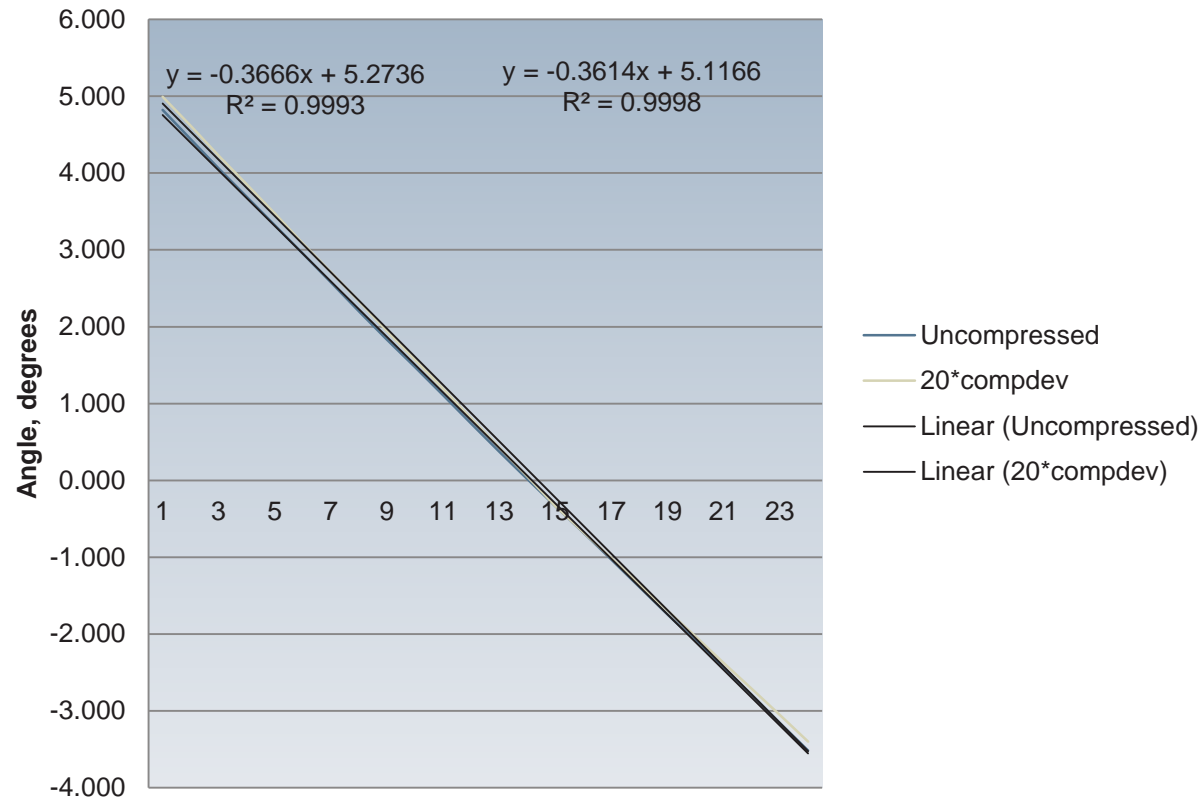


Voltage angle comparison



Zero crossing comparison

Angle zero crossing



Tables (Voltage Magnitude and Current angle

| A | B | C | D | E | F | G | H | I | J |
|-----------------|---------------|-----------------|-----------|--------------------|-----------|------------------|-----------|-------------------|-----------|
| | VoltageMag_30 | VoltageMag16_30 | Delta | VoltageMag_spec_30 | Delta | VoltageMag_5X_30 | Delta | VoltageMag_20X_30 | Delta |
| Average | 286.386572 | 286.386581 | -0.000009 | 286.384490 | 0.002083 | 286.335517 | 0.051055 | 286.747078 | -0.360506 |
| Variance | 0.073778 | 0.073806 | 0.000028 | 0.073327 | 0.000619 | 0.079891 | 0.012695 | 0.008674 | 0.041996 |
| Maximum | 287.094666 | 287.099823 | 0.009155 | 287.065155 | 0.056366 | 287.047974 | 0.281799 | 286.908386 | 0.190887 |
| Minimum | 285.567078 | 285.561707 | -0.009155 | 285.567078 | -0.056366 | 285.659576 | -0.281219 | 286.585754 | -1.081024 |
| Compdev | | | | | 0.056368 | | 0.281841 | | 1.127366 |
| Archived events | 54001 | 54001 | | 2552 | | 135 | | 0 | |
| % Compression | 0 | 0 | | 95.3% | | 99.8% | | 100.0% | |

| A | B | C | D | E | F | G | H | I | J |
|-----------------|-----------------|-------------------|--------|----------------------|--------|--------------------|--------|---------------------|--------|
| | CurrentAngle_30 | CurrentAngle16_30 | Delta | CurrentAngle_spec_30 | Delta | CurrentAngle_5X_30 | Delta | CurrentAngle_20X_30 | Delta |
| Average | -25.952 | -25.952 | 0.000 | -25.953 | 0.000 | -25.954 | 0.001 | -25.955 | 0.002 |
| Variance | 11079.841 | 11079.841 | 0.000 | 11079.841 | 0.000 | 11079.845 | 0.000 | 11079.726 | 0.008 |
| Maximum | 179.998 | 180.000 | 0.005 | 179.998 | 0.010 | 179.998 | 0.050 | 179.998 | 0.200 |
| Minimum | -179.996 | -180.000 | -0.005 | -179.996 | -0.010 | -179.996 | -0.050 | -179.996 | -0.200 |
| Compdev | 0 | | 0 | | 0.01 | | 0.05 | | 0.20 |
| Archived events | 54001 | 54001 | | 42815 | | 19867 | | 3436 | |
| % Compression | 0 | 0 | | 20.7% | | 63.2% | | 93.6% | |

Current magnitude and VA

| A | B | C | D | E | F | G | H | I | J |
|-----------------|---------------|-----------------|----------|--------------------|----------|------------------|----------|-------------------|----------|
| | CurrentMag_30 | CurrentMag16_30 | Delta | CurrentMag_spec_30 | Delta | CurrentMag_5X_30 | Delta | CurrentMag_20X_30 | Delta |
| Average | 110.91319 | 110.91318 | 0.00000 | 110.91364 | -0.00045 | 110.92317 | -0.00998 | 110.99160 | -0.07841 |
| Variance | 11.22509 | 11.22508 | 0.00002 | 11.22435 | 0.00033 | 11.21006 | 0.01634 | 10.79176 | 0.22518 |
| Maximum | 136.02931 | 136.03625 | 0.00763 | 136.02931 | 0.05502 | 136.02931 | 0.27509 | 136.02931 | 1.10043 |
| Minimum | 102.38154 | 102.37434 | -0.00763 | 102.38154 | -0.05502 | 102.52757 | -0.27511 | 103.23901 | -1.10039 |
| Compdev | 0 | | 0 | | 0.05502 | | 0.27512 | | 1.10047 |
| Archived events | 54001 | 54001 | | 35344 | | 11118 | | 1609 | |
| % Compression | 0 | 0 | | 34.5% | | 79.4% | | 97.0% | |

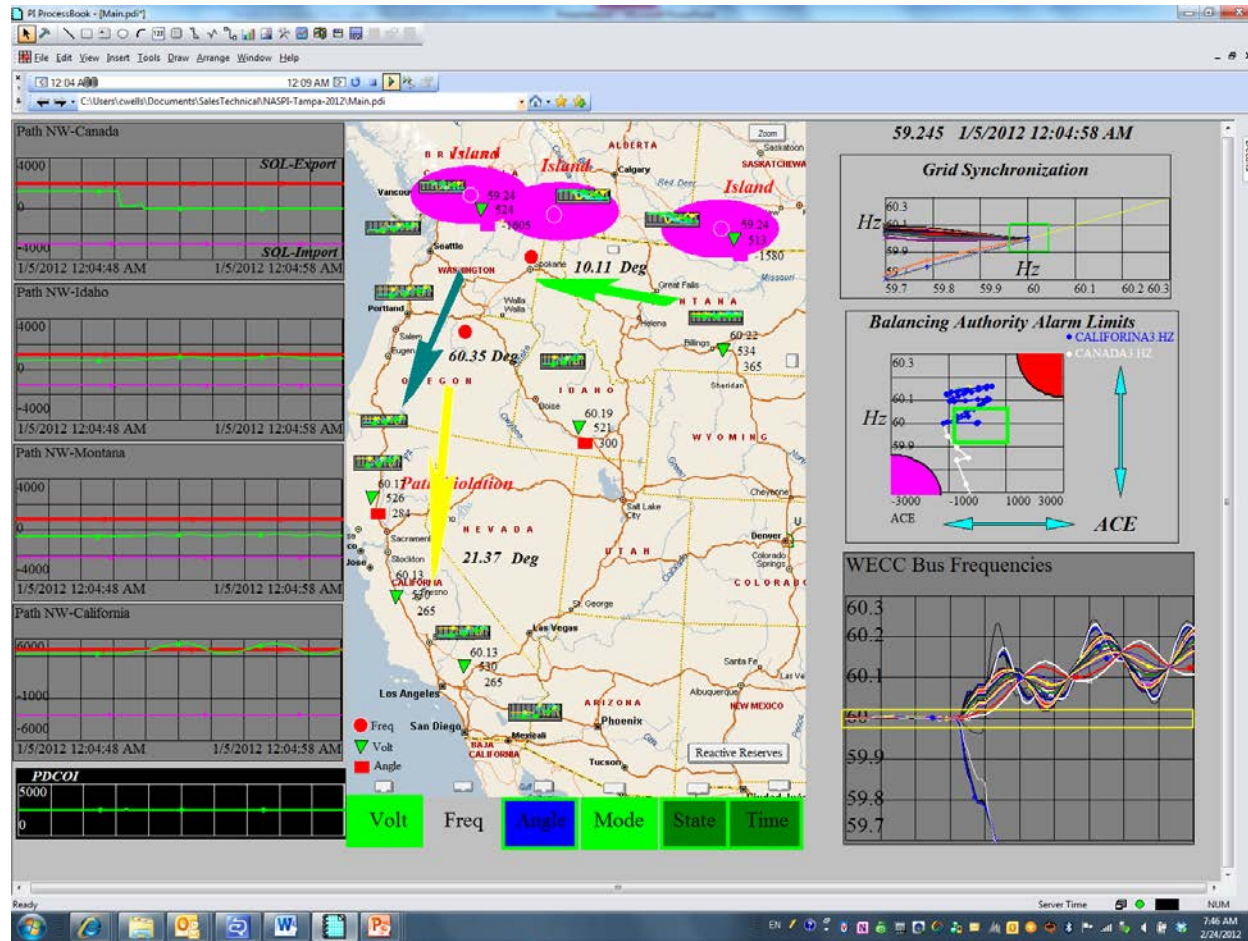
| A | B | C | D | E | F | G | H | I | J |
|-----------------|-------------|-------------|---------|-------------|----------|-------------|----------|-------------|------------|
| | VA_30 | VA16_30 | Delta | VA_spec_30 | Delta | VA_5X_30 | Delta | VA_20X_30 | Delta |
| Average | 31763.4284 | 31763.4270 | 0.0014 | 31763.4992 | -0.0708 | 31765.6848 | -2.2564 | 31777.9052 | -14.4768 |
| Variance | 882450.2707 | 882462.7340 | 0.7773 | 882411.5961 | 16.4871 | 881633.8320 | 894.8653 | 862104.7056 | 12121.7097 |
| Maximum | 38863.8594 | 38865.3203 | 1.5273 | 38863.8594 | 13.0820 | 38863.8594 | 65.4473 | 38863.8594 | 261.7676 |
| Minimum | 29360.5273 | 29361.8574 | -1.5273 | 29360.5273 | -13.0879 | 29403.2168 | -65.4414 | 29444.3438 | -261.7324 |
| Compdev | 0.0000 | | 0.0000 | | 13.0895 | | 65.4476 | | 261.7906 |
| Archived events | 54001 | 54001 | | 37791 | | 13513 | | 2013 | |
| % Compression | 0 | 0 | | 30.0% | | 75.0% | | 96.3% | |

VAR and frequency

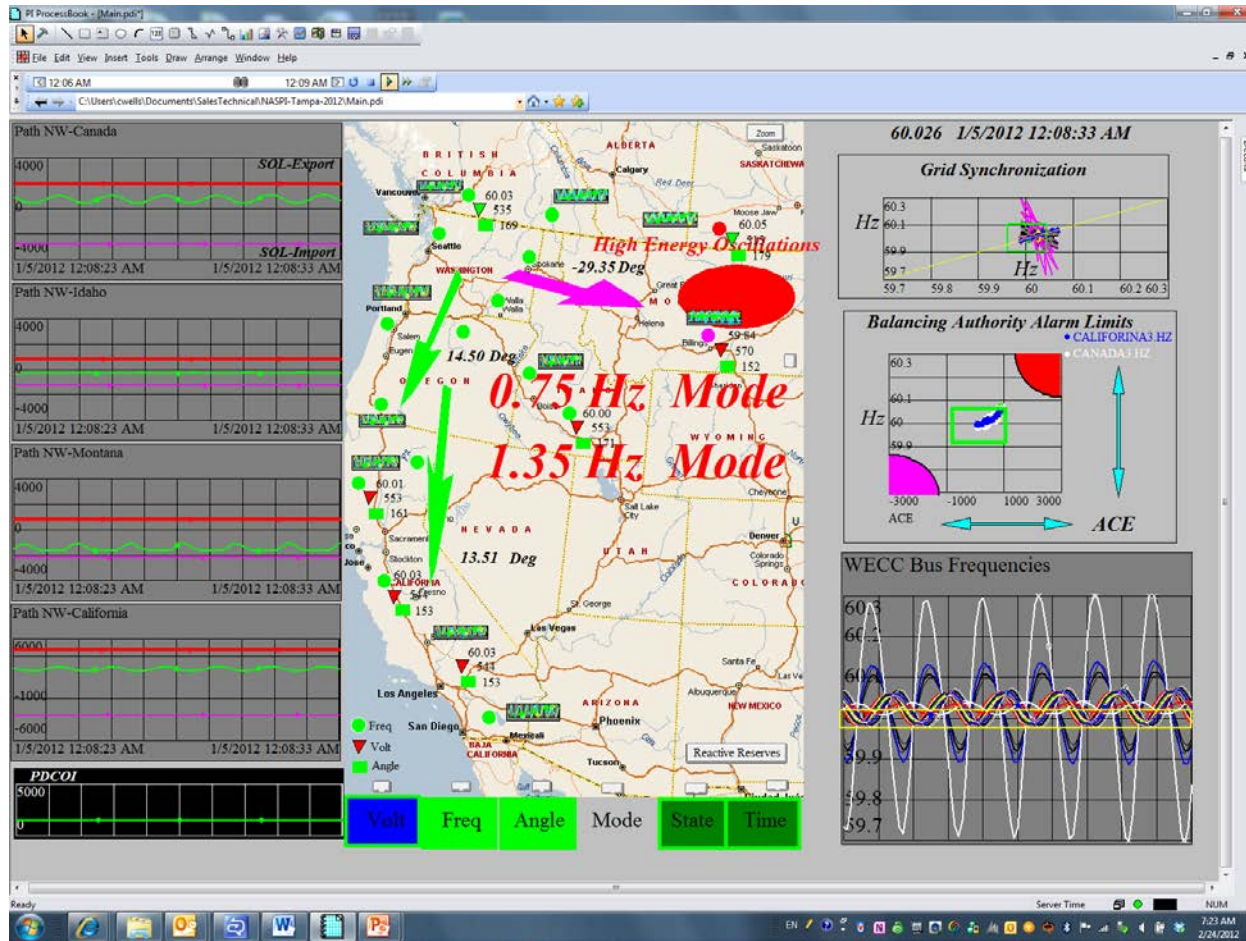
| A | B | C | D | E | F | G | H | I | J |
|-----------------|--------------|--------------|----------|--------------|----------|--------------|-----------|--------------|------------|
| | VAR_30 | VAR16_30 | Delta | VAR_spec_30 | Delta | VAR_5X_30 | Delta | VAR_20X_30 | Delta |
| Average | 9253.44962 | 9253.45127 | -0.00165 | 9253.45610 | -0.00648 | 9253.88072 | -0.43111 | 9257.11393 | -3.66431 |
| Variance | 464815.73667 | 464815.97962 | 0.19366 | 464815.15704 | 0.78254 | 464759.52293 | 63.83568 | 463569.45473 | 1428.92089 |
| Maximum | 14566.08105 | 14566.48438 | 0.76270 | 14566.08105 | 4.15039 | 14566.08105 | 20.74316 | 14566.08105 | 83.00293 |
| Minimum | 7156.90820 | 7156.59033 | -0.76270 | 7156.90820 | -4.14844 | 7156.90820 | -20.75098 | 7170.46924 | -82.99805 |
| Compdev | 0 | | 0 | | 4.15021 | | 20.75104 | | 83.00416 |
| Archived events | 54001 | 54001 | | 46591 | | 27190 | | 7435 | |
| % Compression | 0 | 0 | | 13.7% | | 49.6% | | 86.2% | |

| A | B | C | D | E | F | G | H | I | J |
|-----------------|--------------|----------------|------------|-------------------|------------|-----------------|------------|------------------|------------|
| | Frequency_30 | Frequency16_30 | Delta | Frequency_spec_30 | Delta | Frequency_5X_30 | Delta | Frequency_20X_30 | Delta |
| Average | 59.9968750 | 59.9968747 | 0.0000003 | 59.9968750 | 0.0000000 | 59.9968759 | -0.0000008 | 59.9968732 | 0.0000018 |
| Variance | 0.0001222 | 0.0001222 | 0.0000000 | 0.0001222 | 0.0000000 | 0.0001222 | 0.0000000 | 0.0001219 | 0.0000003 |
| Maximum | 60.0349197 | 60.0350952 | 0.0003052 | 60.0349197 | 0.0000611 | 60.0349197 | 0.0003014 | 60.0349197 | 0.0011979 |
| Minimum | 59.9657326 | 59.9655151 | -0.0003052 | 59.9657326 | -0.0000611 | 59.9657326 | -0.0003014 | 59.9657326 | -0.0011979 |
| Compdev | 0.0000000 | | 0.0000000 | | 0.0000600 | | 0.0002998 | | 0.0011990 |
| Archived events | 54001 | 54001 | | 48319 | | 30763 | | 10946 | |
| % Compression | 0 | 0 | | 10.5% | | 43.0% | | 79.7% | |

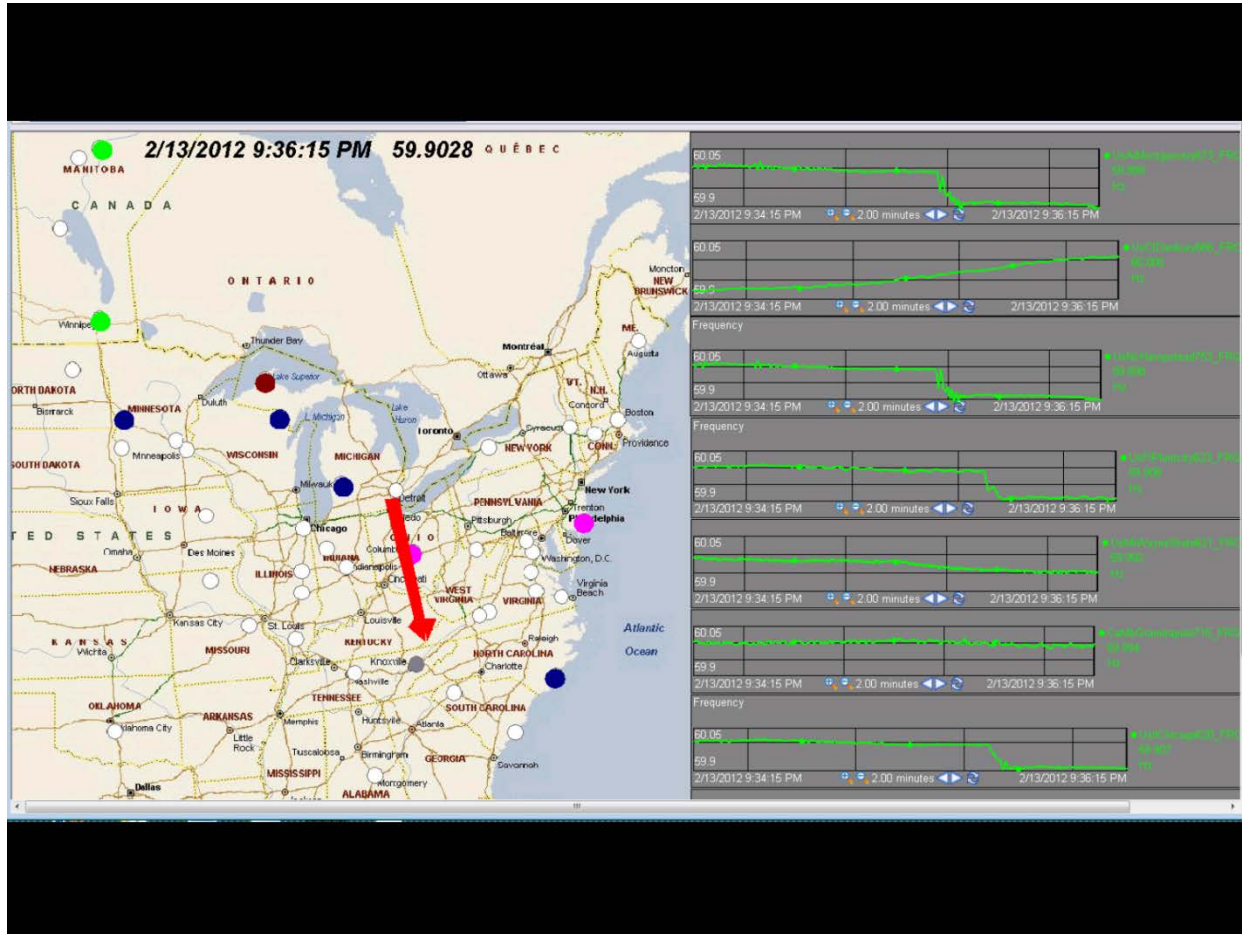
Visualization of phasor data



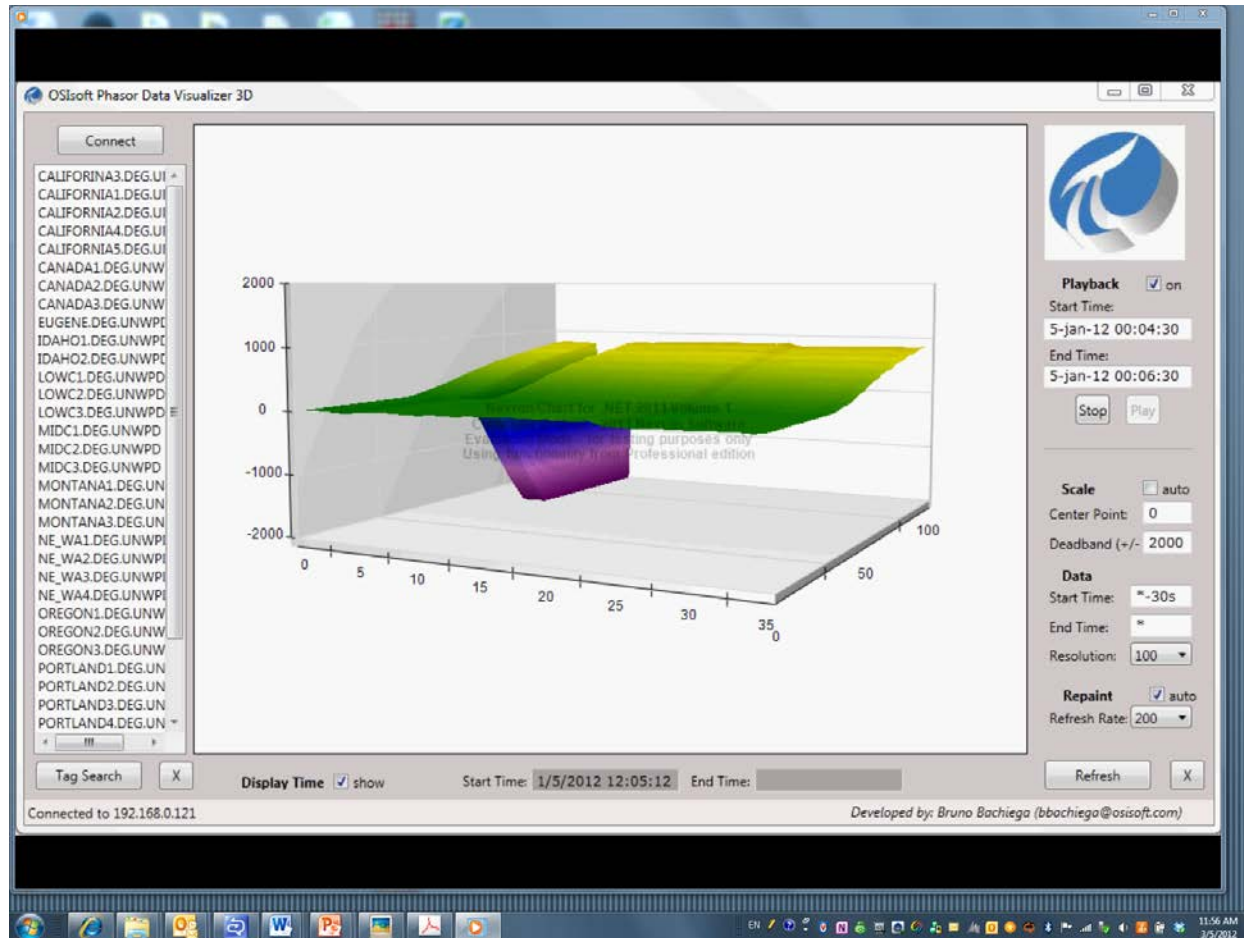
Visualization of phasor data



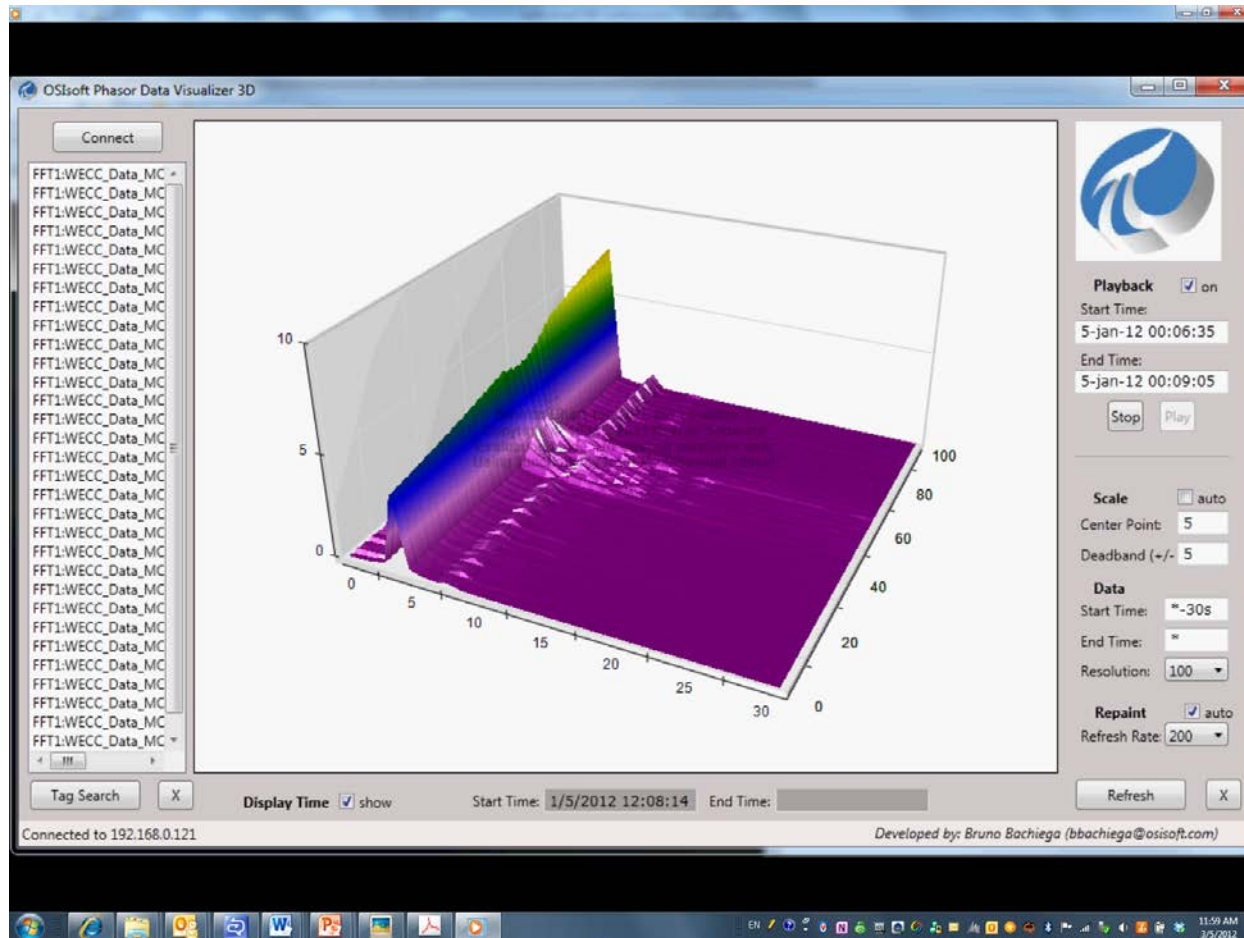
Eastern Interconnection oscillation



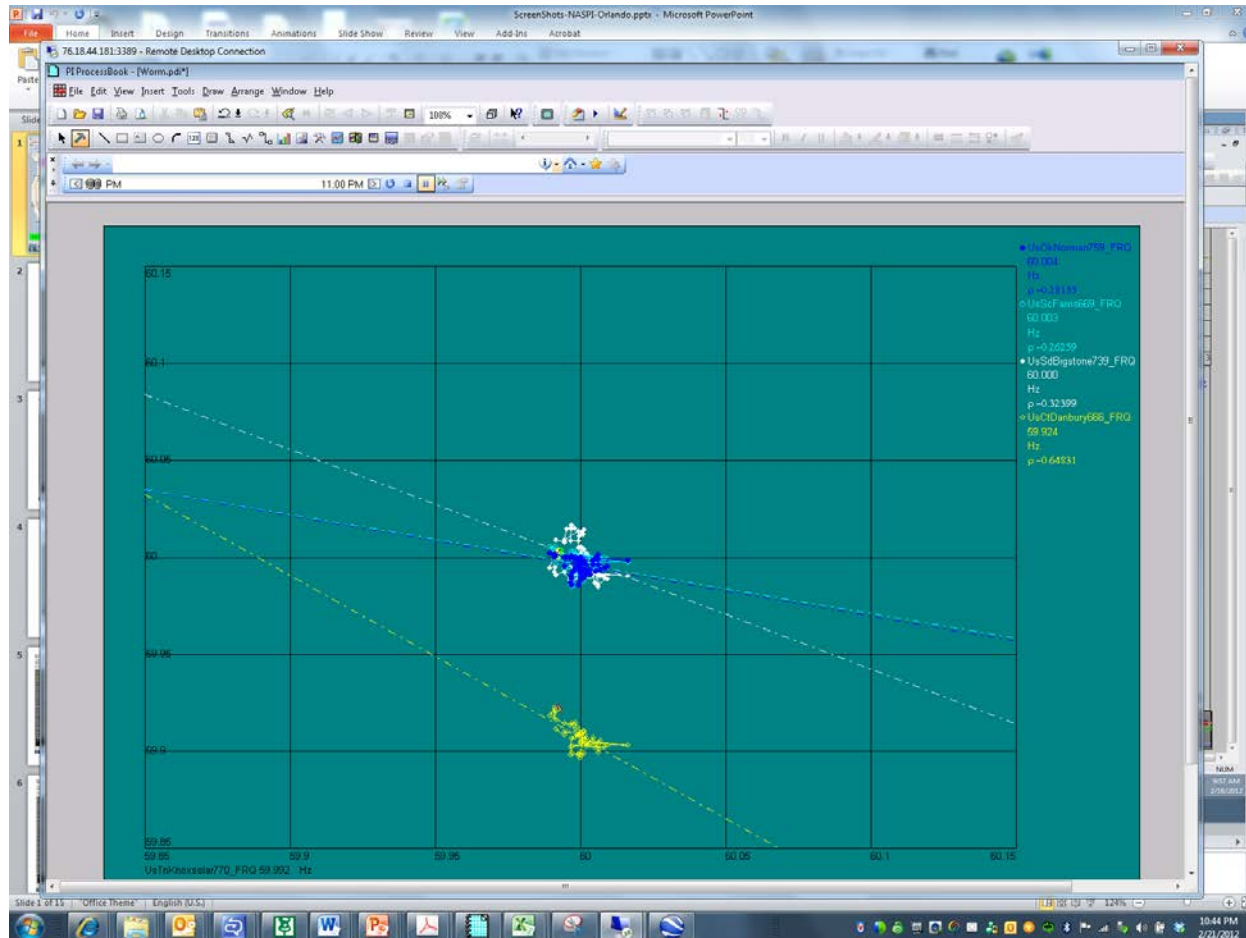
Angle surface



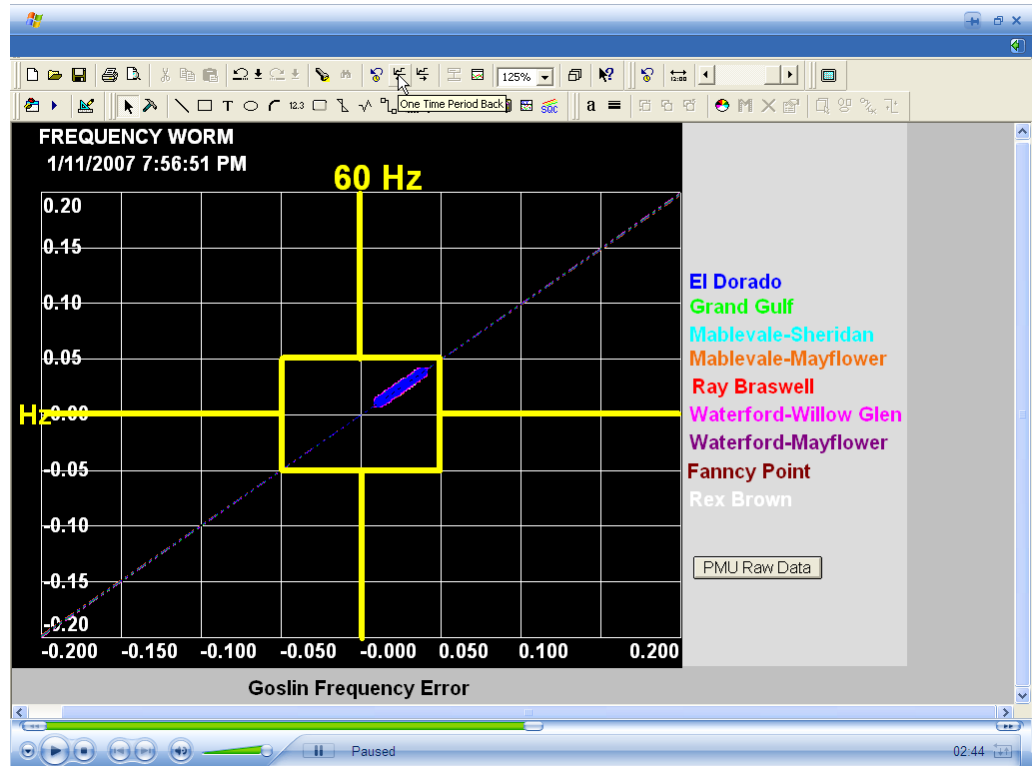
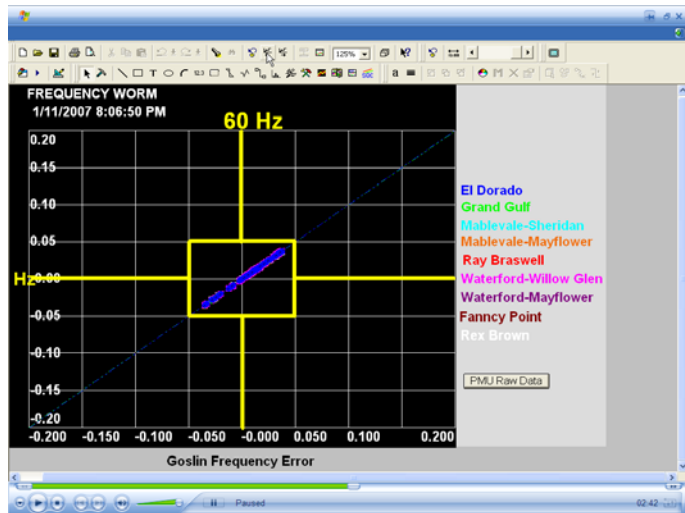
FFT Waterfall



WORM chart Eastern Interconnection (FNET data)



Customer Examples- Grid coherency



Real time FFTs, Phase portraits, SQC

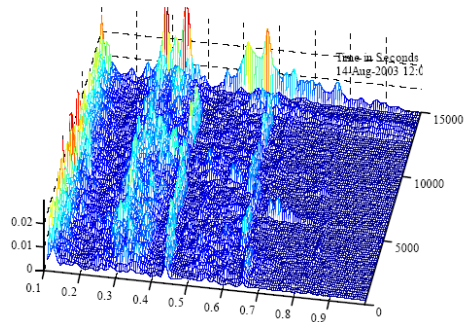
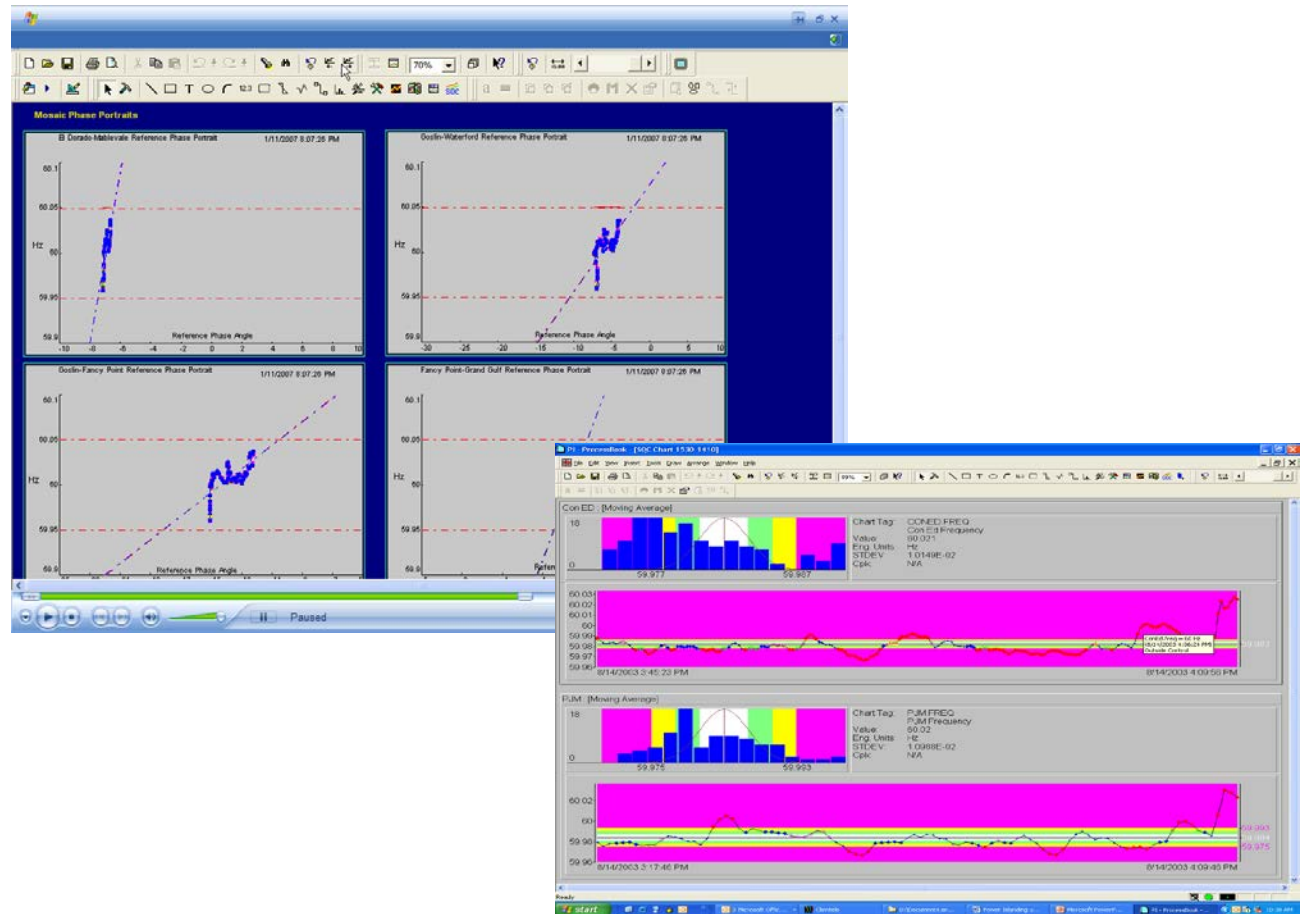
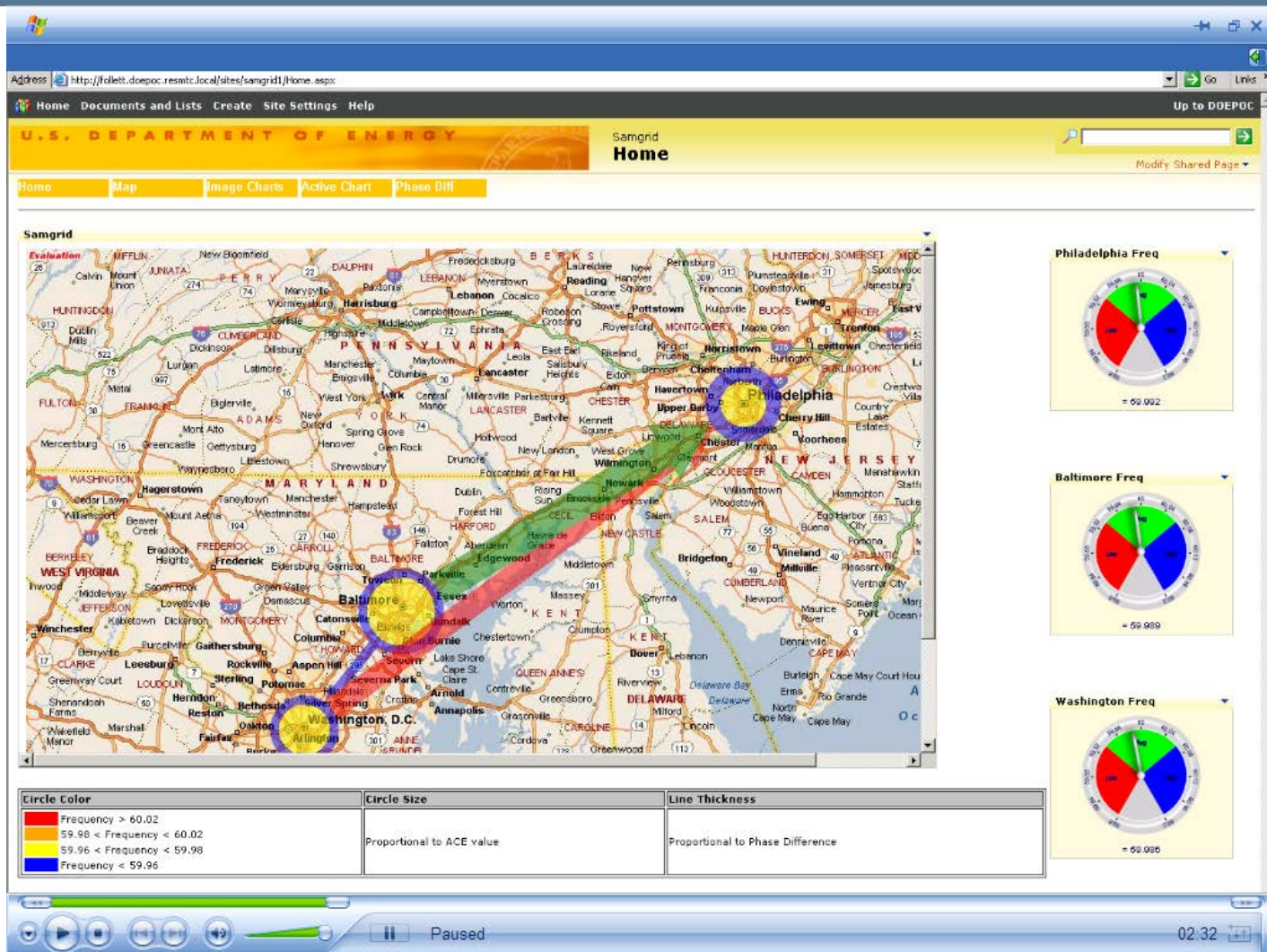


Fig. 12. Spectral history of AEP Kanawha River bus frequency for August 14 Blackout. 12:00-16:10 EDT



Customer Examples



Contacts

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