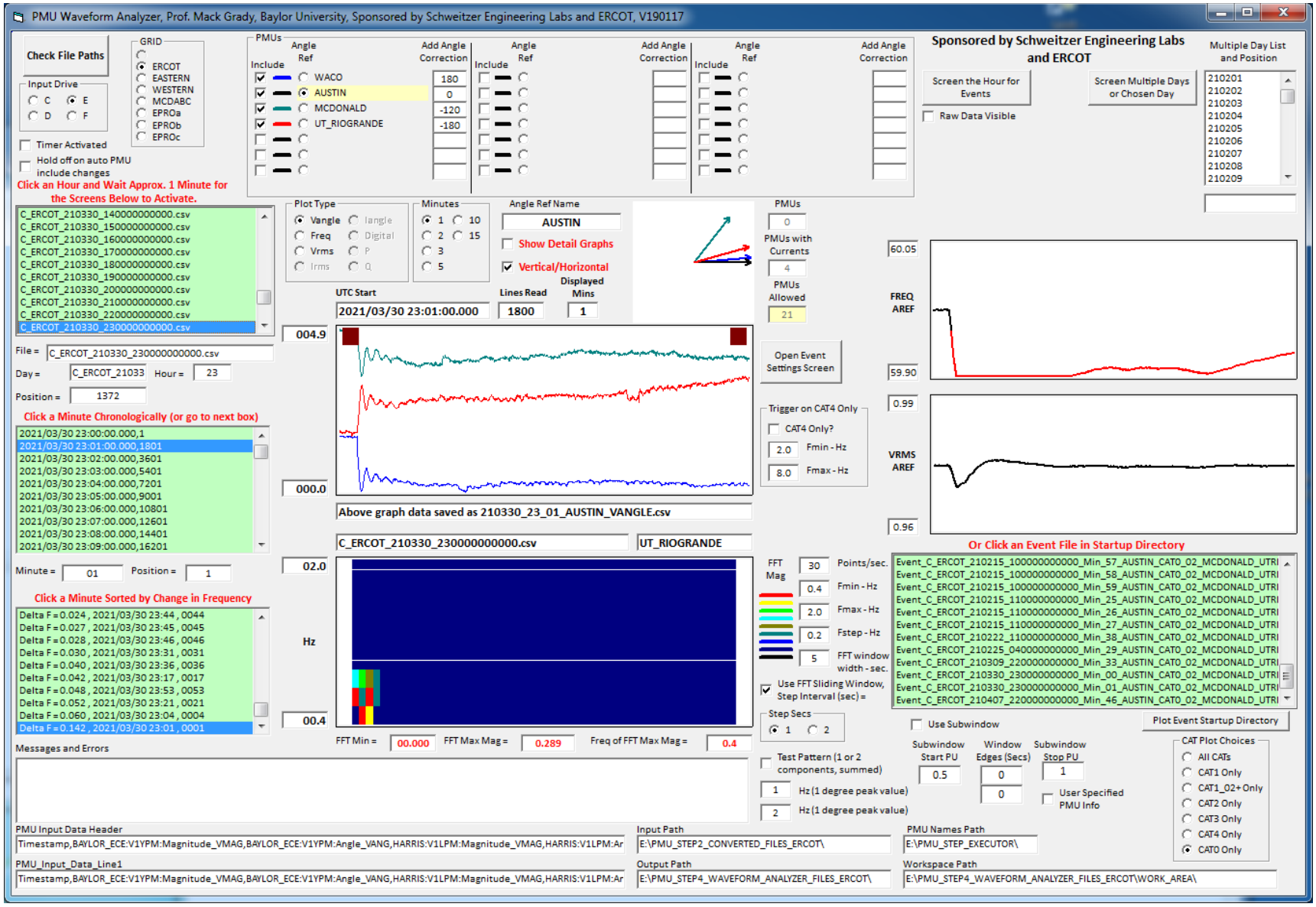
Examples of Using Synchrophasors to Detect and Understand Grid Events and the Impact of Wind and Solar Generation

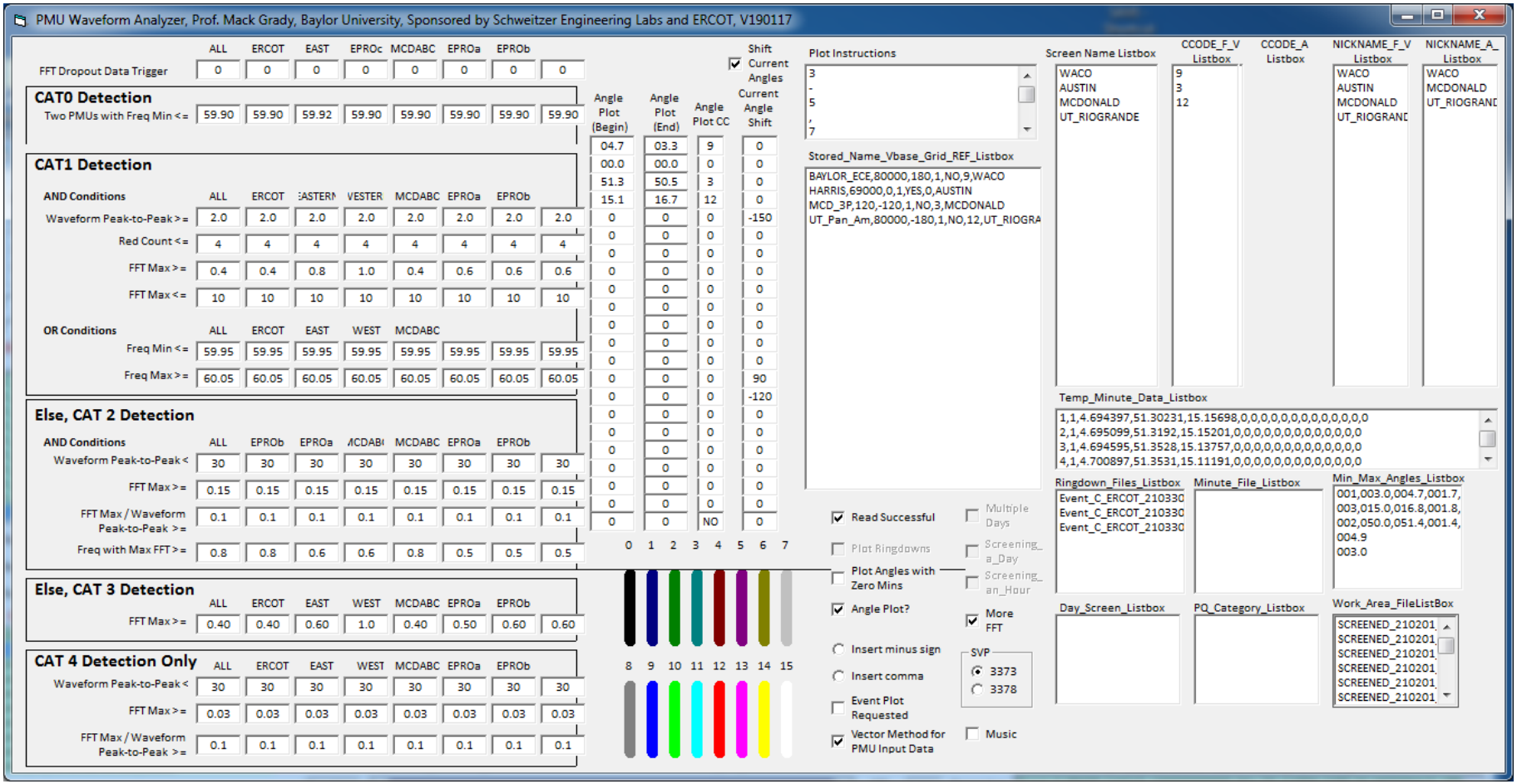
Prof. Mack Grady, Baylor University

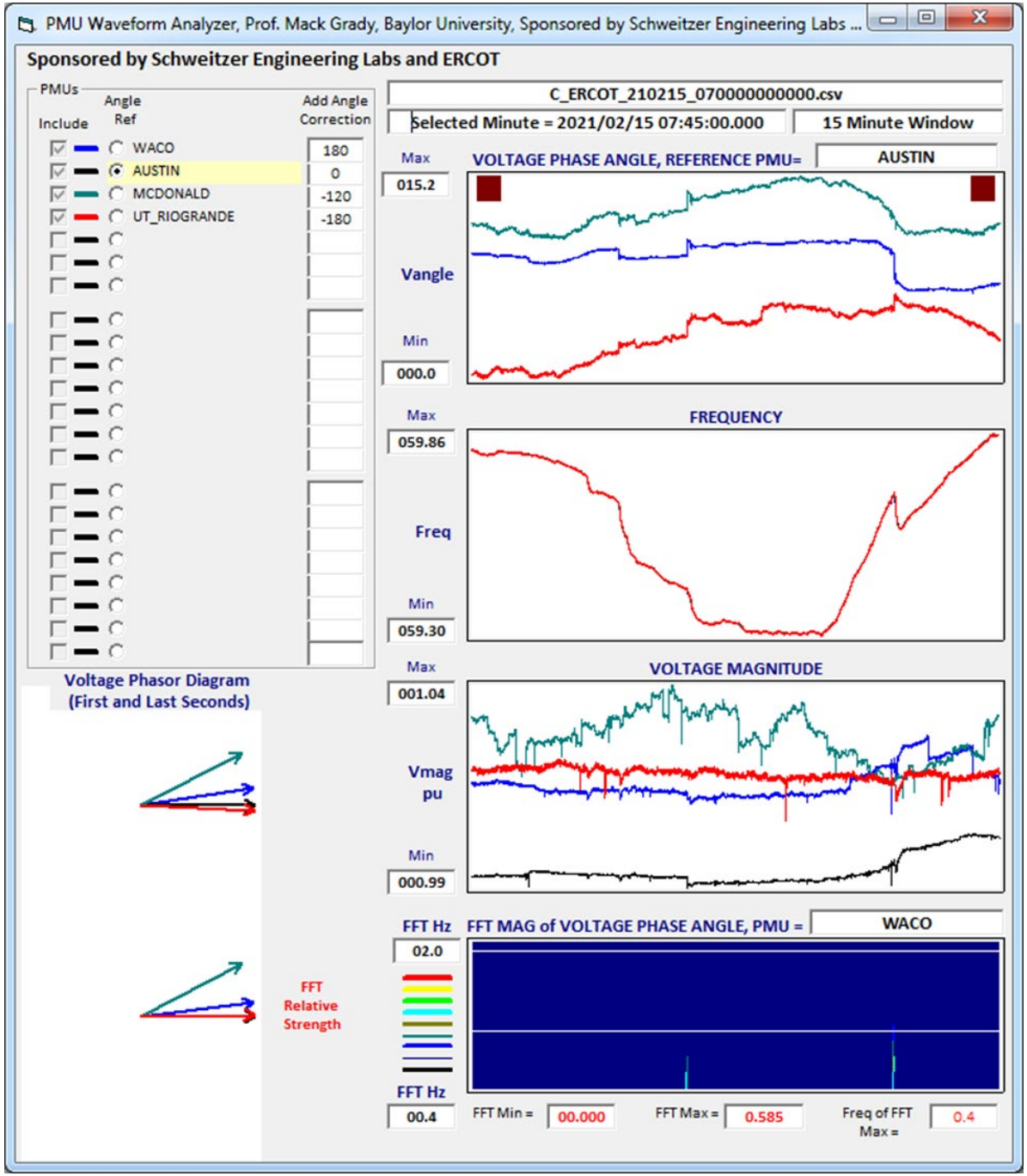
NASPI Work Group Virtual Meeting
April 14, 2021

Event Detection

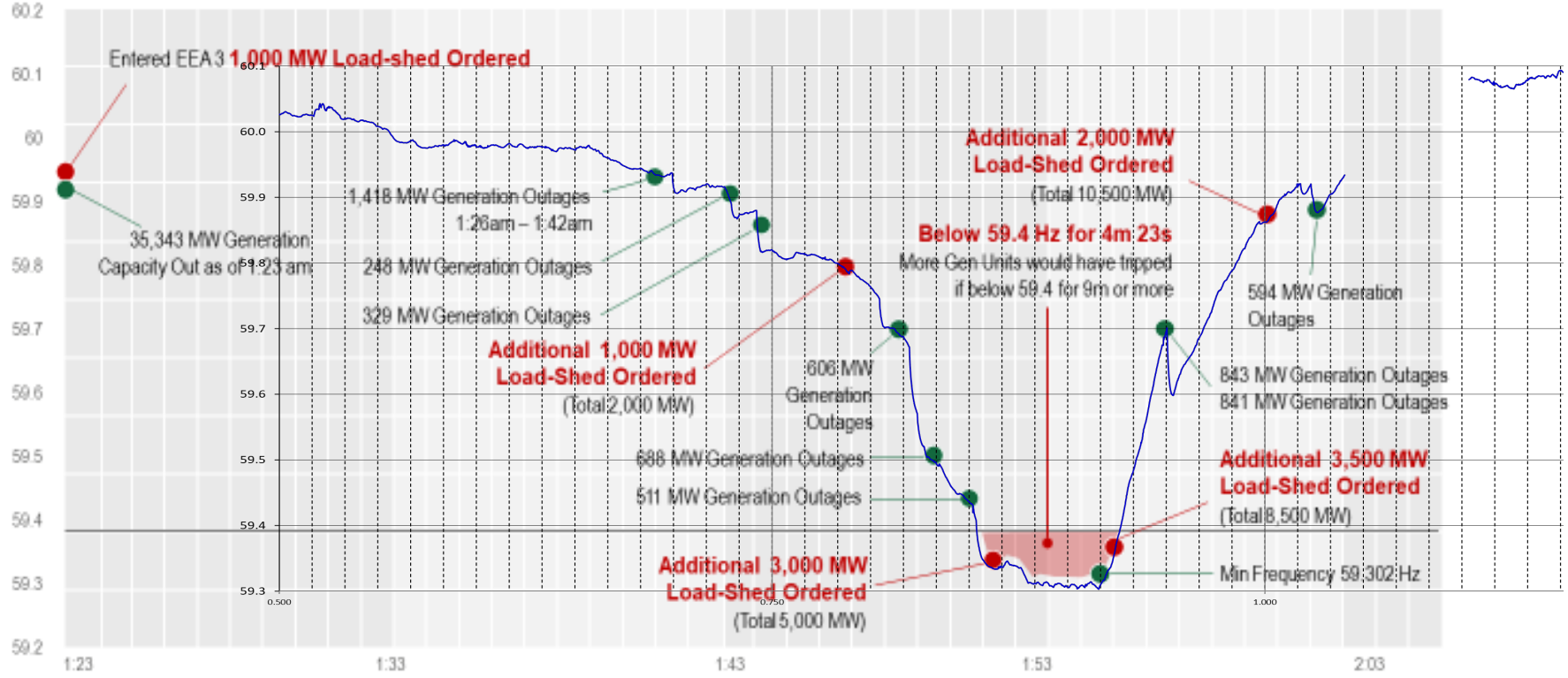


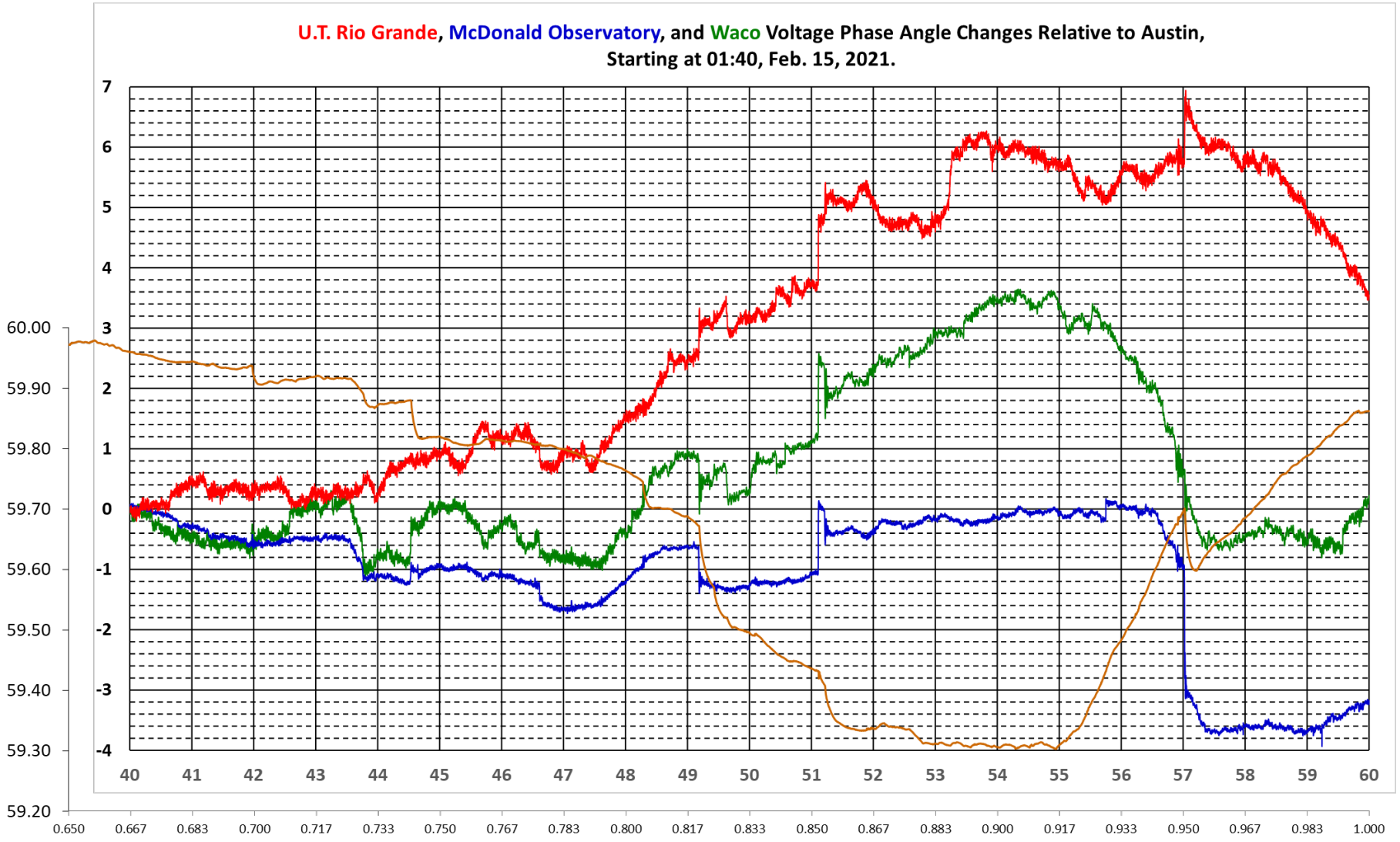
Event Detection Triggers




PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
WACO
180
AUSTIN
0
MCDONALD
-120
UT_RIOGRANDE
-180
C_ERCOT_210215_070000000000.csv
Selected Minute = 2021/02/15 07:45:00.000
15 Minute Window
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Max
015.2
Vangle
Min
000.0
FREQUENCY
Max
059.86
Freq
Min
059.30
VOLTAGE MAGNITUDE
Max
001.04
Vmag pu
Min
000.99
Voltage Phasor Diagram (First and Last Seconds)
FFT Relative Strength
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
WACO
FFT Hz
00.4
FFT Min =
00.000
FFT Max =
0.585
Freq of FFT Max =
0.4

Rapid Decrease in Generation Causes Frequency Drop

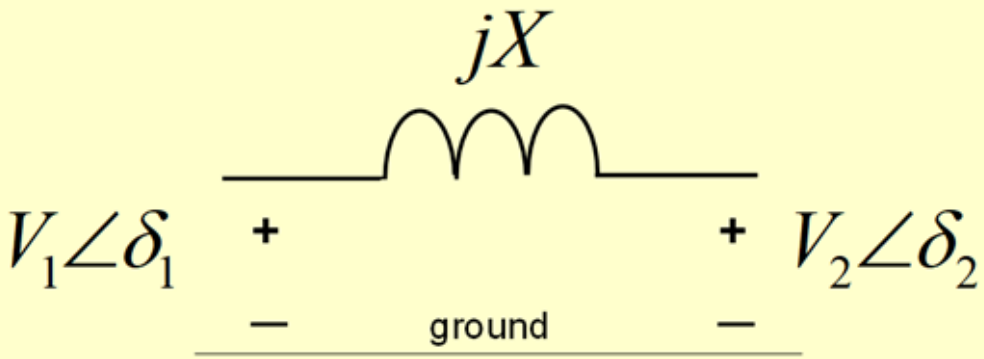



U.T. Rio Grande, McDonald Observatory, and Waco Voltage Phase Angle Changes Relative to Austin,
Starting at 01:40, Feb. 15, 2021.
7
6
5
4
3
2
1
0
-1
-2
-3
-4
60.00
59.90
59.80
59.70
59.60
59.50
59.40
59.30
59.20
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
0.650
0.667
0.683
0.700
0.717
0.733
0.750
0.767
0.783
0.800
0.817
0.833
0.850
0.867
0.883
0.900
0.917
0.933
0.950
0.967
0.983
1.000

Why are Synchrophasors Important?

Here's All You Need to Remember

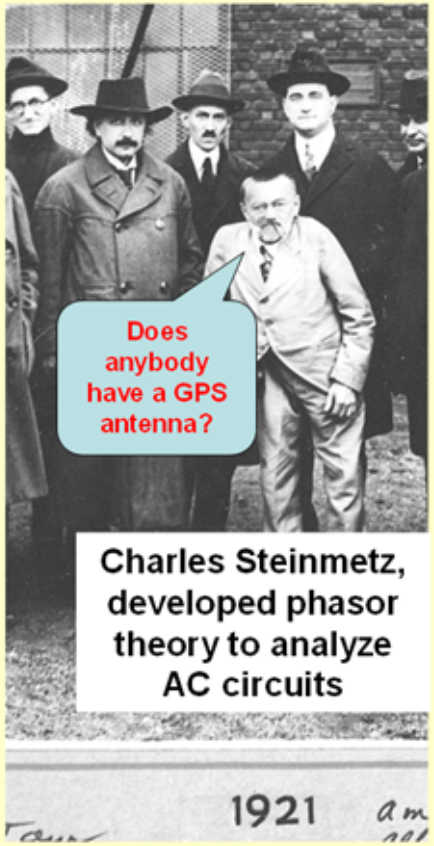
Average Power Flow P Through a Mostly Inductive Transmission Line (138kV and above)



These are about 1pu

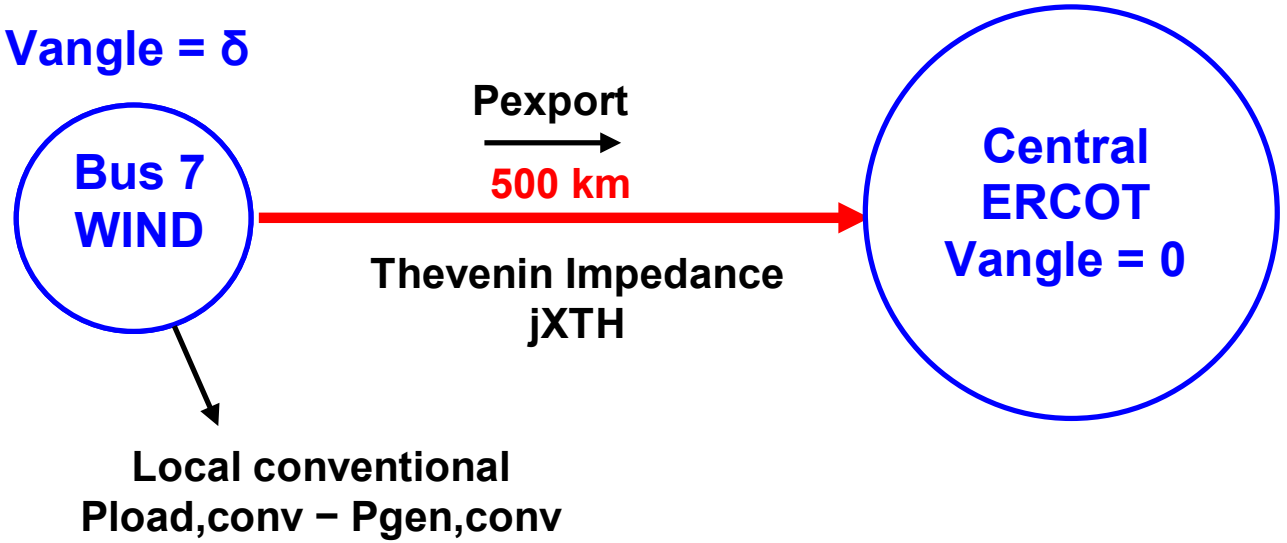
For small x, sin(x) = x

$$P = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$$



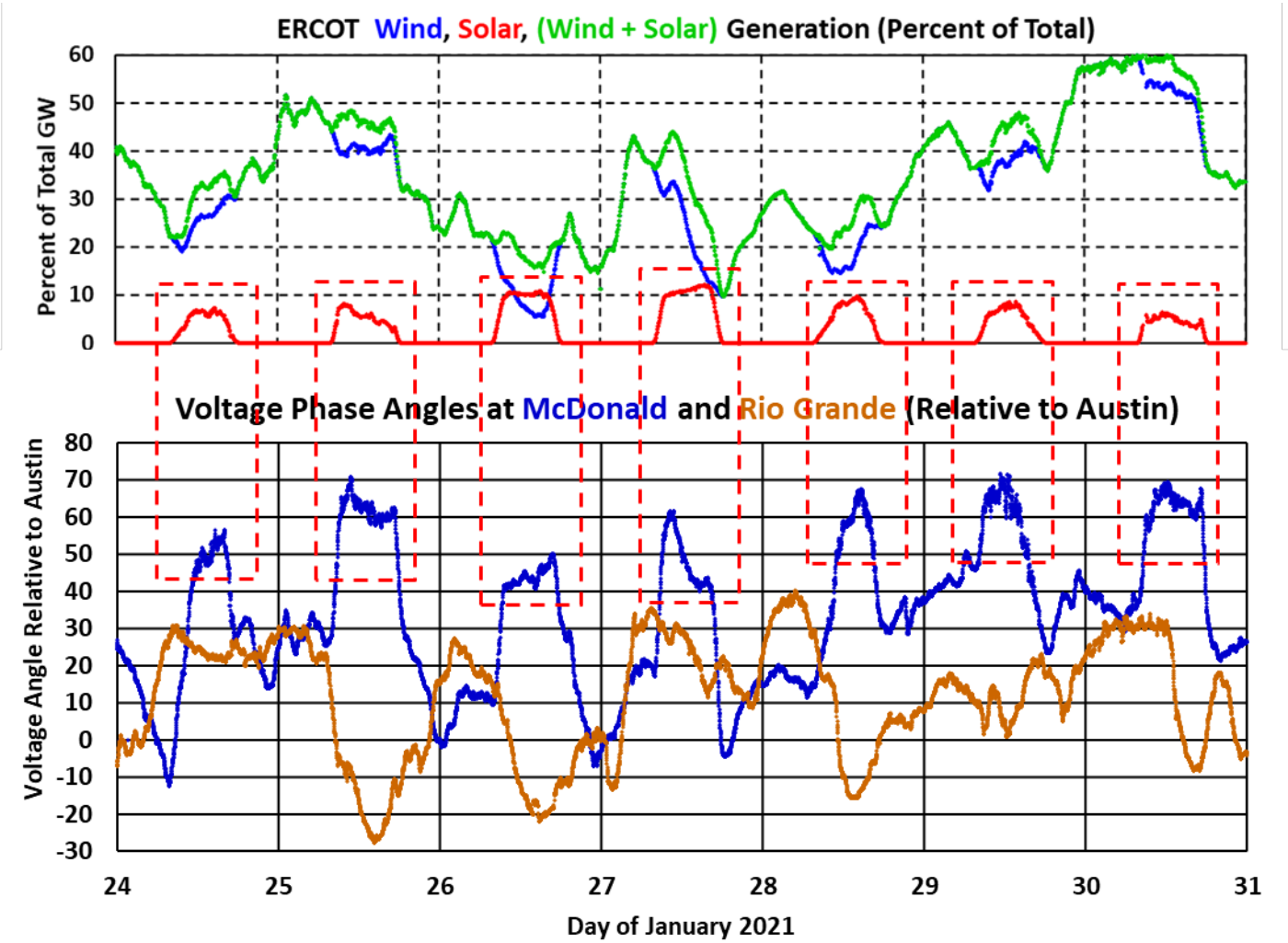
Stability limit is when the angle difference reaches 90 degrees

If Power Transfer Between Two Grid Regions is Known, and the Phase Angle Difference is Also Known, then the Thevenin Equivalent Impedance Between the Two Regions can be Computed

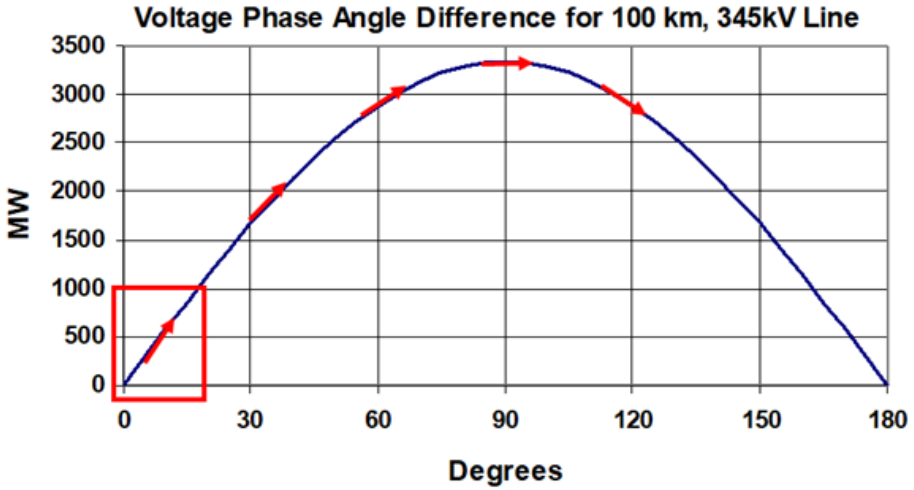


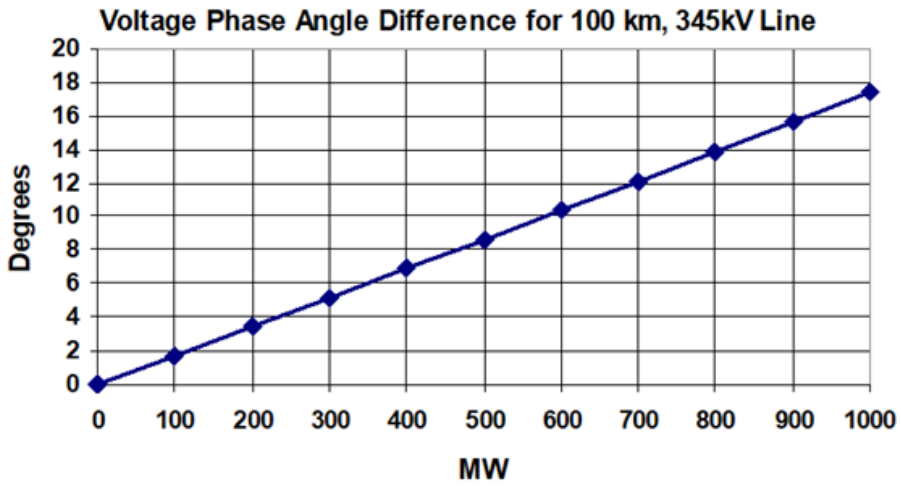
$$P = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$$

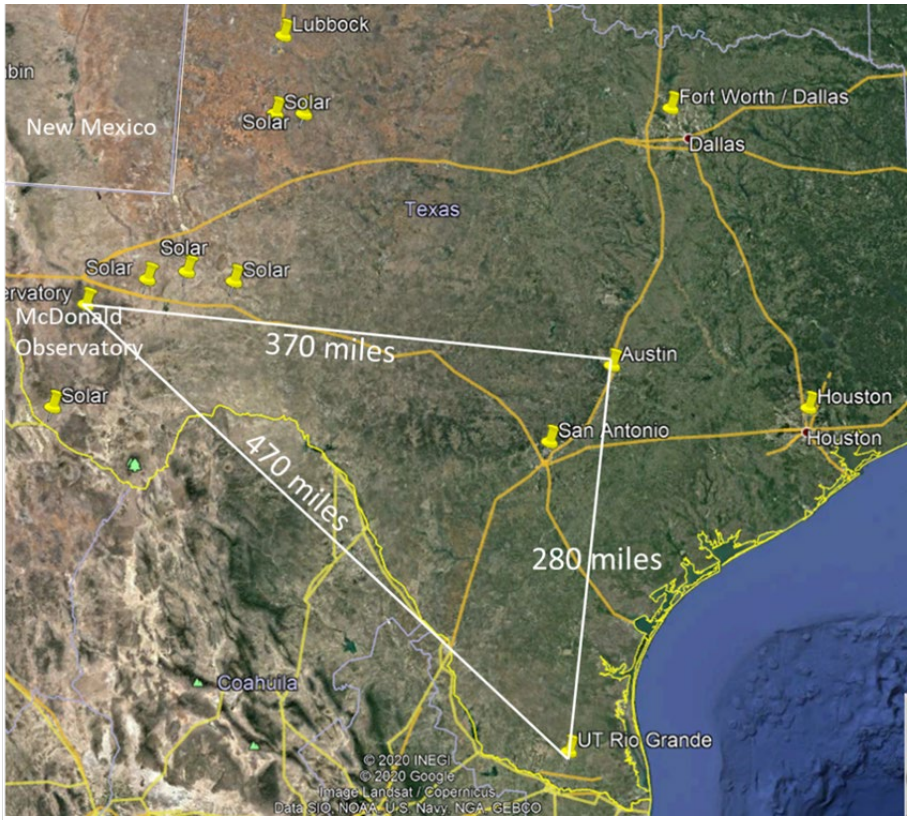
Solve

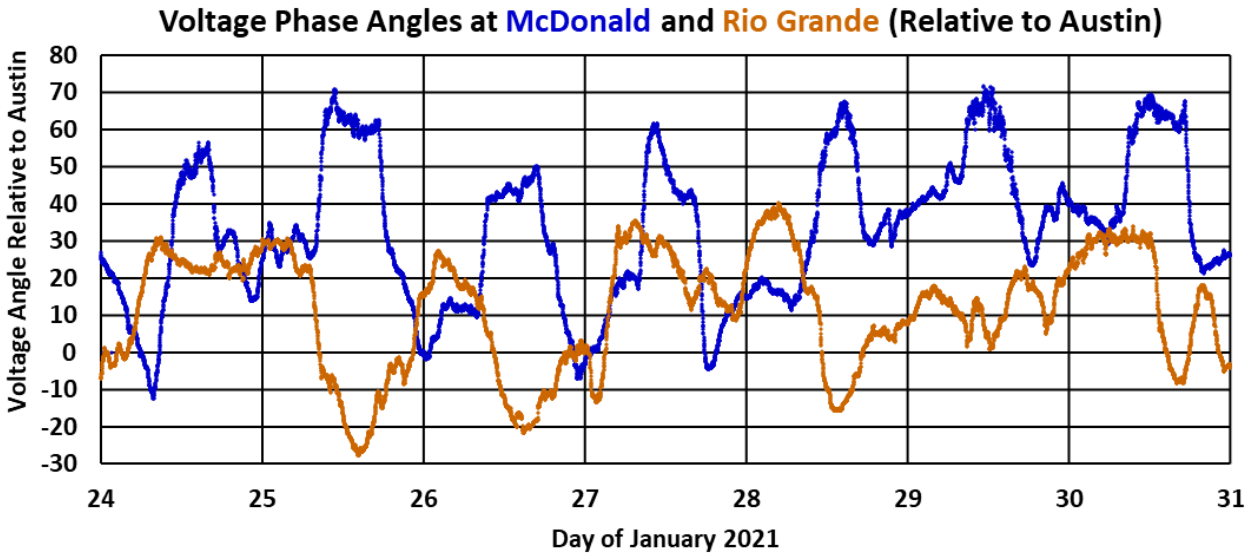

ERCOT Wind, Solar, (Wind + Solar) Generation (Percent of Total)
Percent of Total GW
60
50
40
30
20
10
0
Voltage Phase Angles at McDonald and Rio Grande (Relative to Austin)
Voltage Angle Relative to Austin
80
70
60
50
40
30
20
10
0
-10
-20
-30
24
25
26
27
28
29
30
31
Day of January 2021

Most solar generation is relatively close to McDonald Observatory, and far from the PMU reference at Austin. Voltage angle difference between McDonald and Austin rises as solar generation rises. As a first approximation, MW flow is proportional to the **sine of the voltage angle difference.** You can see in the right-hand curve above that degrees per MW are smallest at zero degrees, and gradually move toward infinity at 90 degrees.

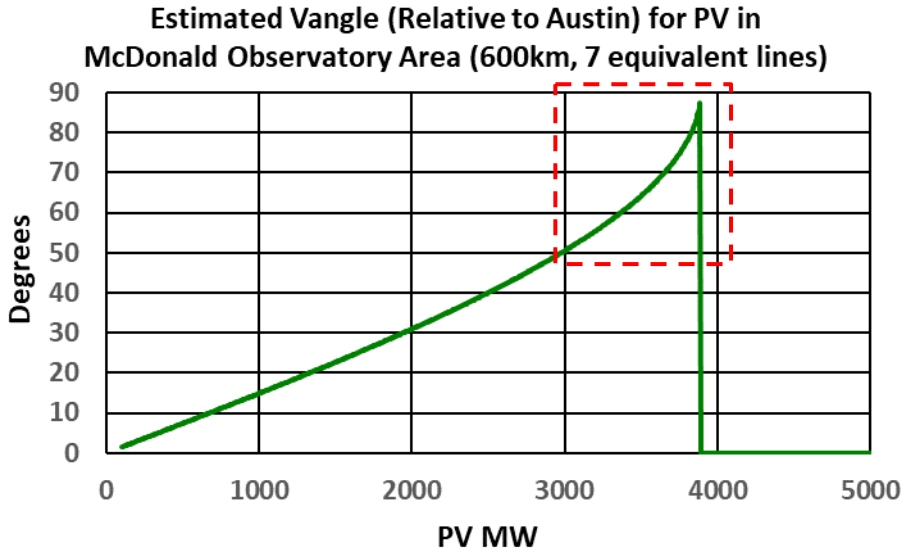


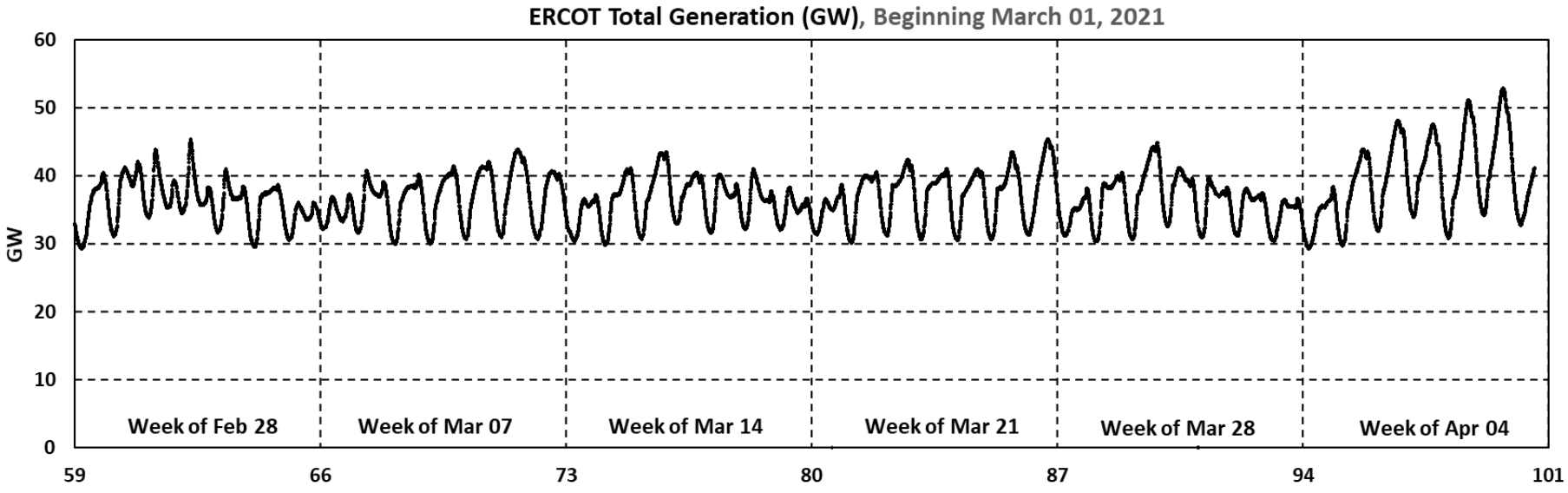


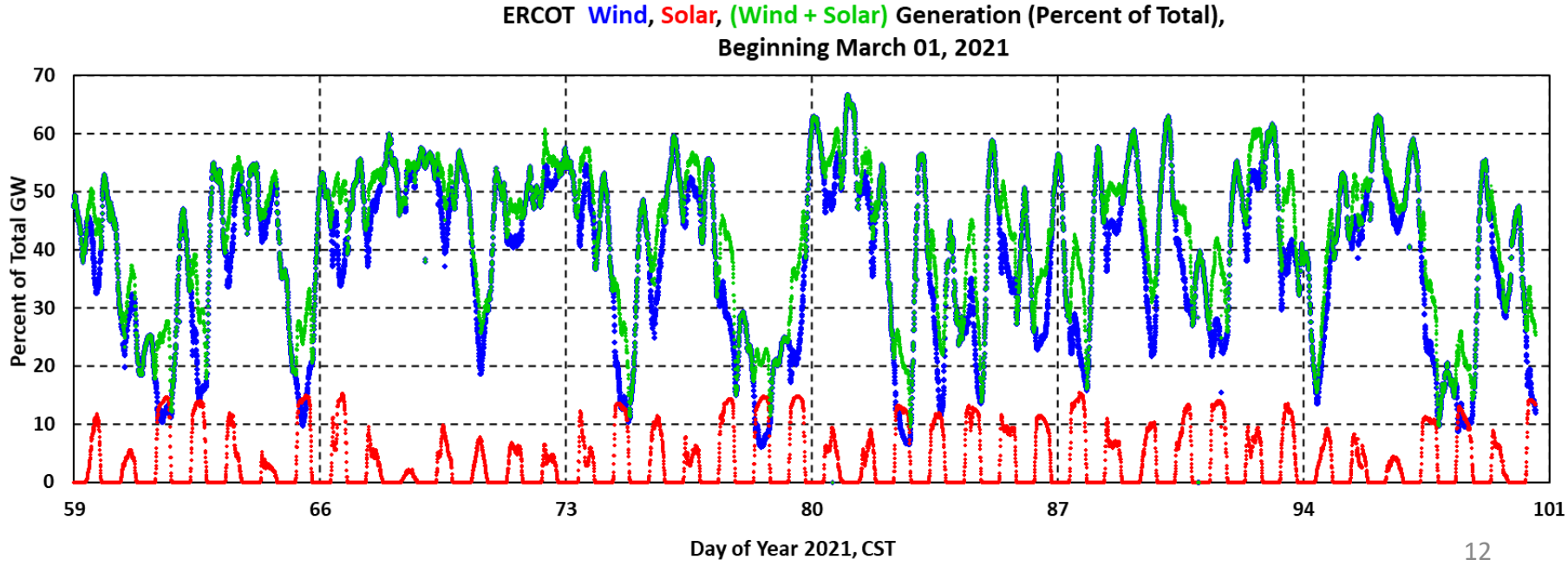


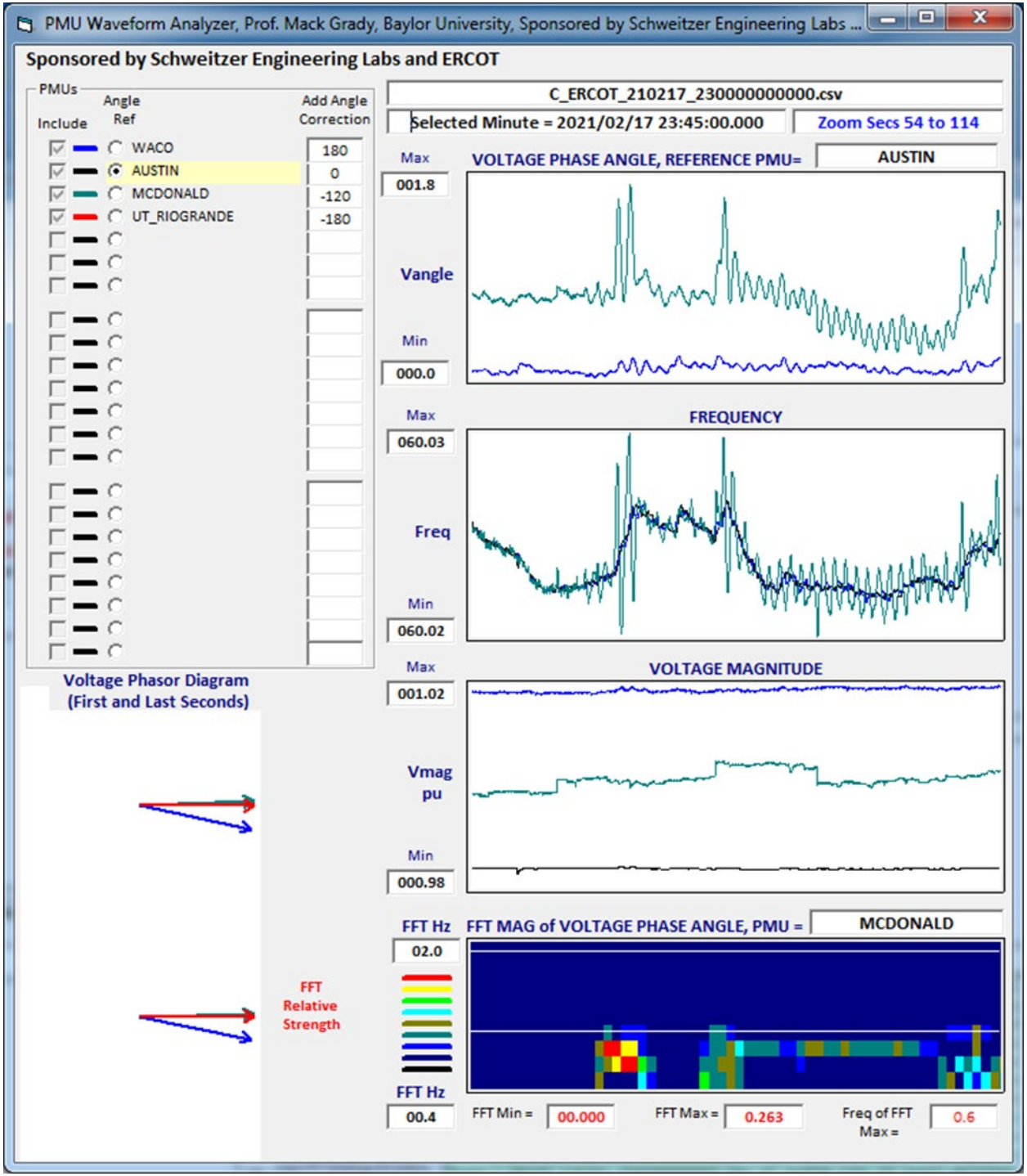


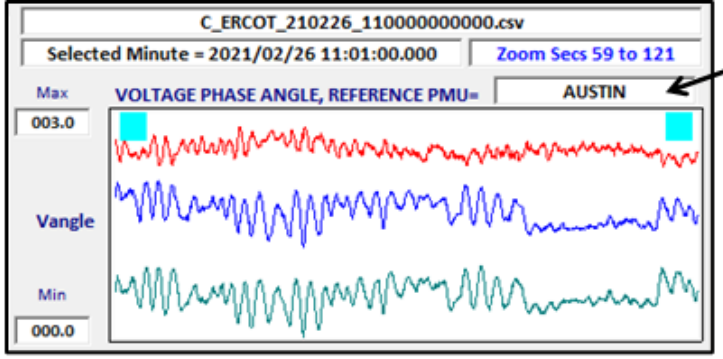
By experimenting with the number of equivalent 345 kV lines between McDonald Observatory and Austin, we find that 7 parallel lines place the sharply nonlinear range of Degrees per MW in the typical PV 3000 to 4000 MW daily range.



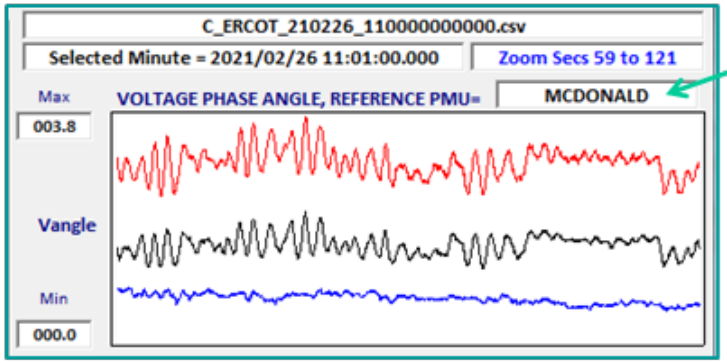

ERCOT Total Generation (GW), Beginning March 01, 2021
GW
60
50
40
30
20
10
0
Week of Feb 28
Week of Mar 07
Week of Mar 14
Week of Mar 21
Week of Mar 28
Week of Apr 04
59
66
73
80
87
94
101


ERCOT Wind, Solar, (Wind + Solar) Generation (Percent of Total),
Beginning March 01, 2021
Percent of Total GW
70
60
50
40
30
20
10
0
59
66
73
80
87
94
101
Day of Year 2021, CST

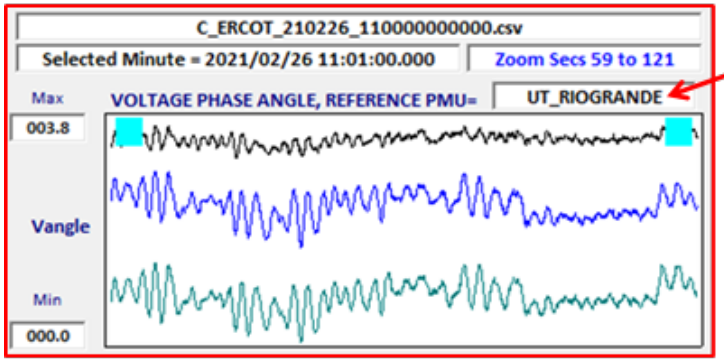

PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
WACO
180
AUSTIN
0
MCDONALD
-120
UT_RIOGRANDE
-180
C_ERCOT_210217_230000000000.csv
Selected Minute = 2021/02/17 23:45:00.000
Zoom Secs 54 to 114
Max
001.8
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Vangle
Min
000.0
Max
060.03
FREQUENCY
Freq
Min
060.02
Max
001.02
VOLTAGE MAGNITUDE
Vmag pu
Min
000.98
Voltage Phasor Diagram (First and Last Seconds)
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
FFT Relative Strength
FFT Hz
00.4
FFT Min =
00.000
FFT Max =
0.263
Freq of FFT Max =
0.6



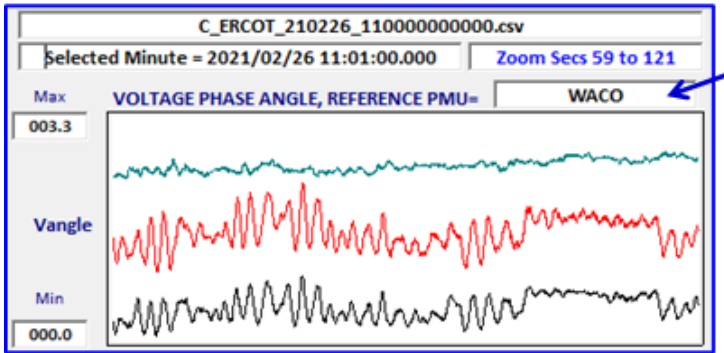
View from **Austin**. **Waco** and **McDonald** are oscillating in-phase. **UT Rio Grande** oscillation is small, and 180 degrees out of phase with **Waco** and **McDonald**.



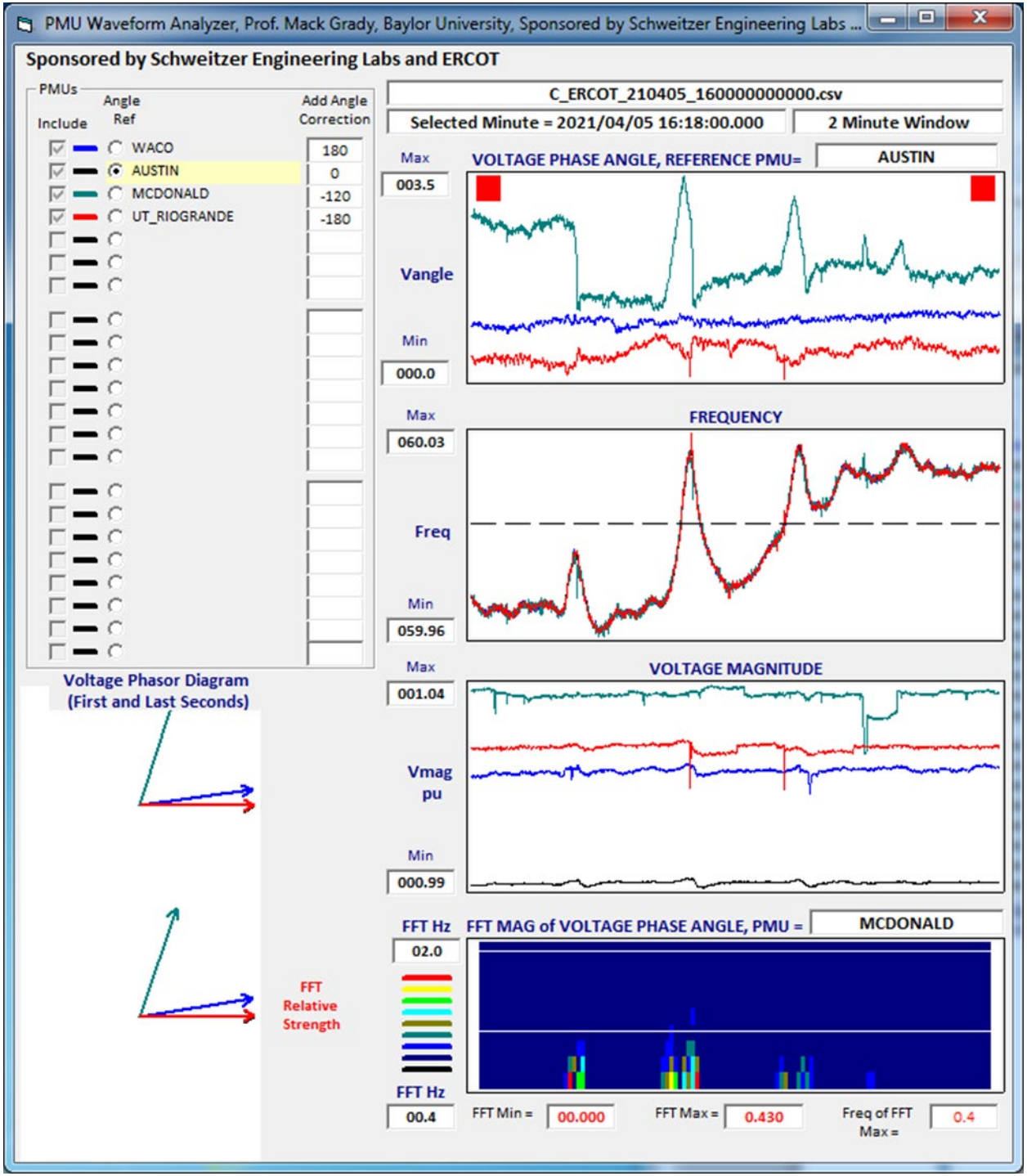
View from **McDonald**, **UT Rio Grande** and **Austin** are oscillating in-phase, and **Waco** is not oscillating.



View from **UT Rio Grande**, **Waco** and **McDonald** are oscillating in phase. **Austin** oscillation is small and 180 degrees out of phase with **Waco** and **McDonald**.



View from **Waco**, **Austin** and **UT Rio Grande** are oscillating in-phase, and **McDonald** is not oscillating.


PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
WACO
180
AUSTIN
0
MCDONALD
-120
UT_RIOGRANDE
-180
C_ERCOT_210405_160000000000.csv
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2 Minute Window
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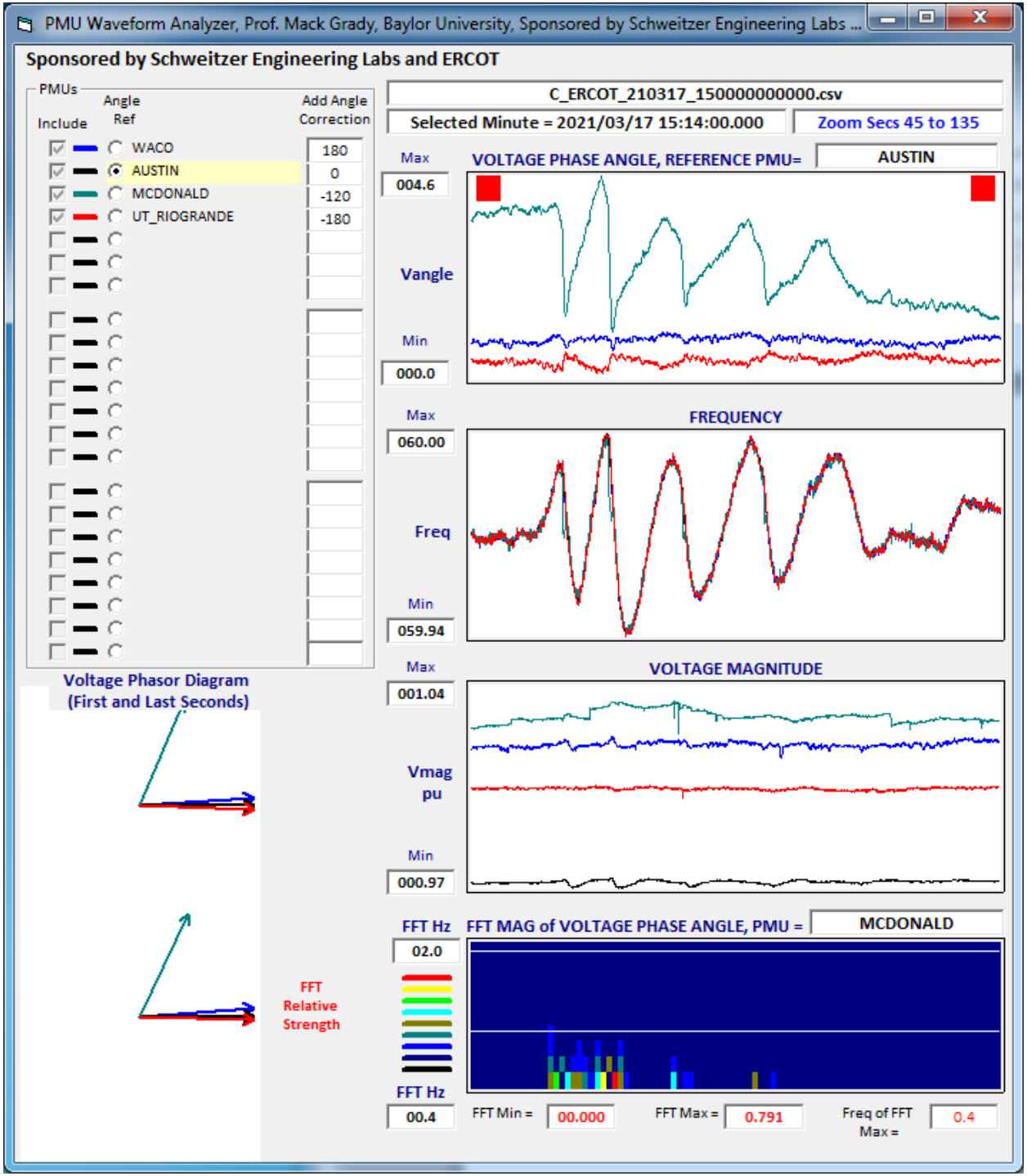
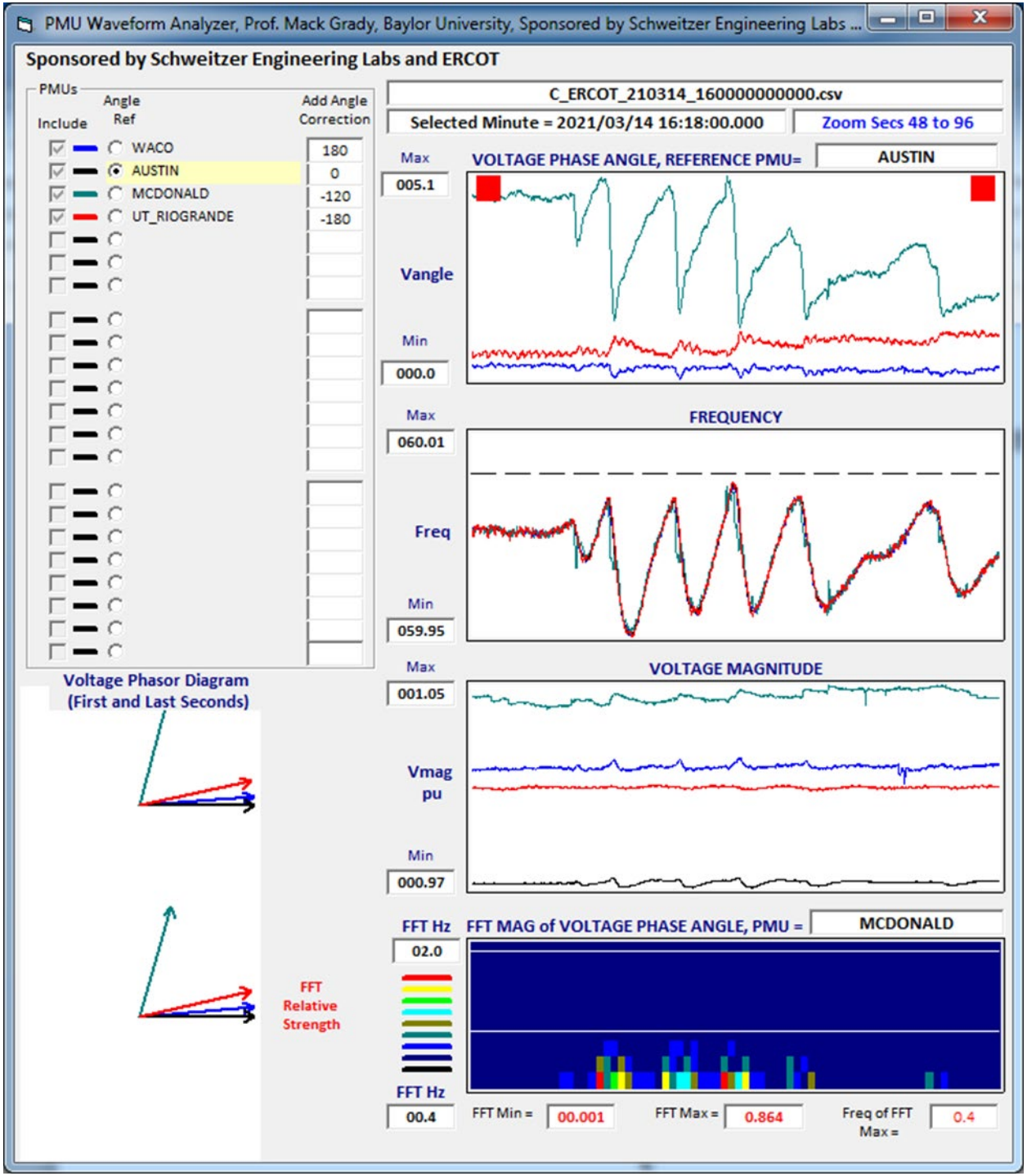
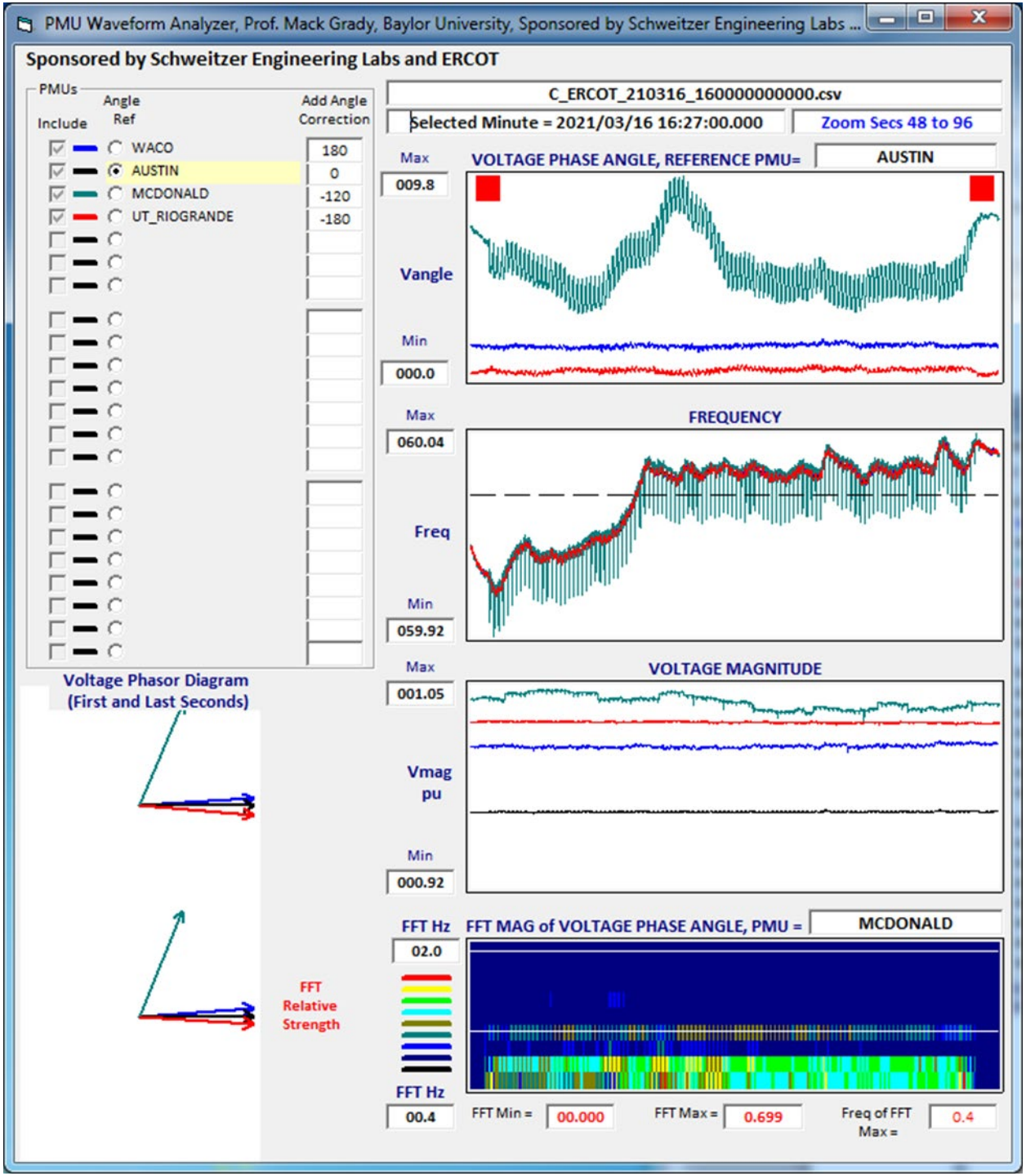
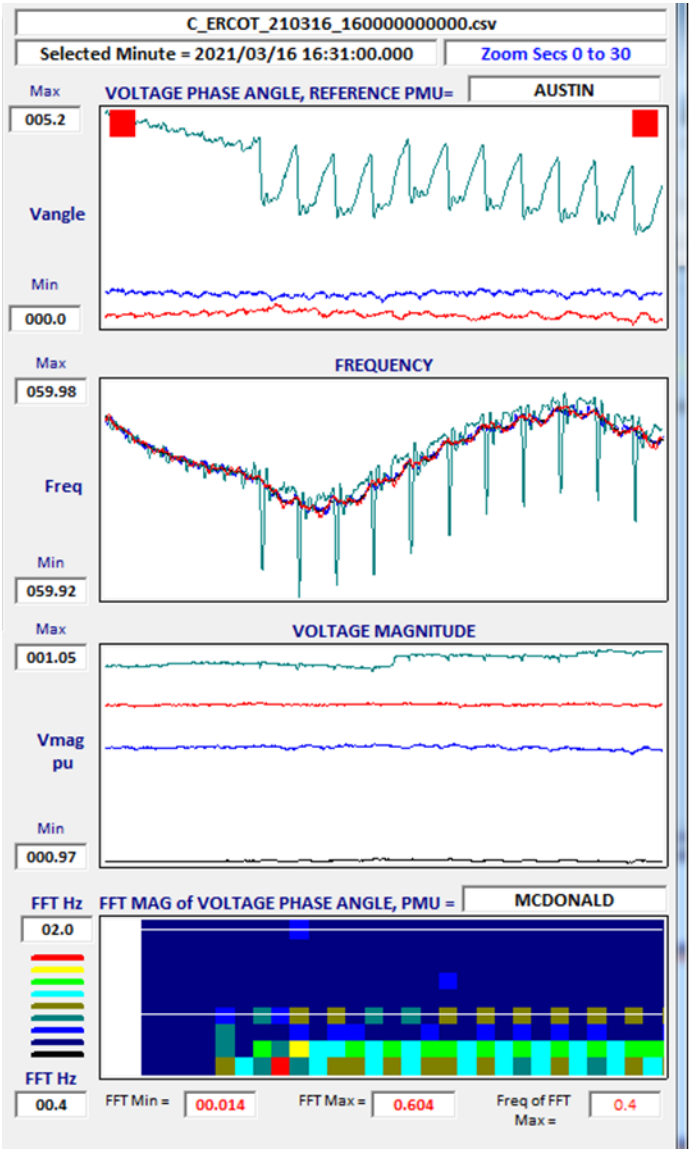
AUSTIN
Max
003.5
Vangle
Min
000.0
FREQUENCY
Max
060.03
Freq
Min
059.96
VOLTAGE MAGNITUDE
Max
001.04
Vmag pu
Min
000.99
Voltage Phasor Diagram (First and Last Seconds)
FFT Relative Strength
FFT Hz
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
02.0
FFT Hz
00.4
FFT Min =
00.000
FFT Max =
0.430
Freq of FFT Max =
0.4


PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
WACO
180
AUSTIN
0
MCDONALD
-120
UT_RIOGRANDE
-180
C_ERCOT_210317_150000000000.csv
Selected Minute = 2021/03/17 15:14:00.000
Zoom Secs 45 to 135
Max
004.6
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Vangle
Min
000.0
Max
060.00
FREQUENCY
Freq
Min
059.94
Voltage Phasor Diagram
(First and Last Seconds)
Max
001.04
VOLTAGE MAGNITUDE
Vmag
pu
Min
000.97
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
FFT
Relative
Strength
FFT Hz
00.4
FFT Min =
00.000
FFT Max =
0.791
Freq of FFT Max =
0.4


PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
WACO
180
AUSTIN
0
MCDONALD
-120
UT_RIOGRANDE
-180
C_ERCOT_210314_160000000000.csv
Selected Minute = 2021/03/14 16:18:00.000
Zoom Secs 48 to 96
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Max
005.1
Vangle
Min
000.0
FREQUENCY
Max
060.01
Freq
Min
059.95
VOLTAGE MAGNITUDE
Max
001.05
Vmag pu
Min
000.97
Voltage Phasor Diagram (First and Last Seconds)
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
FFT Relative Strength
FFT Hz
00.4
FFT Min =
00.001
FFT Max =
0.864
Freq of FFT Max =
0.4


PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
WACO
180
AUSTIN
0
MCDONALD
-120
UT_RIOGRANDE
-180
C_ERCOT_210316_160000000000.csv
Selected Minute = 2021/03/16 16:27:00.000
Zoom Secs 48 to 96
Max
009.8
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Vangle
Min
000.0
Max
060.04
FREQUENCY
Freq
Min
059.92
Max
001.05
VOLTAGE MAGNITUDE
Vmag pu
Min
000.92
Voltage Phasor Diagram (First and Last Seconds)
FFT Relative Strength
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
FFT Hz
00.4
FFT Min =
00.000
FFT Max =
0.699
Freq of FFT Max =
0.4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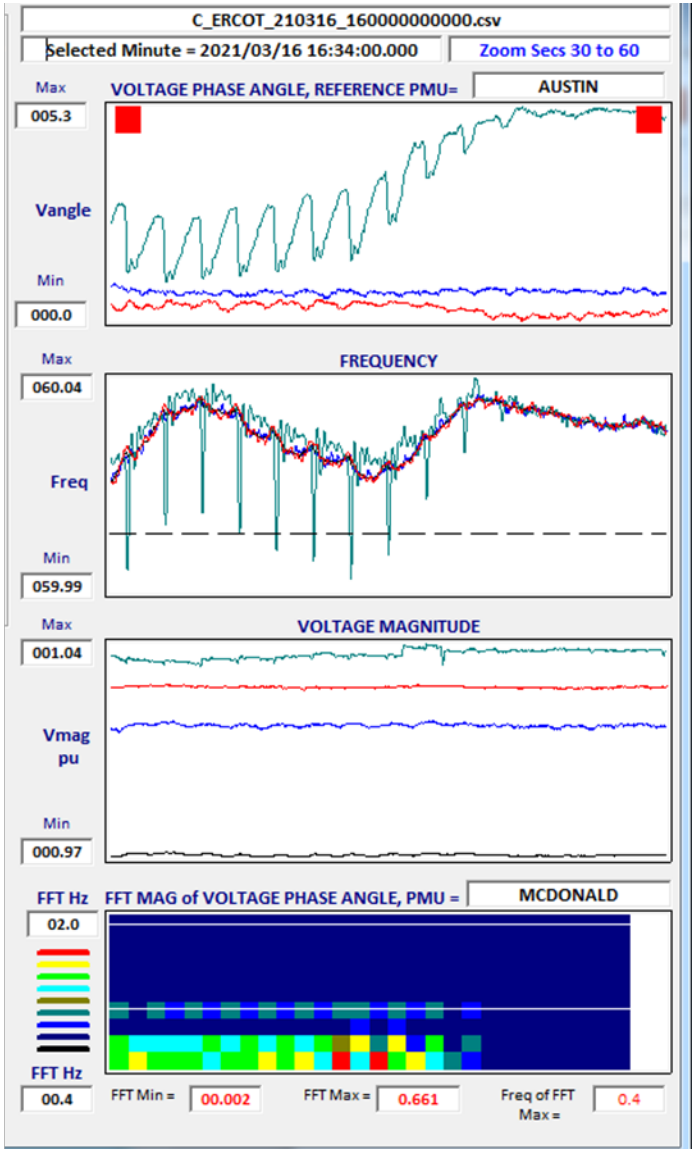
Max
005.2
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Vangle
Min
000.0
Max
059.98
FREQUENCY
Freq
Min
059.92
Max
001.05
VOLTAGE MAGNITUDE
Vmag
pu
Min
000.97
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
FFT Hz
00.4
FFT Min =
00.014
FFT Max =
0.604
Freq of FFT Max =
0.4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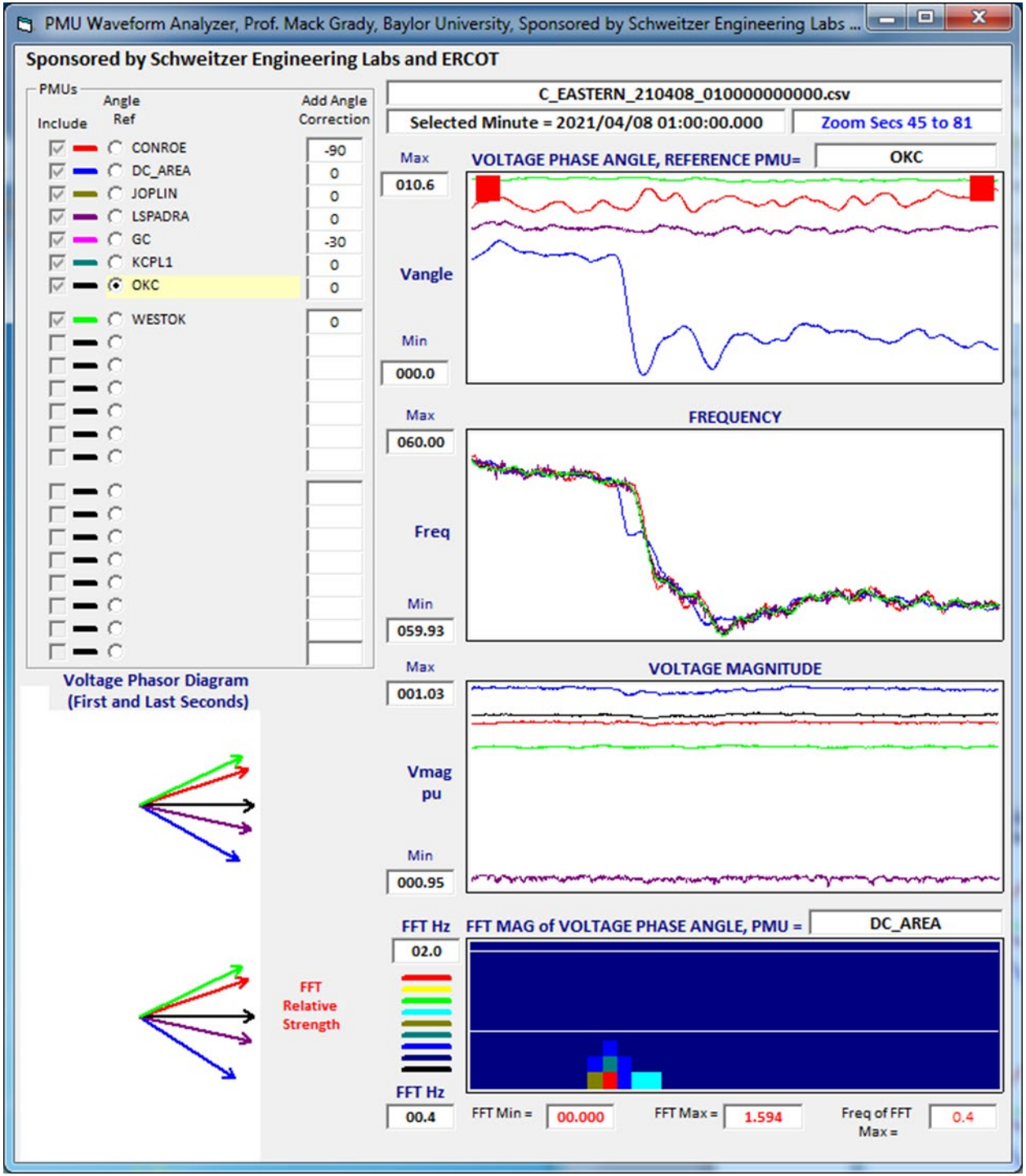
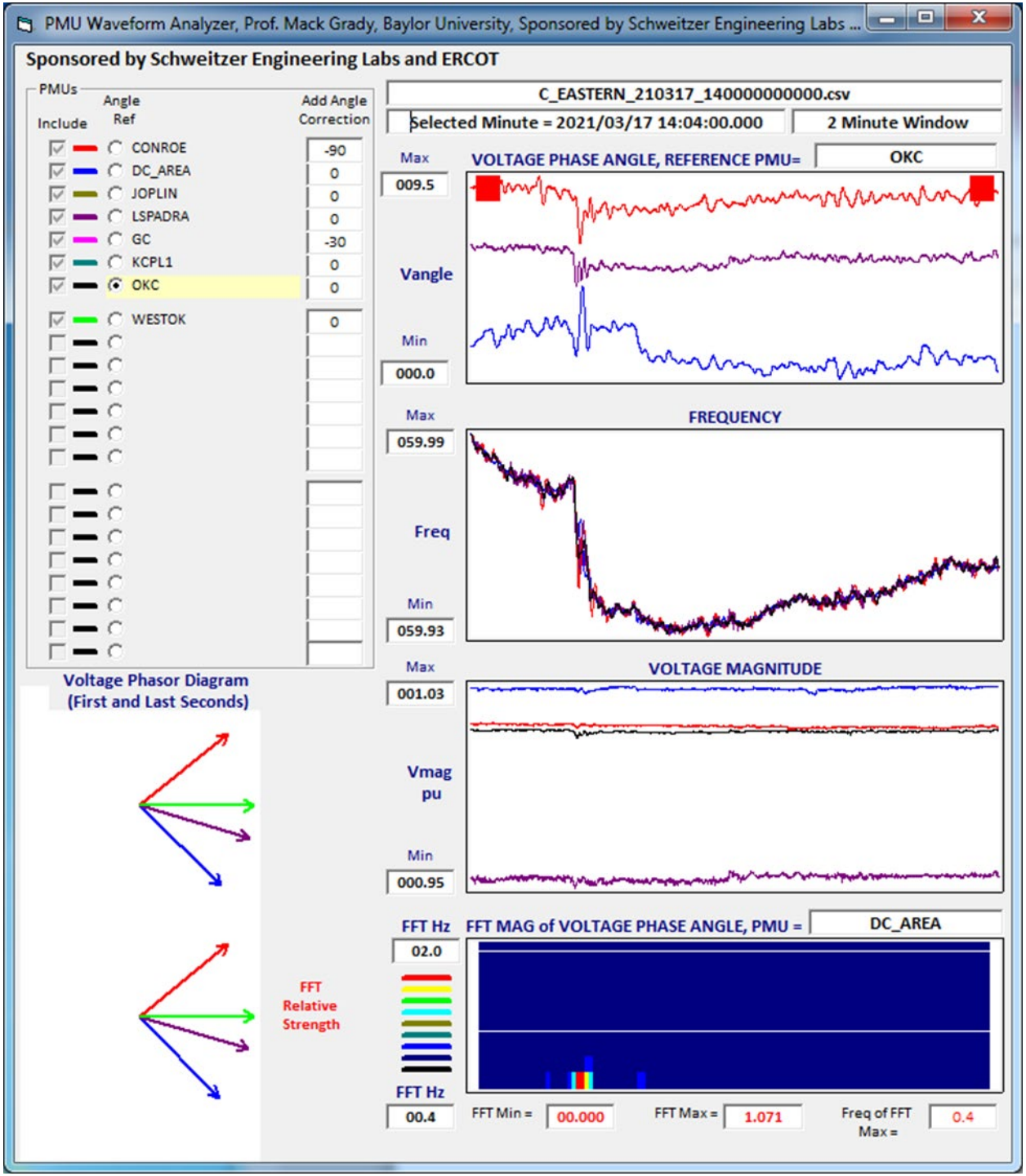
Zoom Secs 30 to 60
Max
005.3
VOLTAGE PHASE ANGLE, REFERENCE PMU=
AUSTIN
Vangle
Min
000.0
Max
060.04
FREQUENCY
Freq
Min
059.99
Max
001.04
VOLTAGE MAGNITUDE
Vmag
pu
Min
000.97
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
MCDONALD
FFT Hz
00.4
FFT Min =
00.002
FFT Max =
0.661
Freq of FFT Max =
0.4


PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
CONROE -90
DC_AREA 0
JOPLIN 0
LSPADRA 0
GC -30
KCPL1 0
OKC 0
WESTOK 0
C_EASTERN_210408_010000000000.csv
Selected Minute = 2021/04/08 01:00:00.000
Zoom Secs 45 to 81
Max 010.6
VOLTAGE PHASE ANGLE, REFERENCE PMU= OKC
Vangle
Min 000.0
Max 060.00
FREQUENCY
Freq
Min 059.93
Max 001.03
VOLTAGE MAGNITUDE
Vmag pu
Min 000.95
Voltage Phasor Diagram (First and Last Seconds)
FFT Relative Strength
FFT Hz 02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU = DC_AREA
FFT Hz 00.4
FFT Min = 00.000
FFT Max = 1.594
Freq of FFT Max = 0.4


PMU Waveform Analyzer, Prof. Mack Grady, Baylor University, Sponsored by Schweitzer Engineering Labs ...
Sponsored by Schweitzer Engineering Labs and ERCOT
PMUs
Include
Angle Ref
Add Angle Correction
CONROE -90
DC_AREA 0
JOPLIN 0
LSPADRA 0
GC -30
KCPL1 0
OKC 0
WESTOK 0
C_EASTERN_210317_140000000000.csv
Selected Minute = 2021/03/17 14:04:00.000
2 Minute Window
VOLTAGE PHASE ANGLE, REFERENCE PMU=
OKC
Max
009.5
Vangle
Min
000.0
FREQUENCY
Max
059.99
Freq
Min
059.93
VOLTAGE MAGNITUDE
Max
001.03
Vmag pu
Min
000.95
Voltage Phasor Diagram (First and Last Seconds)
FFT Relative Strength
FFT Hz
02.0
FFT MAG of VOLTAGE PHASE ANGLE, PMU =
DC_AREA
FFT Hz
00.4
FFT Min =
00.000
FFT Max =
1.071
Freq of FFT Max =
0.4

Questions?