Oscillation Monitoring System at TVA

Gary Kobet, Ritchie Carroll, Ryan Zuo

Tennessee Valley Authority

Mani V. Venkatasubramanian

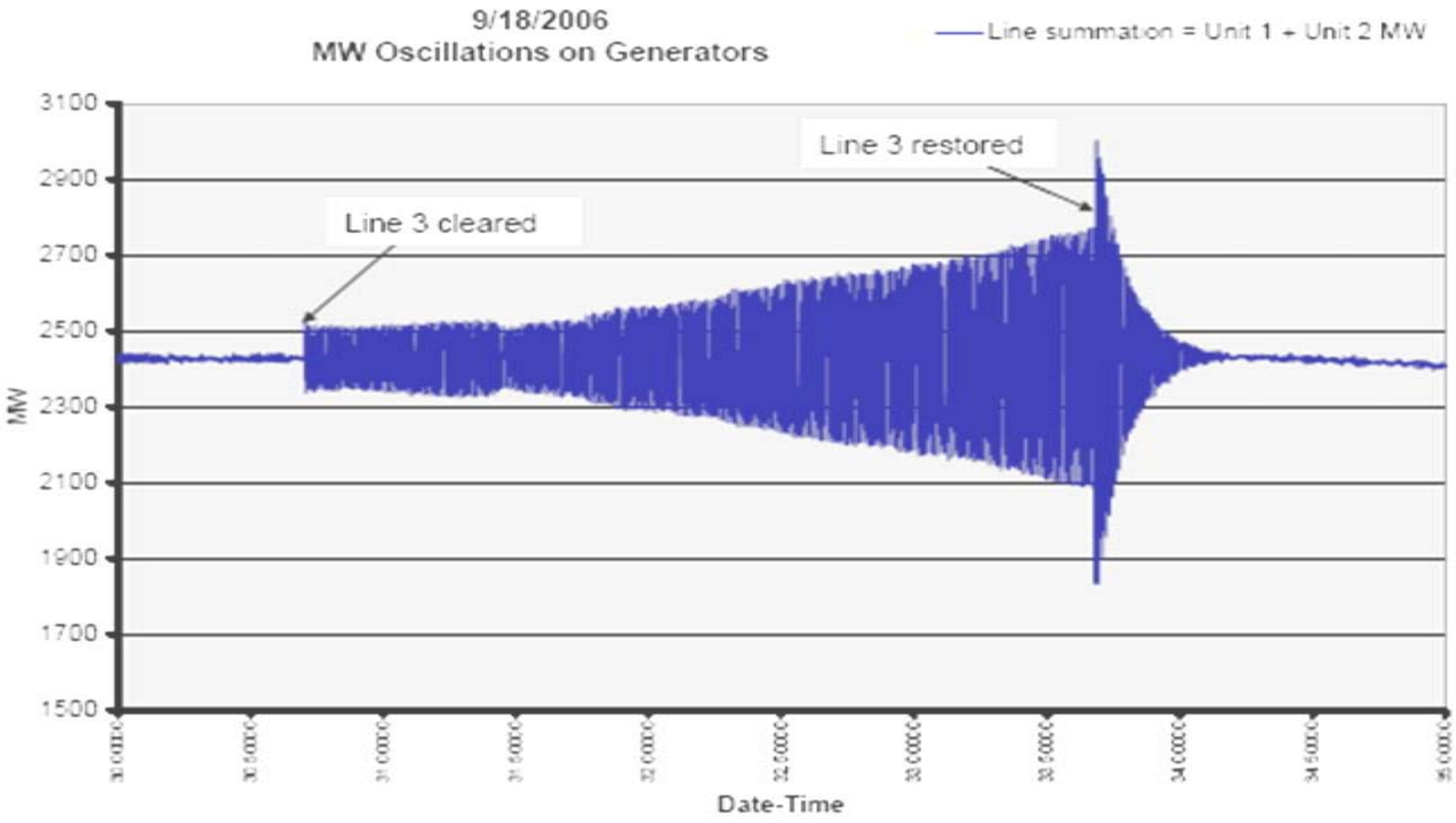
Washington State University

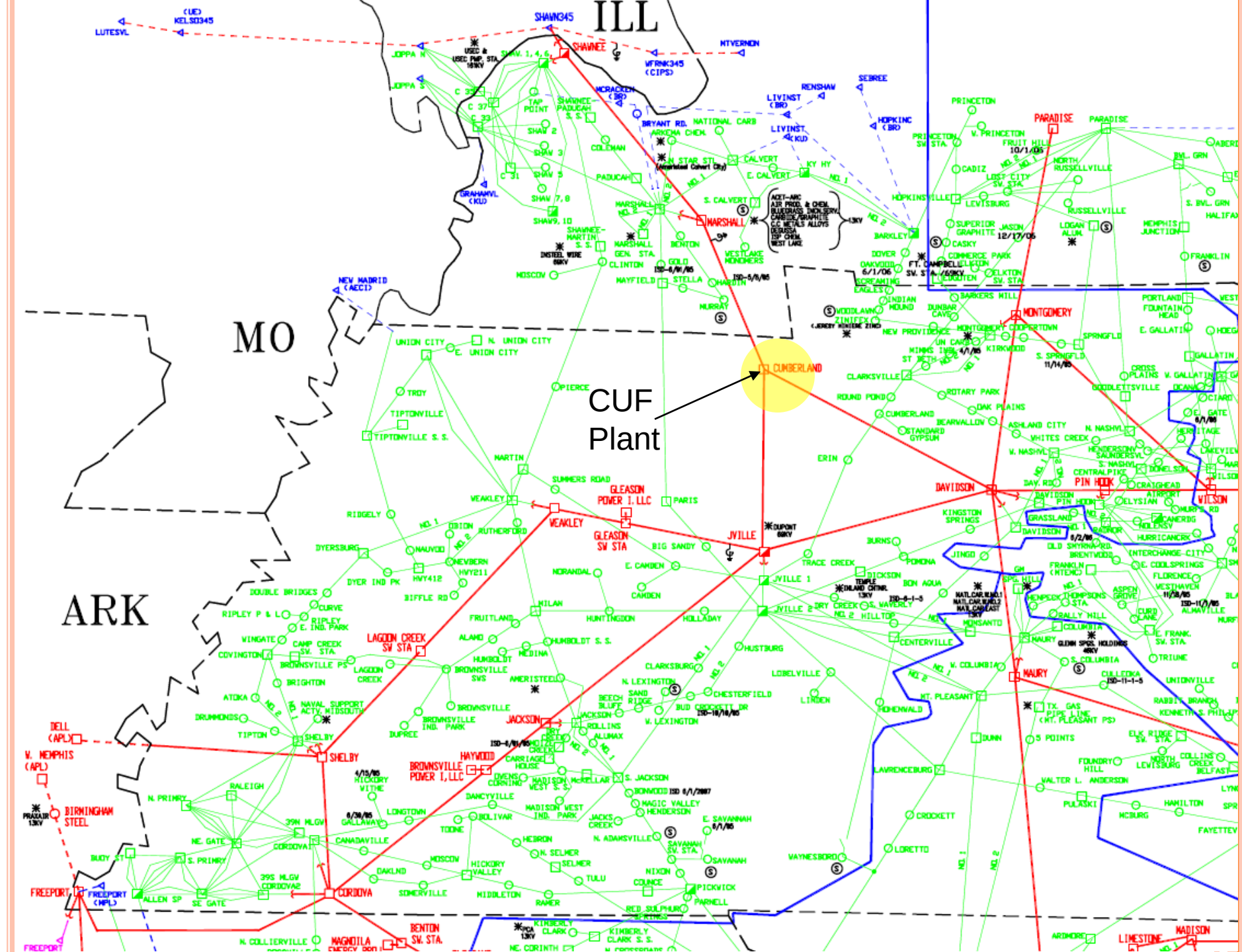
10/11/2009

Project Team

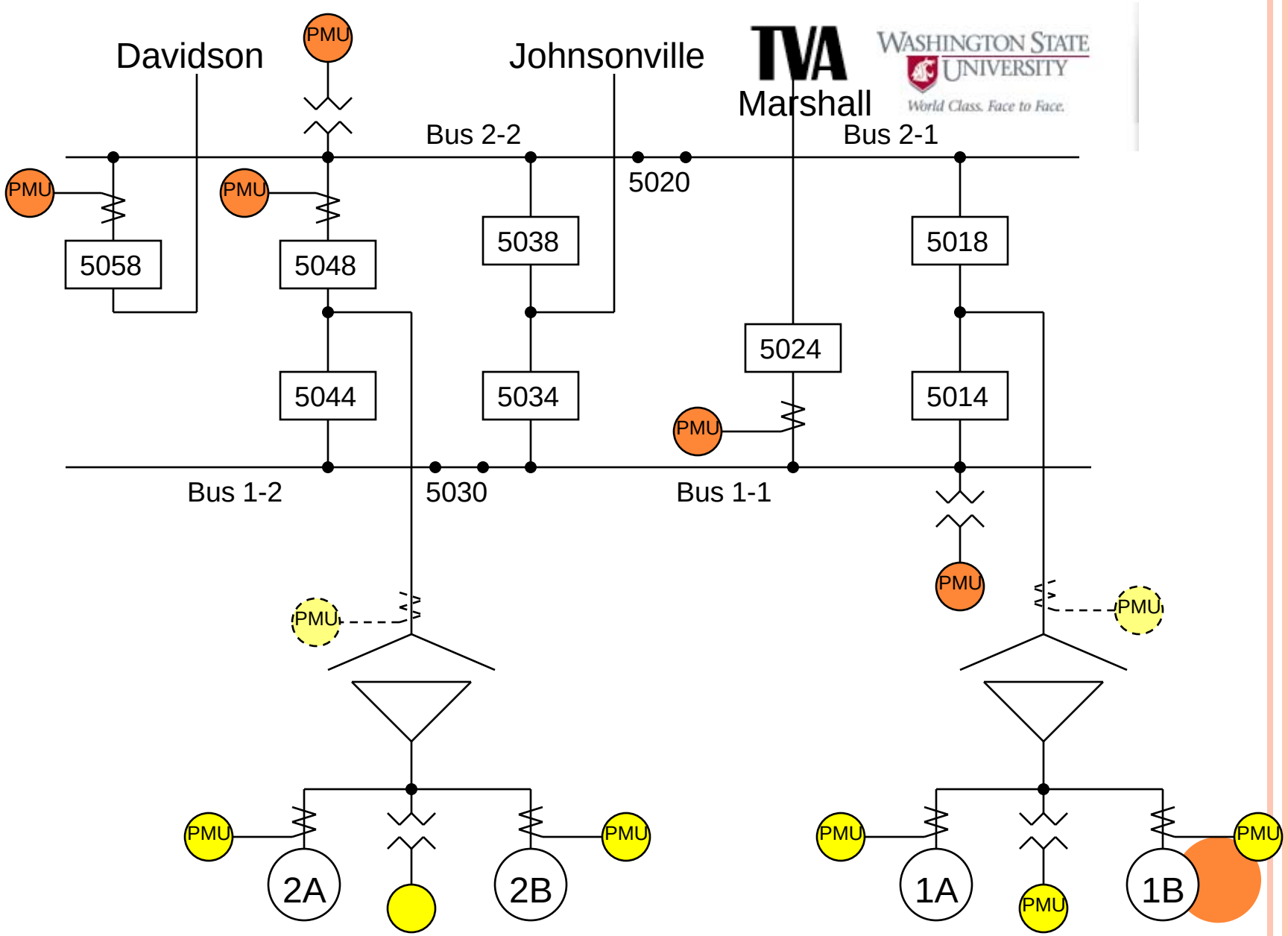
- WSU
  - Guoping Liu, Qiang Zhang, Ran Xu, Jaime Quintero, Mani V. Venkatasubramanian
- TVA
  - Ritchie Carroll, Gary Kobet, Lisa Beard, Ryan Zuo, Paul Trachian, Pinal Patel, Mehulbhi Thakkar, Russell Robertson

TVA CUMBERLAND EVENT(LOCAL MODE)



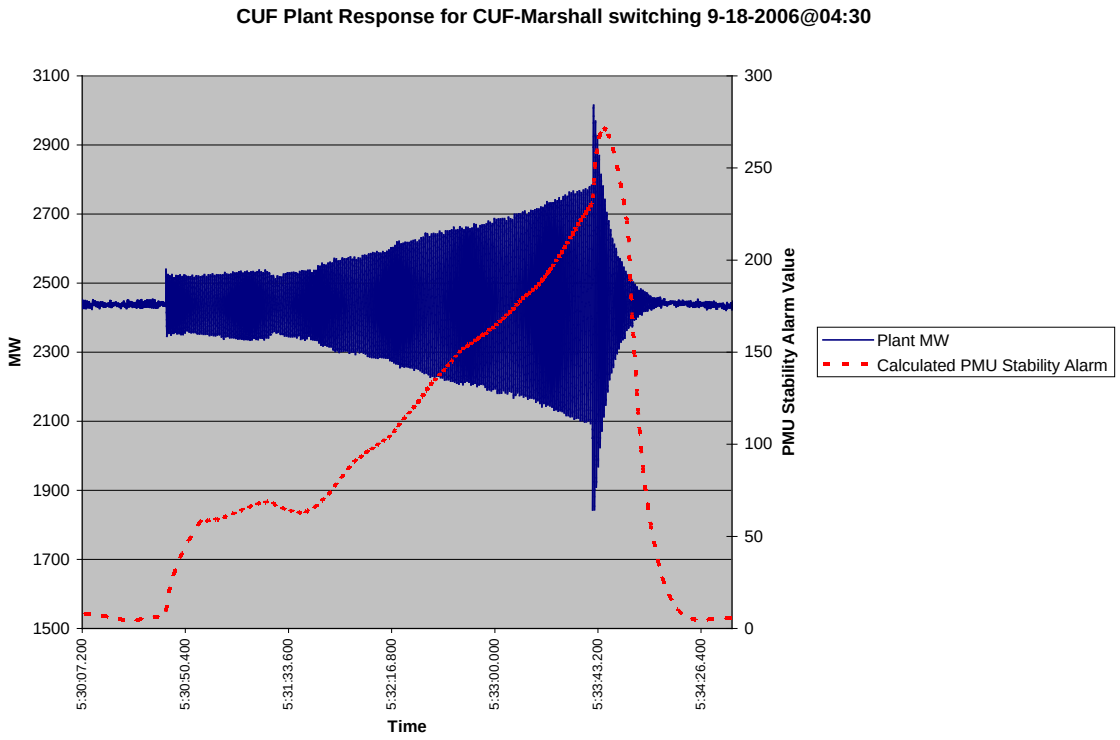

ILL
MO
ARK
CUF
Plant
CUMBERLAND
MONTGOMERY
PARADISE
DAVIDSON
MAURY
SHELBY
CORDOVA
JACKSON
JVILLE
WEAKLEY
MARSHALL
SHAWNEE
PADUCAH
GLEASON
POWER I, LLC
GLEASON
SW STA
BROWNSVILLE
POWER I, LLC
LAGOON CREEK
SW STA
BENTON
SW. STA.
HAYWOOD
DAVIDSON
PIN HOOK
WILSON
SHAWN345
MTVERNON
WFRNK345
(CIPS)
KELSO345
(UE)
LUTESVL
NEW MADRID
(AECI)
GRAHAMVL
(KU)
MCRACKEN
(BR)
LIVINST
(BR)
LIVINST.
(KU)
RENSHAW
SEBREE
HOPKINC
(BR)
HOPKINSVILLE
BARKLEY
MARSHALL
GEN. STA.
SHAWNEE-
MARTIN
S. S.
INSTEEL WIRE
69KV
MOSCOW
CLINTON
MAYFIELD
GOLD
ISD-6/9/05
STELLA
HARDIN
ISD-5/9/05
MURRAY
WESTLAKE
MONOMERS
ACET-ARC
AIR PROD. & CHEM.
BLUEGRASS ENGLSERV.
CARBIDE/GRAPHITE
C.C. METALS ALLOYS
DEGUSSA
ISP CHEM.
WEST LAKE
13KV
NO. 2
DOVER
OAKWOOD
6/1/06
FT. CAMPBELL
SW. STA.
69KV
CLARKSVILLE
ROUND POND
ROTARY PARK
OAK PLAINS
CUMBERLAND
BEARWALLOW
ASHLAND CITY
STANDARD
GYPSUM
ERIN
DAV. RD
PIN HOOK
CRAIGHEAD
AIRPORT
VICSON
KINGSTON
SPRINGS
GRASSLAND
DAVIDSON
BURNS
POMONA
JINGO
TRACE CREEK
DICKSON
TEMPLE
INLAND CNTNR.
13KV
BON AQUA
MATL.CAR.WND.1
MATL.CAR.WND.2
MAT.CAN.EAST
13KV
MONSANTO
ISD-8-1-5
ISD-11/1/05
ALVAVILLE
CENTERVILLE
HILLTOP
HOLLADAY
HUNTINGDON
FRUITLAND
MILAN
NORANDAL
E. CAMDEN
CAMDEN
DUPONT
69KV
JVILLE 1
JVILLE 2
DRY CREEK
S. WAVERLY
NO. 2
NO. 1
HUSTBURG
LOBELVILLE
LINDEN
CLARKSBURG
N. LEXINGTON
SAND
RIDGE
BEECH
BLUFF
JACKSON
ROLLINS
ALUMAX
W. LEXINGTON
CHESTERFIELD
BUD CROCKETT DR
ISD-10/10/05
ISD-6/01/05
ROMEWALD
MT. PLEASANT
W. COLUMBIA
S. COLUMBIA
GLENN SPGS. HOLDINGS
46KV
TX. GAS
PIPE LINE
(MT. PLEASANT PS)
5 POINTS
DUNN
LAWRENCEBURG
WALTER L. ANDERSON
PULASKI
CROCKETT
LORETTO
WAYNESBORO
NO. 1
NO. 2
SAVANNAH
SAVANNAH
SW STA.
E. SAVANNAH
6/1/05
N. ADAMSVILLE
JACKS
CREEK
MAGIC VALLEY
HENDERSON
BONWOOD ISD 6/1/2007
MADISON WEST
IND. PARK
MADISON WEST S. S.
S. JACKSON
OWENS
CORNING
CARRIAGE
HOUSE
HAYWOOD
ISD-6/01/05
BOLIVAR
DANCYVILLE
LONGTOWN
GALLAWAY
6/30/05
HICKORY
WITHE
4/15/05
RALEIGH
N. PRIMRY
BIRMINGHAM
STEEL
PRAXAIR
13KV
DELL
(APL)
W. MEMPHIS
(APL)
DRUMMONDS
TIPTON
SHELBY
ATOKA
NO. 2
NO. 1
E. NAVAL SUPPORT
ACTV. MIDSOUTH
BROWNSVILLE
IND. PARK
DUPREE
BROWNSVILLE
SVS
AMERISTEEL
HUMBOLDT
MEDINA
HUMBOLDT S. S.
ALAND
FRUITLAND
HUNTINGDON
HOLLADAY
CAMP CREEK
SW. STA.
COVINGTON
WINGATE
BROWNSVILLE PS
LAGOON
CREEK
BRIGHTON
RIPLEY P & L
CURVE
RIPLEY
E. IND. PARK
DOUBLE BRIDGES
DYER IND PK
HWY412
HWY211
BIFFLE RD
NEVBERN
NAUVOO
DYERSBURG
RIDGELY
RUTHERFORD
DIXON
NO. 1
NO. 2
WEAKLEY
SUMMERS ROAD
MARTIN
TROY
TIPTONVILLE
TIPTONVILLE S. S.
UNION CITY
N. UNION CITY
E. UNION CITY
PIERCE
NEW MADRID
(AECI)
MURRAY
HARDIN
ISD-5/9/05
STELLA
GOLD
ISD-6/9/05
MOSCOW
CLINTON
MAYFIELD
MARSHALL
GEN. STA.
SHAWNEE-
MARTIN
S. S.
INSTEEL WIRE
69KV
BENTON
WESTLAKE
MONOMERS
MARSHALL
SHAW 9, 10
SHAW 7, 8
SHAW 5
SHAW 3
SHAW 2
C 31
C 33
C 37
C 37
JOPPA S
JOPPA N
USEC &
USEC PMP. STA
161KV
SHAWNEE
SHAWN. 1, 4, 5
TAP
POINT
SHAWNEE
PADUCAH
S. S.
COLEMAN
PADUCAH
BRYANT RD.
NATIONAL CARB
ARKEMA CHEM.
N. STAR STL
(Arrowhead Cohort Cty)
CALVERT
E. CALVERT
KY HY
NO. 1
S. CALVERT
NO. 2
NO. 1
NO. 2
PRINCETON
W. PRINCETON
PRINCETON
SW STA.
PARADISE
FRUIT HILL
10/1/05
CADIZ
LOST CITY
SW. STA.
NORTH
RUSSELLVILLE
LEWISBURG
RUSSELLVILLE
SUPERIOR
GRAPHITE
JASON
12/17/05
CASKY
LOGAN
ALUM.
COMMERCE PARK
ELKTON
ELKTON
SW. STA.
CROFTEN
SCREAMING
EAGLES
INDIAN
MOUND
DUNBAR
CAVE
WOODLAWN
ZINIFEX
JERSEY MINERAL ZINC
NEW PROVIDENCE
MONTGOMERY
COOPERTOWN
MIMMS INN
4/1/05
KIRKWOOD
ST BETH
BARKERS MILL
PORTLAND
FOUNTAIN
HEAD
E. GALLATIN
SPRINGFLD
S. SPRINGFLD
11/14/05
CROSS
PLAINS
W. GALLATIN
GOODLETTSVILLE
DCANA
CIARD
E. GATE
6/1/06
HERITAGE
N. NASHVL
WHITES CREEK
W. NASHVL
HENDERSONVL
SAUNDERSVL
S. NASHVL
CENTRALPIKE
DAV. RD
PIN HOOK
CRAIGHEAD
AIRPORT
VICSON
MURFS RD
GALLATIN
DONELSON
WILSON
HURRICANCRK
(INTERCHANGE-CITY)
E. COOLSPRINGS
FLORENCE
WESTHAVEN
11/28/05
ISD-11/1/05
ALVAVILLE
E. FRANK.
SW. STA.
TRIUNE
UNIONVILLE
RABBIT BRANCH
KENNETH S. PHILLIPS
ELK RIDGE
SW. STA.
NORTH
COLLINS
CREEK
BELFAST
LEWISBURG
FOUNDRY
HILL
HAMILTON
MCBURG
FAYETTEV
LYNN
SPR
ARDMORE
LIMESTONE
MADISON
N. COLLIERVILLE
MAGNOLIA
ENERGY RDG
NE. CORINTH
KIMBERLY
CLARK
KIMBERLY
CLARK S. S.
PCA
13KV
RED SULPHUR
SPRINGS
PARNELL
PICKWICK
NIXON
COUNCE
TULU
SELMER
N. SELMER
HEBRON
MOSCOW
HICKORY
VALLEY
OAKLND
SOMERVILLE
MIDDLETON
RAPER
39S MLGW
CORDOVA2
39N MLGW
CORDOVA1
CANADAVILLE
NE. GATE
S. PRIMRY
BUOY ST
ALLEN SP
SE GATE
FREEPORT
FREEPORT
(MPL)
FREEPORT
(APL)

Cumberland Fossil Plant – 500kV Switchyard



9-18-2006 Event

- On September 18, 2006, a preplanned 500kV line switching event in the vicinity of Cumberland Fossil Plant (CUF) initiated a dangerous undamped plant oscillation. This condition continued for almost three minutes and had steadily escalated to a 700 MW oscillation at 1.2 Hz by that time. It was only arrested after the preplanned line outage was reversed and the line placed back in service.

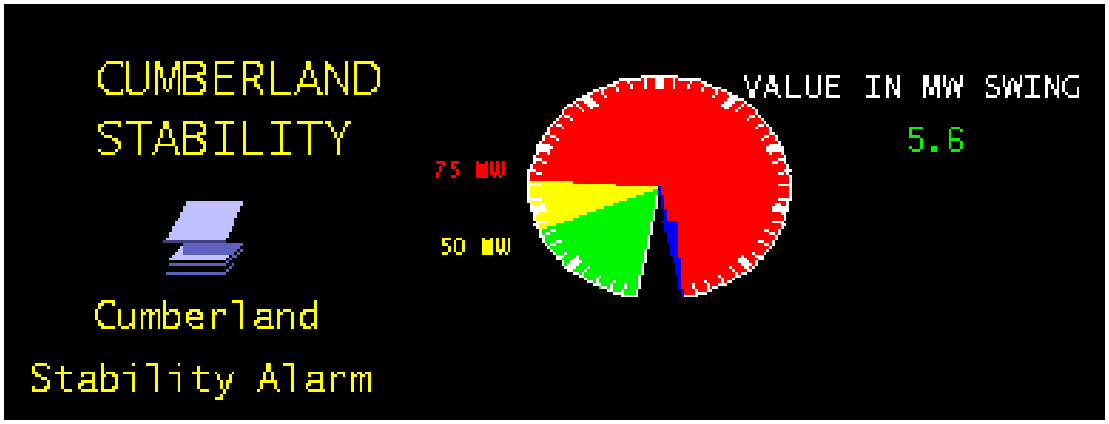


CUF Stability Alarm

- Developed (by Gary Bullock of TVA) within the SCADA system based on data from the PMU at CUF (sampled at 30Hz)
- Based on the standard deviation calculation of the CUF total plant MW output, which is indirectly calculated by summing the MW flows on the three 500kV lines terminated at CUF (each monitored by the PMU)
- Calculated using the previous 450 samples, or previous 15 seconds worth of data. Updated every ten (10) seconds and provides an indication of the MW oscillations occurring on the two units at CUF
- Standard deviation is a measure of how widely sampled values are dispersed from the average value (the mean) of the entire range of samples. It is calculated using the "unbiased" or "n-1" method. The f

$$\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$$

where x is the sample mean AVERAGE (number1,number2,...) and n is the sample size.



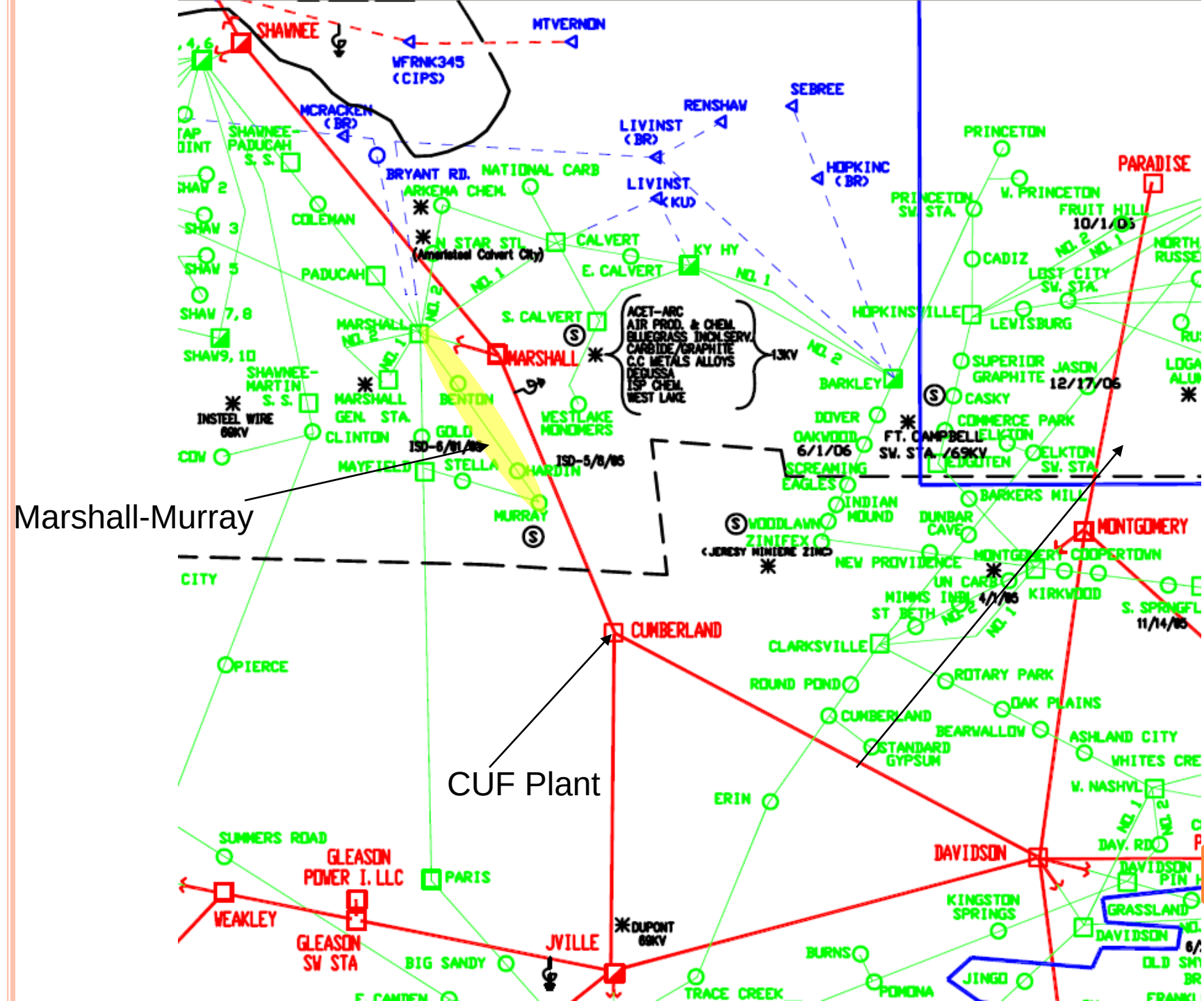
- High values of this stability alarm point indicate unsafe oscillations that can lead to an unstable system state. The pie chart shown on the SCADA single line display for CUF (see above) provides a visual indication of the real-time value.
- Thresholds (see table) were developed empirically by analyzing line switching and fault-clearing events within two buses of CUF

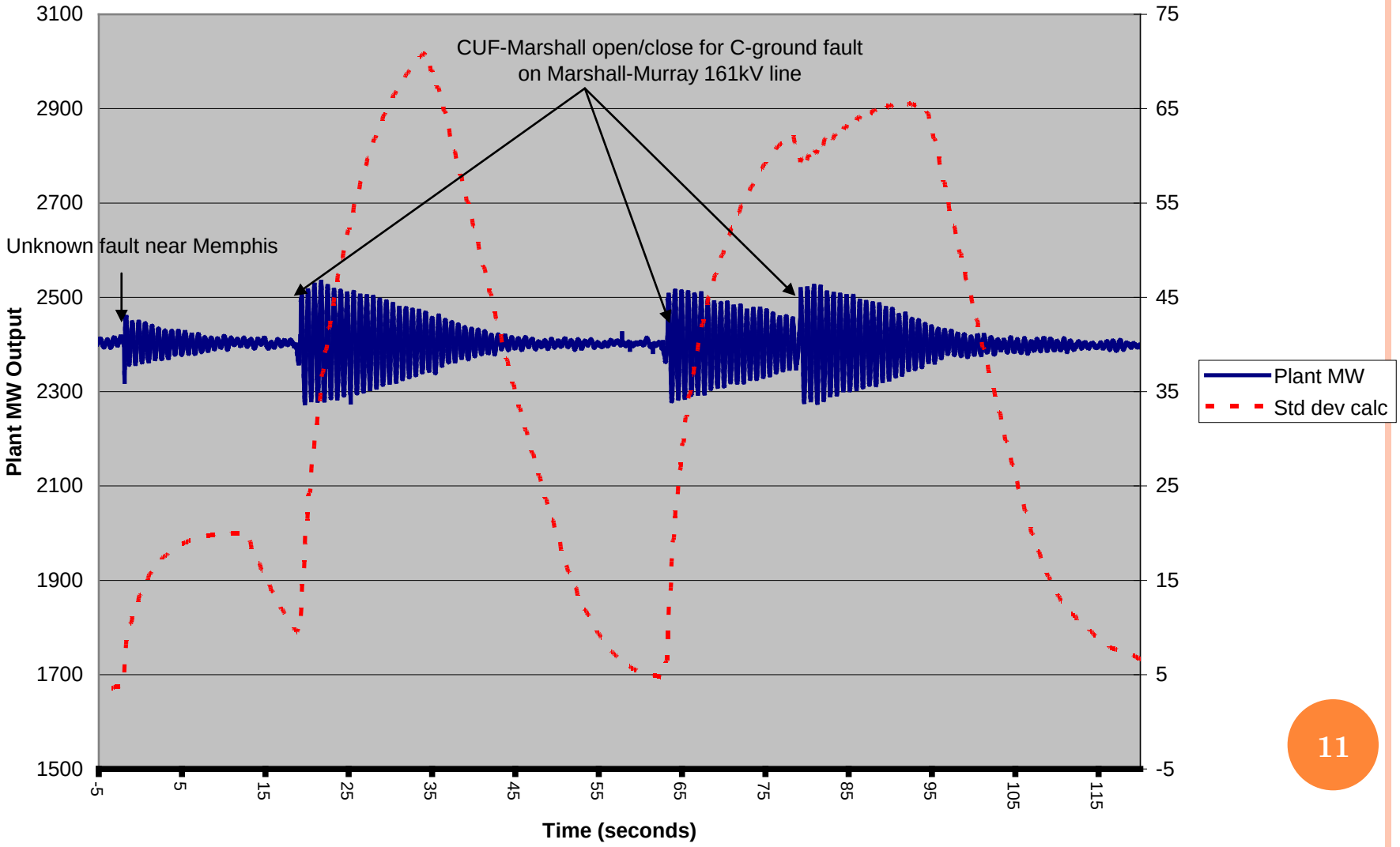
MW Swing Value	Color	Indication
Less than 50MW	Green	Safe - oscillations minimal
Between 50 and 75MW	Yellow	Warning Limit exceeded - Monitor closely
Greater than 75MW	Red	High Operating Limit exceeded - Action required

- Local plant operators and transmission operators monitor this MW swing value. Action required includes controlled derates in steps down to minimum load until the oscillations subside. If derates are not effective, one unit will be removed from service.

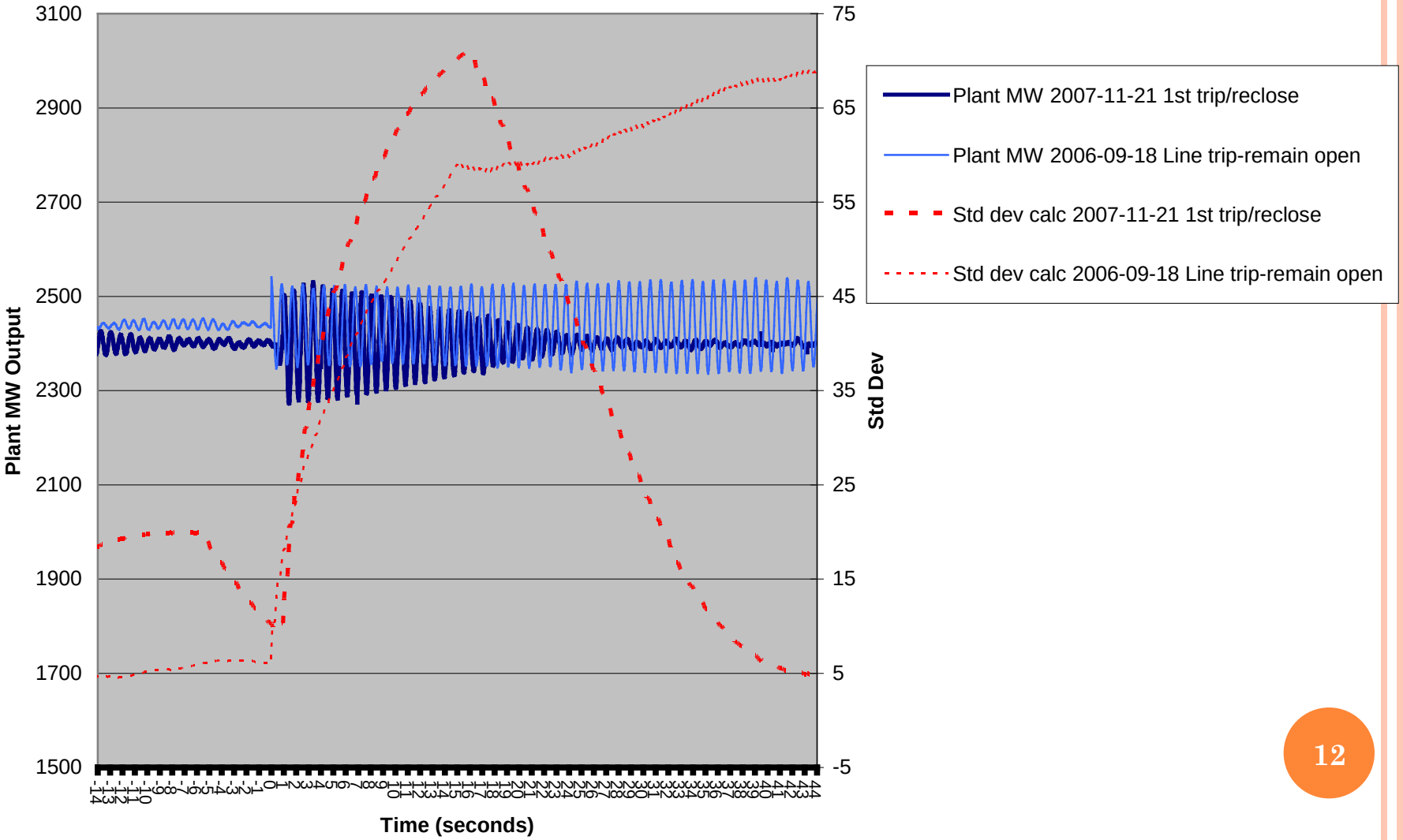
11-21-2007 Event

- On 11-21-2007 @ 18:51:42, 18:52:26, and 18:52:42 system time, the Cumberland-Marshall 500kV line tripped erroneously at the Marshall terminal for a C-ground fault on the Marshall-Murray 161kV line (lightning); Uniflex relays tripped for reverse fault
- High-speed (~30 cycle) sync-check reclosing on Marshall 5044/5074 successful following each erroneous trip
- CUF-Marshall line carrying ~200MW (from Marshall to CUF) pre-event
- Both CUF units on-line, total plant output ~2400MW
- Plant performance/response:
  - 1st trip/reclose: +/-125MW, std dev max 70, damped in ~30 seconds
  - 2nd trip/reclose: +/-110MW, std dev max 62, damping incomplete due to subsequent operation
  - 3rd trip/reclose: +/-125MW, std dev max 65, damped in ~30 seconds
- Unknown if power system stabilizers (PSS) have been installed/were in-service on CUF units 1 or 2
- Comparison of this event with the 9/18/2006 event (CUF-Marshall line removed for maintenance – see slide 18) showed similar response; it is probable that if high-speed sync-check reclosing had failed, the oscillations would likely have increased to the point where operator intervention (unit derating) would have been necessary
- NOTE: Prior to this at 18:51:22, CUF units responded to an A-ground fault somewhere in the Memphis area; fault lasted 5 cycles; CUF units +/-65MW, std dev max 20, damped in ~10 seconds


Marshall-Murray
CUF Plant
SHAWNEE
MTVERNON
WFRNK345
(CIPS)
MCRACKEN
(BR)
RENSHAW
SEBREE
LIVINST
(BR)
LIVINST
KUD
HOPKINC
(BR)
PRINCETON
PARADISE
BRYANT RD.
NATIONAL CARB
ARKEMA CHEM.
SHAWNEE-
PADUCAH
S. S.
COLEMAN
PRINCETON
SW. STA.
W. PRINCETON
FRUIT HILL
10/1/05
CADIZ
LOST CITY
SW. STA.
CALVERT
KY HY
E. CALVERT
PADUCAH
S. CALVERT
HOPKINSVILLE
LEWISBURG
MARSHALL
ACET-ARC
AIR PROD. & CHEM.
BLUEGRASS INDUSTRIAL SERV.
CARBIDE/GRAPHITE
C.C METALS ALLOYS
DEGUSSA
ISP CHEM.
WEST LAKE
13KV
BARKLEY
SUPERIOR
GRAPHITE
JASON
12/17/06
CASKY
SHAWNEE-
MARTIN
S. S.
INSTEEL WIRE
69KV
MARSHALL
GEN. STA.
BENTON
DOVER
COMMERCE PARK
OAKWOOD
6/1/06
FT. CAMPBELL
SW. STA. /69KV
ELKTON
SW. STA
CLINTON
GOLD
ISD-6/81/85
ISD-5/8/85
WESTLAKE
MONOMERS
SCREAMING
EAGLES
BARKERS MILL
MAYFIELD
STELLA
HARDIN
INDIAN
MOUND
DUNBAR
CAVE
MONTGOMERY
MURRAY
WOODLAWN
ZINIFEX
(JERSEY MINIERE ZINC)
NEW PROVIDENCE
COOPERTOWN
KIRKWOOD
S. SPRINGFL
11/14/85
CUMBERLAND
CLARKSVILLE
PIERCE
ROTARY PARK
ROUND POND
OAK PLAINS
CUMBERLAND
BEARWALLOW
ASHLAND CITY
STANDARD
GYPSUM
WHITES CRE
W. NASHVL
ERIN
SUMMERS ROAD
GLEASON
POWER I, LLC
PARIS
DAVIDSON
DAV. RD
DAVIDSON
PIN
KINGSTON
SPRINGS
GRASSLAND
WEAKLEY
GLEASON
SW STA
DUPONT
69KV
JVILLE
BIG SANDY
BURNS
DAVIDSON
TRACE CREEK
POMONA
JINGO
OLD SMY
BR
FRANKL

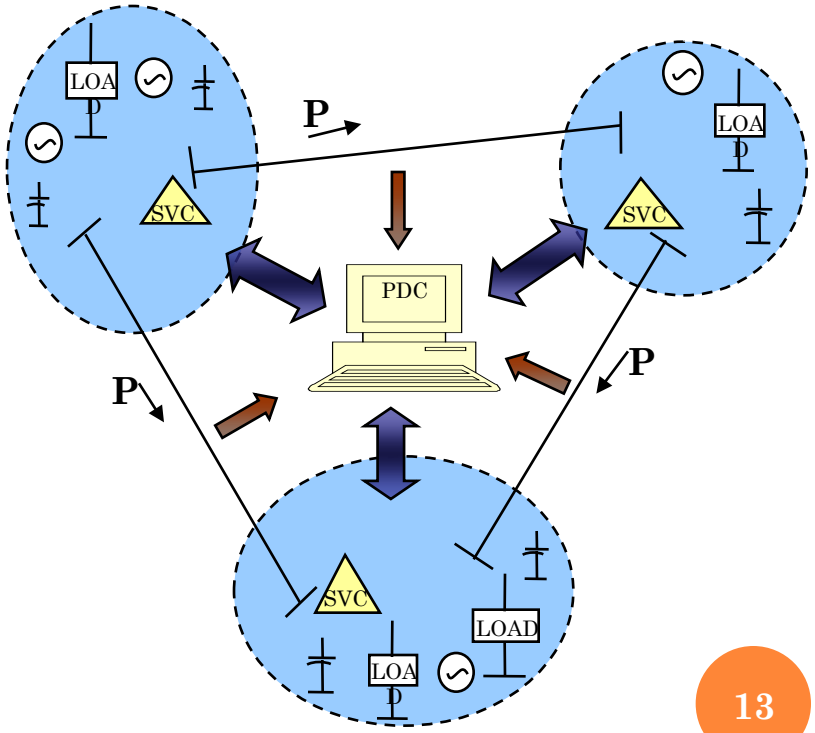

CUF-Marshall Op 20071121@1851
CUF-Marshall open/close for C-ground fault
on Marshall-Murray 161kV line
Unknown fault near Memphis
Plant MW Output
Time (seconds)
Plant MW
Std dev calc
3100
2900
2700
2500
2300
2100
1900
1700
1500
75
65
55
45
35
25
15
5
-5
-5
5
15
25
35
45
55
65
75
85
95
105
115

Comparison of 2007-11-21 with 2006-09-18



Oscillation Monitoring System (OMS)

- **Goal of Oscillation Monitoring System (OMS)**
  - **Early detection of poorly damped oscillations as they appear**
  - **Trigger warning or control signals**
- **OMS is made possible by wide area PMU Measurements**
  - **Growing numbers of PMUs across the power grid**
  - **Real-time applications needed**
  - **Prototype implementation at TVA since 2007**
  - **Local and inter-area oscillations can be detected**



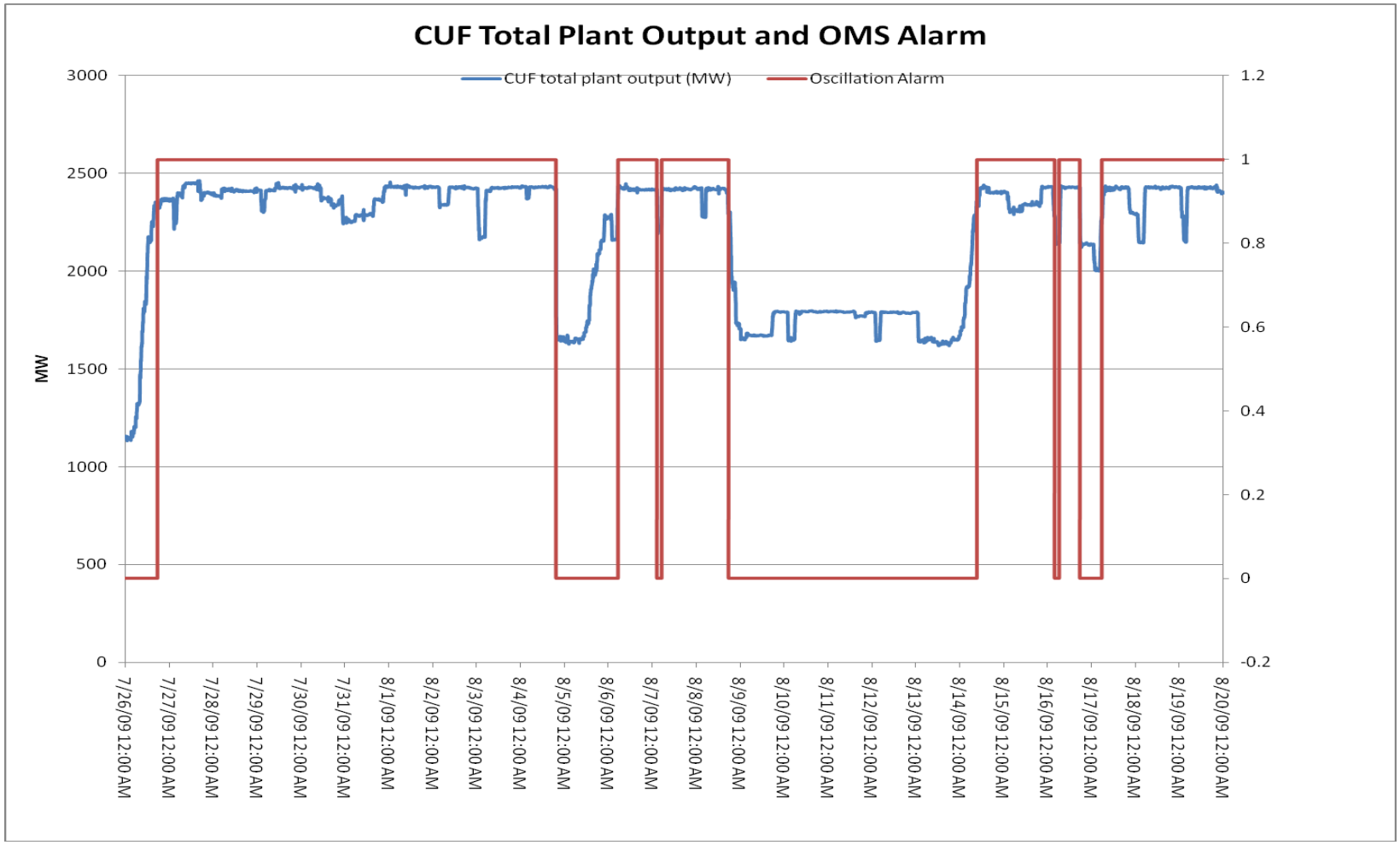
ENHANCED OSCILLATION MONITORING USING OMS

- OMS helpful in detecting when PSS went off-line at Cumberland
- OMS helpful in showing PSS not effective even when on-line. Hardware problem fixed.
- OMS helpful in showing the oscillation at Cumberland is related to the total amount of MW output. PSS may have reached a hardlimit. Still under investigation.
- OMS able to verify the local mode well-damped when Cumberland MW output lower. All recent alarms related to 0.45 Hz and 0.21 Hz eastern system inter-area modes.
- Benefits of real-time continuous monitoring from PMUs. Can detect oscillation problems early.

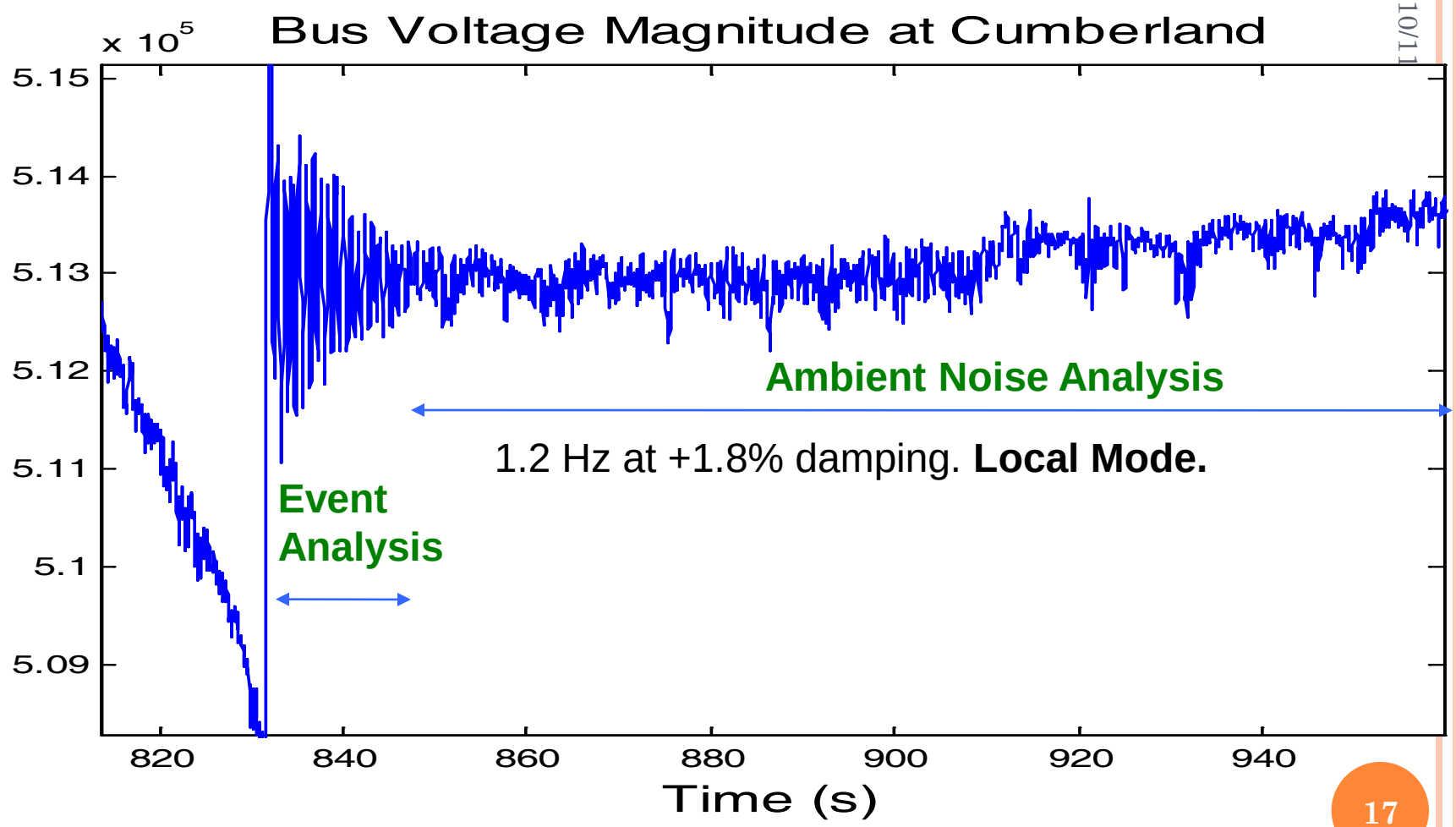
Cumberland Mode between 07/26 and 08/20

- OMS detected 1.3 Hz Cumberland Mode started from 07/26
- The Cumberland Mode disappeared on 08/05 and reappear on 08/06
- The mode disappeared again on 08/09 and reappear on 08/14
- During this period of time, the PSS is on at Cumberland plant.
- Comparing the period of time mode appearing and the total MW output shows PSS may reach its limitation when the total MW exceed the threshold of 2250 MW

CUF Total Plant output and OMS Alarm

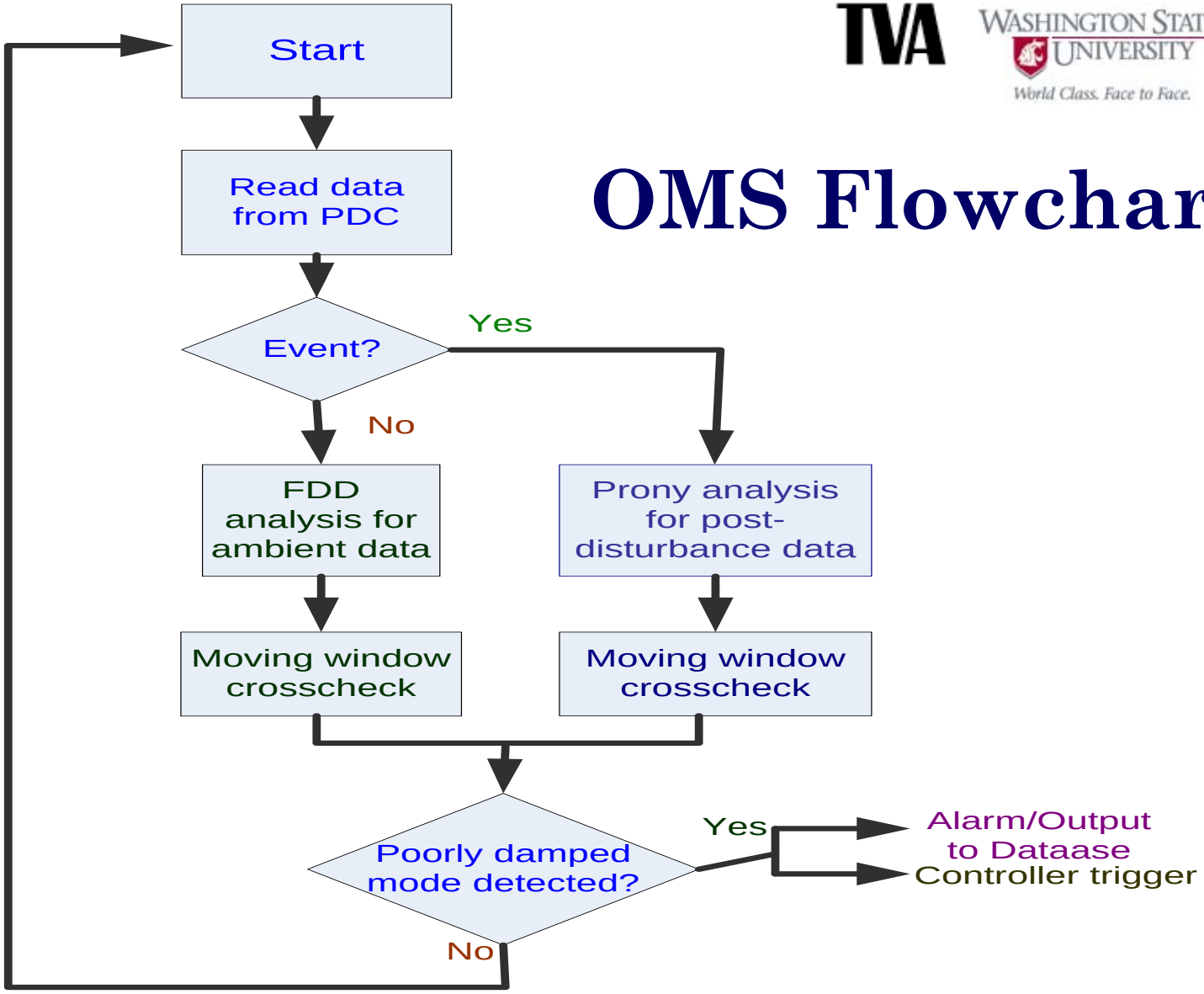


Results from Two Engines



Nov. 29th 2007 TVA event

OMS Flowchart



New implementation of Engine

Old Engine Implementation

- C++ based 32 bits structure
- Based on C math library
- Command console and file system as output
- Hardcode configuration
- Developed by WSU (2006-2007)

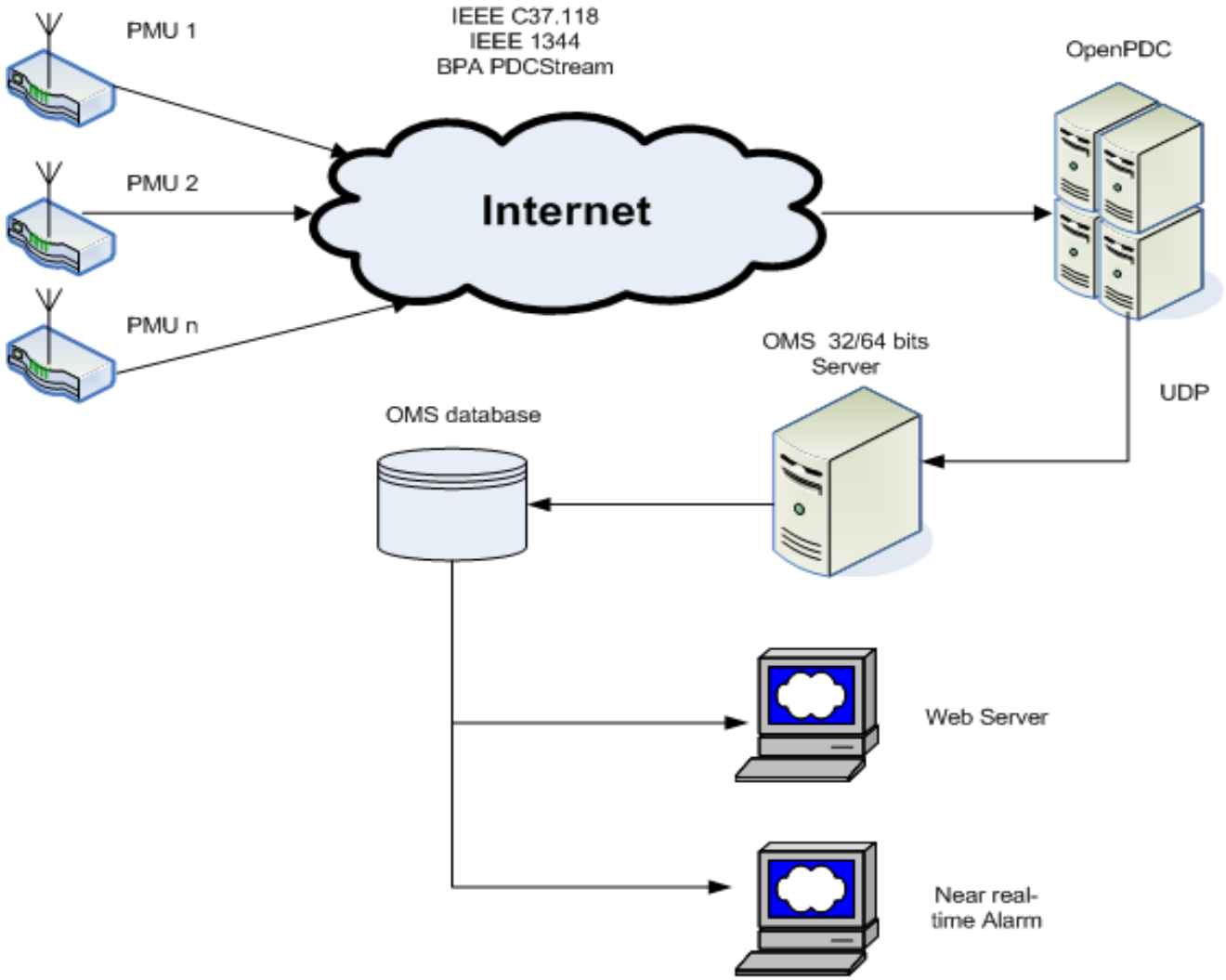
New Engine Implementation

- C# .NET Based 32/64 bits structure
- Based on Optimization Extreme™ C# .Net math library
- Database interface
- XML based configuration
- Developed by TVA based on WSU prototype (2008-2009)

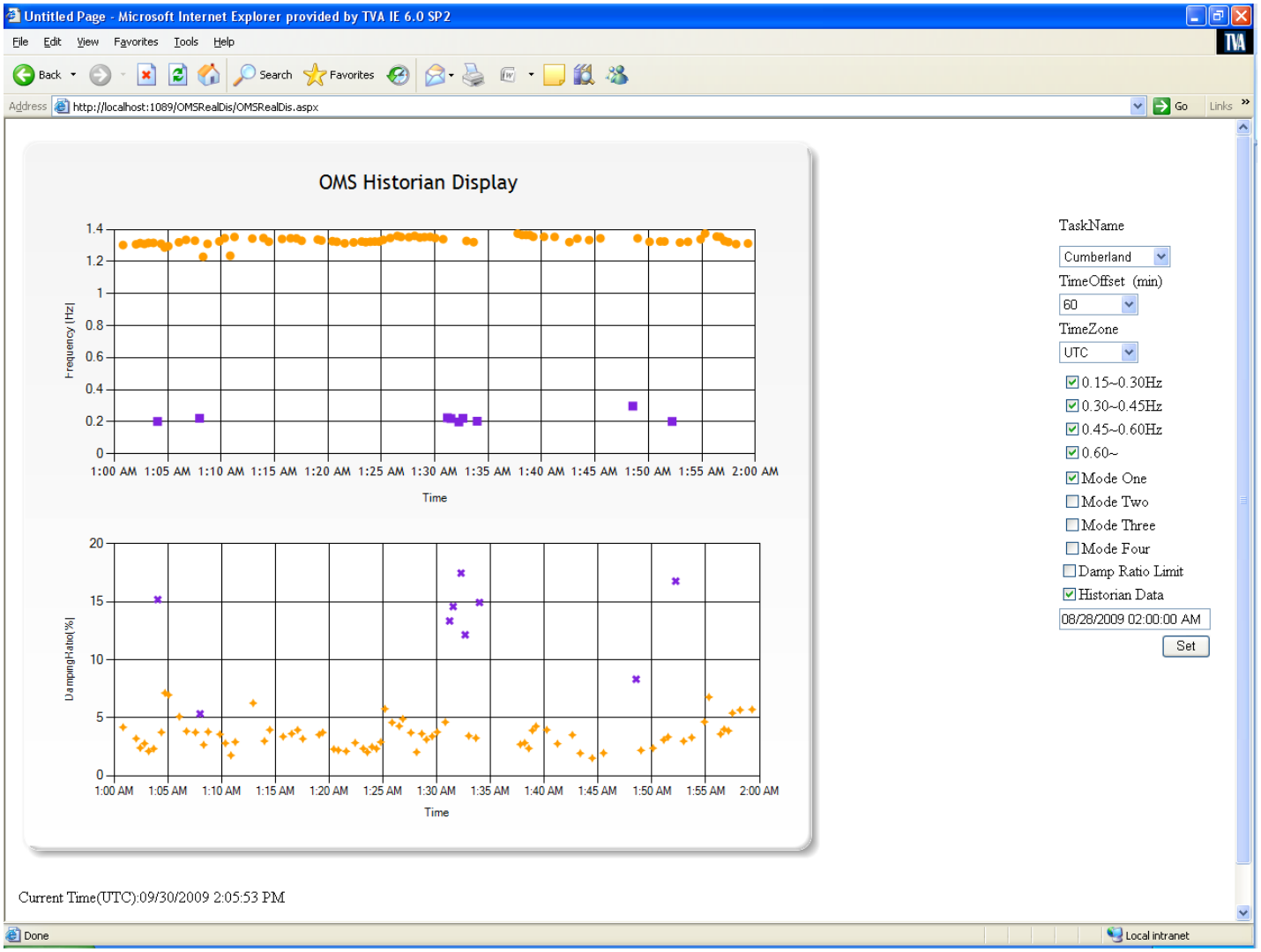
Improvement of New Engine

- Higher performance. Taking the advantage of hardware (64 bits)
- Easy to maintain and expand. C# .net math library provides Matrix function, FFT and SVD etc. math function
- Easy to configure.
- Easy to integrated with other application (Visualization etc.)

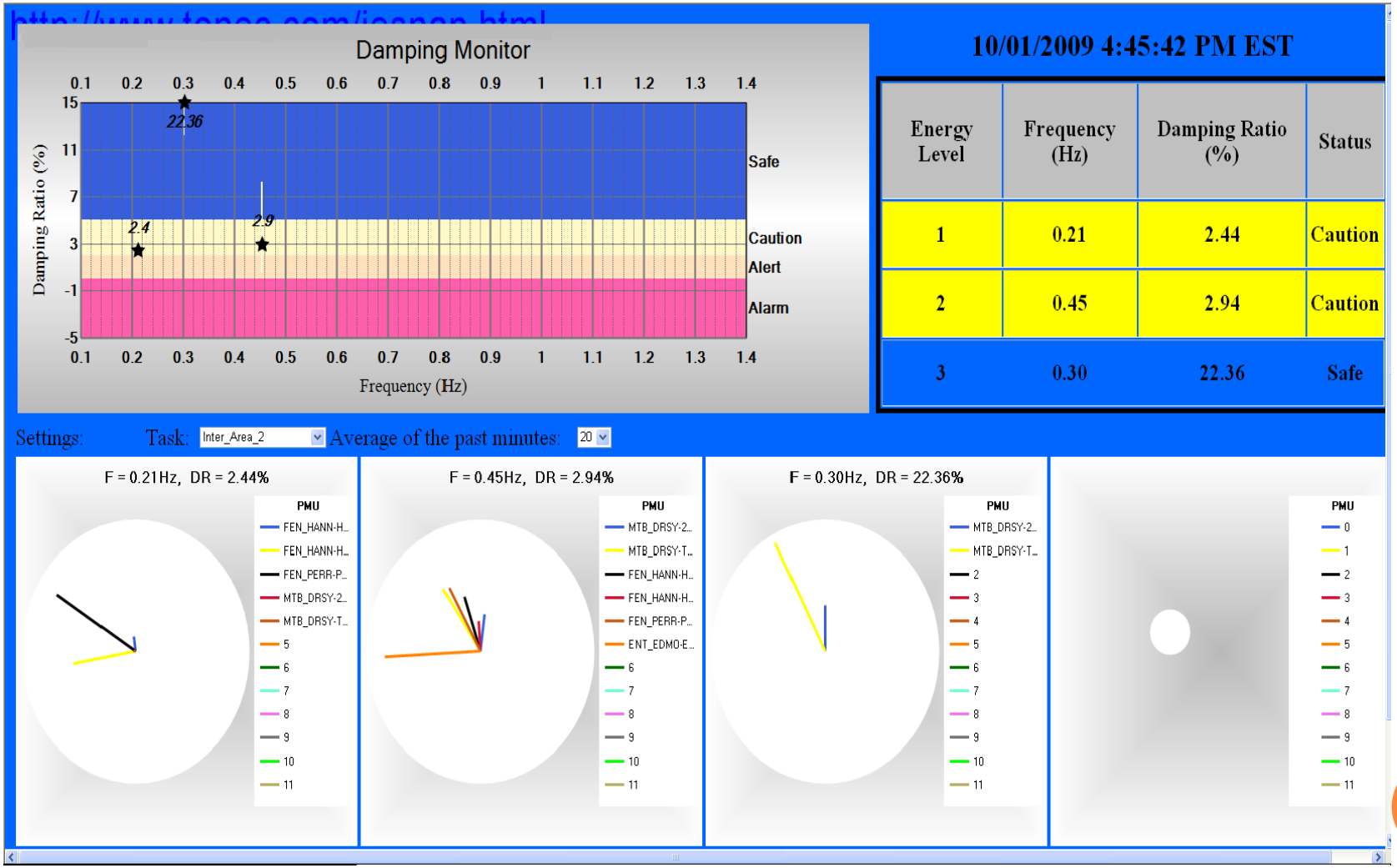
OMS Integration with OpenPDC



OMS Historian Result GUI



OMS Real-time GUI



OMS Status

- Working on mitigating OMS from SuperPDC platform to OpenPDC platform
- Working on mitigating OMS from 32 bits hardware platform to 64 bits hardware platform
- Continuing improving GUI and prepare to deploy on protected NASPI website when it is mature.
- Continuing tuning OMS and studying Oscillation mode in TVA region and Eastern Interconnection

Future work

- Implementation, testing and tuning at TVA
- Historical trends of mode damping from daily load changes, seasonal patterns, special events.
- OMS engines for Entergy and for Eastern Grid
- Operator alerts and alarms
- Operator Actions? Mode shape can tell between local mode, regional mode and inter-area mode. What then?
- Automatic controls