Power Quality and Power Measurement Unit

AGENDA

- Synchrophasor History
- Introduction to Synchrophasor Systems
- Synchrophasor Measurement
- Synchrophasor Communication Framework
- Scada vs. PMU
- Setting up a PMU Device
- Applications
- References

Synchro Phasor Basics

Motivation

The rapid increase in occurrence of line faults, failure of generation system and uncontrolled blackouts have led to a situation where the electrical utility needs dynamic and real time monitoring of critical parameters of power systems such as voltage, current, frequency, load angle etc.

This has resulted into a view in control and monitoring advances employing Phasor Measuring Unit (PMU).

Phasor Measurement Unit

- A phasor measurement unit (PMU) is a device used to estimate the magnitude and phase angle of an electrical phasor quantity (such as voltage or current) in the electric grid using a common time source for synchronization.

- Time synchronized phasor is called Synchro phasor.

- Phasor is a complex form of the sinusoidal waveform.

IEEE Standard defines PMU as follow:

A device that produces synchronized measurements of phasor (i.e. its amplitude and phase), frequency,

ROCOF (Rate of Change of Frequency) from voltage and/or current signals based on a common time source that typically is the one provided by the Global Positioning System UTC-GPS.

interesting history of the PMU

- **In 1893 Charles Proteus Steinmetz** introduced the phasor to represent the sinusoidal waveform.
- **Phasor** was used in Electrical design , operation analysis and trouble shooting.
- **In late 1970s**, the concept of using the computer for protection and control.
- In 1965 DFT algorithm was introduced to computation of fundamental components.
- Late 1970s , computer was introduced to calculate the fundamental and sequence components for protection and control.
- Early **1980s** the Development of GPS technology.
- **In 1988**, the phasor measurement was introduced by Dr. Arun Phadke and Dr James Thorp at Viginia Tech.
- In 1990 Prototype PMU was developed.
- First PMU commercial device was developed in **1992.**
- Bonneville Power Administration was the 1st utility to introduce PMU s to collect data for WAMS.
- Many PMU applications are in operation.

Synchrophasor Standards

1995

IEEE 1344
- The first synchrophasor standard
- Introduction of Phasor Measurement Unit (PMU)

2005

IEEE C37.118-2005
- Steady-state performance requirement: Total Vector Error (TVE)
- Improvement in the data communication specification

2011

IEEE C37.118.1-2011: Measurement
- Dynamic performance requirement
- Classes performance definition: P-class and M-Class

IEEE C37.118.2-2011: Communication

2014

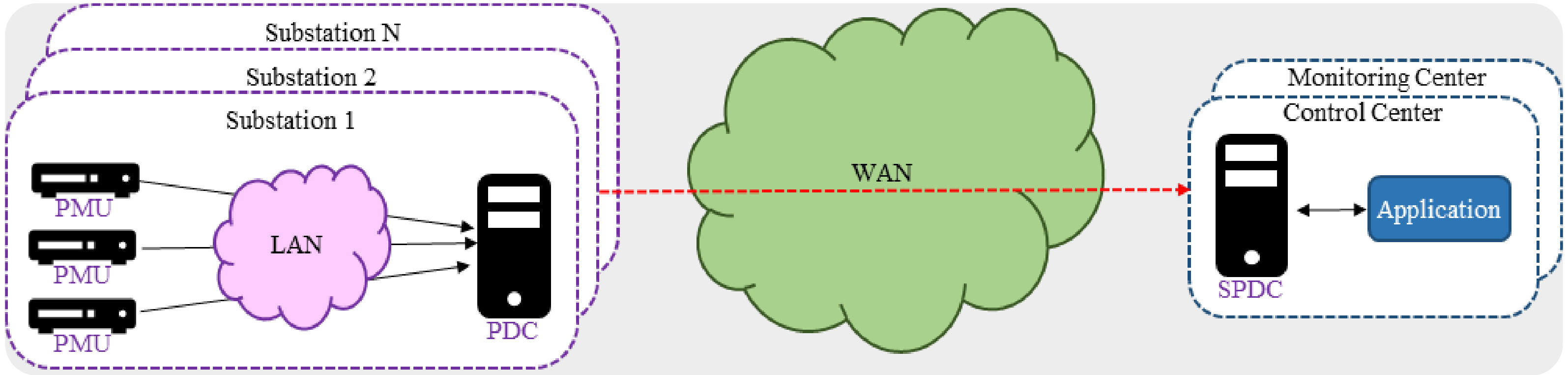
IEC 61850-90-50
- Migration into IEC 61850 architecture
- Cyber-security
- Fast sampling

2018 → Updated with Protection Relaying Application

Introduction to Synchrophasor Systems

Typical Synchrophasor system

- **Phasor measurement unit (PMU)**
  - Performs synchrophasor measurements
  - Transmits synchrophasor data to PDC
- **Phasor data concentrator (PDC)**
  - Receives and aggregates synchrophasor data from multiple PMUs inside substation
  - Transmits data as a single output stream
- **Super PDC (SPDC)** receives synchrophasor data from multiple Local PDCs
- **Communication framework**
- **Control, monitoring, and visualization centers**



Synchrophasor Measurement

What is a phasor (X)?

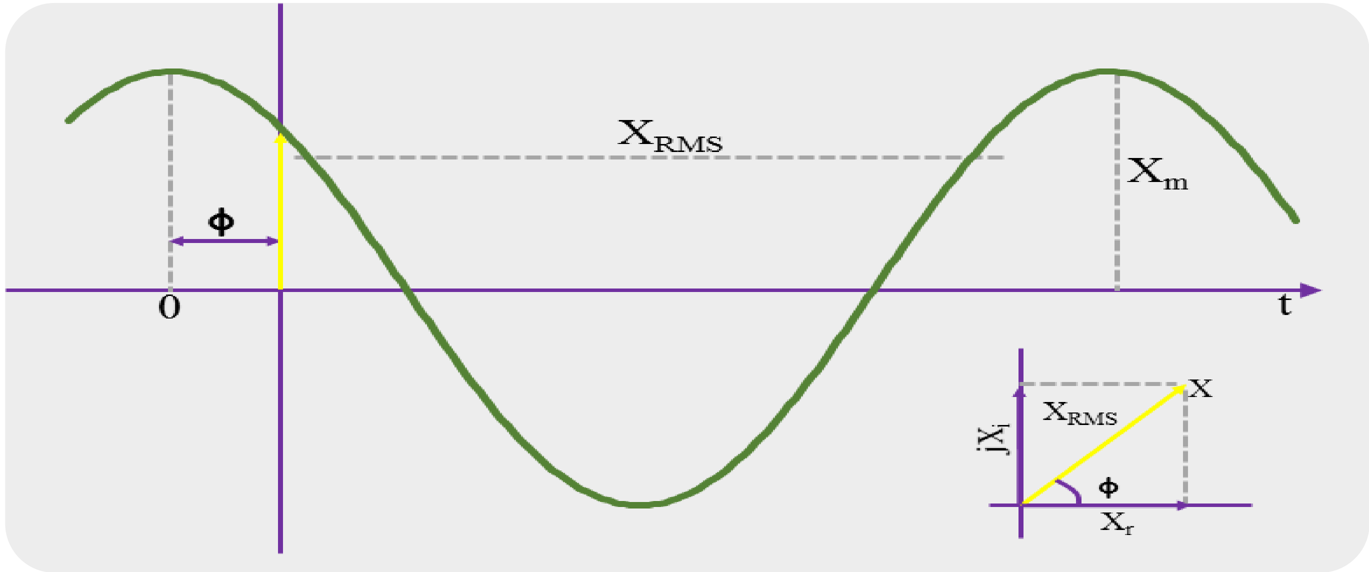
- A complex representation of sine wave quantity

- Phasor equations:

$$x(t) = X_m \cos(\psi(t)) = X_m \cos(\omega t + \varphi), waveform$$

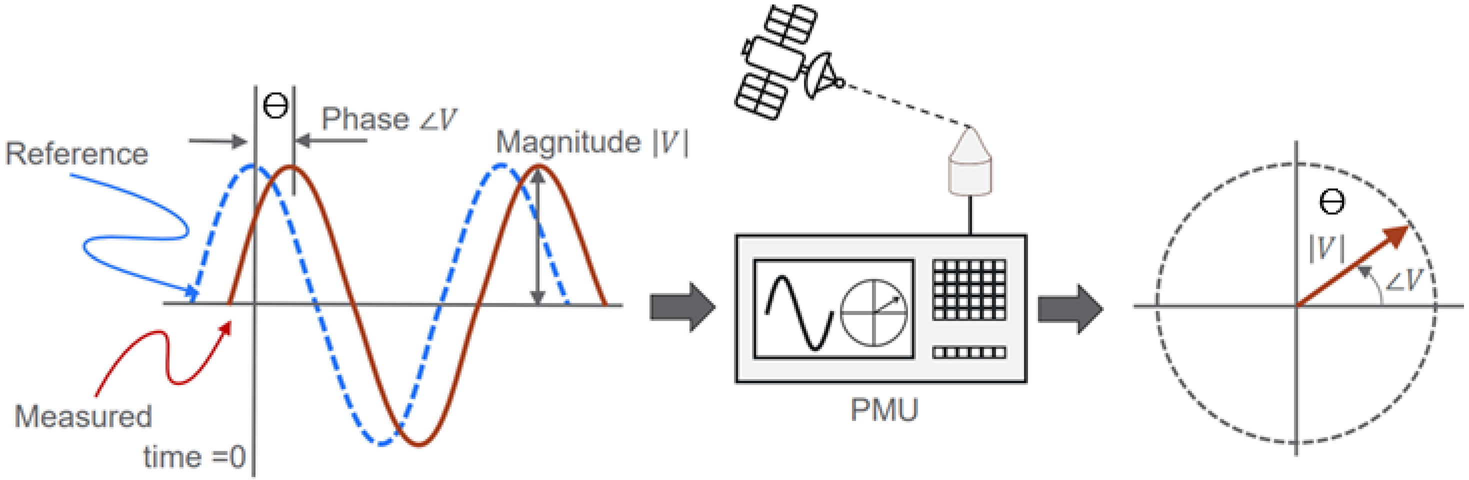
$$X = \frac{X_m}{\sqrt{2}} e^{j\varphi} = X_{rms} e^{j\varphi}, polar\ representation$$

$$X = X_{rms}(\cos\varphi + \text{j}\sin\varphi) = X_r + jX_i, rectangular\ representation$$



Synchrophasor Measurement

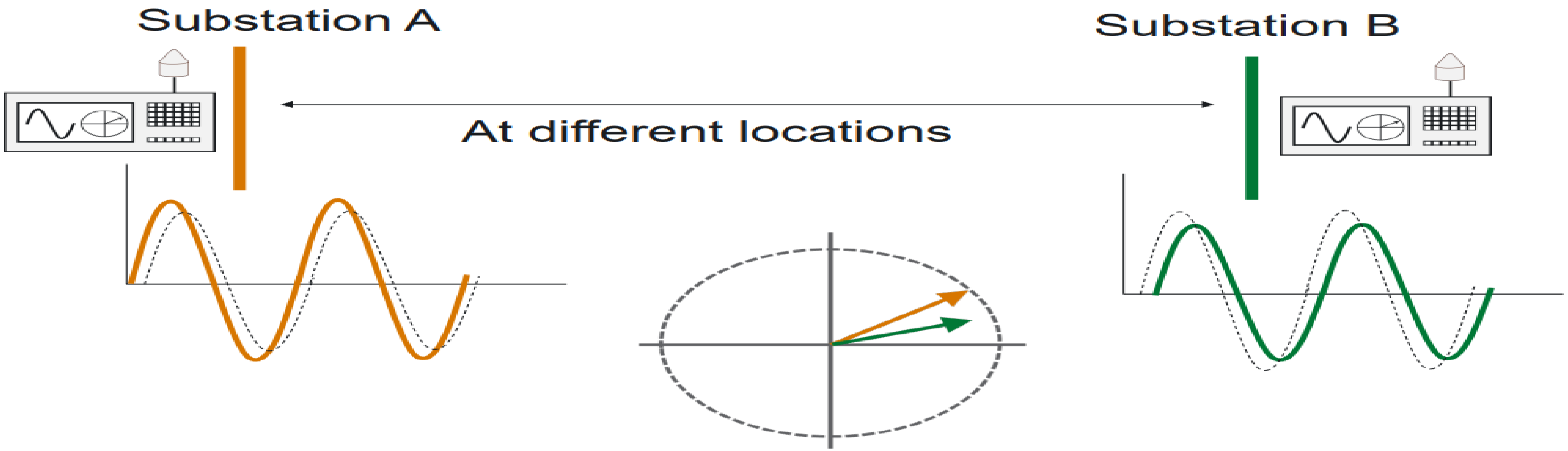
- Synchrophasor is the phasor (vector) with the time stamp reference to a synchronized clock with the time stamping.
- The time is basically from a reference clock with is UTC clock.
- Multiple PMUs are synched to one reference UTC clock.



Ref 5

Why PMUs required time Synchronisation?

- The PMUs are designed to monitor the wide area of the grid system at one glance.
- It is designed to see the grid performance at all the point in WAMS at same time.
- The Synchro phasor data from multiple PMUs can be align reference to time.



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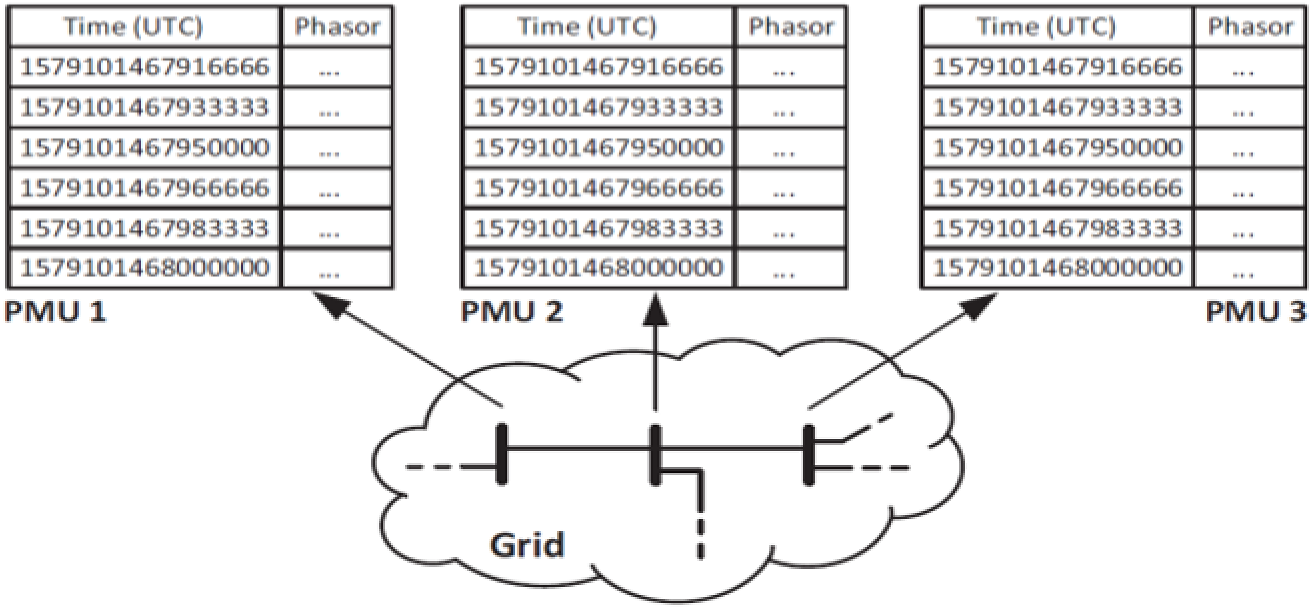
An Example of Time – Stamped measurements from 3 PMUs



UTC Time (micro-second)	Magnitude (V)	Phase Angle (°)
1579101467916666	39832.582	183.680175
1579101467933333	39830.183	183.729736
1579101467950000	39831.321	183.780303
1579101467966666	39830.669	183.832092
1579101467983333	39831.177	183.887145
1579101468000000	39832.093	183.939575
1579101468016666	39833.123	183.991912
1579101468033333	39832.088	184.046417
1579101468050000	39830.748	184.098785
1579101468066666	39831.515	184.145889
1579101468083333	39833.174	184.197860

Synchro phasor Measurement

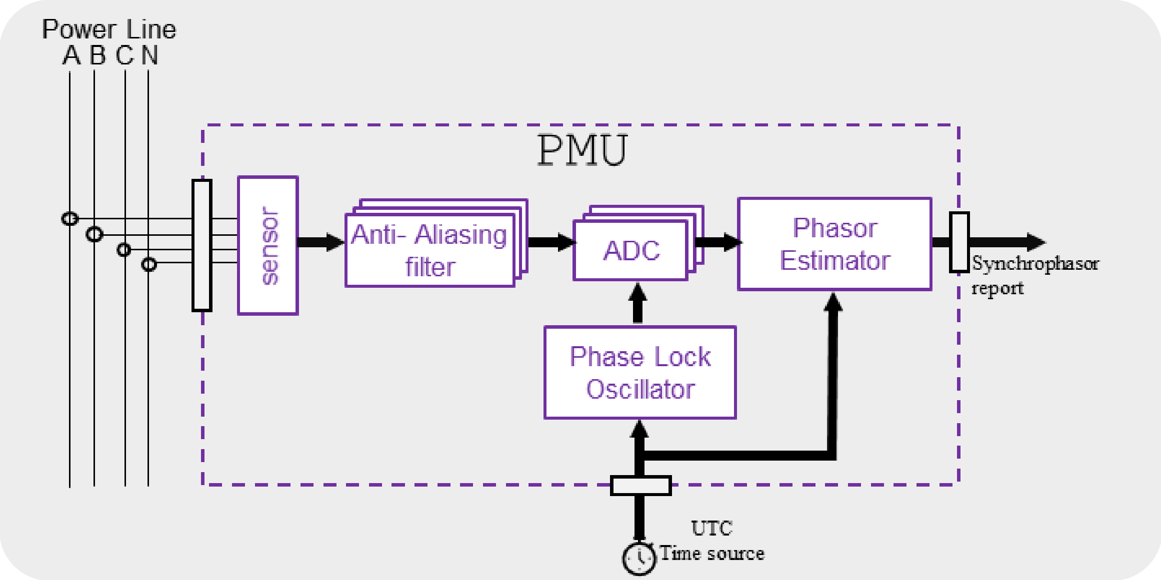
There are three locations and three PMUs provide the Synchro phasor measurements.

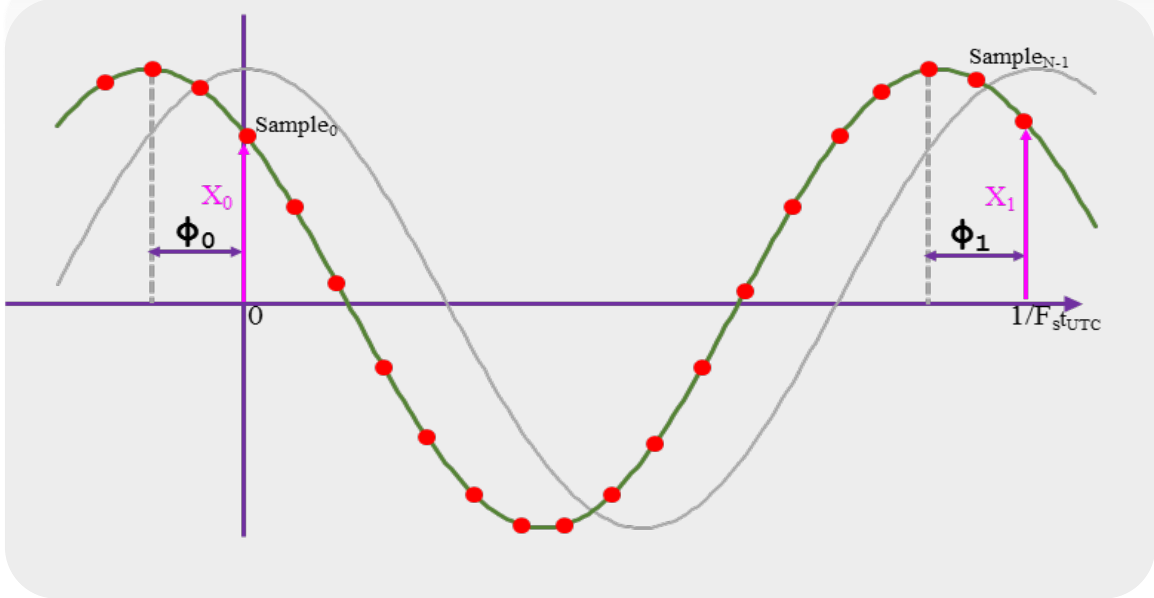
Ref 5

Synchrophasor Measurement

Phasor Measurement Unit (PMU)

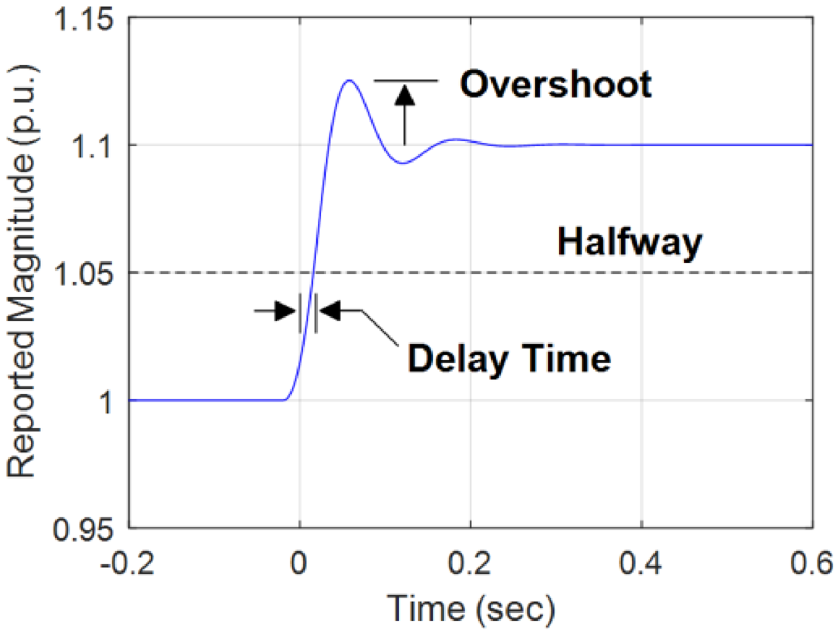
- **Typical architecture**
  - Anti-aliasing filter (AAF)
  - Analogue to digital converter (ADC)
  - Phase-lock oscillator (PLO)
  - Time synchronizing clock
  - Phasor estimator (microprocessor)
    - Discrete Fourier transform (DFT)





Synchrophasor Measurement

- **Measurement Evaluation**
  - Total Vector Error (TVE): $\mathrm{TVE}(n)\sqrt{\frac{\left(\hat{X}_r(n)-X_r(n)\right)^2+\left(\hat{X}_i(n)-X_i(n)\right)^2}{X_r(n)^2+X_i(n)^2}}$
    - As per the standard , TVE must be less than 1%
    - The clock is important and it accuracy shall be 1 microsec.
  - Frequency Error (FE):$|f_{true} - f_{measured}|$
  - ROCOF Error (RFE): $\mathrm{RFE} = \left|\left(\frac{df}{dt}\right)_{true} - \left(\frac{df}{dt}\right)_{measured}\right|$
  - Response and delay time
  - Report latency

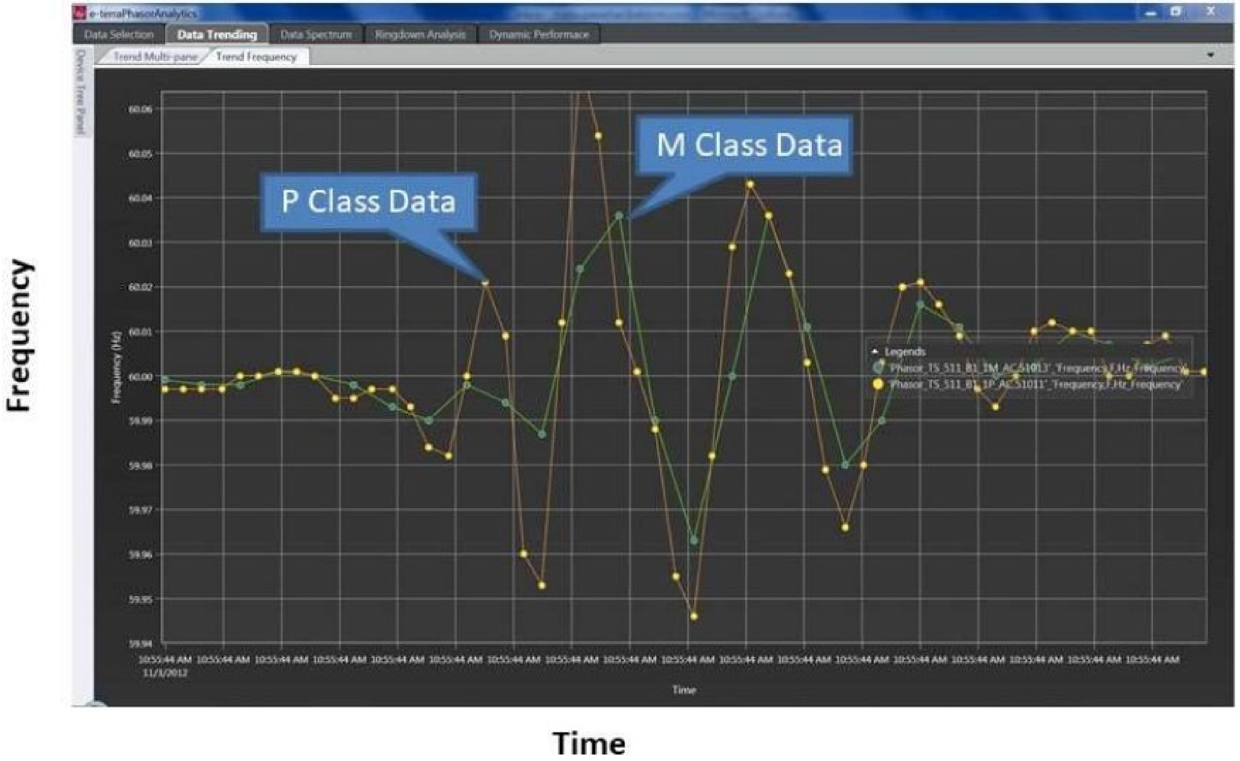


Synchrophasor Measurement

There are **two Classes** of Synchrophasors.

P Class – Protection Class– Fast response

- This can detect fault and transients.
- It uses 2 cycles data to process the phasor
- Triangular filter is applied
- minimal filtering and internal process
- compromised accuracy



M Class – Metering Class - Precise measurement

- Uses 7 cycle samples to compute the phasor.
- Mostly used for more precise application. Metering or monitor steady and dynamic state application.
- High is accuracy but slow in operation, but precise reading.

Synchrophasor Measurement

- **Tests**
  - Steady-state
  - Dynamic
    - Bandwidth
    - Ramp
    - Step
  - Report Latency

Criteria	Requirement	
	P	M
Report Latency	2/Fs	7/Fs

Criteria	Requirement					
	Steady-state		Dynamic - Bandwidth		Dynamic - Ramp	
	P	M	P	M	P	M
TVE	1%	1%	3%	3%	1%	1%
FE	0.005 Hz	Influence quantity dependent	Report rate depended	Report rate depended	0.01Hz	0.01Hz
RFE	0.4Hz/s	Influence quantity dependent	Report rate depended	Report rate depended	0.4Hz/s	0.2Hz/s

Criteria	Requirement – Dynamic - Step					
	P	M	P	M	P	M
	TVE=1%		FE=0.005Hz		RFE=0.4Hz/s	RFE=0.1Hz/s
Response Time	2/f0	7/Fs	4.5/f0	Greater of 14/Fs or 14/f0	4.6/f0	Greater of 14/Fs or 14/f0
Delay Time	1/4Fs	1/4Fs	-	-	-	-

Communication Framework

IEEE C37.118.2

- Defines message format
- Allows any communication or media for message exchange
- Does not address requirements for synchrophasor data storage
- Frames types
    - Data ===========➔(Frames transmitted by PMU/PDC)
    - Header=========➔(Frames transmitted by PMU/PDC)
    - Configuration====➔(Frames transmitted by PMU/PDC)
    - Command =====➔Frames received by PMU/PDC

Communication Framework

IEC 61850

- Interoperability between Intelligent Electronic Devices (IED) from different vendors
- Communication modeled as server/client or Publisher/Subscriber
  - Sampled Value (SV)
  - GOOSE
  - Under Ethernet protocol
- Functions modeled as Logical Device (LD)
- Information modeled a Logical Node (LN)

- IEC 61850-90-5
  - Derived from IEC 61850
  - Fills gaps not addressed in IEEE C37.118.2
  - Transfer synchrophasor data over wide-area network(WAN) between PMU, PDC and wide- area monitoring, protection and control (WAMPAC)
- Data exchanged across large distance under UDP/IP (routable UDP)
  - Routable sampled value (R-SV)
  - Routable GOOSE (R-G)

Communication Framework

IEC 61850-90-5

- Security
  - To avoid damage to physical equipment
  - Merely addressed in IEEE C37.118 standard
  - Confidentiality, integrity, and availability (CIA) triad
    - Confidentiality
      - IEEE C37.118.2 does not address this issue
      - IEC 61850-90-5 address based on group domain of interpretation (GDOI) and key distribution center (KDC)
    - Integrity
      - IEEE C37.118 does not provide enough security
      - IEC 61850-90-5 security is based on digital signature
    - Availability
      - IEEE C37.118 does not address this issue
      - IEC 61850-90-5 does not address this issue

PMU and SYNCHROPHASORS

What is a Phasor Measurement Unit (PMU)?

- A device that measures phasor (magnitude and phase angle of voltage and current) and related data from a specific location on the electrical grid.

- The measurement is synchronized to a common time source. The time-synchronized estimated phasor is called a synchrophasor.

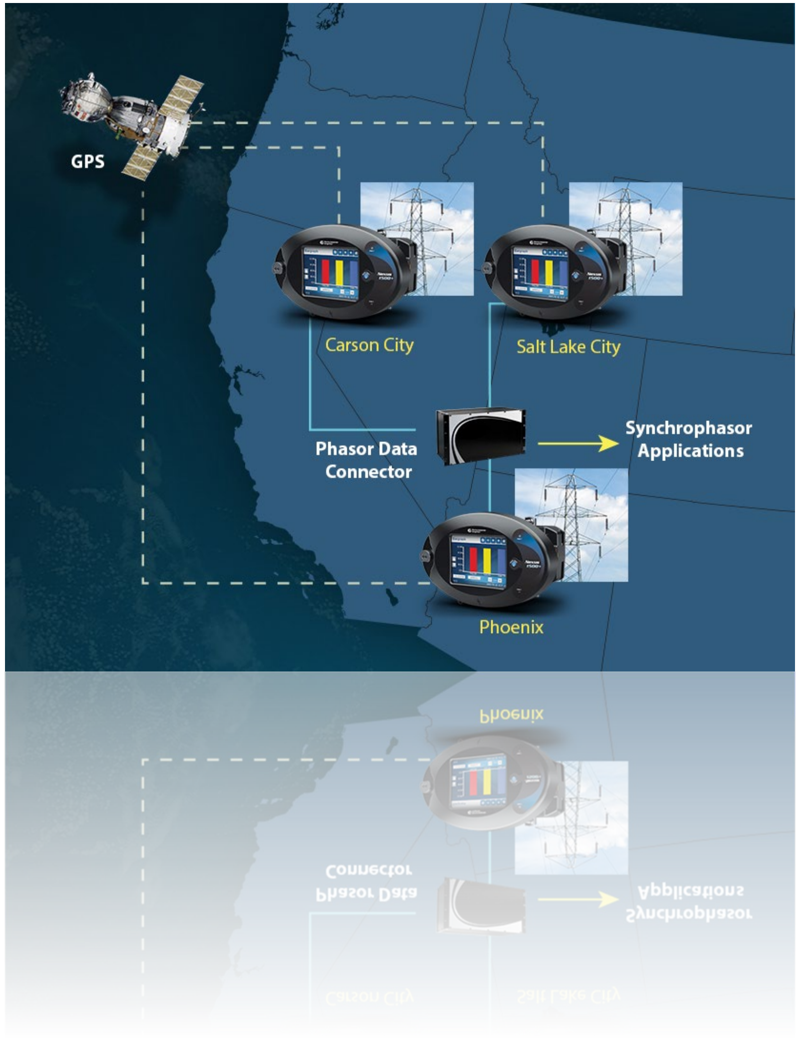
  Time synchronizing sources:

  - IRIG-B - Global Positioning Satellite (GPS)
  - Precision Time Protocol (PTP) – IEEE 1588

- Multiple PMUs transmit the synchrophasors and related data to a phasor data concentrator (PDC), which aggregates and time-aligns the data for real time and post analysis.

Why do you need Synchrophasor measurements?

- Synchrophasors provide instantaneous voltage, current, and frequency at specific locations on the grid, allowing immediate decisions, such as actions to prevent power outages.



PMU Applications

PMU APPLICATIONS

Transmission/Sub-Transmission

- Voltage stability assessment.
- Improve grid resiliency and reliability.
- Determine instability through ROCOF and voltage stability monitoring.
- Monitor reactive margin, phase angle, and power oscillation.
- Determine dynamic line impedance.

Distribution System Applications

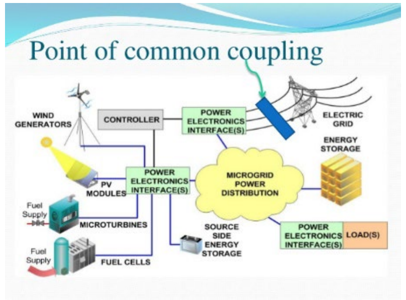
- Enable proactive island detection to prevent outages and ensure reliable power to customers.
- Apparatus monitoring.
- Smart inverter control.
- Volt-VAR optimization.
- Broken wire detection.

Power Generation – Traditional and Alternative

- Provide real time frequency, detection of oscillation, and low damping conditions.
- Facilitate post event analysis through correlating status and analogs.
- Provide data for power system modeling and validation studies.

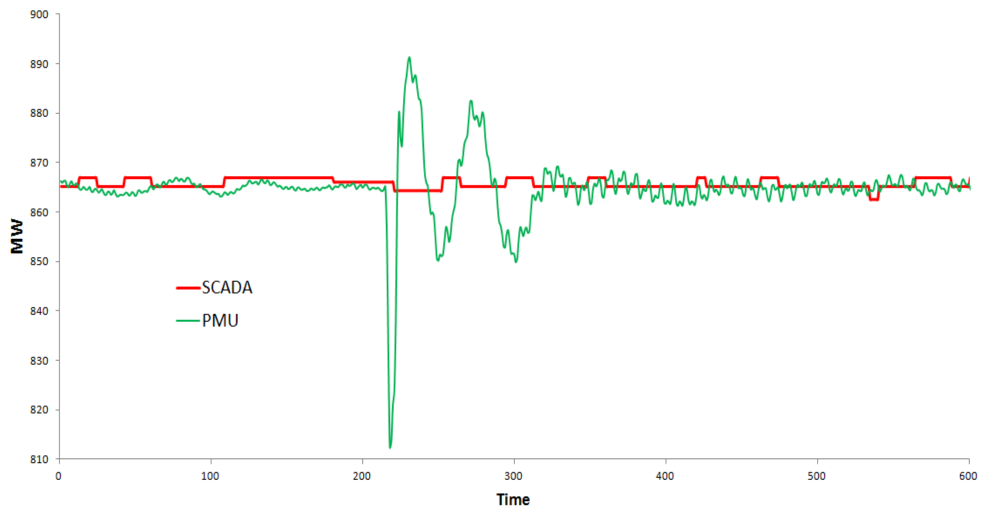
Distributed Energy Resource Monitoring

- DER monitoring.
- DER system angular difference to facilitate long distance check sync.
- Rapid islanding detection for remedial actions.



PMU BENEFITS

- Provide wide-area situational awareness for system operators with improved visibility into dynamic grid conditions.
- Determine stress points of the electric power system.
- Detect and aid in restoring an islanded section of the grid after a storm or major outage disturbance.
- Instantaneous measurements provide early warning detection alerts that SCADA systems miss.
- Built in system wide PMU analysis for future implementation of big data analytics, artificial intelligence and machine learning to proactively improve power systems and prevent outages.



Undamped Oscillation Three-phase fault near power plant. System oscillations not visible on SCADA (red). Power station operators notified System operators of the oscillations.

Power Quality Meters – and PMU IMPLEMENTATION

- The PMU provides the following Synchronized Measurements:
  - Individual voltage/current phasors (VA, VB, VD, IA, IB, IC).
  - Symmetrical components phasors (V0, V1, V2, I0, I1, I2).
  - Frequency and Rate of Change of Frequency (ROCOF).
  - Built-in digital inputs.
  - Analog -
    - Fundamental power: (watt total and per phase, VA total and per phase, VAR total and per phase).
    - Displacement power factor: (total and per phase).
- Supports P (Fast Response) or M (Precise Measurement) classes - user selectable.
- Data frame rates for 50 Hz: 10/25/50 frames per second; for 60 Hz: 10/12/15/20/30/60 frames per second.
- Data format: Configurable float or integer, polar or rectangular.
- Time sync standard: IRIG-B or IEEE 1588 PTPv2 .
- Number of sessions: up to 2 simultaneous clients or multiple clients.
- Supports Ethernet or Fiber over Ethernet: TCP communication for header, configuration, and command; UDP communication for data, including unicast, broadcast, and multicast.

SCADA

SCADA systems

- Have been around since the 1960s
- Have developed over the superseding decades from small control networks to wide area interconnected systems as Ethernet technology developed.
- Are used for monitoring and controlling remote devices at a reasonable speed that complies with the requirements.
- Consist of remote terminal units (RTUs), which transmit data to centralized servers.
- Were originally developed for manufacturing use.
- Are still used throughout industry, including wide use by electrical utilities.

Traditionally, Supervisory Control and Data Acquisition (SCADA) systems have been adopted for high-level monitoring of the grid networks.

SCADA

How SCADA systems fall short today?

- It has a long history but **does not meet the current** requirements.
- Does **not operate quick enough** to monitor the fast transients: With the massive integration of renewables, SCADA systems are inadequate to capture the fast system transients generated.
- Current system requirement is to **capture the events faster and react faster**.
  - Renewable energy sources tend to introduce rapid transients into the grid.
  - Renewable energy sources can cause reactive power consumption from grid which can cause voltage fluctuations.
  - More renewable energy sources are connected to the grid. They are working with conventional generation system.
  - More battery energy storage systems (BESS) are connected to the system due to government incentives and energy arbitrage; these have introduced more complications

Synchro phasors vs. SCADA

ATTRIBUTE	SCADA	PMU
Resolution	1 sample every 2-4 seconds	10-60 samples/sec
Observability	Steady State	Dynamic
Measurements	|V |, I, MW, MVAR	|V |,δ, MW, MVAR , I, frequency, ROCOF
Synchronization	No	Yes
Phase Angle	No	Yes
Focus	Local Monitoring and Control	Wide area Monitoring and Control

Comparison of Devices with Multiple Technology (Ref 4)

	Meters & PQ & Recorders	Relays	Merging Units (61850 SV)	PMU (IEC 61869 defines sampling and output rates)	RTUs and SCADA
Signals sampled	V and I from VTs and CTs	V and I from VTs and CTs	V and I from VTs and CTs	V and I from VTs and CTs	Phase-to-phase voltage
Typical sampling rates	960 to 50,000 Hz	960 to 8,000 Hz	4,800 to 14,400 Hz	960 to 8,000 Hz	Typically under 1,000 Hz
Output data intervals	0.2s (PQ) to 5 minutes	By exception	0.4 ms	8 ms to 33 ms	2s to 10s
Output data rate	12 per hour (0.003 per second)	Irregular	2400 per second	30 to 120 per second	0.1 to 0.5 per second
Number of input channels	6 (3V and 3I)	6 (3V and 3I)	6 (3V and 3I)	6 (3V and 3I)	1 (V_{AB})
Number of parameters measured per device	1 to 20	1 to 6 +	3 to 8	5 to 20 (Vs, Is, f, etc.)	1 (V_{AB}) +
Number of devices acting	1 local	1 to 2 local	1 to 5 per relay 1-200 in substation	100s to 1000s Wide Area	1000s Wide Area

PMU Device Setup Example

Following are the Steps to follow in setting up any PMU device:

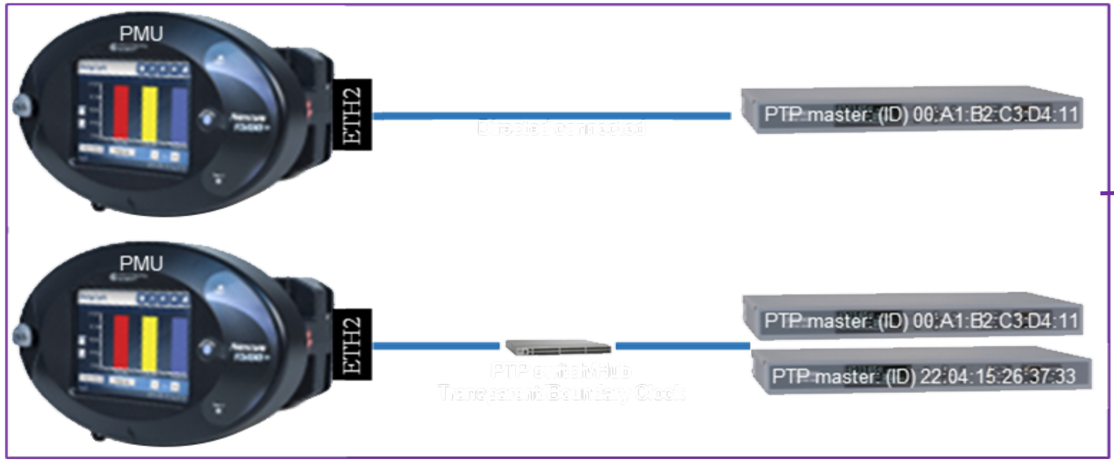
1. Connect to a meter/device with PMU functionality.
2. Program:
    a. Time synchronization
    b. Nominal Frequency
    c. PMU settings

PMU Device Setup Example

Program the PMU

Requirements

- To use the PMU feature effectively, an external time synchronization reference is needed:
  - A stable and accurate external time source is crucial to have the meter to accurately calculate the synchrophasor magnitude and angle
  - PMU devices support the following two-time synchronization methods:
    - IRIG-B
    - Precision Time Protocol (PTP) - IEEE 1588



To be able to obtain the PTP time synchronization with the highest accuracy, the way that the PMU will have access to the PTP master clock is important. The two configurations are either:
- PMU direct connected to a PTP master, or
= PMU connected through a PTP hub/switch.

In the second configuration, it is possible to have multiples PTP masters.

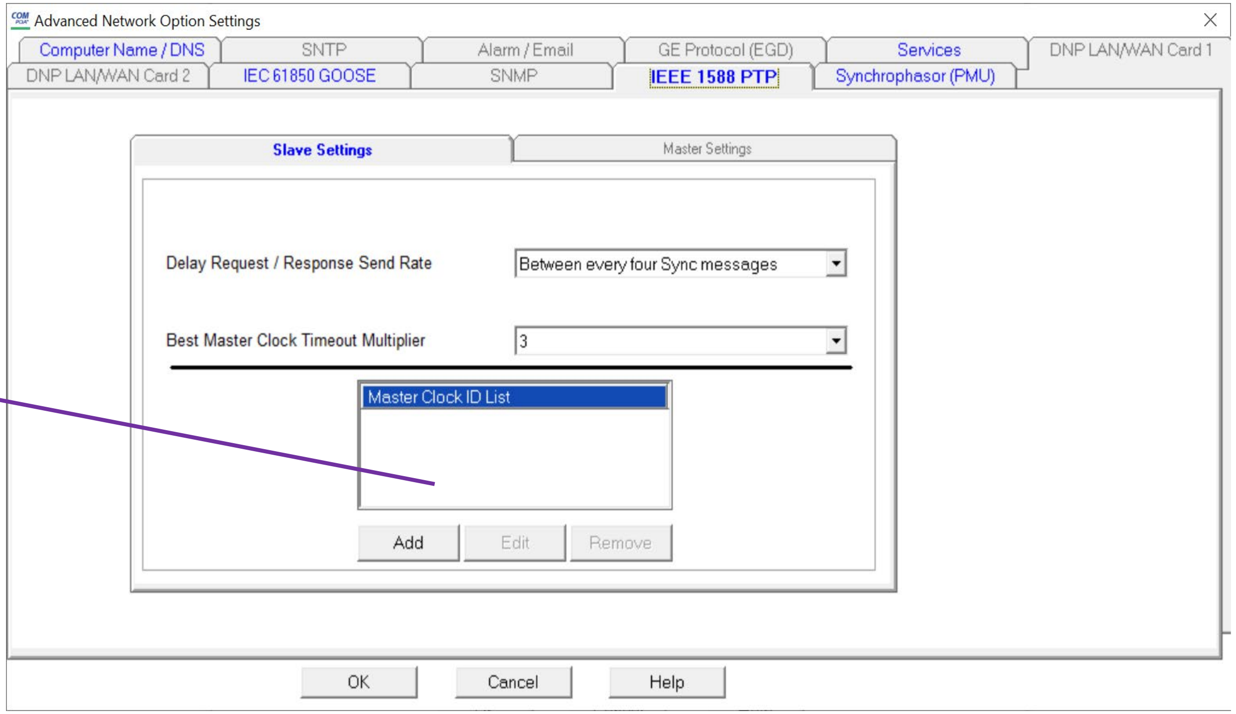
PMU Device Setup Example

Program the PMU – With Multiple PTP masters

Select time synchronization method :

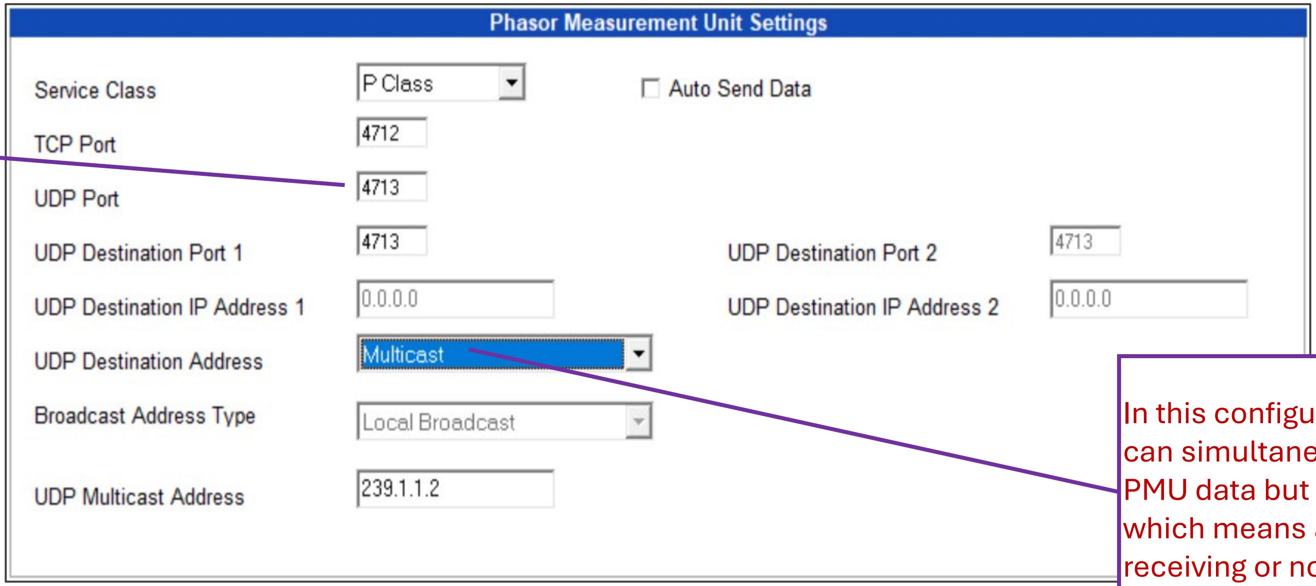
In this example, Device Profile>General Settings>Time Settings, select Time Synchronization Source – IEEE 1588 PTP – continued

If there are multiple PTP masters in the network, the best master clock (BMC) algorithm running in the meter can use the clock ID as the last priority to decide to choose one master clock as the best one. In Master clock ID list add the clock ID in order of priority to be used by BMC algorithm



PMU Device Setup Example

PMU UDP Port. 4713 is the standard value Data frame traffic.

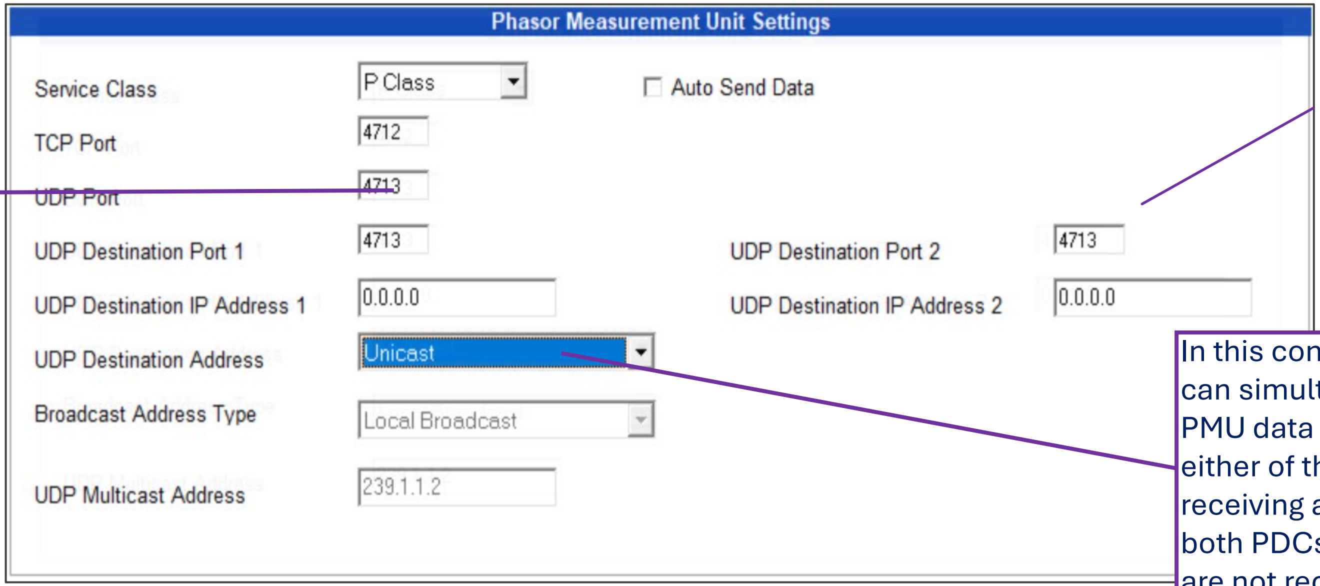


In this configuration, multiple PDCs can simultaneously receive the same PMU data but not independently, which means all PDCs are either receiving or not receiving PMU data.

PMU Device Setup Example

If a second PDC is not available to receive the PMU data, then UDP destination Port 2 and IP address 2 do not need to be configured.
If a second PDC is going to be available to receive the PMU data, then UDP destination Port 2 can be the same as UDP destination Port 1.

PMU UDP Port. 4713 is the standard value Data frame traffic.

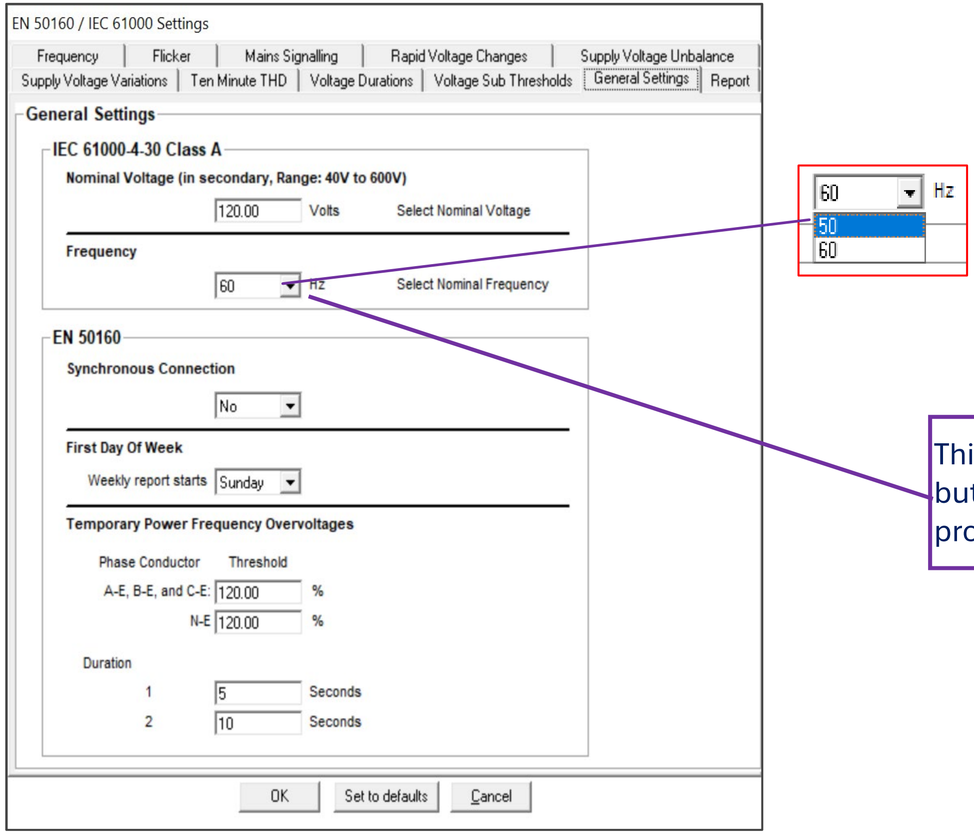


In this configuration, up to two PDCs can simultaneously receive the same PMU data independently, which means either of the following: one PDC is receiving and the other is not receiving; both PDCs are receiving; or both PDCs are not receiving.

PMU Device Setup Example

Program the Nominal Frequency

In this example, Device Profile>Power Quality and Alarm Settings>EN50160/IEC 61000-4-30 setting

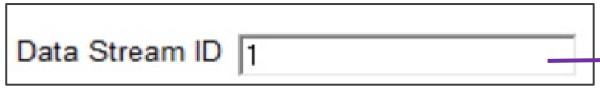


This is not a dedicated PMU setting, but it is required for PMU to work properly.

PMU Device Setup Example

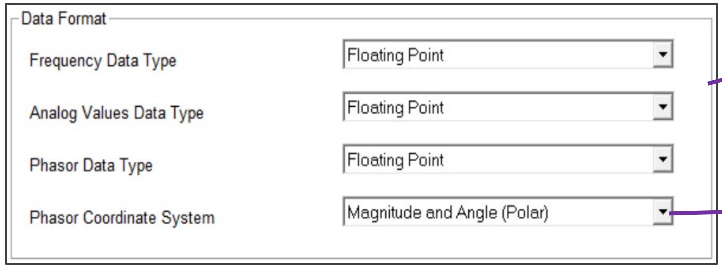
Program the PMU settings

Data Stream ID



Any number from 1 to 65534.
In systems with multiple PMUs, this number should be unique then the PDC can identify each data frame comes from each PMU.

Data Format



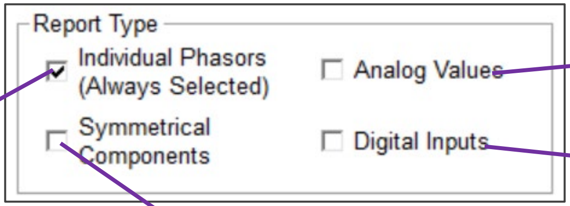
Either “Float Point” or “Integer”

Either “Magnitude and Angle (Polar)” or “Real and Imaginary (Rectangular)”

Data Rate

10/25/50 in 50Hz nominal frequency or
10/12/15/20/30/60 in 60Hz nominal frequency

Report Type



This is always checked, so that PMU data contains at least tho individual synchrophasors - (V_A, V_B, V_C, I_A, I_B, I_C).

Check this box to have these values reported in PMU data. The analog values are PMU’s post-computation data that uses the individual synchrophasor as input to generate the fundamental power values.

Check this box to have these values reported in PMU data.

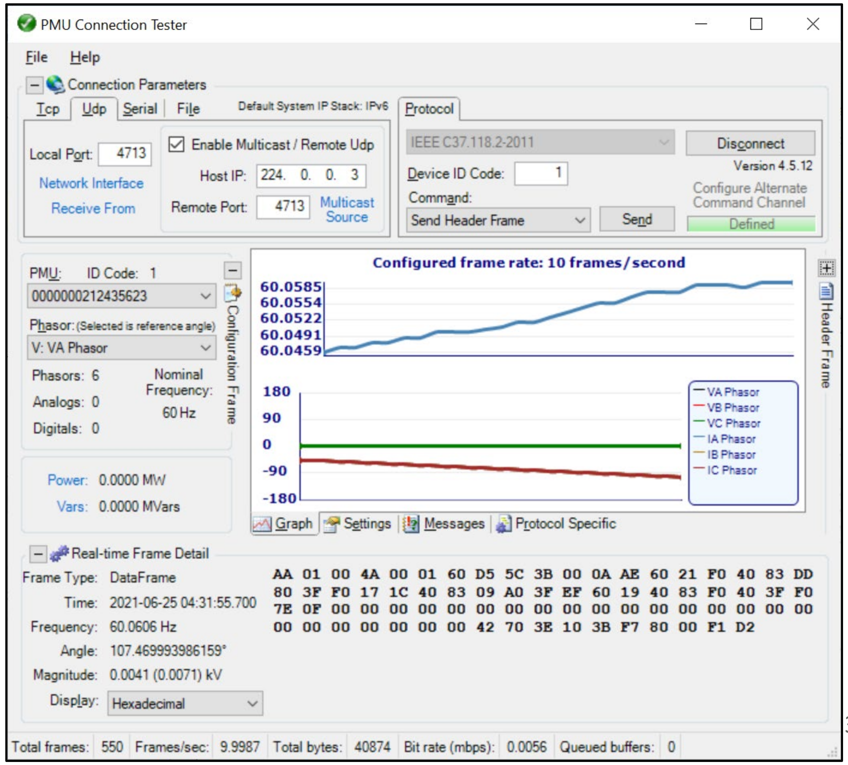
Check this box to have these values reported in PMU data. The symmetrical components are PMU’s post-computation data that uses the individual synchrophasor as input to generate V_0, V_1, V_2, I_0, I_1, I_2.

PDC Discussion

- The PDC is a software application capable of receiving the PMU data and time-aligning it to display in real time or to record for post analysis.

- Any PDC which supports IEEE C37.118.2-2011 will be able to receive PMU data.

- One example of PDC software is the PMU Connection Tester.
  - This is a free software that is available for download from the following link: https://github.com/GridProtectionAlliance/PMUConnectionTester.
  - It can record and display PMU data.
  - It can enable/disable the PMU data stream.
  - It can read the header and configuration frame.



PDC Discussion

- The PMU Connection Tester software, when properly configured and connected to the meter displays real time PMU data and records it for post analysis.
- The recorded PMU data is saved in a .csv file.
- The format of the .csv file for different report types is shown below.

PMU Connection Test data stream output file format when reports individual phasors only																				
Timestamp	STAT[1]	Pha[2]	Mag[3]	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Freq[4]	ROCOF[5]	SOC[6]
		Va		Vb		Vc		Ia		Ib		Ic		V1		I1				

PMU Connection Test data stream output file format when reports individual phasors + Symmetrical Component																												
Timestamp	STAT	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Freq	ROCOF	SOC
		Va		Vb		Vc		Ia		Ib		Ic		V0[7]		V1[8]		V2[9]		I0[7]		I1[8]		I2[9]				

PMU Connection Test data stream output file format when reports individual phasors + Symmetrical Component + Digital Input																													
Timestamp	STAT	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Freq	ROCOF	DI[10]	SOC
		Va		Vb		Vc		Ia		Ib		Ic		V0		V1		V2		I0		I1		I2					

PMU Connection Test data stream output file format when reports individual phasors + Symmetrical Component + Digital Input + Analogue																									
Timestamp	STAT	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag	Pha	Mag
		Va		Vb		Vc		Ia		Ib		Ic		V0		V1		V2		I0		I1		I2	
Freq	ROCOF	Watt				VAR				VA				PF[11]				DI	SOC						
		Total	A	B	C	Total	A	B	C	Total	A	B	C	Total	A	B	C								

1 = STAT (Status bits), 2 = Pha (Phasor Phase), 3 = Mag (Phasor Magnitude),
4 = Freq (Frequency), 5 = ROCOF (Rate Of Change Of Frequency) 6 = SOC (Second of Century),
7 = V0/I0 (Zero symmetrical component), 8 = V1/I1 (Positive symmetrical component), 9 = V2/I2 (Negative symmetrical component)
10= DI (Digital Input State), 11 = PF (Power Factor)

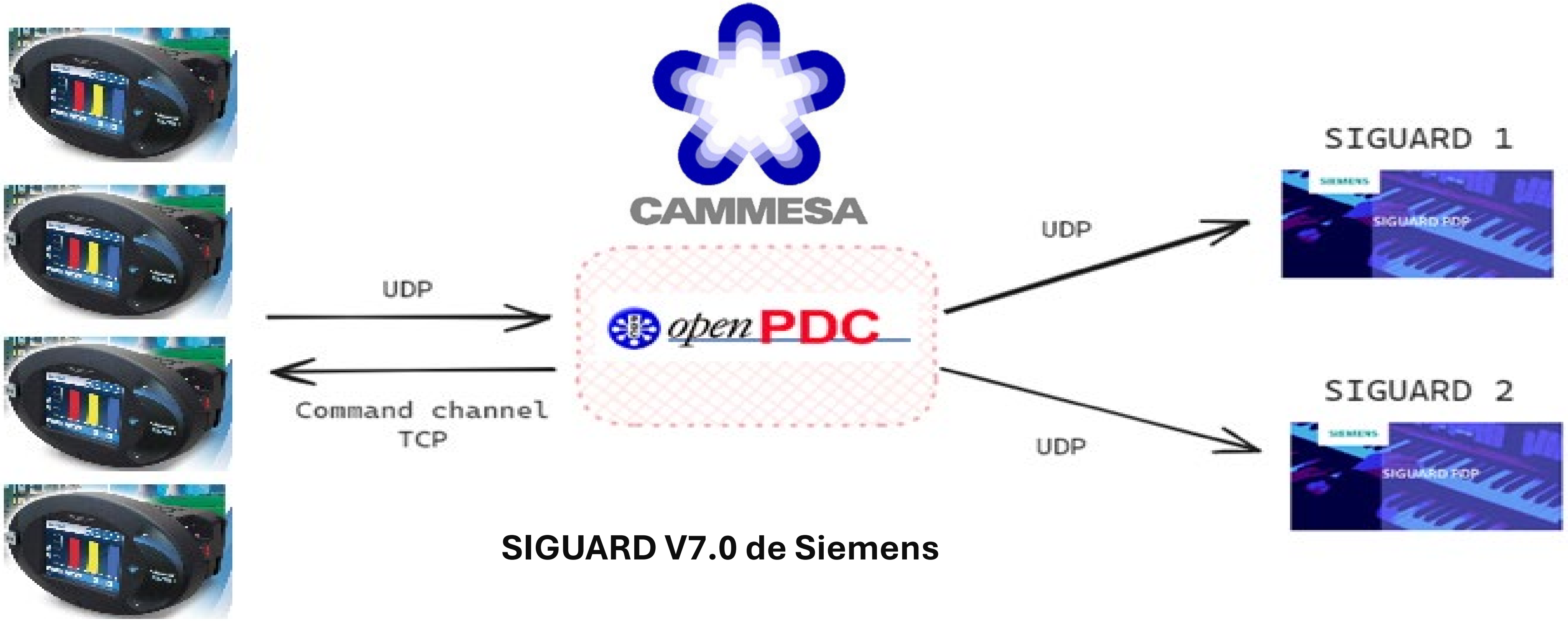
Case Study and Application

Nexus 1500+ V6 meters for PMU Monitoring In Argentina

All data is shared with the Argentine government regulatory entity

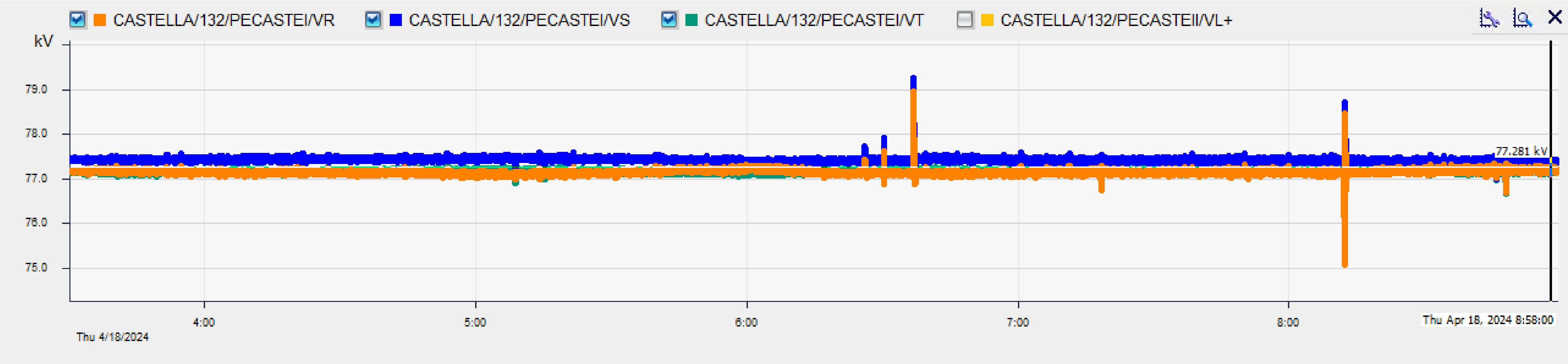
CAMMESA

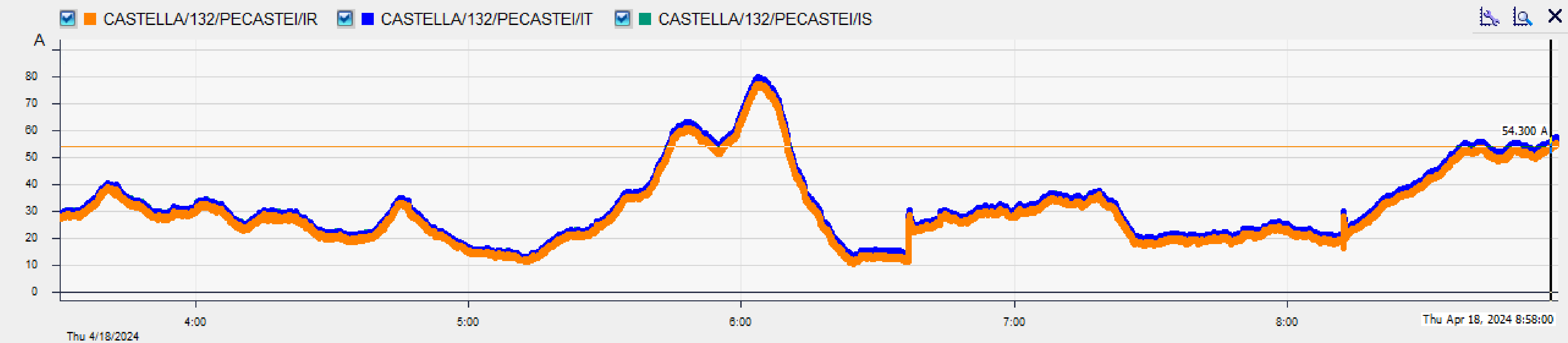
Current Architecture of the System



SIGUARD V7.0 de Siemens

Castella Substation of Central Puerto Electrical Company





Genneia Monitoring 4 substations since 2022

36 Towers

162 MW installed power

705.000 MWh annual production

154,000 customers supplied

352,500t less CO_2 in the atmosphere

Central Puerto

Monitoring 5 substations since 2022

21
Towers

390 GWh
MWh annual production

108.333 customers supplied

179.400t less CO2 in the atmosphere

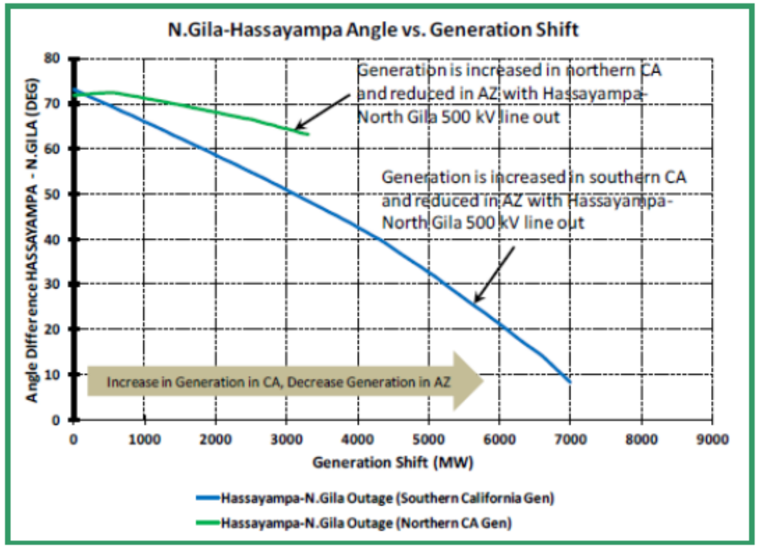
METER PMU BENEFITS

Real World Example:

Result of Undetected Phase Angle Divergence in September 2011 Southwest US Outage

- 11-minute cascading outage in Pacific Southwest.
- Initiated when a single 500 kV line tripped.
- Power was redistributed, increasing flow, dropping voltages, and overloading equipment.
- Led to tripping lines, generators, etc.

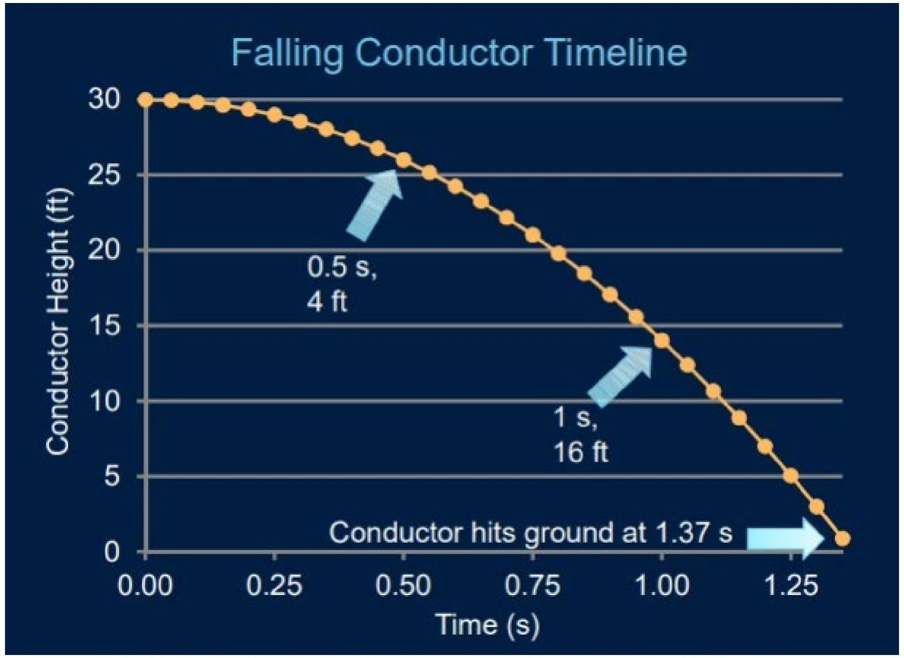
Figure 17: Phase Angle of H-NG vs. Generation Shift



Federal Energy Regulatory Commission and North American Electric Reliability Commission (2012), Arizona-Southern California Outages on September 8, 2011 Causes and Recommendations.

Broken conductor Detection at San Diego gas & Electric

- In California, there are situations where the falling conductor causing fire, and this has a significant concern to many utilities.
- San Diego Gass and Electric found a method to detect and trip on falling conductors while still the conductor in the air using the PMUs.
- PMUs monitors the all three phases V and I , and when they see the situation when V is present without I and other phases carry Vs I, that condition is taken as falling conductor and trip is issued. Changes are very closely monitored.
- A commercial solution is now being implemented using this technique.

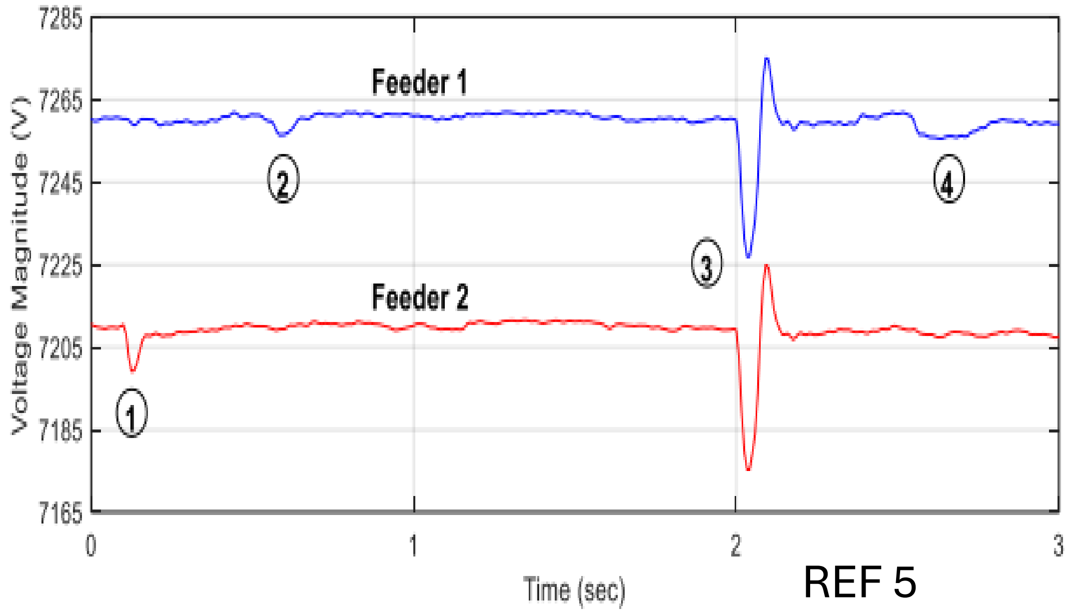


Source: SDG&E, https://www.naspi.org/sites/default/files/2019-10/04_SDGE_Dietmeyer_20191029.pdf

Identification of system wide issue and local issue

Let us study this for our understanding:

- Event 1 is visible in Feeder 2 but not in Feeder 1.
- Events 2 and 4 are visible in Feeder 1 but not in Feeder 2.
- Event 3 is visible in both feeders.
- Therefore, event 3 is caused in transmission or sub-transmission systems while events 1 , 2 , and 4 are caused in distribution systems.



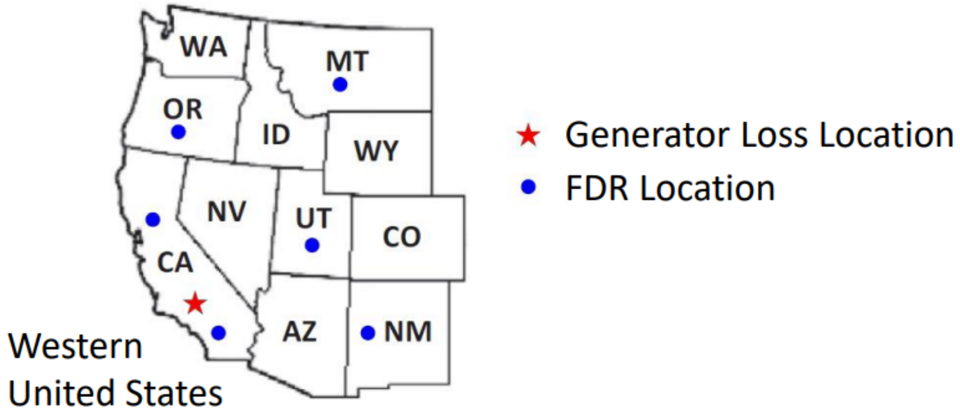
REF 5

This shows the important of the clock. Otherwise , this can create a misleading info.

Having PMUs at Feeder 1 and Feeder 2, by looking at the synchro phasors , it is possible to study the systemic events in detail.

PMUs used to understand the loss of Generator event:

- A group of six FDRs were installed at six different locations on the on the Western Interconnection in the United States as part of the FNET/GridEye project.
- This was performed as an initiative project to implement the PMUs.
- The main generator failed in California state, and we can see how the frequency started to drop at different states.
- State far from gen were dropping slowly due to the influence of the electrical Inertia cause by loads.
- And State close to Gen were dropping the frequency faster.



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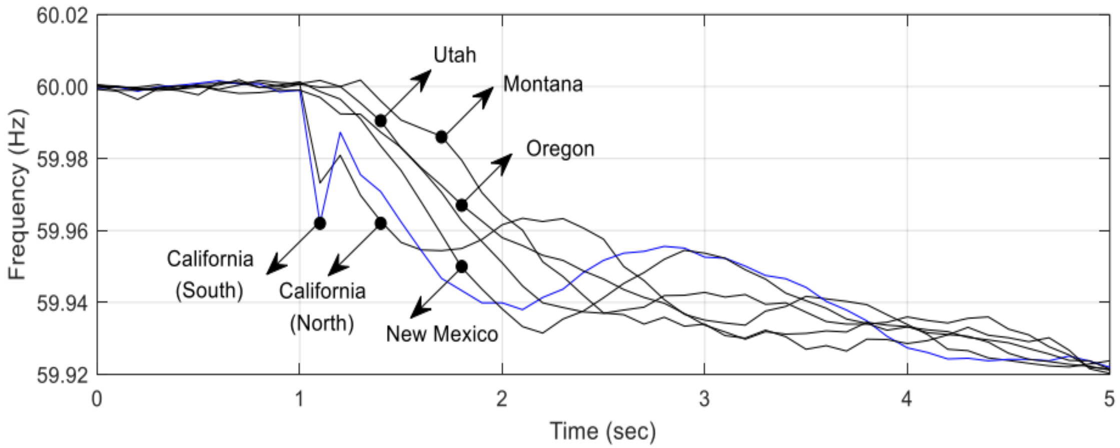

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Power Flow and Relative Phase Angel Difference

Relative Phase Angle Difference: This is one of the applications using the synchro phasor values. Having measurements at two locations, RPAD can be calculated.

Note: Time synch is very important. Otherwise, it has no meaning.

- Power follow between buses on an AC network based on the phase angle difference.

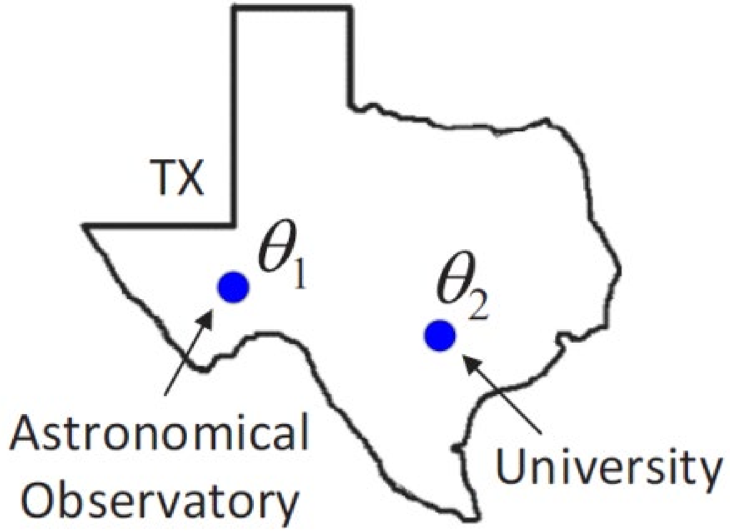
$$P_{12} = \frac{V_1 V_2}{X_{12}} \sin(\theta_1 - \theta_2)$$

- PMU data can be used for monitoring the power follow and the direction. Power flow is proportional to RPAD.
- This is a useful infor for system planning, operation control and generator dispatches.

Texas Synchro Phasor Network

In this application, PMU measurement data are used to understand the power follow from wind turbine source from west side to Tx to the load in East side of TX.

- The daily profile of RPAD with the daily profile of the amount of wind power generation in West Texas looks the same.
- This shows that the power generation from wind is fed to the university load.



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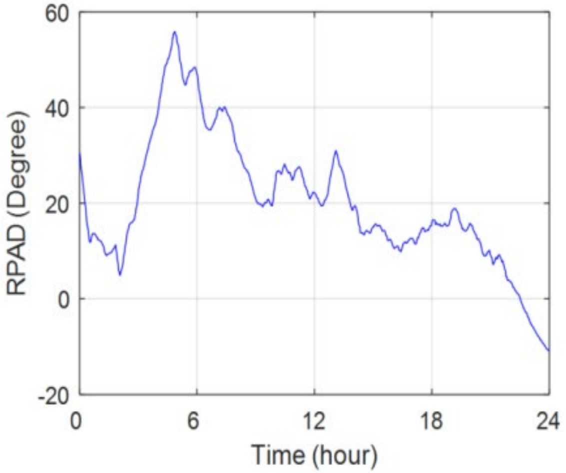
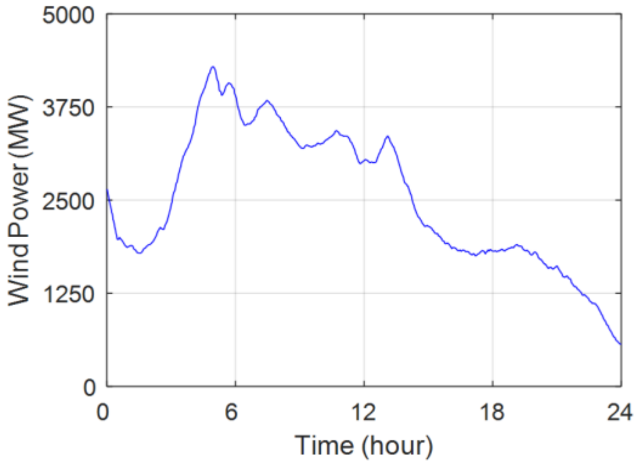




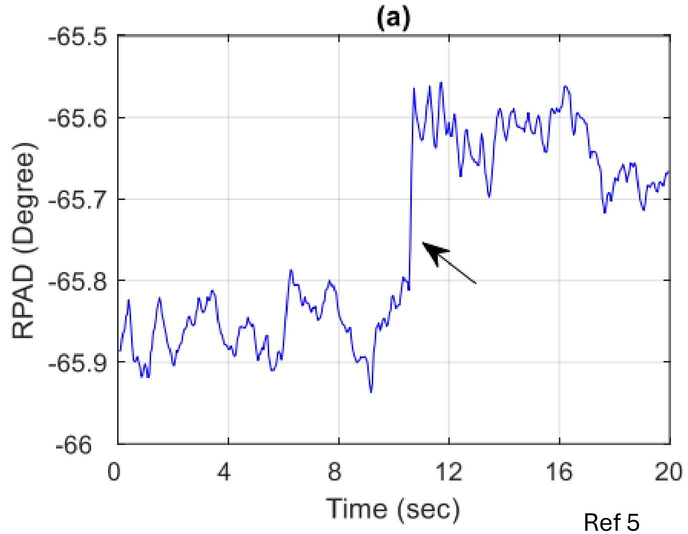
Ref 5

PMU measurement for Stability

Synchro Phasor data can be used to understand the system stability during the transient events.

Figure (a):

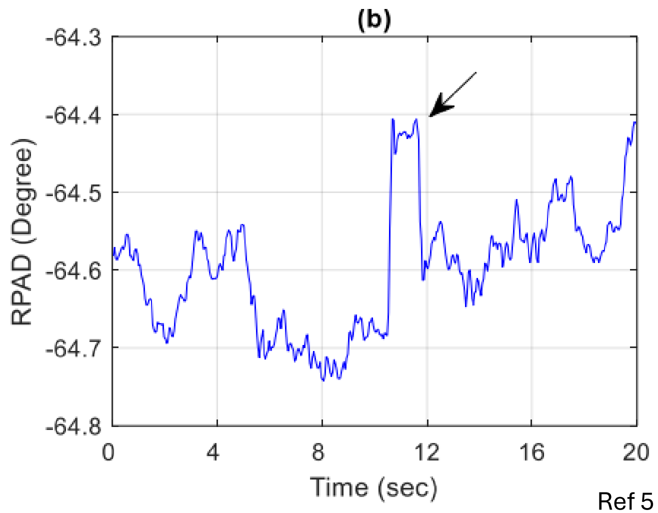
- This was captured when there was a tripping of the transmission line.
- The tripping of the line redirected the power flow to surrounding transmission lines.
- There was an angle drop and drop in power flow due the line dropped . We can see that the RPAD changes by 0.24 figure (a).



Ref 5

Figure (b):

- Temporary fault, tripping and reclosing.
- There was a disturbance when the breaker was opened.
- Power flow dropped and regained back when the reclosure closed.
- The system was back to normal.



Ref 5

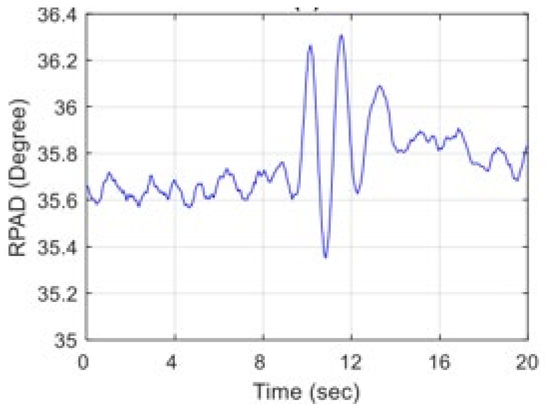
PMUs used for Detection of Inter – Area Oscillations

1. Inter-Area Oscillations typically occur if there is a sudden change in the power system. Example tripping of generators or sudden load change etc.

2. This can cause unintentional power exchanges across the regions.

3. The inter – area oscillation can carry a frequency from 0.15 Hz to 2Hz depending on the condition.

Example:



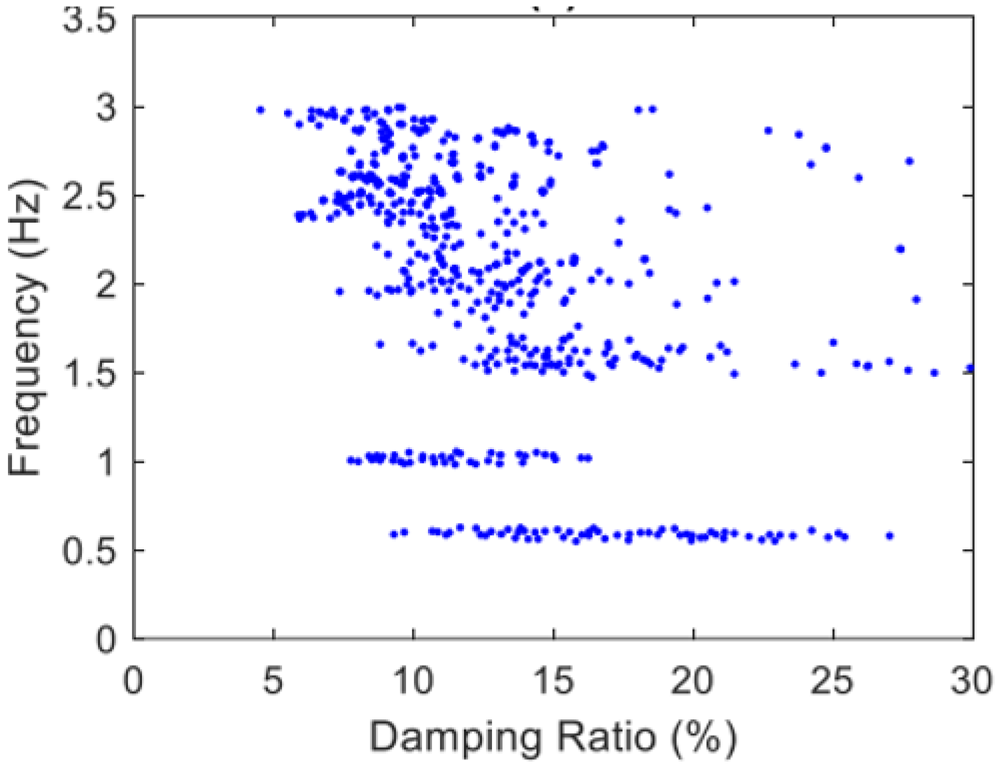
This is a damped transient event.

Duration of the oscillation last for 4.4 sec the swing angle is about 1 degree.

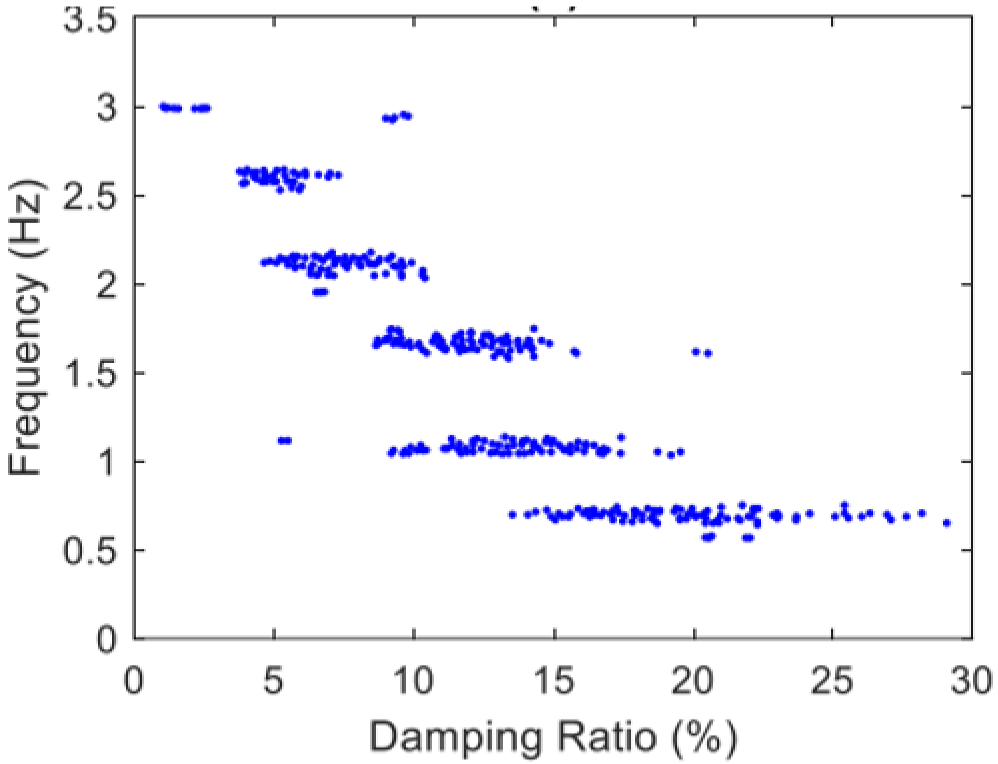
Frequency of oscillation is about 0.59Hz.

Oscillation nature collected from Texas Wind turbine

- We can see how the oscillation behave with the loading of the generator.
- Generators was stable when they are loaded and oscillatory when they are lightly loaded. Ref 5.



Low wind condition
Wind power contribution was 4 to 5%

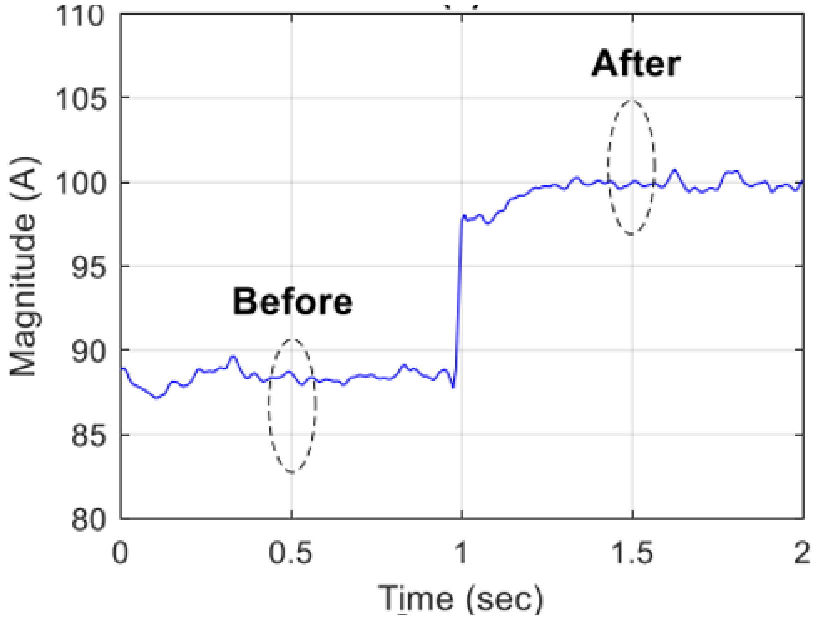


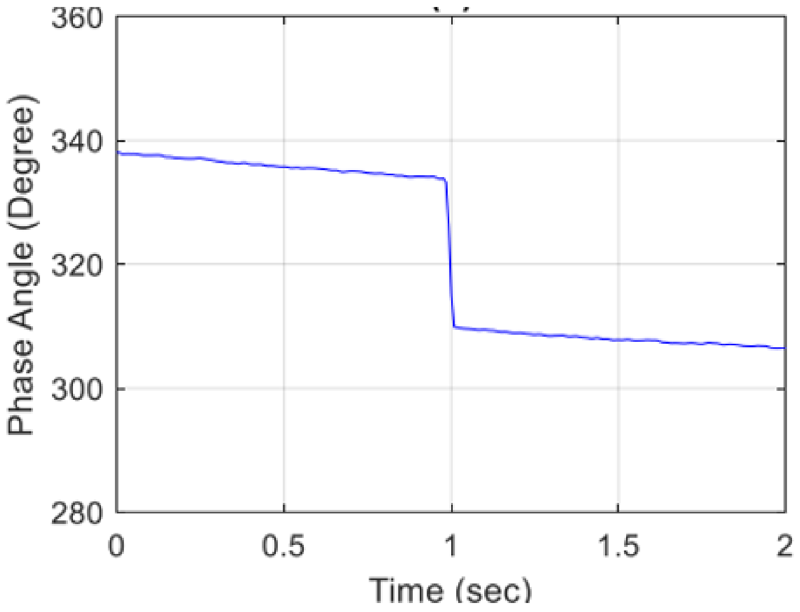
High wind condition.
Wind power contribution 15 to 20%

Phasor differential and Differential Synchro phasors.

What is phasor differential and Differential Synchro Phasor?

- Phasor Differential (PD) is the difference between two phasor measurements - that are obtained from the same PMU.
- Since it has the time stamping respect to time synchronization clock, it is called Differential synchrophasor.
- This is mostly happened due to an event.
- **Example**: Switching of the Capacitor back to a distribution line: PMU measured the time stamped current phasor and voltage phasor moment before switching and moment after switching.





Ref 5

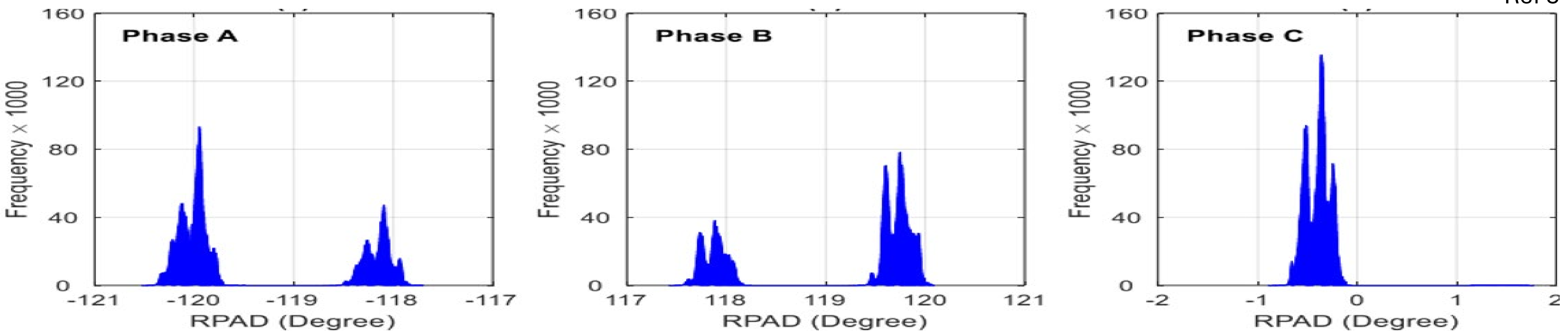
Synchro phasors for phase detection

Another application is phasor identification.

- In the distribution system , the phasor identification is a difficult and challenging job.
- Many transposing could take from substation to substation and at the feeder level.
- Having the PMUs and by using the RPAD, any incorrect phasing can be identified immediately.

Let's look at the situation where the load is connected to unknown phase. Using the RPAD, the correct phase can be identified. Use the PMU measurement at the know phases and compute the RPAD between the connected phase and the know phase and observe for few hours .

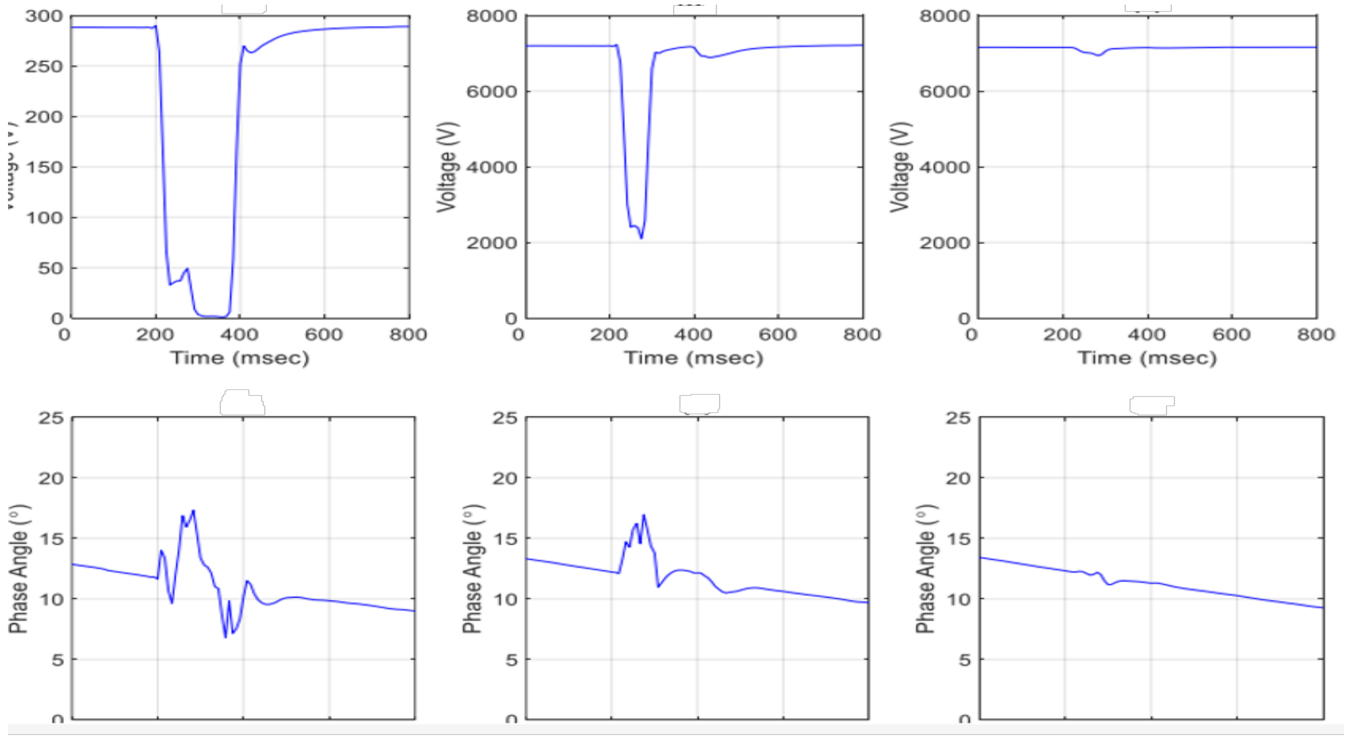
Ref 5



Fault Detection using the Synchro Phasors

PMU measurements are good assert to conduct fault study of the power system fault.

- Since Multiple PMUs located to monitor the wide area of the grid network, the impact of the fault would be captured by PMUs at different locations.



PMU near to Fault

PMU at the substation feeder is connected.

PMU far from the fault

State Estimates

1. State estimation is the action of calculating the state of the system which involves magnitude and phasor angles of the V and I and the different point in the Bus using the available information. (not measured using PMU).

2. If the point where there is a PMU, then we do not require to have the state estimation. (because we measure the values directly from the PMU – state measurement).

3. However, this has a risk, in a case if the PMU fails, we might not be able to get the phasor estimate to conduct or do the functions.

4. However, the security and more integrity to the data can be accommodated by accommodating the state estimates at the point where the phasors are been measured. (in background estimation can be done for the point been measured as well).

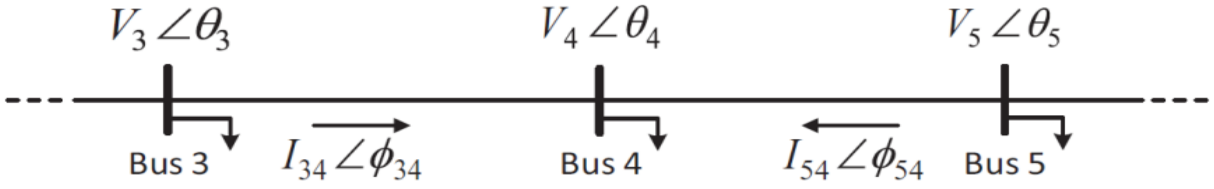
5. This will help to verify the integrity of the measurement as well as find the values if they were lost during the transmission etc.

State Estimates Application Examaple

Let's look at the example below:

Bus 3 and Bus 5 carry PMUs to do the synchro phasor measurements.

Bus 54 does not. However, the state Synchro phasor estimation at Bus 4 can be calculated as follows:



$$I_{34}\angle\phi_{34} = (V_3\angle\theta_3 - V_4\angle\theta_4)\,(G_{34} + jB_{34}),$$

$$I_{54}\angle\phi_{54} = (V_5\angle\theta_5 - \underline{V_4\angle\theta_4})\,(G_{54} + jB_{54})$$

Unknown

Conclusion

- Application of PMU technology and Implementation of Synchro Phaors in power system has been growing in last 30 years.
- Several Pilot modules were implemented and that had showed up constructive results.
- With the growing complexity of the power system network and implementation and growth of the DG and DER systems require more controllability and monitoring of the wide are of the grid network.
- Operations, Controls, generators dispatchers, engineers , designers, testing and commissioning are required with real time data to increase the grid resilience, reliability and sustainability. PMUs can fill will this request.
- NASI with US Energy management and NERC and Utilities trying to implement the PMU technology through out the North America so that more security in operation can be added.
- With the implementation of IEC 61850 architecture to the communication, more reliable, faster and secured communication can be achived.

QUESTIONS AND ANSWERS

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4. Report Review of Electro Industries Nexus 1500+ PMU features

5. Chapter 3 : Phasor and Synchro phasor Measurements and Their Application: Smart Grid Sensor by M=Hamed Mohsenian Rad