SYNCHROPHASORS AND APPLICATIONS

LIMITATIONS OF SCADA

- Slower measurement rate (1 data in1-4s)

- Measurements are not time synchronized

- Does not capture dynamics of power grids

- Limited situational awareness conveyed to the operator

MOTIVATIONS FOR SYNCHROPHASORS

AUGUST 14, 2003 BLACKOUT:

- PROBLEMS DEVELOPED HOURS BEFORE THE SYSTEM COLLAPSE

- SYSTEM OPERATORS WERE UNAWARE OF THE OVERALL WORSENING SYSTEM CONDITIONS

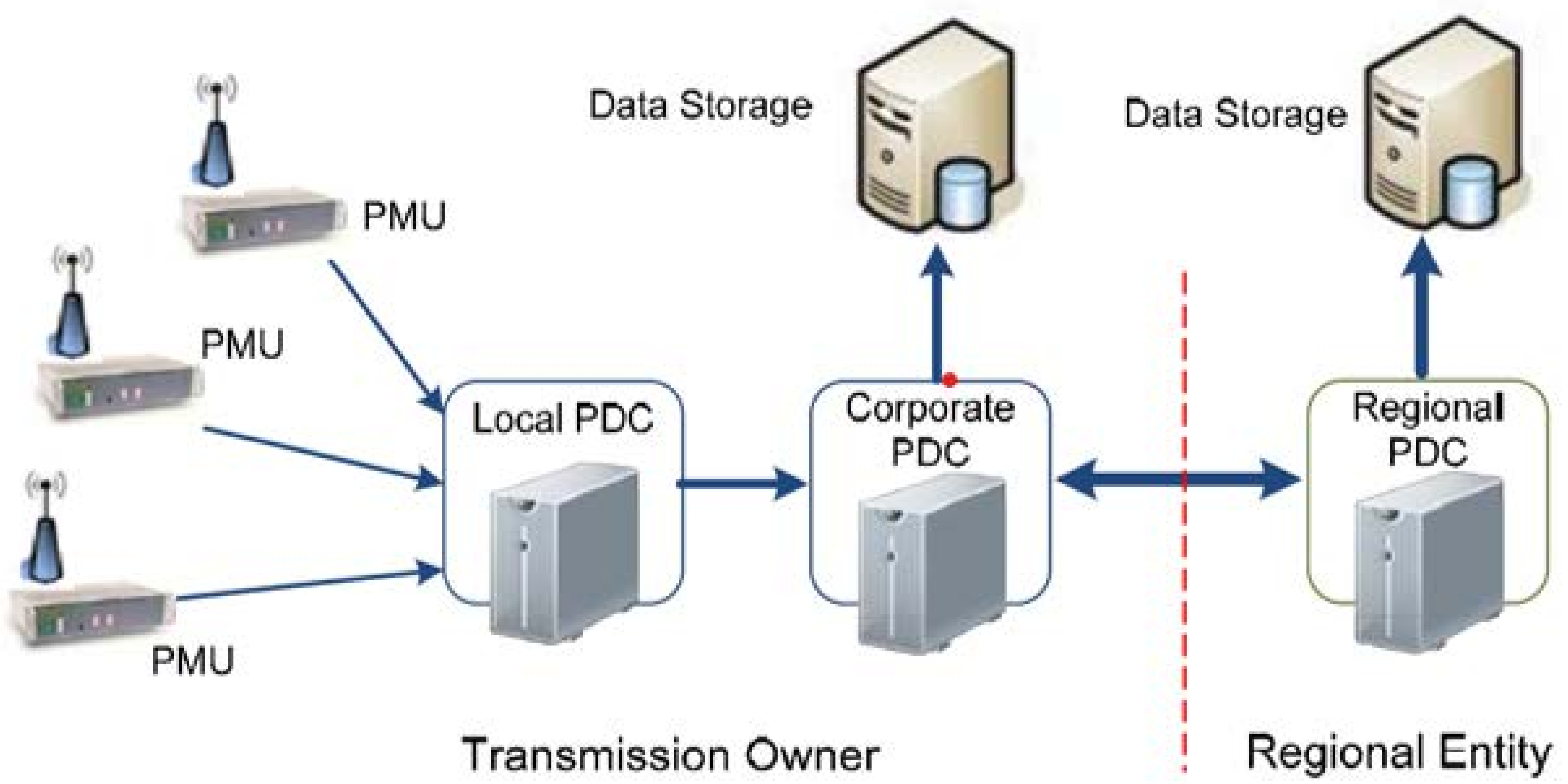
- U.S-CANADA POWER SYSTEM OUTAGE TASK FORCE RECOMMENDED DEPLOYMENT OF PMUS FOR SYNCHROPHASOR MEASUREMENTS

MOTIVATIONS FOR SYNCHROPHASORS

FAST REAL TIME MONITORING OF GRID DYNAMICS NECESSARY TO AVOID BLACKOUTS

NEED OF SYNCHRONIZED MEASUREMENTS

SYNCHROPHASORS TO MONITOR GRID DYNAMICS



BASIC ARCHITECTURE OF WAMS

PHASORS

- Power system voltage/current waveforms sinusoid in nature
- In time domain, a sinusoid is written as:

$$x(t) = X_m \cos(\omega t + \phi)$$

where,

x(t)= voltage/current sample at time 't'

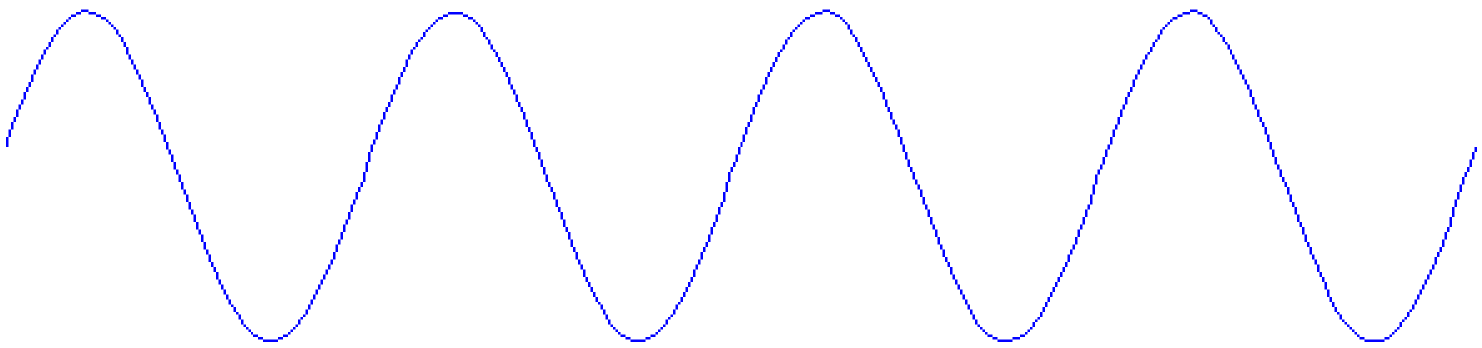
X_m*= Peak value of sinusoid*

ω*= Frequency of sinusoid in radians*

Φ*= Phase angle*

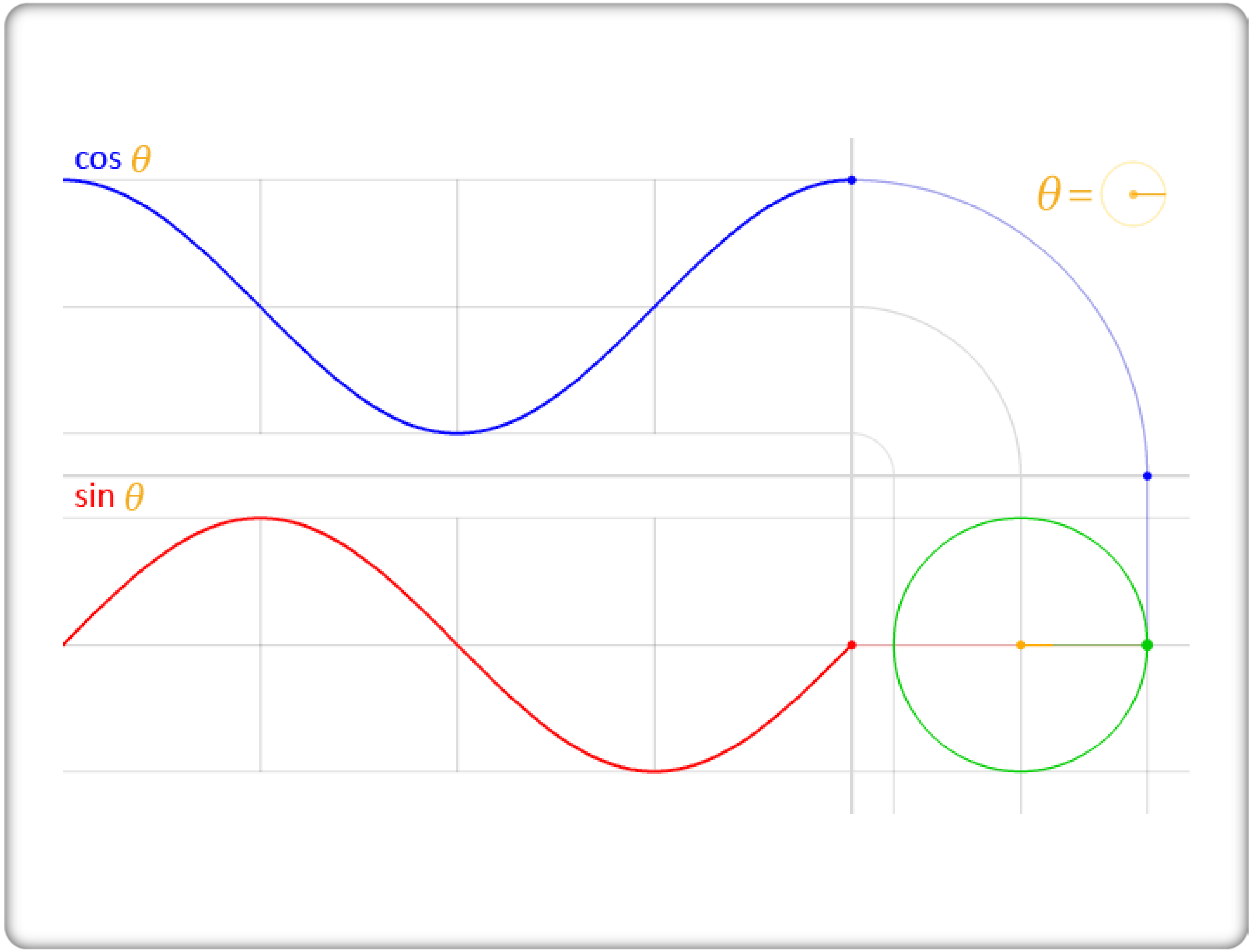
SINOSOIDS

- ‘Sinusoids’ represent both sine and cosine waveforms
- Shapes of ‘Sine’, ‘Cosine’ – Why?

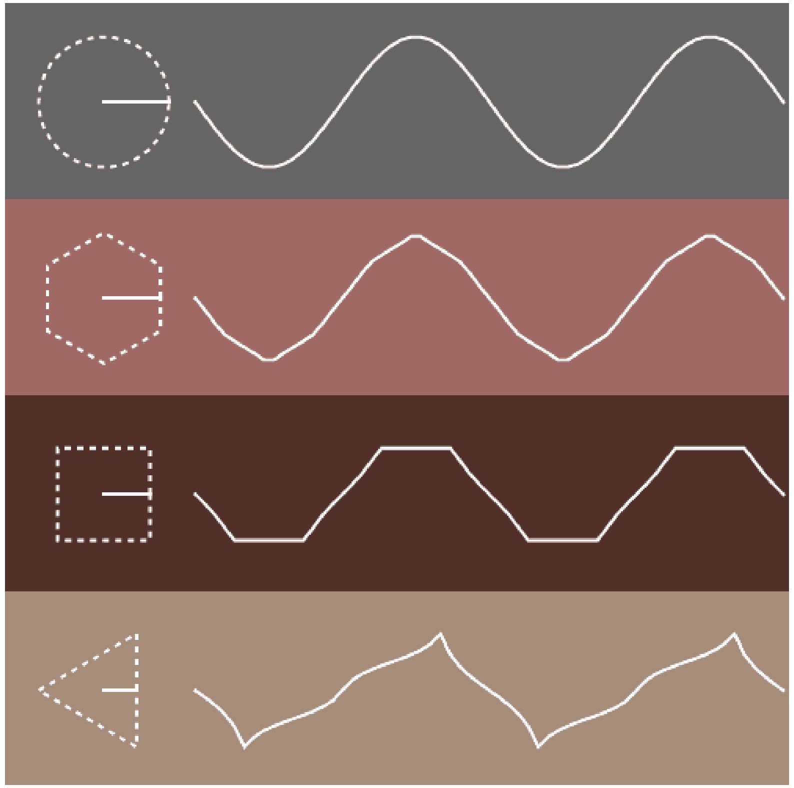


SINOSOIDS

- Unit circle & sinusoids



Sinosoids



Source: http://mathani.tumblr.com/post/51639988954/following-1ucasvb

PHASORS

$$x(t) = X_m \cos(\omega t + \phi)$$

$$or,\ x(t) = \mathrm{Re}[X_m e^{j(\omega t + \phi)}]$$

$$or,\ x(t) = \mathrm{Re}[\{e^{j\omega t}\} X_m e^{j\phi}]$$

$$or,\ x(t) = \mathrm{Re}[\{\sqrt{2} e^{j\omega t}\} \underbrace{\left\{\frac{X_m}{\sqrt{2}} e^{j\phi}\right\}}]$$

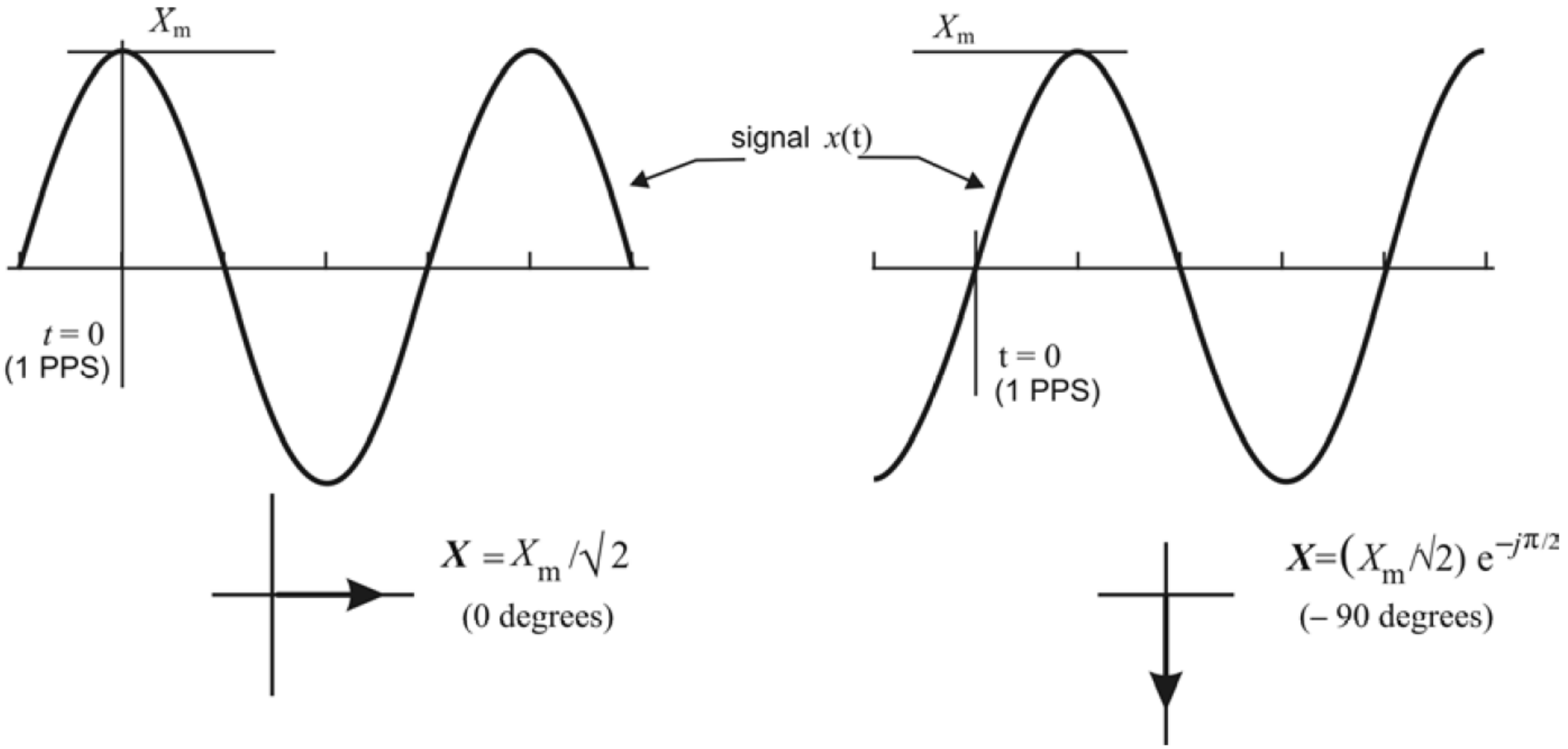
Phasor representation of sinusoid

ω = Nominal Frequency

PHASORS

$$X = X_m \cos(\omega t)$$

$$X = X_m \sin(\omega t)$$



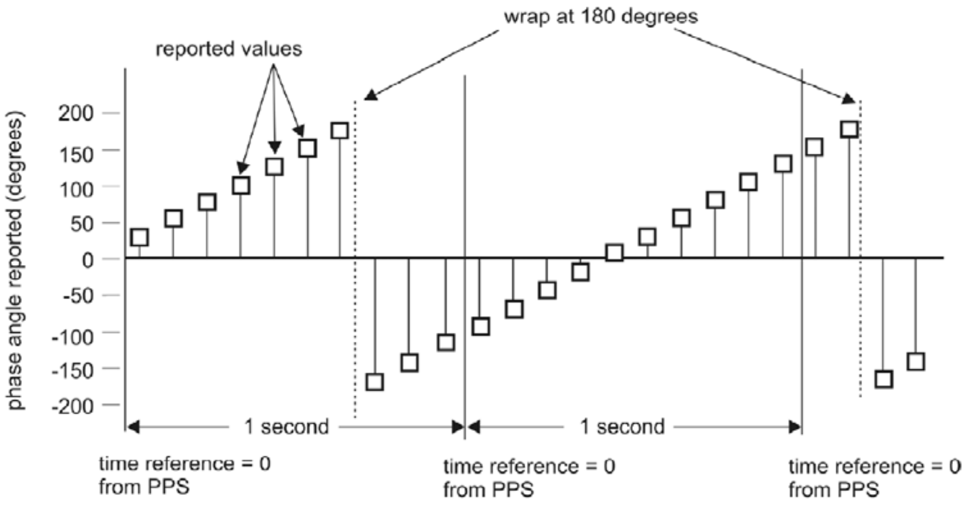
PHASORS

$$
\begin{aligned}
x(t) &= X_m \cos(\omega_1 t + \phi) \\
&= X_m \cos((\omega + \omega_1 - \omega)t + \phi) \\
&= X_m \cos(\omega t + (\omega_1 - \omega)t + \phi)
\end{aligned}
$$

ω = Nominal Frequency

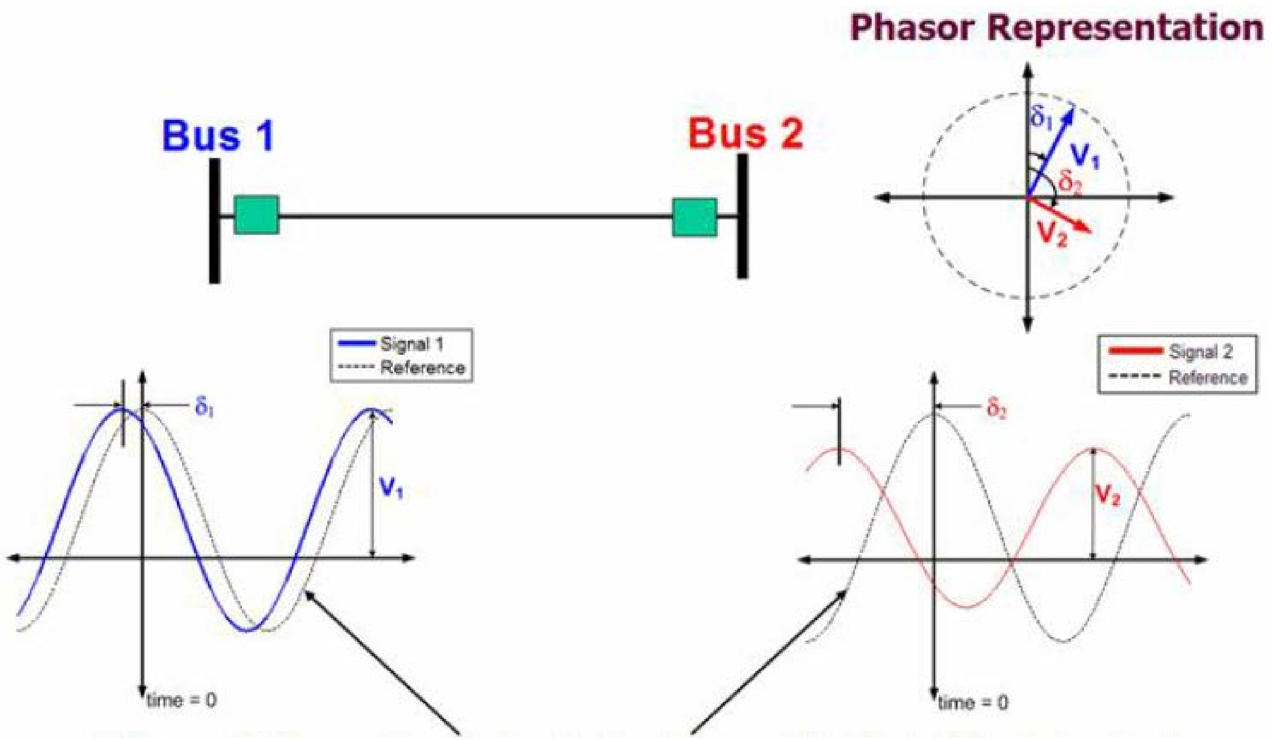
ω_1 = Off-Nominal Frequency

$$\boxed{X = \frac{X_m}{\sqrt{2}} \angle (\omega_1 - \omega)t + \phi}$$

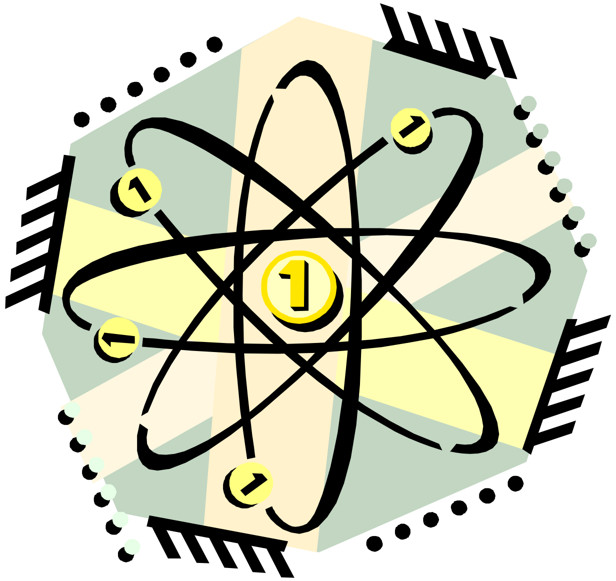


SYNCHROPHASORS

- These are phasors which are computed using a common time reference
- GPS provides time reference for synchronized phasors
- Synchronized phasors of two different devices can be compared with each other due to the time synchronization property



GPS



- Features
  - 24 satellites in 12-hour orbits at an altitude of 10,898 miles
  - Using transmission from 3 satellites, positions of objects can be determined with accuracy of 10 meters in 3 dimension

GPS RECEIVER

RECEIVES 1 PULSE PER SECOND (PPS) SIGNAL FROM GPS

GPS TIME DO NOT CONSIDER LEAP SECONDS

GPS RECEIVER CORRECTS GPS TIME TO TAKE IN ACCOUNT LEAP SECONDS

TIME SYNCHRONIZATION

Achieve common reference by synchronizing ADC sampling using 1 pps signal

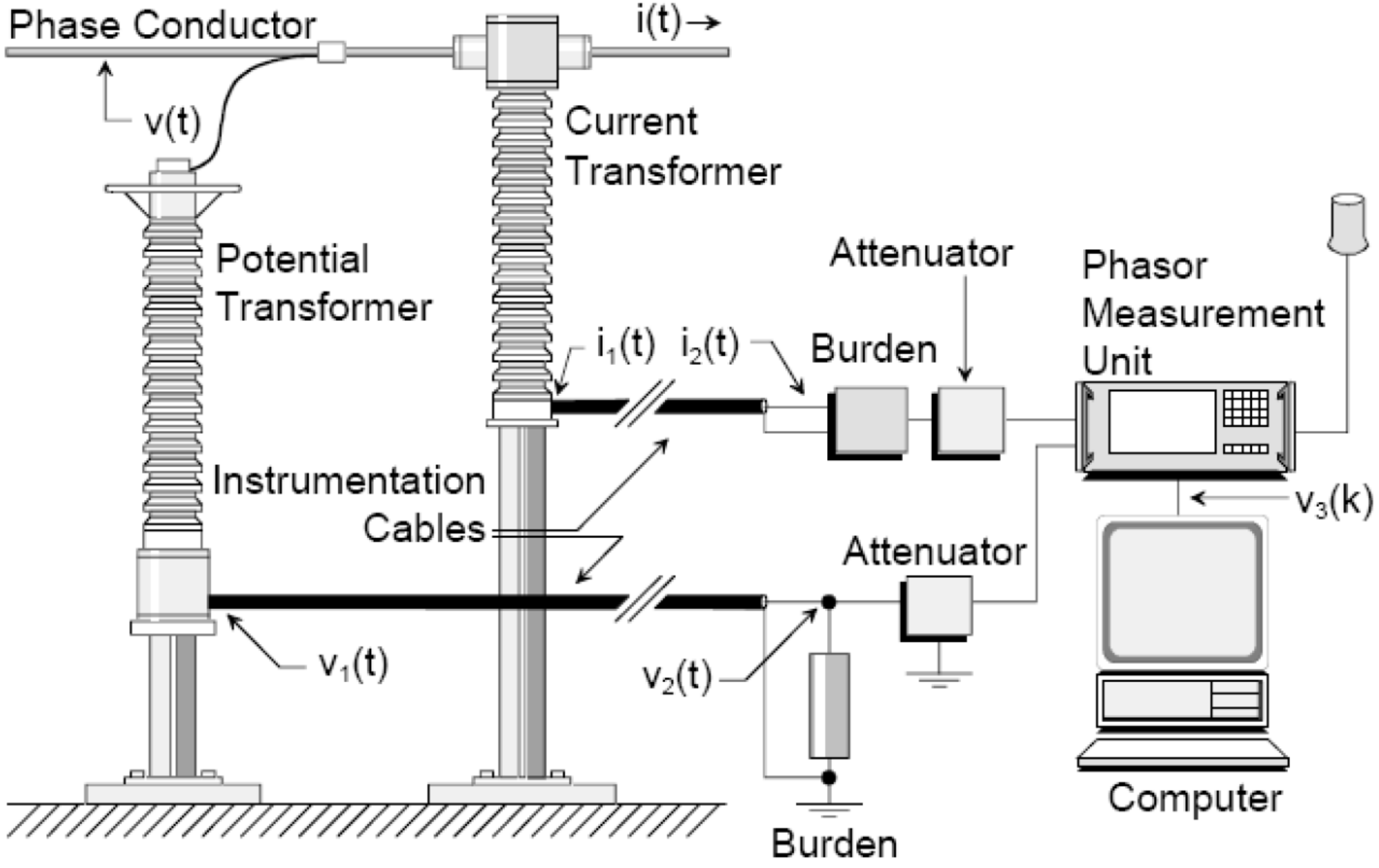
Synchronization accuracies of the order of 1 microseconds are now available

SOURCES OF SYNCHRONIZATION

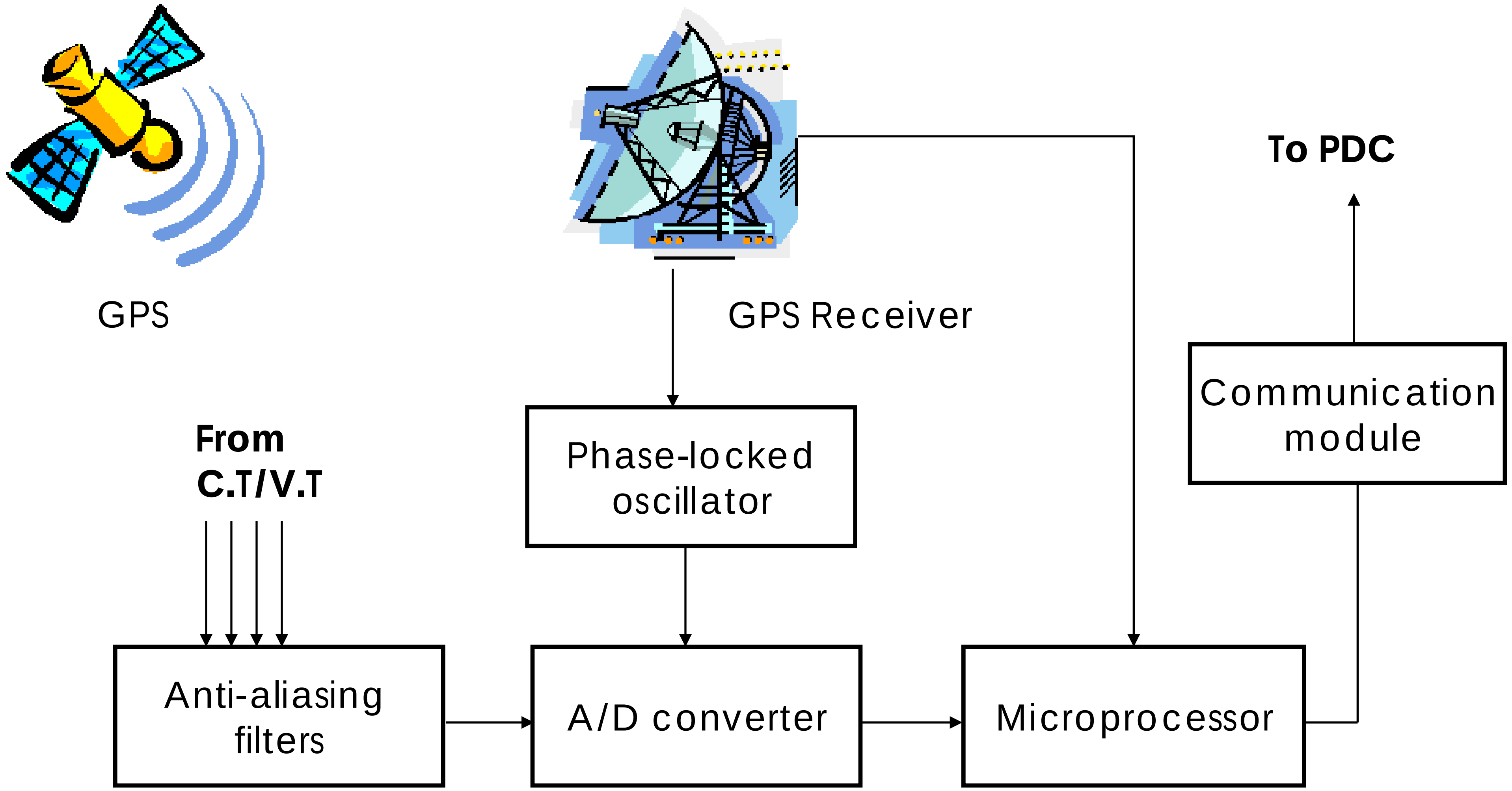
Two sources:

- Common time signal transmitted by the GPS
- Transmission of synchronization pulses over fibre optic communication links

PMU IN A SUBSTATION



BASIC BLOCK DIAGRAM OF A PMU



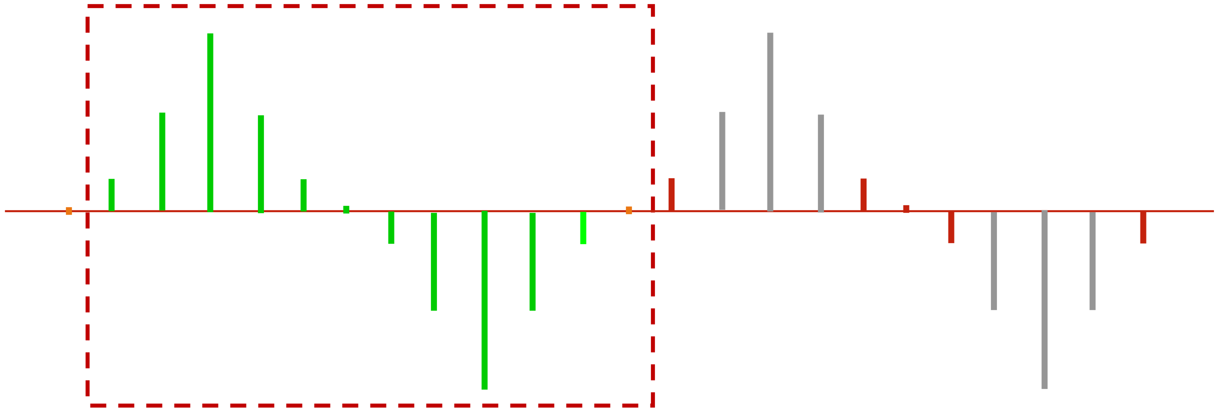
SYNCHROPHASOR ESTIMATION

DFT BASED ESTIMATION ALGORITHMS COMMONLY USED

ESTIMATION FILTERS CAN SPAN MULTIPLE FUNDAMENTAL CYCLES TO ACHIEVE ACCURACY

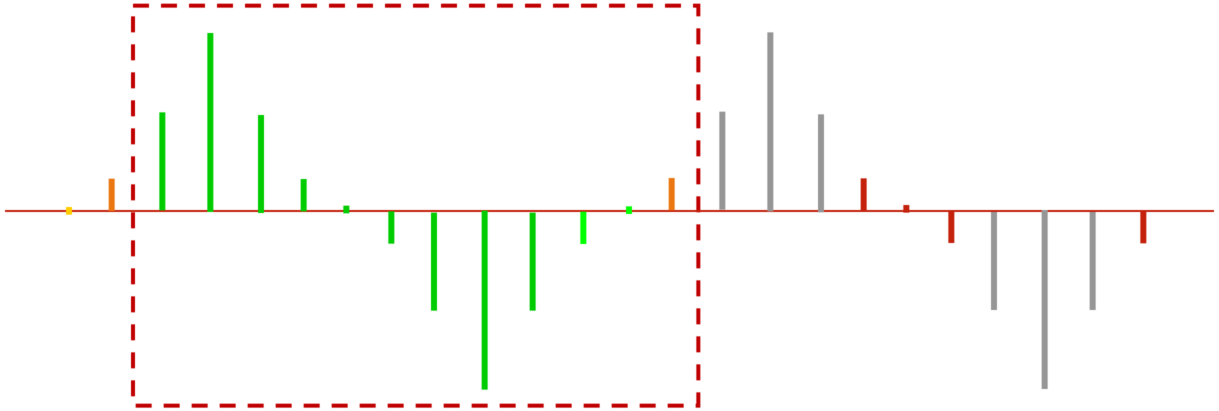
USUALLY, FIXED SAMPLING RATES USED FOR ESTIMATIONS

SYNCHROPHASOR ESTIMATION



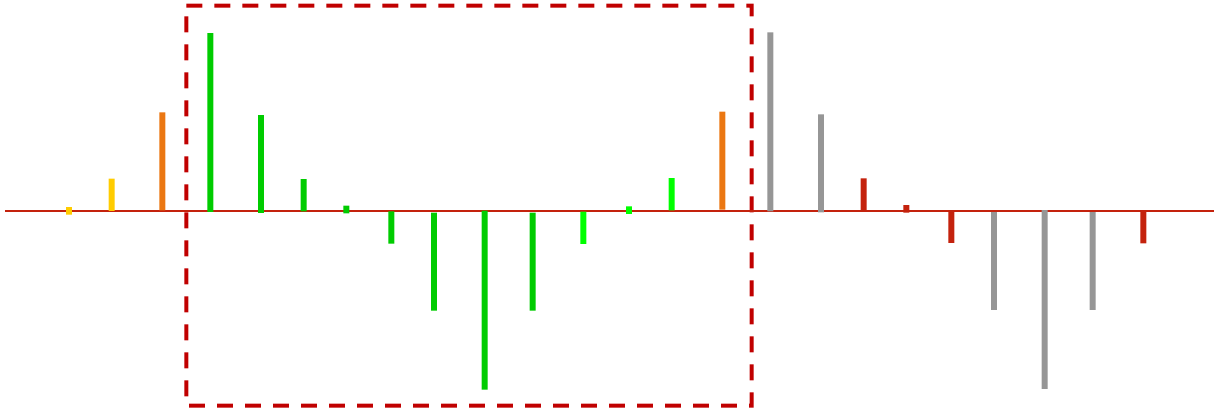
Input waveform

SYNCHROPHASOR ESTIMATION



Input waveform

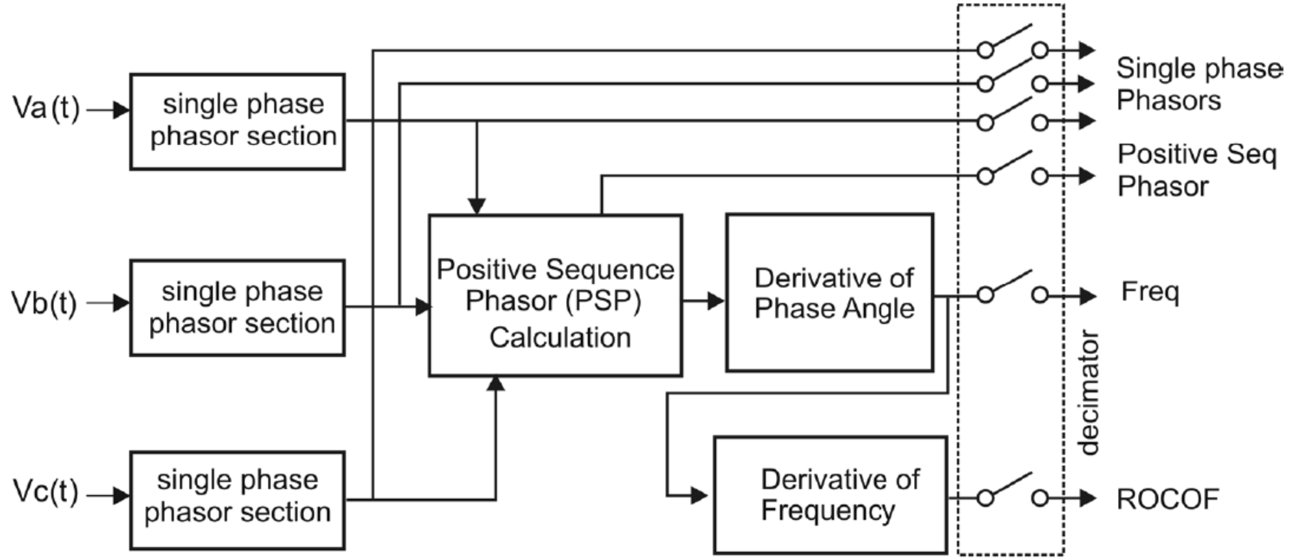
SYNCHROPHASOR ESTIMATION



Input waveform

SYNCHROPHASOR ESTIMATION

- ““IEEE Standard for Synchrophasor Measurements for Power Systems”, IEEE C37.118.1-2011, (Revision of IEEE Std. C37.118-2005)”

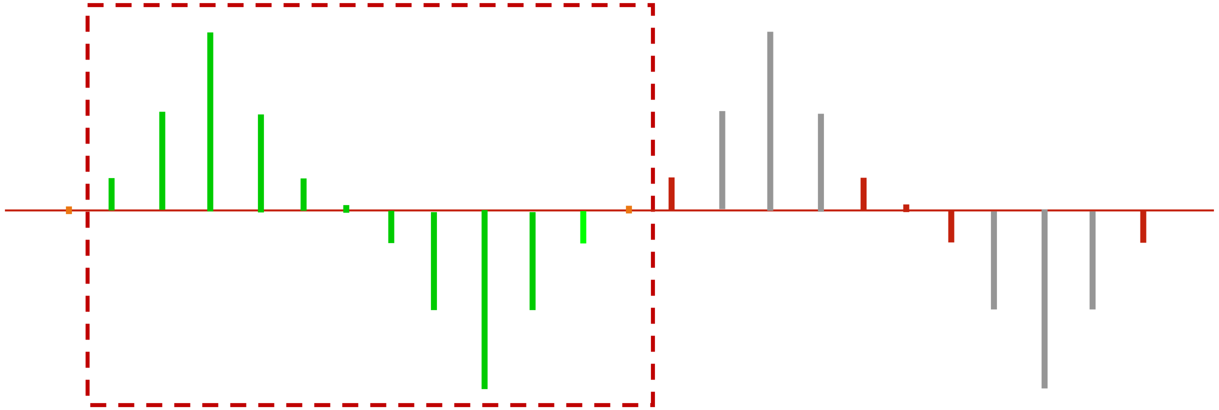


SYNCHROPHASOR ESTIMATION VS. PHASOR ESTIMATION

Synchrophasor Estimation	Phasor Estimation in Conventional Relays
Estimation accuracy priority	Need not be very accurate
Fast computation not necessary	Fast computation priority for protection

DFT ALGORITHM

Input waveform



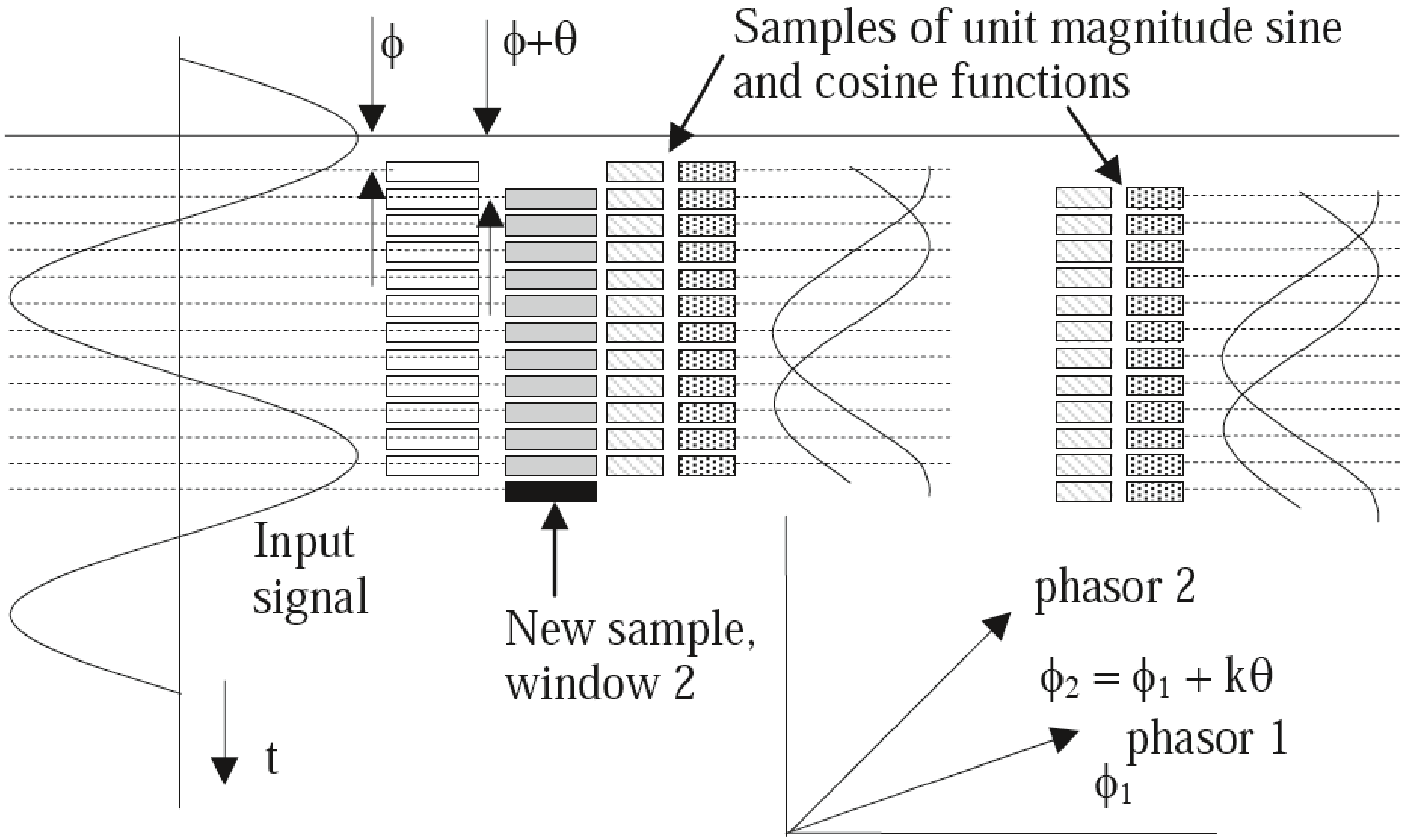
$$X = \frac{\sqrt{2}}{N} \sum_{n=-N/2}^{N/2} x_n [\cos(n \frac{2\pi f_o}{F_s}) - j \sin(n \frac{2\pi f_o}{F_s})]$$

SYNCHROPHASOR ESTIMATION

- DFT based estimation algorithms divided into two categories:
- Non-recursive algorithm
- Recursive algorithm

NON-RECURSIVE DFT ALGORITHM

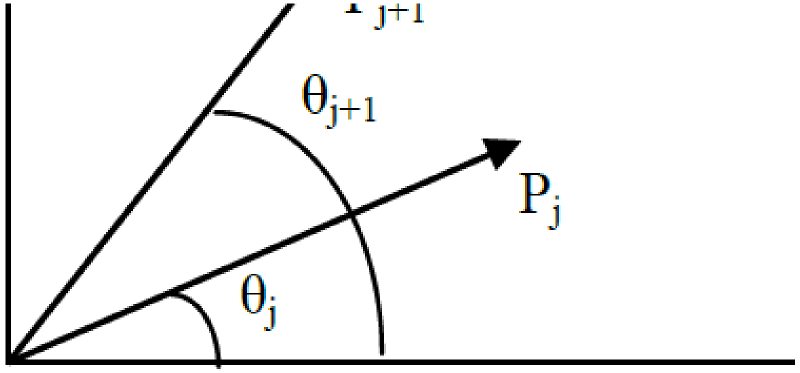
- A window of *N* samples used to estimate a synchrophasor
- Window shifted to compute new synchrophasor
- Estimated synchrophasor *X*



NON-RECURSIVE DFT ALGORITHM

- Phase angle rotation is linked with the system frequency

$${}_{+1} - \theta_j \Big) \times F_s \,/\, (2\pi)$$



RECURSIVE DFT ALGORITHM

- Two consecutive estimation windows have common samples
- Recursive algorithm uses

  - previous computed synchrophasor X^{N+r-1}

  - new sample in the current window

- Estimated synchrophasor X^{N+r}

$$X^{N+r} = X^{N+r-1} + \frac{\sqrt{2}}{N}(x_{N+r} - x_r)\exp^{-jr\frac{2\pi f_o}{F_s}}$$

TOTAL VECTOR ERROR (TVE)

- TVE used to measure estimation error

where, $X_r(n)$, $X_i(n)$ are real and imaginary parts of a reconstructed synchrophasor and X_r, X_i are theoretical values.

$$TVE = \sqrt{\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^2 + X_i^2}} \times 100\%$$

TIMELINE OF STANDARDS

1344–1995

IEEE Std 1344-1995, IEEE Standard for Synchrophasors for Power Systems

2005

IEEE Std C37.118-2005, IEEE Standard for Synchrophasors for Power Systems

2011

IEEE Std C37.118.1-2011 - IEEE Standard for Synchrophasor Measurements for Power Systems

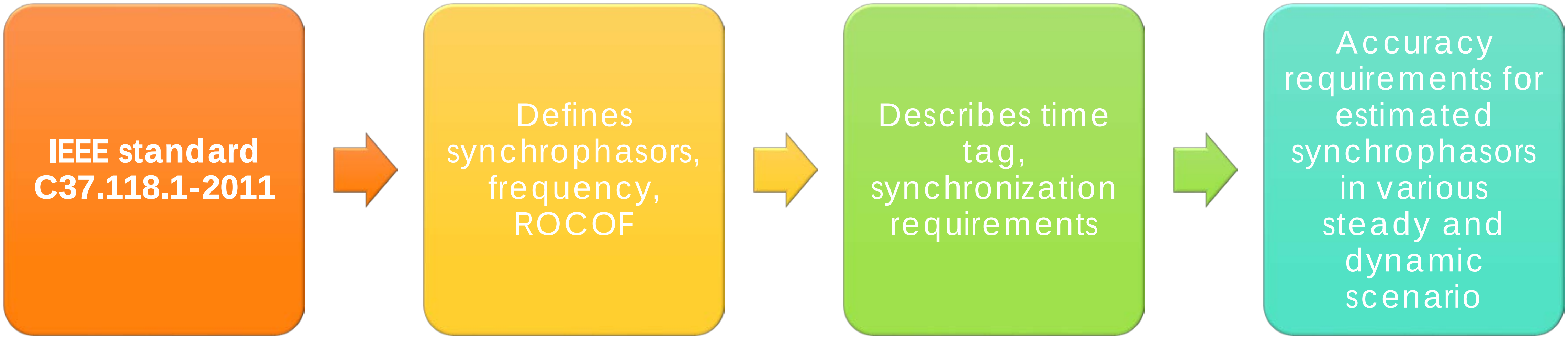
2011

IEEE Std C37.118.2-2011 - IEEE Standard for Synchrophasor Data Transfer for Power Systems

2014

IEEE Std C37.118.1a-2014 Amendment 1: Modification of Selected Performance Requirements

SYNCHROPHASOR STANDARDS



SYNCHROPHASOR STANDARDS

IEEE standard C37.118.2-2011

Defines method for exchange of synchrophasors between PMU and PDCs

Specifies message types, contents, and data formats for real-time communications

TIME TAG OF SYNCHROPHASORS

- Synchronized to UTC time
- Time Tag contains:

  - Second-of-Century Count (SOC)

  - Fraction-of-Second Count (FRACSEC)

  - Time Quality

TIME TAG OF SYNCHROPHASORS

- **Second-of-Century Count (SOC)**

  - 32-bit unsigned integer count of seconds from UTC midnight (00:00:00) of

  January 1, 1970, to the current second

- **Fraction-of-Second Count (FRACSEC)**

  - 24-bit unsigned integer representation of fractional time

  - Divide **FRACSEC** by **TIME_BASE** to get the fractional time

TIME TAG OF SYNCHROPHASORS

- **Time Quality**

  - 8-bit unsigned integer
  - Quality of the time being reported as well as indication of leap second status

Table 3—Time quality flag bit definitions

Bit #	Description
7	Reserved
6	Leap Second Direction—0 for add, 1 for delete
5	Leap Second Occurred—set in the first second after the leap second occurs and remains set for 24 h
4	Leap Second Pending—shall be set not more than 60 s nor less than 1 s before a leap second occurs, and cleared in the second after the leap second occurs
3–0	Message Time Quality indicator code—see Table 4.

TIME TAG OF SYNCHROPHASORS

Time Quality

Table 4—4-bit Message Time Quality indication codes (MSG_TQ)

BINARY	HEX	Value (worst-case accuracy)
1111	F	Fault—clock failure, time not reliable
1011	B	Time within 10 s of UTC
1010	A	Time within 1 s of UTC
1001	9	Time within 10^{-1} s of UTC
1000	8	Time within 10^{-2} s of UTC
0111	7	Time within 10^{-3} s of UTC
0110	6	Time within 10^{-4} s of UTC
0101	5	Time within 10^{-5} s of UTC
0100	4	Time within 10^{-6} s of UTC
0011	3	Time within 10^{-7} s of UTC
0010	2	Time within 10^{-8} s of UTC
0001	1	Time within 10^{-9} s of UTC
0000	0	Normal operation, clock locked to UTC traceable source

REPORTING RATES

System frequency	50 Hz			60 Hz					
Reporting rates (F_s—frames per second)	10	25	50	10	12	15	20	30	60

- The actual rate to be used shall be user selectable. Support for other reporting is permissible, and higher rates such as 100 frames/s or 120 frames/s and rates lower than 10 frames/s such as 1 frame/s are also encouraged.

" "IEEE Standard for Synchrophasor Measurements for Power Systems", IEEE C37.118.1-2011, (Revision of IEEE Std. C37.118-2005)"

REPORTING TIMES

For a reporting rate, N frames per second where N is a positive integer, the reporting times shall be evenly spaced through each second with the time of the first frame coincident with the UTC second.

The first frame will be frame number 0 (frames numbered 0 thru N–1) with a FRACSEC time of 0, the next frame number 1 with a fractional time 1/N, and so on through frame N–1 with a fractional time (N–1)/N.

" "IEEE Standard for Synchrophasor Measurements for Power Systems", IEEE C37.118.1-2011, (Revision of IEEE Std. C37.118-2005)"

EXAMPLE OF SYNCHROPHASOR FRAMES

Table 2—Table of synchrophasor values at a 10 fps reporting rate

Time	Fractional time		Synchrophasor values for: 50 Hz frequency—50 Hz system 60 Hz frequency—60 Hz system		Synchrophasor values for: 51 Hz frequency—50 Hz system 61 Hz frequency—60 Hz system	
Second	Frame num-ber	Fractional second	Synchrophasor (0 degrees)	Synchrophasor (–90 degrees)	Synchrophasor (0 degrees)	Synchrophasor (–90 degrees)
k–1	9	0.900000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle -36°$	$X_m/\sqrt{2}, \angle -126°$
k	0	0.000000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$
k	1	0.100000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 36°$	$X_m/\sqrt{2}, \angle -54°$
k	2	0.200000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 72°$	$X_m/\sqrt{2}, \angle -18°$
k	3	0.300000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 108°$	$X_m/\sqrt{2}, \angle 18°$
k	4	0.400000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 144°$	$X_m/\sqrt{2}, \angle 54°$
k	5	0.500000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 180°$	$X_m/\sqrt{2}, \angle 90°$
k	6	0.600000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle -144°$	$X_m/\sqrt{2}, \angle 126°$
k	7	0.700000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle -108°$	$X_m/\sqrt{2}, \angle 162°$
k	8	0.800000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle -72°$	$X_m/\sqrt{2}, \angle -162°$
k	9	0.900000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle -36°$	$X_m/\sqrt{2}, \angle -126°$
k+1	0	0.000000	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$	$X_m/\sqrt{2}, \angle 0°$	$X_m/\sqrt{2}, \angle -90°$

""IEEE Standard for Synchrophasor Measurements for Power Systems", IEEE C37.118.1-2011, (Revision of IEEE Std. C37.118-2005)"

REPORTING LATENCY

- Reporting latency is defined as the maximum time interval between the data report time as indicated by the data time stamp, and the time when the data becomes available at the PMU output (denoted by the first transition of the first bit of the output message at the communication interface point).

"“IEEE Standard for Synchrophasor Measurements for Power Systems”, IEEE C37.118.1-2011, (Revision of IEEE Std. C37.118-2005)"

PMU CLASSES

Standard specifies two class of performance requirements

- P class : for protection applications (fast response and no explicit filtering); The letter P is used since protection applications require fast response.

- M class : for applications sensitive to aliasing and require greater precision; The letter M is used since analytic measurements often require greater precision but do not require minimal reporting delay.

" "IEEE Standard for Synchrophasor Measurements for Power Systems", IEEE C37.118.1-2011, (Revision of IEEE Std. C37.118-2005)"

IEEE STANDARD C37.118.1-2011

Definitions:

- Synchrophasor $X = X_m \angle \psi(t)$
- Frequency is defined as $f(t) = \frac{1}{2\pi} \frac{d\psi(t)}{dt}$
- ROCOF is defined as $ROCOF(t) = \frac{df(t)}{dt}$

IEEE STANDARD C37.118.1-2011

- **Small signal oscillations**: **Positive sequence time domain signal**

$$X_1 = X_m\,[1 + k_x\cos(\omega t)] \times \cos\,[\omega_0 t + k_a \cos\,(\omega t - \pi)]$$

where, k_x is the amplitude and k_a is the phase angle modulation factor

at reporting time t=nT positive sequence oscillation synchrophasor

$$X(nT) = \{X_m/\sqrt{2}\}[1 + k_x\cos(\omega nT)]\angle\{k_a\cos(\omega nT - \pi)\}$$

IEEE STANDARD C37.118.1-2011

- **Small signal oscillations:** $X_1 = X_m\,[1 + k_x \cos(\omega t)] \times \cos\,[\omega_0 t + k_a \cos\,(\omega t - \pi)]$

$$f(t) = \frac{1}{2\pi}\frac{d\psi(t)}{dt}$$

$$f(nT) = \omega_0/2\pi - k_a\,(\omega/2\pi)\,\sin\,(\omega nT - \pi)$$

$$\mathrm{ROCOF}(nT) = d/dt[f(nT)] = -\,k_a\,(\omega^2/2\pi)\,\cos\,(\omega nT - \pi)$$

IEEE STANDARD C37.118.1-2011

- **Frequency Ramp**: **Positive sequence time domain signal**

$$X_1 = X_m \cos\left[\omega_0 t + \pi R_f t^2\right]$$

at reporting time t=nT positive sequence synchrophasor (frequency ramp) is

$$X(nT) = \{X_m/\sqrt{2}\}\angle\{\pi R_f (nT)^2\}$$

where, R_f is the ramp rate

IEEE STANDARD C37.118.1-2011

- **Frequency Ramp**: $X_1 = X_m \cos\left[\omega_0 t + \pi R_f t^2\right]$

$$f(t) = \frac{1}{2\pi}\frac{d\psi(t)}{dt}$$

$$f(nT) = \omega_0/2\pi + (R_f)(nT)$$

$$d/dt[f(nT)] = R_f$$

STEADY STATE PERFORMANCE

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max TVE (%)	Range	Max TVE (%)
Signal frequency range—f_{dev} (test applied nominal + deviation: $f_0 \pm f_{dev}$)	$F_{nominal}$ (f_0)	± 2.0 Hz	1	± 2.0 Hz for F_s<10 ± F_s/5 for $10 \le F_s < 25$ ± 5.0 Hz for $F_s \ge 25$	1
The signal frequency range tests above are to be performed over the given ranges and meet the given requirements at three temperatures: T = nominal (~23 °C), T = 0 °C, and T = 50 °C					
Signal magnitude—Voltage	100% rated	80% to 120% rated	1	10% to 120% rated	1
Signal magnitude—Current	100% rated	10% to 200% rated	1	10% to 200% rated	1

PERFORMANCE IN PRESENCE OF HARMONICS

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max TVE (%)	Range	Max TVE (%)
Harmonic distortion (single harmonic)	<0.2% (THD)	1%, each harmonic up to 50th	1	10%, each harmonic up to 50th	1
Out-of-band interference as described below (See NOTES 2 and 3)	<0.2% of input signal magnitude		None	10% of input signal magnitude for $F_s \geq 10$. No requirement for $F_s < 10$.	1.3

Out-of-band Interference: A signal whose frequency exceeds the Nyquist rate for the reporting rate Fs can alias into the passband. The test signal described for the out-of-band interference test verifies the effectiveness of the PMU anti-alias filtering. The test signal shall include those frequencies outside of the bandwidth specified above that cause the greatest TVE.

SMALL SIGNAL OSCILLATIONS

Modulation level	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max TVE	Range	Max TVE
$k_x = 0.1$, $k_a = 0.1$ radian	100% rated signal magnitude, $f_{nominal}$	Modulation frequency 0.1 to lesser of $F_s/10$ or 2 Hz	3%	Modulation frequency 0.1 to lesser of $F_s/5$ or 5 Hz	3%
$k_x = 0$, $k_a = 0.1$ radian	100% rated signal magnitude, $f_{nominal}$		3%		3%

Please see "IEEE Std C37.118.1a™-2014 (Amendment to IEEE Std C37.118.1™-2011)" for updated specifications

FREQUENCY RAMP

Test signal	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		Ramp rate (R_f) (positive and negative ramp)	Performance class	Ramp range	Max TVE
Linear frequency ramp	100% rated signal magnitude, & $f_{nominal}$ at start or some point during the test	± 1.0 Hz/s	P class	± 2 Hz	1%
			M class	Lesser of ± (F_s /5) or ± 5 Hz [a]	1%

Please see "IEEE Std C37.118.1a™-2014 (Amendment to IEEE Std C37.118.1™-2011)" for updated specifications

REPORTING LATENCY

- Measurement reporting latency
- *Fs* = Reporting rate

Performance class	Maximum measurement reporting latency (s)
P class	$2/F_s$
M class	$5/F_s$

Please see “IEEE Std C37.118.1a™-2014 (Amendment to IEEE Std C37.118.1™-2011)” for updated specifications

- Defines message format for real time synchrophasor communication

- Four types of messages defined:
  - Data (sent by PMU/PDC)
  - Configuration (sent by PMU/PDC)
  - Header (sent by PMU/PDC)
  - Command (received by PMU/PDC)

IEEE STANDARD C37.118.**2**-2011

- Data message: contains measurements done by a PMU

  - Phasors (either rectangular or polar format)
  - Status of Breakers
  - Status of Switches

IEEE STANDARD C37.118.**2**-2011

- Configuration message: **machine readable** information for synchrophasor data stream, such as:

  - Number of phasors, digital values being sent
  - Substation name
  - Rate of data transmission, scaling etc

IEEE STANDARD C37.118.**2**-2011

IEEE STANDARD C37.118.2-2011

HEADER MESSAGE: HUMAN READABLE INFORMATION ABOUT THE PMU, DATA SOURCE, ALGORITHM, FILTERING ETC.

COMMAND MESSAGE: MACHINE READABLE MESSAGE INDICATING APPROPRIATE ACTIONS TO BE TAKEN

IEEE STANDARD C37.118.2-2011

- Typically, the receiving device requests a configuration and header using the commands at startup or a configuration change only.

Table 15—Commands sent to the PMU/PDC

Command word bits	Definition
Bits 15–0:	
0000 0000 0000 0001	Turn off transmission of data frames.
0000 0000 0000 0010	Turn on transmission of data frames.
0000 0000 0000 0011	Send HDR frame.
0000 0000 0000 0100	Send CFG-1 frame.
0000 0000 0000 0101	Send CFG-2 frame.
0000 0000 0000 0110	Send CFG-3 frame (optional command).
0000 0000 0000 1000	Extended frame.
0000 0000 xxxx xxxx	All undesignated codes reserved.
0000 yyyy xxxx xxxx	All codes where yyyy ≠ 0 available for user designation.
zzzz xxxx xxxx xxxx	All codes where zzzz ≠ 0 reserved.

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- Most of the time the data frame is transmitted continuously from the PMU or PDC at the designated reporting rate. Consequently, the required bandwidth is determined by the data frame size, data rate, and communication overheads.

Transmission rate in bits per second (bps) for example messages using UDP/IP over Ethernet							
PMU reporting rate (data frames/second)	10	12	15	25	30	50	60
Message content: 2 phasors, all quantities integer	6 720	8 064	10 080	16 800	20 160	33 600	40 320
Message content: 2 phasors, all quantities floating point	7 680	9 216	11 520	19 200	23 040	38 400	46 080
Message content: 12 phasors, all integer	9 920	11 904	14 880	24 800	29 760	49 600	59 520
Message content: 12 phasors, 2 analog, 2 digital, all integer	10 560	12 762	15 840	26 400	31 680	52 800	63 360

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Table C.2—Summary of delays' causes and typical ranges

Cause of delay	Typical range of delay
Sampling window (delay ½ of window)	17 ms to100 ms
Measurement filtering	8 ms to 100 ms
PMU processing	0.005 ms to 30 ms
PDC processing & alignment	2 ms to 2+ s
Serializing output	0.05 ms to 20 ms
Communication system I/O	0.05 ms to 30 ms
Communication distance	3.4 µs/km to 6 µs/km
Communication system buffering and error correction	0.05 ms to 8 s
Application input	0.05 ms to 5 ms

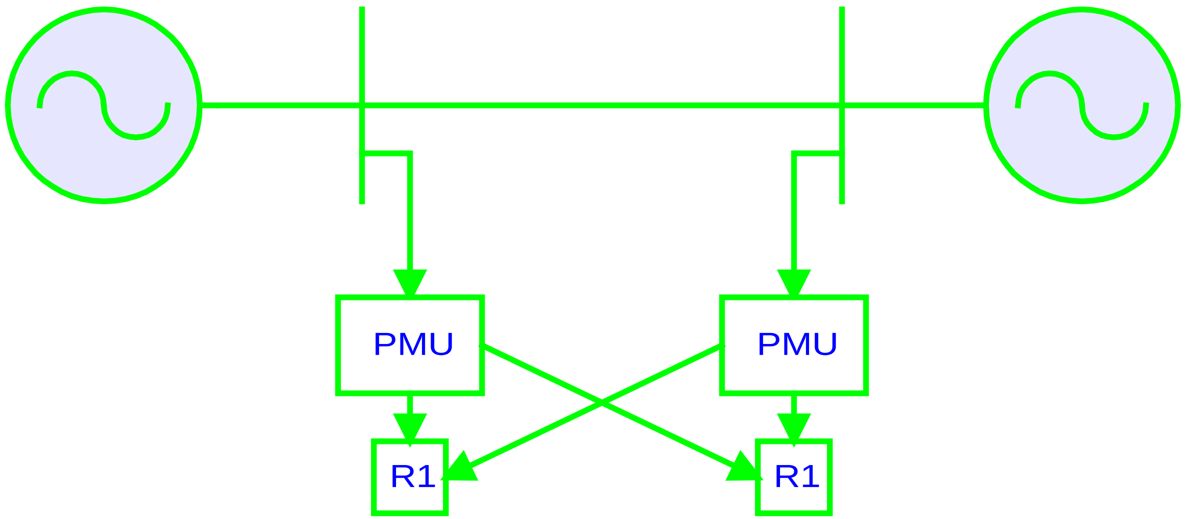
APPLICATIONS

STATE ESTIMATION

- State Estimation:
  - Most promising application
  - Positive sequence voltage phasor is a state vector in power system
  - Comparison of time tags leads to synchronous snap-shot of power system
  - Presently used state estimation procedures are non-linear
  - Estimator based upon phasor measurement does not require iterative techniques and consequently much faster to execute

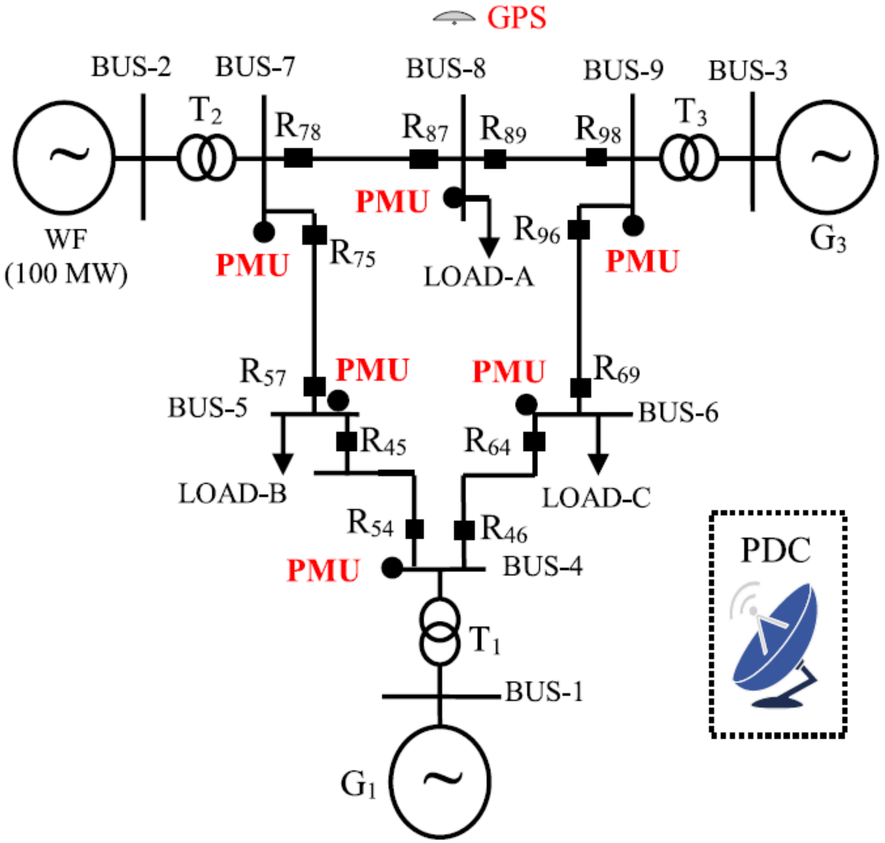
OUT-OF-STEP RELAYING

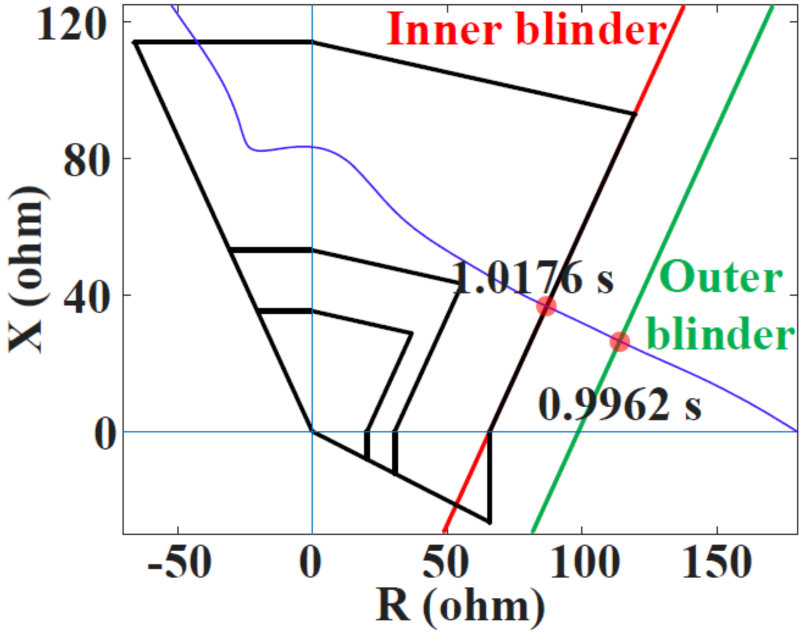
- Out-of-Step Relaying



POWER SWING BLOCKING

- Power Swing Blocking





SMALL SIGNAL OSCILLATION DETECTION

- Small/large disturbances present in the system
- Generators try to reach new operating point
- Oscillation frequency range $\longrightarrow$ 0.1 to 2 Hz
- High '+' system damping $\rightarrow$ oscillations die fast

  Low '+' damping $\rightarrow$ oscillations die after long time

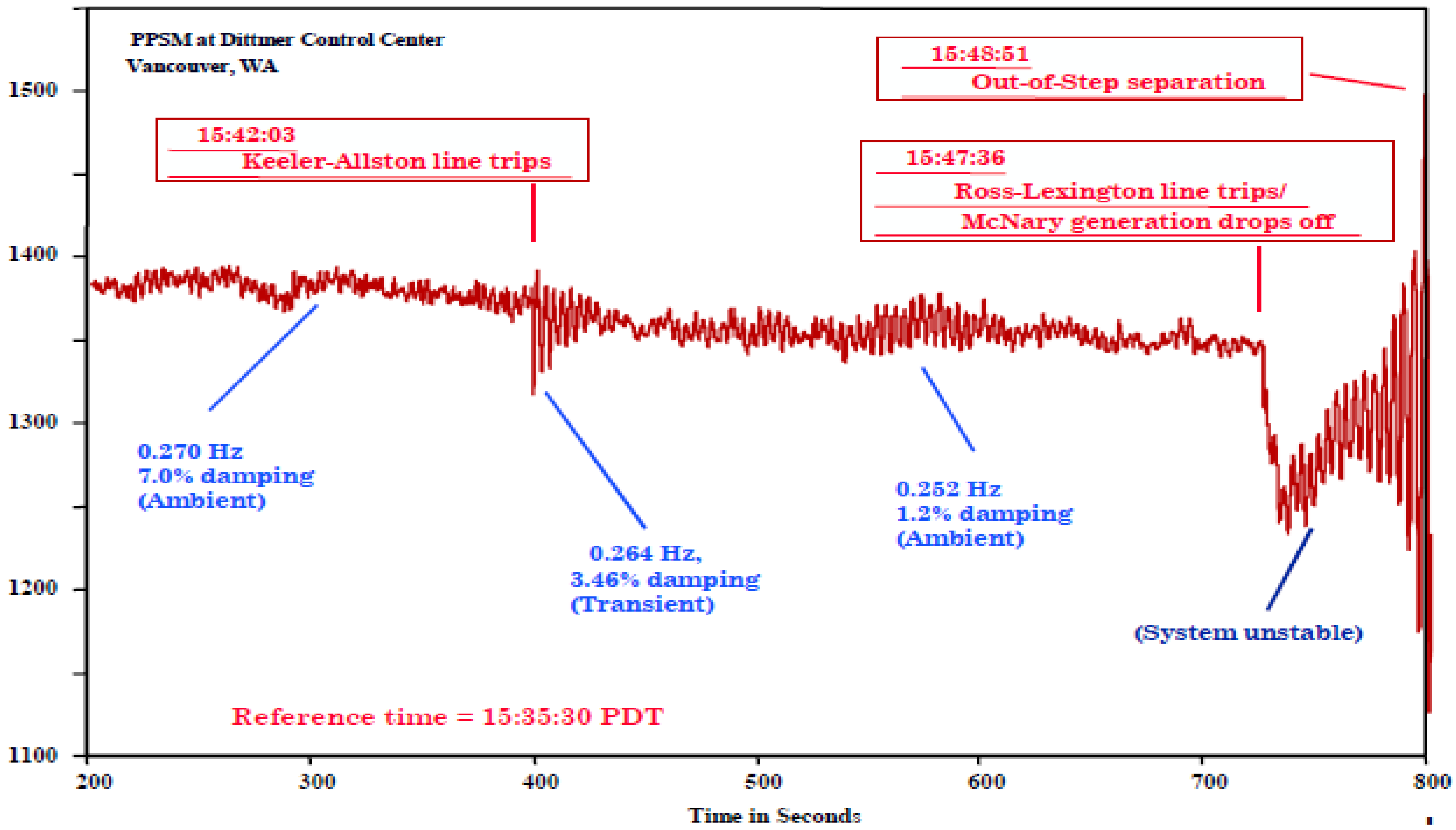
  High/Low '-' damping $\rightarrow$ oscillations grow with time

SMALL SIGNAL OSCILLATIONS

I/P Signal for Oscillation Estimation

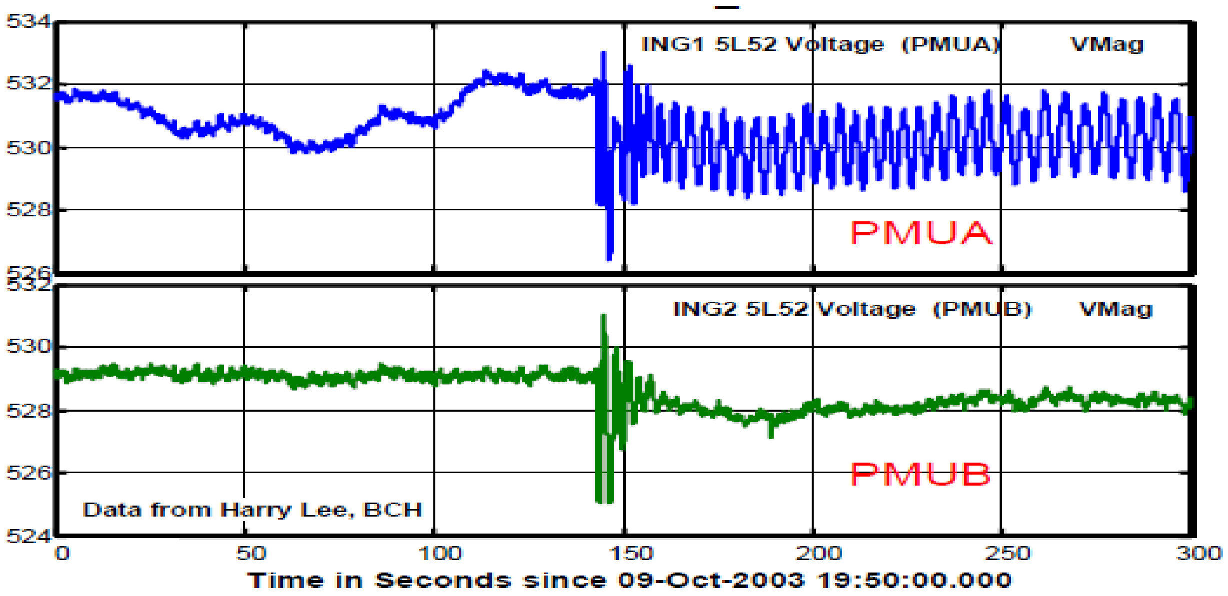
- Voltage phase angle difference (major)
- Voltage magnitude (cross-check)
- Current magnitude (cross-check)
- Computed power (cross-check)

SMALL SIGNAL OSCILLATIONS



ISSUES OF OSCILLATION ESTIMATIONS

- Parasitic Oscillations
  - Inconsistent measurements
  - Poor phasor measurement during dynamics



0.22 Hz parasitic oscillations with light damping

FREQUENCY STABILITY MONITORING AND TRENDING

- Frequency measurements of PMU helps to monitor stability of system frequency
- Predict trend of system frequency
- Frequency stability monitoring will get higher priority with increasing renewables

VOLTAGE INSTABILITY PREDICTION

- Voltage stability limits power flows in many transmission systems
- Voltage collapse can happen very quickly if limits crossed
- Voltage instability predictor estimates the proximity to voltage collapse using measured synchrophasors

DYNAMIC LINE RATINGS

- Transmission line limits are calculated using fixed conditions
- Transmission lines can be under utilized
- Synchrophasor measurements with local weather information can be used to calculate actual ampacity of a transmission line

FIELD EXPERIENCE

- Synchrophasor quality issues (ISO NE)
- Repeated time stamp
- Repeated values of magnitude and angles
- Jump in phase angle, Jump in magnitude rare
- Variation in phase angle within same substation
- Missing data

QUESTIONS