יישומים של מדידות פאזוריות במערכות הספק ורשתות חשמל

Applications of PMU for Monitoring and Control in Power Systems

Prof. Aleksei Korolev, SATEC Ltd.

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Prof. Aleksei Korolev

CTO, SATEC LTD.

Since 2022
SATEC Ltd

CTO

2011 –2022
ETAP Systems LTD, authorized representative of ETAP in Russia

Head of engineering group
Conducted 15+ ETAP Workshops

2017 – 2023
Russian University of Transport (MIIT)

Visiting professor,
15+ graduate theses

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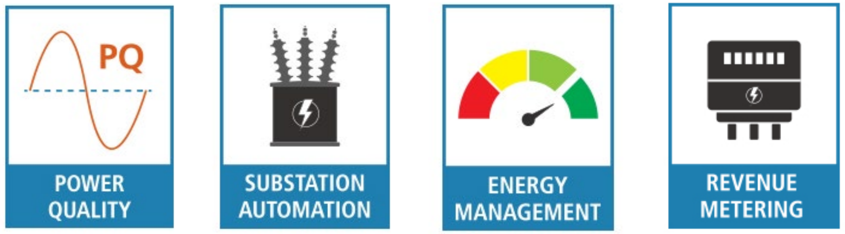
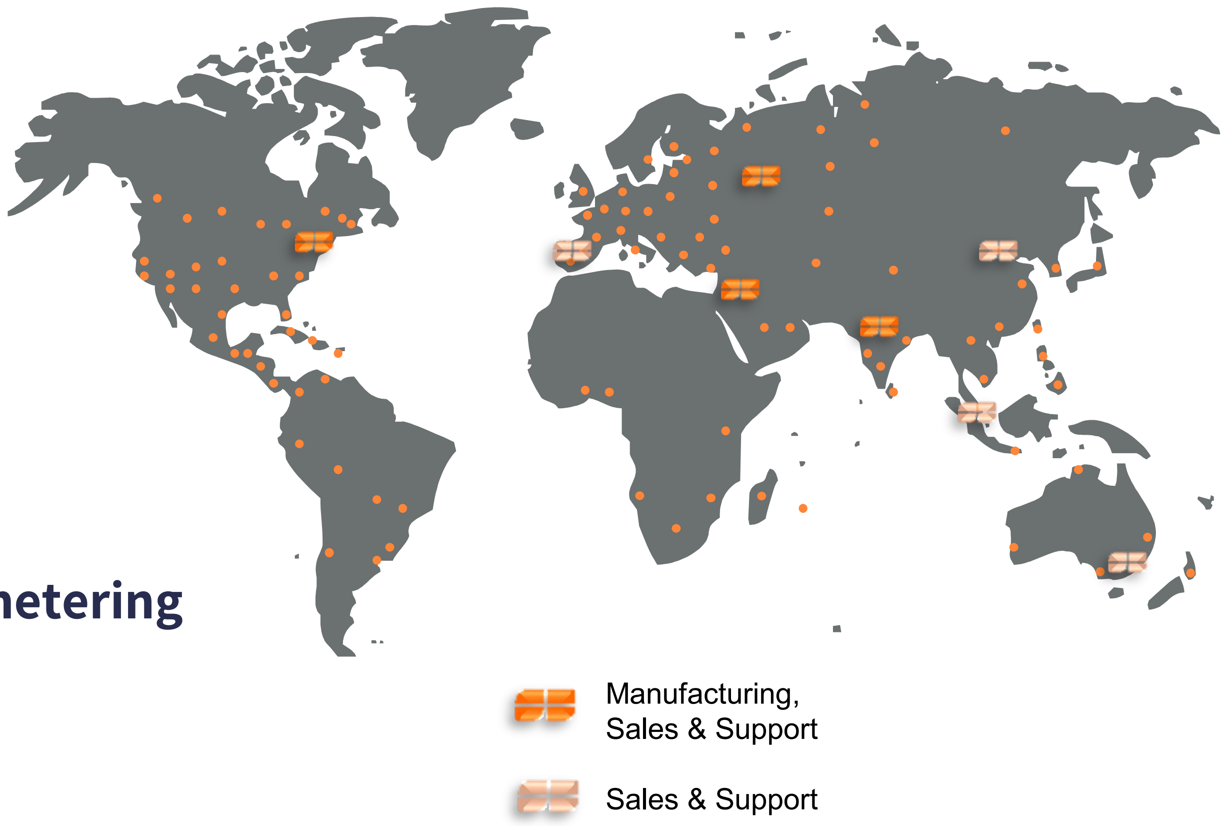
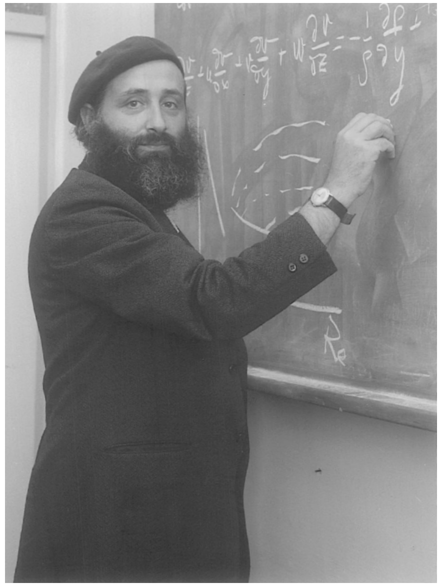
SATEC Ltd.
Israel, Jerusalem



- Founded in 1987
- International Company
- Activities in more than 70 countries
- Market leader in power quality and power metering
- One of the first digital power meters



THE SATEC LEGACY



His vision went **beyond creating a profitable business** for pioneering power analysis.

His focus was on **employment for a wave of immigrants** from the former Soviet Union to Israel in the early 1990s and of whom many were highly educated engineers.

As an immigrant himself, who is also a renowned professor of physics, he appreciated the need for a fitting work environment. However, more than just promoting a social project, Prof. Branover wanted to demonstrate that there was also a **profitable incentive in this approach**.

Thirty six years later, SATEC has proven to be everything Prof. Branover expected of it and much more. Being a home and family to many of the said immigrants, SATEC benefitted beyond measure from these experts who developed and implemented the most innovative ideas in power measurement and telemetry, always affirming SATEC's place as a **global front-runner**.

Prof. German Branover,

The founder of SATEC

What is PMU?

PMU is Phasor Measurement Unit (Synchrophasor)

But what does it mean exactly?

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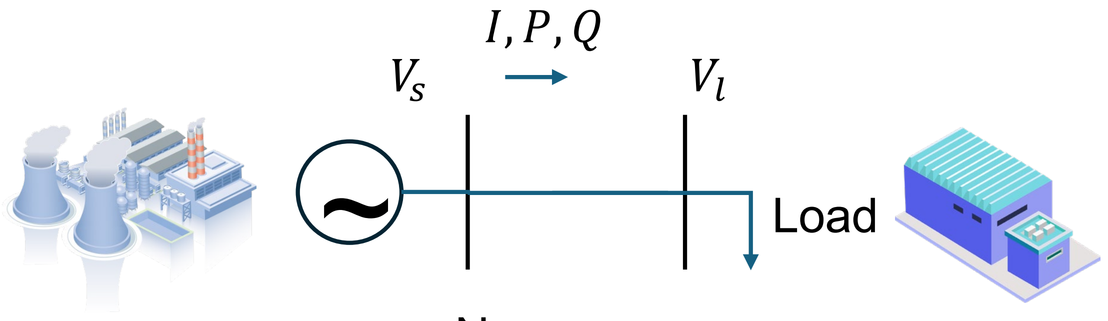
Phasors in AC networks

Regular measurements (meters, PQanalyzers)

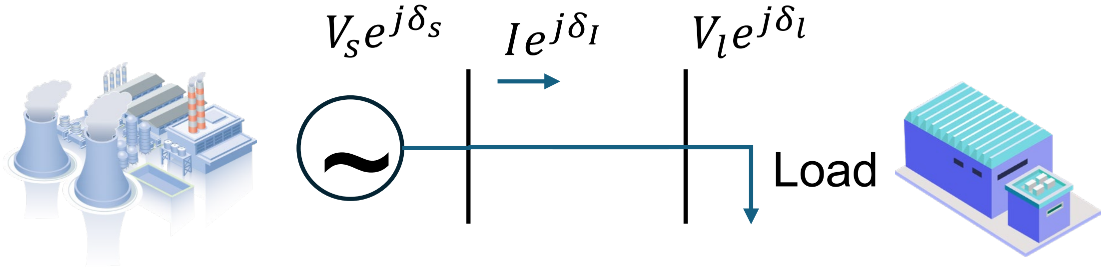
- Voltages, currents as RMS values using IEC 61000-4-30 and IEC 61000-4-7
- No phase angles
- Difficult to analyze the behavior of the network



No angles!!!

Fundamentals of Electrical Engineering, Power Systems Stability and Control

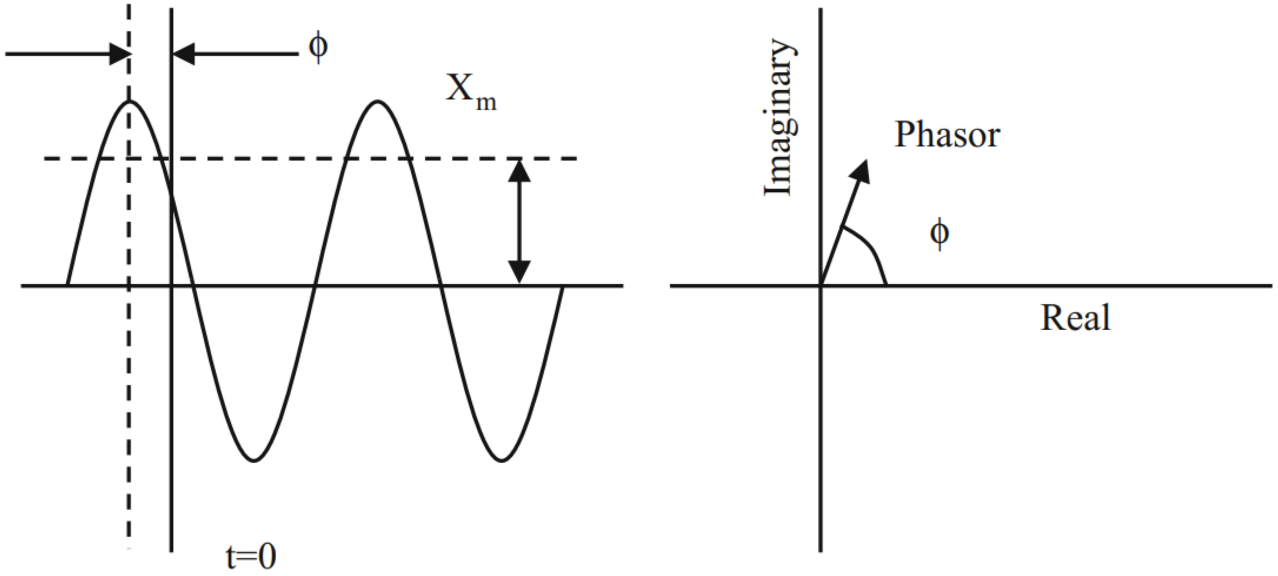
- Circuit equivalents
- Voltage and current sources as complex values
- Currents in branches as complex values
- Voltages in buses as complex values
- Full analysis of the network



Phasor definition

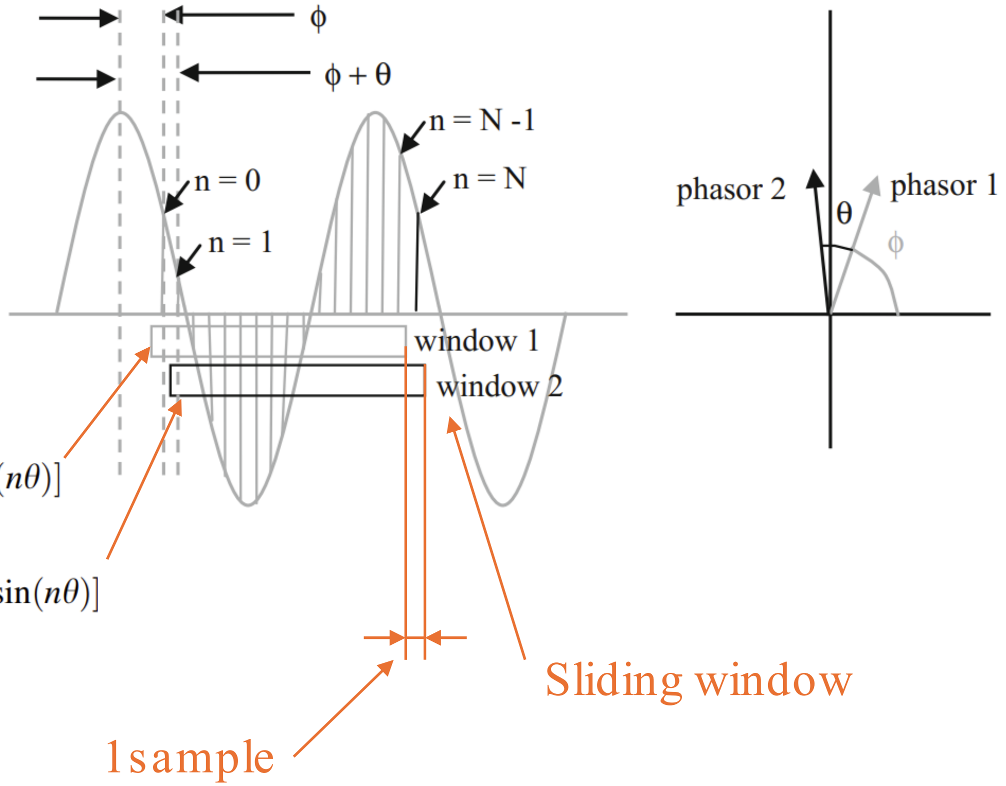
$$x(t) = X_m \cos(\omega t + \phi)$$

$$x(t) \leftrightarrow \mathbf{X} = \left(X_m/\sqrt{2}\right)e^{j\phi} = (X_m/\sqrt{2})[\cos\phi + j\sin\phi]$$



Phasor calculation

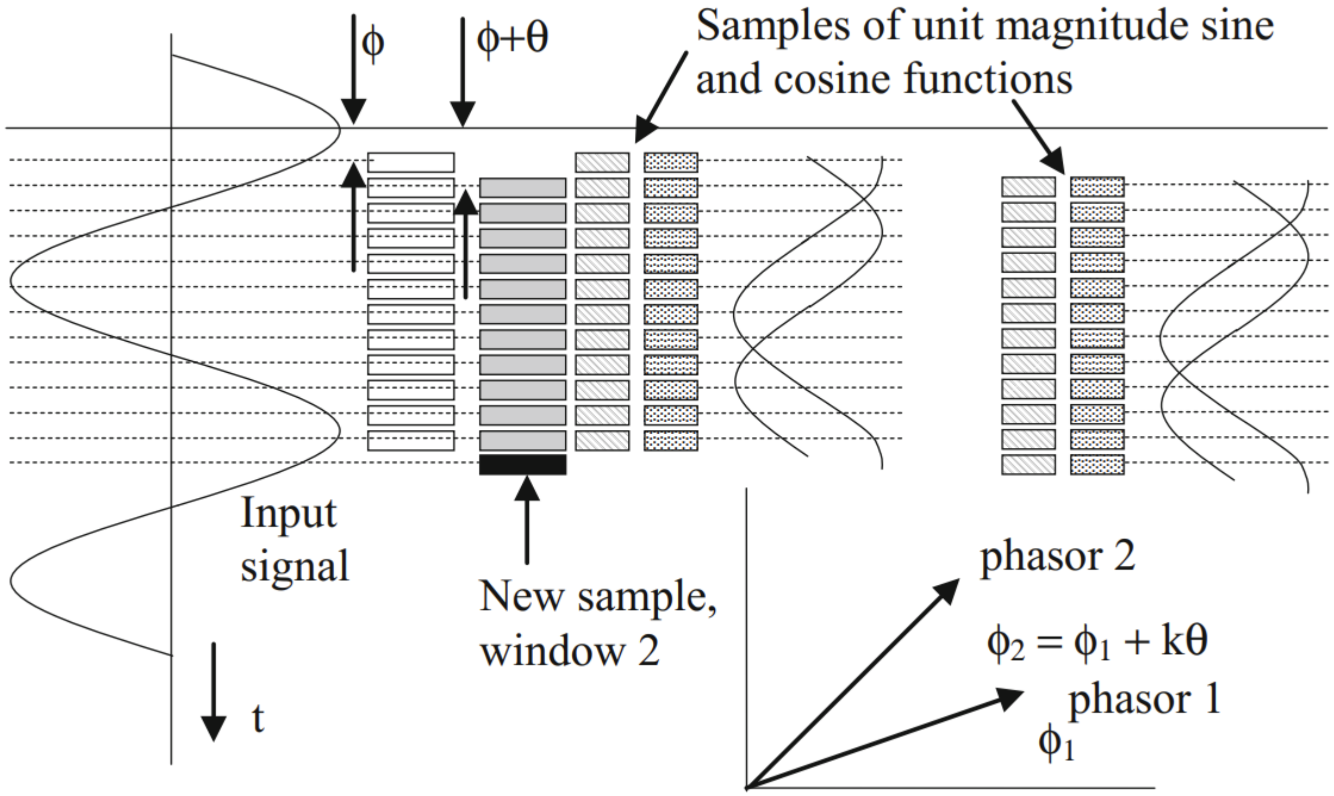
Simplified explanation



$$X^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n[(\cos(n\theta) - j\,\sin(n\theta)]$$

$$X^{N} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_{n+1}[(\cos(n\theta) - j\,\sin(n\theta)]$$

Phasor calculation



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Constant rotation

https://www.linkedin.com/posts/epassa_engineering-electrical-electricalengineering-activity-7212100699910758402-uVqP/?utm_source=share&utm_medium=member_desktop

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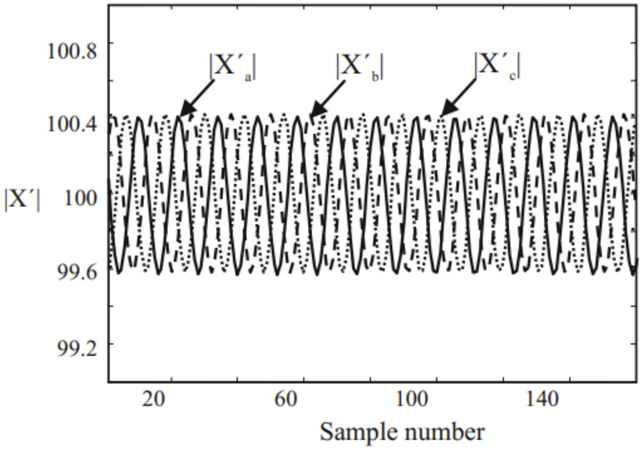
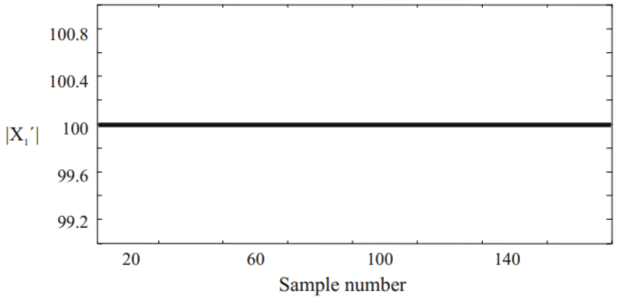
Frequency and ROCOF

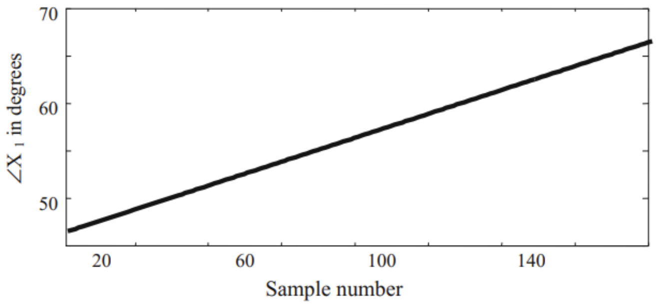
Frequency and ROCOF





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

$$\mathrm{ROCOF}(t) = \frac{df(t)}{dt}$$



Linear change = constant frequency

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Phasor frame

Frame

Phasor

- Time – GPS-based global time
- Magnitude
- Phase angle – based on GPS-based global time related to the start of sampling process
- Frequency
- ROCOF (Rate Of Change of Frequency)

Accuracy

- Magnitude – 0.1%
- Angle

1 µs in time

0.02° for 60 Hz

ANSI C37.118.1-2011

3.2 Special terms

frame: In this standard, a *data frame* or a *frame of data* is a set of synchrophasor, frequency, and ROCOF measurements that corresponds to the same time stamp. The term *frame* is used to differentiate it from *samples,* which are understood as points on an analog waveform.

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Phasor requirements

ANSI C37.118.1-2011

Table 1—Required PMU reporting rates

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

In SATEC we do even more!

Main applications of PMU

1

Preventing blackouts

Work with control and
automation equipment

2

Islanding

Validate voltage magnitudes and angles for
sync Check power balances

3

Grid operation

Voltage, power, frequency regulation

4

Grid restoration

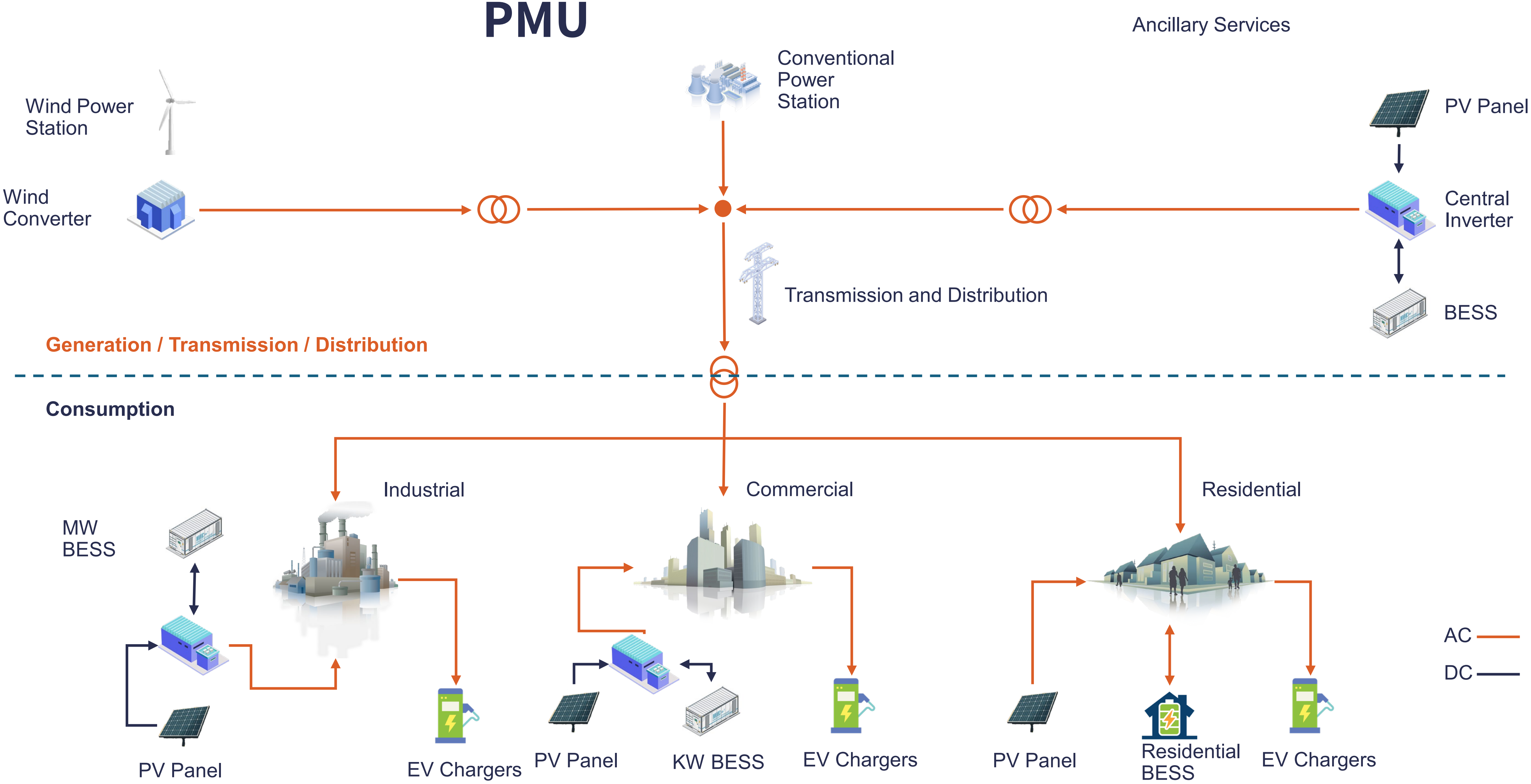
Stability assessment when add new loads and
generation

5

Additional functions

Reserve assessment
Forecasting
Energy market operation

Main applications of PMU



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Monitoring systems overview

Global types

SCADA

- You get only what you measure
- Analytics is limited

Model-based system

- **State Estimation**
- Analytics using both measurements and the model

Digital Twin

Digital Twin- definition

Digital Twin is the combination of a digital model of the real system and input/output channels connecting field measurement devices of the real system.

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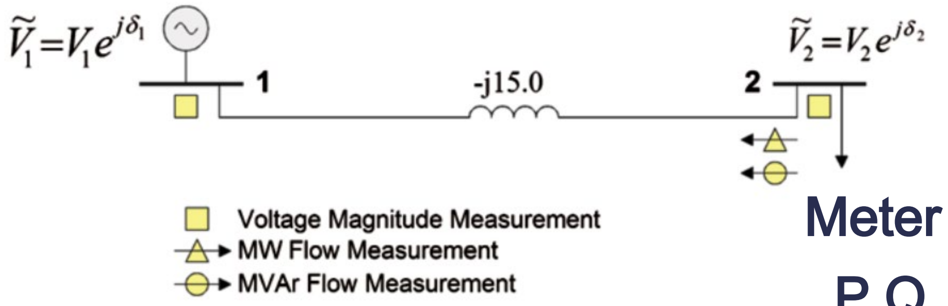
State Estimation

Early developments

F. Schweppe, .J . Wildes, and D. Rom, "Power system static state estimation: Parts I, II, and III," Power Industry Computer Conference (PICA), Denver, Colorado June, 1969

Simple power system

Meter
V1



Meter
P,Q

$$\begin{cases} F_{P_k}(\theta, U) = 0 \\ F_{Q_k}(\theta, U) = 0 \end{cases}$$

$$\begin{cases} \sum_n \left(U_k U_n \left(g_{kn} \cos\theta_n - \theta_k\right) - b_{kn} \sin(\theta_n - \theta_k)\right) - P_k = 0 \\ \sum_n \left(U_k U_n \left(g_{kn} \sin\left(\theta_n - \theta_k\right) + b_{kn} \cos(\theta_n - \theta_k)\right)\right) + Q_k = 0 \end{cases}$$

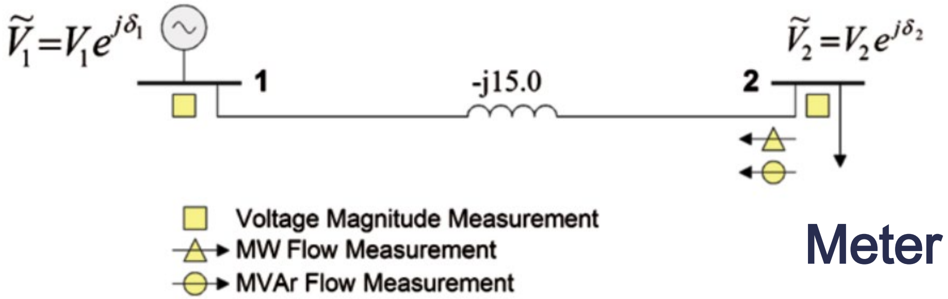
$$\begin{bmatrix} \frac{\partial F_p}{\partial \theta} & \frac{\partial F_p}{\partial U} \\ \frac{\partial F_Q}{\partial \theta} & \frac{\partial F_Q}{\partial U} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = -\begin{bmatrix} F_p \\ F_Q \end{bmatrix}$$

2 variables, 2 equations – solvable system!

State Estimation formulation

Meter
V1

Meter
V2



Meter
P,Q

$$z_1 = V_1 = 1.0, \qquad z_2 = V_2 = 0.99$$
$$z_3 = P_{21} = -1.56, \qquad z_4 = Q_{21} = 0.01.$$

$$x = \begin{bmatrix} V_1 \\ V_2 \\ \delta_2 \end{bmatrix}.$$

$$\begin{aligned} h_1(x) &= V_1 \\ h_2(x) &= V_2 \\ h_3(x) &= 15.0 V_1 V_2 \sin\delta_2 \\ h_4(x) &= 15.0 V_2^2 - 15.0 V_1 V_2 \cos\delta_2. \end{aligned}$$

$$\begin{aligned} 1.0 &= V_1 \\ 0.99 &= V_2 \\ -1.56 &= 15.0 V_1 V_2 \sin\delta_2 \\ 0.01 &= 15.0 V_2^2 - 15.0 V_1 V_2 \cos\delta_2. \end{aligned}$$

$$b = h(x)$$

3 variables, 4 equations – not a solvable system!

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State Estimation formulation

Least mean square method

Minimize the value

$$J = \left[h(x) - b\right]^T W \left[h(x) - b\right]$$

$$\frac{dJ}{dx} = \frac{d}{dx}\left[(Hx - b)^T W (Hx - b)\right] = 2H^T W (Hx - b) = 0$$

$$\frac{\partial h(x)}{\partial x}\Big|_{x=x^0} = H$$

$$x = \left(H^T W H\right)^{-1} H^T W b$$

$$x^{\nu+1} = x^{\nu} - \left(H^T W H\right)^{-1} H^T W \left[h\left(x^{\nu}\right) - b\right]$$

Iterative estimation algorithm!

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Calculation example

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 15V_2\sin\delta_2 & 15V_1\sin\delta_2 & 15V_1V_2\cos\delta_2 \\ -15V_2\cos\delta_2 & 30V_2 - 15V_1\cos\delta_2 & 15V_1V_2\sin\delta \end{bmatrix}$$

$$r^0 = h(x^0) - b = \begin{bmatrix} 0.0 \\ 0.0 \\ 1.56 \\ -0.1585 \end{bmatrix} \quad H(x^0) = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 14.85 \\ -14.85 & 14.7 & 0.0 \end{bmatrix} \quad H^T H = \begin{bmatrix} 221.5225 & -218.295 & 0.0 \\ -218.295 & 217.09 & 0.0 \\ 0.0 & 0.0 & 220.5225 \end{bmatrix} \quad (H^T H)^{-1} H^T r^0 = \begin{bmatrix} 0.00538 \\ -0.00532 \\ 0.10505 \end{bmatrix} \quad x^1 = \begin{bmatrix} 1.0 \\ 0.99 \\ 0.0 \end{bmatrix} - \begin{bmatrix} 0.00538 \\ -0.00532 \\ 0.10505 \end{bmatrix} = \begin{bmatrix} 0.9946 \\ 0.9953 \\ -0.10505 \end{bmatrix}$$

$$r^1 = h(x^1) - b = \begin{bmatrix} -0.0054 \\ 0.0053 \\ 0.0030 \\ 0.0823 \end{bmatrix} \quad H(x^1) = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 \\ -1.5655 & -1.5644 & 14.767 \\ -14.8472 & 15.0222 & -1.557 \end{bmatrix} \quad H^T H = \begin{bmatrix} 223.89 & -220.589 & -0.000647 \\ -220.589 & 229.114 & -46.4911 \\ -0.000647 & -46.4911 & 220.489 \end{bmatrix} \quad (H^T H)^{-1} H^T r^1 = \begin{bmatrix} -0.0027869 \\ 0.0027593 \\ 0.00019540 \end{bmatrix} \quad x^2 = \begin{bmatrix} 0.99741 \\ 0.99255 \\ -0.10525 \end{bmatrix}$$

$$r_1 = V_1 - 1.0 = -0.00259$$
$$r_2 = V_2 - 0.99 = -0.00256$$
$$r_3 = 15.0V_1V_2\sin\delta_2 + 1.56 = 0.00000614$$
$$r_4 = 15.0V_2^2 - 15.0V_1V_2\cos\delta_2 - 0.01 = 0.0000566$$

The system has been estimated!

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PMU-based State Estimation

Linear estimation!

$$x = \left(H^T W H\right)^{-1} H^T W b$$

- Better accuracy
- Robust (no fear of divergence)
- It is faster
- More applications

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Power systems analysis

Power Flow equations

- Number of equations equals to number of variables – system of equations
- Assumptions about element impedances

State Estimation

- Overdetermined system
- Calculations with uncertainty

Uncertainties everywhere

- Metering devices uncertainty
- Current/voltage sensors uncertainties
- Power System elements impedances uncertainties

IEC 60076 Power transformers

Rated kVA	%Z tolerance
<500 kVA	±10%
>2 MVA	±5%

Digital Twin and PMU

Applications

- Virtual measurements using State Estimation
- Equipment Diagnostics
- Optimization
- Transient Analysis
- Load Shedding
- Fault Location Detection

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PM180 PMU +PQM and more

- IEEE C37.118.1
  - class P and class M
- Communication protocols:
  - IEEE C37.118.2
  - IEC 61850-9-2 (SV)
  - DNP/IEC60870-5-101/104
- Time synchronization:
  - IRIG-B
  - PTP IEEE 1588:2008
- Data transferred :
  - V,I,ROCOF (df/dt), f
  - P,Q,S,PF
  - Up to 32DI
- Data Frames:
  - 60 frames/sec on 60Hz
  - 50 frames/sec on 50Hz
- Configuration Frames
  - CFG-1
  - CFG-2
  - CFG-3
- Support form communication
  - TCP – With data reception confirm (delays)
  - UDP – Without data reception confirmation (less reliable)
- NEW!!
  - Data Tags
  - Latitude and Longtitude
  - Dual PDC streaming with different rates
- Have Certification from testing laboratory

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PMU230 – Most Advanced PMU

- IEEE C37.118.1
  - class P and class M
- Communication protocols:
  - IEEE C37.118.2
  - IEC 61850-9-2 (SV)
  - DNP/IEC60870-5-101/104
- Time synchronization:
  - IRIG-B
  - PTP IEEE 1588:2019
- Data transferred :
  - V,I,ROCOF (df/dt), f
  - P,Q,S,PF
- Data Frames:
  - 240 frames/sec on 60Hz
  - 200 frames/sec on 50Hz
- Configuration Frames
  - CFG-1
  - CFG-2
  - CFG-3
- Support form communication
  - TCP – With data reception confirm (delays)
  - UDP – Without data reception confirmation (less reliable)
- **NEW!!**
  - Data Tags
  - Latitude and Longtitude
  - Dual PDC streaming with different rates
- We are working on Certification

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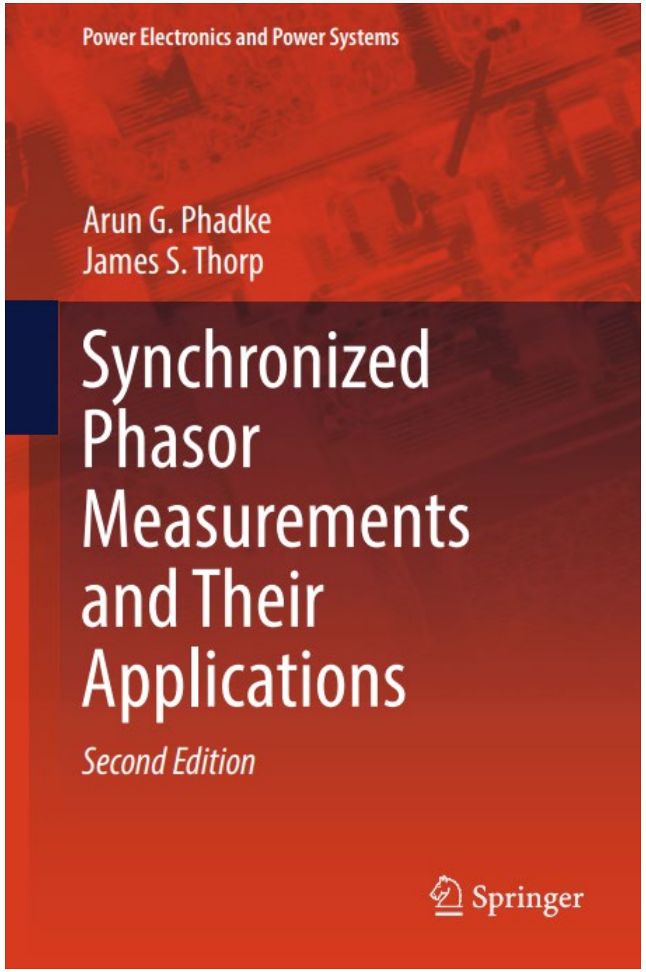
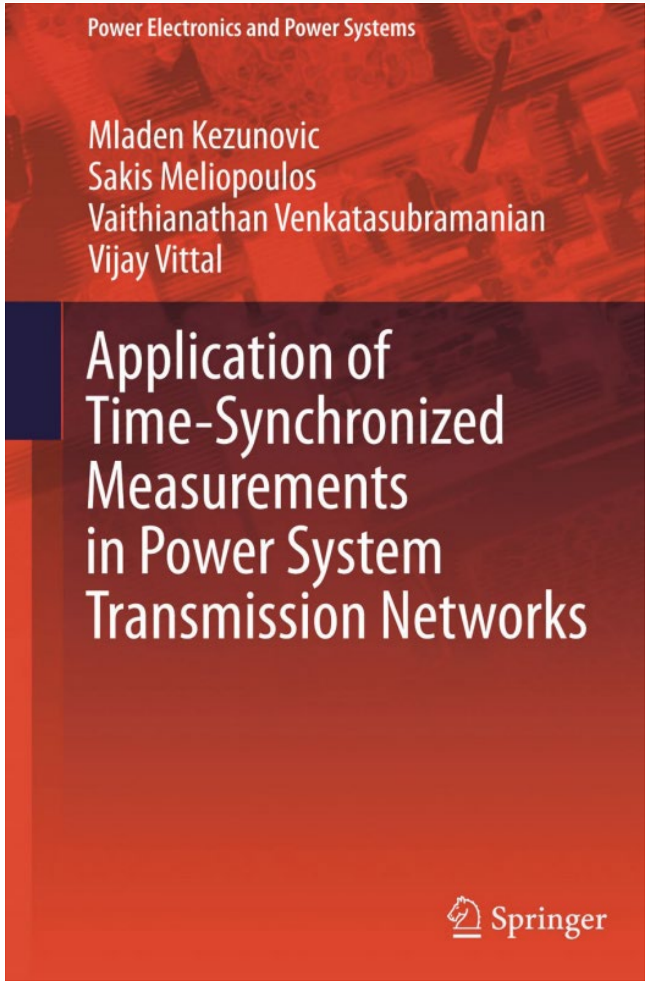
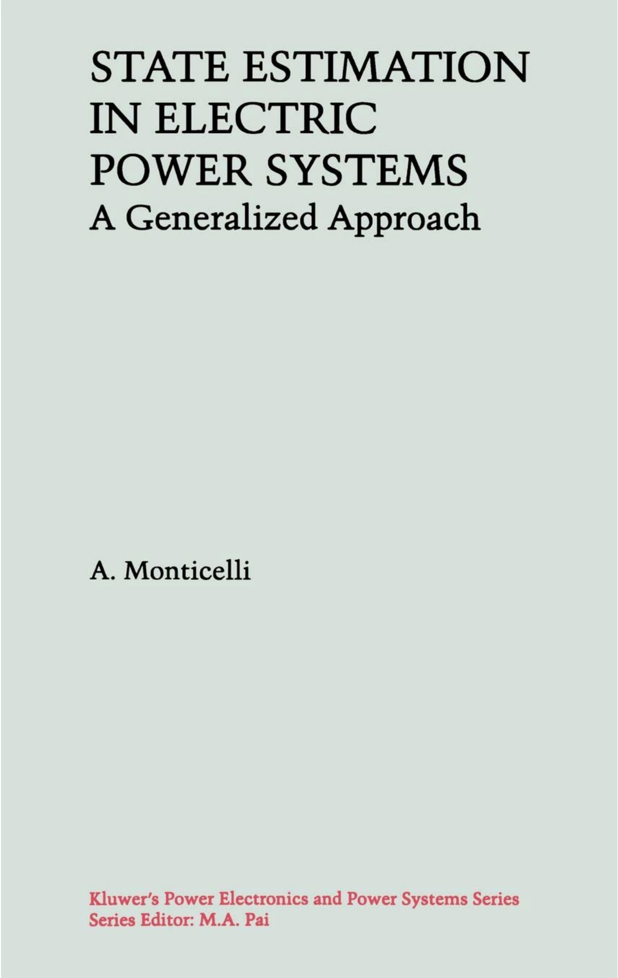
Recommended literature







Thank you!

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