NANYANG TECHNOLOGICAL UNIVERSITY
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Advanced Metering in Smart Grids

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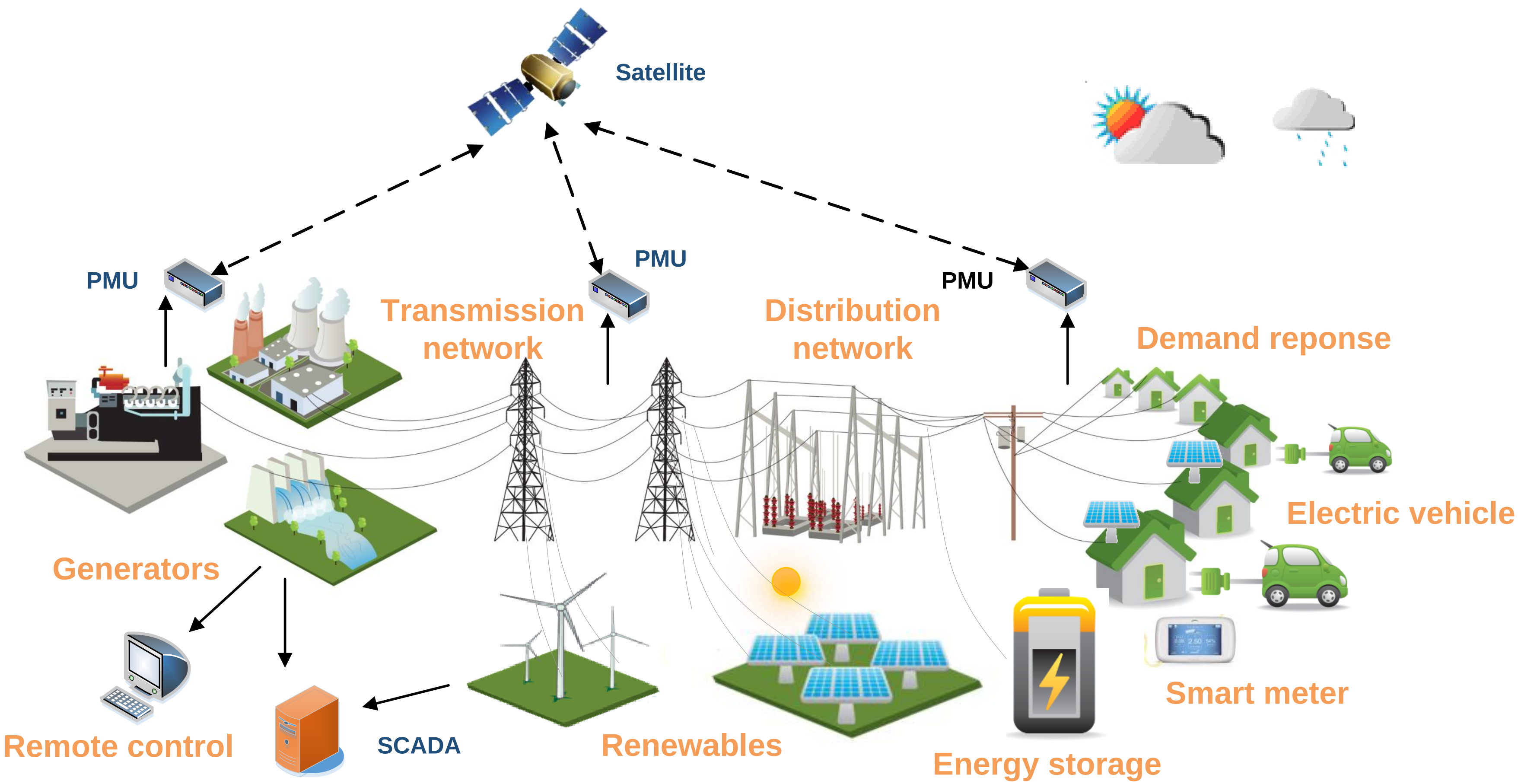
EE6509 – “Renewable Energy Systems in Smart Grids”

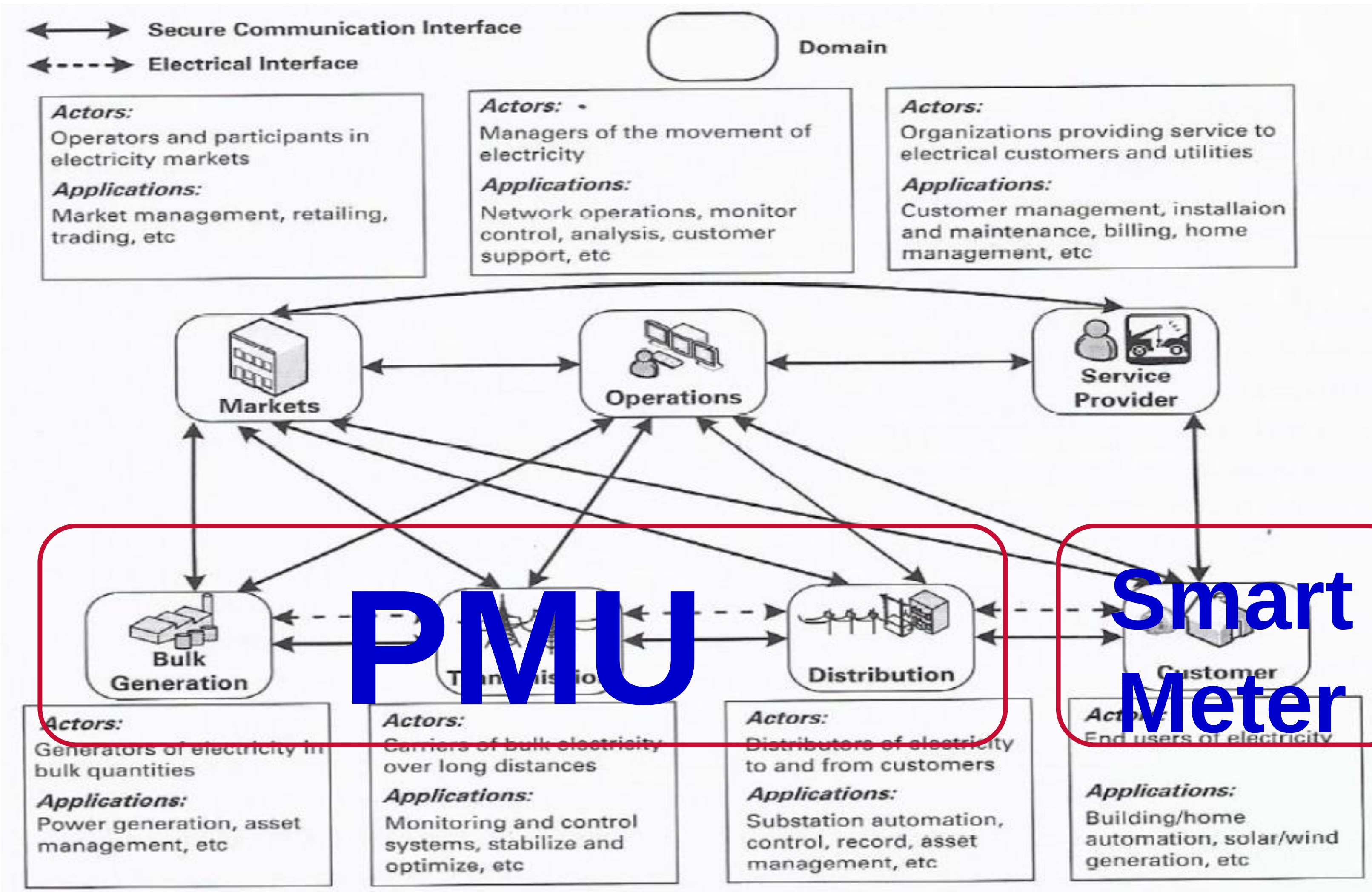
What is a “Smart Grid” ? – review



Outline

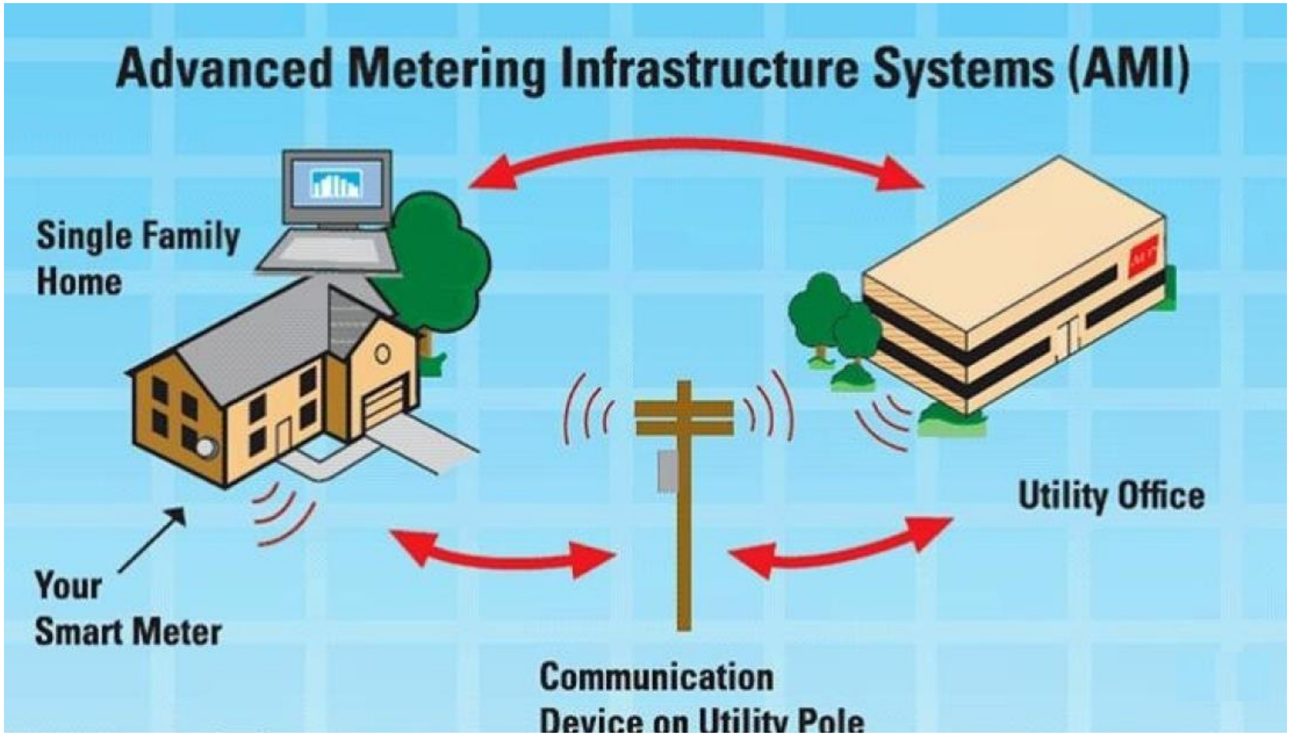
1. **Advanced Metering Infrastructure (AMI)**
2. Smart Meter
3. Phasor Measurement Unit (PMU)

Cyber-Physical View of SG



Why need AMI?

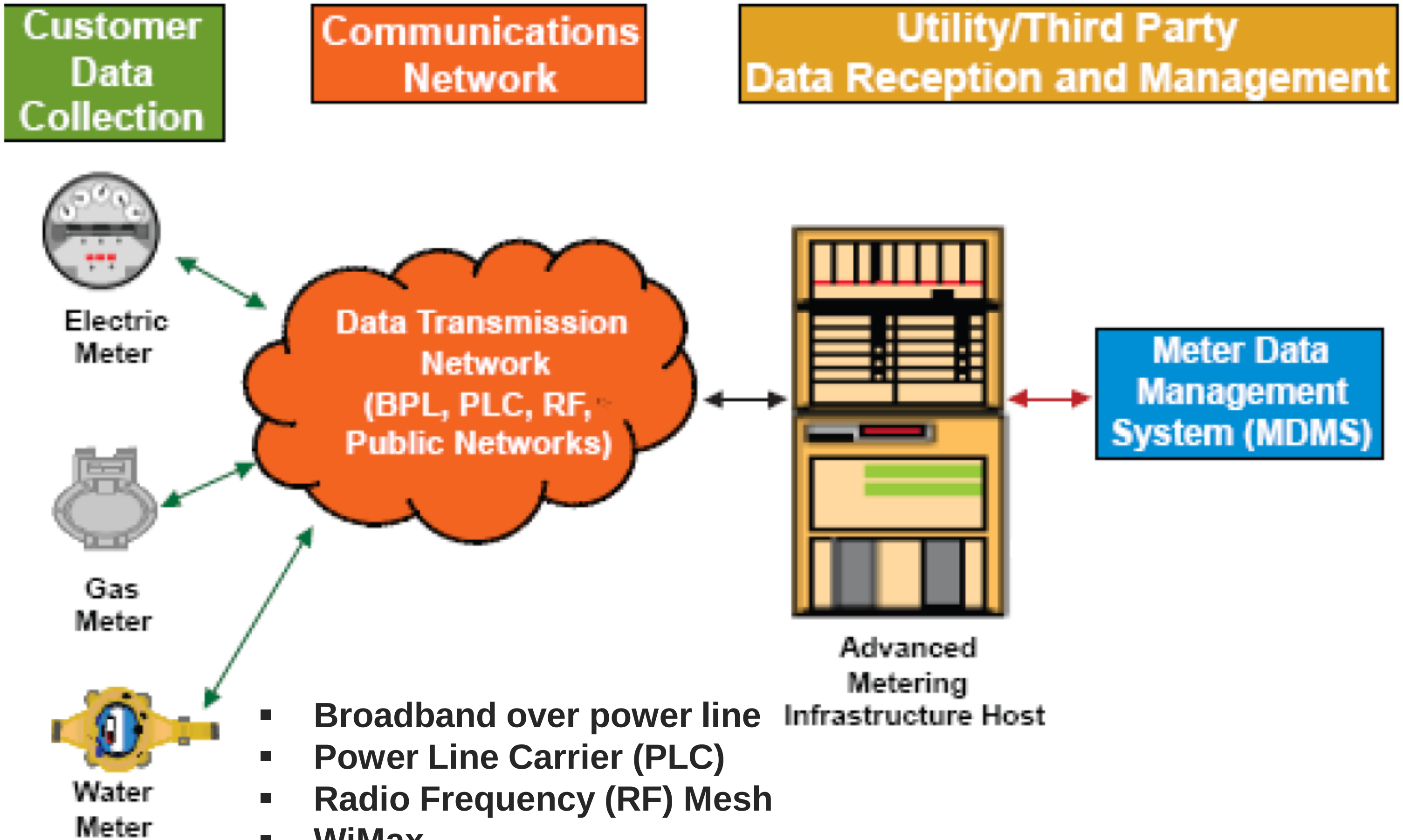
- Enables 2-way flow of info b/w consumers & utilities
- Enables demand response
- Allows service provider to control consumers' electricity usage (direct load control)
- Facilitates Smart Grid deployment & distributed generation



AMI Definition

- **What is it?**
  - Smart meters at consumer’s location
  - Fixed communication networks between consumers & service providers
  - Meter data management system (MDMS)
- **Smart metering: key component of AMI**
- **Communication network b/w consumers & service providers called AMI host system**
- **MDMS: software applications that receive & store meter data & perform other functions**

AMI Structure

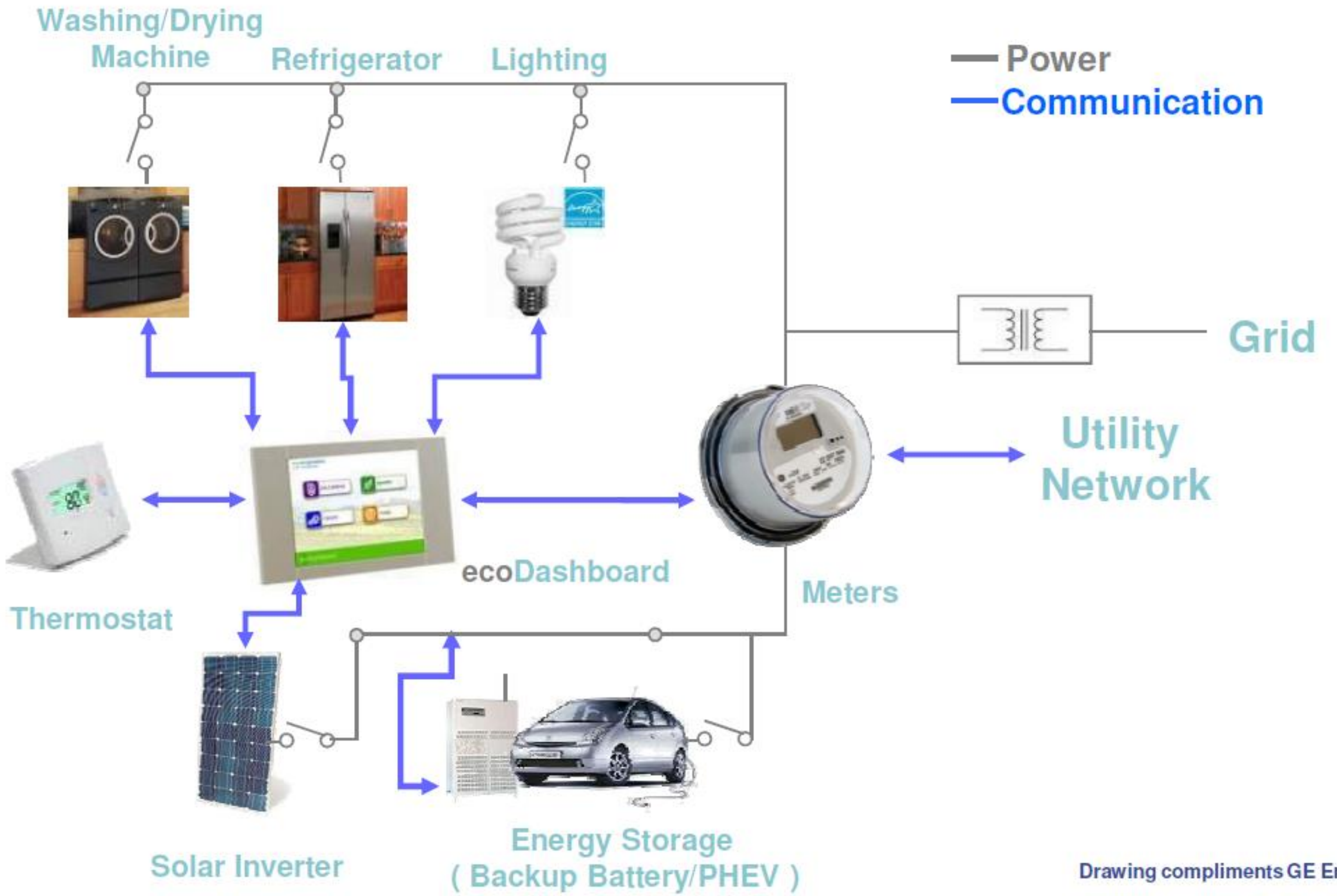


- Broadband over power line
- Power Line Carrier (PLC)
- Radio Frequency (RF) Mesh
- WiMax

AMI Benefits

- **Integrated systems & networks for measuring, collecting, storing, analyzing, using energy usage data**
- **4 parts of AMI technology:**
  - Smart meter
  - Wide area network
  - Meter data management system (MDMS)
  - Home area networks, HAN
- **Benefits SG: system-wide CN, AMI link consumers & utilities for distribution automation & other SG functions**
- **System-wide measurement & visibility by AMI enhance utilities' operation & asset management**
- **Utilities adopt AMI to build integrated CN & IT system for business transformation SG**

Home System Architecture



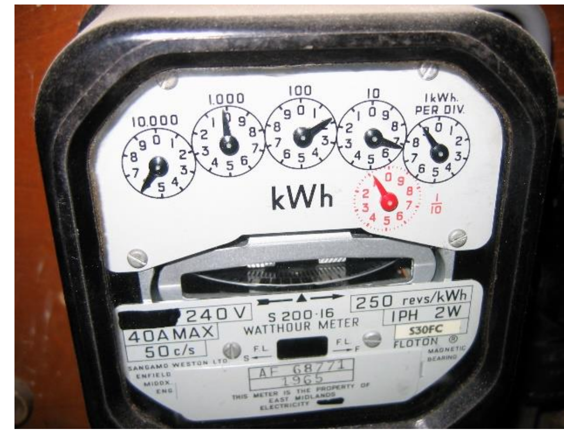
Drawing compliments GE Energy

Outline

1. Advanced Metering Infrastructure (AMI)
2. Smart Meter
3. Phasor Measurement Unit (PMU)

Traditional Meters

www.alamy.com - A837MX



- Mechanical (only energy, no power information)
- low sampling rate (monthly billing)
- No communication (manual reading)

Source: https://www.google.com.sg/search?biw=1920&bih=989&tbm=isch&sa=1&q=electricity+meter&oq=electricity+meter&gs_l=psy-ab.12...0.0.0.380606.0.0.0.0.0.0.0.0..0.0....0...1..64.psy-ab..0.0.0....0.1WWyhWmG8k8

Smart Meters

Sampling rate: every 30min~1hr

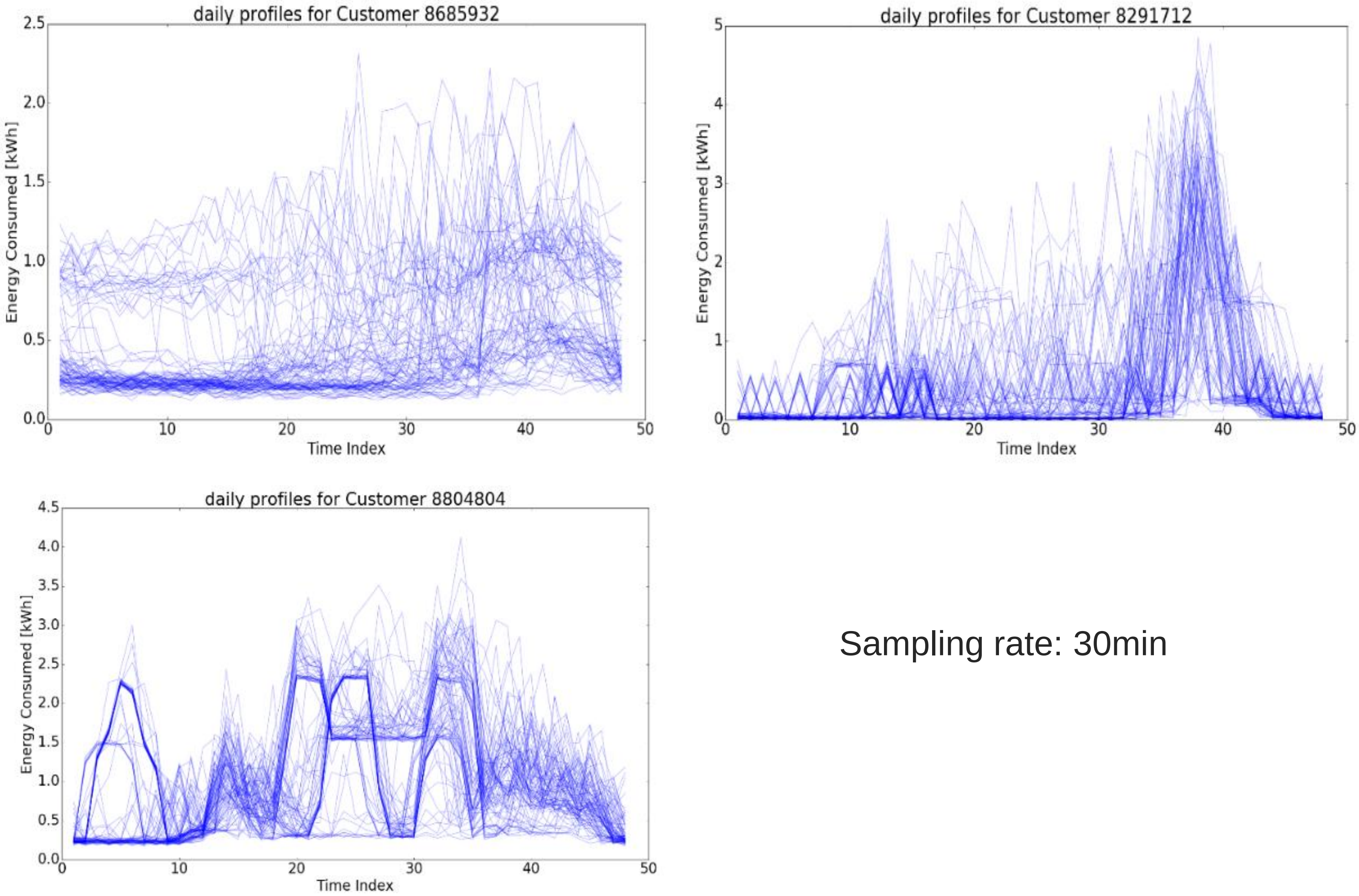
Source: https://www.google.com.sg/search?biw=1920&bih=989&tbm=isch&sa=1&q=smart+meter&oq=smart+meter&gs_l=psy-ab.3...0.0.0.169592.0.0.0.0.0.0.0.0..0.0....0...1..64.psy-ab..0.0.0....0.DCICjHp1tkE

Smart Meters

How are smart meters different than current meters?

- Conventional meters only collect **non-time-stamped energy data** – mainly for utility's billing
- Smart meters collect **time-stamped power data** – for both utility and customer applications
- **Bidirectional** or **two-way communication** with utility's communications network & smart grid, as well as consumer's home area network (HAN), programmable thermostat, smart appliances etc.

Smart Meter Data Illustration

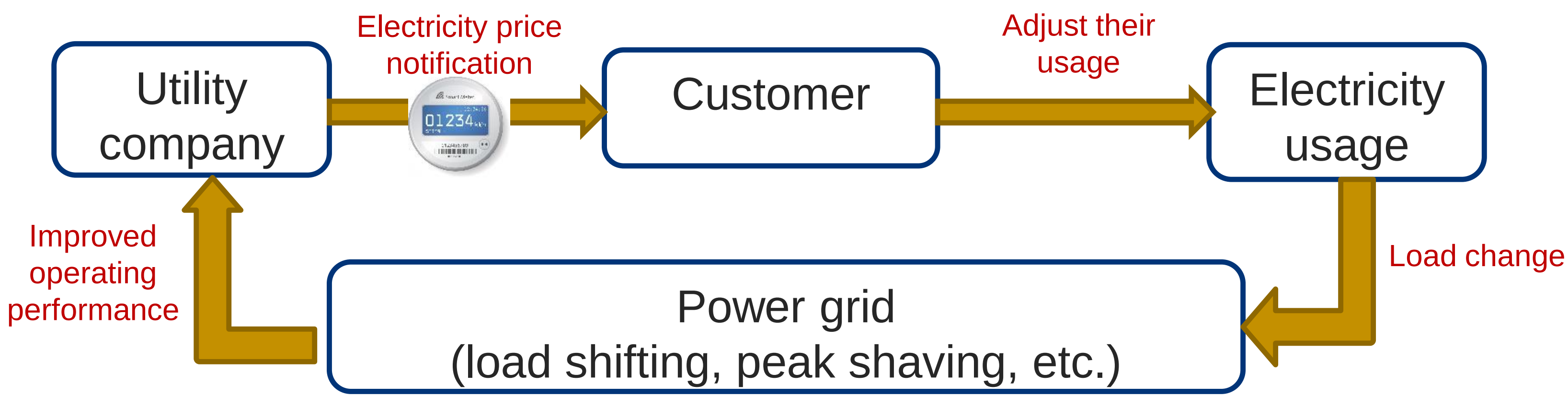


Sampling rate: 30min

https://researchdata.ands.org.au/smart-grid-smart-customer-trial/644597

Smart Meter Applications (1)

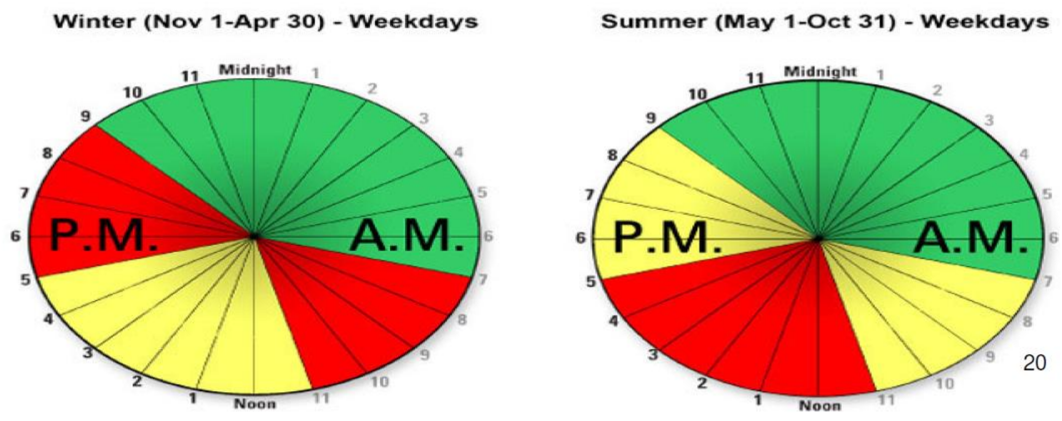
- Price-based demand response



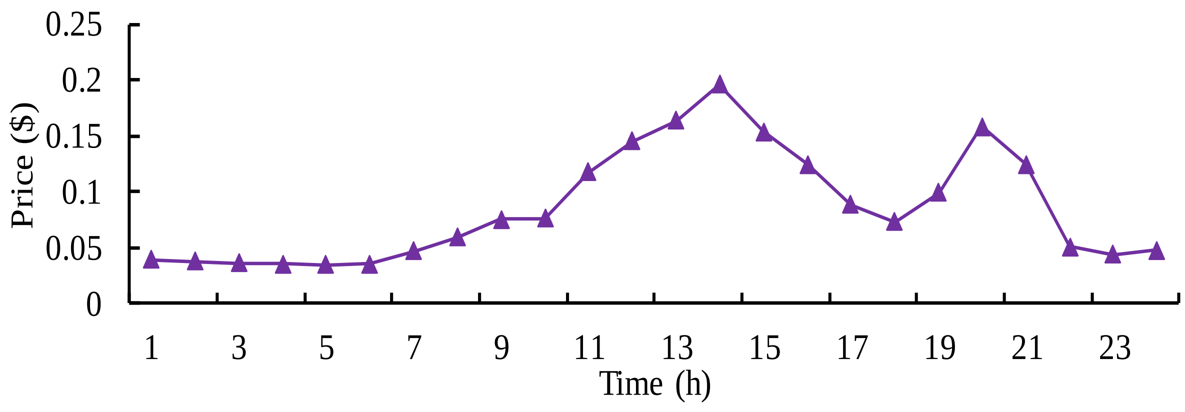
Price-based demand response (PBDR) has been widely applied in day-ahead power market. It allows customers to manage their electricity usage flexibly without partial loads being controlled directly: the hourly electricity price in the following day is delivered to the customers a day ahead, then the customers adjust their demand based on the electricity price. A lower price would encourage the customers increase their electricity usage, and vice versa.

Complex Price Rate

1. Fixed price – conventional
2. Time-of-use (ToU) price



3. Dynamic (real-time) price



Smart Meter Applications (1)

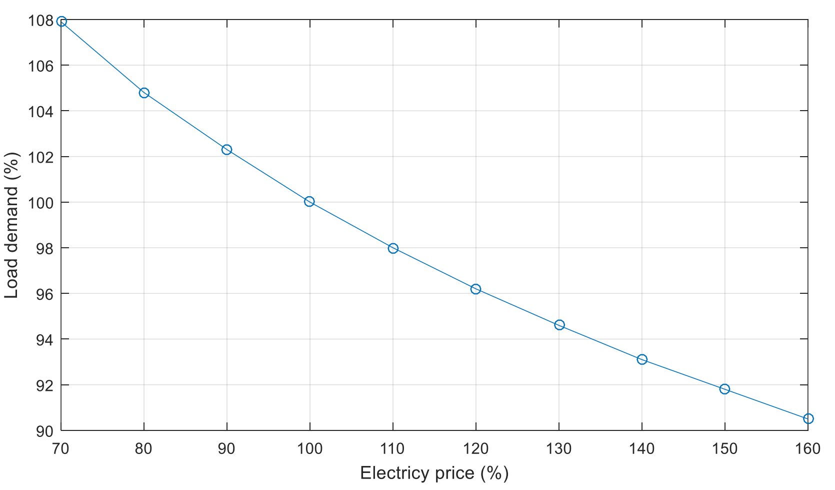
- Price-based demand response

For the PBDR, the mathematical relationship between the electricity price Pr_t and the electric loads P_t^D is modelled as:

$$P_t^D = \mathrm{A}\, {Pr_t}^{\varepsilon}$$

where ε is **price elasticity** of electric demand, and A is a constant value modeling the relationship between the price and load demand. E.g., the price elasticity of load is -0.38 for Australian power systems.

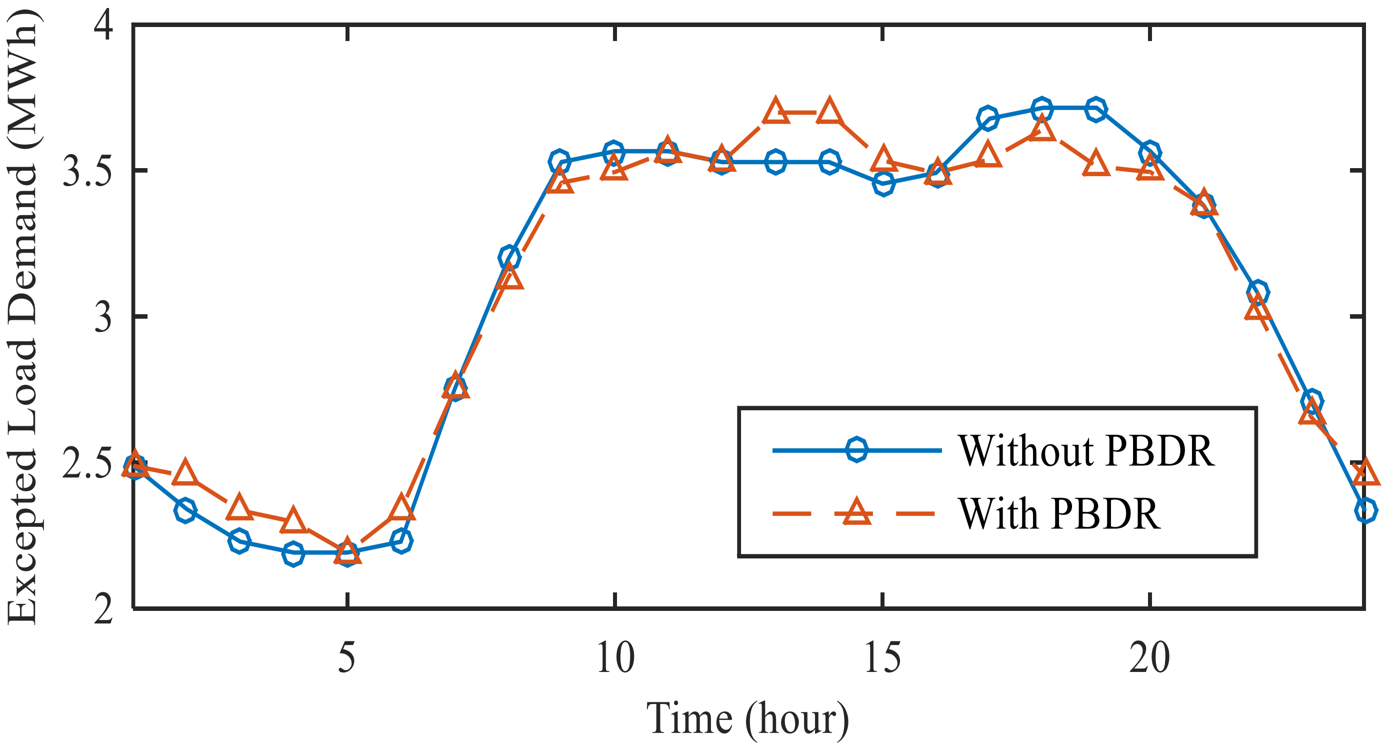
Price Level	Price Rate (%)	Load Demand Rate (%)
1	70	107.9
2	80	104.8
3	90	102.3
4	100	100.0
5	110	98.0
6	120	96.2
7	130	94.6
8	140	93.1
9	150	91.8
10	160	90.5



C. Zhang, **Y. Xu**, et al "Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids," *IEEE Trans. Smart Grid*, 2017

Smart Meter Applications (1)

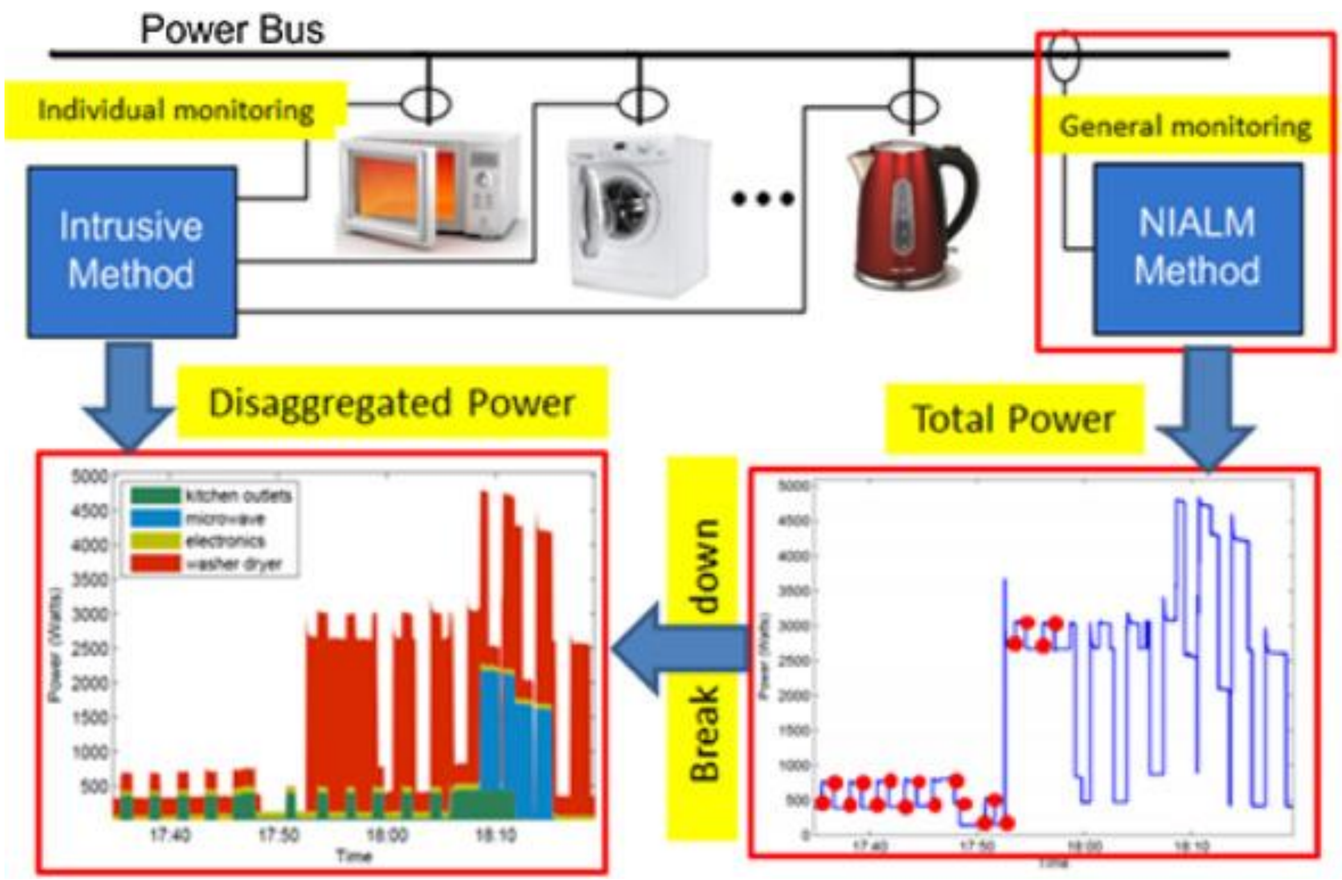
- Price-based demand response – illustration of results



C. Zhang, **Y. Xu**, et al "Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids," *IEEE Trans. Smart Grid*, 2017

Smart Meter Applications (2)

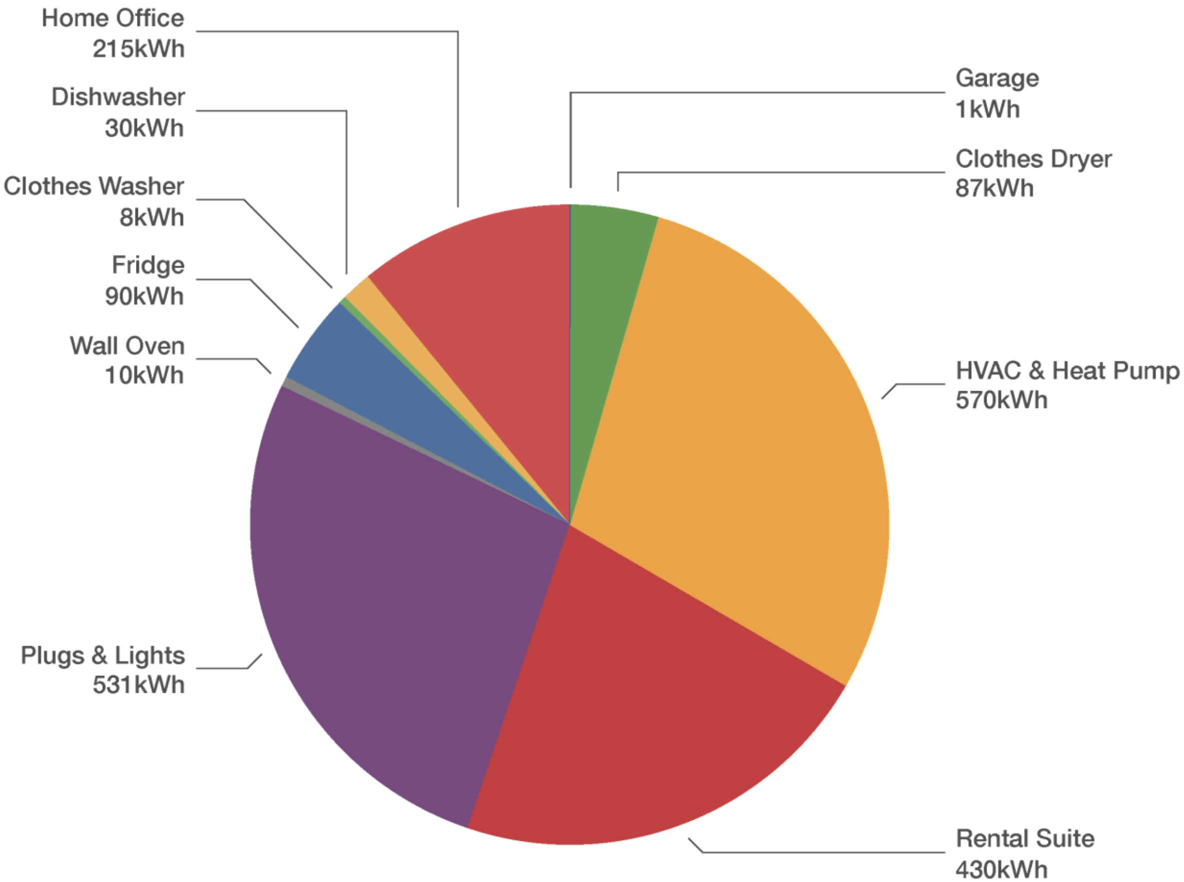
- **Non-intrusive load monitoring**



Source: website (searched in Google)

Smart Meter Applications (2)

- **Non-intrusive load monitoring**



Source: website (searched in Google)

For utility company

- Refine customer rebate and incentive programs
- Understand customer behavior to improve capacity planning
- Identify appliances that could participate in demand response

For customers

- Understand your bill
- Take advantage of time-on-use (ToU) tariff
- Energy saving

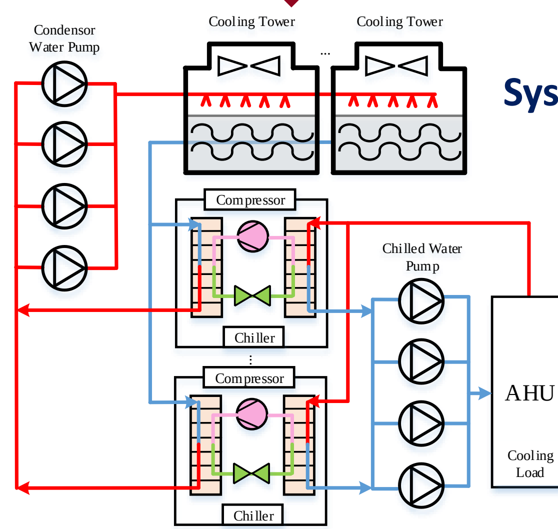
W. Kong, Z.Y. Dong, D. Hill, F. Luo, and **Y. Xu**, "Improving Non-Intrusive Load Monitoring Efficiency via a Hybrid Programming Method," ***IEEE Trans. Industrial Informatics*, 2016.**

Smart Meter Applications (2)

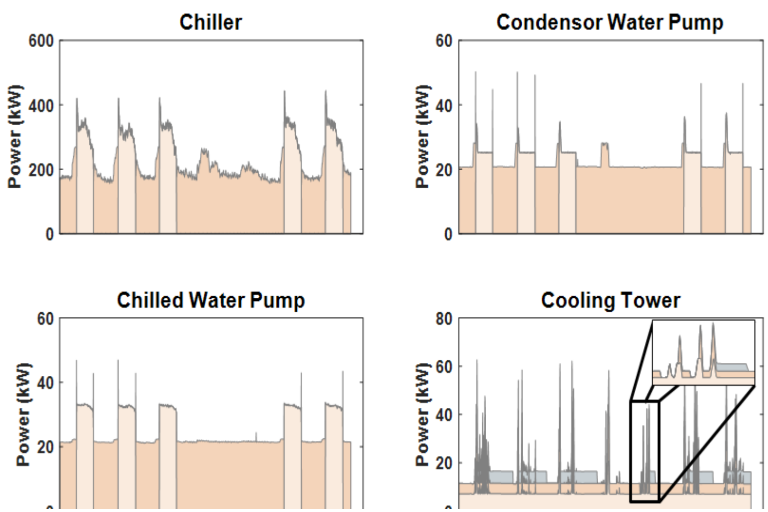
- **Non-intrusive load monitoring – a real-world project at NTU**

NTU's Clean Tech One Building

Chiller Plant System

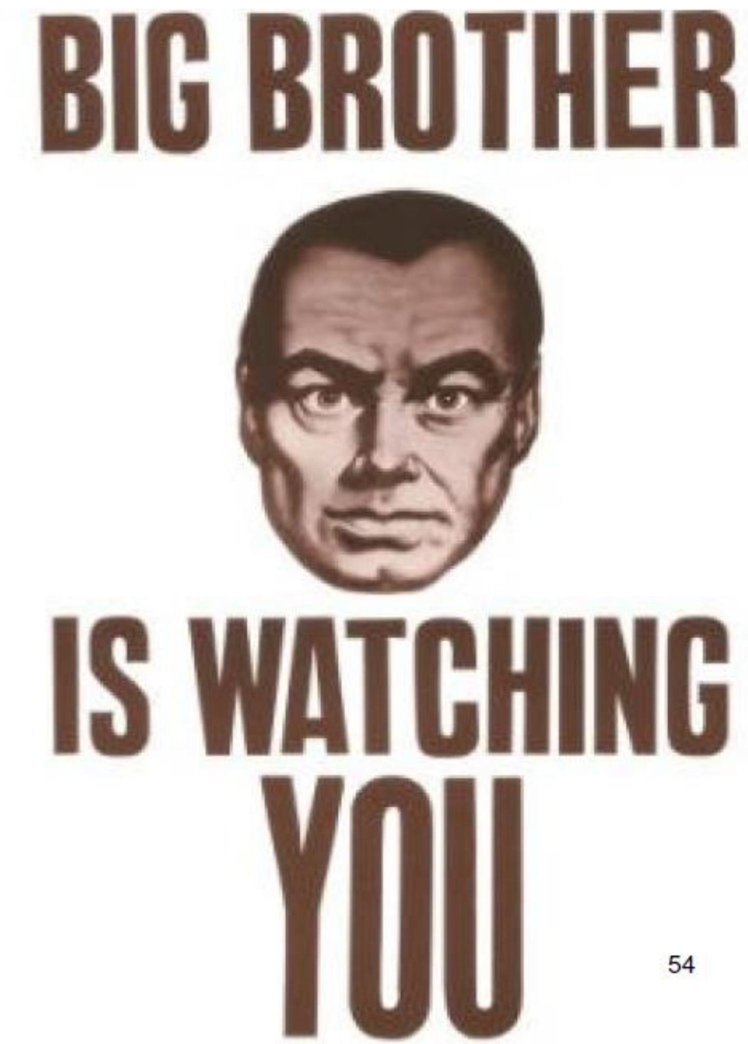


System Diagram



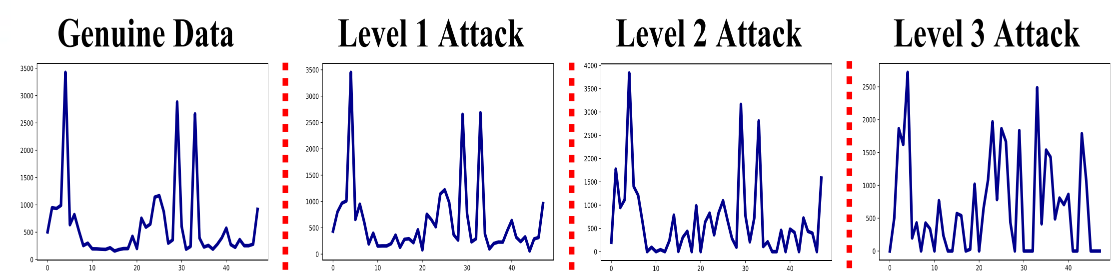
Cooling Sub-System Exploratory Data Analysis

Security Issues



- Privacy
  - ➢ Can determine if someone is home
  - ➢ Can determine usage patterns

- Exposure to cyber attack risk
  - ➢ False Data Injection (FDI)
  - ➢ Denial-of-Service (DoS)



Z. Du, Z. Yan, and **Y. Xu***, “A Dimensional Augmentation-based Data-Driven Method for Detecting False Data Injection in Smart Meters,” *IEEE Trans. Smart Grid*, 2023.

Security Issues

Utilities should consider following security risks at onset & during AMI program deployment:

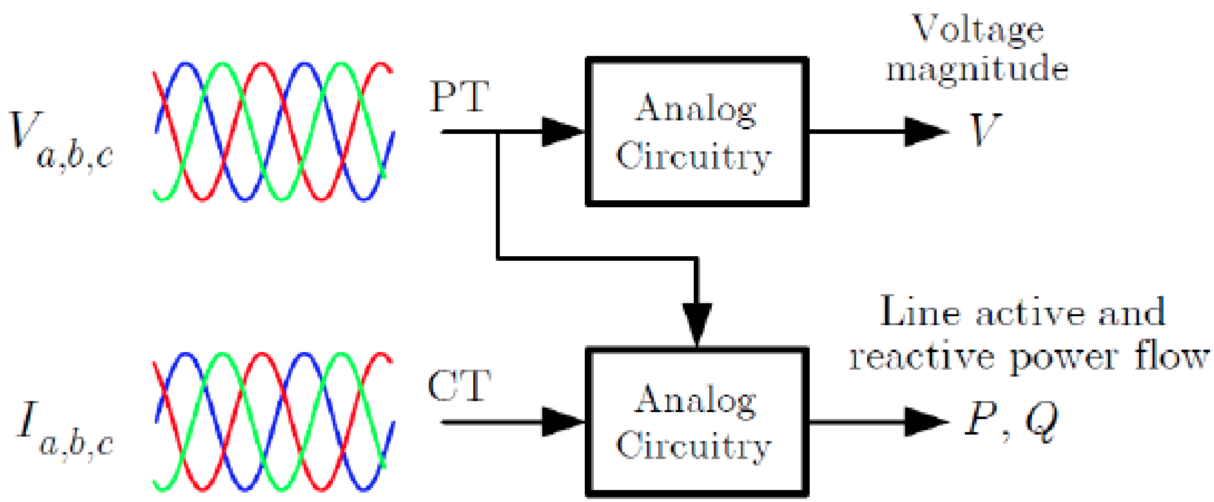
- Vendor and product selection
- AMI network management and system integration
- Corporate governance and regulatory compliance
- Privacy and integrity of data
- Identity and access management
- Physical, operational control, and infrastructure security assessments and remediation
- Web services and portals
- Business continuity and resiliency
- Security events and network monitoring (7x24x365)
- Digital investigative (forensics) assessments
- Vulnerability and threat management

Outline

1. Advanced Metering Infrastructure (AMI)
2. Smart Meter
3. **Phasor Measurement Unit (PMU)**

Traditional SCADA

- Traditional **Supervisory Control and Data Acquisition (SCADA)** system measures electrical quantities (sampled every 2~4 seconds).
- *V* and *P, Q* are generally transmitted via modems, microwave, or internet directly to the power system control rooms.

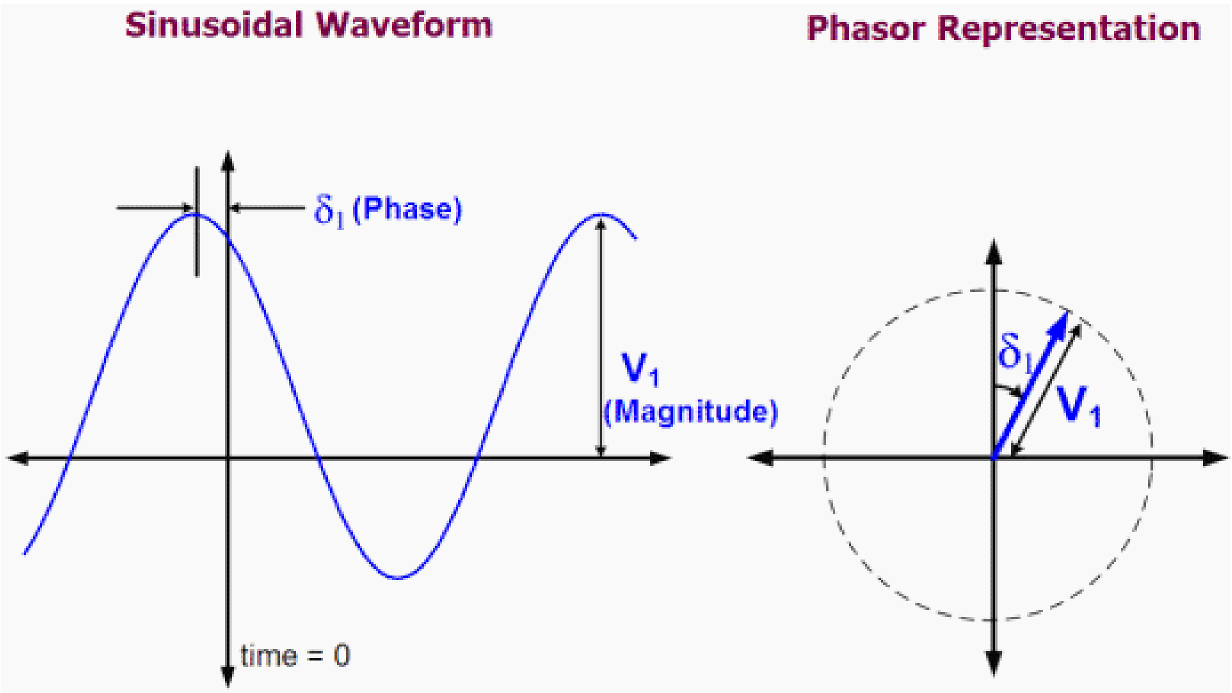


Inadequacies of SCADA

- The data from different locations are not captured at **precisely** the same time.
- **Low** sampling rate, cannot provide dynamic information of the system, especially during the disturbance and transient event.
- Can only support **steady-state** operation and control (power flow dispatch, network reconfiguration, etc.)

Real-time control is possible when real-time system measurements are available!

What is Phasor?



An AC waveform can be mathematically represented as

$$V(t) = V\cos\left(2\pi f + \delta\right)$$

where,

V = magnitude of the sinusoidal waveform (RMS value)
f = the instantaneous frequency (50 or 60 Hz)
δ= Angular starting point for the waveform, i.e., phase

In a phasor notation, this waveform is typically represented as:

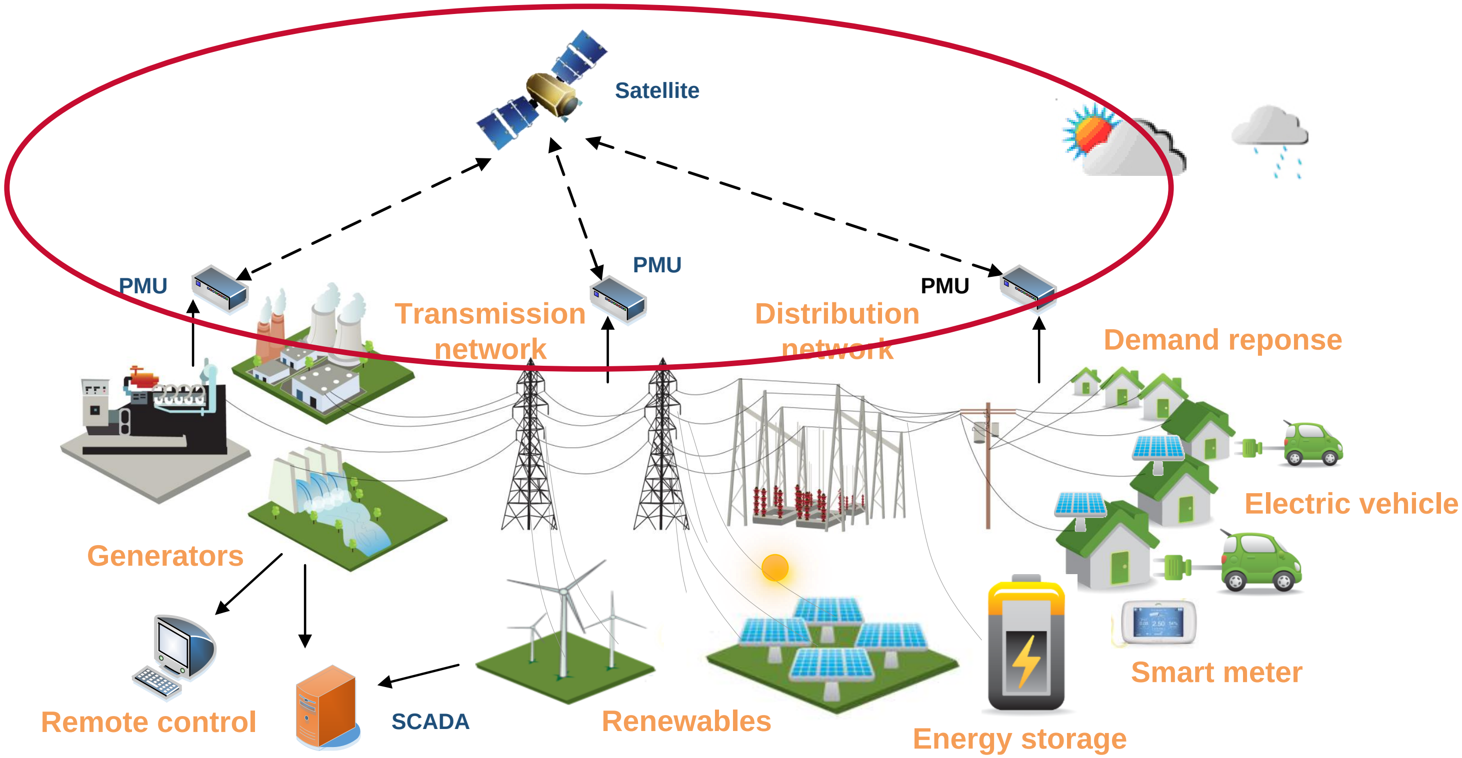
$$\vec{V} = V\angle\delta$$

What is Synchrophasor?

Synchrophasors are precise **time-synchronized measurements** of certain parameters at different locations of the electricity grid.

The synchrophasors can be measured by a **Phasor Measurement Unit (PMU),** which is “a device that produces Synchronized Phasor, Frequency, and Rate of Change of Frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal”.

PMU

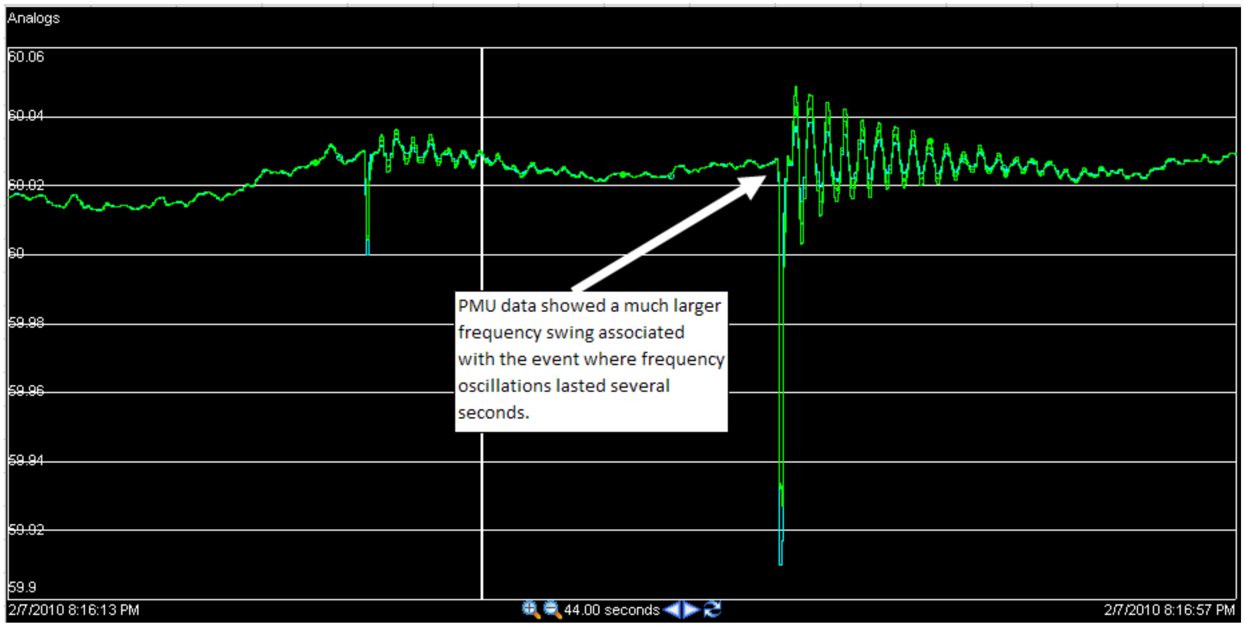


- PMUs measure **voltage, current and frequency** and calculate phasors.
- Each phasor measurement is timestamped against **Global Positioning System (GPS)** universal time; when a phasor measurement is timestamped, it is called a synchrophasor.

SCADA v.s. PMU

Attribute	SCADA	PMU
Sampling rate	1 sample every 2-4s (steady-state observability)	10-60 samples every second (dynamic observability)
Measurement	Magnitude only	Magnitude and phase angle
Time synchronization	No	Yes
Focus	Static monitoring and control	Wide-area real-time monitoring and control

SCADA v.s. PMU



Upper: SCADA data
Lower: PMU data

Source: “Real-time application of synchrophasors for improving reliability”, NERC, 2010.

Value of Synchrophasor Measurement

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- Phasor data are highly valuable because they give grid operators and planners unprecedented insight into what is happening on the grid at high resolution, over a wide area in time synchronized mode, and where needed, in real-time.
- Current SCADA systems observe grid conditions every 2 to 4 second, which is too slow to track dynamic events on the grid. They also do not monitor key indicators such as phase angles, SCADA data are not consistently time-synchronized and time-aligned and those data are not shared widely across the grid. Thus SCADA does not give grid operators real-time, wide area visibility into what is happening across a region or interconnection.
- In contrast, synchrophasor systems allow the collection and sharing of high-speed, real-time, time-synchronized grid condition data across an entire system. This data can be used to create wide-area visibility across the bulk power system in ways that let grid operators understand real-time conditions, see early evidence of emerging grid problems, and better diagnose, implement and evaluate remedial actions to protect system reliability.

Source: “Real-time application of synchrophasors for improving reliability”, NERC, 2010.

Applications

Real-time operations applications

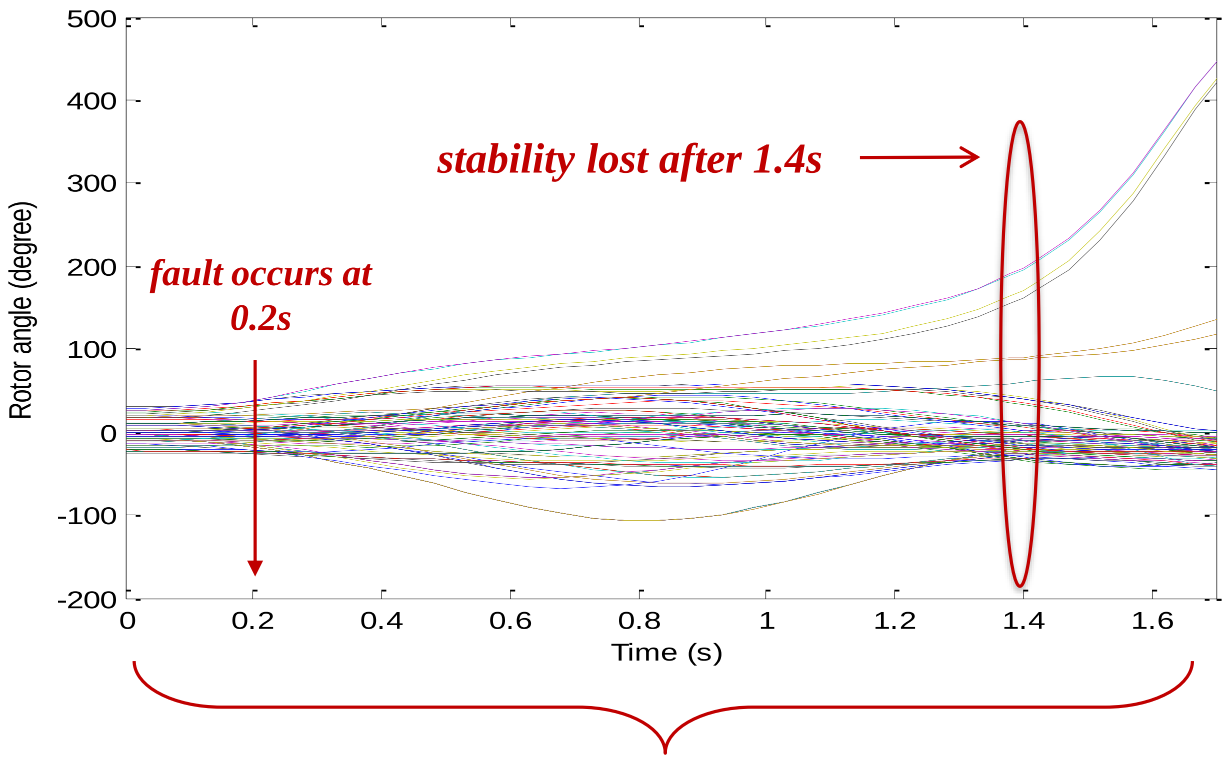
- Wide-area situational awareness
- Frequency stability monitoring and trending
- Power oscillation monitoring
- Voltage monitoring and trending
- Alarming and setting system operating limits, event detection and avoidance
- State estimation
- Dynamic line ratings and congestion management
- Outage restoration

Planning and off-line applications

- Baselining power system performance
- Event analysis
- Static system model calibration and validation
- Dynamic system model calibration and validation
- Power plant model validation
- Load characterization
- Special protection schemes and islanding
- Primary frequency (governing) response

Source: “Real-time application of synchrophasors for improving reliability”, NERC, 2010.

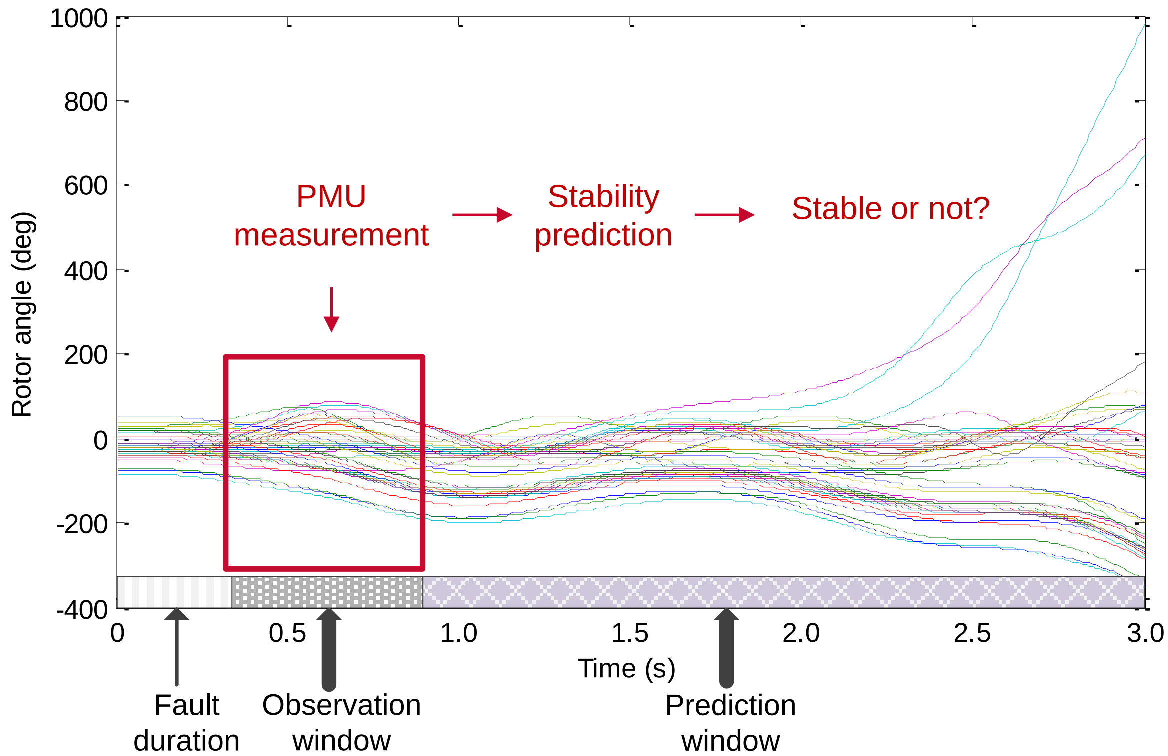
Eg: Data-driven Stability Assessment



Computer simulation costs 2.2s CPU time!

That means if we rely on computer simulation for stability assessment, it is too late…

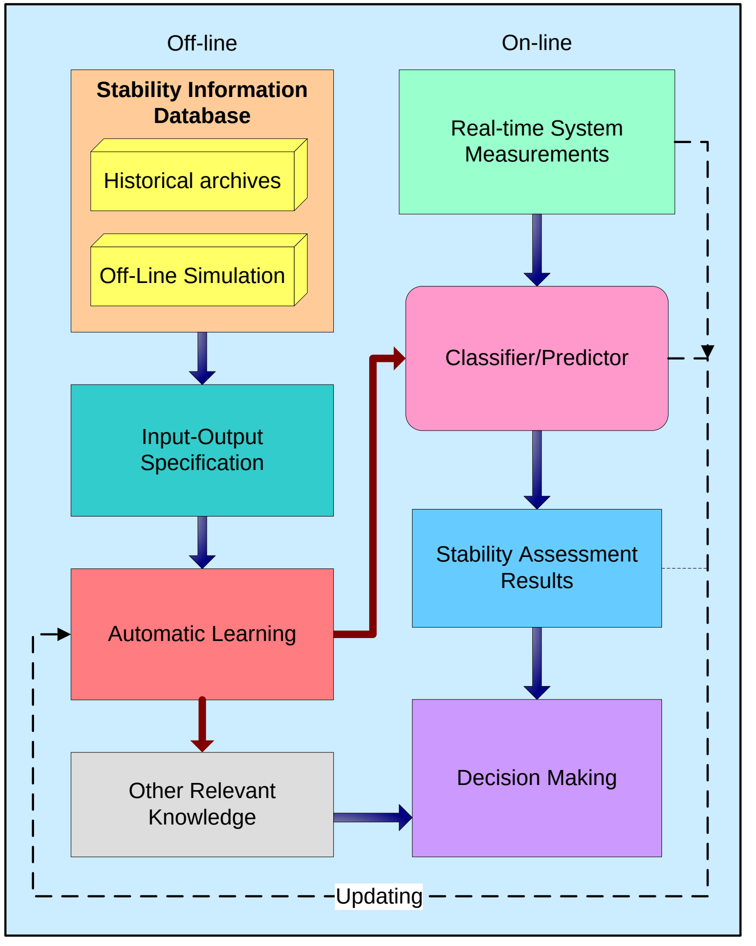
Eg: Data-driven Stability Assessment



Eg: Data-driven Stability Assessment

Intelligent system method

- Offline learning: learn from a stability database to extract the mapping relationship between post-disturbance variables (input) and the stability status (output).
- Online application: once the input is fed, the output can be instantaneously determined.
- Advantages: much fast speed, less data requirement.
- Key techniques: feature selection, machine learning, intelligent decision-making, etc.



Zhao Yang Dong, **Yan Xu**, Pei Zhang, and Kit Po Wong, "Using intelligent system to assess an electric power system's real-time stability," *IEEE Intelligent Systems Magazine*, 2013.

References (optional)

1. Generate a comprehensive stability **database**
2. Select/extract **significant features**
3. Evaluate the **credibility** of the model output
4. Improve & tradeoff **accuracy & speed**
5. Extract **interpretable knowledge** for stability control
6. **Update** the model timely and effectively
7. Mitigate abnormal measurements, such as **missing data, communication delay**
8. Adapt the trained model to unforeseen scenarios, e.g., **unexpected fault, different topologies.**

1. **Y. Xu**, Z.Y. Dong, K. Meng, R. Zhang and K.P. Wong, "Real-time transient stability assessment model using extreme learning machine," *IET Gen. Trans. & Dist*., 2011.
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3. **Y. Xu**, Z.Y. Dong, Z. Xu, K. Meng, and K.P. Wong, "An intelligent dynamic security assessment framework for power systems with wind power," *IEEE Trans. Industrial Informatics*, 2012.
4. R. Zhang, **Y. Xu*,** Z.Y. Dong, and K.P. Wong, "Post-disturbance transient stability assessment of power systems by a self-adaptive intelligent system," *IET Gen. Trans. & Dist*., 2015.
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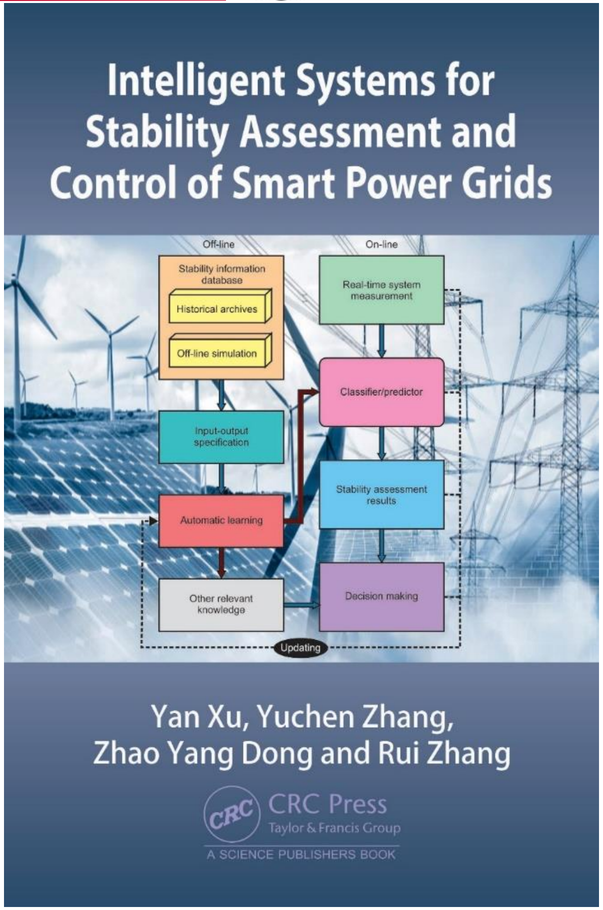
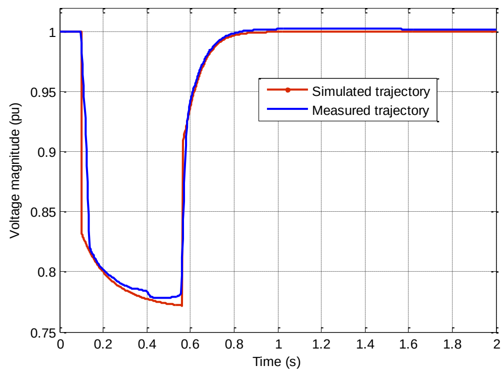
13. C. Ren, **Y. Xu***, Y. Zhang, and R. Zhang, "A Hybrid Randomized Learning System for Temporal-Adaptive Voltage Stability Assessment of Power Systems," *IEEE Trans. Industrial Informatics*, 2020.
14. C. Ren and **Y. Xu***, "Incremental Broad Learning for Real-Time Updating of Data-Driven Power System Dynamic Security Assessment Models," *IET Gen. Trans. & Dist.*, 2020.
15. C. Ren, **Y. Xu*,** and R. Zhang, "An Interpretable Deep Learning Method for Power System Dynamic Security Assessment via Tree Regularization," *IEEE Trans. Power Syst.*, 2021.
16. C. Ren, **Y. Xu*,** B. Dai, and R. Zhang, "An Integrated Transfer Learning Method for Power System Dynamic Security Assessment for Unlearned Faults with Missing Data," *IEEE Trans. Power Syst.*, 2021.
17. C. Ren, **Y. Xu*** "An Interpretable Deep Learning Method for Power System Dynamic Security Assessment via Tree Regularization," *IEEE Trans. Power Syst.*, 2022.

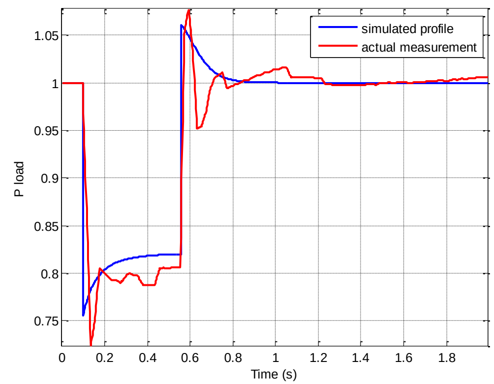


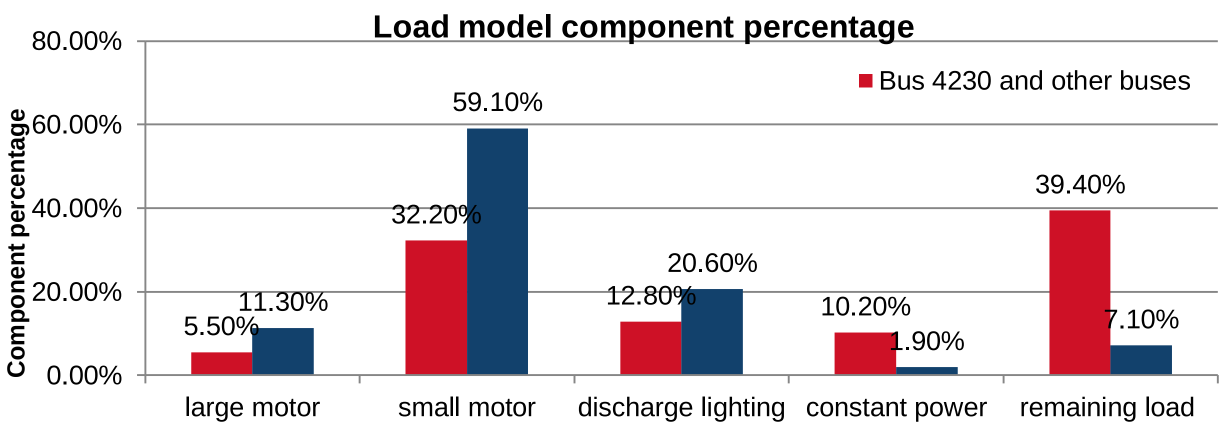
Y. Xu, Y. Zhang, Z.Y. Dong, and R. Zhang, "*Intelligent Systems for Stability Assessment and Control of Smart Power Grids*," CRC Press, 2020. ISBN-13: 978-1138063488

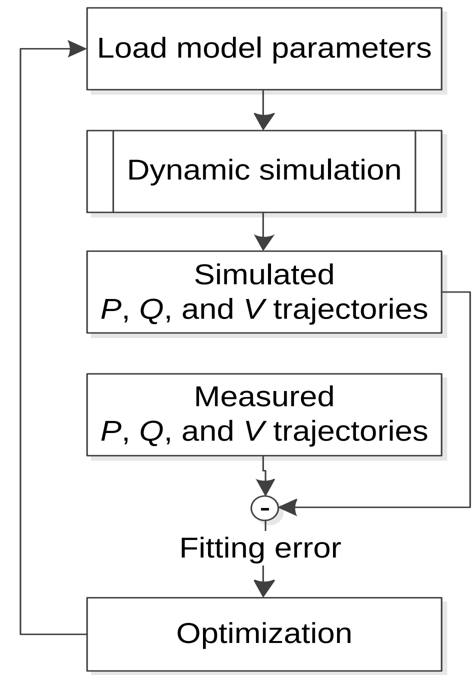
Eg: Load modelling and monitoring

Based on PowerQuality data, to derive dynamic load models and place STATCOM for voltage stability improvement – applied by Ausgrid (NSW’s DSO)









Y. Xu*, “Multi-objective dynamic VAR planning against short-term voltage instability using a decomposition-based evolutionary algorithm,” ***IEEE Trans. Power Systems***, 2014.

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Thank you!

Q&A

BIG
DATA
ANALYTICS
COMPLEX
STORAGE
INTERNET
MANAGEMENT
PETABYTES
SYSTEMS
SEARCH