EPFL

Smart Grid and
Its Requirements on Networking

Jean-Yves Le Boudec

EPFL I&C, Lausanne, Switzerland

Contents

1. What it the “Smart Grid” ?

Smart Grid = IT technology for operation and maintenance of an electrical grid.

Has been deployed in many countries for decades in several applications.

Example : substation automation

- Real-time + multicast communication, small scale (Local area network)

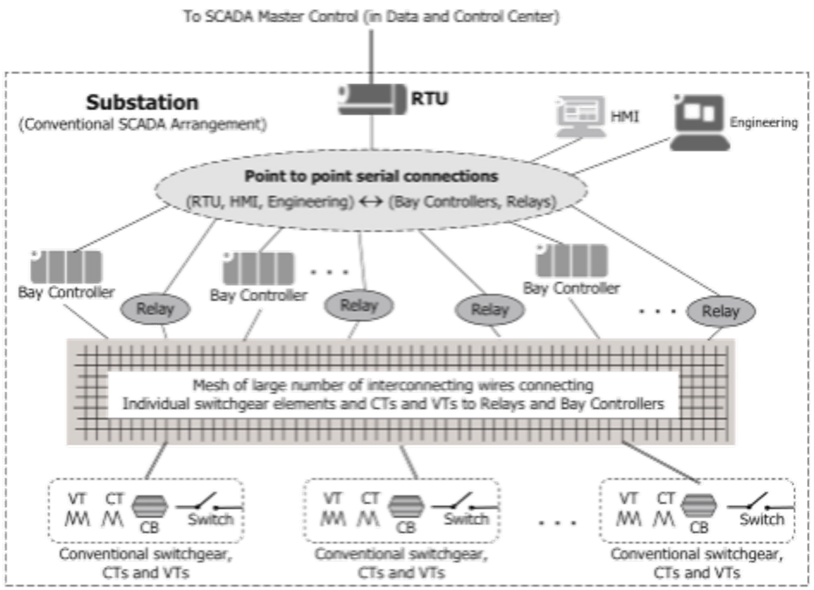


Figure from [Budka 2014]

Fig. 4.2 Traditional SCADA schematics

1. Circuit breaker trips a line, status info sent to SCADA
2. SCADA/operator decides to open or close a switch
3. Voltage and Current measurements sent to SCADA

Example: Teleprotection

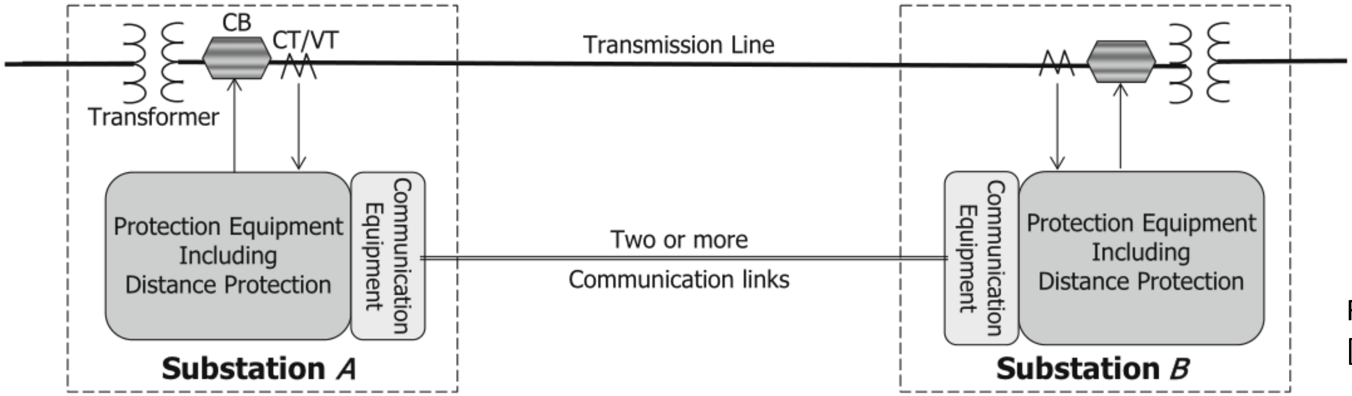


Fig. 4.6 Teleprotection configuration

Figure from
[Budka 2014]

Measurements at A and B can be used to infer fault conditions and quickly react (within 4 msec).

Existing systems use Power-Line Communication.

Example: Transmission Network

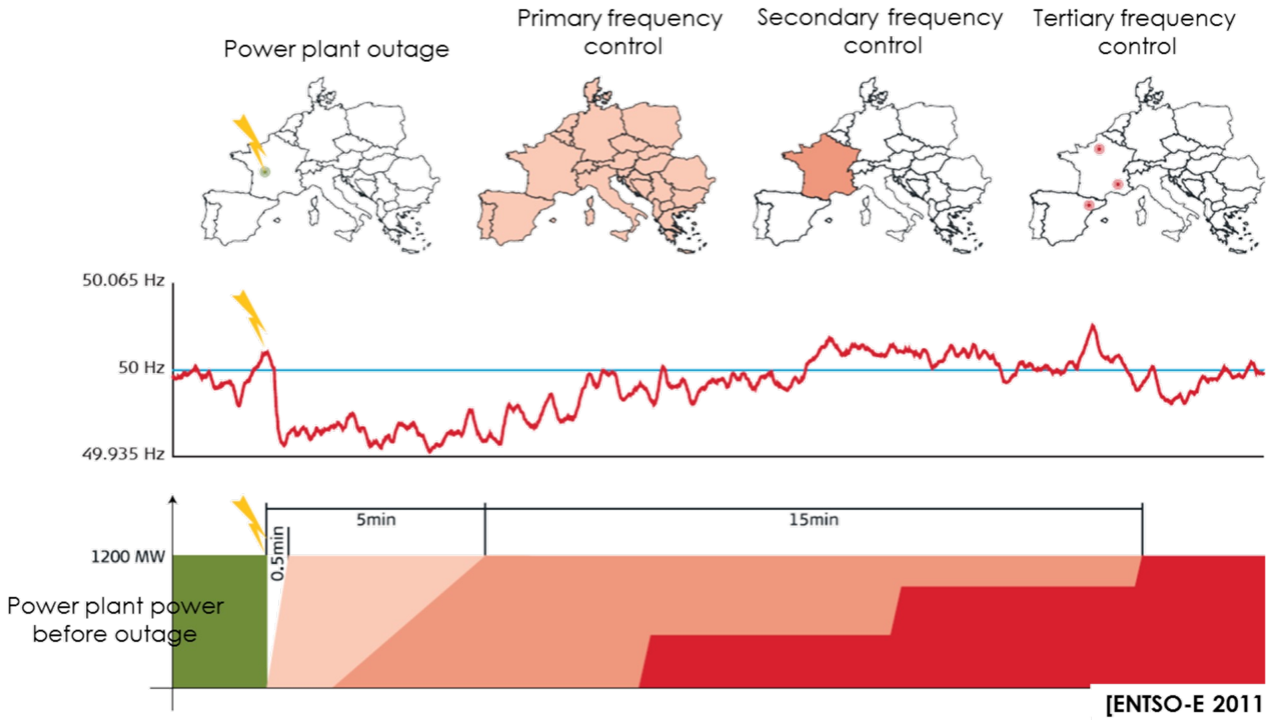
High Voltage AC grid / One per country or per region

Responsible for global operation / market

Monitors power flows and manages reserves

Data integrated in a decision support system

Reliable computing, not real-time



Smart Meters

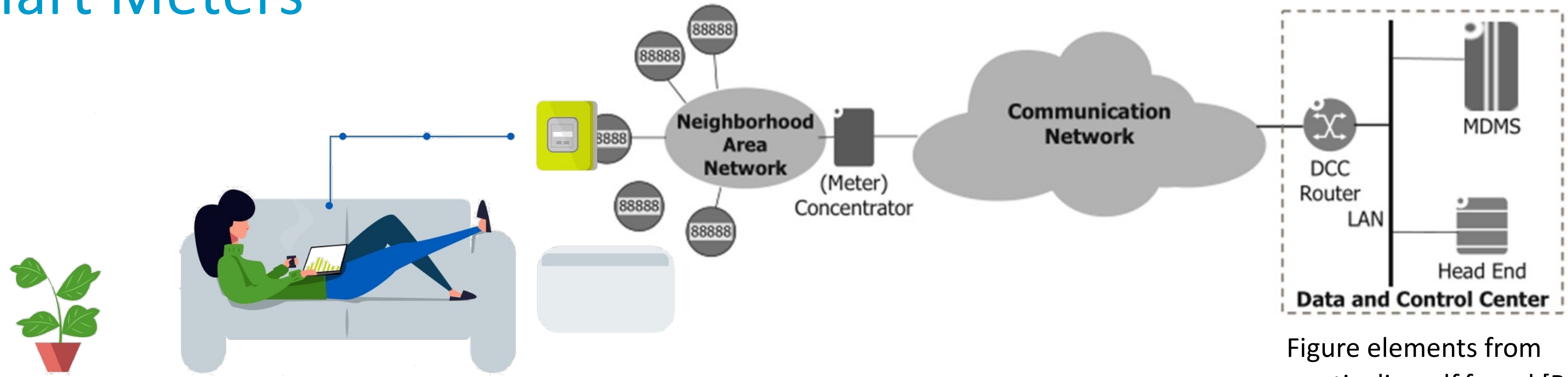


Figure elements from particulier.edf.fr and [Budka 2014]

Smart meters allows

- Online communication with Distribution System Operator (at low bit rate)
- Dynamic pricing (e.g every 15mn)

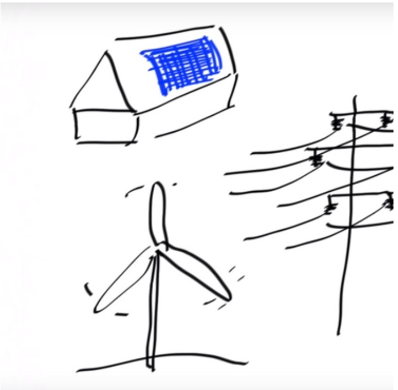
Deployment depends on country

Support new applications

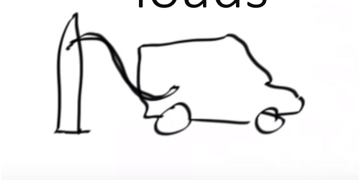
- Post failure recovery (e.g localisation of homes affected by storm)
- Demand response by price (e.g. reduce peak demand in winter days)

Emerging Challenges: Renewables + Electrification

Variability, uncertainty, reduced inertia of renewables

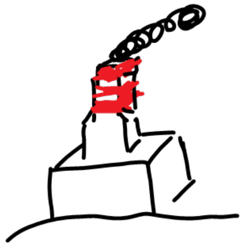


Large, stochastic loads



More reserves

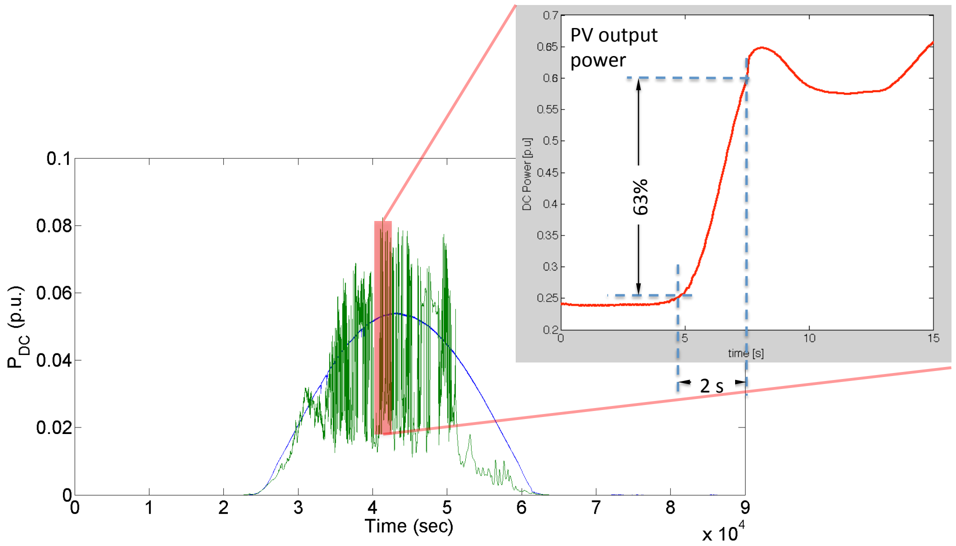
More fuel based generators for regulation



Demand Response

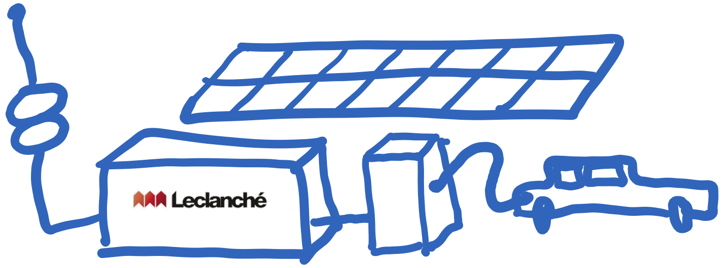
Emerging Challenges: Short-term Volatility of Renewables

Daily measured power injected by solar arrays at EPFL



Quality of service issues in distribution grids

Short-term volatility



Emerging Technology: Real-Time State Estimation

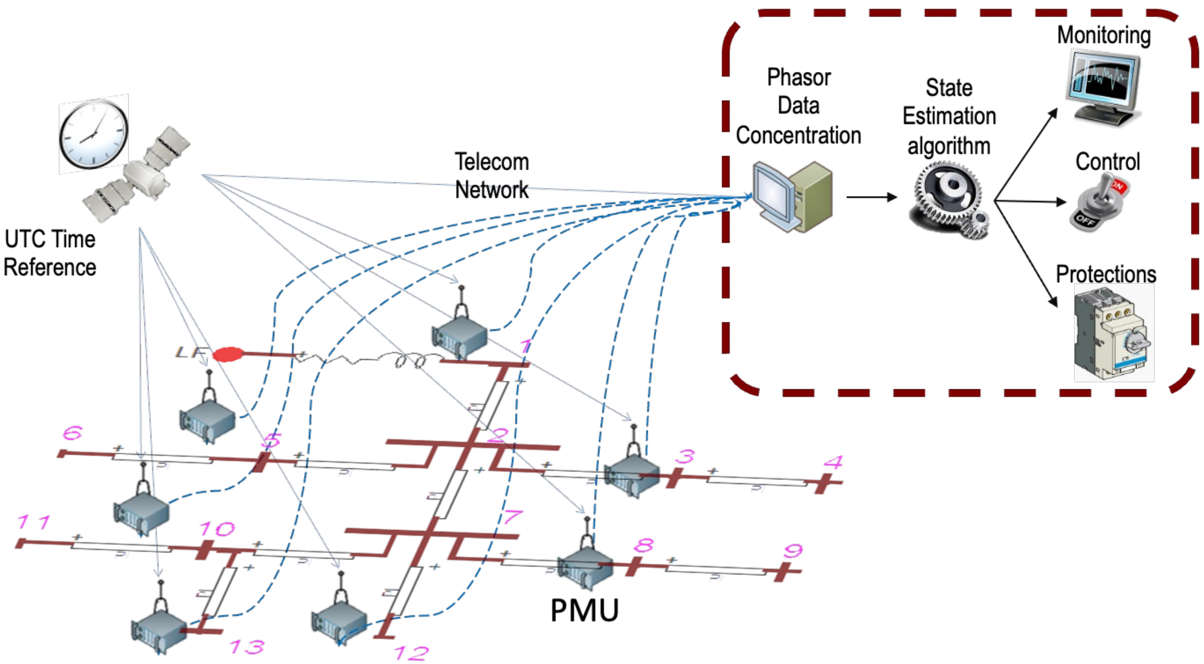
State estimation: computation of electrical state of a grid (instantaneous values of complex voltages and currents at all nodes).

Enabled by Phasor Measurement Units (PMUs), devices that produce synchronized measurements of phasors (every 16.7 or 20 msec).

Post-processed by State-Estimation Algorithms.

Requires reliable and real-time network + accurate time sync (below μsec).

[Pignati 2015]



Applications enabled by Real-Time State Estimation

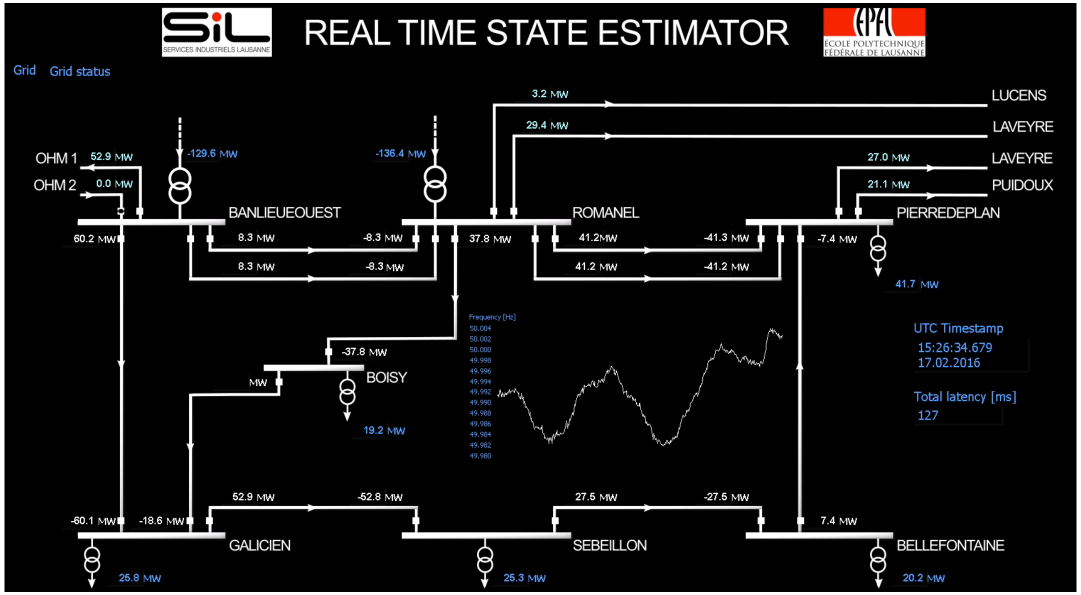
Real-time monitoring

Fault identification, isolation, localization

Control of voltage / currents

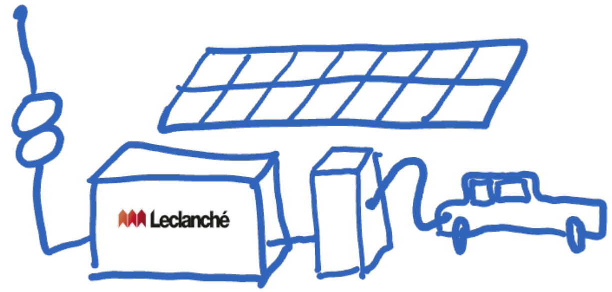
Islanding and back-synchronization

Real-time control of a distribution grid.



From [Zanni 2020]

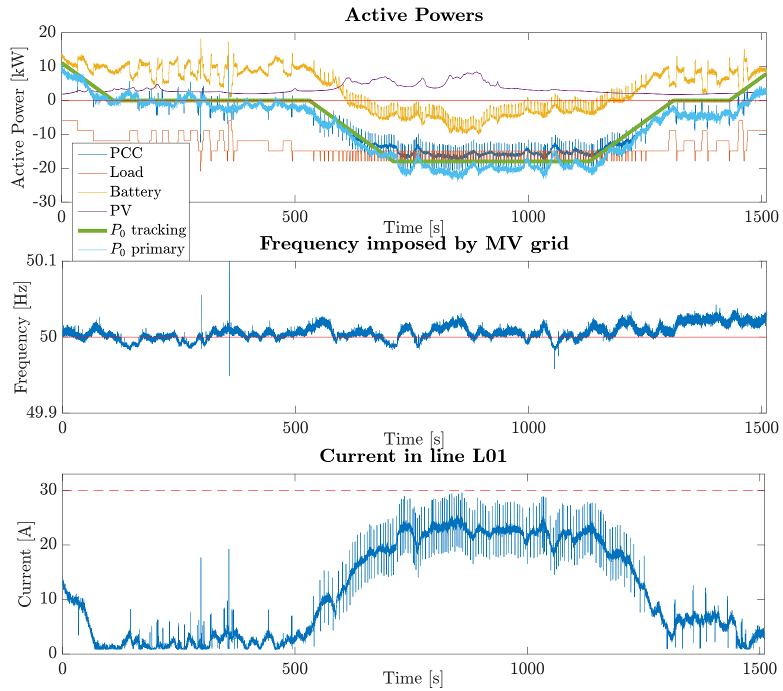
Example of Real-Time Control of Microgrid: Optimal Use of Grid



Controls power injections of battery, PVs and charging station of electric vehicles.

- Allows to use fluctuating PV production in full, by controlling all voltages and currents (no tripping when PVs fluctuate).
- Provides frequency support to main grid (artificial inertia).

Real-time, one control action every 100msec.



The Commelec system [Berstein 2015]

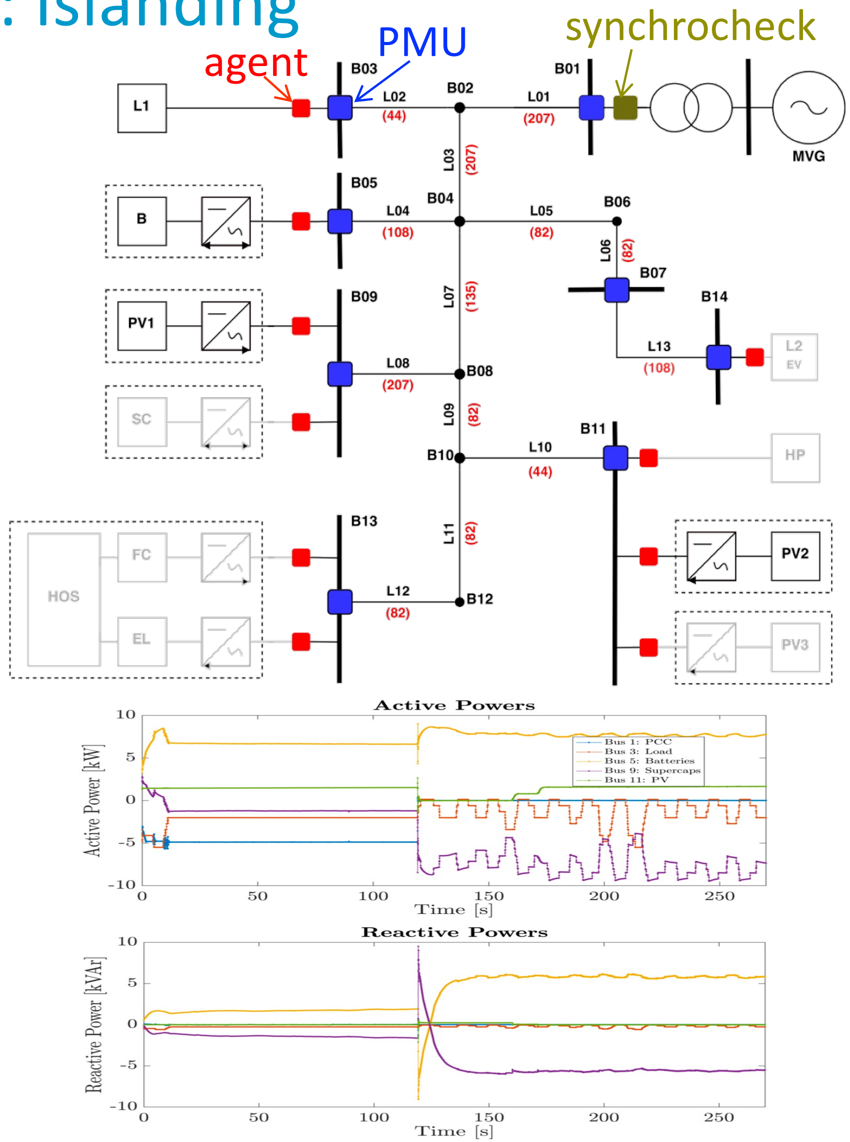
Example of Emerging Fast Control System: Islanding

Real-time microgrid control supports loss of connection to main grid (unintentional islanding) and re-connection (re-synchronization) without disruption.

- Unintentional islanding requires storage to be prepared.
- Resynchronization requires phasor of main grid and of local grid to be aligned.

Requires real-time communication (at msec latency) between agents, PMUs and synchrocheck device.

[Reyes 2018b, Fahmy 2022]



2. Requirements on Networking

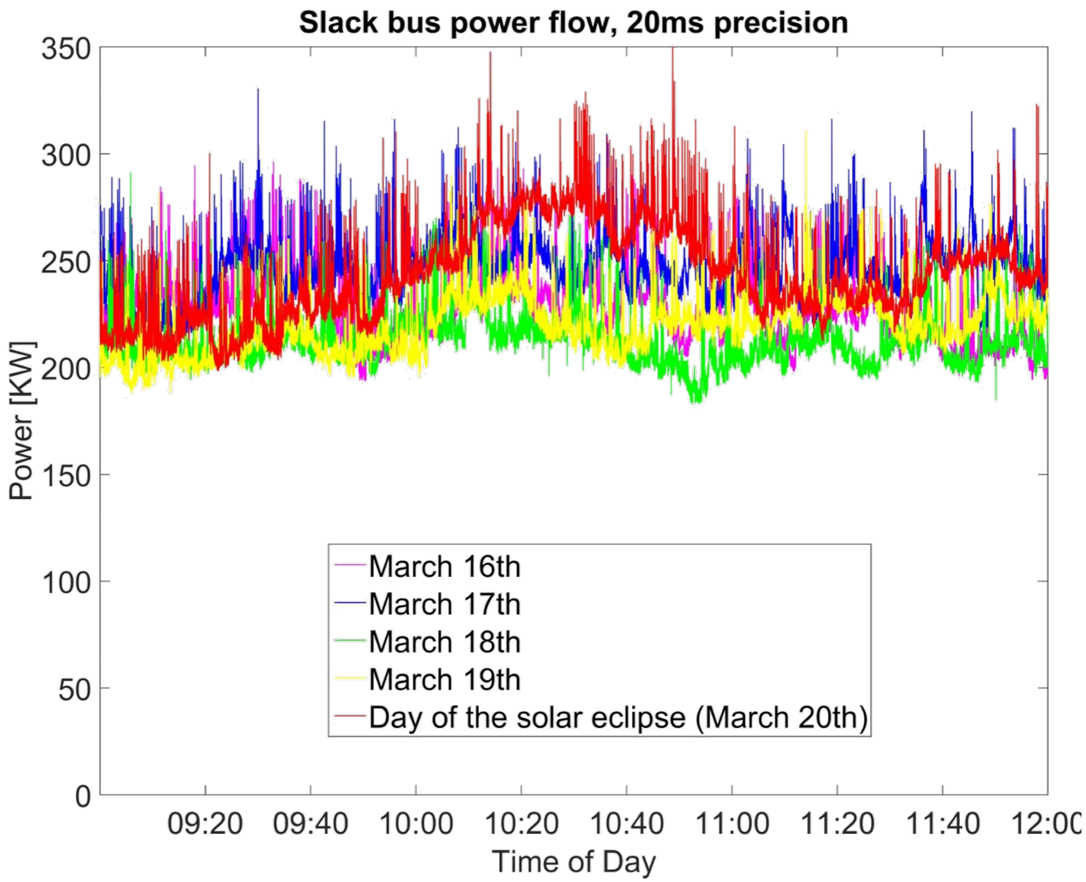
The smart grid is becoming increasingly digital (smart meters, PMUs)

Monitoring and control is increasingly based on digital means. It requires the same features as most enterprise networks

- Large data sets
- Cyber-security

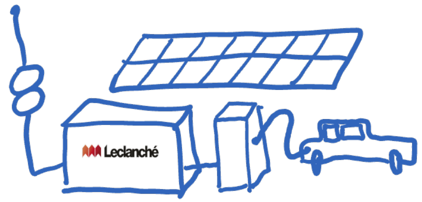
Plus some special features

- Some apps require low delay
- Large reliability
- Secure and accurate time sync

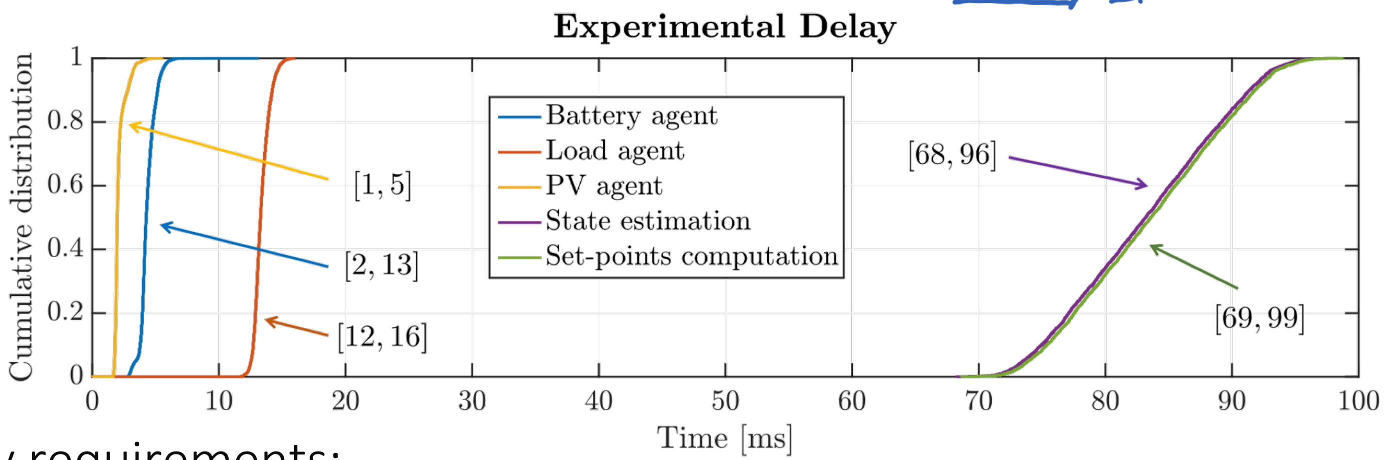


https://smartgrid.epfl.ch

Some Smart Grid Apps require Time Sensitive Networking



Most smart grid data does
 not require low delay
(e.g. dispatching,
energy measurements,
topology estimation etc.)



Some critical apps have low delay requirements:

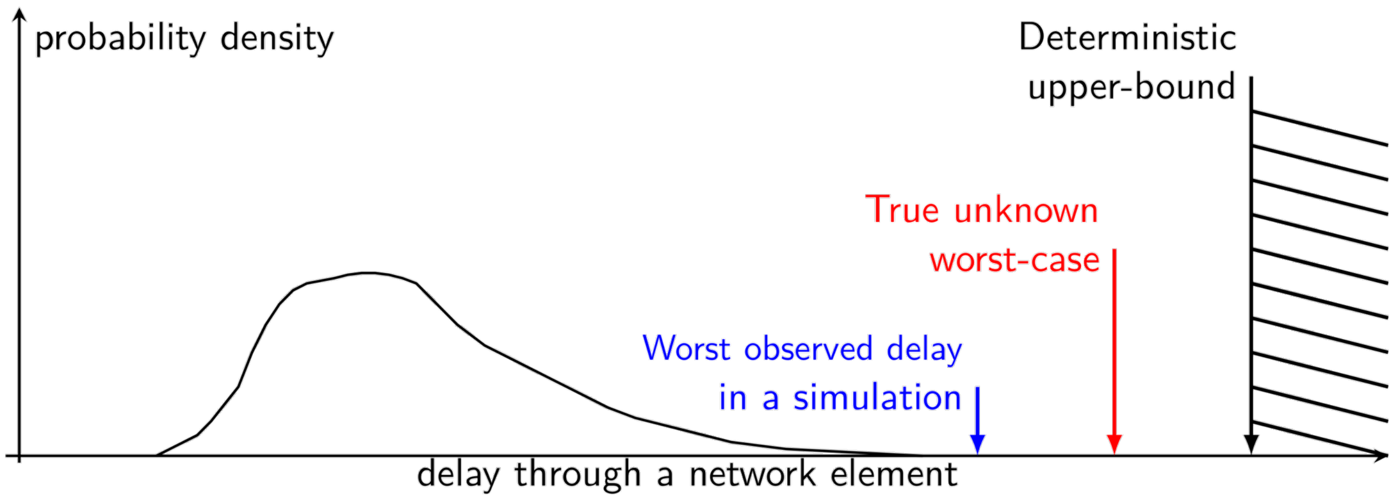
- teleprotection, state estimation, fault localization, real-time control

They are best served by Time Sensitive Networking

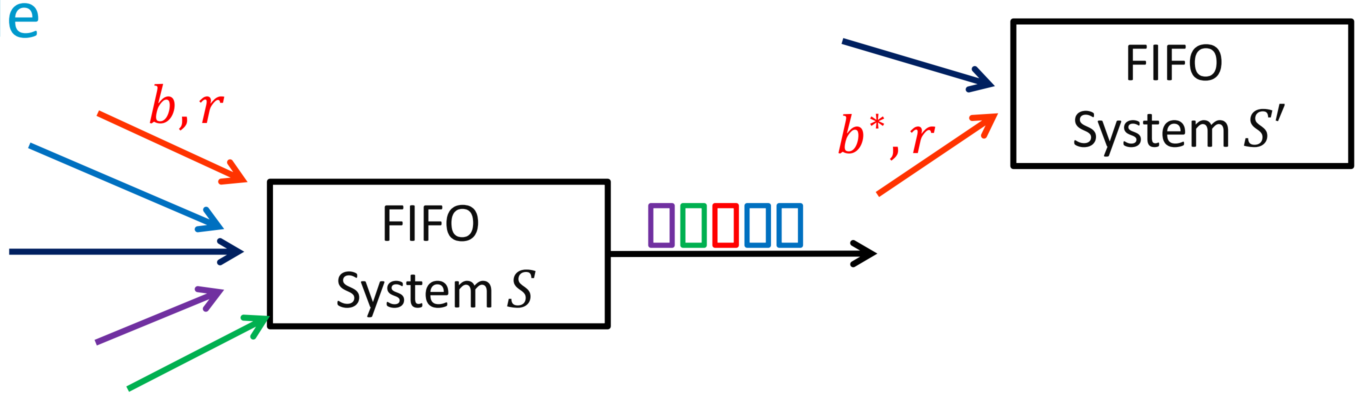
Time Sensitive Networking

IEEE TSN (local area network → substation, microgrid) and IETF Detnet (large scale networks → distribution networks). They provide:

- Buffer sizing for 0 congestion loss + guaranteed bounds on delay and jitter bound, obtained with Network Calculus : source constraints (e.g. token bucket) + service guarantee (service curves)
- 0 msec packet loss repair with packet duplication
- Time synchronization



Network Calculus Example



A set S of flows, each constrained by leaky bucket r_f, b_f are aggregated into one class;

$r_{tot} = \sum_{f \in S} r_f \, , b_{tot} = \sum_{f \in S} b_f$

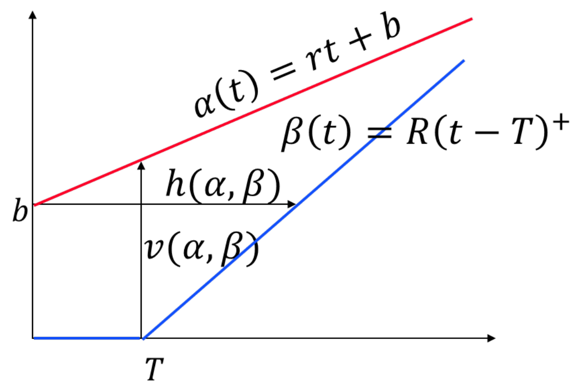
At one node, this class receives a rate-latency service curve R, T (e.g. Non pre-emptive static priority, DRR, AVB, CBS). FIFO inside the class; $r_{tot} \leq R$

delay jitter bound for any packet of any flow in S: $D = \frac{b_{tot}}{R} + T$

backlog bound for the aggregate of whole S: $B = b_{tot} + r_{tot} T$

output arrival curve for flow f is leaky bucket r_f, b_f^* with

$$b_f^* = b_f + r\left(T + \frac{b_{tot} - b_f}{R}\right) > b_f$$



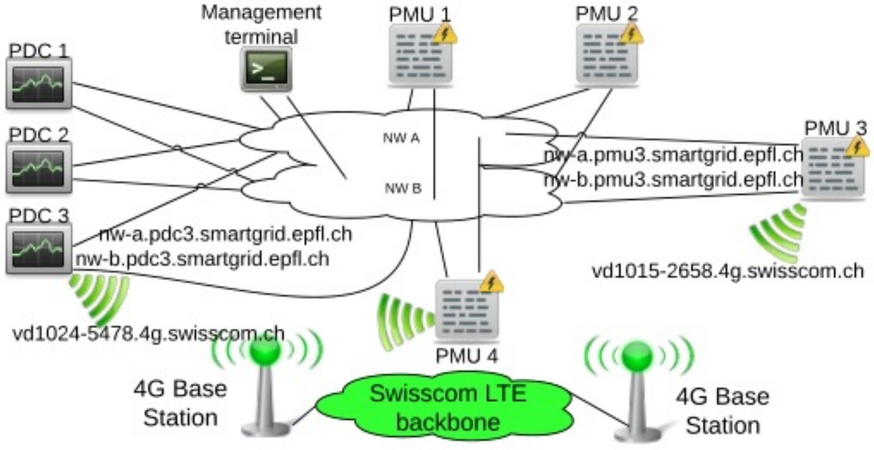
[Le Boudec-Thiran 2001, Section 6.4]

Better bounds are obtained using more detailed modelling [Mohammadpour 2018]

Packet Duplication: 0 msec repair.

At source (PRP, iPRP) : well deployed in substation automation, emerging in state estimation networks. Uses independent, replicated networks. Works with multicast.

[IEC 2013, Popovic 2016]



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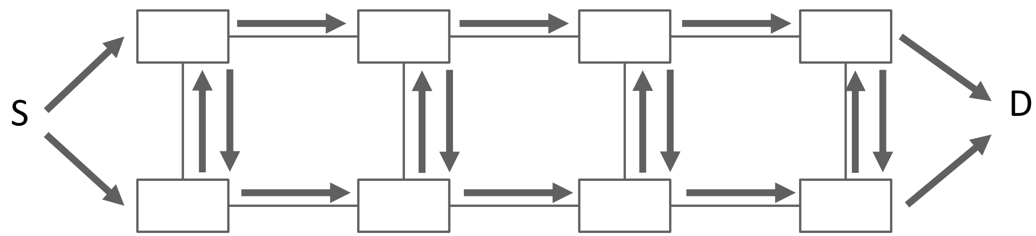
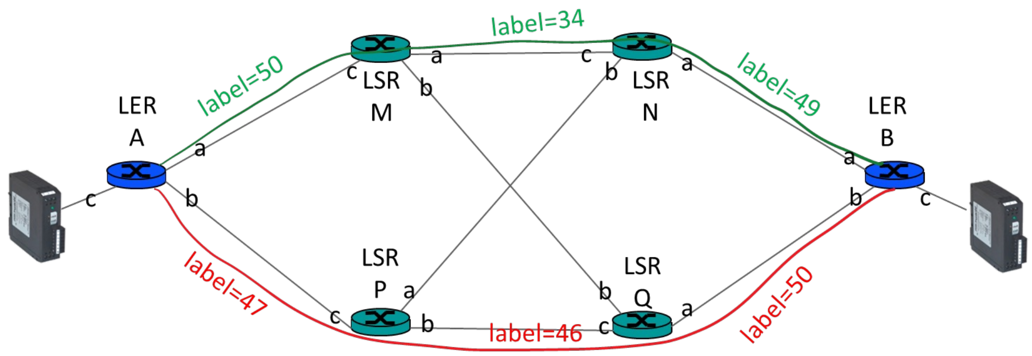
In-network (TSN: FRER, Detnet: PREOF): dramatically improves reliability:

[IEEE 802.1CB, Thomas 2022]



Fast Reroute: 50 msec repair.

Uses MPLS with redundant paths (e.g. one LSP is backup).



Failures are detected using a hello mechanism (BFD, Bidirectional Forwarding Detection sent every 3-4 msec and follow the same path as the data. When a path is broken, this is detected after the absence of 3 BFD packets.

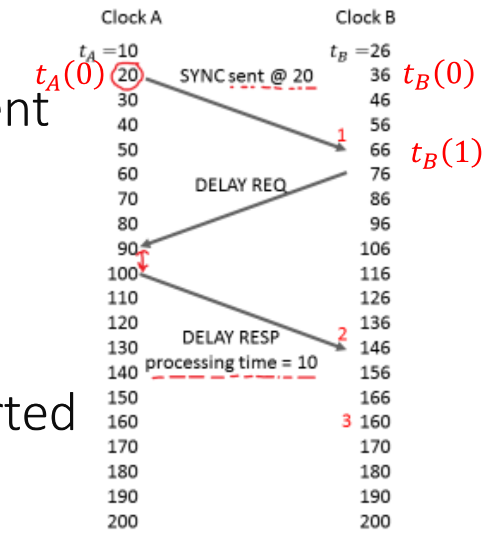
Time Synchronization

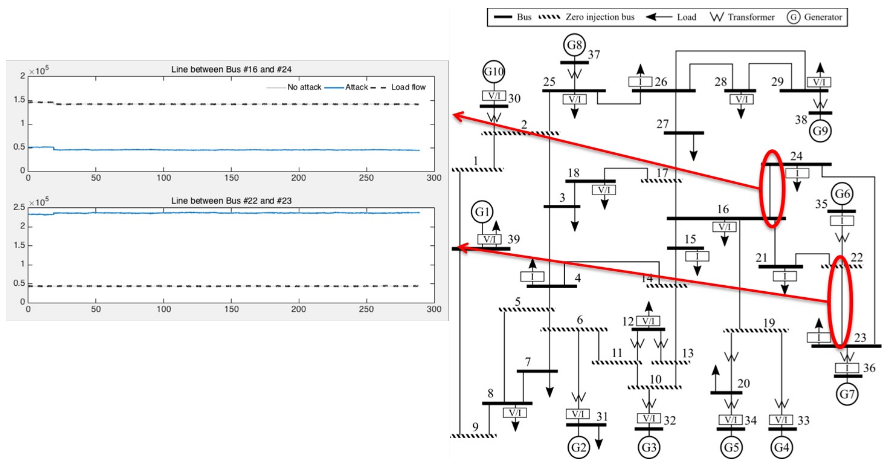
Used for state estimation (PTP, precision sub μsec) and for time alignment of monitoring (msec precision).

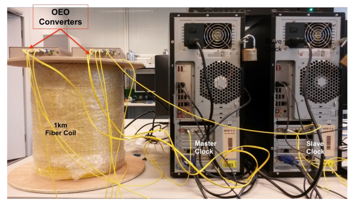
Can be attacked by forging messages (unless authenticated).

Fast multicast authentication (msec) is a requirement [Tesfay 2017].

Some physical attacks (manipulation of physical delays) cannot be thwarted with authentication. Can lead to wrong state estimation even if all messages are encrypted and authenticated.





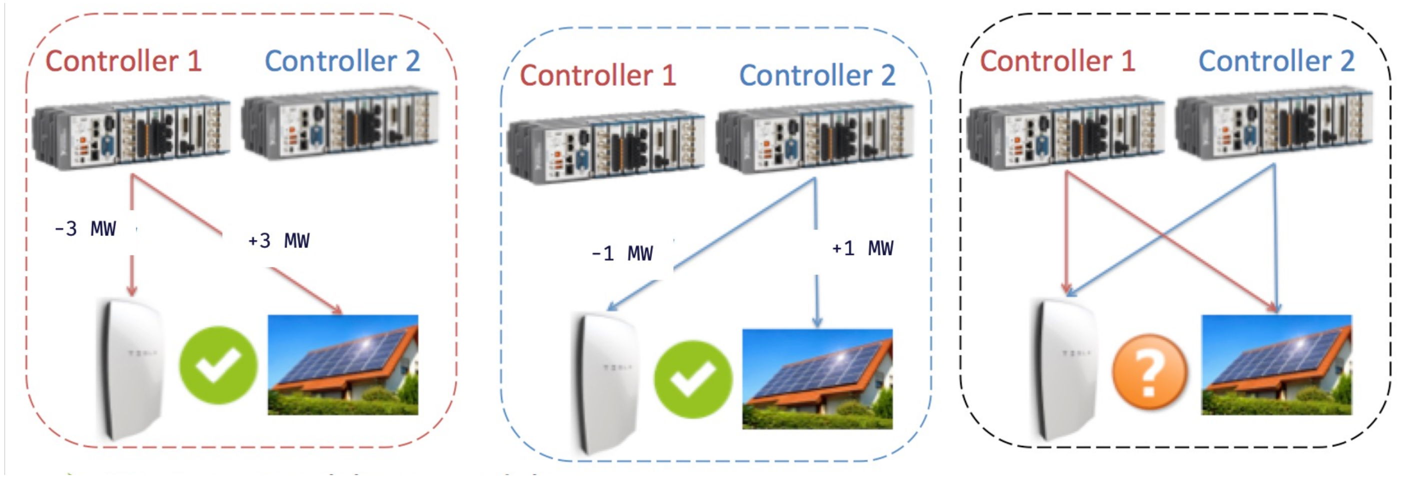


Undetectable delay box can forge PTP errors at will [Barreto 2016]. Modifies phasor angles and leads to wrong estimation [Shereen 2019].

Fog Computing

Beyond transport of packets, smart grids also need fault tolerant + real-time computing [Mohiuddin 2017].

Fog computing = cloud computing for real-time and fault-tolerant services promises cost-efficiency and reliability.



Conclusion

The smart grid emerges as a very large scale industrial system.

Depends heavily on computer networks, with all the needs of telecom networks + special features

- Real-time
- Multicast
- Power line communication
- Reliability and fault-tolerance
- Accurate and secure time synchronization

It is also a critical infrastructure and of primary importance is security.

It also relies on large data streams and needs large data processing.

Thank You !

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