Enhancement to SCADA/EMS for hybrid AC/DC networks

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INNOVATIVE TOOLS FOR OFFSHORE WIND AND DC GRIDS

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Communication Requirements for HVDC/AC Transmission Networks State Estimation

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Modern SCADAs in power systems

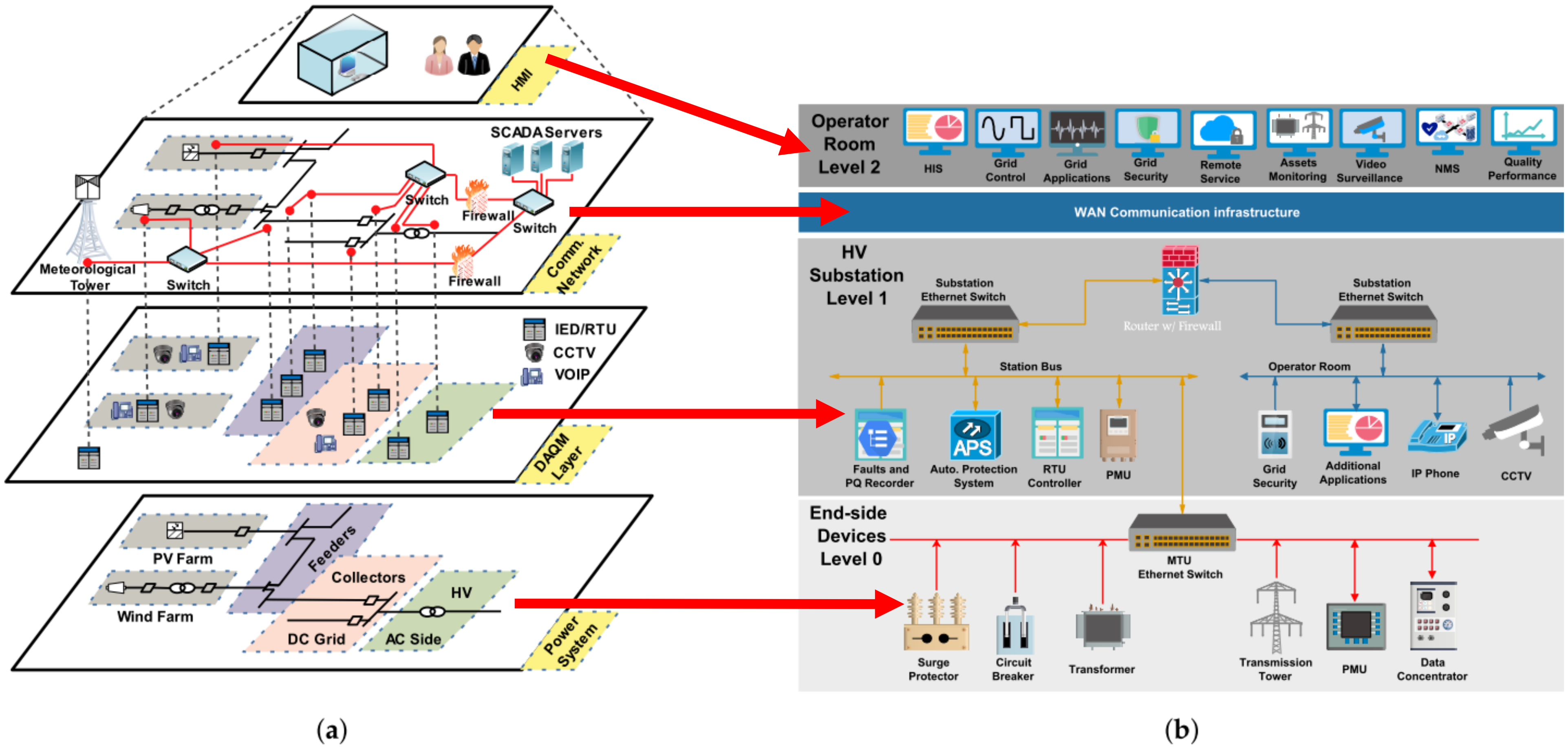


Figure 1. The layers of transmission systems SCADA. (**a**) The four layers of a power system SCADA. (**b**) SCADA in HV Transmission Network.

Modern SCADAs Challenge due to HVDC

The main challenge: new timescale requirements for the modern SCADA communication network due to the intensive integration of low-carbon technologies.

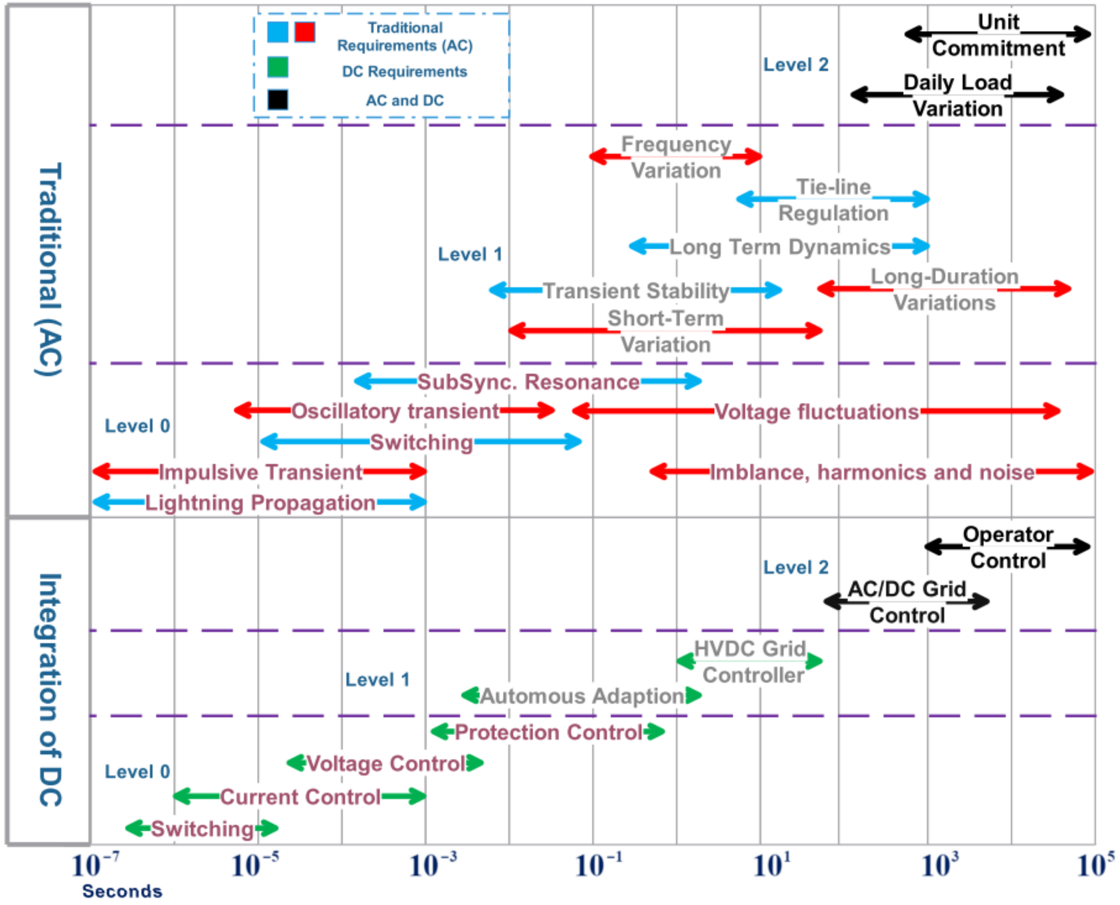


Figure 2. Different operation/control timescales in an AC/DC power system.

SCADA Components and Structure

Remote and Master Terminal Units

Communication Infrastructure

Operator Room

SCADA Components and Structure

Remote and Master Terminal Units

Communication Infrastructure

Operator Room

- Generations:
1. Monolithic (1st Generation)
2. Distributed (2nd Generation)
3. Networked (3rd Generation)
4. Internet of Things (IoT) (4th Generation)

- Mediums:
1. Fiber Optic cables
2. Power Line Carrier communication (a/d)
3. Satellites
4. Microwave Radio
5. Omnidirectional Wireless/Cellular

- Protocols:

Modbus	DNP3	IEC 60870-5 (101-104)	IEC 60870-6	**IEC 61850**
Profibus	HART	Modbus+	DH-485 & DH+	Fieldbus

HV AC/DC SCADA

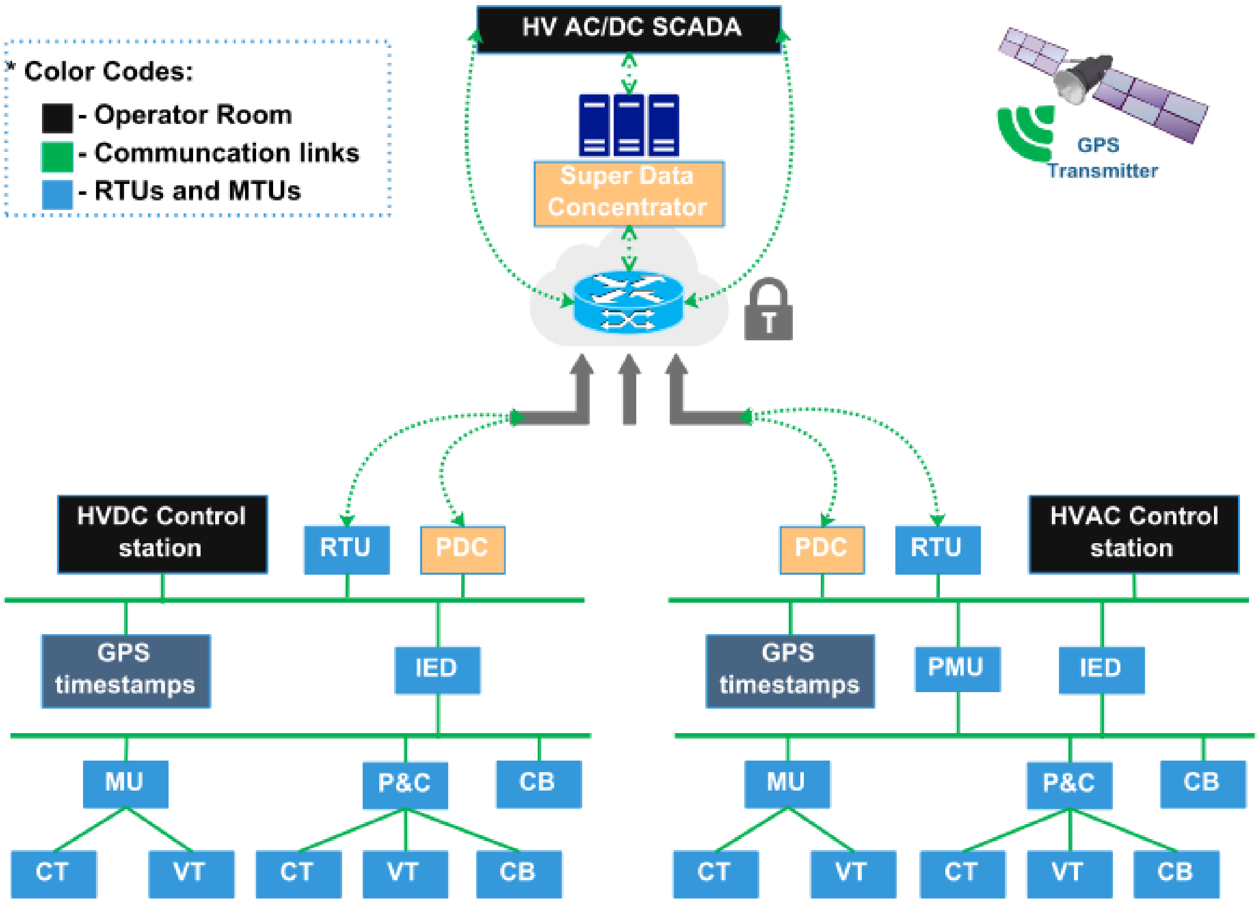


Figure 6. HV AC/DC SCADA: Structure from top to bottom.

RTUs Requirements for HVDC/AC

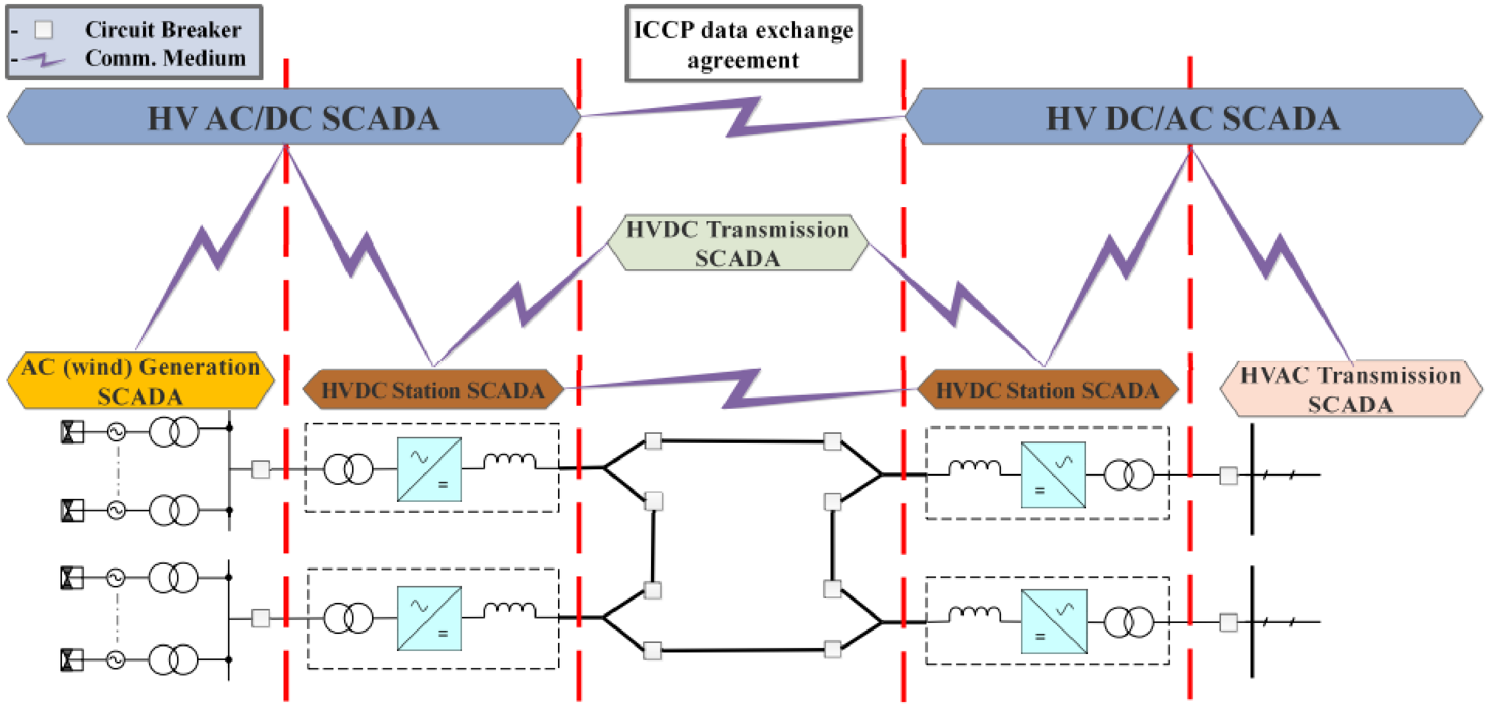
Table 2. AC and DC RTUs characteristics and measurements.

	Characteristics	Measurements
AC	I/O: −8 digital input and 8 to 32 analog input with 16–24 bits A/D resolution and sampling frequency of 4 or 8 kHz for a 50 Hz system [57]. −16 to 264 digital output for large scale protection RTU [58].	Voltages, Currents. Active and reactive power/energy. Power factor. Frequency, rate of change of frequency (ROCOF), total vector error (TVE) and the frequency error (FE) [19]. Digital inputs (e.g., CB).
	IEC 61131-3 based or FPGA processor	
	Transfer rate: 64 Kbps to 2 Mbps	
	Time-Synchronization based on global navigation satellite system or GPS. The standard acceptable error is in range of ±500 nanoseconds [19].	
	Reporting rate based on IEC/IEEE 60255-118-1 are {10, 25, 50, 100} frame per second (fps) for 50 Hz system, and {10, 12, 15, 20, 30, 60, 120} fps for 60 Hz [19].	
DC	I/O: −32 analog input with 24 bits A/D resolution. −16 to 264 digital output for large scale protection RTU (ABB [8] Open Source [29]).	Voltages, Currents. Real power/energy. Digital inputs (e.g., CB).
	Sensors with Very high sampling frequency (in range of 100 kHz) [57,59–63] due to the voltage fluctuations (approx. 1.6% per minute [13])	
	Sensing time interval is within 30 ms. Transmitting time interval between RTU and MTU is within 10 ms [24].	

Communication Requirements for HVDC/AC

Inter-Control Center Communications Protocol ICCP

There is a need for an ICCP agreement to enable data exchange between the different AC and DC network operators.



Time Requirements for HVDC/AC

Recent publications have estimated these time ranges based on similar standards or experiments as shown in Table 5 and 6.

Table 5. Communication timing for wide area power network under IEC 61850 standard.

Protocol	Message Application	Delay Tolerance (ms)
GOOSE	Fast trips Fast commands/messages Measurements/Parameters	3–10 20–100 100–500
SMV	Raw data	3–10
TS	Station bus Process bus	1 0.004–0.025
(Reset)	File Transfer Low–Medium speed	≥1000 100–500

Table 6. Data exchange timescale & size requirements (AC based on IEEE P1646 vs. DC).

Data Type	AC Substations (S)		DC Substations (S)		Data Size [7]
Information	Within S_i (ms)	Between S_i and S_j (ms)	Within S_i (ms)	Between S_i and S_j (ms)	Range
Error Time Synchronization	<0.1 [52], <2 [19]	-	<0.020 [10]	<1000 [10]	Bytes
Protection	5/4 for 50/60 Hz (1/4 cycle)	8–12, 5–10 [28]	0.1–0.5 [62,69]	3–4 [62,69]	10 s of Bytes
Monitoring and control	16	1000	10 [70]	250–500 [70,71]	10 s of Bytes
Operation and Maintenance	1000	10k	1000	10k	100 s of Bytes
Text Data	2000	10k	2000	10k	KB to MB
Files	10k–60k	30k–600k	10k–60k	30k–600k	KB to MB
Data Streams	1000	1000	1000	1000	KB to MB

Case Study: HVDC/AC State Estimation Cycle Time

The case study aims to find the total elapsed time for an HVDC/AC state estimation cycle (from sensors to SCADA).

$$t_{total} = \underbrace{t_{RTU}}_{\text{Sensors to RTUs}} + \overbrace{t_{DataCon}}^{\text{RTUs to DataCon.}} + \underbrace{t_{Comm}}_{\text{DataCon. to SCADA}} + \overbrace{t_{SE}}^{\text{SE processing time}}.$$

Case Study: HVDC/AC State Estimation Cycle Time

The Cigre B4 network, RTUs, Data concentrators, and SCADA are shown in Figure 8.

43 virtual RTUs are installed in different locations.

These RTUs are collecting data from power lines, converters, and generators and transmit them to 10 data concentrators, which are connected to a centralized SCADA.

The communication medium of the entire network is optical-based - Fiber Optic.

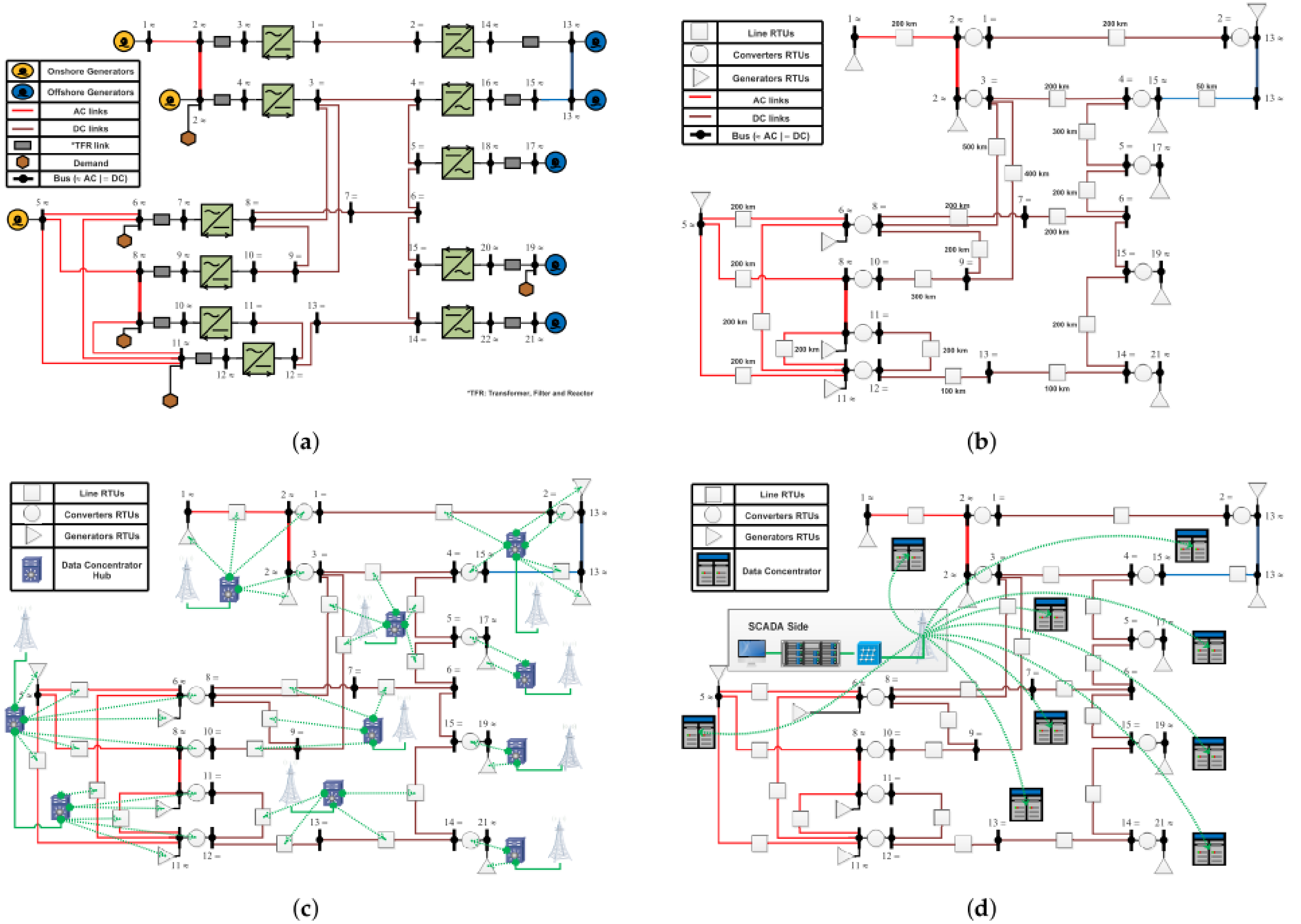


Figure 8. Multi-HVDC/AC transmission systems based on Cigre B4 network test case. (**a**) The Original Network. (**b**) The RTUs distribution. (**c**) The RTUs and data concentrators distribution. (**d**) The SCADA and data concentrators distribution.

Case Study: The 1st Layer, From Sensors to RTUs

A simulation test case is implemented on OptiSPICE. An electrical-optical sensor is implemented that converts the sensor’s 32 bits generated @ 100 Mbit/s into laser beams.

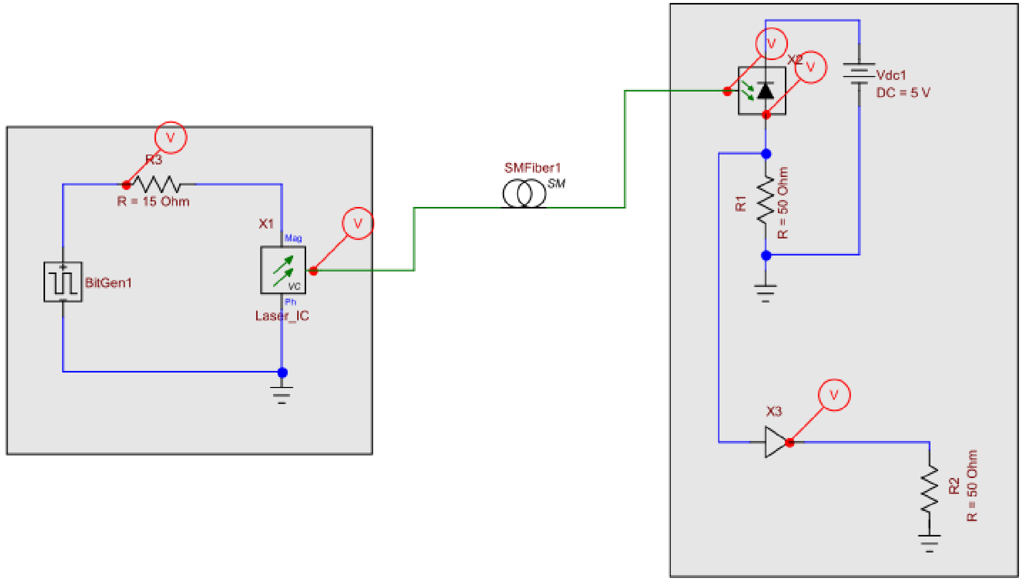


Figure 10. OptiSpice schematic for an optical sensor.

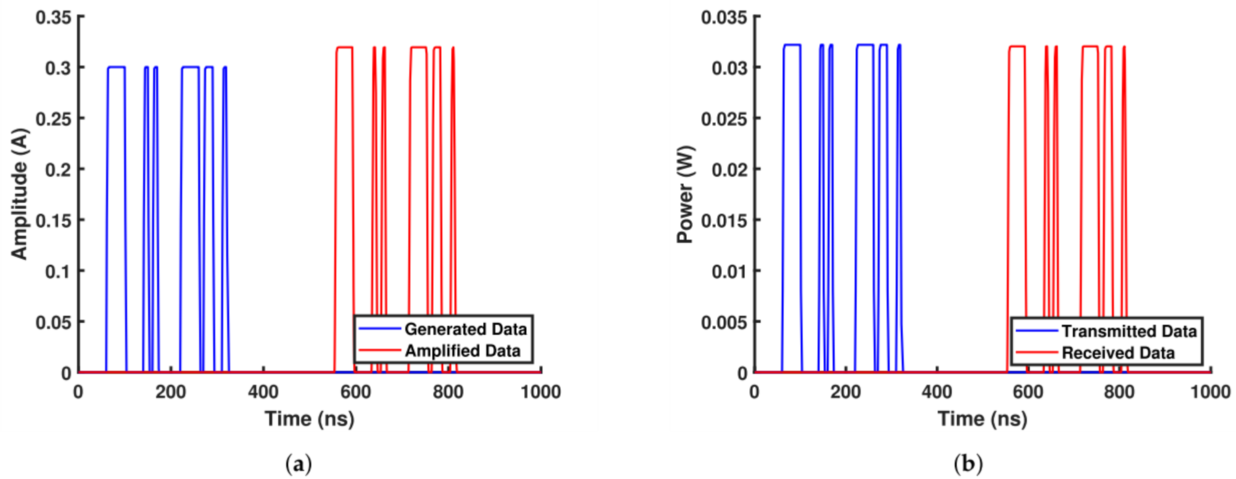


Figure 11. The total time elapsed in sending 32 bits to the input port of the RTU. (**a**) 32 generated bits vs the received amplified data. (**b**) Propagation delay in the fiber cable.

Case Study: The 1st Layer, From Sensors to RTUs

Table 7. Time delays from 32-bits sensors to RTU.

Time Delay Type	Theoretical (ns)	Simulation (ns)
Propagation	489.66	491.959
Transmission	306	326.6521
Amplification	-	0.0258
Total	795.66	818.6111

The data arrived at the receiver side after 818.611 ns.

An additional constant guard time delay (by the optical fiber transponders) is added per sensor.

$$t_{RTU} = T_s + N \times T_g$$

20 ns is commonly used

The sensing time delay for 4 sensors is: **818.611 + 4 × 20 ≈ 0.9 µs**.

Case Study: The 2nd Layer, RTU to Data Concentrator

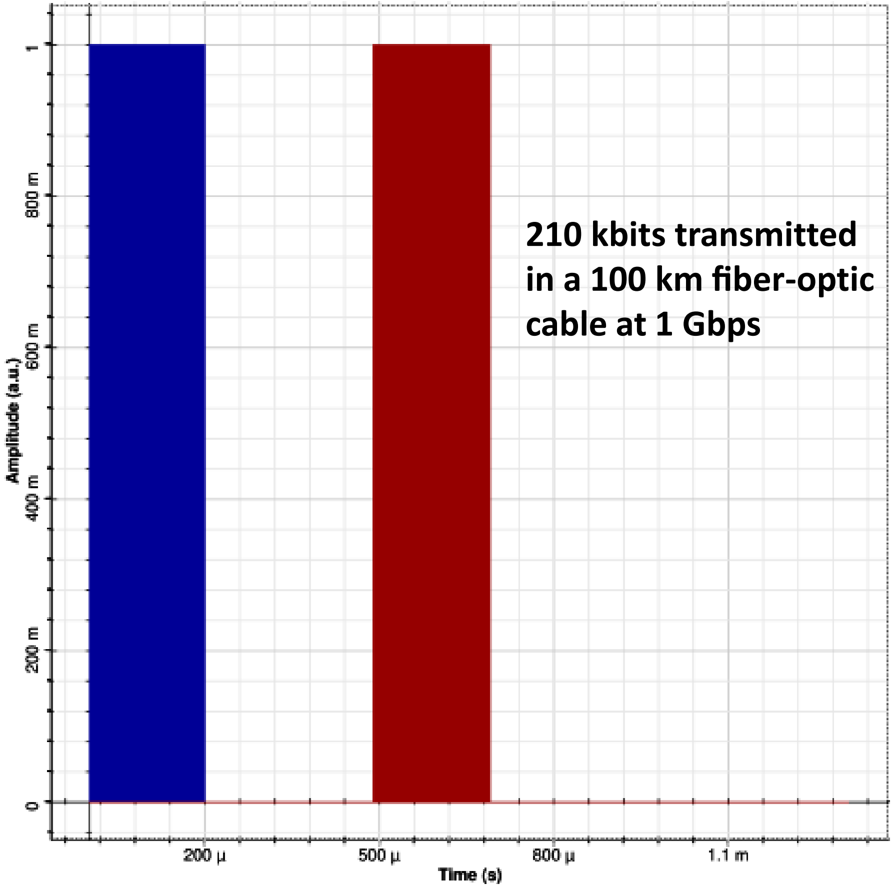
The data from the sensors to the RTU are aggregated and transferred to the data concentrators.

Table 9. Transmission delays per RTU type.

RTU Location/Type	Generated Data	Theoretical (ms)	Simulated (ms)
Line	0.623 MB	0.004867	0.005226
Converter	1.574 MB	0.012296	0.01320355
Generator (50 Hz)	1.027 MB	0.008023	0.008615

Table 10. Propagation delays based on fiber cable length.

Distance (km)	Theor. (ms)	Simu. (ms)	Distance (km)	Theor. (ms)	Simu. (ms)
50	0.244834	0.24483625	250	1.224170	1.2241813
100	0.489668	0.4896725	300	1.469004	1.4690175
150	0.734502	0.73450875	350	1.713838	1.7138538
200	0.979336	0.979345	400	1.958672	1.958690



Case Study: The 2nd Layer, RTU to Data Concentrator

The IEC 61850 protocol delays are estimated from previous studies. The maximum value is used in this work (37.4 μs per RTU).

Table 12 shows the communication delays for a P2P architecture from the RTUs to each data concentrator.

Table 12. P2P total delays: Data concentrators and its corresponding RTUs (in ms).

Type	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Prop.	2.44836	3.23183	0.004896	0.004896	0.004896	4.57843	1.95869	2.44836	4.01531	4.45602
Tran.	0.0485	0.05337	0.02181	0.02181	0.02181	0.02433	0.01946	0.01946	0.05337	0.11161
Prot.	0.187	0.2244	0.0748	0.0748	0.0748	0.187	0.1496	0.1496	0.2244	0.2992

As a result:

P2P	4.86683 ms
Muxponders	2.130885 ms

Case Study: The 3rd Layer, DataCon. to SCADA

Table 13. Transmission delays per data concentrator.

Data Conc. #	Generated Data	Theoretical (ms)	Simulated (ms)
#1	5.825 MB	0.045507	0.048863
#2	6.448 MB	0.050375	0.054089
#3	2.601 MB	0.02032	0.021818
#4	2.601 MB	0.02032	0.021818
#5	2.601 MB	0.02032	0.021818
#6	3.115 MB	0.024336	0.0261302
#7	2.492 MB	0.019468	0.020904
#8	2.492 MB	0.019468	0.020904
#10	13.519 MB	0.105617	0.1134045

The protocol delay is estimated to be 0.3366 ms.

Table 14. P2P total delays: Data concentrators to the SCADA (in ms).

Type	D1	D2	D3	D4	D5	D6	D7	D8	D10
Prop.	1.22418	1.46901	1.07728	0.97934	1.95869	0.97934	1.46901	1.71385	1.22418

As a result:

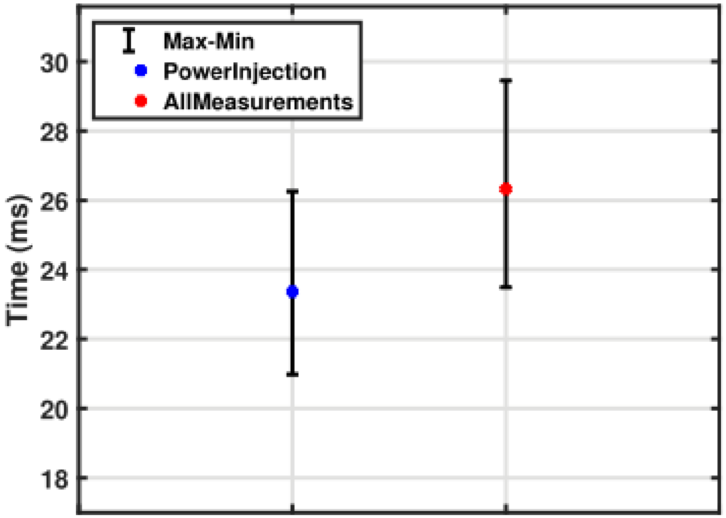
P2P	12.83535 ms
Muxponders	10.11 ms

Case Study: The 4th Layer, State Estimation Processing Time

The 4th Layer: State Estimation Processing Time

Let t_{SE-AC} and t_{SE-DC} represent the processing time of an AC and DC networks state estimation.

However, in a unified centralized approach further measurements are added. Therefore:



$$t_{SE} = t_{\text{unified}} \gg t_{P_{\text{coupling}}} > t_{V_{\text{coupling}}} > max(t_{SE-AC}, t_{SE-DC}).$$

Table 15. Time delays (t_{SE}) of unified WLS state estimation.

Data Set	Measurements Count	Elapsed Time (ms)
Power-injection only	89	23.3709
Powerflow and Injection	140	26.3246

Figure 15. The time performance of two sets of measurements in a unified state estimation.

Case Study: Outcomes and Results

The total delays of a state estimation cycle from the sensors up to the SCADA based on a fiber-optic communication network are as follow:

In a P2P architecture:

$$t_{\text{total}} = 0.0009 + 4.8669 + 12.8354 + 26.3246 = \boxed{44.0278\,\text{ms}}$$

In server-based network (muxponders) :

$$t_{\text{total}} = 0.0009 + 2.1309 + 10.1100 + 26.3246 = \boxed{38.5664\,\text{ms}}$$

A noticeable outcome:

- The dynamic state estimation can be implemented at the local level since the accumulated delays are in few milliseconds.

For further details

Ayiad, M.; Maggioli, E.; Leite, H.; Martins, H. Communication Requirements for a Hybrid VSC Based HVDC/AC Transmission Networks State Estimation. *Energies* **2021**, *14*, 1087.

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Enhancement to SCADA/EMS for hybrid AC/DC networks

Unified state estimation of HVDC/AC transmission networks: GMM and BD

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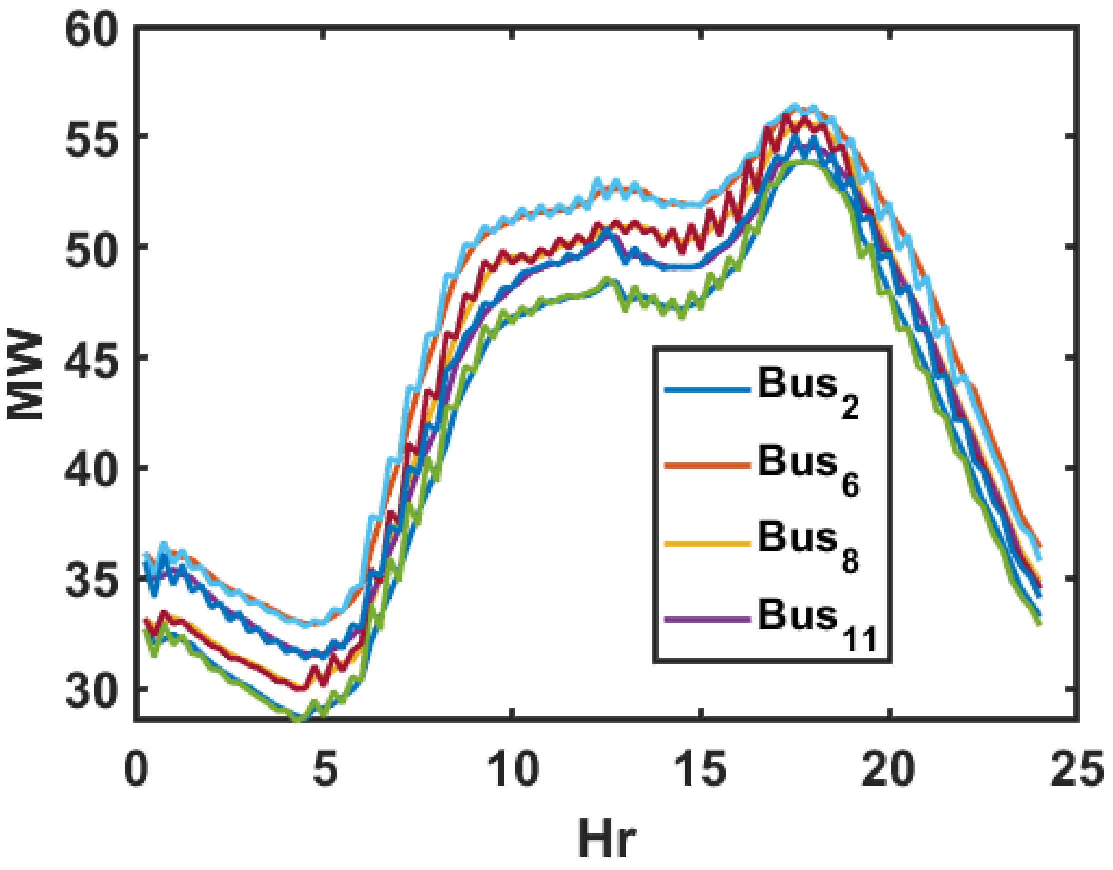
Current work – GMM and BD

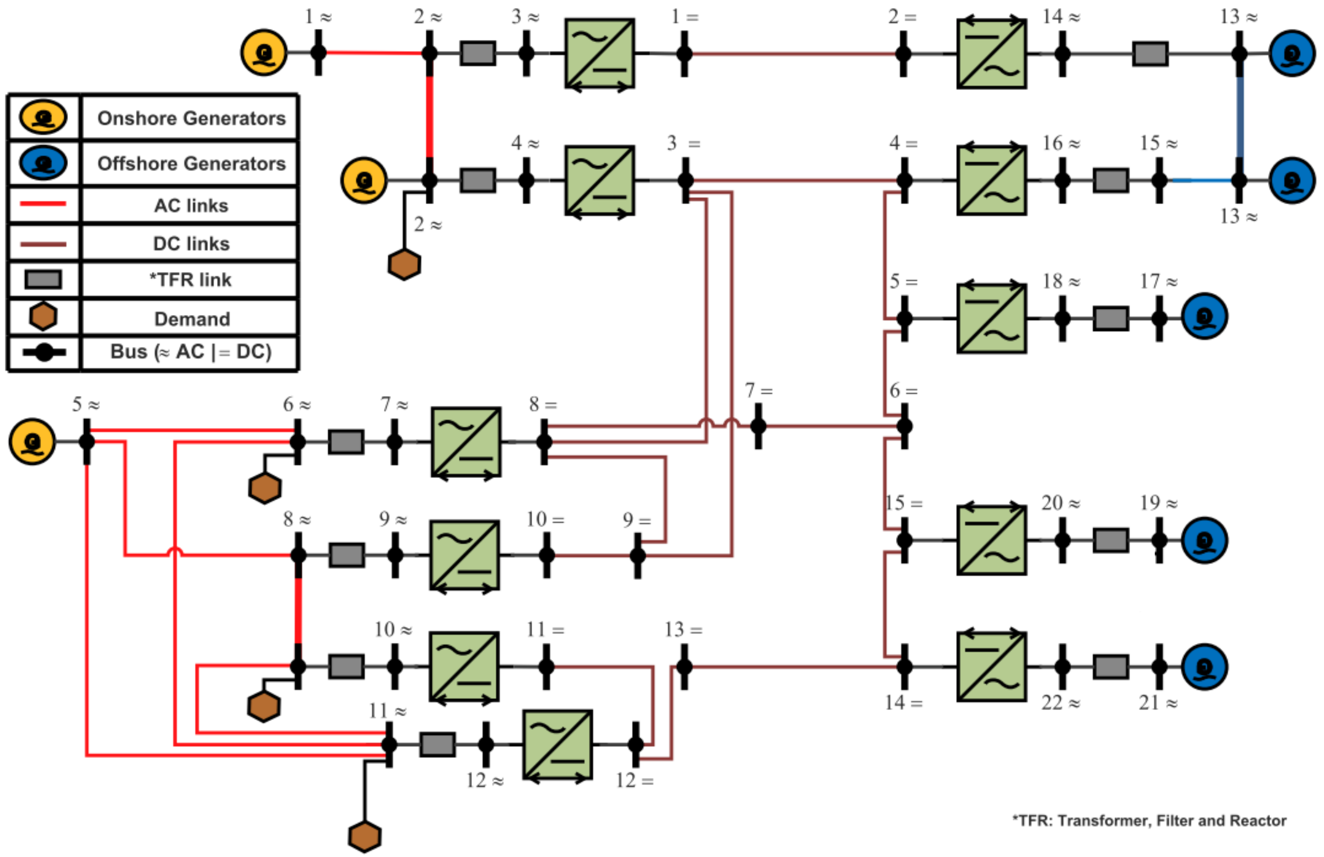
Integrating statistical method (GMM) in state estimation to improve the WLS weights and Bad data detection.

GMM models the load and generation profiles from historical data (UK Nationalgrid Jan. 2021).

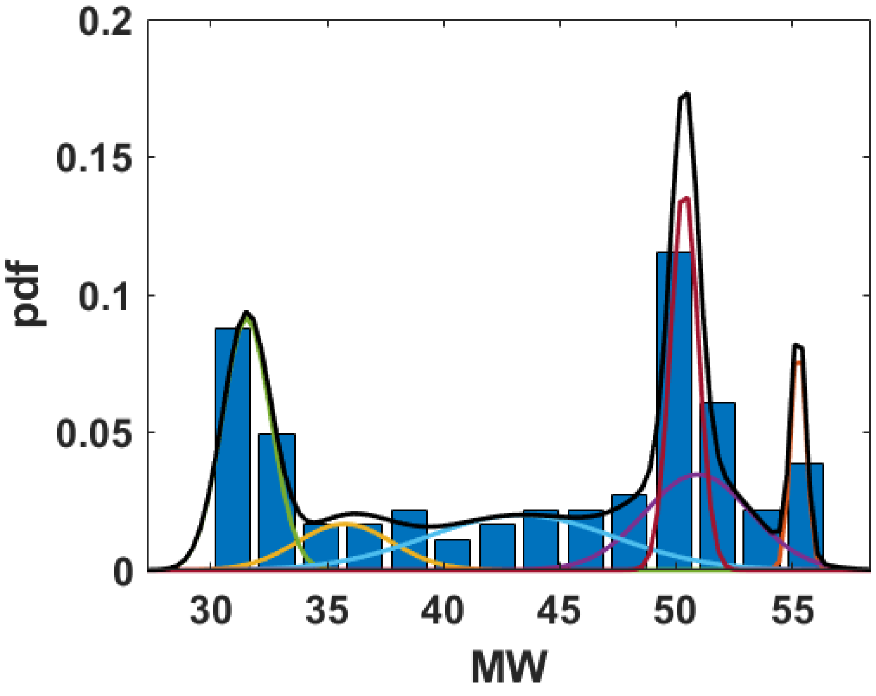
Cigre B4 HVDC/AC network is used in the study.

Current work – glimpse

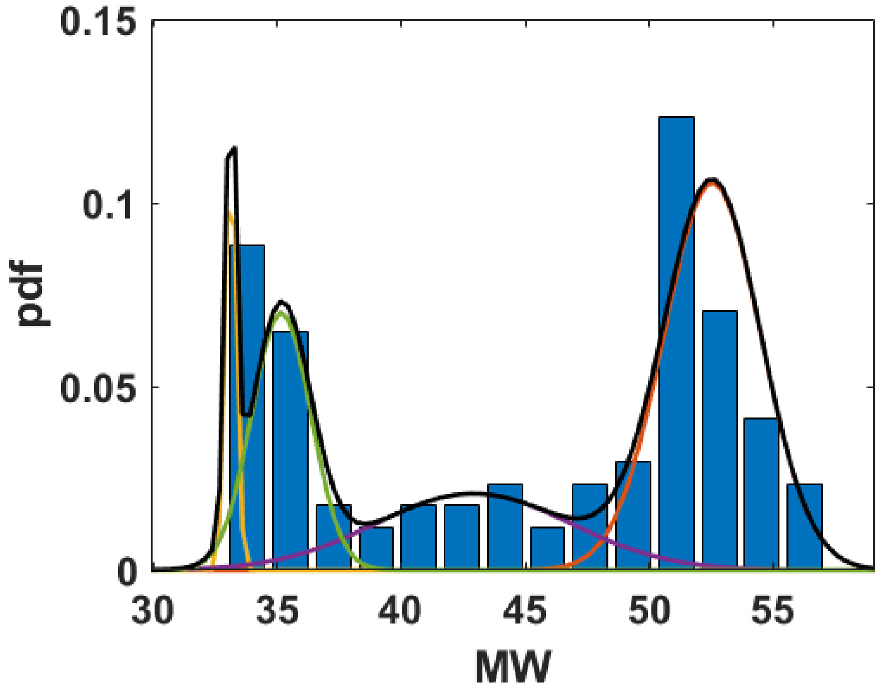




Current work – glimpse

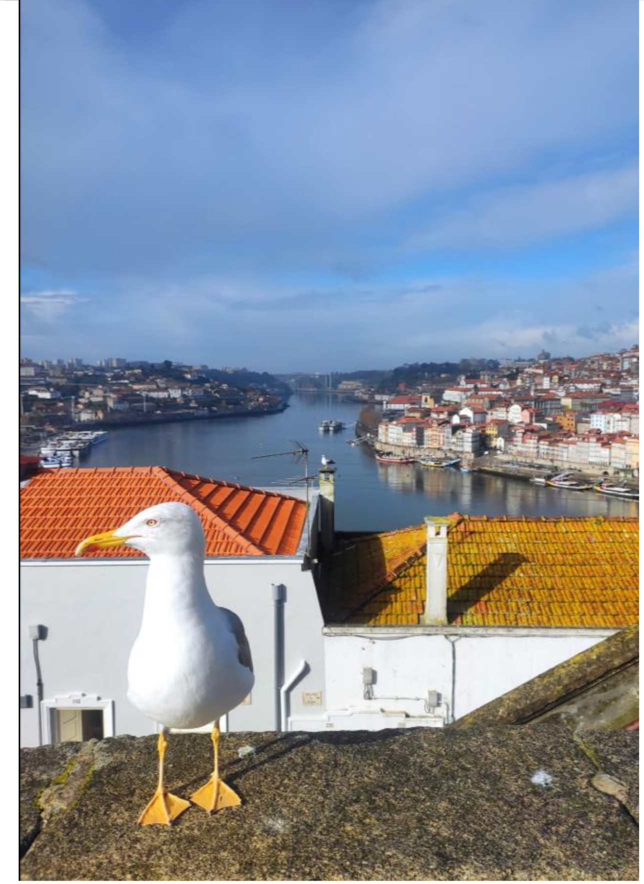


GMM of bus 8 Load profile.

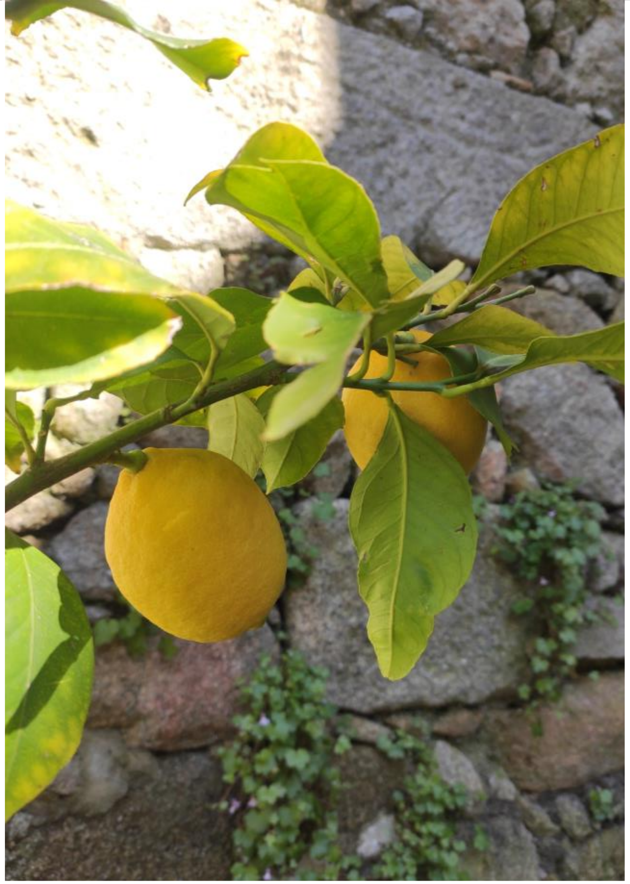


GMM of bus 6 Load profile.

Nov 2020 – Vila do Conde



Dec 2020 – Gaia



Feb 2021 – Home (Porto)

2 lemons only :D

Mar 2021 - Porto

Portugal

Thank you