Smart grids: from traditional to modernized resilient systems

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Smart Grids

January 13, 2021

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- Smart grids are becoming a necessity in order to integrate renewables, accommodate new actors, improve the observability and efficiency.
- The transition from conventional systems towards smart grids is challenging:
  - Incorporate distributed sources of energy.
  - Integrate storage systems.
  - Rely less on large traditional centralized power plants.

Thus, we have divided the progressive adaptations:

Chapter	Activities
Phase 1	Initial solution of the system
Phase 2	Addition of lines
Phase 3	Integration of wind and solar
Phase 4	Rehabilitated power plant and storage
SGAM	HLUC related to contingencies

Table 1: Phases of the project to move towards smart grids

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System overview

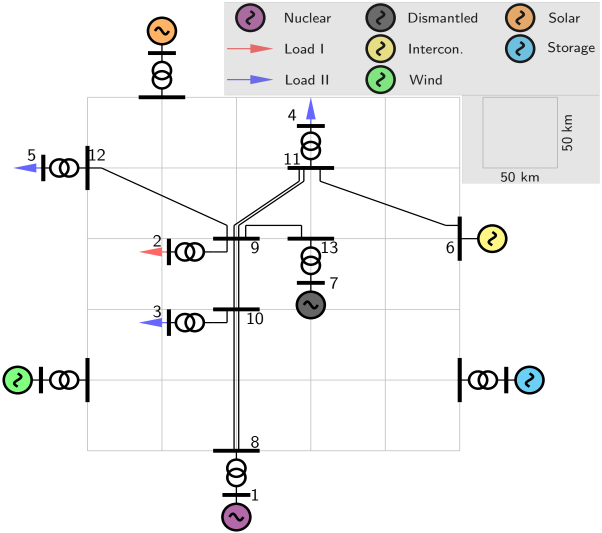

Figure 1: Overview of the network

Initial bus voltages

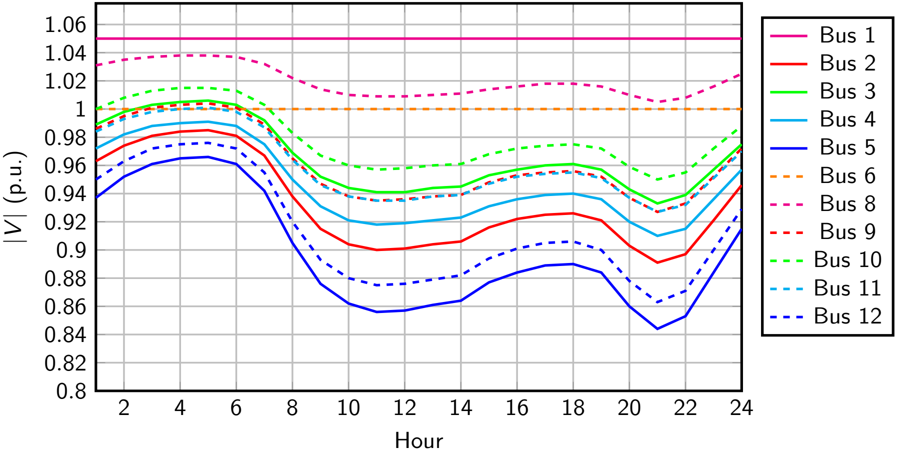

Figure 2: Voltage profile during 24 hours for the initial grid. The low-voltage buses are plotted in solid lines; the high-voltage ones are in dashed lines.

Initial lines loading

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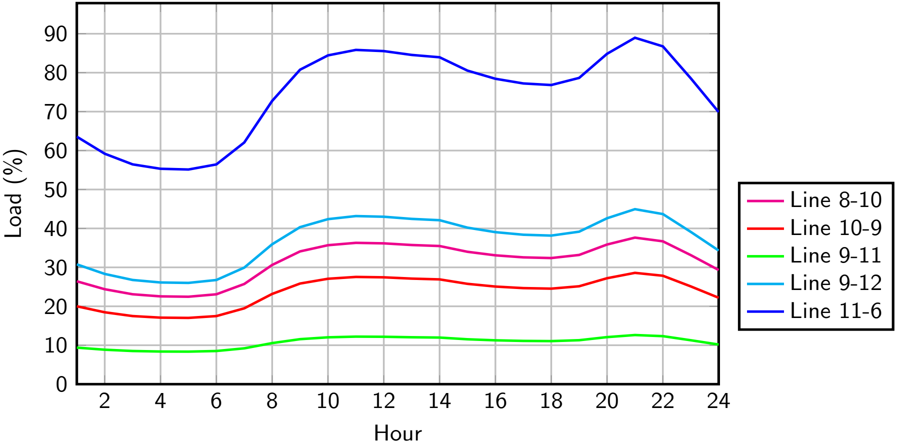

Figure 3: Representation of the percentual loading of the lines during 24 hours

Technical issues

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The main observed issues are:

- Some load buses are below 0.9 p.u. during peak hours.
- While no lines surpass 100% of load, the interconnection line is close to 90%.
- In addition, the $N-1$ criteria is not met:

Element	**Disconnection time (h)**	**Consequences**
Line 8-10	12.50	No load served - divergence
Line 9-10	6.25	No load served - divergence
Line 9-11	8.85	Loads at buses 2, 3 and 5 unserved
Line 9-12	13.98	Load at bus 5 unserved
Line 11-6	13.98	No load served
Trafo 1-8	1.20	No load served - divergence
Trafo 2-9	1.20	Load at bus 2 unserved
Trafo 3-10	1.20	Load at bus 3 unserved
Trafo 4-11	1.20	Load at bus 4 unserved
Trafo 5-12	1.20	Load at bus 5 unserved

Table 2: Disconnection time and consequences of losing each element

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Potential addition of lines

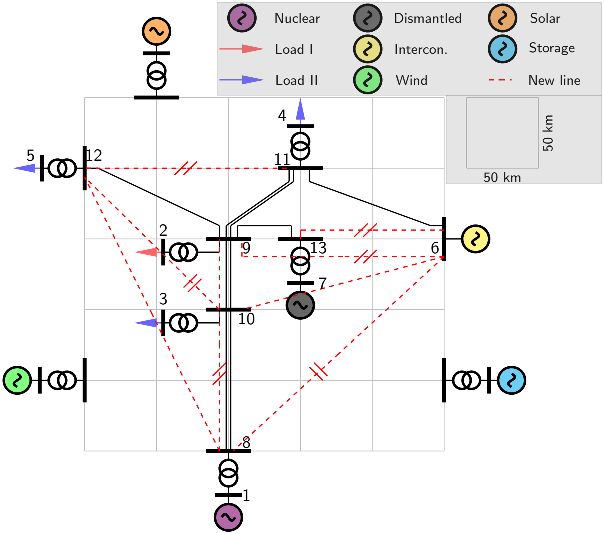

Figure 4: Overview of the new network. Double line indicates double circuit.

Algorithm to compute contingencies

Input: `net` initialized class, j, n

Output: stored results

Generate permutations $\forall \boldsymbol{\sigma}_g$ where $g = [1, 2, ..., 2^{(n-j)}]$

for $i = [1, 2, ..., j]$ **do**

  $\sigma_i \leftarrow$ `false`

  $\sigma_r \leftarrow$ `true`, where $r \neq i$ and $r \leq j$

  $\mathcal{A} \leftarrow \{\mathbf{1}_{\sigma_1}, \mathbf{1}_{\sigma_2}, ..., \mathbf{1}_{\sigma_j}\}$

  for $g = [1, 2, ..., 2^{(n-j)}]$ **do**

    $[\sigma_{j+1}, \sigma_{j+2}, ..., \sigma_n] \leftarrow \boldsymbol{\sigma}_g$

    $\mathcal{B} \leftarrow \{\mathbf{1}_{\sigma_{j+1}}, \mathbf{1}_{\sigma_{j+2}}, ..., \mathbf{1}_{\sigma_n}\}$

    $\mathcal{N} \leftarrow \mathcal{A} \cup \mathcal{B}$

    `pandapower.timeseries.run_timeseries(`$\mathcal{N}$`,net)`

    Store results

  end

end

Algorithm 1: Pseudocode to solve the contingencies

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Contingency analysis for additional lines

Top 10 optimal configurations. Requirements are met and cost is minimized.

Identifier	New lines	Infraestructure cost (M€)
19	[6-13, 6-10, 8-9, 10-12]	359.50
214	[6-13, 6-10, 11-12, 8-9]	362.99
77	[6-13, 8-9, 10-12, 9-6]	375.04
49	[6-13, 11-12, 8-9, 9-6]	378.54
80	[6-13, 6-10, 11-12, 8-9, 10-12]	420.63
189	[6-13, 6-10, 8-9, 10-12, 9-6]	420.63
45	[6-13, 6-10, 8-9, 10-12, 8-12]	423.96
70	[6-13, 8-9, 10-12, 9-6]	424.12
157	[6-13, 6-10, 11-12, 8-9, 8-12]	427.46
250	[6-13, 11-12, 8-9, 10-12, 9-6]	436.17

Table 3: Best configurations with the additional lines

Serious need to install more lines connected to the interconnection bus.

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Same for a rise in the voltage.

Identifier	New lines	Lines (M€)	Transformers (M€)	Total (M€)
163	[6-13, 8-9, 10-12]	313.92	64.79	378.71
133	[6-13, 11-12, 8-9]	317.41	64.79	382.20
235	[6-13, 8-9, 8-12]	320.75	64.79	385.54
30	[6-13, 8-12, 6-8]	346.07	64.79	410.86
19	[6-13, 6-10, 8-9, 10-12]	359.50	64.79	424.29
214	[6-13, 6-10, 11-12, 8-9]	362.99	64.79	427.78
58	[6-13, 6-10, 8-9, 8-12]	366.33	64.79	431.12
77	[6-13, 8-9, 10-12, 9-6]	375.04	64.79	439.83
169	[6-13, 8-9, 10-12, 8-12]	378.38	64.79	443.17
49	[6-13, 11-12, 8-9, 9-6]	378.54	64.79	443.33

Table 4: Economic results of replacing the substations

Three additional lines instead of four are required. However, the cost becomes a bit larger. It becomes a sub-optimal choice.

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Connection of renewables to the system

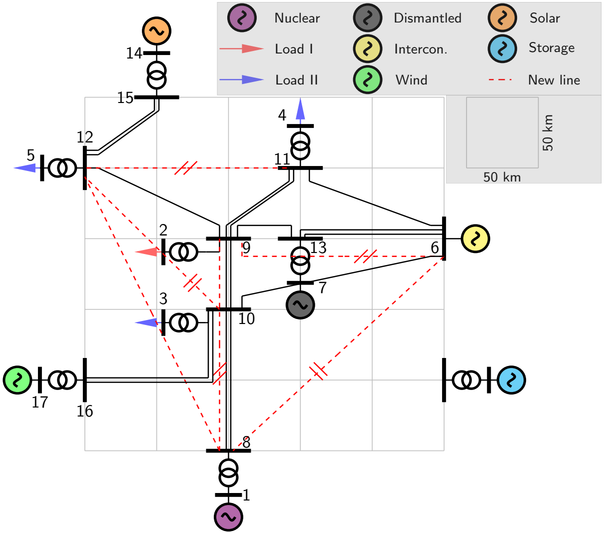

Figure 5: Overview of the network with renewables and the potential addition of lines

Solar resources

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Profile extracted from PVGIS:

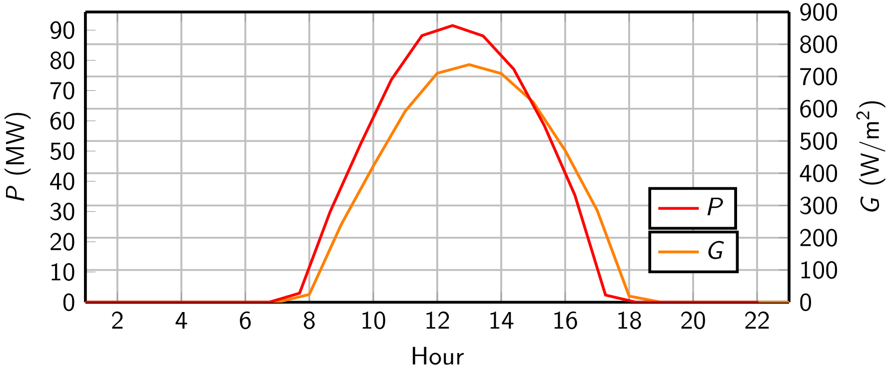

Figure 6: Irradiance and power from the PV plant along a representative day

Wind resources

Profile extracted from NASA database:

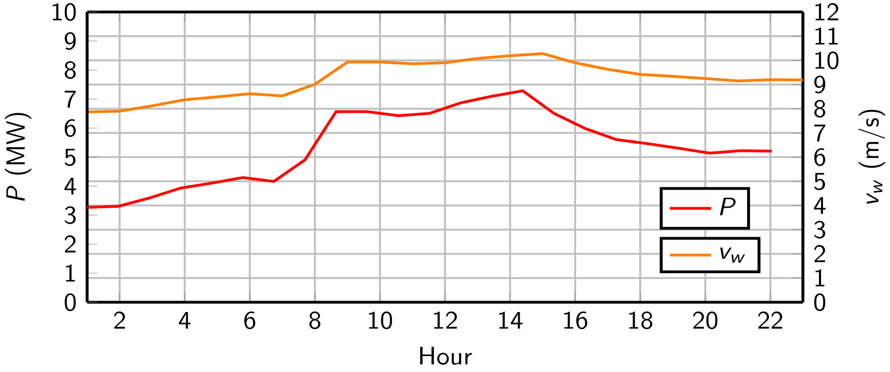

Figure 7: Wind speed and output power from the wind farm

Improvement due to renewables

It is worth it to compare the variation of the magnitudes due to renewables in normal operation.

Attributes	**Without renewables**	**With renewables**
V_{min} (p.u.)	0.962	0.968
V_{max} (p.u.)	1.050	1.050
Max. load (%)	41.65	40.76
Max. losses (MW)	14.54	14.43
Correct operation?	Yes	Yes

Table 5: Main results to compare between the grid with and without renewables

Results improve a bit. Unfortunately, the installed renewable power is not significant to cause a large impact.

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Still four lines have to be added (interconnection lines have been set as static). The cost increases slightly because renewable power plants require extra lines.

Identifier	New lines	Infraestructure cost (M€)
24	[8-9, 10-12]	402.71
12	[8-9, 9-6]	406.21
46	[11-12, 8-9]	406.21
8	[8-9, 8-12]	409.54
0	[11-12, 8-9, 10-12]	463.84
4	[8-9, 10-12, 9-6]	463.84
37	[11-12, 10-12, 9-6]	463.84
63	[8-9, 10-12, 8-12]	467.18
20	[11-12, 8-9, 9-6]	467.34
38	[11-12, 8-9, 8-12]	470.67

Table 6: Best configurations with the additional lines

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Connection of a storage unit and a dismantled plant

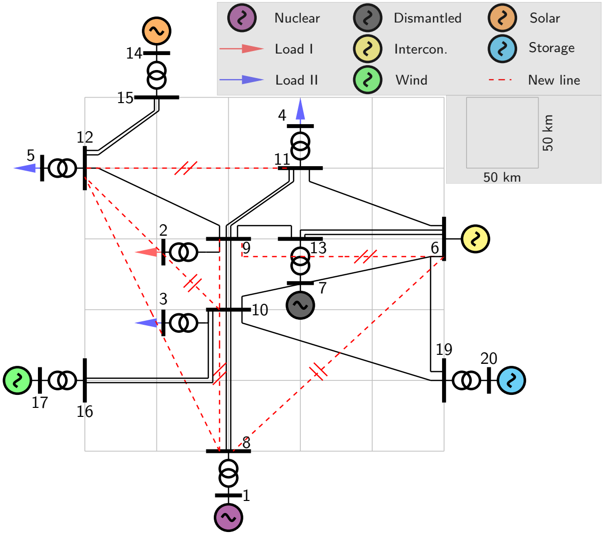

Figure 8: Overview of the network with storage and the dismantled plant

Daily profile of storage

The battery is based on lithium-ion technology.

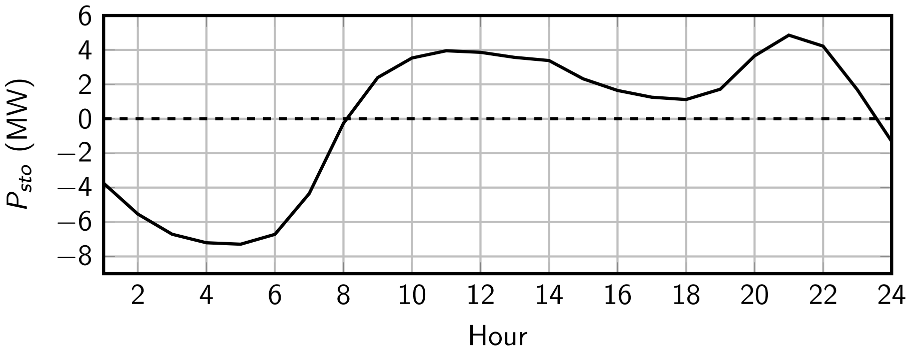

Figure 9: Daily charge and discharge profile for the battery system

Daily profile of the dismantled plant

Four fossil fuels were considered: coal, diesel, natural gas, and biomass.

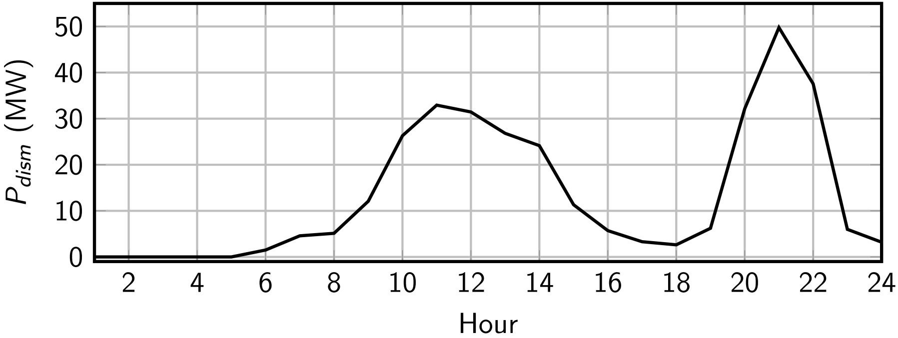

Figure 10: Daily generation profile of the rehabilitated plant

Base case results

Improvement of all grid attributes.

Attributes	**Phase 2**	**Phase 3**	**Phase 4**
V_{min} (p.u.)	0.962	0.968	0.971
V_{max} (p.u.)	1.050	1.050	1.050
Max. load (%)	41.65	40.76	39.63
Max. losses (MW)	14.54	14.43	13.89
Correct operation?	Yes	Yes	Yes

Table 7: Main results to compare between phases

Whole emission factor of 63 kg CO_2/MWh. Biomass is the cheapest option.

Fuel	**Dismantled** (tCO_2-eq)	**Interconnection** (tCO_2-eq)	**Total** (tCO_2-eq)
Coal	108.56	890.34	998.90
Diesel	89.64	890.34	979.98
Gas	59.76	890.34	950.10
Biomass	0.00	890.34	890.34

Table 8: Total daily emissions depending on the scenario

Contingency analysis

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The combination of storage and the dismantled plant help at having to install one less additional line.

Identifier	New lines	Infraestructure cost (M€)
33	[8-9]	419.49
24	[8-9, 10-12]	477.12
12	[8-9, 9-6]	480.62
46	[11-12, 8-9]	480.62
8	[8-9, 8-12]	483.96
57	[8-9, 6-8]	505.94
0	[8-9, 10-12]	538.25
4	[8-9, 10-12, 9-6]	538.25
37	[11-12, 10-12, 8-12]	538.25
63	[8-9, 10-12, 8-12]	541.59

Table 9: Best configurations with storage and a rehabilitated plant

The total cost rises a bit due to the connections of storage.

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HLUC: contigency analysis

HLUC layers:

- Component
- Business
- Function

Involved PUC layers:

- Information
- Communication

- **Scope:** evaluate the effects of a fault and calculate any overloads based on a computer application that simulates the power system to be prepared for any possible fault.
- **Objective:** protection of the impact of faults.
- **Grid issues:** short-circuits, overloads, undervoltages.
- **Relation to other use cases:** PUC 01: demand and generation forecasting; PUC 02: grid operation scheduling; PUC 03: grid observability and monitoring; PUC 04: fault detection and localization. Extracted from RESOLVD.
- **Viewpoint:** Technical.
- **Type:** HLUC.

Table 10: General description of the HLUC

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HLUC actors

- Geographical Information System (GIS)
- Grid Operation Scheduler (GOS)
- Weather Forecast (WF)
- Reserve Aggregator (RA)
- Energy Forecaster (EF)
- Transmission System Operator (TSO)
- Distribution System Operator (DSO)
- Transmission Management System (TMS)
- Distribution Management System (DMS)

Business and function layer

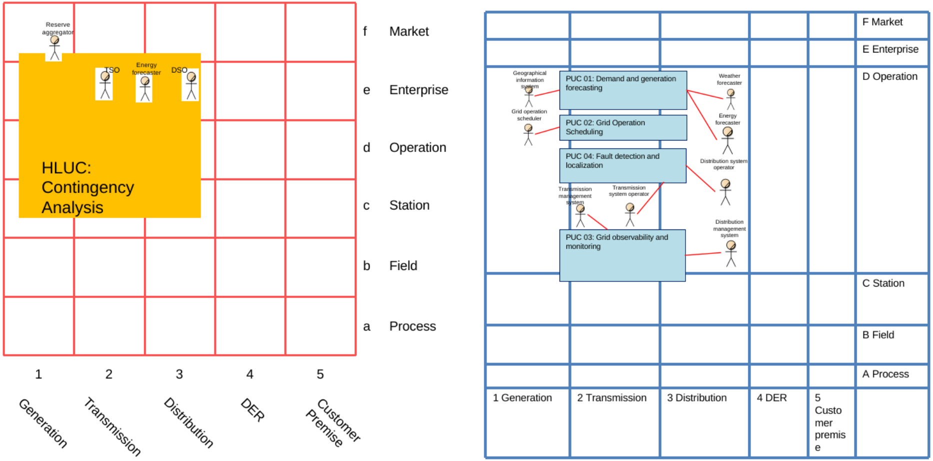

Figure 11: Business and function layer mapping

Context

- Wind speeds exhibit unpredictable fluctuations.
- These variations in wind speed cause drastic changes in power:

$$P_{wt} = \frac{1}{2}\rho A C_p v_w^3. \tag{1}$$

Store the peaks of power and retrieve the energy once the wind speed diminishes.

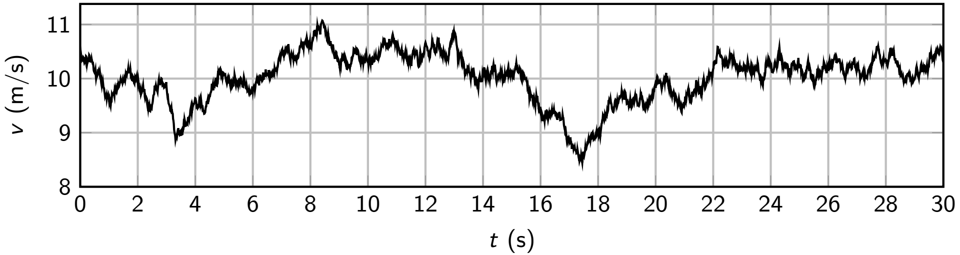

Figure 12: Example of wind speed profile

Aim of the project

Goals:

- Minimize the fluctuations in the power exchanged with the grid.
- Ensure the supercapacitor operates inside the allowed limits.
- Quantify the results and compare them with other techniques.

Steps:

1. Model the back-to-back converter configuration of a wind turbine.
2. Size the energy storage unit (supercapacitor).
3. Model the control of a buck converter to integrate the supercapacitor.
4. Test the full model in Matlab/Simulink for a realistic scenario.

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General scheme

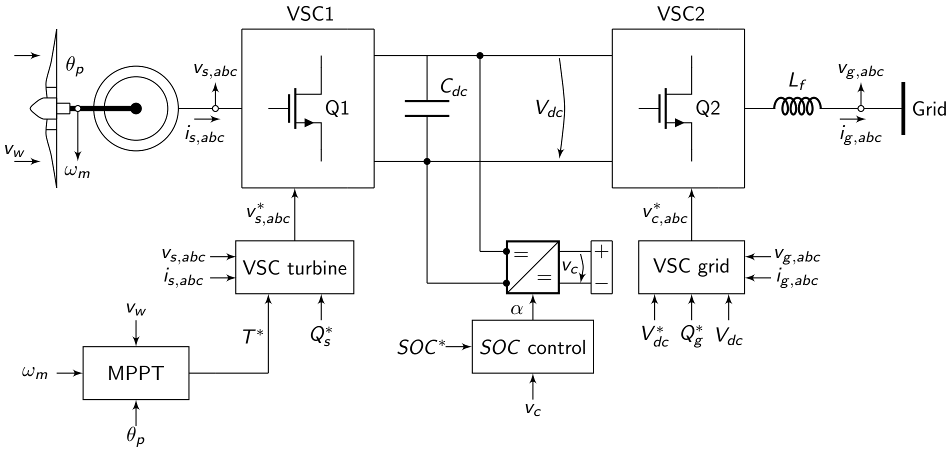

Figure 13: Scheme of the full system with the turbine, the converters, and the energy storage unit

Maximum power point tracking

The machine-side converter has to be controlled so as to extract the maximum power from the wind.

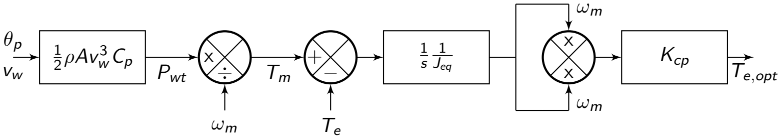

Figure 14: Block diagram of the MPPT

The key part is the quadratic relationship between speed and torque:

$$K_{cp} = \frac{1}{2}\rho A\left(\frac{D}{2}\right)^3\left(\frac{c_1}{c_2^2 c_7^4}(c_2 + c_6 c_7)^3 e^{-(c_2+c_6 c_7)/c_2}\right). \tag{2}$$

Machine-side converter

Two references are received: reactive power and optimal torque.

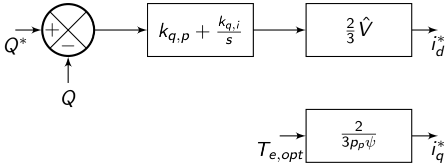

Figure 15: Reactive power control and current references calculation

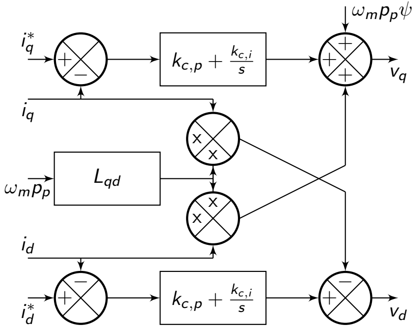

Figure 16: Inner current control loop

With the inner current control loop, the current references are transformed into the *qd* voltages to synthetize.

Grid-side converter

Two references are received: the DC bus voltage and the reactive power to exchange with the grid.

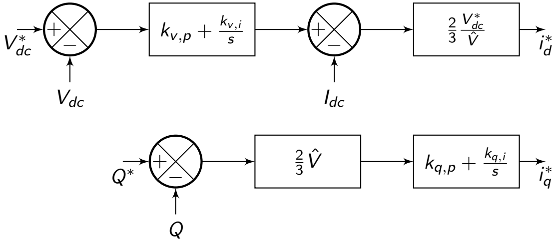

Figure 17: Reactive power control and DC voltage control loop

Just like before, an inner current control loop is also present.

Buck converter

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Responsible for controlling the charge and discharge processes of the supercapacitor.

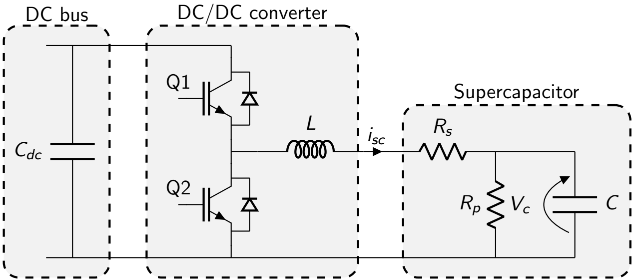

Figure 18: DC/DC buck converter with the supercapacitor

Switches Q1 and Q2 are turned on and off according to the desired duty cycle D.

Supercapacitor control

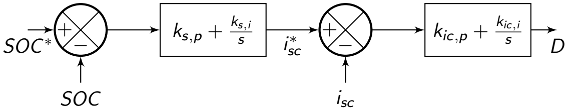

Figure 19: Control diagram of the SOC of the supercapacitor

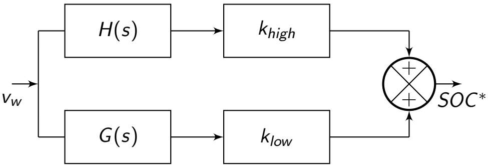

Figure 20: Calculation of the reference of the SOC

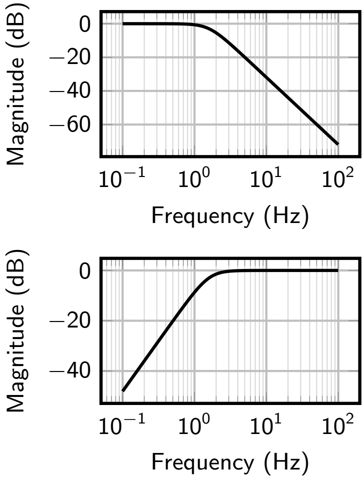

Figure 21: Bode plot of $H(s)$ and $G(s)$

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The supercapacitor is sized based on a sinusoidal perturbation:

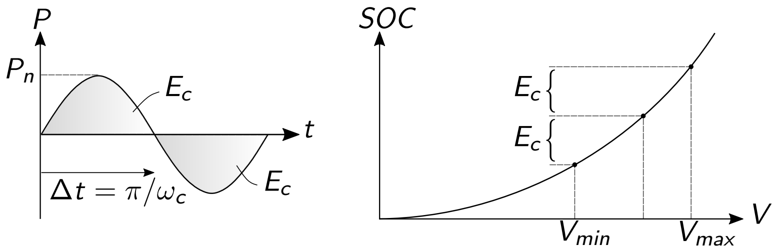

Figure 22: Perturbation and SOC as a function of the voltage of the supercapacitor

$$C = \frac{8\frac{P_n}{\omega_c}}{V_{max}^2 - V_{min}^2}. \tag{3}$$

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Configuration

- For the considered case study, $C = 0.91$ F.
- Configuration of 4 parallel branches and about 1600 series cells.
- In total, they occupy about 0.382 m^3 and last for 500000 cycles.

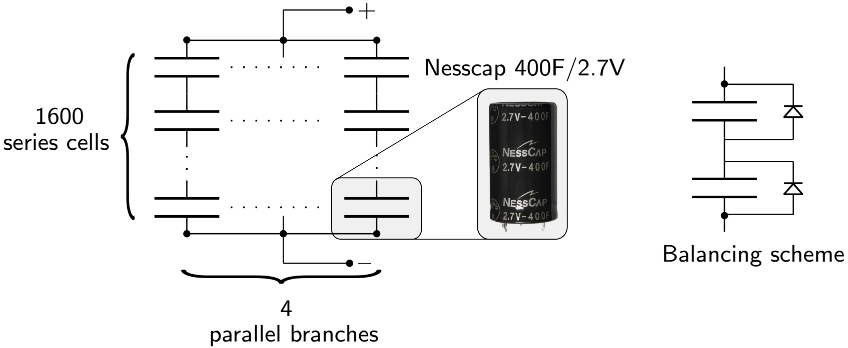

Figure 23: Chosen configuration of cells

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Indicators

Apart from qualitative observations, quantitative indicators are considered. Assessment based on:

- Maximum variation in the output power:

$$\Delta P = \max(P) - \min(P). \tag{4}$$

- Roughness index:

$$RI = \sum_{i=1}^{n-1} [P(i+1) - P(i)]^2 . \tag{5}$$

- Simple moving average:

$$SMA_k = \frac{1}{k} \sum_{i=n-k-1}^{n} P(i). \tag{6}$$

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Example in a two-bus system

The supercapacitor mitigates the fluctuations to obtain a smoother power profile.

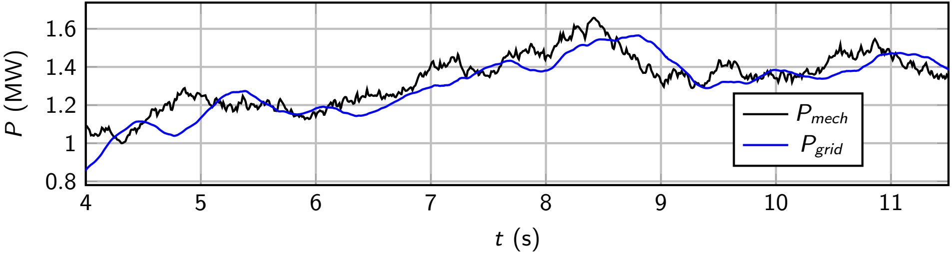

Figure 24: Mechanical power and active power exchanged with the grid

Indicator	P_{mech}	P_{grid}
ΔP (MW)	0.531	0.439
RI (MW^2)	0.066	0.003

Table 11: Numerical indicators results

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- The combination of type-IV wind turbines with an energy storage device offers great controllability.
- The supercapacitor manages to reduce the fluctuations in power.
- It was preferable to prioritize the low frequencies. However, other control strategies may be equally convenient, if not more.

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January 13, 2021