Smart grids: from traditional to modernized resilient systems

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Smart Grids

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Introduction

- 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

System overview

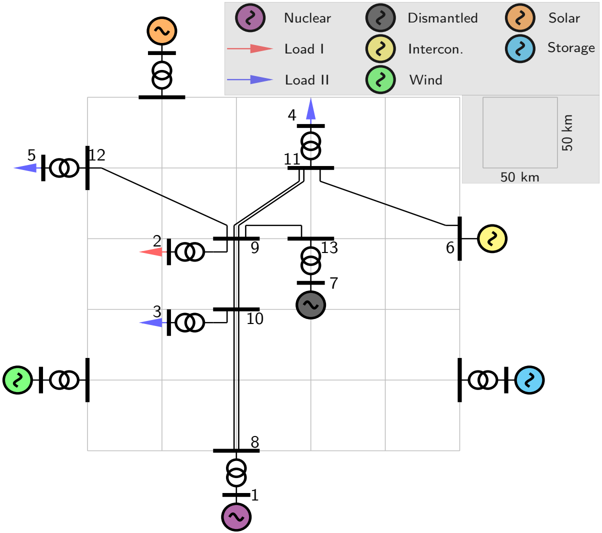

Figure 1: Overview of the network

Initial bus voltages

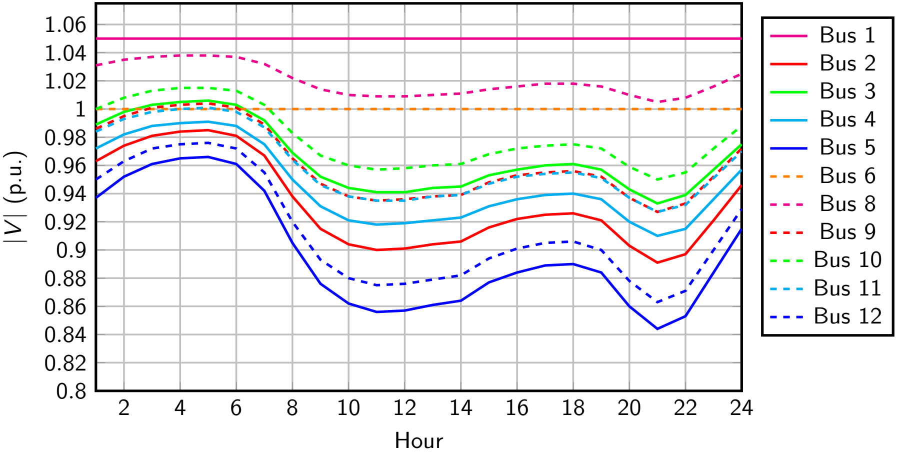

Figure 2: Voltage profile during 24 hours for the initial grid. The low-voltage buses are plotted in solid lines; the high-voltage ones are in dashed lines.

Initial lines loading

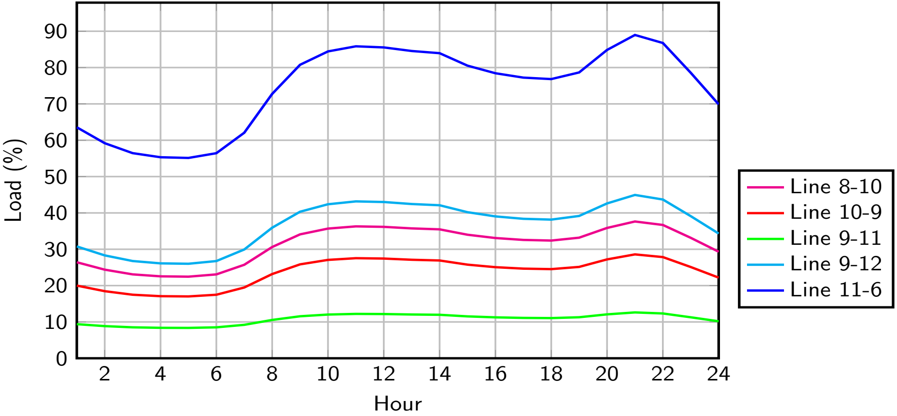

Figure 3: Representation of the percentual loading of the lines during 24 hours

Technical issues

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

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.

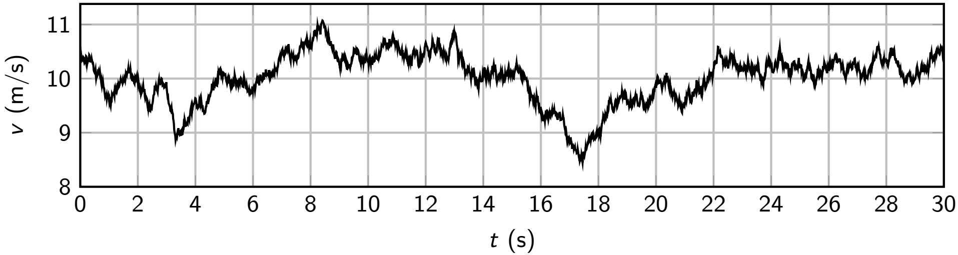

Figure 4: Example of wind speed profile

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.

General scheme

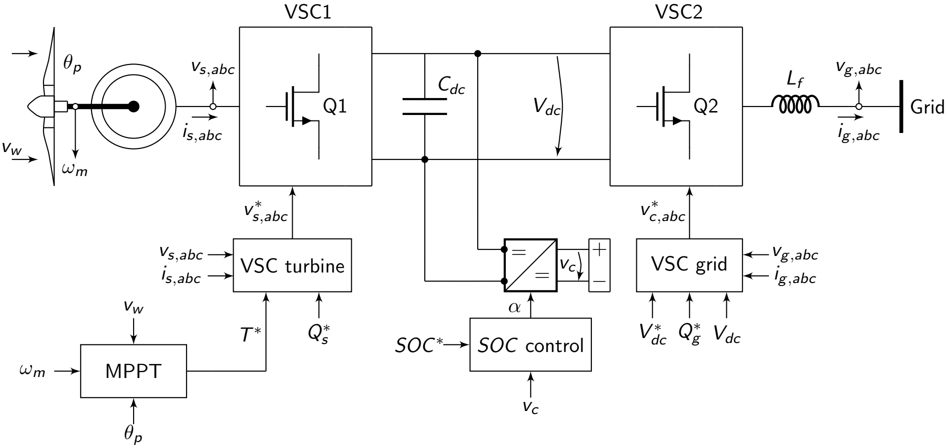

Figure 5: Scheme of the full system with the turbine, the converters, and the energy storage unit

Maximum power point tracking

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

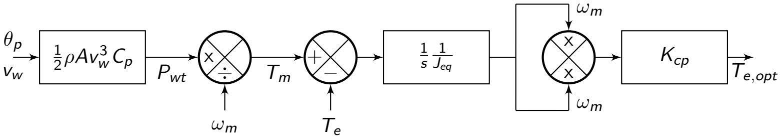

Figure 6: Block diagram of the MPPT

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.

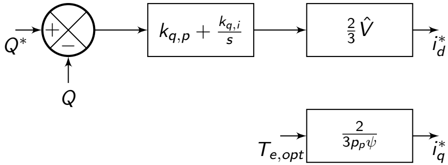

Figure 7: Reactive power control and current references calculation

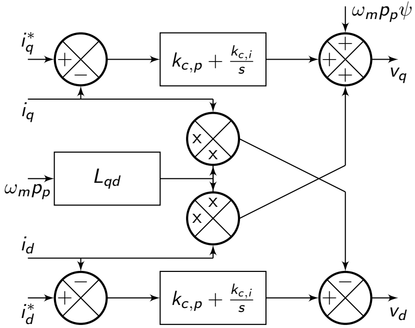

Figure 8: Inner current control loop

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.

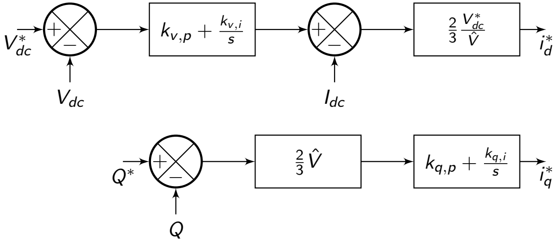

Figure 9: Reactive power control and DC voltage control loop

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

Buck converter

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

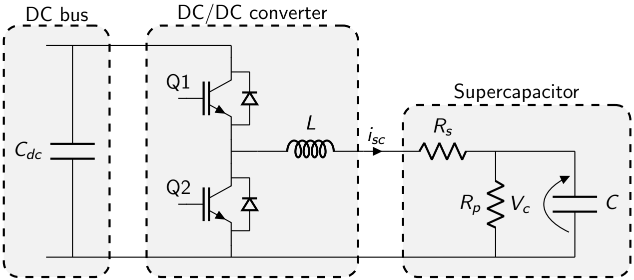

Figure 10: DC/DC buck converter with the supercapacitor

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

Supercapacitor control

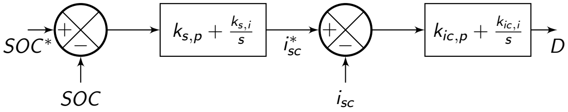

Figure 11: Control diagram of the SOC of the supercapacitor

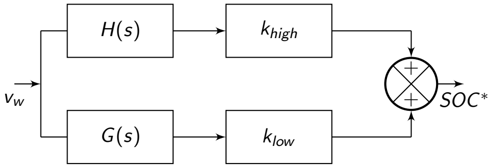

Figure 12: Calculation of the reference of the SOC

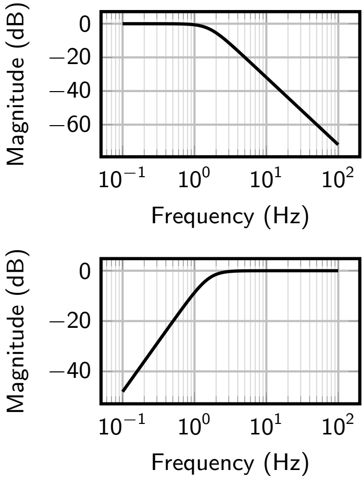

Figure 13: Bode plot of $H(s)$ and $G(s)$

Sizing calculations

The supercapacitor is sized based on a sinusoidal perturbation:

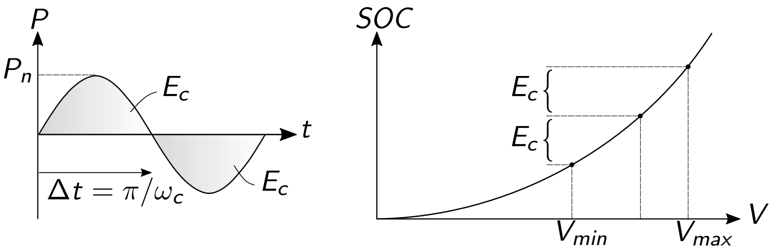

Figure 14: Perturbation and SOC as a function of the voltage of the supercapacitor

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

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.

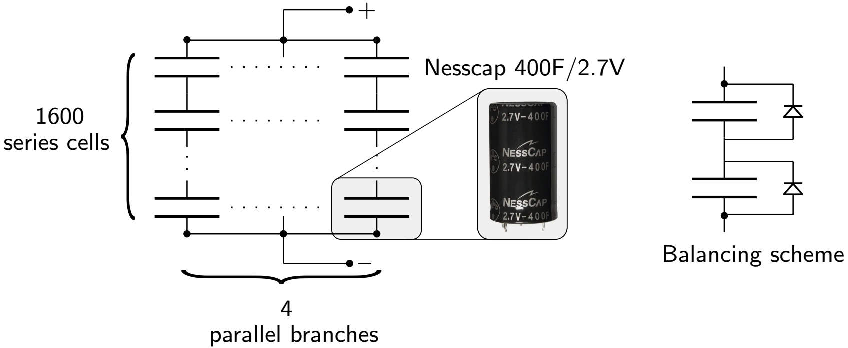

Figure 15: Chosen configuration of cells

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:

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

- Simple moving average:

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

Example in a two-bus system

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

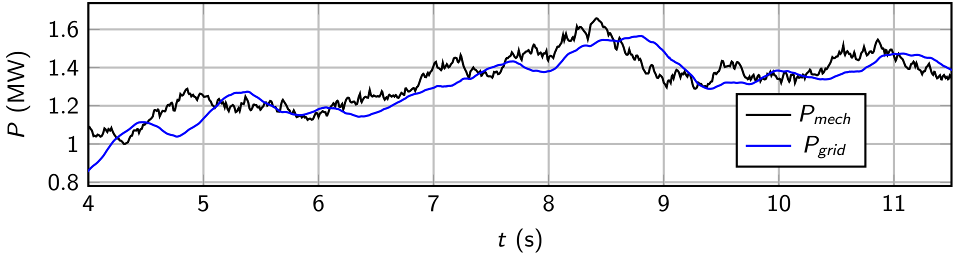

Figure 16: Mechanical power and active power exchanged with the grid

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

Table 3: Numerical indicators results

Conclusions

- 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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