

École polytechnique de Louvain

Design of a low-tech water wheel for electricity production in remote areas

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Academic year 2024–2025

Master [120] in Energy Engineering

Abstract

In the context of the urgent energy transition and the high potential of low-head hydropower sites, this thesis explores the potential of using a low-tech water wheel to generate electricity in remote areas. These systems offer a promising solution for decentralized energy production, particularly in locations with limited access to industrial infrastructure.

The study adheres to the low-tech philosophy by prioritizing usefulness, sustainability, and accessibility. After a review of historical designs, the Zuppinger wheel was selected for its efficiency and adaptability to low-head conditions. A detailed design was created following W. Müller's guidelines and evaluated through 2D CFD simulations in ANSYS Fluent. Both curved and straight blade geometries were tested. Although curved blades provided slightly better hydraulic performance, straight blades were favored for their simpler and more accessible construction.

The mechanical-to-electrical conversion system was also analyzed, comparing permanent magnet synchronous generators (PMSG), wound rotor synchronous generators (WRSG), and asynchronous generators, alongside transmission methods like belt drives and gearboxes. A configuration combining a PMSG with belt transmission and power electronics was identified as the most efficient and compatible with low-tech constraints.

A case study at the Les Avins site showed that the system could meet around half of the annual energy needs for local water pumping. While the electrical subsystem presents some challenges with regard to low-tech ideals, the overall solution demonstrates strong feasibility. With thoughtful design choices, water wheels can provide a viable and sustainable energy source for isolated communities.

Acknowledgements

I would like to express my gratitude to all those who contributed to the development of this work. I would like to thank my supervisors Prof. Hervé Jeanmart and Nicolas Parmentier who guided me all along the completion of this thesis. Their expertise and support were from great help in the development of this work.

I would also like to thank my family and friends for their support and encouragement throughout this journey. Their understanding and patience were invaluable during the challenging times of this research. Especially, I would like to thank Victoria for her unwavering support and encouragement, which were crucial in the completion of this thesis.

Special thanks to my parents for their investment in trying to understand what I was explaining, the challenges I was facing, and the suggestions they made to help me overcome them.

During the preparation of this work, the author used Antidote and ChatGPT-4o in order to improve the writing and make the text clearer and more concise. After using Antidote and ChatGPT-4o, the author reviewed and edited the content as needed and took full responsibility for the content of the thesis.

Nomenclature

Symbol	Description	SI Units
Q	flow rate	m^3/s
$\dot{m}$	mass flow rate	kg/s
H	total head	m
g	gravitational acceleration	m^2/s
D	diameter	m
B	width	m
Z	number of blades	-
W	work	J
D_o	outer diameter	m
R	radius	m
a	radial depth	m
ω	wheel's rotational velocity	rad/s
l	peripheral distance between blades	m
n	number of blades	-
ρ	density	kg/m^3
η	efficiency	-
h	pressure head	m
z	elevation head	m
v	flow velocity	m/s
u	tangential velocity	m/s
P	power	W
V	voltage	V
R	resistance	Ω
T	torque	Nm
F	force	N
p	pressure	Pa
f	frequency	Hz

Abbreviations

Abbreviation	Meaning
AC	Alternating current
AVR	Automatic voltage regulator
CAD	Computer-aided design
CFD	Computational fluid dynamics
DC	Direct current
ELC	Electronic load controller
IGBT	Insulated gate bipolar transistor
MPPT	Maximum power point tracking
PCC	Point of common coupling
PMSG	Permanent magnet synchronous generator
PWM	Pulse width modulation
SEIG	Self-excited induction generator
STATCOM	Static synchronous compensator
VOF	Volume of fluid
WRSG	Wound rotor synchronous generator

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Chapter 1

Introduction

In a world where 58% of the electricity produced comes from fossil energy sources [1] and where renewable energy becomes the only viable option to prevent climate change, hydropower energy is a good candidate with a lot of potential. Hydropower is the most used renewable energy source on the planet, representing 57% of the total installed capacity of renewable energy sources [2] and 16% of the total electricity production in the world [3].

According to the United Nations Industrial Development Organization (UNIDO) and their 2022 report on small hydropower, there would be an unexploited small hydropower (<10 MW) potential of 221.7 GW in the world, mainly in Asia [4]. UNIDO classifies hydropower plants in five categories : large, small, mini, micro and pico. Large hydropower plants have a capacity of more than 10 MW, small for less than 10 MW, mini for less than 1 MW, micro for less than 100 kW and pico for less than 5 kW [2]. The recent resurgence of interest in mini and pico hydropower, particularly for self-sufficiency in remote regions [5], has prompted the scientific community to revisit and study water wheels using modern approaches. In fact, nowadays most of the potential low-head sites are unexploited due to the lack of economical solutions, as it can be observed on Figure 1.1 [5]. Therefore, water wheels may contribute to solving this problem.

Water wheels have been a revolution in the history of mankind, especially because they allowed mankind to produce flour [6]. According to Philippe Fleury [6], the first water wheel was invented in Byzance in the 3rd century BC and the technology was widely spread in the oriental Roman Empire at the end of the 1st century BC. During the 19th and 20th centuries, water wheels were widely used as energy converters but disappeared around the 1950s due to the emergence of the electric motor and its low costs [7].

Another advantage of such a technology is that it is easy to build, has low costs and lower pay-back periods than large hydropower plants. As a matter of fact, E.

Quaranta and R. Rivelli [2] state that, depending on the type of wheel, the costs range from €3900 to €8700 per kW of installed capacity. Those costs include the wheel, the installation and the electrical system and grid connection. Furthermore, the costs can be reduced if an old abandoned water wheel site is reused. For the payback periods it ranges from 7.5 to 17 years which is low compared to large hydropower, such as Kaplan turbines, which has a payback period of 25–30 years [2].

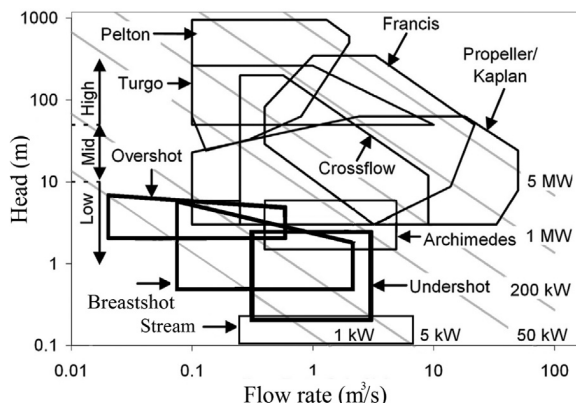


Figure 1.1: Hydropower map [2], showing the potential of water wheels in low-head sites.

state that this technology can be useful for electricity production in remote areas. However, those remote areas are not always connected to the grid and don't have the same access to technology as in Europe. At the time of the writing, 9% of the world population don't have access to electricity [9]. The present thesis will address this issue by studying the feasibility of producing electricity with a water wheel while following the low-tech philosophy. The low-tech philosophy is a philosophy that promotes the use of simple and sustainable technologies. It aims to reduce the complexity of technologies and to make them accessible to everyone. The low-tech philosophy is based on three main principles: useful, sustainable and accessible.

The structure of this thesis will be as follows. First, a state-of-the-art review will present the main types of water wheels and their performance characteristics. Next, the low-tech philosophy and its principles. Then, the thesis will detail the numerical modeling and design of an optimized water wheel, followed by an analysis of the associated electrical systems, comparing their performance, costs, and compliance with low-tech criteria. Finally, a practical case study will illustrate the real-world implementation of the proposed solution.

Water wheels are eco-friendly regarding wildlife. Indeed, due to their low rotational speed and the fact that they operate at atmospheric pressure, the water wheel can be considered as a fish-friendly technology [8]. According to the same article, a study showed a fish mortality of 3.8% for a water wheel.

Recent research shows that the water wheel offers good efficiency and good performance, but few studies have been done on the whole system. Furthermore, a lot of articles

Chapter 2

State of the Art

2.1 Types of water wheels

There are various types of water wheels such as the undershot, overshoot, breastshot. The main difference between those types of wheels is the position of the water entry point with respect to the wheel or rotation axis. The overshoot water wheel has the water entry point above the wheel's axis. For the undershot, breastshot and high breastshot water wheels, the water enters the wheel at the bottom, on the same level and above the rotation axis respectively.

The different types of water wheels are shown in Figure 2.1.

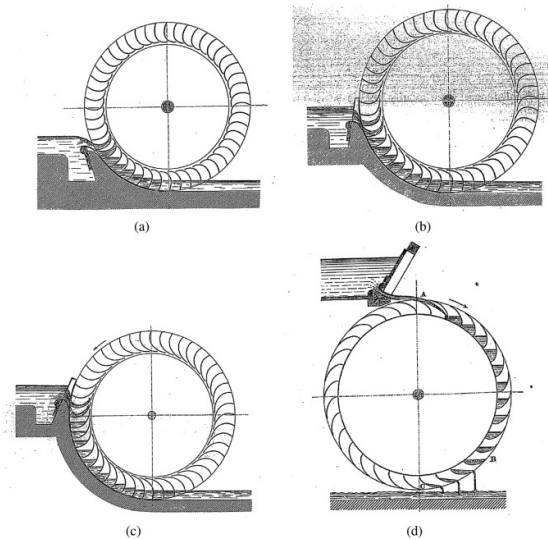


Figure 2.1: a) Undershot water wheel b) breastshot water wheel c) High breastshot water wheel d) overshoot water wheel [2]

2.1.1 Overshot water wheel

The overshot water wheel has the water entry point above the rotation axis. This can be observed on Figure 2.1 d).

It exploits the potential energy of water. In fact, it uses the weight of the water to produce work. First, the water enters a bucket and fills it, the weight of the water in the bucket will induce torque on the wheel, thus creating momentum and make the wheel rotate.

This type of wheel is used with heads ranging from 2.5-6 m. The maximum flow rate per meter width recommended [2] is $Q_{max} = 0.2 \text{ m}^3/\text{s}$. Buckets in the wheel are filled at 30-50% of their volume.

This wheel's maximum efficiency is 85%. The efficiency of the wheel follows a nearly constant maximum efficiency for flow rates ranging $0.2Q_{max}$ to Q_{max} .

According to Quaranta and Revelli [2], a maximum ratio between the tangential speed (u) of the wheel and the inflow velocity (v) has been identified. This ratio should not exceed $\frac{u}{v} = 0.75$ or $\frac{u}{v} < 0.6$. This result is confirmed by Müller and Kauppert [10] where it was shown that for varying flow rates but constant inflow velocity, the efficiency didn't vary much for a certain range of rotational speeds before decreasing when the rotational speed was too high.

The wheel diameter should be close to the water head H . Regarding the number of buckets, a formula is given by [2] : $n = 16R$ or $l = 0.75d + 0.1 \text{ m}$, for diameters ranging from 3-6m.

The depth of the buckets ranges from $d = 0.2 - 0.35m$.

For example, a wheel with a total head of $H = 3 \text{ m}$ will have a diameter of $D \approx 3 \text{ m}$ and a number of buckets of $n = 16 \cdot 3 = 48$. The peripheral distance between the buckets is $l = 0.75 \cdot 0.2 + 0.1 = 0.25 \text{ m}$.

2.1.2 Breastshot water wheel

Breastshot water wheels have the water entry point on the same level as the rotation axis. This type of wheel works with heads ranging from 1.5-4 m [2].

It functions properly with flow rates per meter width between $0.5 - 0.75 \text{ m}^3/\text{s}$.

There are several design guidelines given in Quaranta and Revelli [2]. The diameter of the wheel is given by $D \approx 2H$ with H the total head.

For the peripheral distance between the blades, it is recommended to set it up at 1.3-1.5 times the upstream water depth.

The depth of the cell is given by $d = 0.4-0.5 (D/H)^{1/3}$.

For example, a breastshot water wheel with a total head of $H = 3 \text{ m}$ will have a diameter of $D \approx 6 \text{ m}$ and a cell depth of $d = 0.4 \cdot (6/3)^{1/3} = 0.5 \text{ m}$.

2.1.3 Undershot water wheel

This master thesis is focused on undershot water wheels because this type of wheel can be implemented in a wide variety of sites due to the low heads that the wheel can work with. Therefore, this subsection will address on different types of undershot water wheels, namely the Poncelet, Sagebien and Zuppinger water wheels. Those types of undershot wheels appeared in the middle of the 19th century, they were originally built with flat blades, but the previously mentioned authors developed curved blades that increased the undershot wheel efficiency [2].

An undershot water wheel have the water entry point below its rotation axis. This type of wheel works with low heads and flow rates per meter width up to 1.5 m³/s. The most efficient models of undershot water wheel are Sagebien and Zuppinger wheels. Each one of them minimizing the inflow and the outflow power losses respectively.

The total head difference is obtained by the Bernoulli equation :

$$p + \frac{1}{2}\rho v^2 + \rho g z = cst \quad (2.1)$$

With p the pressure, ρ the water density, v the flow velocity, g the gravity acceleration and z the water depth.

Since work is extracted at the wheel, the total head difference can be obtained :

$$H = (z_1 + h_1 + \frac{v_1^2}{2g}) - (z_2 + h_2 + \frac{v_2^2}{2g}) \quad (2.2)$$

Where z_1 and z_2 are the elevation heads (i.e. the height of the water entry and exit points with respect to the ground) and h_1 and h_2 are the pressure heads. The various quantities in the Bernoulli equation are illustrated in Figure 2.2, where the reference height is set such that $z_2 = 0$.

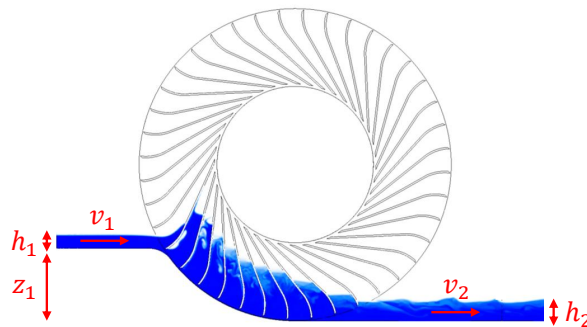


Figure 2.2: Different quantities in the Bernoulli equation

The total head difference being known, the input hydraulic power can be obtained :

$$P_{in} = \rho g Q H \quad (2.3)$$

$$P_{in} = \dot{m} g H \quad (2.4)$$

With Q the volumetric flow rate in m^3/s and $\dot{m}$ is the mass flow rate in kg/s .

The wheel efficiency is then obtained by the equation :

$$\eta_{wheel} = \frac{P_{wheel}}{P_{in}} = \frac{T \cdot \omega}{\dot{m} g H} \quad (2.5)$$

2.1.3.1 Poncelet

In 1827 Victor Poncelet published his master thesis on undershot water wheels. In his wheel, the water enters the wheel at approximately the same level as the exit point. Poncelet stated that in order to extract the maximum power from the water, the exit water velocity should be zero, making the ratio between the inflow velocity and the peripheral wheel velocity equal to $\frac{\omega R}{v_1} = \frac{1}{2}$ [11]. Since the pressure head are approximately the same and since the difference in the elevation head is roughly the same, the total head difference is given by the kinetic energy of the inflow water.

Therefore, wheel exploits only the kinetic energy of the water. Thus, the total head $H = \frac{v_1^2}{2g}$. The number of blades lies around 36 and must be tilted at 25° with respect to the incoming water flow.

Furthermore, the flume geometry should be a circle involute. The diameter of the wheel lies between 4-5 m.

The blades' depth is recommended to be a quarter of the total head for feasibility reasons.

Finally, the wheel's efficiency is around 60-75% [11].

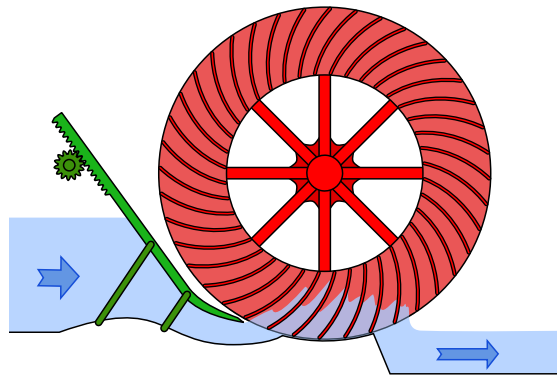


Figure 2.3: Poncelet water wheel [12]

2.1.3.2 Sagebien

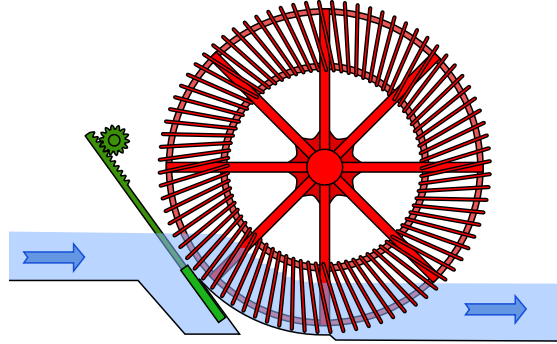


Figure 2.4: Sagebien water wheel [12]

Sagebien water wheels are wheels with blades tilted at 45° with respect to the incoming water flow. This angle minimizes the inflow power losses [13]. In fact, the water enters the wheel such that its relative velocity is parallel to the blade [14]. Furthermore, the wheel does not make noise when the blades hit the water. The diameter of this wheel ranges from 7 to 12 m. The peripheral distance between the blades is 0.30-0.4 m [15, 16]. The maximum flow rate per meter width is $1.5 \text{ m}^3/\text{s}$ with a maximum efficiency achieved at flow rates per meter width ranging from 0.6 to $0.7 \text{ m}^3/\text{s}$. The wheel achieves efficiencies of 80-90% [13]. The tangential velocity for such wheel is $0.6\text{--}0.8 \text{ m/s}$ [16, 14]. The rotational speed of Sagebien wheels is thus very low (1-2 rpm).

For the bucket depth, Busquet [17] proposed a depth of 0.4–1 m while Chaudy [15] proposed a depth of 0.35–0.4 m (for wheel diameter of approximately 4 m).

The Sagebien wheel has the advantage of performing well over a wide range of flow rates as shown in an experimental study conducted by E. Quaranta and G. Müller [14] (see Figure 2.5).

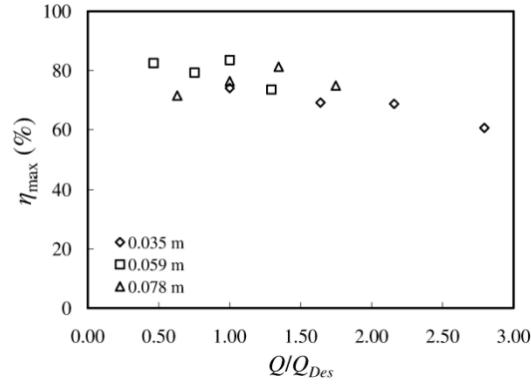


Figure 2.5: Efficiency of the Sagebien wheel for different flow rates and sluice gate openings [14]

2.1.3.3 Zuppinger

This wheel is called after its inventor, a Swiss engineer, Walter Zuppinger. The wheel was patented in 1849 [18].

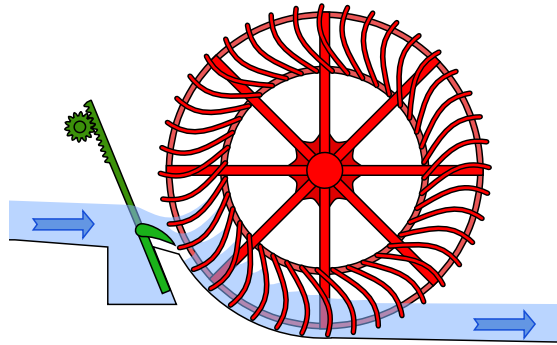


Figure 2.6: Zuppinger water wheel [12]

In 1849, a German engineer, Julius Weisbach, published a design method for undershot water wheels [19]. According to this method, the radius of the wheel is given by the following formula of its book:

$$R = \frac{h - h'}{1 - \cos(\alpha)} \quad (2.6)$$

With h the drop height, $h' = 4.4u^2/2g$; u being tangential velocity of the wheel

and g the gravity acceleration. α is given by :

$$\sin(\alpha) = \sqrt{\frac{h' - h^*}{h'}} \quad (2.7)$$

The value of h' is determined to ensure that the incoming water flow velocity is twice the tangential velocity of the wheel, with an additional 10% safety margin to account for splash losses on the blade. The value h^* is given by :

$$h^* = 0.3093 \cdot \left(\frac{Q}{\mu \cdot e_1} \right)^{2/3} \quad (2.8)$$

Where e_1 is the width of the sluice way (in feet), μ the filling ratio of the bucket (between 0.5 and 0.6) and Q the flow rate in cubic feet per second.

Wilhelm Müller published a book in 1899, *Die Eisernen Wasserräder Berechnung*, literally translated : The iron water wheels. This book described design rules for different water wheels including the Zuppinger water wheel. According to W. Müller there are several design parameters for the Zuppinger wheel [20] :

- the outer diameter:

$$D_o = 2 \cdot \underbrace{((z_1 + h_1 - h_2) + h_2 + h_m)}_{\Delta h} [m] \quad (2.9)$$

where h_2 lies between 0.3 m and 0.5 m, h_m is the height between the upstream water level and the wheel's axis and Δh the drop height between the upstream and downstream water level.

- the tangential velocity:

$$u \in [1.40, 1.80] \text{ m/s} \quad (2.10)$$

- the angular velocity:

$$\omega = \frac{2 \cdot u}{D_o} [rad/s], \quad n = \frac{\omega \cdot 60}{2 \cdot \pi} [rpm] \quad (2.11)$$

- the blade depth a , which varies regarding the flow rate. The detail of this variation can be observed in Table 2.1.
- the wheel width:

$$B = \frac{Q}{0.3 + \frac{Q}{5}} [m] \quad (2.12)$$

This is an empirical formula that gives the wheel's width in meters.

- the number of blades:

$$Z = \frac{D_o \cdot \pi}{l} \quad (2.13)$$

where l is the peripheral distance between blades, and according to Müller, this distance is $l \approx 0.45$ m.

A numerical application of the rules mentioned above will be done in chapter 4.

Table 2.1: Blade depth regarding the flow rate

$Q < 0.5 \text{ m}^3/\text{s}$	$Q > 0.5 \text{ m}^3/\text{s}$ and $Q < 1 \text{ m}^3/\text{s}$	$Q > 1 \text{ m}^3/\text{s}$
$a = \frac{D_o}{6}$ to $a = \frac{D_o}{5}$	$a = \frac{D_o}{5}$ to $a = \frac{D_o}{4}$	$a = \frac{D_o}{4}$

According to Müller the blade is divided into three parts :

- the front part (I-II)
- the middle part (II-III)
- the back part (III-IV)

Figure 2.7 gives more insight about the topology mentioned above.

The front part (I-II) has a radial depth of $\frac{a}{6}$ to $\frac{a}{5}$. The leading blade can be either straight or formed with radius r_1 . The radius r_1 should not be less than 1.00 m and should not exceed 1.80 m. The center of the circle with radius r_1 lies near the circumference of the wheel. The middle blade has a radius r_2 between 0.80 m and 1.10 m. For large blades, r_2 can be up to 1.50 m. The shape of the straight trailing blade is defined by the connection of two tangents. The first tangent is to the circle with radius r_2 . The second tangent touches the circle with radius r_3 . Finally, the back part has to form an angle of 30° with the horizontal going through the center of the wheel [20].

$$r_3 = \frac{\Delta h + h_2}{2} \quad (2.14)$$

The center of this circle is located at the center of the wheel, and r_3 is half the sum of the drop height Δh and the trailing depth h_2 (h_t on Figure 2.7) of the blades underwater. The number of arms that connect the wheel to the shaft is in W. Müller's book [20], the values are found in Table A.1.

The distance between two blades or buckets is important and affect the efficiency of the wheel.

Some author proposed their formula to calculate the peripheral distance between

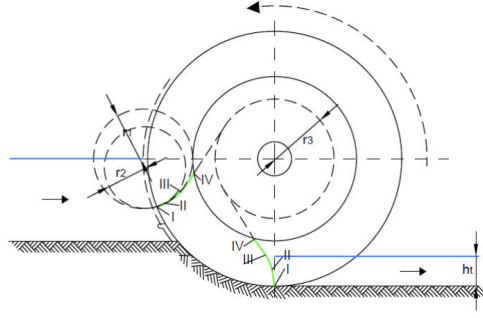


Figure 2.7: Different parts of the blade [21]

two blades or buckets. Table 2.2 shows the different formulas and proposal from different authors for the bucket water wheels. It has to be noted that for the formulas of Weisbach, a choice has to be made between the peripheral distance and the number of blades. The distance between two blades determining the number blades and vice versa.

Table 2.2: Different formulas to calculate the peripheral distance between buckets [20, 2]

Author	Number of blades	Peripheral distance between the blades	Typical radius	Typical bucket depth
Weisbach	$n = 18 + 9.8R$	$l = 7(1 + 4d)$	-	0.37–0.45 m
Pacinotti	$n = 12R$	-	2.5–3.5 m	-
Cadolini	45–56	0.28–0.45 m	4–8 m	-
Müller	-	0.45 m	4–10 m	-

Since W. Müller seems to be more cited, and its design rules are exhaustive, the author will use those design rules further in this text.

The measured efficiency of the Zuppinger wheel is 72-75%, but some experiments have shown up to 85% efficiency. In 2022, a study showed a 75% efficiency for an undershot Zuppinger water wheel with a maximum difference of 8% regarding the numerical model [22].

Chapter 3

The Low-Tech Philosophy

3.1 Origins

In the 70s, the economic boom resulted in technologies getting into every household [23]. Some started to think the limits of such a growth with a finite amount of resources on the planet. From this point, a philosophy emerged, mostly in the US. The philosophy sought the use of soft and sustainable technologies. However, this philosophy did not spread widely until the beginning of the years 2000. In fact, the magazine "Les Centraliens" explains that several factors lead to the extinction of the philosophy in 1980. The causes given by "Les Centraliens" are the weight of big industrial lobbies, investment choices, a big international competition and the lack of a proper definition a what is considered low-tech and what is not [24]. The environmental concerns rising in the beginning of the 2000s gave a helping hand to the low-tech philosophy.

In 2007, the "Low-Tech Magazine" was created by Kris de Decker. The magazine gathers low-tech solutions and discuss the use of high-tech technologies that require rare earth and polluting materials and processes. The magazine also promotes the use of old technologies. Those technologies are revised with modern science.

In 2014, the low-tech technologies gained widespread interest thanks to the French engineer Philippe Bihouix who published a book called "L'âge des low-tech". The book is a manifesto for the low-tech movement. It explains the limits of high-tech and the need to go back to low-tech. In fact, Philippe Bihouix denounces that the technology is believed to be the planet savior but is resources-intensive which is paradoxical because it is meant to help in the sustainable development [25].

3.2 Principles

The low-tech philosophy is based on 3 core principles [26]:

- **Usefulness:** The technology must be useful to an individual or a community. It enables sane production, consumption in a variety of domains such as energy, food, water, waste, transportation, hygiene and health. It also encourages coming back to the basics and gives sense to action.
- **Sustainability:** The technology must be eco-designed, resilient, repairable, recyclable. It must think and optimized regarding environmental, social and societal impacts related to the use the technology all along its life cycle. Sometimes it may require to use less technique and involves more collaboration and sharing.
- **Accessibility:** Low-tech technologies must be accessible to everyone. Thus, they must be affordable to the local population. Furthermore, they must be locally produced and maintained. The technologies must be easy to understand. All of this creates a local autonomy and a better breakdown of value and work.

3.3 The water wheel as a low-tech solution

The water wheel itself can be considered as a low-tech solution. When it was used mainly before the 20th century, it was build from basic materials such as wood and iron. Already then, it fulfilled the three principles of low-tech. It was useful to the local population, it was made from local materials, it was easy to understand, and it was repairable and recyclable. The water wheel is a good example of a low-tech solution that can be used in the modern world.

The aim of this master thesis is to determine whether a water wheel for electricity production can be designed such that the low-tech principles are respected. At this point, the usefulness criterion is already fulfilled. The water wheel is useful to the local population for the energy production. From a sustainable point of view, the water wheel is already a good solution since it is easily repairable and does not require exotic materials. Furthermore, compared to microturbines, the water wheel is much easier to manufacture. However, the electrical system or the gear reduction can enter into conflict with the sustainability and the accessibility criteria. This will be further developed in chapter 5.

Chapter 4

Numerical Model

4.1 Case Scenario

In order to assess the performance of the wheel, it was first designed on the CAD software SolidWorks. The design was based on a case in W. Müller's book. In this example, the flow rate is set to $1.5 \text{ m}^3/\text{s}$. The wheel's rotating at a speed of 0.52 rad/s (corresponding to a tangential velocity $u = 1.5 \text{ m/s}$). Table 4.1 summarizes the wheel's parameters (based on equations 2.9, 2.10, 2.11, 2.12 and 2.13).

Once the CAD geometry was obtained, the wheel was simulated on the CFD

Table 4.1: Wheel parameters

Given data		Computed values	
Parameter	Value	Parameter	Value
Δh	1.3 m	D_0	5.8 m
h_1	0.25 m	a	1.45 m
h_2	0.3 m	B	2.5 m
h_m	1.3 m	Z	40
Q	$1.5 \text{ m}^3/\text{s}$	ω	0.52 rad/s
u	1.5 m/s	P	17 kW

software Ansys Fluent. A 2D simulation was used, as Fluent interprets 2D geometry as a 3D model with a 1 m width which is sufficient for performance assessment. In this section, two designs were analyzed (Figure 4.1):

- A base (curved blade) design
- A straight blade design, introduced to improve the low-tech "accessibility" criterion and ease of manufacturing.

The gap between the blades tip and the ground is set to 3 cm. Figure 4.2 shows the different subdomains.

4.2 CAD Geometry

The drawing was made following Müller's rules given above. The drawing contains 4 main parts:

1. The *rotating* domain - the wheel is enclosed in a ring for meshing
2. The *inner wheel* domain - the air inside the wheel
3. The *inner* domain - the stationary domain around the wheel
4. The *outer* domain - a large domain enclosing the two other domains, used to give stability to the CFD solution

The gap between the blades tip and the ground is set to 3 cm. Figure 4.2 shows the different subdomains.

4.3 Mesh

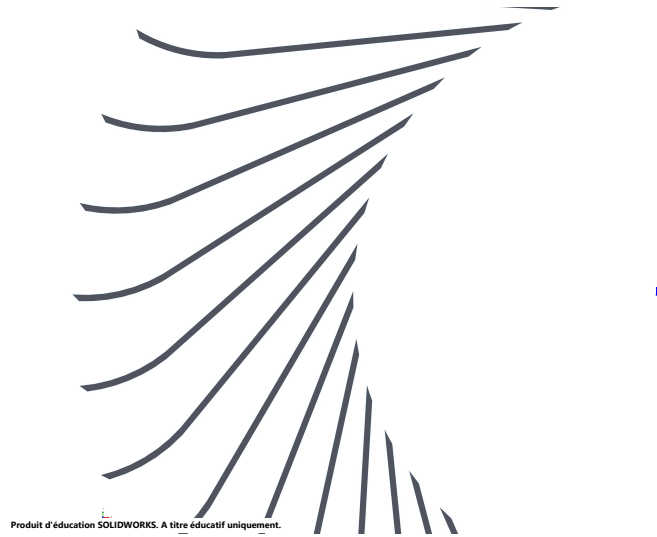
The mesh was created using Ansys Meshing. The different subdomains were meshed separately.

For the *outer* domain, a coarse mesh was used. In fact, this part of the mesh is used to increase the stability of the solution. The mesh size is not important in this part, therefore, a cell size of 0.2 m was used.

For the *inner* domain, a sphere of influence was used to refine the mesh around the wheel. In fact, since the water is only flowing around the wheel, it is not necessary to have a fine mesh in the whole domain, hence saving computational time. The diameter of the sphere was chosen at 3.25 m which is larger than the one of the wheel to ensure that the cells are small enough to capture the flow around the wheel. The mesh size for the sphere of influence was set to 0.01 m. For the *rotating* domain, the same mesh size as in the sphere of influence was used. This is to ensure that the mesh is continuous between the two domains. The cell size was set to 0.01 m.

For the *inner wheel* domain, a bigger cell size was chosen. In fact, mainly air is occupying this domain. The mesh size was therefore set to 0.08 m.

Furthermore, in order to have a good mesh resolution for the free surface flow, a body of influence was used on the upstream and downstream channel. The size of



(a) Curved blades



(b) Straight blades

Figure 4.1: Studied designs of the wheel. Flat blades, obtained by extending curved blades, are easier to build

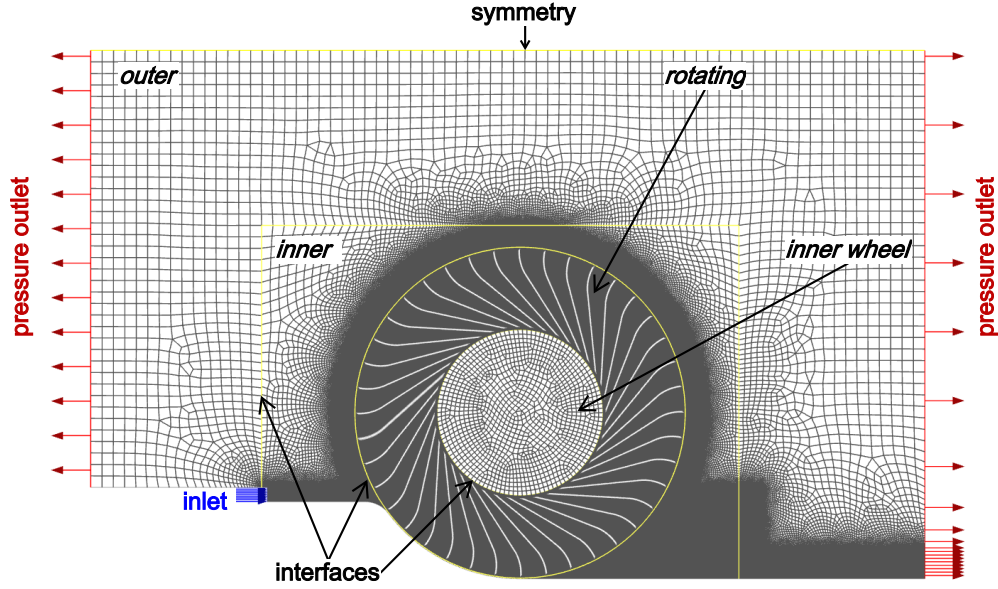


Figure 4.2: Mesh of the wheel, the areas of interest have a denser mesh.

the body of influence is the same as in the *rotating* domain (0.01 m).

Quads and triangles were used to mesh the different domains.

The total number of elements is 306378.

4.4 Numerical Simulation

4.4.1 Solver Settings and Setup

Every simulation was computed using Ansys Fluent. They were run on a 32GB RAM workstation with an Intel Core i7-12700K processor (12 cores were used). The time step size was set to $5e-4$ s. Each time step took approximately 2.25 s to be computed.

The transient formulation was chosen due to the complexity of the problem. Furthermore, the implicit formulation is more stable and can work with bigger time step sizes.

The multiphase problem was solved using the VOF (volume of fluid) coupled with the level-set method. The coupling of the two methods allows having a good accuracy at the two phases' interface, especially in complex interfaces while preserving volume conservation [27].

The implicit body force option was enabled. This option is used to improve the convergence of the solver for flows with large body forces such as rotating machinery

which is the case here [28].

The surface tension option was also enabled, and its value was set to 0.072 N/m. For the viscous model, the SST (shear stress transport) k-omega model was used. According to Quaranta E. and Rivelli R. this model performs better than the k-epsilon model in regions with adverse pressure gradients, flow separation and turbulent shear stresses at in near wall regions [27, 29], such conditions appear at the bucket filling. The model also resolves the boundary layer which provides accurate body forces [29]. Furthermore, the turbulence damping option was enabled. This option is used to suppress the over-estimation of turbulence diffusion at the interface, which helps to capture the high velocity gradient near the interface [28]. The curvature correction option was also enabled to improve the accuracy and the sensitivity of the turbulence model in regions with high curvature (i.e. near the wheel) [30]. The PISO scheme was used for the pressure-velocity coupling. The latter is recommended by Ansys for transient simulations [31]. The PRESTO! interpolation scheme for pressure was chosen for its ability to deal with rotating and curved domains [32].

For the volume fraction scheme, the modified HRIC (high resolution interface capturing) scheme was used. This scheme makes the solver more stable and allow a larger time step size [27]. The other scheme for spatial discretization (momentum, turbulent kinetic energy, specific dissipation rate and level set) were set to second order upwind for better accuracy in the results.

The maximum iterations per time step was set to 20.

4.4.2 Boundary conditions and interfaces

A mass flow was imposed at the inlet. The other default parameters at the inlet were kept as such. Two pressure outlets were defined: One on the right side of the domain and one on the left. Those two pressure outlets can be observed in red on the figure 4.2. This type of outlet boundary condition set the atmospheric pressure at the outlet. A symmetry boundary conditions was imposed at the top of the domain. Since the domain is symmetrical regarding the vertical direction, this condition was imposed.

Since the domain is divided in several subdomains, interfaces were created between the different subdomains. The interfaces are used to ensure that the flow is continuous between the different subdomains. The interfaces are also used to ensure that the mesh is continuous between the different subdomains. The interfaces are defined as *interior* in Ansys Fluent.

Three interfaces were created :

- *rotating - inner wheel*
- *inner wheel - inner*

- *inner - outer*

Those interfaces can be observed in yellow on the figure 4.2. The *rotating* domain is a rotating mesh, therefore, a non-conformal mesh is used.

The no-slip boundary condition was used on the defined walls. The latter is applied on the wheel walls and the ground. On the wheel walls, the moving wall option was enabled. This option is used to set the velocity of the wall to the velocity of the wheel.

4.5 Results

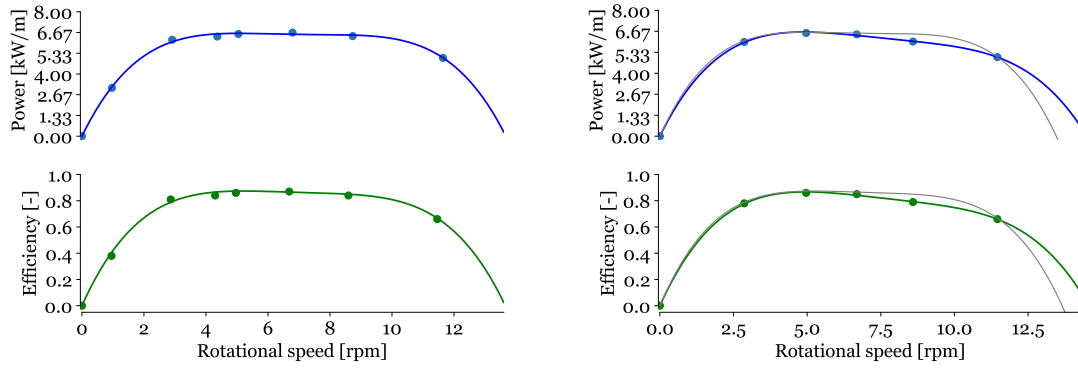
4.5.1 Base Case Wheel: Curved Blades

To evaluate the wheel's performance under several flow conditions, multiple simulations were conducted at varying rotational speeds while keeping all other parameters constant. The rotational speed ranged from 0.1 rad/s to 1.2 rad/s. Figure 4.3a shows power and efficiency vs speed. On the right side of the curve, the efficiency and the extracted power decreases because the wheel can't absorb the incoming flow rate. On the left side, the power and the efficiency decrease due to the excessive rotation speed where the water barely enters the bucket and does not efficiently fill them.

The interesting part is the middle of the curve where the power and the efficiency are on a plateau. It means that the wheel can operate at a wide range of rotational speeds without losing significant efficiency, if the optimal downstream water level is submerging the blades.

It is important to note that Figure 4.3a was generated for a wheel operating in free discharge conditions. Free discharge conditions refer to a scenario where the downstream water level does not influence the upstream flow. In this case, the wheel discharges water freely into the tailrace, and the downstream water level is determined by the flow characteristics and geometry of the wheel itself. As a result, the curve represents the maximum power that can be extracted from the wheel at a given rotational speed.

For a wheel operating in submerged tailwater conditions, the downstream water level is imposed by the river. In this case the performance characteristic of the wheel would be different, especially at high rotational speeds. In fact, as stated above, at high rotational speeds, the wheel buckets are not filling properly. When the blades are submerged and the downstream water level is higher than the water level inside the wheel, a hydrostatic back pressure develops. This pressure resists the wheel's rotation and disrupts the smooth discharge of water from the buckets. The resulting flow interference increases turbulence around the blades and inside



(a) Curved blade wheel. A plateau is observed in the middle of the curve, indicating a wide range of efficient operation. (b) Straight blade wheel compared to the curved blade wheel in gray

Figure 4.3: Performance curves from CFD simulations for both wheel designs. The flat blade design shows a lower efficiency at high rotational speeds.

the buckets, reducing the wheel's hydraulic efficiency. At low rotational speeds, again, the water wheel will not be able to absorb the incoming flow rate.

For submerged tailwater conditions, three simulations were run. The simulated rotational speeds are 0.3 rad/s, 0.52 rad/s and 0.9 rad/s (2.8, 5 and 8.6 rpm respectively). Fewer points were obtained due to long simulation duration. In fact, due to an initialized water level, there is more interaction between the upstream and the downstream water, taking more time to converge at every time step. The simulations were run with a downstream water level of 0.3 m. The results are shown in Figure 4.4. The results show a total different curve than the one for the free discharge conditions. The efficiency of the submerged wheel drops significantly when the rotational speed increases or decreases around the maximum power-point.

4.5.2 Simplified Design: Straight Blades

As seen in chapter 2 at Figure 2.7, the blade is divided in three parts : two curved parts and a straight part. The curved parts can be quite challenging to manufacture because each curved part is a circular arc of different radius. Therefore, a straight blade design will be studied to see its impact on the wheel's performance. The straight blade design consists of removing the curved parts of the blades and prolonging the straight part of the original design. Figure 4.1 show the difference between the two designs. This design brings the shape of the wheel closer to the Sagebien wheel.

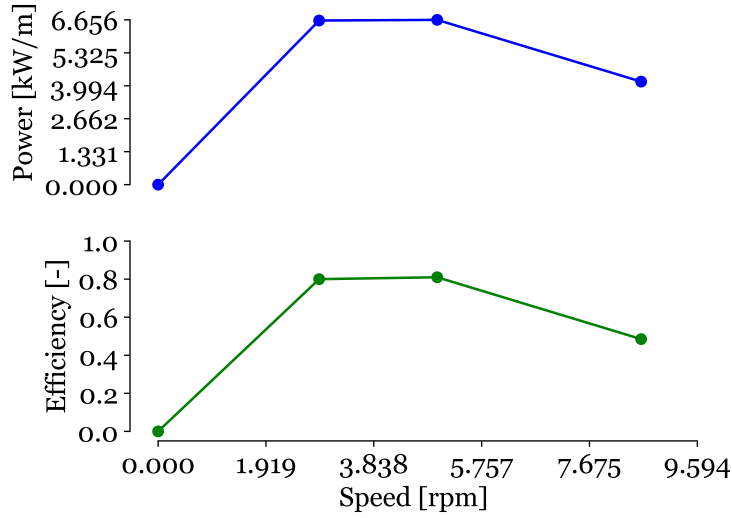


Figure 4.4: Performance curve of the submerged curved blade wheel with a downstream water level of 0.3m

One can observe on the figure 4.3b that the straight blade wheel has a slightly lower efficiency than the curved blade wheel. Furthermore, the straight blade wheel has a smaller plateau than the curved blade wheel. Making it less efficient over the studied range of rotational speeds, particularly at high rotational speeds. It can be explained by the fact that at high rotational speeds, the relative velocity angle with respect to the flow surface deviates from the angle of the blade with the respect to the flow, leading to more impact losses and therefore a lower power extraction and a lower efficiency.

The straight blade is still a good candidate regarding its ease of design and manufacturing.

4.5.3 Torque Oscillations

Figure 4.5 shows the torque in steady state for a rotational speed of 0.52 rad/s. One can observe that the torque is oscillating. This is due to the fact that water in the buckets is moving and sometimes impacting the wheel's blades. In the simulation, the wheel is kept at constant speed, therefore, no inertia is taken into account. In reality the wheel would be accelerating or decelerating depending on the torque variations.

At low rotational speeds, the torque oscillations are less important. In fact, at

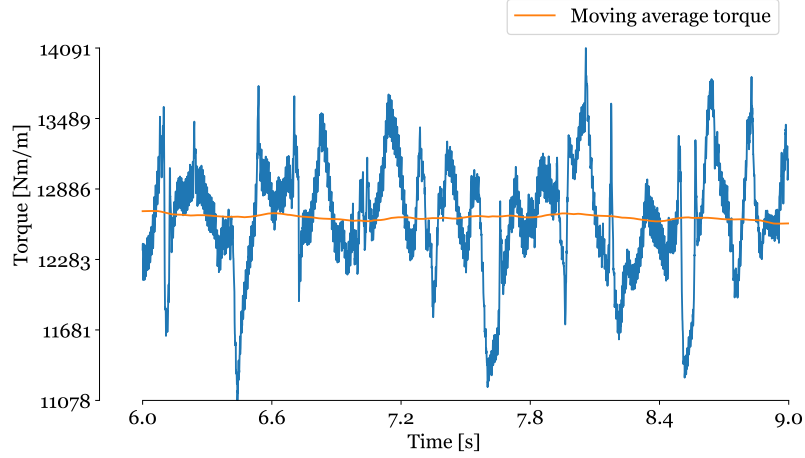


Figure 4.5: Torque evolution over a half revolution of a curved blade wheel at a rotational speed of 4.96 rpm where to torque oscillations of $\pm 10\%$ occur

Table 4.2: Average mean square error around the moving average torque (in % of the mean torque)

Rotational speed [rpm]	Rotational speed [rad/s]	Curved blade	Straight blade
2.86	0.3	1.51 %	1.55 %
4.96	0.52	3.45 %	4.42 %
6.68	0.7	4.24 %	3.59 %
8.6	0.9	5.79 %	5.41 %
11.45	1.2	8.88 %	7.39 %

low rotational speeds, the water in the buckets is not moving as fast as at high rotational speeds. Therefore, the impact of the water on the blades is less important leading to a smoother flow entry. Table 4.2 shows the importance of the oscillations for the different rotational speeds, for the two designs.

The wheel being coupled to a generator, the speed variations can impact the power quality. Therefore, it is important to have a good control system such that the desired wheel speed is kept constant.

Finally, it can be concluded that a variable speed operation will improve the energy extracted by the wheel throughout the year. In fact, as seen in Figure 4.4, the wheel efficiency can be strongly impacted by the downstream water level. Furthermore, Figure 4.3b and Figure 4.3a show that the wheel can operate efficiently over a wide range of rotational speeds. Therefore, a variable speed operation will allow the wheel to operate at its best efficiency point.

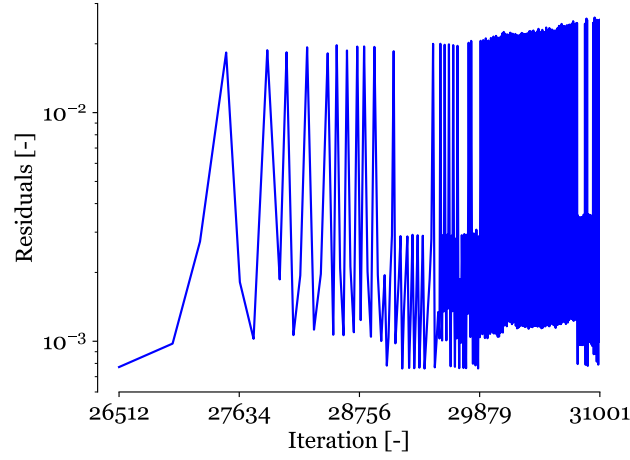


Figure 4.6: Example of residuals evolution for a simulation

4.5.4 Mass Check

In order to check the mass conservation of each simulation, the mass flow rate was checked at the inlet and at the outlet. When steady state was achieved, the mass flow rate at the inlet should be equal to the mass flow rate at the outlet. The mass deficiency is defined as :

$$\Delta\dot{m} = \frac{\dot{m}_{in} - \dot{m}_{out}}{\dot{m}_{in}} \cdot 100\% \quad (4.1)$$

The mass deficiency occurs due to computing errors. Specifically, since a defined set of time steps is used, if the solution at the end of a time step is not converged after the maximum number of iterations, the solution from the last iteration is carried forward in the simulation. This can therefore lead to mass deficiency.

Furthermore, the convergence criteria were set by default by Ansys Fluent to 1e-3. An example of one of the simulation residuals is shown in the figure 4.6.

Table 4.3 and Table 4.4 show the mass deficiency for the two designs. One can observe that the mass deficiency is more important for the curved blade design. This is due to the fact that the curved blade design has a more complex mesh due to the curved parts. This is called a skew-mesh. A skewed mesh can lead to numerical diffusion and errors [33]. One can also observe that the less the rotational speed is, the bigger the mass deficiency. This is also due to the skewness on curved surfaces. Since the fluid stays longer in the buckets, it interacts more with skewed mesh cells leading to increased computational errors.

Table 4.3: Mass deficiency of the normal wheel for different rotational speeds. NA means that the output flow rate could not be computed since the wheel could not absorb the incoming flow rate.

Rotational speed [rpm]	Angular speed [rad/s]	Mass deficiency ($\Delta\dot{m}$)
0.95	0.1	NA
2.86	0.3	-8.9%
4.3	0.45	-3.7%
4.96	0.52	-3.33%
6.68	0.7	-4.33%
8.6	0.9	-2.5%
11.45	1.2	-3.0%

Table 4.4: Mass deficiency of the straight blade wheel for different rotational speeds. NA means that the output flow rate could not be computed since the wheel could not absorb the incoming flow rate.

Rotational speed [rpm]	Angular speed [rad/s]	Mass deficiency ($\Delta\dot{m}$)
0.95	0.10	NA
2.86	0.30	-7.6%
4.3	0.45	NA
4.96	0.52	-1.27%
6.68	0.70	-2.1%
8.6	0.90	-1%
11.45	1.20	-1.1%

Chapter 5

System

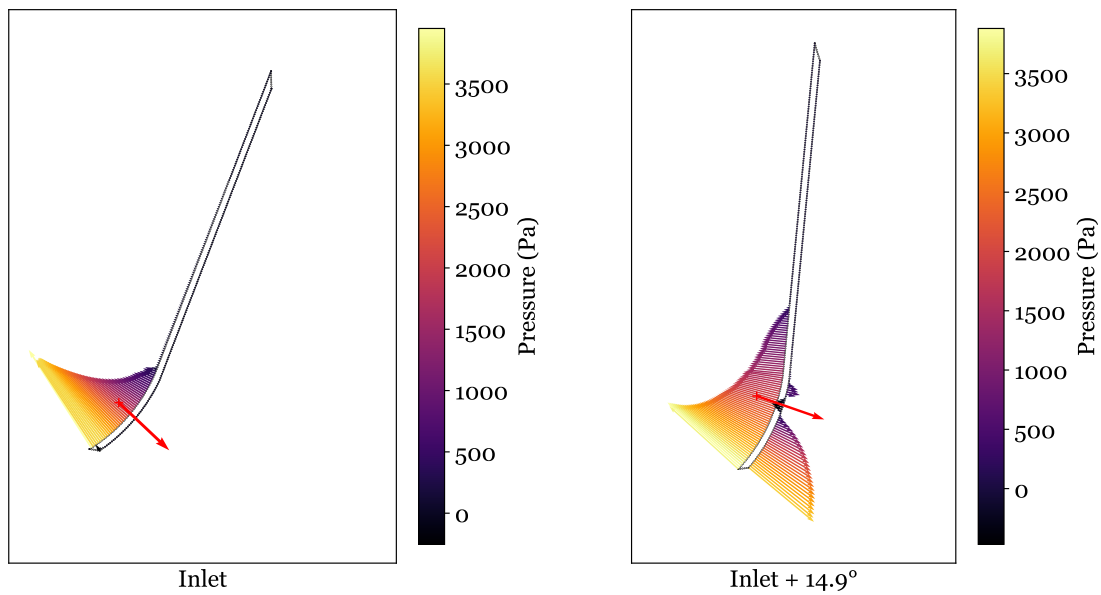
For electricity production the wheel has to be coupled to several components. First the water wheel must be coupled to a gear reduction system to increase the rotational speed of the wheel. Then, the gear reduction system is coupled to an electrical machine that will convert the mechanical energy into electrical energy. The electrical machine is then connected to a load controller that will ensure that the power balance is satisfied at every time. Finally, a dump load is used to dissipate the power excess produced by the generator.

5.1 Wheel

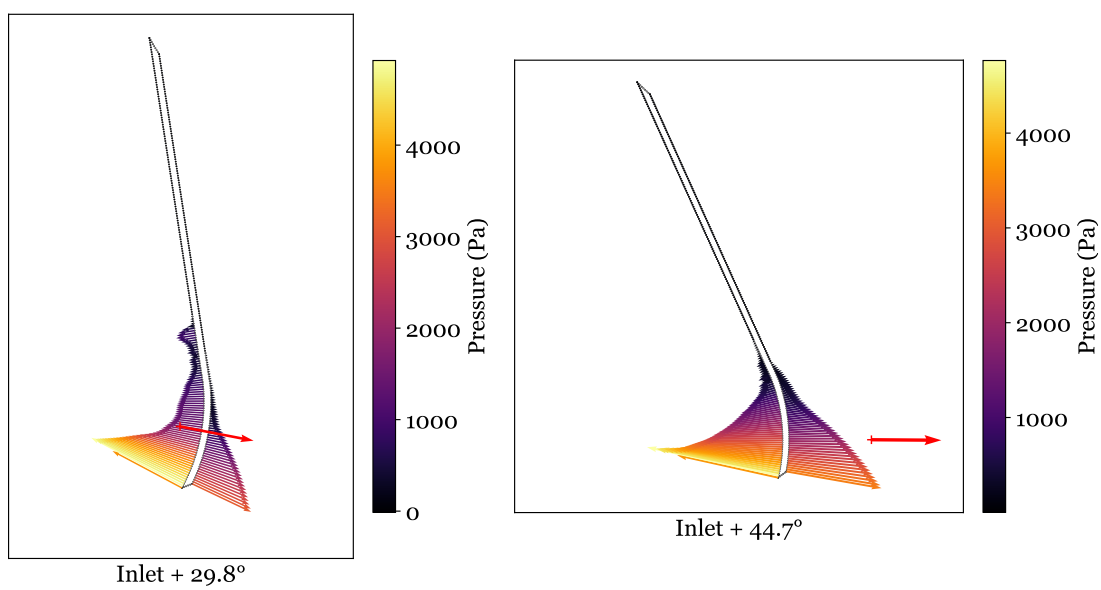
5.1.1 The physics of the wheel

The undershot water wheel converts the kinetic energy and the potential energy of the incoming water into hydrostatic pressure due to the filling of the buckets. Then, the weight of the water on the blades will create torque that gives motion to the wheel.

The force acting on the blade is obtained by integrating the pressure field over the surface of the blade. One can observe that only a small part of the blade is in contact with the water. Furthermore, the pressure field along the blade's rotation path is not constant. In fact, at Figure 5.1a on the right that the pressure field is smooth. However, at Figure 5.1b on the left, the pressure field is not smooth anymore. This is due to the fact that when the water enters the wheel, it will convert some of its kinetic energy into potential energy and then fall back such that the water level in the bucket is flat. After that, the pressure field continues to be smooth.



(a)



(b)

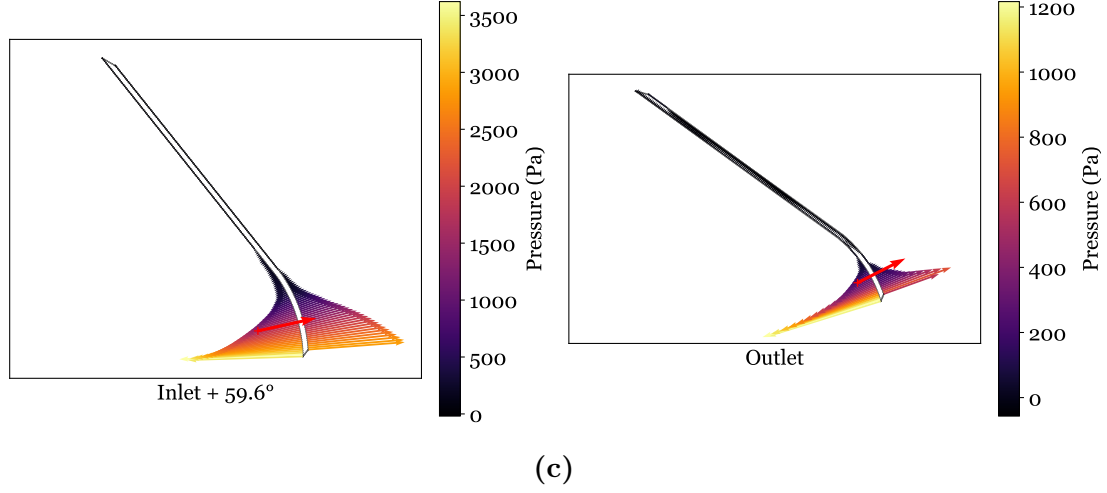


Figure 5.1: Evolution of the pressure field on a single blade at different times (time spacing of 0.5 s, $\omega = 0.52$ [rad/s] (5 rpm)). The center of pressure is indicated by the red cross and the resultant force is indicated by the red arrow. One can observe that the center of pressure is not always on the blade surface. This is normal; the center of pressure is the point where the resultant force acts to create the same torque as the one applied by the pressure field on the blade surface.

The force is thus computed via the following equation:

$$\vec{F}_{w_i} = \oint p(\vec{r}) \vec{n} dS \quad (5.1)$$

By neglecting the pressure field at the top and at the bottom of the blade, 5.1 can be simplified to:

$$\vec{F}_{w_i} = \int_{S_{front}} p(\vec{r}) \vec{n} dS - \int_{S_{back}} p(\vec{r}) \vec{n} dS \quad (5.2)$$

The pressure field at different times can be observed Figure 5.1.

The total torque T_w applied on the wheel is calculated by summing up the torque contributions from each blade:

$$T_w = \sum_i^N \vec{F}_{w_i} \times \vec{r}_{w_i} \quad (5.3)$$

Where $\vec{r}_{w_i}$ is the center of pressure, i.e., the point where the resultant force acts to create the same torque as the one applied by the pressure field on the blade surface. The coordinates of the center of pressure are given by:

$$\vec{r}_{w_i} = \frac{\int \vec{r} \times p(\vec{r}) \vec{n} dS}{\int p(\vec{r}) \vec{n} dS} \quad (5.4)$$

5.1.2 Flow Rate Control

The wheel is designed to operate at a certain flow rate. Therefore, the flow rate has to be controlled such that the wheel operates at its nominal flow rate. The easiest way to control the flow rate is to use sluice gates (see Figure 5.2a). Depending on the sluice gate opening, more or less flow rate will enter the wheel. The sluice gate flow rate equation is given by:

$$Q = B \cdot C_d \cdot a \cdot \sqrt{2gh_{us}} \quad (5.5)$$

$$Q = B \cdot C_d \cdot h_{ds} \cdot \sqrt{2gh_{us}} \quad (5.6)$$

$$\dot{m} = \rho \cdot B \cdot C_d \cdot h_{ds} \cdot \sqrt{2gh_{us}} \quad (5.7)$$

Where C_d is the coefficient of discharge and B the wheel's width. The coefficient of discharge for a vertical sluice gate is 0.61 [34]. The coefficient of discharge depends on the inclination of the sluice gate. In the equations above, it is assumed that the sluice gate is very close to the wheel such that no hydraulic jump can occur. Hence, it can be assumed that $a = h_{ds}$ (Equation 5.5 to Equation 5.6).

In order to avoid sudden stops of the wheel due to objects (leaves, wooden branches or plastic) in the water and to avoid flow rate reduction, a trash rack can be installed in front of the sluice gate. The trash rack is a grid that will filter the water before it enters the wheel. The trash rack is the blue-tilted parallelogram on Figure 5.2b. The trash rack has to be cleaned regularly.

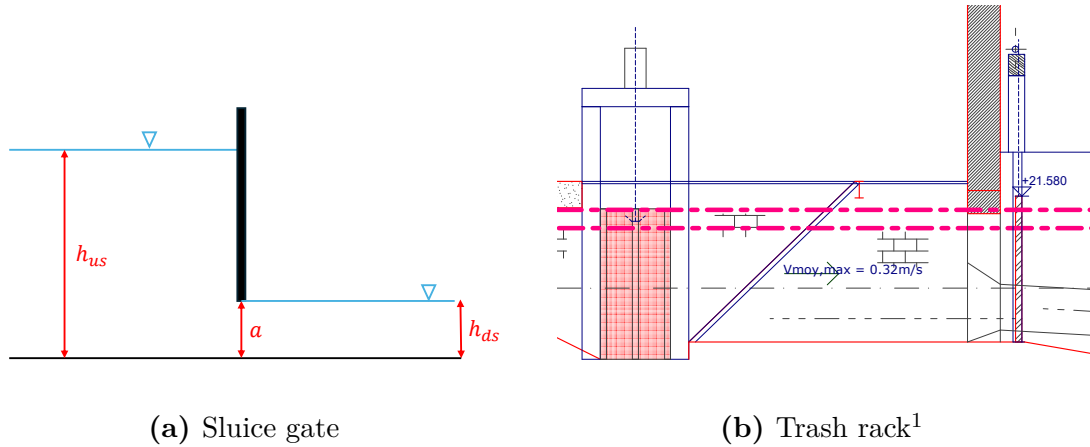


Figure 5.2: (a) Sluice gate and (b) trash rack used for flow rate control and debris filtering.

¹The figure obtained from the blueprints of the water wheel of Les Avins. The blueprints were made by Olivier Marchal.

5.2 Civil Work

The water wheel requires civil work to be installed. It will be composed of a flume (i.e., canal), sluice gates and the wheel enclosure. Figure 5.3 gives more insight into the typical topology of a water wheel site.

The flume will bring the deviation from the river to the wheel. The flume's slope is small while the river continues its natural path (the level curves on Figure 5.3 highlight the fact that the flume stays approximately on the same level curve as its intake). This is how the wheel can extract the potential energy of the water from the created height difference. Furthermore, two sluice gates are used to control the flow rate and the level of the river. The sluice gate on the left is used to control the flow rate that goes into the wheel, while the sluice gate on the right is used to control the flow rate into the flume and the level of the river. The sluice gate on the right is segmented into three "sub" sluice gates. By choosing to open only one of the sluice gates, the level of the upstream river can be controlled. In fact, looking at equation 5.5 if the width B of the river is changed at a constant flow rate, the height of the upstream river can be controlled.

5.3 Generator

The aimed application of this master's thesis is to provide electrical power to remote areas. Therefore, it is very likely that there is no grid connection available on the potential sites. This means that the generator will operate in an isolated grid, in stand-alone mode. This implies that not every type of generator can be used. This section will address different types of generators and discuss the advantages and disadvantages of each type. Because of its low efficiency and due to the high need for maintenance [35], the DC generator is not considered as a viable option.

The generator must satisfy the power balance at every time in order to avoid instabilities in the system. It means that the power produced by the generator must be equal to the power consumed by the load. The power demand of a load is divided into two components:

- The active power P which is the real power consumed by the load. This is the power that is used to do work.
- The reactive power Q which is the power that is used to create the magnetic field in inductive loads, or the electric fields in capacitive loads. This power is not used to do work but is necessary for the operation of the grid and of the load. The reactive power is not consumed by the load but is exchanged between the generator and the load.

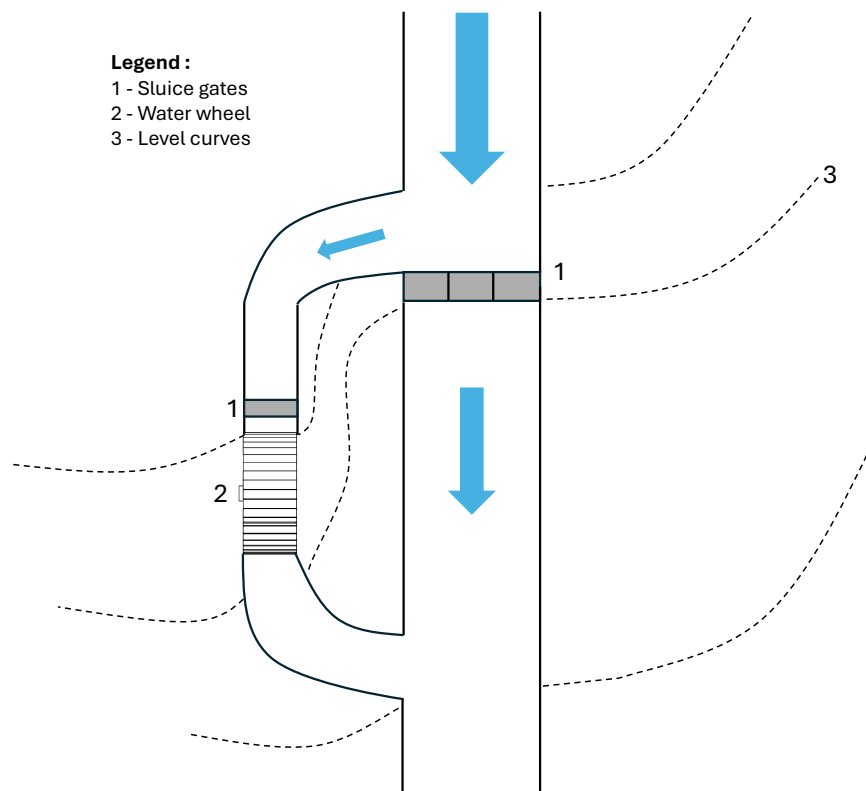


Figure 5.3: Overview of a typical water wheel site

If one of the load power demands is not satisfied, the system might become unstable or collapse. Therefore, the generator should ideally be designed such that the generator rated power corresponds to the maximal load power demand with the lowest annual flow rate.

That is if the generator is the only source of power in the microgrid. If there are other sources of power such that solar panels, the generator rated power could be lowered.

5.3.1 Synchronous Generator

There are two types of synchronous generators. The first type is the permanent magnet synchronous generator (PMSG), which uses a permanent magnet to create the rotating magnetic field. The second type is the wound rotor synchronous generator (WRSG), which uses copper windings and a current flowing through these windings to create a rotating magnetic field.

The required rotation speed of the synchronous generator is given by the following equation:

$$n = \frac{f \cdot 120}{p} \quad (5.8)$$

Where n represents the generator's rotational speed in rpm, f represents the frequency of the grid, and p represents the number of pole pairs.

5.3.1.1 Permanent Magnet Synchronous Generator

This generator has permanent magnets mounted on the shaft providing the rotating magnetic field that will induce a current in the stator. The PMSG offers high efficiency and a high power factor [36]. However, the voltage regulation of the PMSG is not possible, making it not suitable for stand-alone mode if it is directly connected to the grid. This is due to the fact that the PMSG has a fixed magnetic field determined by the magnets. Therefore, it has a constant power factor and can't control the voltage, since it can't provide varying active power. However, the voltage control can be solved by connecting a back-to-back converter to the generator terminal. The converter will ensure a proper voltage magnitude and a proper AC frequency. The PMSG has the advantage of having more pairs of poles than the WRSG. This allows lower speed operation regarding equation 5.8. The PMSG often has more pole pairs than a WRSG because, at a certain point, the WRSG becomes too big, too heavy and uneconomical. Therefore, the PMSG is preferred for gearless applications [37]. Furthermore, the back-to-back converter allows a variable speed operation.

5.3.1.2 Wound Rotor Synchronous Generator

The WRSG has a wound rotor. The latter is made of copper windings. The rotor is connected to the grid through slip rings allowing DC current coming from the stator to excite the copper windings and thus create a magnetic field (electromagnet). The slip rings used to deliver this current increase the need for maintenance due to wear and tear. Modifying the electromagnet field intensity via the DC current will increase or decrease the induced voltage on the stator windings. The voltage regulation is therefore easier to implement, since the excitation current can be directly controlled. The machine can thus adjust its active and reactive power production regarding the load requirements. The rotational speed of such generators is generally 1500 rpm (2 pole pairs).

5.3.2 Asynchronous (induction) Generator

The asynchronous generator is the most common type of generator; it's easy of conception, reliable, and robust. Hence, it is cheaper than the synchronous generators [38].

However, this generator needs a rotating magnetic field to start. The latter is provided by reactive power. In normal operation, the generator is connected to the grid, which provides a part of the necessary reactive power to magnetize the stator. Typically, the remaining reactive power is provided by capacitor banks installed near the generator to compensate for the high inrush current that can occur at generator startups. Without compensation high inrush currents can cause instabilities in the grid.

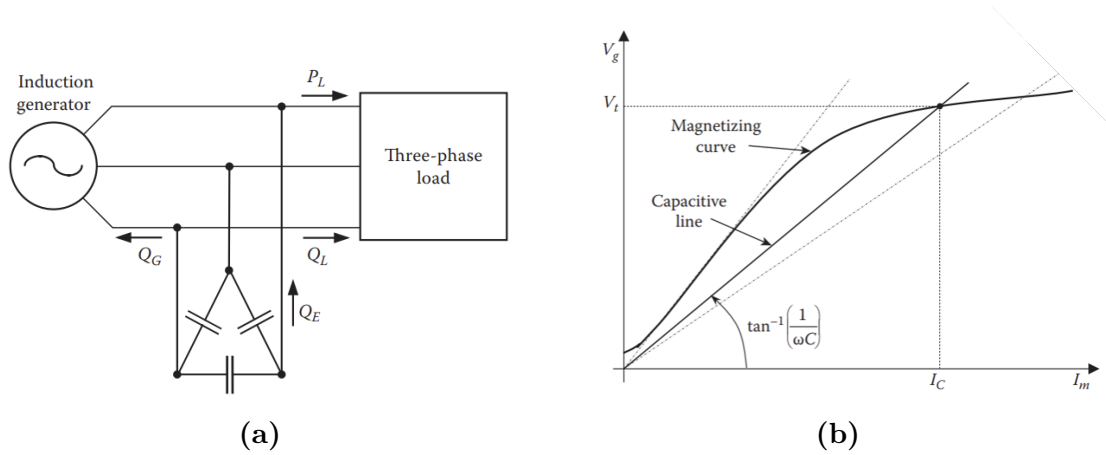


Figure 5.4: (a) Self-Excited Induction Generator schematic and (b) magnetizing curve with capacitive reactance intersection [39].

In stand-alone mode, the generator is not connected to the grid. Therefore, all the whole reactive power is provided by the capacitor banks. It is called a self-excited induction generator (SEIG). The way that this system works is shown in Figure 5.4a. The reactive power Q_G required to magnetize the stator is given by the interception of the magnetizing curve and the capacitive reactance [39]. This is shown in Figure 5.4b. The interception point should be designed so that the voltage at this point (terminal voltage V_t) is the voltage desired for the application. Then the value of the capacitor is chosen accordingly.

Voltage control is not possible on those machines unless using a power electronic compensator (e.g., STATCOM) at the generator's terminal [38, 40].

5.4 Gear reduction

As seen previously, the wheel's rotational speed is low (around 5–10 rpm). Section 5.3 addressed different types of generators. If the generator is a WRSG with 2 pairs of poles, the generator has to rotate at 1500 rpm. Therefore, a gear reduction system is required to increase the rotational speed of the shaft.

Each reduction system has the same governing equations. First, regardless of the losses in the reduction system, the power is conserved between the input and output of the system. The power is given by the following equation:

$$P_{in} = P_{out} \quad (5.9)$$

$$T_{in} \cdot \omega_{in} = T_{out} \cdot \omega_{out} \quad (5.10)$$

$$\frac{T_{in}}{T_{out}} = \frac{\omega_{out}}{\omega_{in}} = \frac{1}{N} \quad (5.11)$$

Where T is the torque, ω the angular speed and N the reduction ratio.

The equations mentioned above that if one wants to increase the output angular speed, the output torque has to decrease.

On the other hand, the inertia of the generator seen from the wheel is not the inertia of the generator itself. Based on the principle of energy conservation, the relationship between the input and output inertia can be expressed as:

$$\frac{1}{2} J_{in} \cdot \omega_{in}^2 = \frac{1}{2} J_{out} \cdot \omega_{out}^2 \quad (5.12)$$

$$J_{in} \cdot N^2 \cdot \omega_{out}^2 = J_{out} \cdot \omega_{out}^2 \quad (5.13)$$

$$J_{in} = \frac{J_{out}}{N^2} \quad (5.14)$$

Therefore, if a piece is spinning after the reducer, its apparent inertia before the reducer is its inertia divided by the reduction ratio squared.

The aimed application of the reduction system in the water wheel application is to increase the output angular speed; therefore, $N < 1$. For example, given a gear reduction of 1:300, it follows:

$$J_{in} = \frac{J_{out}}{\frac{1}{300^2}} = J_{out} \cdot 90000 \quad (5.15)$$

For several stages in a gear reduction system, one can write the equivalent inertia seen from the input:

$$J_{eq,in} = \sum_i \frac{J_i}{N_i^2} \quad (5.16)$$

Where N_i is the speed ratio between the input side and stage i . Inversely, the equivalent inertia of the generator side is small and thus more sensitive to the oscillation of the wheel.

In fact, by conservation of angular momentum:

$$J_{out} \frac{d\omega_o}{dt} = T_{m,out} - T_{e,out} \quad (5.17)$$

$$J_{in} \frac{d\omega_i}{dt} = T_{m,in} - T_{e,in} \quad (5.18)$$

$$J_{in} \frac{d\omega_i}{dt} = \frac{T_{m,out}}{N} - \frac{T_{e,out}}{N} \quad (5.19)$$

$$J_{in} \frac{d\omega_i}{dt} = \frac{1}{N} \cdot J_{out} \frac{d\omega_o}{dt} \quad (5.20)$$

$$\frac{d\omega_i}{dt} = N \cdot \frac{d\omega_o}{dt} \quad (5.21)$$

Therefore, since $N < 1$, a small variation in the wheel speed (low speed side) will cause enormous variation from the generator side (high-speed side).

To mitigate this effect, one can use a flywheel. The flywheel can be placed on the generator side to increase the inertia of this high-speed side. The flywheel will thus damp the oscillations, leading to a more stable system.

5.4.1 Gearbox

This type of gear reduction allows high reduction ratios. For example, the wheel rotating at 5 rpm coupled to a WRSG with 2 pairs of poles requires a reduction ratio of 1:300.

Such a ratio requires a heavy and expensive gearbox. For example the *FLENDER ONE H4SHN 200*² gearbox allows that reduction ratio. The gearbox is a helical gearbox with a 4-stage reduction with 96.3% efficiency.

²The datasheet is available in Figure B.2

Regarding the low-tech criteria, the gearbox does not fulfill the "accessibility" criterion. In fact, the gearbox is a complex machine that requires a lot of knowledge to be manufactured. Furthermore, it is hard to sustain maintenance and repair it on site. One can, however, think about providing training to local people. The gearbox also requires oil lubrication. After some time, the oil has to be changed. Even though oil is recyclable, this will likely not be on site of the water wheel, since it requires a refinery [41]. Therefore, it enters into conflict with the "accessibility" and the "sustainability" low-tech criteria.

5.4.2 Belt Drive

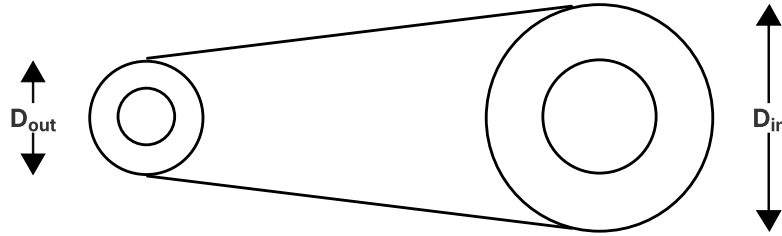


Figure 5.5: Pulley belt system. The big wheel is the drive gear and the small wheel is the driven gear. The speed of the driven gear is increased by the ratio of the diameters of the two wheels.

A pulley belt system can also be used to increase the rotational speed of the wheel. This system is much easier to manufacture and to maintain than a gearbox. However, the ratio of the pulley belt system is limited to 1:6 per stage [42]. Furthermore, the flat belt pulley system has an efficiency of 99% per stage. The system complies with the three main low-tech criteria, making it a viable option. However, it may require an electrical machine with a lower pair of poles, since too many stages will be required.

The speed reduction of such a system is given in Equation 5.22 (following the same convention as the gearbox). Figure 5.5 shows a schematic of the system where D_{in} is the diameter of the input pulley and D_{out} the diameter of the output pulley; therefore, the speed of the output shaft is increased.

$$N = \frac{D_{out}}{D_{in}} \quad (5.22)$$

The belt drive system has the advantage that, in case of a sudden stop, the belt will slip, ensuring that no other component in the system is damaged.

5.5 Dump Load

As stated in section 5.3, the generator must satisfy the power balance at every time. However, the water wheel can't adjust the power it extracts from the water. It can only be done by adjusting the flow rate but for this, a control system is required on the sluice gate, which adds extra complexity to the system.

Therefore, a dump load is required to dissipate the excess of power. The dump load is a resistive load that will dissipate the excess of power and ensure the electrical system stability. It can also be a more complex system such as a water heater or a battery. In fact, for better energy efficiency, it is better to use those instead of just dissipating the excess of power into heat.

Since dump loads are only used to dissipate the excess of power, in case of a sudden drop in power generation (e.g., a sudden change in the water flow rate), the water wheel will produce less power. If the demand is higher than the power produced, the system will collapse or trigger load shedding (i.e., deliberately disconnecting some loads to avoid a blackout). Therefore, batteries can be used to store the excess of power. The batteries can then be used to provide the lack of power when the water wheel is not able to produce enough power. The whole grid system with batteries and other devices will not be further investigated in this thesis. From this point forward, the term "dump load" refers to any combination of devices mentioned above. The simulations performed further in this thesis will only consider a safe operation case where the water wheel is able to produce enough power.

5.6 Practical Cases

The type of electrical machine depends on the application. In this section, three different applications will be addressed: a microgrid with a generator (WRSG) connected to a gearbox, a microgrid with a generator (PMSG) connected to a pulley belt system and finally grid connected generator.

5.6.1 Microgrid With WRSG Connected to a Gearbox (Figure 5.6)

The first system is such that the water wheel is the grid forming unit. The gearbox between the wheel and the WRSG increases the shaft speed to match the frequency requirements. The generator is connected to the electrical load controller (ELC), which is connected to the load and the dump load. The ELC is used as a speed controller. In fact, the mechanical equation that links the generator speed to the

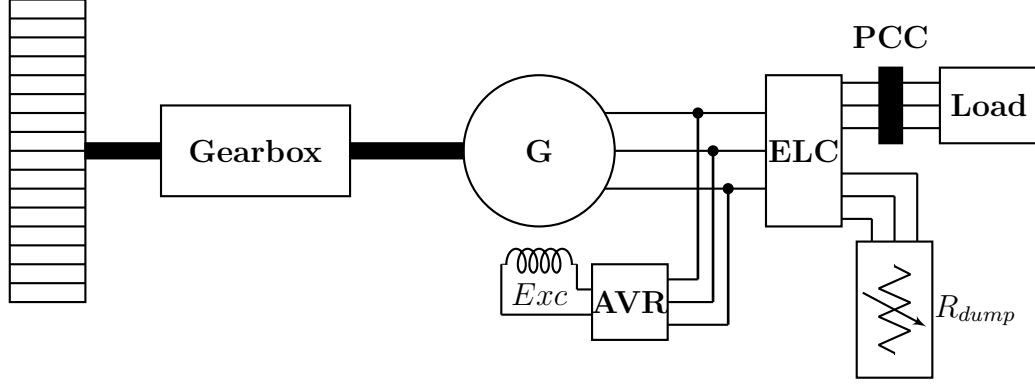


Figure 5.6: WRSG grid forming generator

mechanical and electrical power is given by:

$$J \frac{d\omega_m}{dt} = T_m - T_e \quad (5.23)$$

$$J\omega_m \frac{d\omega_m}{dt} = P_m - P_e \quad (5.24)$$

From those equations, one can see that the speed of the generator can be controlled by adjusting the electrical power.

For microgrid applications, the wheel is designed such that, at the nominal flow rate, the generator supplies the nominal power. If the load demand is lower than the nominal power, the excess of electrical power is dissipated in the dump resistors. If suddenly the flow rate decreases, the generator will produce less power. The ELC will detect this and will increase the resistor value of the dump load, since the power in this load is given by $P_{dump} = \frac{V^2}{R}$, increasing the value of the resistor will decrease the power dissipated by the load. It will therefore decrease the electromagnetic torque T_e such that the generator speed does not decrease outside the tolerated limits.

The generator must be designed such that it can satisfy the maximum load demand and therefore, in no-load conditions, the dump should be able to dissipate this power.

The voltage must also be regulated. For a WRSG, this can be done by adjusting the excitation current of the rotor. This is done by the automatic voltage regulator (AVR).

The AVR will take a small part of the output current and rectify it into DC to modify the excitation of the rotor electromagnet. This will thus change the stator terminal voltage and, therefore, the reactive power consumption/production of the generator.

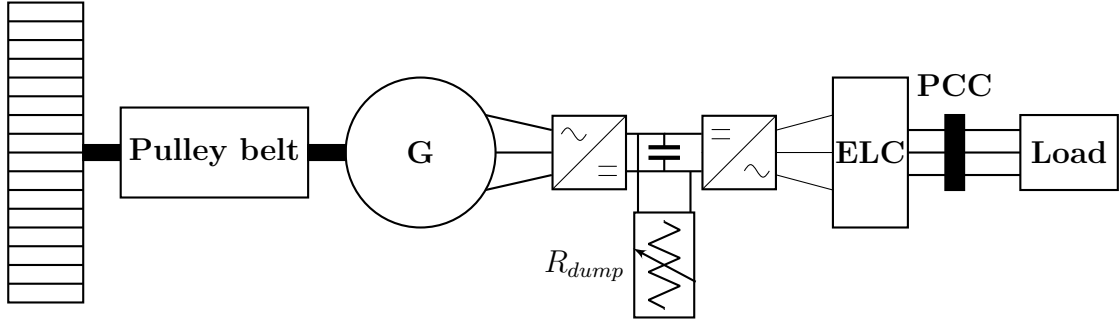


Figure 5.7: PMSG connected to a grid forming back-to-back converter

5.6.2 Microgrid With PMSG and Pulley Belt. (Figure 5.7)

In this case, the generator is connected to the wheel via pulley-belt stages. The generator will thus be a PMSG which has a lower rated rotational speed. The speed of the generator is controlled by the back-to-back converter. The speed is determined by MPPT (maximum power-point tracking) from which a controller will draw a current reference. The MPPT outputs a reference speed and therefore a reference torque given by [43]:

$$T_e = -\frac{3}{2}p\psi_f i_q = \frac{P_{PMSG}}{\omega} \quad (5.25)$$

Where p is the number of pole pairs, ψ_f the flux linkage and i_q the current in the q axis (i.e., in the park reference frame). Aligning the current reference on the q -axis will reduce Joule's losses [44]. The current reference is then transformed into a voltage reference. The voltage reference is then fed into an algorithm that controls the active rectifier (IGBT rectifier). By imposing the value of the generator's terminal, the reference current will be obtained. The output of the active rectifier is then fed into a DC bus. The active rectifier is preferred to a passive rectifier (diode rectifier) because it creates less current harmonics and therefore increases the generator's efficiency [45].

The DC voltage is set such that the grid side inverter (i.e., the right part of Figure 5.8) can inject a reference rms voltage of classical low-voltage grid magnitude (230 V rms in phase-to-neutral voltage). The DC bus voltage can be computed from the AC voltage using the following equation:

$$U_{DC} = 2 \cdot \frac{V_{L,peak}}{\sqrt{3}} \quad (5.26)$$

Where $V_{L,peak}$ is the peak phase-to-neutral voltage ($\sqrt{2} \cdot 400$). The factor 2 comes from the three-phase rectifier topology. In fact the peak to zero voltage for one

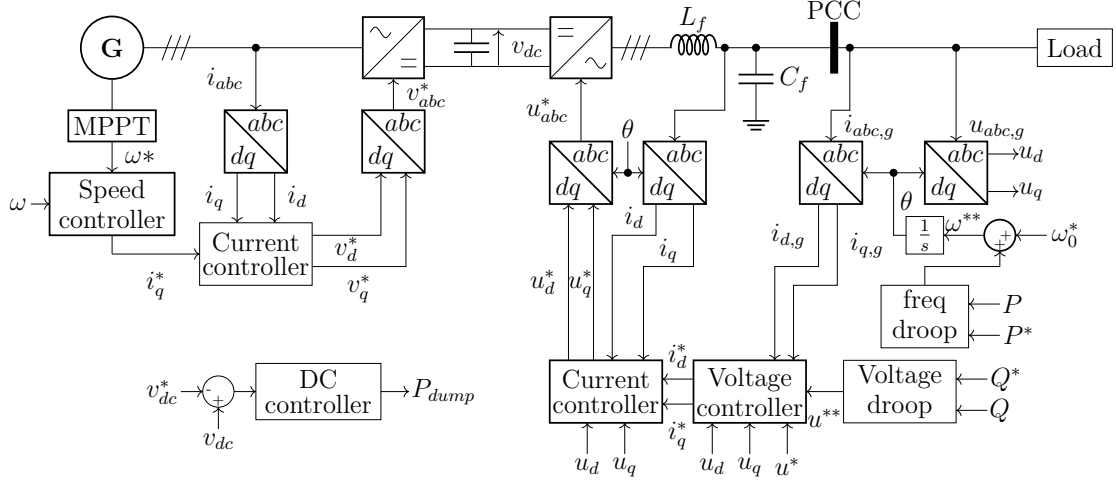


Figure 5.8: Control schematic of the back-to-back converter.

phase can be at most $\frac{U_{DC}}{2}$. Therefore, $V_{L,peak} = \sqrt{3}\frac{U_{DC}}{2}$ which is Equation 5.26. For a classical low-voltage grid, the required phase-to-phase voltage is 400 V rms. Therefore, U_{DC} should be at least 650 V. A value of 700 V will be chosen for safety margin.

As stated before, the water wheel can't adjust the power it extracts from the wheel; therefore, if there is too much power injected into the microgrid regarding the power demand, the excess of power has to be dissipated somewhere. Again, dump resistors can be used. The dump resistors are placed on the DC bus. The DC bus is connected to the grid side inverter (IGBT inverter). The inverter will convert the DC voltage into AC voltage and will inject the right amount of active and reactive power based on control signals that are measured at the point of common coupling (PCC). The whole conversion chain is in grid-forming mode. The converter will thus set voltage and frequency references.

Furthermore, it can be observed at Figure 5.8 that there are two droop controls at the output in the control loops of the inverter. Those two droop controls are there to mimic the behavior of a synchronous generator as if it was directly connected to the grid. The control is the frequency droop control. This control will set a frequency reference based on the difference in the active power produced by the generator and the active power consumed in the grid. Contrary to the traditional droop in power plants where the active power is changed based on the frequency, here the frequency is set based on the active power [37]. Similarly, the voltage droop control will set the voltage reference based on the reactive power consumed in the grid. Here the reference active power is set to 0.

Furthermore, the voltage in the grid is controlled such that the voltage vector is only oriented in the d-axis of the dq frame ($u_q^* = 0$) [43].

This system has the advantage of being able to operate at variable rotational speeds. In fact, since the MPPT is used, the generator will always extract the maximum power from the wheel. This is a great advantage, since it has been shown in chapter 4 that the wheel efficiency and power can highly vary due to flow conditions.

5.6.3 Grid Connected Generator (Figure 5.9, Figure 5.10)

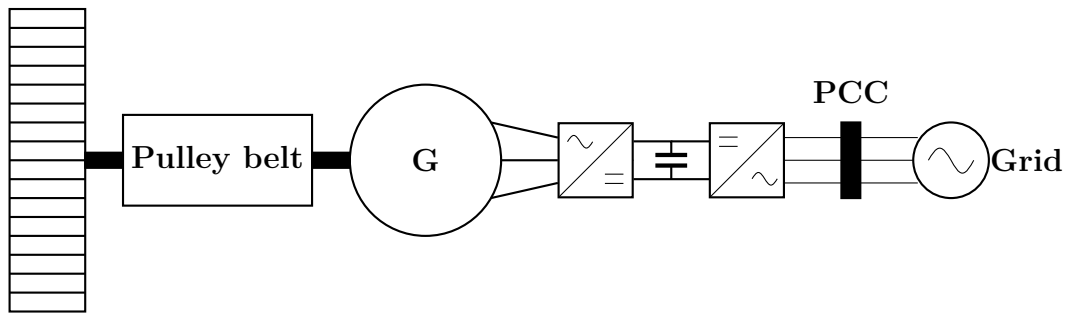


Figure 5.9: Decoupled generator indirectly connected to an existing grid

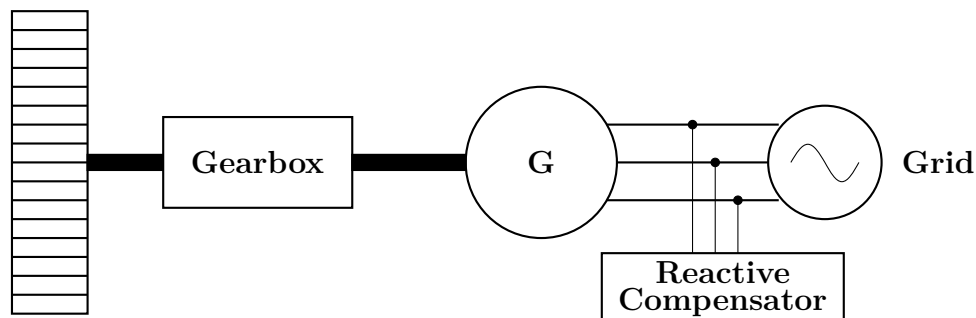


Figure 5.10: Schematic of a grid-connected induction generator

Here the generator can be an induction generator (see Figure 5.10) because the system is connected to the grid. Therefore, the grid provides the necessary reactive power to magnetize the stator. The voltage and frequency are set by the existing grid. As discussed in 5.3, a reactive compensator is used to ensure that the voltage of the grid remains stable.

However, this system requires a gearbox, since a typical induction generator has 2 pairs of poles and thus needs a speed of 1500 rpm.

The generator can also be a PMSG (Figure 5.9) indirectly connected to the grid via a back-to-back converter. In this case, the back-to-back converter can be used either in grid-forming or grid-following mode. The control strategy of both modes can vary from the one shown on Figure 5.8.

5.7 Simulated Cases

In this section, the two systems suitable for stand-alone operation are simulated. The two cases are:

- A WRSG connected through the load via a gearbox
- A PMSG connected through the load via a belt drive, and back-to-back converted

Both systems have dump loads to dissipate the excess of power.

5.7.1 WRSG system

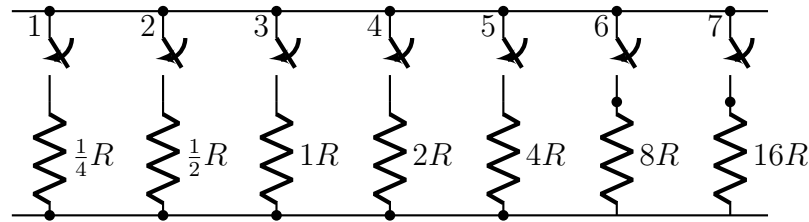


Figure 5.11: Dump load schematic

Since the flow rate coming into the wheel is only controlled manually via a sluice gate, the potential rapid changes in power demand have to be compensated by something in order to keep the frequency constant. This is done by using the dump loads. Dump loads will act as a speed controller for the generator. If the load demand is lower than the power produced by the generator, the dump loads will dissipate the excess of power. Various solutions exist to control the power delivered to the dump loads. Some of them use power electronics, which can be expensive and influence power quality by introducing harmonics.

The solution that best met the low-tech criteria was to use a set of resistors and switches. The way the system works is by using parallel resistors with binary increasing values (see Figure 5.11). This means that their values increase as such:

$$R_i = 2^i \cdot R \quad (5.27)$$

Where R is the base resistor value of the dump loads and $i \in [-2, -1, 1, 2, 3, 4, 5]$. Here the base value of the resistor is chosen such that it can dissipate 1 kW. The number of resistors was chosen in order to have a good resolution for the power they have to dissipate. Each time a switch is triggered, a voltage dip occurs. The bigger the power dissipated in a resistor in the switch circuit, the bigger the voltage dip. Therefore, a high number of resistors is desired in order to trigger the perfect amount of switches to match excess power. In fact, if too few resistors are used, there would be a poor power resolution, requiring to switch one and off a high resistance which, on average, corresponds to the excess power. This would lead to big and frequent voltage dip. However, for practical and economic reasons, it has to stay at a reasonable limit. At first, 5 resistors were used, but the voltage dips were too high, so the number was increased to 7 resistors.

The value of the resistor is designed based on the power they have to dissipate. Since the grid is a three-phase grid and given that the load is a star-connected load, the value of the resistor per phase is given by:

$$P_R = \frac{V_L^2}{R} \quad (5.28)$$

$$R = \frac{V_L^2}{P_R} \quad (5.29)$$

Where V_L is the line-to-line voltage and P_R is the power dissipated in the three-phase resistive load.

The resistors mentioned above are connected to a switch. This switch is a solid-state relay (SSR). SSR are electronic switches that can switch faster than conventional electromechanical ones, since SSR do not have movable parts. The switching frequency of SSR ranges between 0.5 ms and 1 ms [46]. The SSR is controlled by a microcontroller. The microcontroller will measure the frequency of the generator and will compare it to the reference frequency. If the frequency is too high, the microcontroller will close one or more switches. This will connect the resistors in parallel and thus decrease the total resistance. The microcontroller gets as input the power that has to be dissipated in the dump load.

In order to know the power required to be dissipated, a droop control is used. The droop control is a simple control strategy that is used to limit frequency deviations in power systems. In classical gas turbines, the droop is used as a primary control to increase or decrease the steam flow to the turbine in order to increase or decrease the mechanical power output (P_m).

In the case of this thesis, the droop control will act on P_e , the electrical power consumed.

The droop block diagram is shown in Figure 5.12. Two signals are first compared: the measured frequency (f_{meas}) and the reference frequency (f_{ref}). The difference between the two signals is then multiplied by a gain ($\frac{1}{\sigma}$). The term σ is the droop

coefficient. It will determine the amount of power to be dissipated based on the difference in frequency. The droop coefficient is defined as (see Figure 5.13):

$$\sigma = \frac{\Delta f}{\Delta P_{dump}} = 0.075 \text{ [Hz/kW]} \quad (5.30)$$

The maximum frequency deviation (Δf) tolerated in a microgrid is, according to ISO 8528-5 standard [47], ± 1.5 Hz, thus $\Delta f = 1.5$ Hz. The dump power range ΔP_{dump} is set to be the rated power of the generator.

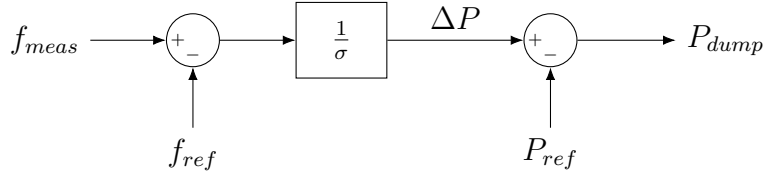


Figure 5.12: Droop control block diagram

The equation of the whole block diagram is given by:

$$P_{dump} = P_{ref} + \frac{1}{\sigma}(f_{meas} - f_{ref}) \quad (5.31)$$

Where P_{ref} and f_{ref} are the reference power and frequency respectively and are

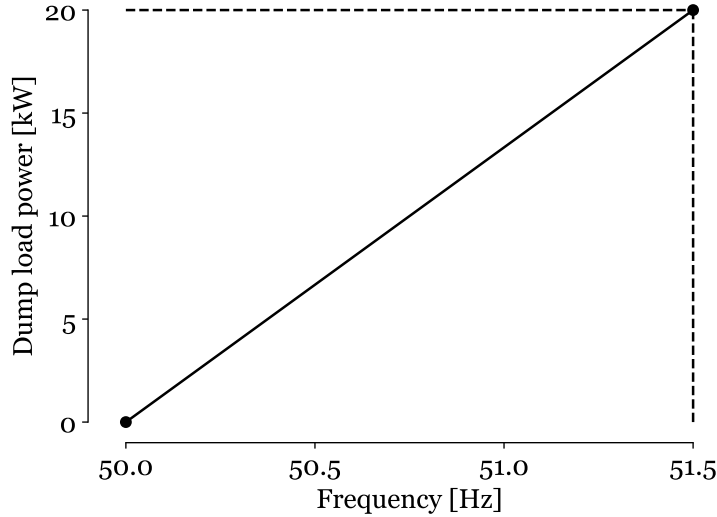


Figure 5.13: Droop control slope

set to 0 Hz and 50 Hz. Such that, when the generator output is equal to the load demand, the frequency will be equal to the reference frequency.

5.7.1.1 Microcontroller of the Dump Load

The microcontroller governs the operation of the dump load by measuring generator frequency and controlling solid-state relays (SSRs). After the droop control, the microcontroller receives as input the power that has to be dissipated in the dump load. The microcontroller then computes the number of switches that have to be closed. Since the resistors have a fixed value, it is not possible to dissipate exactly the required power. P_{dump} will thus be rounded to the closest value that can be dissipated by the dump load. Obviously, this will have an impact on the frequency, but the latter is under control via the droop. Figure 5.14 shows the algorithm used by the microcontroller.

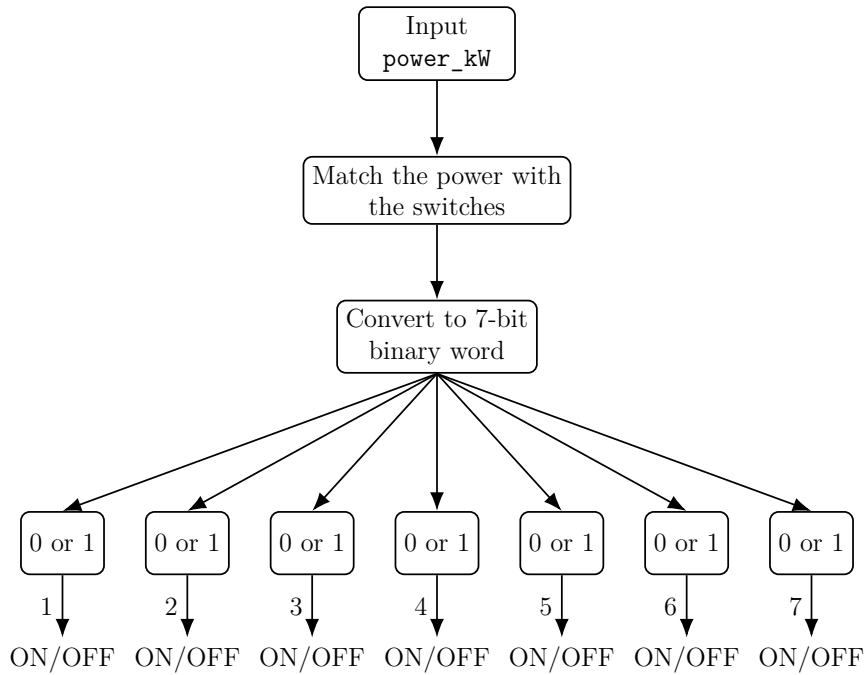


Figure 5.14: Microcontroller algorithm. The algorithm takes the power as input, round it to the closest value that can be dissipated by the dump loads and then converts it into a 7-bit binary word that contains the information which switches have to be closed. Each bit is then retrieved to turn on or off the corresponding switch.

5.7.1.2 Results

To ensure the system is properly working, a simulation was performed on Matlab/Simulink. The AVR is already implemented in Simulink. The default values

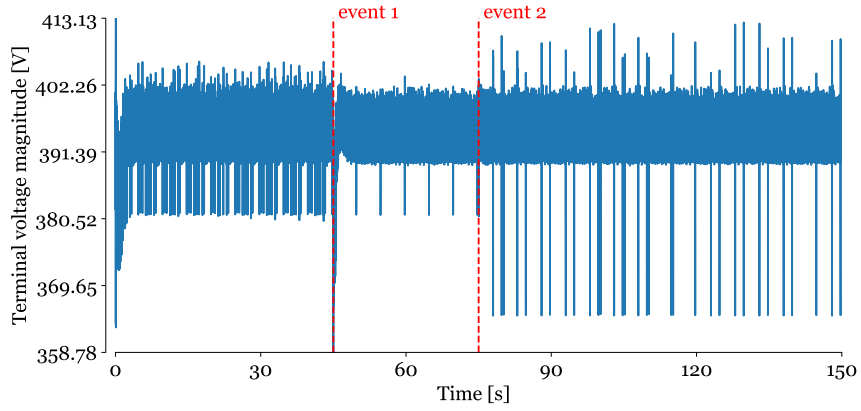
were used. The simulation consists of a WRSG connected to a load and a dump load. The generator has a rated power of 20kW / 25kVA and has 2 pole pairs, and a rated line-to-line voltage of 400 V. The base load is a three-phase resistive inductive load (series RL, 8 kW and 5 kVAr). The dump load is composed of 7 resistors. The value of the resistors can be found in Table 5.1. The input power was 17 kW with some oscillations around this value as discussed in chapter 4.

Table 5.1: dump load values

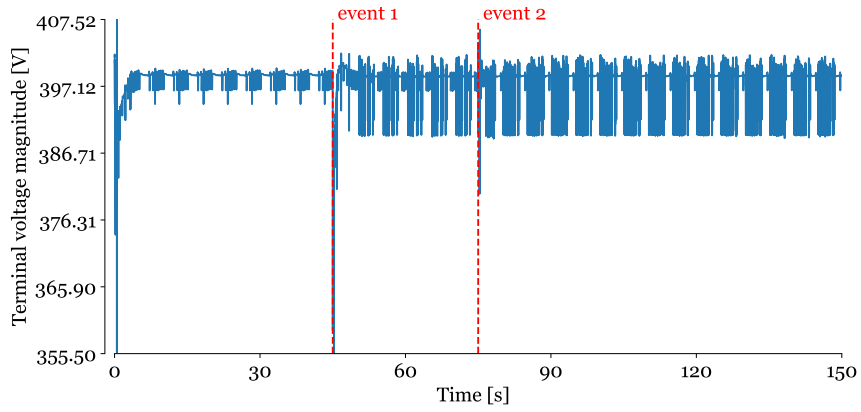
Load	Rated power [kW]	Resistor value [Ω]
1	0.25	640
2	0.5	320
3	1	160
4	2	80
5	4	40
6	8	20
7	16	10

Empty test

First a no-load test was performed to check the response of the dump load. All the power produced by the generator was thus dissipated into the dump load. The generator was initialized at 50 Hz and a torque similar to Figure 4.5 was given as input. As stated before, the torque of the wheel oscillates around its average value, which can cause significant variations in power, frequency and voltage. The inertia of the wheel was computed by building a model of the wheel in SolidWorks (see Figure B.1). The inertia of the gearbox was found in the manufacturer's datasheet (see Figure B.2); finally, the inertia of the generator was set 0.03 kg.m². The total computed inertia of the system seen from the generator side is 0.154 kg.m². In order to smooth those oscillations, a flywheel of inertia 10 kg · m² is placed on the generator shaft. Figure 5.15a and Figure 5.15b demonstrate the contrast between zero inertia and added inertia. This adds more stability to the system and therefore less stress on the various components. Figure 5.16 shows that the frequency stays below the threshold of 51.5 Hz. The threshold value is not reached because the generator is not operating at its rated power of 20 kW.

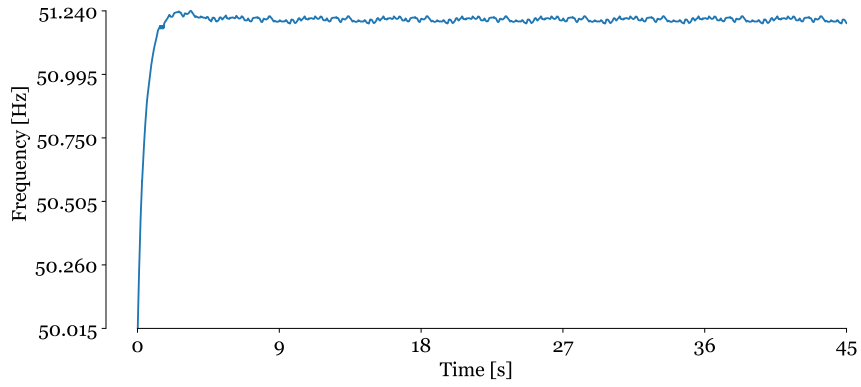


(a) Terminal voltage of the generator without inertia

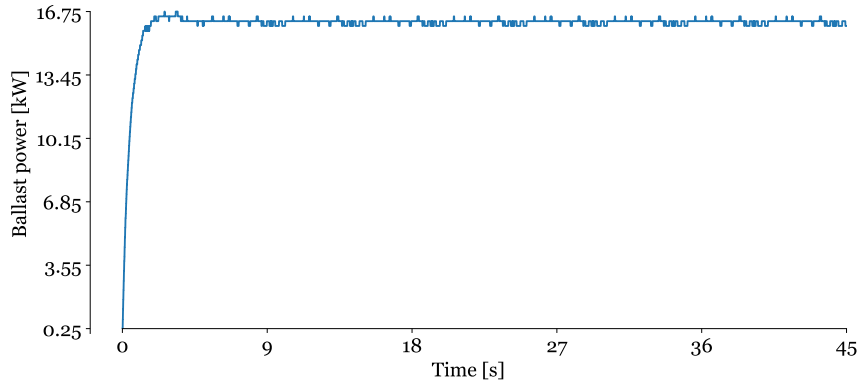


(b) Terminal voltage of the generator with increased inertia

Figure 5.15: Comparison of terminal voltage of the generator with and without inertia.

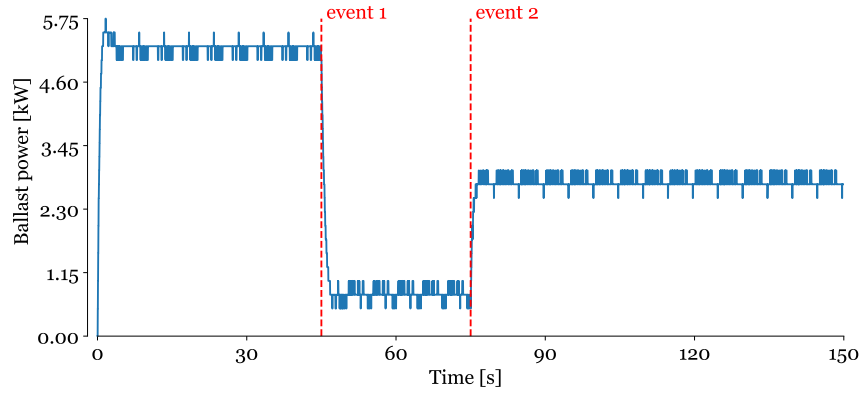


(a) Frequency during empty test

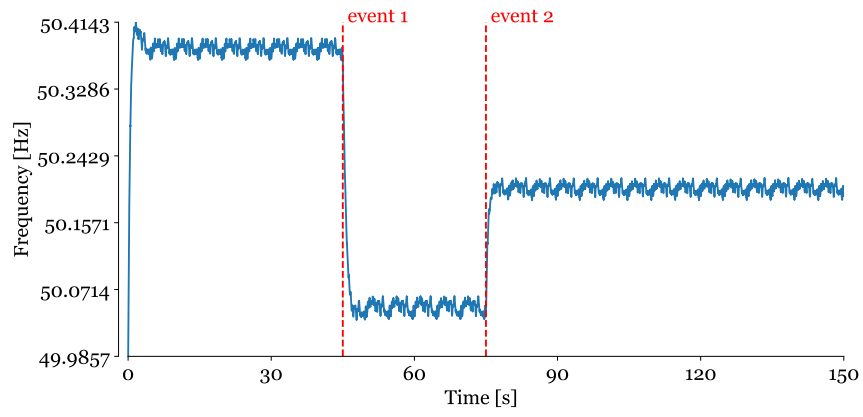


(b) dump power during empty test

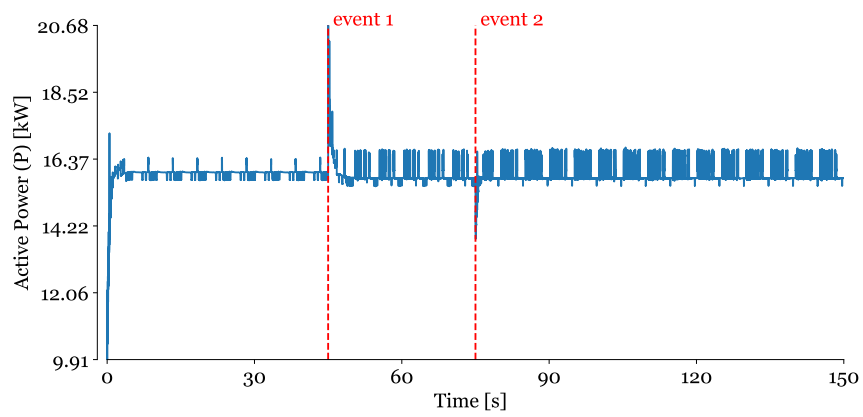
Figure 5.16: Empty test results showing frequency and dump power. The frequency stays under the threshold of 51.5 Hz.



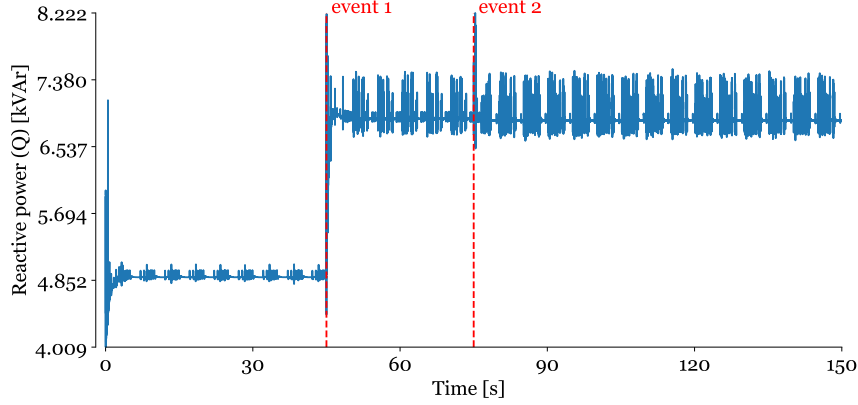
(a) dump power during dynamic test with load increase and decrease



(b) Frequency during dynamic test with load increase and decrease



(c) Active power during dynamic test with load increase and decrease



(d) Reactive power during dynamic test with load increase and decrease

Figure 5.17: Dynamic test results showing dump power, frequency, active power, and reactive power during load increase and decrease.

Dynamic test

In this test, the load is the base load mentioned above. Then two events occur at $t = 45s$ and $t = 75s$. The first event is a load increase of 4 kW and 2 kVAr. The second event is a load decrease of 2 kW. One can observe the results on figure Figure 5.17a. The system reacts as expected to the load variations and the dump algorithm dissipates the correct amount of power in the dump loads. One can also observe some power oscillations in steady state. This is due to the fact that the number of dump resistors is finite. Therefore, the power dissipated into the dump will never perfectly match the excess of generated power. It thus leads to frequent switching to stay around the frequency value corresponding to the excess of power and therefore, voltage dips.

5.7.2 PMSG System

Unlike the WRSG system, the PMSG grid forming system sets its own reference in frequency. Therefore, one can't base the decision of dissipating the excess of power in the dump load on the frequency. In this system, if there is an imbalance, the voltage on the DC bus will increase, since the inverter on the microgrid side will not inject as much power as the rectifier injects into the DC bus.

The equation of a capacitor is given by:

$$C \frac{dV}{dt} = I_{in} - I_{out} \quad (5.32)$$

Where C is the capacitance of the DC bus, I_{in} is the current injected by the rectifier and I_{out} is the current injected by the inverter. The voltage on the DC bus will increase if $I_{in} > I_{out}$ and decreases otherwise.

In order to keep the DC voltage constant and therefore, the power balance, a DC controller is used. The power that will be dissipated by the dump load will be modulated by a chopper [48], in this case a Buck converter. The governing equation of the Buck converter is given by:

$$V_{out} = \theta \cdot V_{in} \quad (5.33)$$

Where $\theta \in [0, 1]$ is the duty cycle applied to the switch inside the Buck converter. By adjusting the duty cycle, the output voltage and therefore, the power dissipated in the dump load can be controlled. The dump load consists of a DC resistor is used to dissipate the excess of power. The resistor is placed in parallel with the Buck converter. The power dissipated in the dump load is given by:

$$P_{dump} = \frac{(\theta U_{DC})^2}{R_b} \quad (5.34)$$

The value of the dump resistor R_b is designed to dissipate the nominal power of the generator (when $\theta = 1$). The duty cycle θ of the Buck converter is controlled by PI controller.

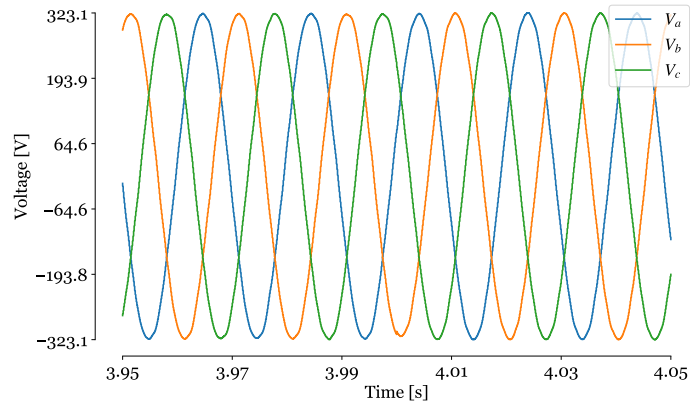
5.7.2.1 Results

The PMSG system was also simulated on Matlab/Simulink. The grid side of the back-to-back converter was implemented with the control strategy mentioned above. The gains of the various controllers were computed following the design methods of the power electronics company Imperix [49, 50]. These articles provided realistic delays due to signal processing in the whole converter. The filter sizing was made using the design methods of the PhD thesis of D. Solatalkaran [51]. The detailed computations can be found in Appendix C.

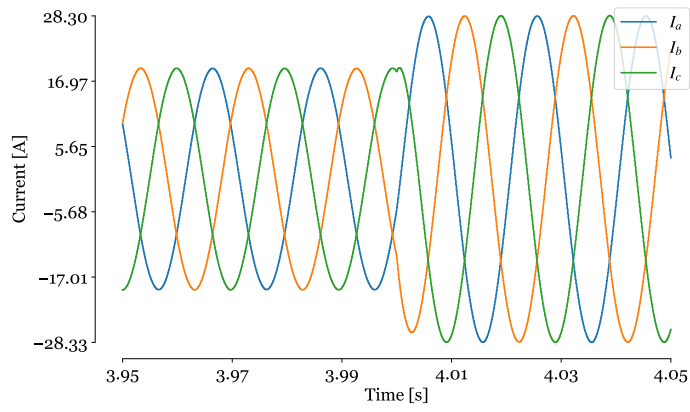
The generator side was modeled as a current source with ripple on the source to model the torque variations on the wheel. The input power due to this source on the DC bus was 17 kW on average.

Two loads were connected to the grid side inverter. One load that was constant through the whole simulation and the other that was triggered at $t = 4s$. The first load was a series RL load with a rated power of 8 kW and 5 kVAR. The second load was a series RL load with a rated power of 4 kW and 2 kVAR.

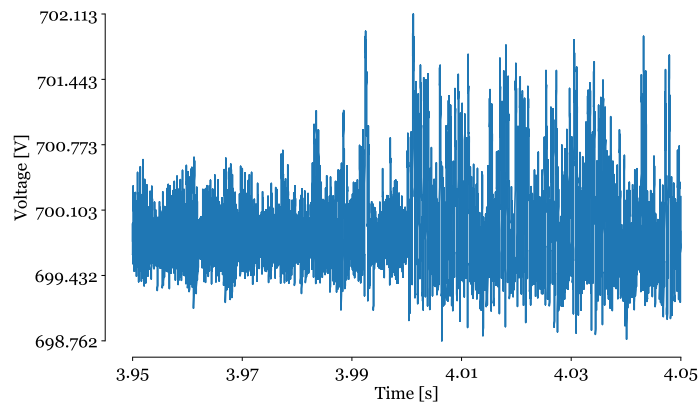
The results are shown in Figure 5.18. One can notice that the load triggering has no impact on the AC voltage magnitude because the grid-side inverter is controlled in such a way that its AC output voltage magnitude varies only with a change



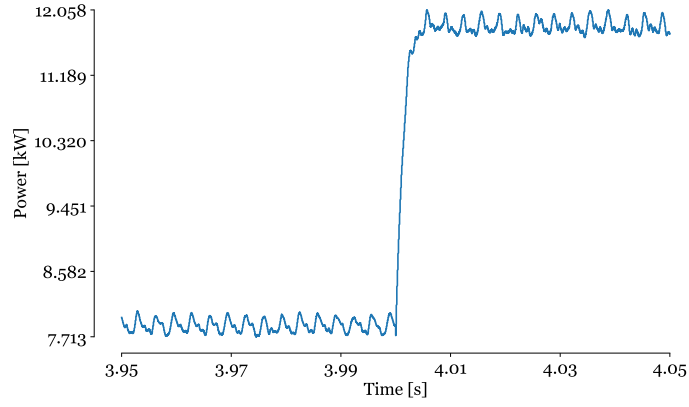
(a) Load voltage



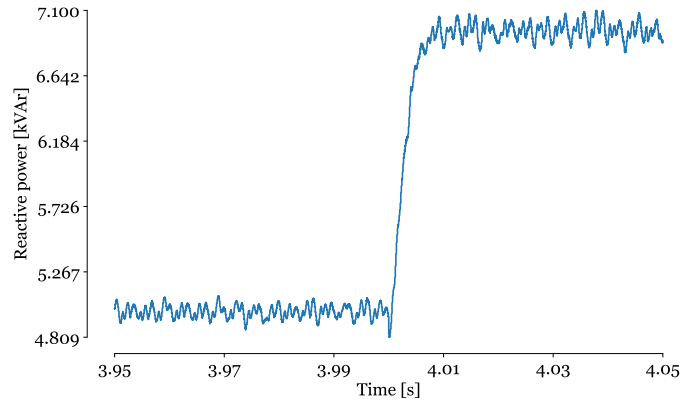
(b) Load current



(c) DC bus voltage



(d) Active power through the load



(e) Reactive power through the dump

Figure 5.18: Electrical results: (a) Load voltage, (b) Load current, (c) DC bus voltage, (d) Active power through the load, (e) Reactive power through the dump.

in reactive power demand in the system. One can also notice that the phase to ground voltage magnitude is not the rated voltage magnitude ($230\sqrt{2} = 325.3V$). This is because of the droop control of the reactive power. Since there is a demand for reactive power, the voltage magnitude is lower than the rated voltage. One can also observe on Figure 5.18d and Figure 5.18e that the target power is well reached by the system.

The droop coefficient of the active power is equal to the one computed in 5.30. The same value was used for the reactive power droop coefficient. This choice is arbitrary, but the voltage reference will never cross a threshold of $\pm 10\%$ of the voltage nominal value, as it is the standard in common power systems. One can also notice that the DC bus voltage is well oscillating between the threshold values. It is also not visible on the voltage plot but the frequency of voltage changes from 50.61 Hz to 50.24 Hz due to the droop control of the power.

Finally, one can observe in figure Figure 5.18c is maintained nearly constant around 700 V.

5.8 System Comparison

In this section, the two grid forming systems will be compared:

1. The grid forming system with the WRSG and the dump load
2. The grid forming system with the PMSG and the dump load

The comparison will be made based on the following criteria:

- The cost of the system
- The conversion efficiency of the system from the wheel's shaft to the electricity produced
- The low-tech criteria

5.8.1 Cost

Regardless of the wheel cost and the civil work costs, the different components of each system will be here compared. One should note that the prices are indicative and can vary depending on the supplier and the country.

WRSG System

- **Gearbox:** The price of a gearbox for a reduction ratio of 1:300 is around €18,500. One could think about using a higher pair of pole generators, but the price of the gearbox is determined by the input torque.
- **Generator:** The price of a 20 kW ($\approx$ 25 kVA) generator is around €2,150–2,550³ ⁴
- **ELC and dump loads:** For some ready to use ELC, the price is around €2,000 and each dump load is a few dozen euros. The total cost of the 7 dump loads is around €500.

PMSG System

- **Pulley-belt drive:** As stated before, to reach the 300 rpm of generator rated speed, one needs three stages of 1:4 pulley-belt drive. If the wheel shaft pulley is around 300mm, the bigger pulley one can have is 1200 mm. For such pulley, the price is around €1,000⁵. For the smaller pulley, the price is around €100⁶. The belt cost is around €100 per belt. This system requires two auxiliary shafts (other than the one of the wheel and the one of the generator) to support the pulley belt stages. Therefore, 4 bearings (4x€70), and two more shafts (2x€300) are required. This brings the total cost of the pulley-belt drive to around €4500.
- **Generator:** The price of a 20 kW - 300 rpm permanent magnet synchronous generator is around €4,700-6,000€⁷.
- **Back-to-back converter:** For the back-to-back converter, the price is around €3,000⁸. The price of the DC resistor is negligible compared to the back-to-back converter.

5.8.2 Efficiency

WRSG system

The efficiency given by the manufacturer (Stamford) of the WRSG is around

³<https://www.ato.com/>

⁴<https://www.stamford-avk.com/>

⁵<https://shop.eriks.be/fr/>

⁶<https://bep ltd.com/>

⁷<https://rx-energy.en.made-in-china.com/product>

⁸<https://www.poweralia.com/>

$\eta_g = 86.4\%$. As stated in section 5.4.1, the efficiency of the gearbox is $\eta_g = 96.3\%$. Therefore, the efficiency from the wheel's shaft to the electricity produced is given by:

$$\eta_{WRSG} = \eta_g \cdot \eta_{gearbox} = 0.864 \cdot 0.963 = 0.832 \quad (5.35)$$

PMSG system

The efficiency of the generator is given by the manufacturer (RX Energy) and given as $\eta_g = 95\%$. The efficiency of the back-to-back converter is around $\eta_{B2B} = 98.44\%$ [52]. The efficiency of the pulley-belt drive is 99% per stage. Since there are three stages, the efficiency of the pulley-belt drive is $\eta_{pulley} = 0.99^3 = 0.9703$. Therefore, the efficiency of the wheel's shaft to the electricity produced is given by:

$$\eta_{PMSG} = \eta_g \cdot \eta_{B2B} \cdot \eta_{pulley} = 0.95 \cdot 0.9844 \cdot 0.9703 = 0.92 \quad (5.36)$$

5.8.3 Low-Tech Criteria

Both systems fulfill the "usefulness" low-tech criterion. In fact, the technology is useful for energy production for the local community.

WRSG system

Regarding the "sustainability" criterion, the gearbox of the WRSG is not considered low tech. The gearbox is complex and hard to repair. Repairing the gearbox will cause long downtime, since it is required to disassemble the whole gearbox to inspect the cause of the failure. Furthermore, the gearbox requires a lot of knowledge and experience to be repaired. The "accessibility" criterion is thus not fully respected either. Therefore, training to the local community will be required. Furthermore, sometimes it may require to be fully replaced if the damage is too high [53]. Since the cost of the gearbox is high, it again enters into conflict with the "accessibility" criterion because of the high costs of a new gearbox.

PMSG system

The critical low-tech part of the PMSG is power electronics. The advantage of this system is that it is modular. In fact, the power electronics can be repaired quite easily. The manufacturer of the back-to-back converter (Poweralia) also sells spare parts. This favors the "sustainability" criterion. However, power electronics and its PCBs are not sustainable. Recycling them is possible but the fact that this system will be installed in remote areas, it will make recycling a hard task. Some

companies are currently starting to design sustainable PCBs, but it is still in the test phase [54].

Diagnosing and repairing power electronics requires specialized expertise, which may limit local accessibility. Therefore, the "accessibility" low-tech criterion is not respected unless adequate training is provided.

5.9 Summary

Table 5.2: Summary of the comparison between the two systems

Category	WRSG	PMSG
Gearbox	Yes	No (belt drive)
Power quality	Good	Good
Power electronics	A few (only the AVR)	A lot (back-to-back converter)
Variable speed operation	No	Yes
Cost	$\approx$ €23,000	$\approx$ €13,900
Efficiency	83.2%	92%
Sensitive to torque variations	Yes (requires more inertia)	No
Requires qualified personnel	Yes (for the gearbox)	Yes (for the power electronics)

As shown in Table 5.2, the PMSG system is cheaper and more efficient than the WRSG system. The PMSG system is also more modular and easier to repair. However, it requires more power electronics, which are not low tech. The WRSG system is also complex and requires expertise to be repaired. It can be concluded that the water wheel for electricity production is feasible, but it does not strictly respect the low-tech criteria; especially the "accessibility" and the "sustainability" criterion.

Chapter 6

Case Study: The Water Wheel of Les Avins

6.1 Introduction to the Case Study

In the village of Les Avins, located in the province of Liège, Belgium, a Sagebien water wheel was in operation until the '70s. The water wheel was used to drive a pump to supply water to the surroundings villages. The water was pumped such that it could be delivered to the local water tower situated 5km away from the wheel and 130m higher. The water wheel has a diameter of 9.20m [55]. Other geometrical parameters are given in Table 6.1.

Table 6.1: Geometrical parameters of the water wheel of Les Avins.

Parameter	Value
rotational speed	1.5 rpm
radial depth	1.3 m
width	1 m
distance between blades	0.4 m
number of blades	72
number of arms	8

The water that the wheel used to pump is now routed to the water tower by electric pumps. This causes heavy electrical bills for the municipal water supplier (CIESAC¹). If the water wheel could be restored, it could be reused to produce the electricity required to feed the electrical pumps. Therefore, decreasing the costs of the operation of the water supplier.

¹http://www.ciesac.be/ciesac_web/fr/index.awp

6.2 System Description

In order to drive the ancient pump, the rotational speed of the wheel had to be increased. This was done using two stages of spur gears. One stage having a ratio of 1:5 and the other having a ratio of 1:4. Thus, the total speed ratio was 1:20. The output speed of the system was 30 rpm.

The second stage of spur gears has a "fail" wheel. This means that if the wheel stops suddenly for some reason, the "fail" wheel, which has wooden teeth, will lose its teeth and the latter will ensure that no other component in the system is damaged. Photos of the system can be found in appendix D.

6.3 Reusability of the System

Assuming the wheel can fully be restored, as it was before its shut down, some parts of the system can be reused. In fact, no spur gear seems to be damaged and can thus still play their role in the system. The only part that needs to be replaced is the "fail" wheel.

A solution for this would be to use a pulley belt instead of a spur gear. This would allow for the same safety feature as the "fail" wheel with the same reduction ratio. Nevertheless, the pulley belt would need more space to be built in order to ensure the right cover angle on the pulleys.

However, the speed ratio is not enough to reach the required speed of any synchronous generator. As seen previously, a 300 rpm 10 pair of poles synchronous generator can be used for electricity production. Furthermore, it was seen in the previous chapter that this system favors the low-tech criteria more than a gearbox and decreases the costs of the system. The required rotational speed of 300 rpm means that the speed ratio of the existing system should be increased by a factor 10 (since the current reduction system brings the rotational speed from 1.5 rpm to 30 rpm). This can be done by either using two other stages of a pulley belt in the system or by using a small gearbox. The gearbox could only be a one stage planetary gearbox. A one stage gearbox is quite a simple system and thus easy to repair in case of failure. Additionally, since the site is in Belgium, companies in the neighborhood will be able to repair the small gearbox and other components of the system. This can be a good solution, since it is compact and can fit in the room where the system is located.

6.4 Required Power

The CIESAC nowadays has to pump 800m^3 of water per day ($\dot{m} = 9.26 \text{ kg/s}$). The water has to be pumped to a height of 130m over a distance of 5km. From this information, the power required to pump the water can be calculated. Following the shaft work equation, one can write:

$$W_m = v\Delta p + \Delta k + g\Delta z + \omega_f \quad [J/kg] \quad (6.1)$$

Where W_m is the mechanical power required to pump the water, v is the specific volume of water, Δp is the pressure difference, Δk is the kinetic energy difference, g is the gravity constant, Δz is the height difference and ω_f is the friction losses. Assuming no significant kinetic energy difference between the inlet and the outlet and considering that 130 m height is negligible regarding the atmospheric pressure (since it is an open system), one can write that $\Delta k = \Delta p = 0$. Assuming regular pressure losses, ω_f can be written as:

$$\omega_f = \lambda \frac{L}{D_h} \frac{v^2}{2} \quad (6.2)$$

The pipe diameter being $D = D_h = 0.3\text{m}$. The Reynolds number in the pipe is given by:

$$Re = \frac{4\dot{m}}{\mu\pi D_h} \simeq 43000 \quad (6.3)$$

The flow is thus turbulent. For a steel pipe of roughness $\epsilon = 0.045$, one can find λ by using Colebrook's formula. The value is obtained through some iterations and the converged value was: $\lambda = 0.13$.

Finally, the work required by the pump can be computed.

The resultant worth is $W_m = 1,312 \text{ kW/kg}$. The power required to pump this amount of water is then easily obtained:

$$P_{pump} = \dot{m}W_m = 12.150 \text{ kW} \quad (6.4)$$

Assuming a $\eta_p = 0.8$ efficiency for the electricity to power transmitted by the pump to the water, a $\eta_g = 0.90$ efficiency from the mechanical power of the generator shaft to the rectified electricity and $\eta_r = 0.93$ for the full gear reduction chain (0.98 for each spur gear and 0.96 for the small gearbox). The power that the water wheel should be able to produce is given by:

$$P_{wheel} = \frac{P_{pump}}{\eta_p \cdot \eta_g \cdot \eta_r} = 18.670 \text{ kW} \quad (6.5)$$

Finally, assuming an efficiency of $\eta_w = 0.8$ for the wheel to transform the hydraulic power into mechanical power. The hydraulic power that should be available in the flume is:

$$P_{water} = \frac{P_{wheel}}{\eta_w} \simeq 23.35 \text{ kW} \quad (6.6)$$

Therefore, knowing that there is a $\Delta h = 2.54 \text{ m}$ height drop on site, the flow rate of the water at the wheel inlet should be:

$$Q = \frac{P_{water}}{\rho \cdot g \cdot \Delta h} = 0.915 \text{ m}^3/\text{s} \quad (6.7)$$

6.5 Simulation

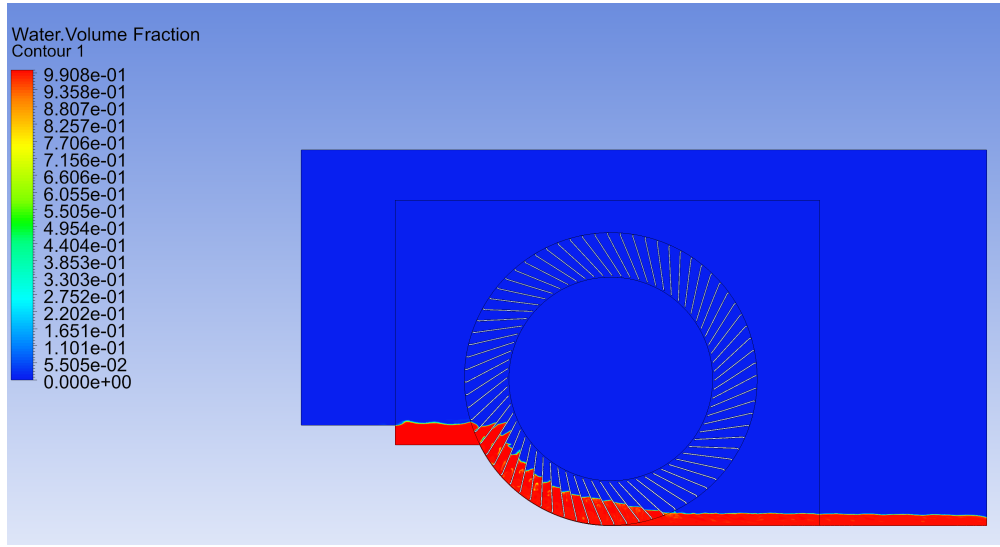


Figure 6.1: Simulation results of the water wheel. The total head H was found at 2.57 m.

A simulation was run in order to verify the assumption of the efficiency of the wheel and its power output found at equation Equation 6.7. The simulation was run with the same parameters as subsection 4.4.1. The wheel rotational speed was set to 1.5 rpm. Here, the domain is larger than in chapter 4 which yields the number of elements to be at 578556.

The simulation results showed that the wheel was not able to absorb the full flow rate of the water. Therefore, another simulation was run with a rotational speed of 2.5 rpm. Figure 6.1 shows that the wheel can absorb the required flow rate at 2.5 rpm. The efficiency found through the simulation was 81% confirming the assumption of $\eta_{wheel} = 0.8$ taken above. The power extracted from the wheel is

18.9 kW.

The current average flow rate near the site (Modave) is 1.453 m³/s [56]. In order to estimate the flow rate at Les Avins one can use the catchment area method. The catchment area of the Hoyoux river at Modave is 93.98 km² [56]. No information is available on the catchment area at Les Avins. Therefore, the ArcMap software was used to estimate the catchment area at Les Avins and to confirm the catchment area at Modave. Then, to find the flow rate at Les Avins will be given by [57] :

$$Q_{LesAvins} = \left(\frac{A_{LesAvins}}{A_{Modave}} \right)^a \cdot Q_{Modave} \quad (6.8)$$

Where $A_{LesAvins}$ and A_{Modave} are the catchment areas at Les Avins and Modave

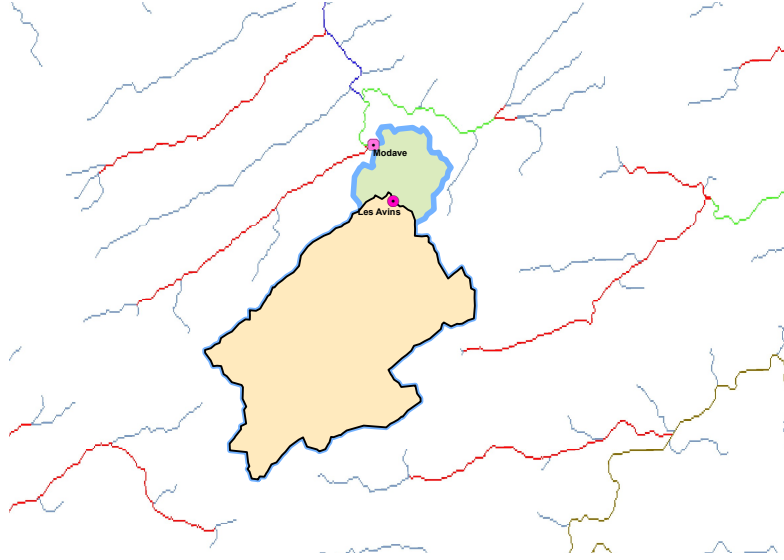
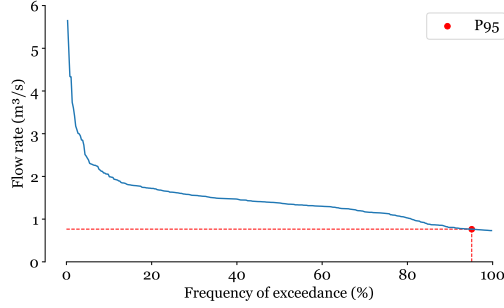


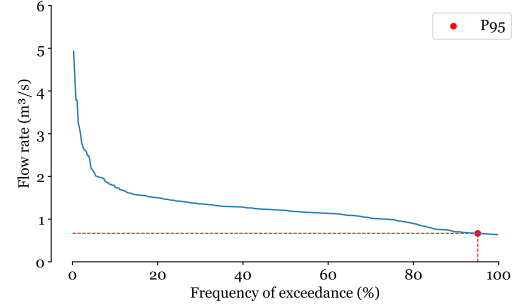
Figure 6.2: Map of the catchment areas of the Hoyoux river. The catchment area at Modave is 55 km² and the one at Les Avins is 48 km². The catchment area borders of Modave is shown in blue (around area green and beige) and the ones of Les Avins is shown in black (around the beige area)

respectively, $Q_{LesAvins}$ and Q_{Modave} are the flow rates at Les Avins and Modave respectively and a is the "regional coefficient" which is a correction factor that takes into account the local hydrological conditions. The value of a will be set as 1 here. The catchment area at Modave found of the software was 55 km² and the catchment area at Les Avins was found to be 48 km². The reason why the catchment area at Modave is smaller than the one given by the SPW was not found. It will be assumed that the ratio of catchment area obtained in ArcMap will be the same as in reality. Therefore, the flow duration curve at Modave can be used

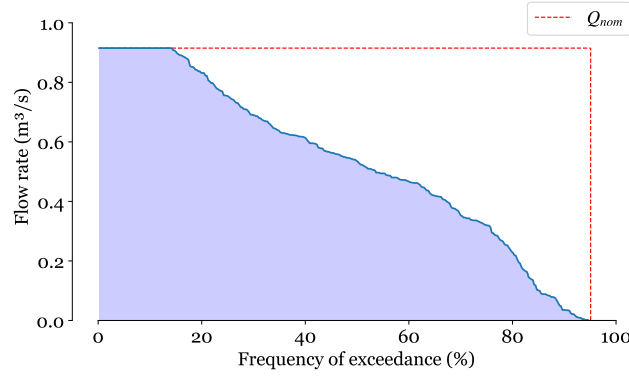
to estimate the flow rate at Les Avins by multiplying the flow rate at Modave by the ratio of catchment areas. Figure 6.2 shows the catchment areas at Modave and Les Avins. In order to verify that one can deviate the required flow rate from



(a) Flow duration curve of the Hoyoux at Modave with a $Q_{P95} = 0.763 \text{ m}^3/\text{s}$. [56]



(b) Adapted flow duration curve of the Hoyoux at Les Avins with a $Q_{P95} = 0.668 \text{ m}^3/\text{s}$.



(c) Flow rate that can be used by the water wheel to produce electricity. The blue area is the flow rate that can be used by the water wheel to produce electricity.

Figure 6.3: (a) Flow duration curve, (b) adapted flow duration curve, and (c) usable flow rate for electricity production.

the river (Equation 6.7), the rules on the minimum flow rate of the river should be respected. The Public Service of Wallonia (SPW) imposes that a reserved flow rate that should be maintained at anytime in the river to preserve the ecological balance of the river. The flow rate must always be above the 95th percentile of the flow duration curve [58]. For the Hoyoux river at Modave, this value is $0.763 \text{ m}^3/\text{s}$ [56] as it can be observed on Figure 6.3a. The corrected value is $0.667 \text{ m}^3/\text{s}$ at Les Avins, as shown in Figure 6.3b.

Therefore, to output the nominal electrical power to drive the pumps, the minimum flow rate that must flow in the river before the deviation is $1.582 \text{ m}^3/\text{s}$. This flow rate occurs 14.5% of the time when looking at Figure 6.3a. This means that the water wheel can be used to drive the pumps at nominal power 14.5% of the time. The rest of the time, the electricity that will be produced by the wheel will have to be completed by the electric grid to ensure the CIESAC daily water supply. Figure 6.3c shows the flow rate that can be used by the water wheel to produce electricity. By integration the flow rate over the frequency of exceedance (blue area), one can obtain the weighted average flow rate that can be used by the water wheel. The weighted average of the flow rate is $Q_{avg} = 0.611 \text{ m}^3/\text{s}$. The potential energy that can be produced by the water wheel yearly is given by the following equation:

$$E_{year} = Q_{avg} \cdot H \cdot g \cdot 366 \cdot 24 = 104.35 \text{ MWh} \quad (6.9)$$

While the energy that is required to pump the water yearly is given by:

$$E_{year} = P_{wheel} \cdot 366 \cdot 24 = 205.11 \text{ MWh} \quad (6.10)$$

Therefore, the water wheel can cover 50.88% of the energy required to pump the water yearly. This is an approximation since the wheel efficiency and the total head H is not constant regarding the flow rate and with the rotational frequency. However, this study gives an idea of the potential of the water wheel.

6.6 Case study conclusion

The case study of the water wheel of Les Avins shows that the water wheel could be restored and reused to produce electricity. The system can be adapted to drive a synchronous generator at 300 rpm. It would require a small gearbox or, belt-drive stages depending on the space available on site. It would additionally require and back-to-back converter.

The required flow rate to produce the nominal power is $0.915 \text{ m}^3/\text{s}$. The simulation results show that the wheel can absorb this flow rate at a rotational speed of 2.5 rpm with an efficiency of 81%. The water wheel can cover 50.88% of the energy required to pump the water yearly. This shows that the water wheel has a significant potential to reduce the costs of the CIESAC operation. Further economical viability studies should be conducted to assess the feasibility of the project.

Chapter 7

Conclusion

This master's thesis aimed to evaluate the feasibility of using water wheels for electricity production in remote areas, while aligning with the principles of the low-tech philosophy: usefulness, sustainability, and accessibility. The goal was to determine whether such a technology could serve as a viable alternative for decentralized renewable energy generation.

The first part of the thesis explored various types of water wheels, with a focus on the Zuppinger wheel due to its high efficiency, exhaustive design rules and suitability for low-head sites. Design parameters were established following historical references, particularly the guidelines from W. Müller. Next, detailed 2D CFD simulations were carried out using ANSYS Fluent to evaluate the performance of the wheel under various flow conditions and rotational speeds. Both curved and straight blade configurations were analyzed to assess their influence on efficiency and manufacturability.

The simulations showed that the curved blade design offered slightly higher efficiency and a wider operating range in terms of rotational speed. However, the straight blade configuration remained a relevant option due to its simpler design and manufacturing process, making it more accessible in low-tech contexts. The torque oscillation analysis also highlighted the importance of speed control to ensure stable operation when coupled with an electrical generator. Furthermore, the simulations showed the importance of the downstream water level and its impact on the wheel efficiency. It highlighted the fact that variable speed operation could optimize the extracted hydraulic power from the wheel.

Subsequently, the study addressed the mechanical-to-electrical energy conversion system. Different generator types were compared, including permanent magnet synchronous generators (PMSG), wound rotor synchronous generators (WRSG),

and asynchronous generators. Simulations of full systems demonstrated the trade-offs between cost, efficiency, and ease of implementation. Gear reduction systems, including belt drives and gearboxes, were considered to match the wheel's low rotational speed with the generator's requirements. The belt drive system showed less complexity than the gearbox, favoring the low-tech "accessibility" criterion.

If a water wheel were used for standalone electricity production, the following recommendations can be made to try to respect the low-tech criteria as much as possible.

- From a design perspective, straight blades provide slightly lower efficiency than curved blades. However, for simplicity and manufacturability, they are a recommended option for low-tech applications.
- For the mechanical transmission system, belt drives are preferred over gearboxes due to their simplicity, flexibility, and reduced maintenance requirements, especially in rural or isolated areas.
- The use of a PMSG is recommended for its high efficiency and low maintenance requirements. Nevertheless, it requires power electronics for grid connection, which may not completely align with the three main low-tech principles. This system maximizes energy extraction from the water wheel due to its variable speed operation.
- Implementing a robust speed regulation and load management strategy, including dump loads or smart controllers, is crucial to ensure system stability and power quality in varying flow and load conditions.

In conclusion, this thesis has demonstrated that a water wheel-based micro hydropower system can be designed to align with most of the low-tech values while providing reliable electricity for isolated communities. However, the electrical system intrinsically prevents all the low-tech values from being strictly respected, especially the "accessibility" and the "sustainability" criteria. Further work could include experimental validation of the numerical results, optimization of the control algorithms, and field-testing on real installation sites. Additionally, viability studies from a financial point of view need to be performed. Finally, it is essential to consider the full lifecycle of the system and favor locally available materials, modular components, and repairability to maintain adherence to low-tech principles.

Appendix A

Number of arms on the wheel

Table A.1: Blade parameters according to wheel diameter [20]

Wheel Diameter (m)	Number of Blades Z	Number of Arms A	Remarks
10.00	70	10	
9.00	60	9	
8.50	63	9	
8.00	54	8	Large flow rates
7.50	54	8	
7.00	48	8	
6.50	42	7	Large flow rates
6.00	40	7	Small / medium flow rates
5.80	36	6	Large flow rates
5.50	40	6	
5.00	36	6	Small water rates
4.50	30	6	
4.00	30	6	

Appendix B

System inertia

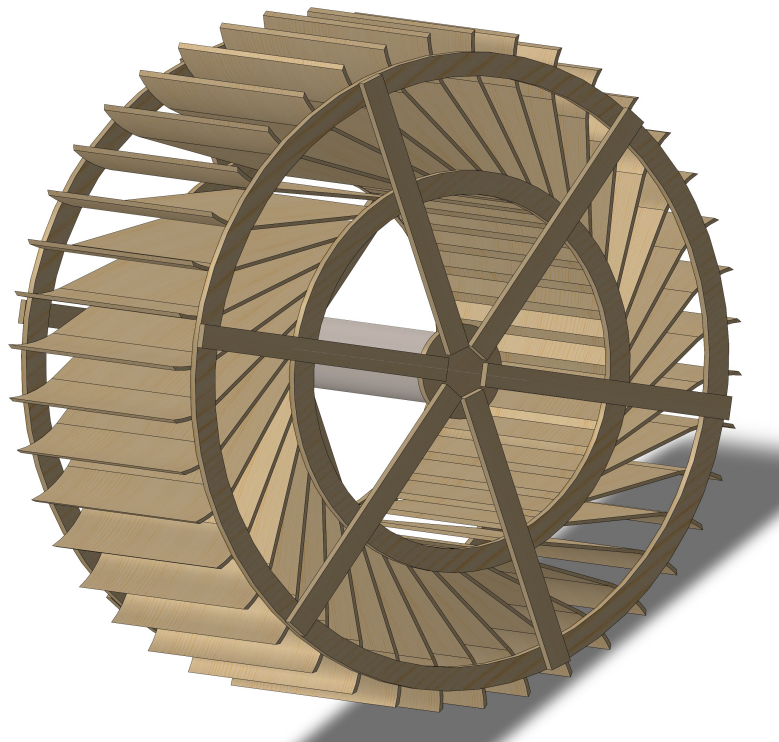
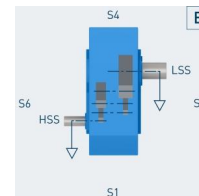


Figure B.1: Full wheel, computed inertia in SolidWorks : 11000 kgm^2 . The wheel is made of wood with a steel shaft.

DATASHEET

FLENDER ONE H4SHN 179

Project data	
Reference number	
Reference	
Configuration ID	QmkrV11xSECMTGimMwtaQ



Operating conditions			
Industrial sector	Power generation	Installation region	Europe
Machine	Crossflow turbine	Installation height	below 1000 m
Motor power	22 kW	Place of installation	Indoor - industrial halls
Power	22.0 kW	Air velocity	1.4 m/s
Torque	41115 Nm	Corrosivity category	C3
Speed HSS (n1)	1500 1/min	Min. ambient temperature	5 °C
Speed LSS (n2)	5.11 1/min	Min. start-up temperature ¹⁾	5 °C
Max. input torque (T1max)	224 Nm	Avg. ambient temperature ²⁾	25 °C
Application factor (KA)	1.2	Max. ambient temperature	40 °C
Operating cycle per hour	100 %	Gearbox support	Footmounted on steel
Starting frequency	up to 1 event/h	Rotation direction motor shaft ³⁾	Counterclockwise (ccw)
Alternating load directions	No	Rotation direction machine shaft ³⁾	Clockwise (cw)
Start-up method	Inverter	Rotation direction shaft end HSS ³⁾	Clockwise (cw)
		Rotation direction shaft end LSS ³⁾	Counterclockwise (ccw)

Product description			
Basics		Product properties	
Type	Helical gearbox	Real add. safety (sty) ⁶⁾	19.0 %
Stages	4	Nominal output torque (T2N_act)	58700 Nm
Mounting position	Horizontal	IP code (protection class)	IP44
Size	179	Minimum bearing lifetime	80.000 h
Design	B	Efficiency	96.28 %
Ratio	293.462	Power dissipation	0.8184 kW
Housing material	EN-GJL-x	Calculated oil sump temperature	≤ 90 °C
High speed shaft (HSS)		Oil quantity	87 l (without oil fill)
Shaft design HSS	Solid shaft - parallel keyway	Weight	1388 kg
Shaft-hub connection HSS S6	One keyway acc.DIN6885-B-N9	Mass moment of inertia J1 ⁴⁾	0.0035 kgm ²
Shaft dimensions HSS S6	d1 = 32.0mm m6; l1 = 80.0mm, G1 = 250.0mm	Mass moment of inertia J2 ⁵⁾	298.8361 kgm ²
Sealing type HSS S6	Radial shaft seal	Cooling	
Low speed shaft (LSS)		Additional air cooling	Without
Shaft design LSS ⁸⁾	Solid shaft - parallel keyway	Additional water cooling	Without
Shaft-hub connection LSS S3	One keyway acc.DIN6885-B-N9	Lubrication	
Shaft dimensions LSS S3	d2 = 170.0mm n6; l2 = 300.0mm; G2 = 270.0mm	Lubrication type	Dip lubrication
Sealing type LSS S3	Radial shaft seal	Breather	Standard
Shaft cover LSS	No	Oil type	PAO oil
Sensors		Oil viscosity	ISO VG 150
		oil drain	Screw plug

<https://flender.com/en/spc/QmkrV11xSECMTGimMwtaQ>

4/15/2025 | 19:51 (UTC) | 1/2

Figure B.2: H4SHN179 gearbox datasheet

Appendix C

Simulink models

Listing C.1: load microcontroller code

```
1 function turn_on = get_resistor_states(power_kw)
2     resistor_values = [0.25, 0.5, 1, 2, 4, 8, 16]; % in kW
3
4     % Round up to nearest 0.25 kW
5     step = 0.25;
6     rounded_power = ceil(power_kw / step) * step;
7
8     turn_on = ones(1, length(resistor_values)); % 1 = OFF,
9         0 = ON
10     remaining = rounded_power;
11
12     for idx = length(resistor_values):-1:1 % start from
13         largest
14         if remaining >= resistor_values(idx)
15             turn_on(idx) = 0; % turn on this resistor
16             remaining = remaining - resistor_values(idx);
17         end
18     end
19 end
```

3.1 Inverter output filter

The design rules given in [51] are as follows:

$$L_f = \frac{V_{dc}}{8.29f_{sw}0.1I_{rated}} \quad (C.1)$$

$$C_f = \frac{0.05P_{rated}}{2\pi f_g V_{rated}^2} \quad (C.2)$$

Where V_{dc} is the DC bus voltage, f_{sw} is the switching frequency, I_{rated} is the rated current, P_{rated} is the rated power, f_g is the grid frequency (50 Hz), and V_{rated} is the rated voltage. Therefore, with the following parameters:

$$\begin{aligned} V_{dc} &= 700 \text{ V} \\ f_{sw} &= 10 \text{ kHz} \\ I_{rated} &= 30 \text{ A} \\ P_{rated} &= 25 \text{ kVA} \\ V_{rated} &= 230 \text{ V} \end{aligned}$$

the filter inductance and capacitance are given by:

$$\begin{aligned} L_f &= 3 \text{ mH} \\ C_f &= 75 \text{ }\mu\text{F} \end{aligned}$$

3.2 PI controller gains

3.2.1 Current controller PI gains

Assuming a small resistance $R_f = 54 \text{ m}\Omega$, the PI gains for the current controller are given by [50]:

$$\begin{aligned} k_p &= \frac{L_f}{2T_d} \\ k_i &= \frac{R_f}{2T_d} \end{aligned}$$

Where T_d is the sum of all the delays in the current loop, which is set to $T_d = 1.5 \cdot T_s$, with $1/T_s = f_{sw} = 10 \text{ kHz}$, leading to:

$$\begin{aligned} k_p &= 10 \\ k_i &= 180 \end{aligned}$$

3.2.2 Voltage controller PI gains

The PI gains for the voltage controller are given by [49]:

$$k_p = \frac{C_f}{2T_{d,eq}}$$
$$k_i = \frac{k_p}{2^2 T_{d,eq}}$$

Where $T_{d,eq}$ is the equivalent delay in the voltage loop, which is set to $T_{d,eq} = 10 \cdot T_{d,i} = 10 \cdot 1.5 \cdot T_s$, with $1/T_s = f_{sw} = 10$ kHz, leading to:

$$k_p = 0.25$$
$$k_i = 41.66$$

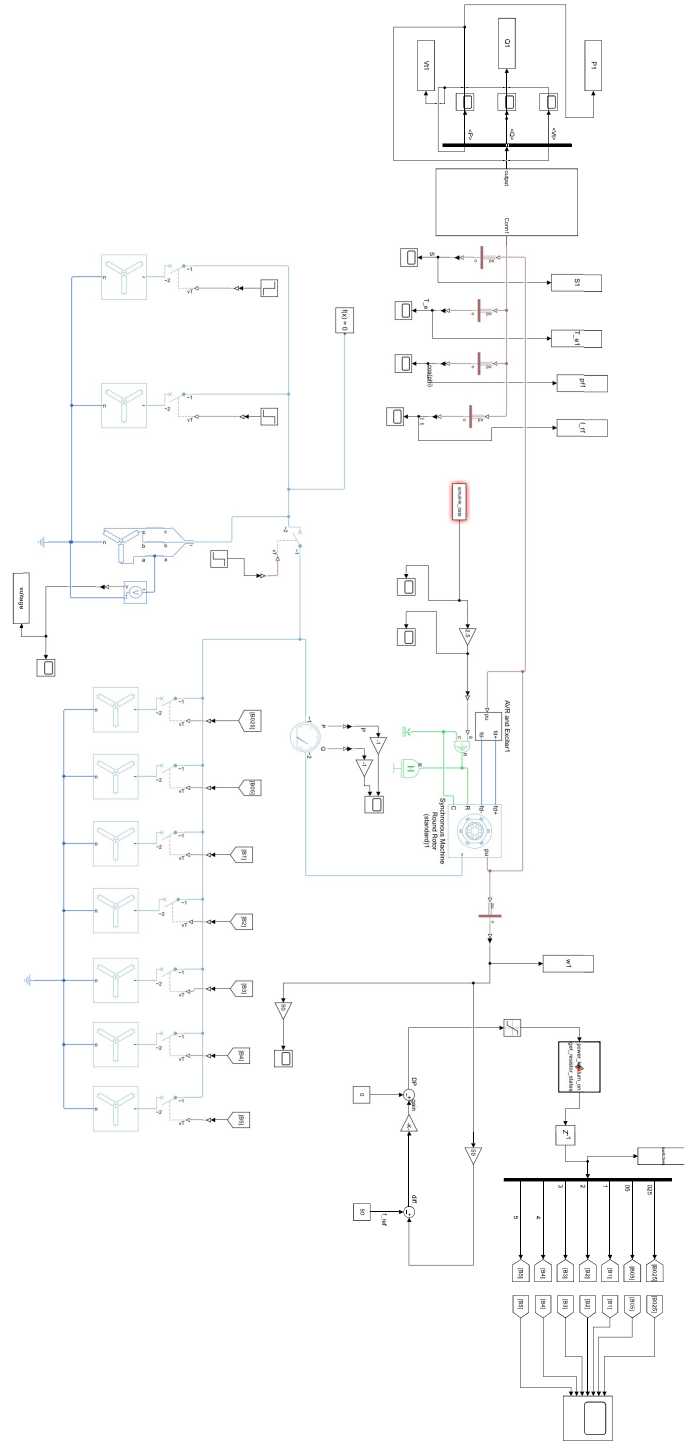


Figure C.1: Simulink model of the WRSG system

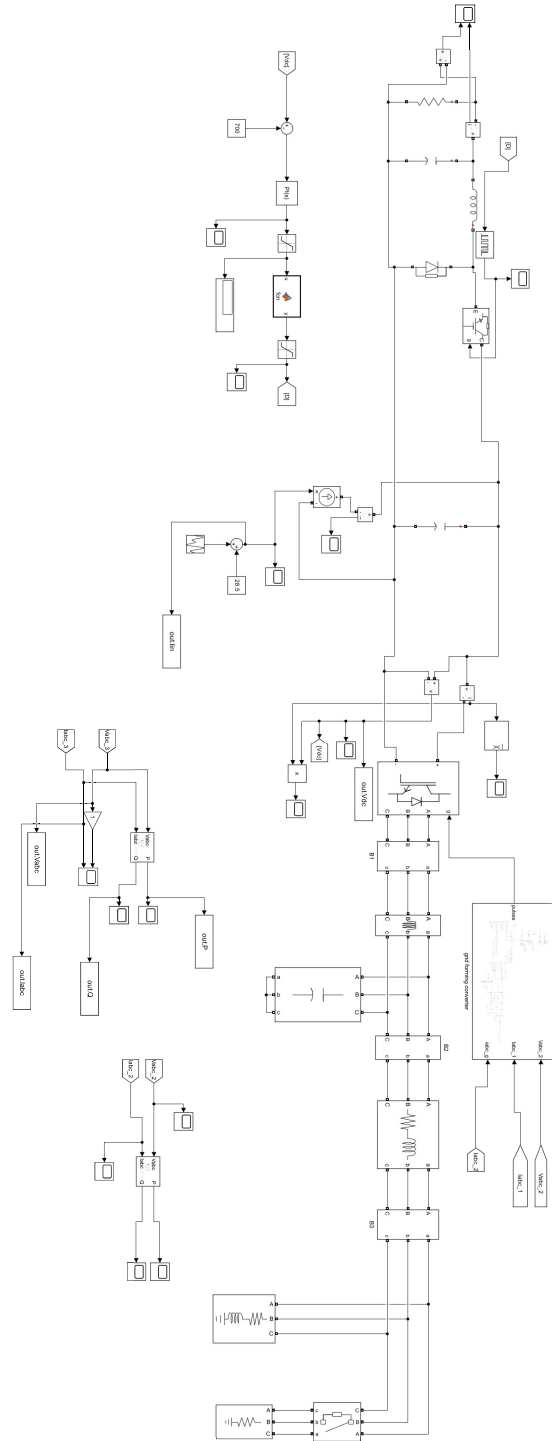


Figure C.2: Simulink model of the PMSG

Appendix D

Case study photos



Figure D.1: Drive gear of the reduction of 1:5



Figure D.2: Driven gear of the reduction of 1:5



Figure D.3: Drive gear of the reduction of 1:4 (fail wheel)



Figure D.4: Driven gear of the reduction of 1:4



Figure D.5: Sagebien Wheel of Les Avins

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