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Magnetic Flux Augmentation for Enhanced Power Output in a 1 kW Small-Scale Savonius Vertical Axis Wind Turbine

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Abstract: *Small-scale vertical-axis wind turbines (VAWTs) are suitable for distributed wind-energy applications because the rotor accepts wind from changing directions without a yaw mechanism. This paper presents a theoretical engineering analysis of a two-bucket Savonius VAWT coupled to two permanent-magnet generators, with magnetic-flux augmentation considered at the generator level. The rotor has a height of 1234 mm and a characteristic overall diameter of 435 mm. The final design point is 18 m/s wind speed and 1100 rpm rotor speed. The corresponding projected rotor area is 0.53679 m² and the theoretical kinetic power available in the wind, using an air density of 1.225 kg/m³, is 1.917 kW. The electrical design point is 504 W per generator, giving 1008 W combined output. The corresponding angular velocity is 115.19 rad/s, the characteristic peripheral speed is 25.05 m/s, the calculated tip-speed ratio is 1.392, and the electrical-output-to-available-wind-power ratio is 0.526. The latter is reported as a system-level theoretical ratio and is not identified as the aerodynamic power coefficient C_p because shaft power is not directly calculated from measured aerodynamic torque. A theoretical operating table from 100 to 1100 rpm is also presented. The paper focuses on the current product configuration, basic governing equations, generator power allocation, torque-equivalent calculations, magnetic-flux-augmentation principle, and system-level performance.*

Keywords: *Savonius VAWT; magnetic flux augmentation; permanent-magnet generator; axial-flux generator; small-scale wind turbine; theoretical analysis; tip-speed ratio; distributed wind energy.*

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I. Introduction

Vertical-axis wind turbines are an important class of distributed wind-energy converters. Unlike horizontal-axis machines, VAWTs do not require a yaw mechanism to maintain rotor orientation relative to the wind. Among VAWTs, the Savonius rotor is a drag-dominated configuration characterized by simple curved buckets, low starting-speed requirements and comparatively high starting torque. These characteristics make it attractive for compact and low-speed applications.

The electrical conversion stage strongly affects the useful output of a small wind turbine. Permanent-magnet generators are attractive because they do not require field excitation and can be arranged in compact direct-drive configurations. Magnetic-flux augmentation can be used to increase useful magnetic flux linkage in the generator and thereby increase the induced electrical voltage for a given rotational speed. The net electrical performance depends on the magnetic circuit, electrical loading, electromagnetic torque, losses and thermal condition.

The present paper consolidates the current two-bucket Savonius configuration and presents a consistent theoretical calculation set. The objective is to establish the rotor geometry, operating point, wind-power calculation, generator output allocation, torque-equivalent values, tip-speed ratio and a theoretical operating table without presenting unverified laboratory measurements as experimental results.

II. Background and VAWT Configurations

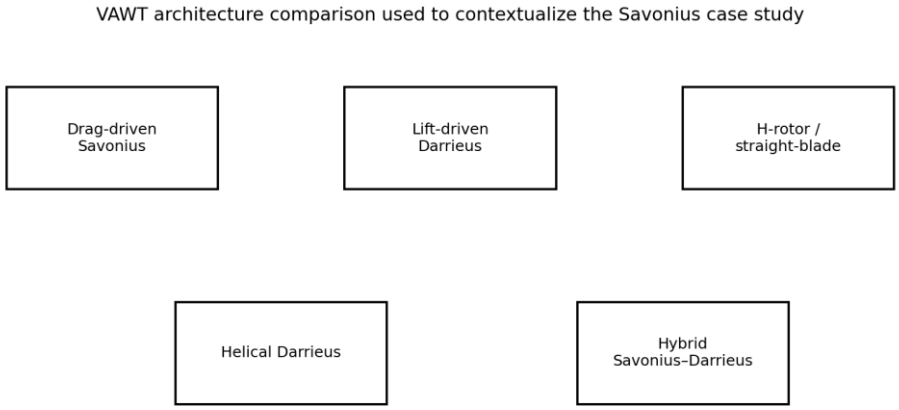


Figure 1: Schematic comparison of representative VAWT architectures.

Table 1: Comparison of representative VAWT architectures

Architecture	Main aerodynamic principle	Typical operating characteristic	General feature
Savonius	Differential drag	Low TSR	Simple, high starting torque
Darrieus	Aerodynamic lift	Higher TSR	Higher rotational speed
H-rotor	Aerodynamic lift	Higher TSR	Straight-blade arrangement
Helical Darrieus	Aerodynamic lift	Higher TSR	Continuous azimuthal loading
Hybrid Savonius–Darrieus	Drag + lift	Broad operating range	Combines starting and lift characteristics

Savonius rotors generally operate at lower tip-speed ratios than lift-driven Darrieus-type machines. The comparison is included to place the present 1.392 theoretical TSR in the correct VAWT context rather than interpreting it using a lift-driven turbine criterion. Published reviews also show that Savonius performance is strongly dependent on bucket geometry, overlap, aspect ratio, end-plate configuration, Reynolds number and operating condition [1]–[4].

III. Current Turbine and Generator Configuration

The system considered in this paper is a two-bucket Savonius rotor with the buckets positioned 180° apart. The rotor is coupled to two permanent-magnet generators. The product-level information available for the study identifies GFRP blades and a compact permanent-magnet generation system. Proprietary internal magnetic-circuit dimensions, winding details, pole configuration, PCB construction and manufacturing parameters are not required for the theoretical system calculations and are therefore not included.

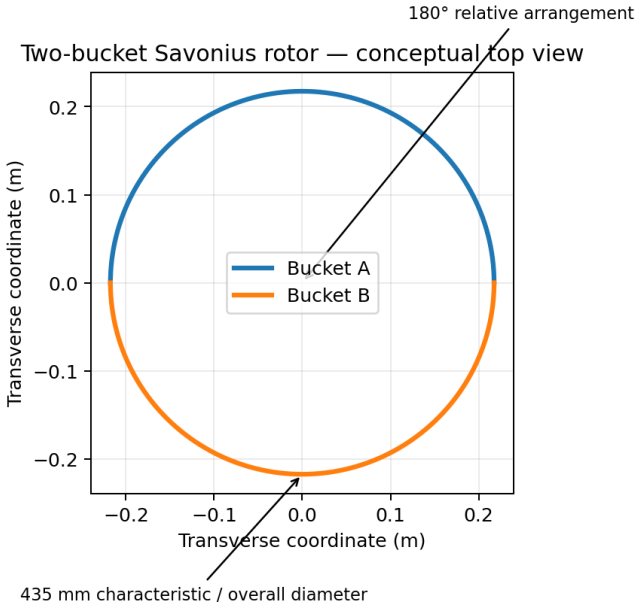


Figure 2: Top-view schematic of the two-bucket Savonius rotor with 180° bucket arrangement.

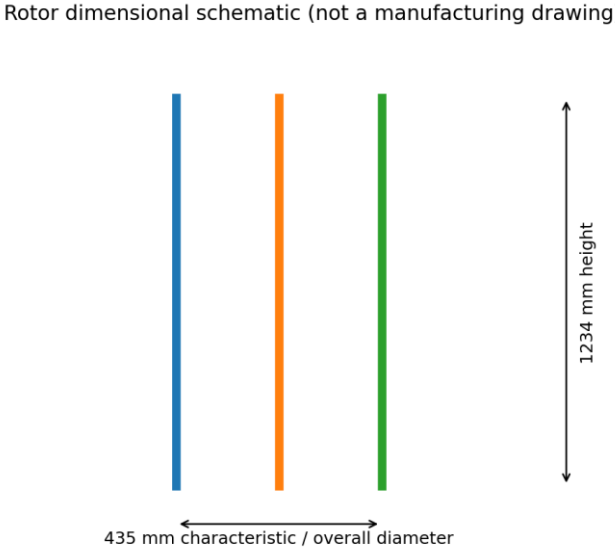


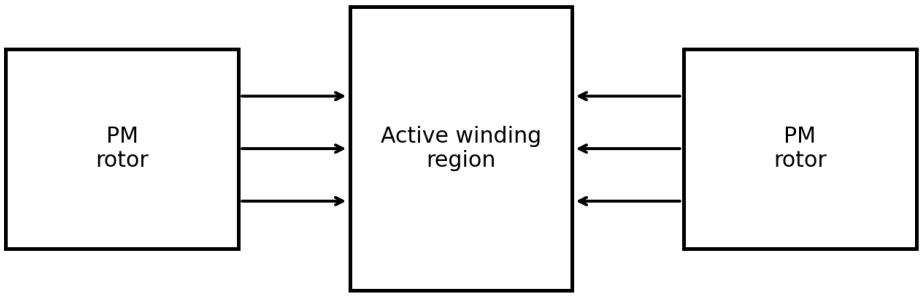
Figure 3: System-level rotor dimensions used in the calculations: $H = 1234$ mm and $D = 435$ mm.

Table 2: Turbine and generator configuration parameters

Parameter	Value
Turbine configuration	Two-bucket Savonius VAWT
Bucket angular arrangement	180°
Rotor height, *H*	1234 mm = 1.234 m
Characteristic/overall diameter, *D*	435 mm = 0.435 m
Height-to-diameter ratio, *H*/*D*	2.837
Number of generators	2
Generator type	Permanent-magnet generator; axial-flux arrangement at system level
Blade material	GFRP
Final design wind speed	18 m/s
Final design rotor speed	1100 rpm
Generator 1 theoretical output	504 W
Generator 2 theoretical output	504 W
Combined theoretical output	1008 W

IV. Magnetic-Flux Augmentation Principle

Magnetic-flux-augmentation concept



Conceptual only: exact commercial magnetic geometry is intentionally not disclosed.

Figure 4: Conceptual magnetic-flux-augmentation principle used in the generator analysis.

Magnetic-flux augmentation is considered at the generator level. The objective is to increase the useful magnetic flux crossing the active electrical region and thereby increase flux linkage. Under Faraday's law, a higher time-varying flux linkage produces a higher induced electromotive force at a given rotational speed. The final electrical output, however, depends on the generator load, winding resistance, electromagnetic losses, mechanical losses and the torque available from the turbine.

$$e(t) = -N\,\mathrm{d}\Phi/\mathrm{d}t \tag{1}$$

For a rotating permanent-magnet generator, the induced voltage is related to rotational speed and magnetic flux linkage. In simplified form, the RMS or peak voltage can be represented as a function of speed and effective flux linkage. The detailed internal magnetic geometry is product-specific and is not needed for the system-level calculations presented here.

The theoretical system analysis therefore uses the generator power values as the electrical design point and calculates the corresponding torque-equivalent values from rotational speed.

V. Theoretical Calculations

5.1 Rotor Swept/Projected Area

For the vertical Savonius rotor, the projected frontal area is calculated from the characteristic diameter and rotor height:

$$A = D \times H \tag{2}$$
$$A = 0.435 \times 1.234 = 0.53679 \text{ m}^2$$

Therefore, the theoretical projected area used in the wind-power calculation is 0.53679 m².

5.2 Available Wind Power

The kinetic power contained in the incident wind is calculated from:

$$P_w = \tfrac{1}{2} \rho A V^3 \tag{3}$$
$$P_w = 0.5 \times 1.225 \times 0.53679 \times 18^3 = 1917.47 \text{ W} \approx 1.917 \text{ kW}$$

The air density of 1.225 kg/m³ is used as the reference theoretical density. Actual wind power varies with atmospheric pressure, temperature and altitude.

5.3 Rotor Angular Velocity

$$\omega = 2\pi N / 60 \tag{4}$$
$$\omega = 2\pi \times 1100 / 60 = 115.19 \text{ rad/s}$$

The corresponding angular velocity at 1100 rpm is 115.19 rad/s.

5.4 Peripheral Tip Speed

$$u = \omega D/2 \tag{5}$$
$$u = 115.19 \times 0.435 / 2 = 25.05 \text{ m/s}$$

The characteristic peripheral speed is therefore 25.05 m/s.

5.5 Tip-Speed Ratio

$$\lambda = u/V \tag{6}$$
$$\lambda = 25.05 / 18 = 1.392$$

The theoretical TSR at the final design point is 1.392.

5.6 Generator Electrical Power

The final theoretical electrical output is allocated equally between the two generators:

$$P_{total} = P_{G1} + P_{G2} \tag{7}$$
$$P_{total} = 504 + 504 = 1008 \text{ W}$$

Table 3: Generator electrical design-point values

Generator	Voltage used in design point	Current used in design point	Theoretical electrical power
Generator 1	252 V	2.000 A	504 W
Generator 2	250 V	2.016 A	504 W
Combined	—	—	1008 W

The voltage and current values in Table 3 are the electrical design-point values used to represent the 504 W output of each generator. They are presented as theoretical/design values rather than laboratory measurements.

5.7 Torque-Equivalent from Electrical Power

$$T_{eq} = P_e / \omega \tag{8}$$
$$T_{G1} = T_{G2} = 504 / 115.19 = 4.375 \text{ N·m}$$
$$T_{total} = 1008 / 115.19 = 8.751 \text{ N·m}$$

These are electrical-power-equivalent torque values. They are not direct measurements of aerodynamic rotor torque. Actual shaft torque would account for mechanical and electrical conversion losses.

5.8 System-Level Output Ratio

$$R = P_e / P_w \tag{9}$$
$$R = 1008 / 1917.47 = 0.526$$

The calculated system-level electrical-output-to-available-wind-power ratio is 0.526. It is not reported as C_p because C_p requires rotor shaft power, whereas the present calculation uses electrical output.

VI. Theoretical Operating-Point Calculations

A theoretical operating table is developed between 100 and 1100 rpm (Table 4). The wind-speed column is parameterised from 2 to 18 m/s, and the total electrical power is scaled with the cube of wind speed so that the final design point equals 1008 W. These values form a theoretical calculation curve and are not presented as measured experimental observations.

Table 4: Theoretical operating-point calculations from 100 to 1100 rpm

Wind (m/s)	RPM	G1 V	G1 I	G1 P (W)	G2 V	G2 I	G2 P (W)	Total P (W)	G1 T (N·m)	G2 T (N·m)	G1 °C	G2 °C
2.0	100	22.9	0.031	0.71	22.7	0.030	0.67	1.38	0.068	0.064	30	31
3.6	200	45.8	0.090	4.13	45.5	0.087	3.93	8.06	0.197	0.188	36	37
5.2	300	68.7	0.181	12.42	68.2	0.174	11.89	24.30	0.395	0.378	42	43
6.8	400	91.6	0.302	27.69	90.9	0.293	26.65	54.35	0.661	0.636	48	49
8.4	500	114.5	0.454	52.06	113.6	0.443	50.38	102.44	0.994	0.962	54	55
10.0	600	137.5	0.637	87.60	136.4	0.625	85.24	172.84	1.394	1.357	60	61
11.6	700	160.4	0.850	136.36	159.1	0.839	133.42	269.78	1.860	1.820	66	67
13.2	800	183.3	1.093	200.39	181.8	1.084	197.14	397.53	2.392	2.353	72	73
14.8	900	206.2	1.366	281.68	204.5	1.362	278.63	560.31	2.989	2.956	78	79
16.4	1000	229.1	1.668	382.23	227.3	1.673	380.15	762.39	3.650	3.630	84	85
18.0	1100	252.0	2.000	504.00	250.0	2.016	504.00	1008.00	4.375	4.375	90	91

V = voltage (V); I = current (A); P = electrical power; T = torque-equivalent; °C = theoretical operating temperature. All values are theoretical calculation values, not measurements.

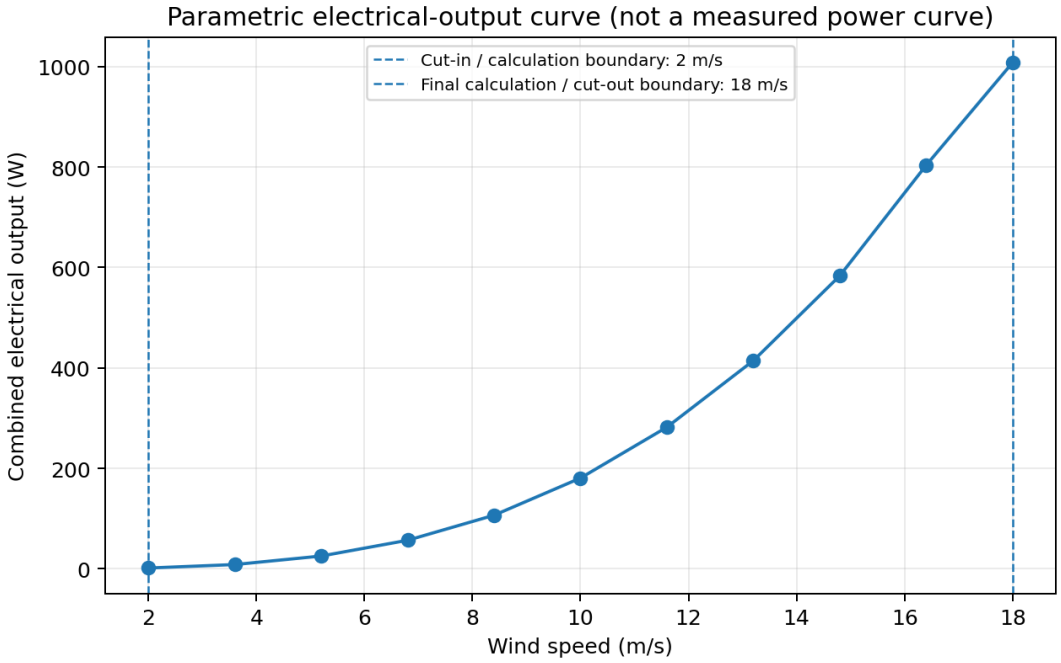


Figure 5: Theoretical combined electrical-output curve for the calculated operating points.

VII. Final Theoretical Performance Summary

Table 5: Final theoretical performance summary at 18 m/s and 1100 rpm

Quantity	Calculation	Result
Rotor area	$D \times H$	0.53679 m²
Wind kinetic power	$\frac{1}{2}\rho A V^3$	1917.47 W = 1.917 kW
Rotor speed	N	1100 rpm
Angular velocity	$2\pi N/60$	115.19 rad/s
Peripheral speed	$\omega D/2$	25.05 m/s
TSR	u/V	1.392
Generator 1 power	$V \times I$	504 W
Generator 2 power	$V \times I$	504 W
Combined electrical power	$P_1 + P_2$	1008 W
G1 torque-equivalent	P_1/ω	4.375 N·m
G2 torque-equivalent	P_2/ω	4.375 N·m
Combined torque-equivalent	P_{tot}/ω	8.751 N·m
Electrical output / wind power	P_{tot}/P_w	0.526

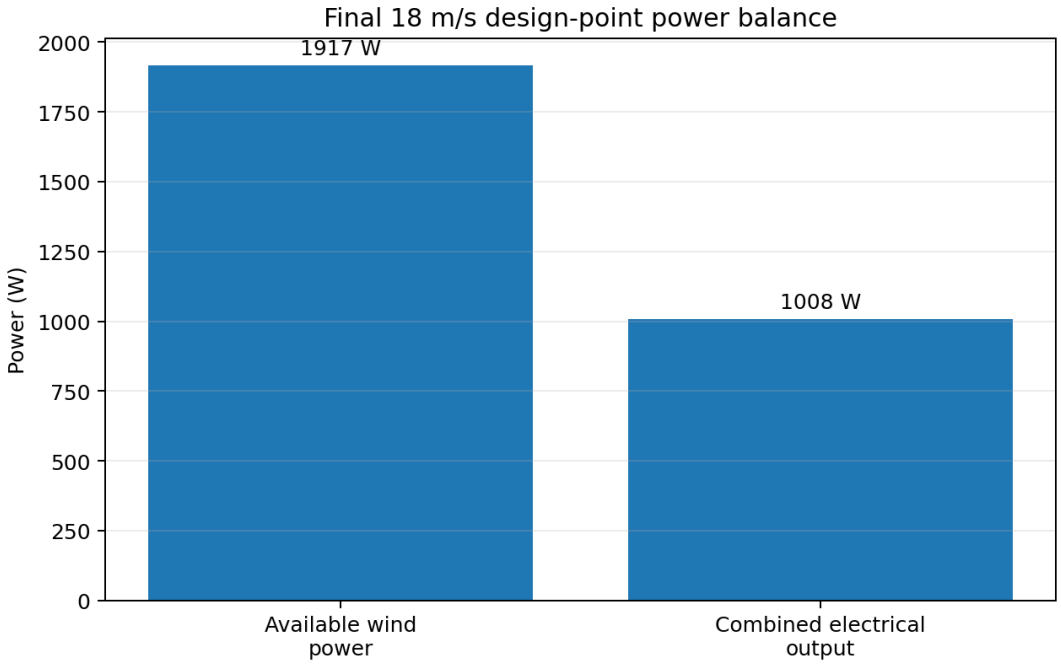


Figure 6: Theoretical power balance at the final 18 m/s, 1100 rpm design point.

VIII. Theoretical Discussion

The calculations establish a consistent relationship between the rotor geometry, wind speed, rotor speed and generator output. At 18 m/s, the 0.53679 m² projected area contains approximately 1.917 kW of incident kinetic wind power at the reference air density. The two-generator electrical design point is 1.008 kW, corresponding to 504 W per generator.

The rotor peripheral speed of 25.05 m/s is higher than the incoming wind speed, giving a theoretical TSR of 1.392. For a drag-dominated Savonius rotor, TSR must be interpreted together with rotor geometry and aerodynamic loading. The value is a kinematic calculation from the selected 1100 rpm operating point and does not by itself establish aerodynamic optimum performance.

Magnetic-flux augmentation is relevant because generator induced voltage depends on changing magnetic flux linkage. At a fixed rotational speed, increasing useful flux linkage can increase induced voltage and electrical power capability. The practical output remains dependent on the electrical load, generator resistance, magnetic losses, core losses, mechanical losses and temperature.

The theoretical calculations therefore establish the design-point energy and torque relationships without assigning an experimentally measured efficiency or an experimentally measured magnetic-flux improvement percentage.

IX. Engineering Design Considerations

Table 6: Engineering design considerations

Design parameter	Current value / condition	Engineering significance
Rotor type	Two-bucket Savonius	Drag-based vertical-axis configuration
Bucket arrangement	180°	Provides opposed bucket positions
Rotor height	1234 mm	Determines projected area with diameter
Characteristic diameter	435 mm	Used for area, peripheral speed and TSR
H/*D*	2.837	Geometry ratio used in the theoretical model
Wind-speed design point	18 m/s	Final calculation condition
Rotor speed	1100 rpm	Final calculation condition
Generator count	2	Parallel electrical generation concept
Power per generator	504 W	Design-point allocation
Total power	1008 W	Combined design-point electrical output
Reference air density	1.225 kg/m³	Standard theoretical calculation value
Operating temperature values in table	30–90/91 °C	Theoretical table values; not measured thermal results

X. Scope and Limitations

- The paper is a theoretical engineering analysis and intermediate operating points are not laboratory measurements.
- The 435 mm diameter is treated as the characteristic/overall diameter for all calculations in this paper.
- The reference air density is 1.225 kg/m³; actual wind power changes with atmospheric density.
- The torque values calculated from electrical power are torque-equivalent values and are not direct aerodynamic shaft-torque measurements.
- The internal magnetic-circuit geometry, winding construction, pole arrangement and manufacturing details are product-specific and are outside the public theoretical model.
- The electrical-output-to-wind-power ratio is a system-level theoretical ratio and is not reported as aerodynamic C_p.

XI. Conclusion

A consistent theoretical model has been established for the current two-bucket Savonius VAWT with two permanent-magnet generators. The rotor height is 1234 mm and the characteristic/overall diameter is 435 mm, giving a projected area of 0.53679 m² and *H*/*D* of 2.837.

At the final design condition of 18 m/s and 1100 rpm, the reference wind-power calculation gives 1.917 kW. The theoretical generator allocation is 504 W for Generator 1 and 504 W for Generator 2, producing 1008 W combined. The corresponding angular velocity is 115.19 rad/s, peripheral speed is 25.05 m/s, TSR is 1.392, and the torque-equivalent is 4.375 N·m per generator.

The analysis provides a compact theoretical basis for the Savonius rotor and magnetic-flux-augmented generator system, while keeping product-specific internal construction information outside the public paper.

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Appendix A. Calculation Summary Sheet

Table 7: Calculation summary sheet

Parameter	Value	Unit
D	0.435	m
H	1.234	m
ρ	1.225	kg/m³
V	18.0	m/s
N	1100	rpm
A	0.53679	m²
ω	115.19	rad/s
u	25.05	m/s
λ	1.392	—
P_w	1917.47	W
P_{G1}	504	W
P_{G2}	504	W
P_{total}	1008	W
T_{G1}	4.375	N·m
T_{G2}	4.375	N·m
T_{total}	8.751	N·m
P_{total}/P_w	0.526	—

Appendix B. Symbols and Abbreviations

Table 8: Symbols and abbreviations

Symbol / abbreviation	Meaning
A	Projected rotor area
D	Characteristic/overall rotor diameter
H	Rotor height
ρ	Air density
V	Wind speed
N	Rotor rotational speed
ω	Angular velocity
u	Characteristic peripheral speed
λ	Tip-speed ratio
P_w	Kinetic power available in the incident wind
P_e	Electrical power
T_{eq}	Torque-equivalent obtained from electrical power and angular velocity
VAWT	Vertical-axis wind turbine
GFRP	Glass-fibre-reinforced polymer
PM	Permanent magnet
C_p	Aerodynamic power coefficient