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A Systematic Design Methodology for Electromagnetic Brakes Applied to Low-Power Wind Turbines Using Analytical Modeling, Numerical Validation, and Experimental Verification

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Abstract. Low-power wind turbines require reliable braking systems to ensure safe operation during emergency conditions, maintenance procedures, and high wind speeds. Among the available alternatives, eddy-current electromagnetic brakes offer an attractive solution because they operate without mechanical contact, thereby reducing component wear and maintenance requirements compared with conventional braking systems. However, existing studies have primarily focused on the analysis of electromagnetic behavior, the optimization of specific configurations, or industrial applications, while relatively few have addressed a comprehensive methodology for the design and experimental validation of electromagnetic braking systems for low-power wind turbines. This study proposes a reproducible design methodology for an eddy-current electromagnetic brake intended for a 1 kW wind turbine. The proposed methodology integrates the definition of design requirements, the development of an analytical model for electromagnetic sizing, three-dimensional finite element analysis (FEA), and the experimental validation of a prototype manufactured according to the obtained design parameters. The proposed methodology was assessed through three complementary validation stages: analytical modeling, finite element simulation, and experimental testing using a dedicated test bench. The comparison of the obtained results demonstrated good agreement among the analytical predictions, numerical simulations, and experimental measurements, with a relative difference of 1.18% between the magnetic flux density predicted by the analytical model and that obtained from the finite element analysis. Furthermore, the developed prototype successfully achieved complete rotor stoppage under the prescribed design conditions, confirming the effectiveness of the pro-

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posed braking system. The main contribution of this work lies not only in the development of an electromagnetic braking device but also in the formulation and validation of a systematic design methodology that integrates analytical modeling, numerical validation, and experimental verification into a unified design framework. The proposed methodology provides a reproducible approach for the development of electromagnetic brakes for low-power wind turbines and establishes a foundation for future protection strategies, speed regulation systems, and scaling to higher-power wind energy applications.

1 Introduction

The safe operation of wind turbines depends on the ability of their protection systems to limit or stop rotor rotation whenever operating conditions exceed the design limits, during maintenance procedures, or under emergency events. Among these protection systems, the braking mechanism plays a fundamental role in safeguarding critical components such as the rotor, generator, and supporting structure, thereby reducing the risk of mechanical damage and improving overall system reliability. For low-power wind turbines, commonly employed in distributed generation and stand-alone energy systems, the development of robust, reliable, and low-maintenance braking solutions remains a significant challenge for increasing operational availability and extending service life (Bianchini et al., 2022). The selection of an appropriate braking system directly affects the safety, reliability, and operational performance of a wind turbine. An effective braking system must be capable of generating the required braking torque under a wide range of operating conditions, maintaining stable performance during overspeed events, and minimizing maintenance requirements throughout the turbine's service life. These characteristics become particularly important in low-power wind turbines installed in remote or isolated locations, where maintenance interventions are costly and system availability is a key factor determining technical and economic feasibility (Bianchini et al., 2022). Wind turbine braking systems can generally be classified as mechanical, aerodynamic, electrical, and electromagnetic, operating either independently or in combination to ensure safe system operation. Mechanical brakes are commonly employed for emergency shutdowns and maintenance procedures because of their high braking torque capability. However, continuous contact between friction elements results in progressive wear, heat generation, and the need for periodic inspection and replacement. Aerodynamic braking systems, such as pitch control and stall regulation, reduce the aerodynamic power captured by the rotor and consequently decrease mechanical loads without physical contact between components, although their performance depends on the control strategy and transient wind conditions (Hau, 2013; Burton et al., 2011). Electrical braking, in contrast, utilizes the generator and the associated power electronic converter to dissipate the energy generated during rotor deceleration. Nevertheless, its braking capability depends on the electrical architecture, the implemented control strategy, and the availability of energy dissipation elements during transient events (Anaya-Lara et al., 2011). These limitations have motivated the investigation of contactless braking technologies capable of reducing mechanical wear while improving the reliability of low-power wind turbines. Among the available contactless braking technologies, eddy-current electromagnetic brakes have attracted considerable attention be-

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cause they generate braking torque through the interaction between a magnetic field and a moving conductive element. In these systems, the induced eddy currents produce an opposing magnetic field, in accordance with Lenz's law, generating a resistive force that opposes rotor motion while dissipating mechanical energy primarily as heat. The absence of mechanical contact significantly reduces wear, noise, and maintenance requirements compared with conventional friction brakes, making this technology attractive for rotating machinery, railway transportation, automotive systems, and industrial equipment (Wouterse, 1991; Gosline and Hayward, 2008; Hu et al., 2019; Xiang et al., 2020). In the wind energy field, Jee et al. (2012), Koswatta et al. (2019), Koswatta et al. (2020a), Koswatta et al. (2020b), and Jeong et al. (2021) have investigated the application of magnetic and eddy-current braking systems for small wind turbines, demonstrating their potential as an alternative braking technology for low-power applications. Recent research on eddy-current electromagnetic brakes for wind energy systems has primarily focused on the analysis of electromagnetic phenomena, numerical simulation, and parametric design studies. Koswatta et al. (2019, 2020a, b) investigated the application of eddy-current brakes for speed control in small wind turbines operating under variable and high wind conditions, with emphasis on numerical simulations. Jeong et al. (2021) conducted a finite element parametric study to evaluate the influence of the number of magnets, pole arrangement, disc thickness, radial position, magnetic flux density, and rotational speed on braking torque. Carrasco et al. (2022) reported an experimental development for small-scale wind turbine testing, whereas Aliyev et al. (2023) proposed an electromagnetic parameter synthesis for wind energy installations. Although these studies have significantly improved the understanding of eddy-current braking systems, most of them address only specific stages of the development process, such as analytical modeling, numerical simulation, parametric optimization, or the evaluation of particular design configurations. Despite these advances, the existing literature shows limited integration of analytical sizing, finite element simulation, prototype development, and experimental validation within a unified design methodology for eddy-current electromagnetic brakes applied to low-power wind turbines. The separation of these stages reduces the reproducibility of the design process, limits objective comparisons among different approaches, and hinders the transfer of research outcomes to practical engineering applications. Consequently, there is a need for comprehensive methodologies capable of establishing a direct relationship between the braking requirements of a wind turbine, the electromagnetic design of the braking system, numerical validation, and the experimental performance of the resulting prototype. A preliminary analytical and numerical assessment of the proposed eddy-current braking concept was previously reported by Jimenez-Velazquez et al. (2025). That study established the initial electromagnetic sizing and finite element evaluation of the braking system, while prototype fabrication and experimental validation were identified as subsequent stages. Building upon that preliminary work, the present study substantially extends the previous contribution by developing a systematic and reproducible design methodology that integrates refined analytical sizing, magnetic-circuit and electrical design, finite element validation, prototype fabrication, and experimental verification under controlled laboratory conditions.

To address this need, this work presents a systematic design methodology for the development and experimental validation of an eddy-current electromagnetic brake for a 1 kW low-power wind turbine. The proposed methodology sequentially integrates the definition of braking requirements, analytical electromagnetic sizing, three-dimensional finite element analysis (FEA), prototype fabrication, and experimental validation under controlled operating conditions. Unlike previous studies focused exclusively on analytical modeling, numerical simulation, or experimental evaluation, the proposed approach establishes a

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systematic relationship among all stages of the design process, providing a reproducible methodology that can serve as a reference for the development of electromagnetic braking systems for low-power wind turbines.

2 Methodology

The proposed methodology integrates analytical modeling, electromagnetic design, finite element analysis (FEA), prototype fabrication, and experimental validation into a unified framework for the development of an eddy-current electromagnetic brake for a 1 kW low-power wind turbine. The procedure begins with the definition of the braking system design requirements, followed by the determination of the required braking torque, the analytical sizing of the electromagnetic system, numerical validation through finite element analysis, prototype fabrication, and finally, experimental validation under representative operating conditions. Figure 1 summarizes the overall workflow of the proposed methodology.

2.1 Design Requirements

The design of the electromagnetic brake was established based on the operational requirements of the wind turbine and the operating characteristics of the electrical generator. The braking system was conceived as a protection mechanism intended to bring the rotor to a complete stop during emergency conditions and maintenance operations. Accordingly, the primary design criterion was to develop a braking torque equal to or greater than the generator's rated mechanical torque. Consequently, the proposed device was not intended to operate as a continuous speed regulation system but rather as a braking mechanism whose primary function is to ensure the safe shutdown of the wind turbine whenever required by the operating conditions.

A 1 kW horizontal-axis wind turbine (HAWT) equipped with a permanent magnet synchronous generator (PMSG) was selected as the study platform. This configuration was chosen because low-power wind turbines intended for distributed generation and stand-alone applications require braking solutions that are compact, reliable, and require minimal maintenance, characteristics that make contactless electromagnetic braking systems an attractive alternative. The electrical and mechanical specifications of the generator constitute the initial design conditions because they determine the mechanical load that the braking system must withstand. The parameters considered include the rated power, torque, rotational speed, voltage, operating current, and generator efficiency. These parameters were obtained using OptiGen, a software tool developed for the electromagnetic design of the permanent magnet synchronous generator employed as the experimental platform, and are summarized in Table 1.

Based on these parameters, the following design criteria were established:

- Develop a braking torque equal to or greater than the generator's rated mechanical torque.
- Eliminate mechanical contact between braking components to prevent friction-induced wear.
- Minimize the size of the electromagnetic system while maintaining the required braking capability.
- Prevent magnetic core saturation under rated operating conditions.

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Figure 1. Methodology (Part 1): theoretical analysis and numerical validation. Source: own elaboration.

– Employ commercially available materials and conventional manufacturing processes to facilitate prototype reproducibility.

– Ensure that the proposed design procedure can be reproduced through a combination of analytical modeling, numerical simulation, and experimental validation.

These criteria constitute the foundation of the proposed methodology and define the design constraints governing the sizing of the electromagnetic brake.

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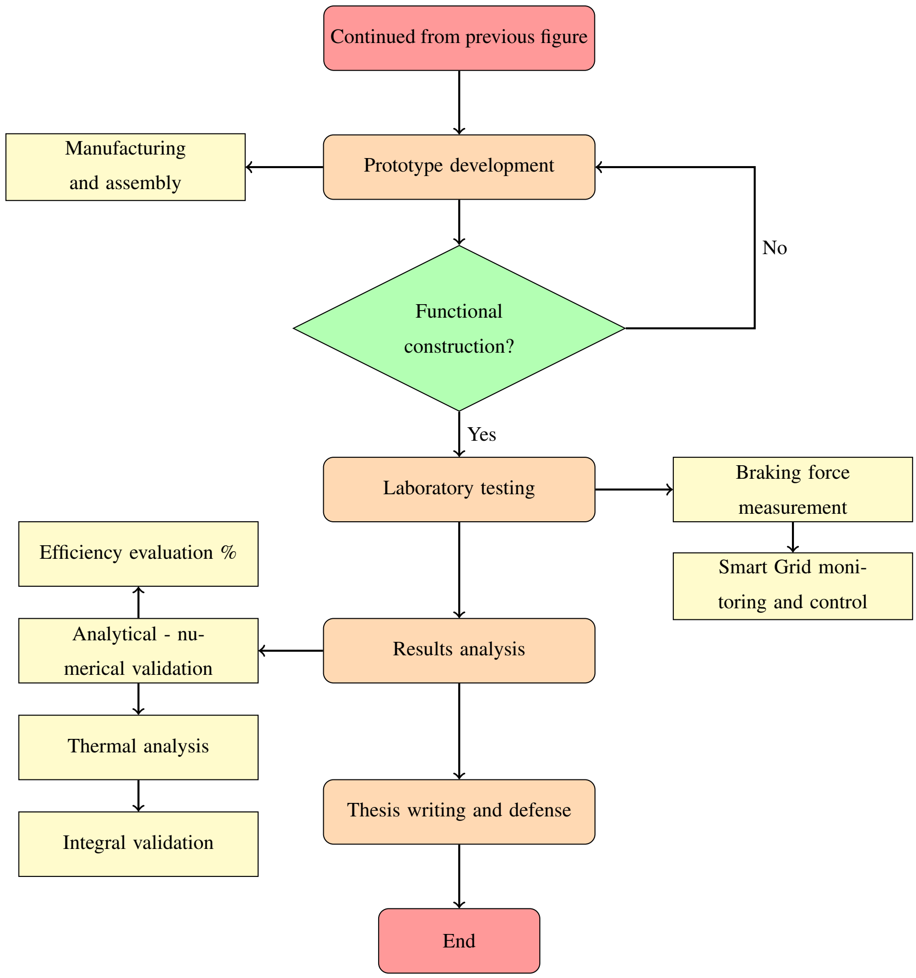

Figure 2. Methodology (Part 2): construction, experimental validation and results analysis. Source: own elaboration.

Table 1. Electric generator parameters for brake design.

Parameter	Value	Unit
Power, P	1000	W
Phase current, I_F	10	A
Torque, τ	17.8	N m
Angular speed, ω_r	55.95	rad/s
Line voltage, V_L	57.3	V
Phase voltage, V_F	33.1	V
Efficiency	82	%

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2.2 Design Torque Determination

The design of the electromagnetic brake first requires the determination of the mechanical torque that must be counteracted to ensure complete rotor stoppage under the rated operating conditions of the wind turbine. This torque represents the design torque of the braking system and defines the minimum mechanical effort that the brake must generate to fulfill its function as a protective device. The analytical model proposed by Gosline and Hayward (2008) was selected because it describes the braking torque generated by eddy currents induced in a conductive disc subjected to a stationary magnetic field, which corresponds to the operating principle of the electromagnetic brake developed in this work. Furthermore, this model directly relates the braking torque to the magnetic flux density, rotational speed, disc geometry, and electrical conductivity of the conductive material, which constitute the primary design variables of the proposed braking system. According to the design criterion established in Section 2.1, the braking torque generated by the electromagnetic brake must be equal to or greater than the required design torque, which can be expressed as

$$\tau_b \geq \tau_d \tag{1}$$

where

- τ_b is the braking torque generated by the electromagnetic brake.
- τ_d is the design torque determined from the generator rated operating conditions.

The design torque is obtained from the relationship between the generator rated mechanical power and its angular velocity,

$$\tau_d = \frac{P}{\omega} \tag{2}$$

where

- P is the rated mechanical power of the generator.
- ω is the rated angular velocity.

Substituting the generator rated parameters presented in Table 1 yields a design torque of 17.8 N·m, which represents the minimum braking capability required to ensure complete rotor stoppage under rated operating conditions. It should be emphasized that the objective of this work is the design of a braking system capable of safely stopping the rotor rather than the development of a continuous speed regulation system. Consequently, the design torque represents the minimum braking capacity required, whereas the system performance under different operating conditions is subsequently evaluated through numerical simulation and experimental validation.

Once the design torque has been established, the next stage consists of determining the electromagnetic characteristics required to generate the corresponding braking torque. To this end, the following section develops the analytical magnetic circuit model used to size the magnetic core, the excitation winding, and the principal geometric parameters of the eddy-current electromagnetic brake.

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2.3 Electromagnetic System Design

Once the design torque has been determined, the next step is to establish the electromagnetic characteristics required to generate the corresponding braking torque. For this purpose, an analytical design procedure was developed to relate the braking torque to the magnetic flux density, the properties of the conductive material, and the geometry of the braking system. Based on this analytical model, the magnetic circuit, the electromagnet winding, and the principal geometric parameters of the brake were determined.

The proposed methodology is carried out sequentially. First, the analytical model is employed to determine the required magnetic flux density. Next, the magnetic circuit is sized through magnetic reluctance analysis. Finally, the required number of turns, excitation current, and physical dimensions of the system are determined, providing a reproducible methodology for the design of an eddy-current electromagnetic brake.

2.3.1 Analytical Model for Braking Torque Generation

The design of the electromagnetic system is based on an analytical model describing the braking torque generated by eddy currents induced in a conductive disc rotating under the influence of a stationary magnetic field. Since the braking system developed in this work consists of a conductive disc coupled to the wind turbine shaft and a set of DC electromagnets, this formulation accurately represents the physical operating principle of the proposed device while establishing a direct relationship between the electromagnetic variables and the required braking torque.

The analytical formulation proposed by Gosline and Hayward (2008) was selected because it relates the braking torque to the magnetic flux density, rotational speed, conductive disc geometry, and electrical properties of the material, which constitute the principal design variables of the electromagnetic brake. Furthermore, this model has been widely adopted as the basis for the analysis of eddy-current braking systems because it provides an initial estimation of the electromagnetic behavior prior to numerical evaluation using finite element analysis (FEA).

Under the assumptions of quasi-steady-state operation, a uniform magnetic field within the interaction region, and a homogeneous isotropic conductive material, the electromagnetic braking torque can be expressed as Gosline and Hayward (2008):

$$\tau = A_n r_e^2 B^2 \omega_r G_d \sigma_e \tag{3}$$

where:

- τ is the electromagnetic braking torque.
- A_n is the effective area of the magnetic pole.
- r_e is the effective radius of the conductive disc.
- B is the magnetic flux density.

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– ω is the angular velocity of the disc.

– G_d is the thickness of the conductive disc.

– σ_e is the electrical conductivity of the disc material.

Since the objective of the design procedure is to determine the electromagnetic characteristics required to satisfy the design torque established in Section 2.2, Eq. (3) is rearranged to obtain the required magnetic flux density:

$$B = \sqrt{\frac{\tau}{A_n r_e^2 \omega_r G_d \sigma_e}} \tag{4}$$

This expression constitutes the starting point for the electromagnetic system design, as it enables the determination of the minimum magnetic flux density required to generate the specified braking torque. The resulting value is subsequently used in the magnetic circuit analysis to size the ferromagnetic core, air gap, and electromagnet winding.

2.3.2 Magnetic Circuit Design

Once the required magnetic flux density has been determined, the next step is to design the magnetic circuit capable of conducting this magnetic flux from the electromagnet core to the conductive disc. The objective of this stage is to establish a low-reluctance magnetic path capable of generating the required magnetic field while minimizing the magnetomotive force (MMF) required.

The magnetic circuit considered in this work consists of the ferromagnetic core, the air gap, and the conductive disc, which together define the path followed by the magnetic flux during brake operation. To simplify the analysis, the magnetic flux was assumed to remain confined within the magnetic circuit, neglecting leakage flux while assuming homogeneous and isotropic material properties.

Under these assumptions, the total magnetic reluctance of the circuit can be expressed as the sum of the reluctances of its individual components:

$$\mathcal{R}_T = \mathcal{R}_n + \mathcal{R}_g + \mathcal{R}_d \tag{5}$$

where:

– $\mathcal{R}_T$ is the total magnetic reluctance of the magnetic circuit.

– $\mathcal{R}_n$ is the reluctance of the ferromagnetic core.

– $\mathcal{R}_g$ is the reluctance of the air gap.

– $\mathcal{R}_d$ is the reluctance of the conductive disc.

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The individual reluctances were calculated using the classical magnetic circuit relationships:

$$\mathcal{R}_n = \frac{\ell_n}{\mu_n \mu_0 A_n}, \quad \mathcal{R}_g = \frac{g - G_d}{\mu_0 A_n}, \quad \mathcal{R}_d = \frac{G_d}{\mu_d \mu_0 A_n} \tag{6}$$

where:

- ℓ_n is the mean magnetic path length of the ferromagnetic core (m).
- A_n is the effective cross-sectional area of the core (m^2).
- μ_n is the relative permeability of the core material.
- μ_d is the relative permeability of the conductive disc.
- μ_0 is the permeability of free space.
- g is the total air-gap length (m).
- G_d is the thickness of the conductive disc (m).

The resulting equivalent reluctance represents the parameter governing the opposition of the magnetic circuit to the establishment of magnetic flux and allows the required magnetomotive force (MMF) to be determined for producing the specified magnetic flux density. Consequently, this parameter establishes the link between the analytical braking torque model developed in Section 2.3.1 and the sizing of the electromagnet winding, which is presented in the following subsection.

2.3.3 Determination of the Excitation Current and Number of Turns

Once the equivalent magnetic reluctance has been determined, the next step is to establish the electrical conditions required for electromagnet excitation. The permanent magnet synchronous generator (PMSG) delivers a three-phase electrical output that is converted to direct current through a three-phase diode bridge rectifier. The rectifier therefore establishes the DC-link voltage and current available for the braking system. Because the electromagnet requires a controlled excitation current, a current-regulation stage, such as a controlled DC–DC converter, is required between the rectifier output and the electromagnet winding. This stage allows the electromagnet excitation current to be regulated independently of the rectified DC-link voltage. The DC-link voltage is estimated as:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} \tag{7}$$

where:

- V_{dc} is the rectified DC-link voltage.

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– V_{LL} is the line-to-line voltage.

$$I_{dc} = \eta_r \frac{P_a}{V_{dc}} \tag{8}$$

where:

– I_{dc} is the current available at the rectifier output.

– P_a is the active electrical power available at the PMSG output.

– η_r is the rectifier efficiency.

– V_{dc} is the rectified DC-link voltage.

For the electromagnetic sizing procedure, the current available at the rectifier output was adopted as the design reference for the electromagnet excitation current. Therefore, the design excitation current was defined as:

$$I_{\mathrm{exc,des}} = I_{\mathrm{dc}} \tag{9}$$

Using the available PMSG electrical power, the rectified DC-link voltage, and the assumed rectifier efficiency, the resulting design excitation current was 12.41 A.

In practical implementation, the electromagnet excitation current, I_{exc}, is established by the current-regulation stage connected between the DC link and the electromagnet winding. Accordingly, V_{dc} should not be interpreted as the voltage applied directly to the winding. Instead, the regulation stage adjusts the winding voltage required to obtain the prescribed excitation current.

$$V_w = I_{exc} R_w \tag{10}$$

where:

– I_{exc} is the electromagnet excitation current.

– Vw is the electromagnet winding voltage.

– R_w is the winding resistance.

The calculated number of turns constitutes one of the fundamental design parameters of the electromagnet, as it determines the total conductor length, the electrical resistance of the winding, the Joule losses, and the final dimensions of the coil. These parameters define the physical configuration of the electromagnet and provide the basis for the geometric sizing procedure presented in the following subsection.

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$$N = \frac{B A_n \mathcal{R}_T}{I_{exc}} \tag{11}$$

where:

- A_n is the effective cross-sectional area of the core.
- N is the number of turns.
- $\mathcal{R}_T$ is the total magnetic reluctance.
- B is the magnetic flux density.
- I_{exc} is the electromagnet excitation current.

2.3.4 Physical Design of the Electromagnet

Once the required number of turns has been determined, the next step is to define the physical configuration of the electromagnet. This stage includes the selection of the magnet wire, the sizing of the winding, and the definition of the core dimensions, ensuring that the assembly can generate the required magnetomotive force (MMF) without exceeding the geometric and thermal constraints of the system.

The conductor was selected according to the excitation current determined in the previous subsection and the current-carrying capacity of the magnet wire in order to limit winding heating and ensure reliable operation during the braking process. Likewise, the winding dimensions were defined so that the calculated number of turns could be completely accommodated around the ferromagnetic core while maintaining a uniform winding distribution and efficient utilization of the available space.

Based on the calculated number of turns and the geometric characteristics of the conductor, the total winding length, the electrical resistance of the winding, and the final coil dimensions were determined. These parameters allow the estimation of Joule losses and provide the basis for prototype fabrication. The electrical resistance of the fabricated winding was subsequently measured experimentally, yielding a value of 0.20 Ω. At the design excitation current of 12.41 A, this resistance corresponds to an estimated winding voltage drop of 2.48 V and Joule losses of approximately 30.8 W.

Finally, the dimensions of the core and the winding were verified to ensure mechanical compatibility with the conductive disc and the air gap defined during the magnetic circuit design. The resulting configuration corresponds to the physical design of the electromagnet employed in both the finite element simulations and the experimental prototype.

2.4 Finite Element Model

The finite element model employed in this study builds upon the preliminary numerical assessment reported byJimenez-Velazquez et al. (2025) and is incorporated here as part of the extended design and experimental validation methodology.

The analytical model developed in the previous section provides the parameters required for sizing the electromagnetic system. However, because of the inherent simplifications of the analytical approach, it is necessary to verify the spatial distribution

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of the magnetic flux and assess whether the proposed geometry is capable of generating the magnetic flux density required by the analytical design. For this purpose, a numerical model based on the Finite Element Method (FEM) was developed using COMSOL Multiphysics.

The objective of the numerical analysis was to validate the magnetic circuit design before prototype fabrication by evaluating the magnetic field distribution, magnetic flux lines, and the influence of the electromagnet geometry on the resulting magnetic flux density. In this way, the FEM model constitutes an intermediate stage between the analytical design and the experimental validation, allowing potential design deviations to be identified before physical construction of the brake.

2.4.1 Model Geometry

A three-dimensional model of the electromagnetic system was developed, including the ferromagnetic core, the winding, the conductive disc, and the surrounding air domain. The geometry was constructed from the dimensions obtained during the design procedure described in Section 2.3, ensuring consistency between the analytical and numerical models.

To ensure the reproducibility of the study, all geometric dimensions employed in the simulation correspond to the parameters defined during the electromagnet sizing procedure and subsequently used for prototype fabrication.

2.4.2 Material Properties

The physical properties assigned to each computational domain correspond to the materials employed in the prototype construction. The magnetic core was modeled using JFE Steel 50JN400 electrical steel because of its high magnetic permeability, whereas the winding was defined as a copper conductor supplied with direct current (DC). The braking disc was modeled as aluminum using the material properties corresponding to the experimental prototype, while the surrounding region was represented as an air domain. In the present magnetostatic analysis, the finite element model was used to evaluate the magnetic flux distribution and magnetic circuit behavior rather than the transient eddy-current response of the rotating disc.

The use of material properties corresponding to commercially available materials allows the numerical results to be directly compared with the experimental behavior of the fabricated prototype.

2.4.3 Boundary Conditions and Mesh Discretization

The model was solved using the Magnetic Fields (mf) interface available in COMSOL Multiphysics under magnetostatic conditions, with a constant excitation current applied to the winding. The outer domain was defined using open boundary conditions to represent an unbounded magnetic space and to prevent artificial reflections of the magnetic flux.

Spatial discretization was performed using a tetrahedral finite-element mesh with local mesh refinement applied in regions where high magnetic field gradients were expected, particularly within the air gap and at the interfaces between the ferromagnetic core and the surrounding air. This strategy improved numerical accuracy without unnecessarily increasing the computational cost of the simulations. Accordingly, the FEM analysis was used to validate the magnetic circuit and the predicted magnetic flux density rather than the transient braking torque generated by the induced eddy currents.

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2.4.4 Simulation Procedure

A two-dimensional (2D) model was initially developed to verify the overall behavior of the magnetic circuit and to perform a preliminary validation of the design with a low computational cost. Once the consistency of the analytical design had been confirmed, a three-dimensional (3D) simulation was performed to investigate the spatial distribution of the magnetic field and magnetic flux lines throughout the complete electromagnetic system in greater detail.

The simulations were solved using a stationary solver, and the resulting data were used to evaluate the magnetic flux density distribution, magnetic field intensity, and magnetic flux concentration within the core and the air gap. These results constitute the basis for the numerical validation of the analytical model presented in the following section.

3 Results and Discussion

This section presents the results obtained using the proposed design methodology and their validation through numerical simulations and experimental testing. First, the parameters obtained from the electromagnetic design procedure are presented, providing the basis for the finite element model and the fabrication of the experimental prototype. Subsequently, the agreement among the analytical model, the numerical simulations, and the experimental results is analyzed in order to evaluate the predictive capability of the proposed methodology and verify its applicability to the design of electromagnetic braking systems for low-power wind turbines.

3.1 Electromagnetic Design Results

The proposed methodology yielded an electromagnetic configuration capable of satisfying the braking torque required for the 1 kW wind turbine, while simultaneously determining the characteristics of the magnetic circuit, the electromagnet winding, and the electrical supply conditions of the braking system. The parameters obtained through the analytical design procedure are summarized in Table 2, which presents the principal design results subsequently used for the numerical and experimental validation.

The obtained results indicate that the proposed methodology leads to a consistent and physically feasible electromagnetic configuration for the braking system. The calculated magnetic flux density is sufficient to generate the required magnetic flux while preventing the ferromagnetic core from operating near magnetic saturation, thereby promoting stable operation of the magnetic circuit. Furthermore, the magnetomotive force (MMF) determined from the analytical model provides the excitation required to satisfy the design torque using the electrical supply conditions established for the braking system.

The magnetic circuit analysis confirms that the air gap is the component contributing most significantly to the total magnetic reluctance. This behavior is consistent with classical magnetic circuit theory, owing to the much lower magnetic permeability of air compared with that of the ferromagnetic core. Consequently, most of the MMF generated by the electromagnet is expended in overcoming the magnetic reluctance introduced by the air gap, highlighting the importance of its proper sizing during the design process.

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Table 2. Parameters obtained from the proposed electromagnetic design methodology.

Category	Parameter	Value	Unit
Design	Rated power	1000	W
	Torque required	17.8	N m
	Generator phase current	10	A
Magnetic circuit	Flux density	0.1522	T
	Total reluctance	4797998.62	A/Wb
Winding	Excitation current	12.41	A
	Number of turns	147	—
	Wire length	29.39	m
	Measured winding resistance	0.20	Ω
	Rectified DC voltage	77.4	V
	Winding voltage at design current	2.48	V
	Estimated Joule losses at design current	30.8	W

In addition, the calculated number of turns ensures that the required MMF can be achieved at the design excitation current while maintaining a configuration compatible with the geometric and electrical constraints of the system. This demonstrates that the analytical design procedure not only determines the electromagnetic parameters required to satisfy the braking torque but also provides a manufacturable design prior to numerical validation and prototype fabrication.

Overall, the results presented in this section constitute the initial solution to the design problem and establish the reference conditions for the finite element validation presented in the following subsection.

3.2 Numerical Validation of the Analytical Model

To evaluate the predictive capability of the analytical magnetic circuit model, the electromagnetic design obtained analytically was verified through finite element simulations. This numerical stage focused on the magnetic flux distribution and magnetic flux density predicted by the analytical design. The objective of this stage was to verify that the assumptions adopted during the analytical design procedure accurately reproduce the magnetic field distribution and the behavior of the electromagnetic circuit prior to prototype fabrication. Thus, the numerical simulation serves as an intermediate validation stage between the analytical design and the experimental implementation.

Figure 3 shows the two-dimensional magnetic field distribution obtained from the numerical model. As observed, the magnetic flux remains primarily confined within the ferromagnetic core and is concentrated in the air-gap region, where the interaction with the conductive disc takes place. This behavior is consistent with that predicted by the analytical model and confirms that the proposed geometry provides a low-reluctance magnetic path, thereby minimizing magnetic flux leakage into the surrounding air.

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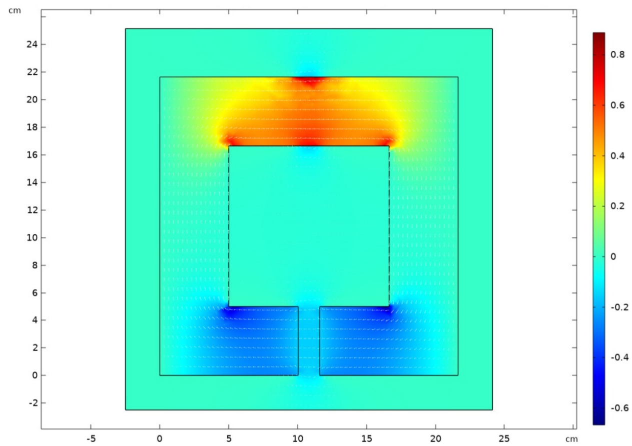

Figure 3. Two-dimensional magnetic field distribution obtained from the finite element model.

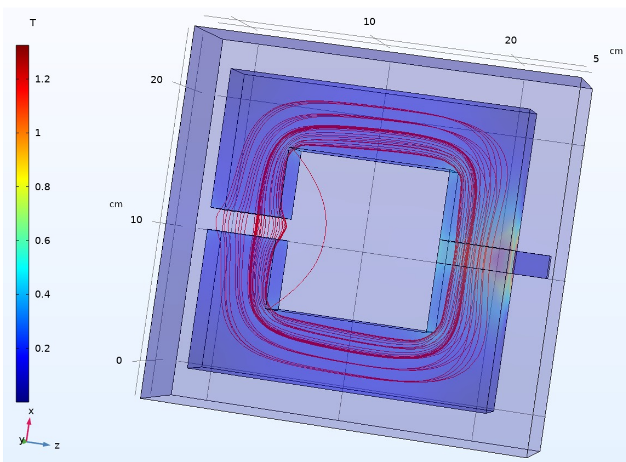

Figure 4. Three-dimensional distribution of the magnetic flux lines obtained from the finite element model.

Subsequently, the three-dimensional distribution of the magnetic flux lines was analyzed to verify the spatial behavior of the electromagnetic circuit. Figure 4 illustrates that the magnetic flux lines follow the trajectory predicted by the analytical design, closing through the ferromagnetic core and crossing the air gap toward the conductive disc. The magnetic flux is predominantly confined to the intended magnetic path, although localized increases in magnetic flux density are observed near geometric discontinuities and pole regions. The continuity of the magnetic flux lines confirms the expected behavior of the magnetic circuit.

As part of the quantitative validation, the magnetic flux density predicted by the analytical model was compared with the value obtained from the finite element model at the same evaluation point. The analytical procedure predicted a magnetic flux density of 0.1522 T, whereas the numerical simulation yielded a value of approximately 0.1540 T, corresponding to a relative

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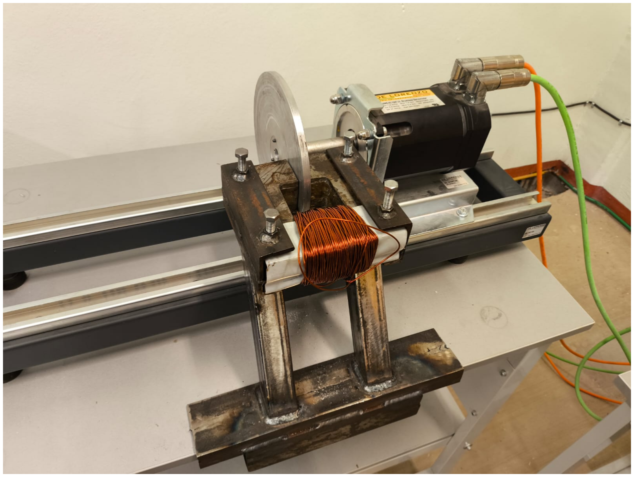

Figure 5. View of the electromagnetic brake mounted on the test bench.

error of 1.18%. This small discrepancy confirms that the assumptions adopted in the analytical model accurately capture the electromagnetic behavior of the system and provide sufficient accuracy for the preliminary sizing of the electromagnetic brake.

Overall, the numerical simulation results confirm the consistency of the analytical design procedure and demonstrate that the proposed methodology successfully reproduces the expected electromagnetic behavior prior to prototype fabrication. Consequently, the analytical model constitutes a reliable tool for the preliminary design of the electromagnetic brake, while the finite element validation provides an additional level of confidence before prototype fabrication and experimental evaluation.

3.3 Experimental Validation

To verify the practical implementation of the proposed methodology, an electromagnetic brake prototype was fabricated using the parameters obtained from the analytical design procedure and subsequently evaluated through experimental testing. The prototype was manufactured following the dimensions of the magnetic circuit, the calculated number of winding turns, and the electrical supply conditions established during the design process, without introducing empirical modifications that could alter the analytical design results.

Figure 5 shows the prototype developed for the experimental validation. The system integrates the ferromagnetic core, the electromagnet winding, and the aluminum conductive disc, reproducing the configuration considered in both the analytical and numerical models. The close correspondence between the theoretical design and the fabricated device enabled a direct assessment of the methodology's ability to translate the analytical design parameters into a physically realizable system.

To evaluate the performance of the braking system under controlled operating conditions, the prototype was integrated into the experimental test bench shown in Figure 6. The test bench was developed using a modified De Lorenzo Smart Grid platform adapted for the evaluation of the proposed braking system. The wind turbine emulator, previously calibrated by the

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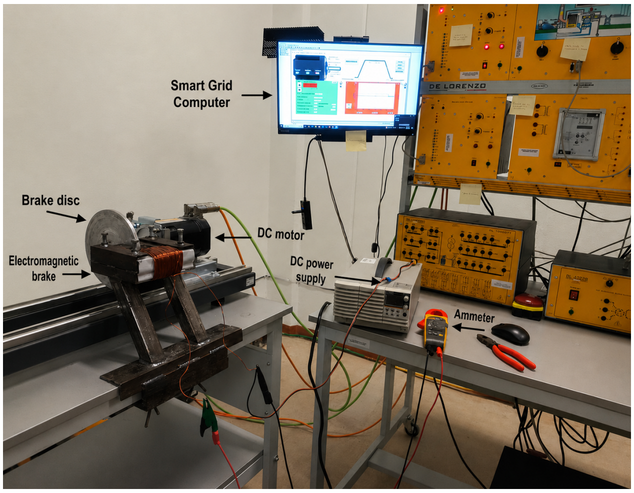

Figure 6. Test bench developed.

manufacturer, reproduced the mechanical torque corresponding to the 1 kW wind turbine considered in this study, thereby providing consistent and repeatable operating conditions throughout the experimental tests.

During the experimental validation, the required electromagnet excitation current was supplied using a regulated DC power supply. This arrangement reproduced the function of the current-regulation stage considered in the proposed braking system, allowing the excitation current to be varied independently of the DC-link voltage. The experimental configuration therefore enabled controlled evaluation of the braking response at different excitation current levels without directly connecting the electromagnet winding to the rectified PMSG voltage.

The use of this experimental platform enabled the nominal operating conditions of the wind turbine to be reproduced while ensuring consistent application of the mechanical torque during the experimental campaign. Consequently, the test bench provided a reliable platform for comparing the behavior of the physical prototype with the predictions obtained from both the analytical model and the finite element simulations.

Figure 7 presents the variation of the rotor speed and braking effectiveness as a function of the electromagnet excitation current. As expected, increasing the excitation current produces a progressive enhancement of the braking effect owing to the increase in magnetic flux density and, consequently, the higher eddy currents induced in the conductive disc. The resulting increase in electromagnetic braking torque leads to a corresponding reduction in rotor speed.

The braking effectiveness was determined from the percentage reduction in the rotor angular velocity relative to the unbraked operating condition, considering the difference between the rotor speed without braking and the speed measured under the action of the electromagnetic braking system.

$$E_b = \frac{n_0 - n_b}{n_0} \times 100 \qquad (12)$$

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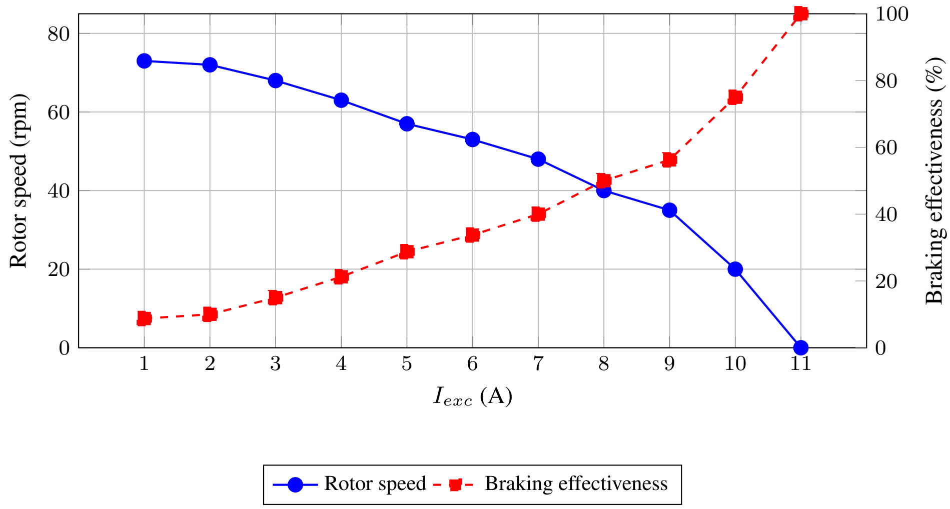

Figure 7. Variation of rotor speed and braking effectiveness as a function of the electromagnet excitation current.

where:

- E_b is the braking effectiveness (%).
- n_0 is the rotor speed without braking (rpm).
- n_b is the rotor speed with the electromagnetic brake activated (rpm).

For excitation currents below 5 A, the braking system produced only a partial reduction in rotor speed, whereas for currents exceeding 8 A, the braking effect increased significantly, achieving braking effectiveness values greater than 50%. Complete rotor stoppage was experimentally achieved at an excitation current of approximately 11 A, thereby verifying the capability of the proposed braking system to satisfy the design requirements established for the 1 kW wind turbine considered in this study.

A particularly relevant finding is that complete rotor stoppage was achieved experimentally at an excitation current of approximately 11 A, which is slightly lower than the 12.41 A predicted during the analytical design stage. This difference indicates that the proposed design procedure provides a conservative estimate of the excitation requirements of the electromagnet, resulting in an additional braking capacity margin that enhances operational safety under wind conditions exceeding the nominal design point.

The experimental tests demonstrated that the braking system responded consistently with the behavior predicted during the design stage. Activation of the electromagnet generated the magnetic field required to induce eddy currents in the conductive disc, producing the expected braking torque and progressively reducing the rotor speed. The observed behavior agrees with the physical principles incorporated into the analytical model, confirming that the proposed methodology accurately reproduces the electromagnetic phenomenon responsible for the braking process.

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The experimental results also exhibited excellent agreement with the predictions obtained from the analytical model and the finite element simulations. The observed discrepancies can be primarily attributed to manufacturing tolerances, small variations in the air-gap length, magnetic losses not considered in the idealized analytical model, and the inherent uncertainties associated with the measurement process. Nevertheless, these differences do not affect the overall system behavior and remain within an acceptable range for the design of braking systems intended for low-power wind turbines.

Overall, the experimental validation confirms that the proposed methodology enables the development of a functional electromagnetic brake through a systematic design procedure, reducing the reliance on empirical adjustments during prototype fabrication. The close agreement among the analytical model, the finite element simulations, and the experimental results demonstrates that the proposed procedure constitutes a reliable engineering methodology for the design of electromagnetic braking systems applied to low-power wind turbines.

3.4 Discussion

The results demonstrate that the proposed methodology provides a consistent and reliable procedure for the design of electromagnetic braking systems intended for low-power wind turbines. The close agreement among the analytical model, the finite element simulations, and the experimental validation confirms that the assumptions adopted during the analytical sizing procedure accurately predict the electromagnetic behavior of the system, thereby providing a reliable basis for preliminary design before resorting to computationally intensive numerical simulations. Furthermore, the ability of the braking system to achieve complete rotor stoppage with an excitation current lower than that predicted during the design stage confirms the conservative nature of the proposed methodology and provides an additional operational safety margin under wind conditions exceeding the nominal operating point. Recent studies on eddy-current braking systems for wind turbines have primarily focused on evaluating the performance of specific brake configurations through numerical simulations (Koswatta et al., 2019; Jeong et al., 2021). In this context, Jeong et al. (2021) conducted a parametric study to investigate the influence of disc thickness, number of magnets, pole arrangement, and rotational speed on the braking torque of an electromagnetic brake for small-scale wind turbines, using the Finite Element Method (FEM) as the principal design tool. Their results established the sensitivity of these parameters and provided useful guidelines for preliminary brake sizing. However, their work was primarily directed toward the parametric evaluation of brake performance rather than the development of a comprehensive and reproducible design methodology based on the operating conditions of the wind turbine. Similarly, analytical and numerical approaches have been employed to reduce computational cost during the early stages of electromagnetic brake design and to support subsequent numerical refinement (Wouterse, 1991; Gosline and Hayward, 2008; Jeong et al., 2021). These approaches demonstrate the usefulness of analytical models for preliminary electromagnetic brake sizing, particularly when complemented by subsequent numerical refinement (Gosline and Hayward, 2008; Jeong et al., 2021). Nevertheless, the primary objective of these studies has been to improve the electromagnetic performance of specific brake configurations rather than to establish a complete methodological framework for system design. Other investigations involving braking systems for low-power wind turbines have assessed the feasibility of eddy-current brakes as an alternative to conventional mechanical braking systems, highlighting advantages such as the absence of mechanical contact, reduced maintenance requirements, and extended service life (Jee et al., 2012; Koswatta et al., 2020a, b;

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Carrasco et al., 2022). In these studies, the emphasis has been placed on demonstrating brake performance and dynamic response under different operating conditions through mathematical modeling and numerical simulations to verify the feasibility of the proposed concept (Jee et al., 2012; Koswatta et al., 2020a, b; Carrasco et al., 2022).

The analytical and numerical results obtained in the present study are consistent with the preliminary findings reported by Jimenez-Velazquez et al. (2025). However, the present work extends those findings through the fabrication of the electromagnetic brake prototype and the experimental evaluation of its braking response, thereby completing the analytical–numerical–experimental design framework proposed in this study.

In contrast to these approaches, the present work proposes a systematic methodology that integrates all the stages required for the development of an electromagnetic braking system. The proposed procedure begins with the mechanical requirements of the wind turbine, continues with the determination of the required braking torque, the sizing of the magnetic circuit, the design of the electromagnet winding, and the selection of the electrical operating parameters, and concludes with numerical validation through the Finite Element Method (FEM) followed by experimental verification of the fabricated prototype. From this perspective, the principal contribution of this work lies not merely in the development of an electromagnetic brake but in the integration of analytical, numerical, and experimental tools into a reproducible engineering methodology that can serve as a guideline for the design of similar braking systems.

Another distinguishing feature of the proposed methodology is the incorporation of three complementary levels of validation. First, the analytical model establishes the initial dimensions of the magnetic circuit together with the electrical parameters of the electromagnet. Subsequently, the finite element simulations confirm the magnetic flux distribution and verify the consistency of the analytical design, yielding a relative error of only 1.18% in the predicted magnetic flux density. Finally, fabrication and experimental evaluation of the prototype demonstrate that the design parameters obtained from the proposed methodology can be directly implemented in a functional physical system. The integration of these three validation stages significantly reduces the uncertainty between theoretical design and practical implementation, thereby increasing confidence in the proposed design methodology.

Although the methodology was developed for a 1 kW low-power wind turbine, its general structure can be extended to systems of different power ratings by updating the operating conditions, magnetic circuit geometry, and electrical characteristics of the generator. However, its application to higher-power systems will require the incorporation of additional physical phenomena, including magnetic saturation, thermal effects in the winding, three-dimensional magnetic flux losses, and transient behavior during prolonged braking events. Future work may also integrate multi-objective optimization techniques to simultaneously minimize system volume, power consumption, and overall electromagnetic assembly weight while maintaining the braking torque required for each application.

Overall, the results demonstrate that the proposed methodology constitutes a reproducible engineering framework for the design of electromagnetic braking systems for low-power wind turbines. Beyond the performance of the fabricated prototype itself, the principal contribution of this work is the development of a structured design methodology that integrates analytical modeling, numerical validation, and experimental verification within a unified engineering workflow, facilitating the transition from conceptual design to physical implementation with a minimal number of design iterations.

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4 Conclusions

This work presented the development and validation of a systematic design methodology for electromagnetic braking systems applied to low-power wind turbines. The proposed procedure establishes a direct relationship between the mechanical requirements of the wind turbine and the sizing of the magnetic circuit, the design of the electromagnet winding, and the determination of the electrical operating parameters required for electromagnet excitation, thereby providing a structured engineering framework for the development of electromagnetic braking systems.

The results demonstrate that the analytical model constitutes an effective tool for the preliminary sizing of the electromagnetic brake. Validation through the Finite Element Method (FEM) confirmed the consistency of the designed magnetic circuit and accurately reproduced the spatial distribution of the magnetic flux, yielding a relative error of only 1.18% with respect to the analytical prediction of the magnetic flux density. Furthermore, experimental evaluation of the fabricated prototype verified the physical feasibility of the proposed methodology and confirmed the capability of the braking system to generate the expected braking performance under the prescribed operating conditions.

The principal contribution of this work lies not only in the development of an electromagnetic braking device but also in the integration of analytical modeling, numerical validation, and experimental verification within a unified design methodology. This integrated approach provides a reproducible engineering procedure that facilitates the transition from conceptual design to physical implementation while reducing the dependence on iterative design processes based exclusively on numerical simulations. Although the proposed methodology was developed for a 1 kW low-power wind turbine, its general framework can be extended to systems with different power ratings by updating the operating conditions and the electromagnetic design parameters. Consequently, the methodology has the potential to serve as a practical design framework for the development of electromagnetic braking systems in a broad range of distributed wind energy applications.

Future work will focus on incorporating multi-objective optimization techniques aimed at simultaneously reducing system volume, weight, and power consumption while maintaining the required braking torque. Additional developments will include the consideration of magnetic saturation, winding thermal behavior, three-dimensional magnetic flux effects, and transient operating conditions associated with prolonged braking events. Furthermore, investigating the dynamic response of the braking system under variable wind conditions represents an important research direction for extending the applicability of the proposed methodology.

Code and data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request. No dedicated software code was developed as part of this study.

Author contributions. JAE-S: conceptualization, methodology, supervision, project administration, and writing – review and editing. AJJ-V: methodology, formal analysis, investigation, and writing – original draft. AV-A: validation and writing – review and editing. RCA: software, formal analysis, and validation. ALL: investigation and resources. RMSA: formal analysis and investigation. AAB: resources and project administration. EDR: resources and project administration.

Competing interests. The authors declare that they have no conflict of interest.

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References

Bianchini, A., Bangga, G., Baring-Gould, I., Croce, A., Cruz, J. I., Damiani, R., Erfort, G., Ferreira, C. S., Infield, D., Nayeri, C. N., Pechlivanoglou, G., Runacres, M., Schepers, G., Summerville, B., Wood, D., and Orrell, A.: Current status and grand challenges for small wind turbine technology, Wind Energy Sci., 7, 2003–2037, https://doi.org/10.5194/wes-7-2003-2022, 2022.

Hau, E.: Wind Turbines: Fundamentals, Technologies, Application, Economics, 3rd edn., Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-27151-9, 2013.

Burton, T., Jenkins, N., Sharpe, D., and Bossanyi, E.: Wind Energy Handbook, 2nd edn., John Wiley & Sons, https://doi.org/10.1002/9781119992714, 2011.

Anaya-Lara, O., Jenkins, N., Ekanayake, J., Cartwright, P., and Hughes, M.: Wind Energy Generation: Modelling and Control, John Wiley & Sons, 2011.

Wouterse, J. H.: Critical torque and speed of eddy current brake with widely separated soft iron poles, IEE Proc. B Electr. Power Appl., 138, 153–158, https://doi.org/10.1049/ip-b.1991.0019, 1991.

Gosline, A. H. C. and Hayward, V.: Eddy Current Brakes for Haptic Interfaces: Design, Identification, and Control, IEEE/ASME Trans. Mechatronics, 13, 669–677, https://doi.org/10.1109/TMECH.2008.2004623, 2008.

Hu, D., Yan, Y., and Xu, X.: Energy saving optimal design and control of electromagnetic brake on passenger car, Mech. Sci., 10, 57–70, https://doi.org/10.5194/ms-10-57-2019, 2019.

Xiang, C., Chen, S.-A., Yao, M., Gu, Y.-F., and Yang, X.: Optimization of Braking Force for Electromagnetic Track Brake Using Uniform Design, IEEE Access, 8, 146065–146074, https://doi.org/10.1109/ACCESS.2020.3014122, 2020.

Jee, I. H., Nahm, S. Y., Kang, S. J., and Ryu, K.: A Magnetic Brake for Small Wind Turbines, J. Magn., 17, 33–35, https://doi.org/10.4283/JMAG.2012.17.1.033, 2012.

Koswatta, A., Shiroma, Y., Tamaki, S., Alsharif, F., and Tamura, J.: Power Analysis of Eddy Current Brake System Applied on Small-Scaled Wind Turbine for DC Greenhouse, in: 2019 4th International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS), 105–109, https://doi.org/10.1109/ICIIBMS46890.2019.8991519, 2019.

Koswatta, A., Alsharif, F., Shiroma, Y., Khosravy, M., Tamaki, S., and Tamura, J.: Alternative Braking Method for Small Scaled-Wind Turbines Connected DC Green House with Analogical Experiment on Blade Destruction, Adv. Sci. Technol. Eng. Syst. J., 5, 500–511, https://doi.org/10.25046/aj050264, 2020a.

Koswatta, A., Alsharif, F., Shiroma, Y., Tamaki, S., and Tamura, J.: Maximum Power-Point Tracking and Stall Control with Eddy Current Brake System on Small-Scaled Wind Turbines and its Application on Agricultural Harvesting, Adv. Sci. Technol. Eng. Syst. J., 5, 81–93, https://doi.org/10.25046/aj050411, 2020b.

Jeong, H., Ji, H., Choi, S., and Baek, J.: Parametric Study of Eddy Current Brakes for Small-Scale Household Wind Turbine Systems, Energies, 14, 6633, https://doi.org/10.3390/en14206633, 2021.

Carrasco, L. L., dos Santos, E., de Avila, L. R., and Dias, G. C.: Development of an Eddy Current Brake Applied in Small Scale Wind Turbine Tests, in: Proceedings of the 19th Brazilian Congress of Thermal Sciences and Engineering (ENCIT 2022), https://doi.org/10.26678/ABCM.ENCIT2022.CIT22-0709, 2022.

Aliyev, N. A., Ahmadov, E. N., Khanahmedova, S. A., and Rzayeva, S. V.: Synthesis of the Exact Parameters of the Electromagnetic Brake of a Wind Electric Installation, Przegl. Elektrotech., 99, 120–124, https://doi.org/10.15199/48.2023.10.123, 2023.

https://doi.org/10.5194/wes-2026-153
Preprint. Discussion started: 15 September 2026

Jimenez-Velazquez, A., Enriquez-Santiago, J., Verde-Anorve, A., Iracheta-Cortez, R., and Dorrego-Portela, J.: Eddy Currents as a Braking Alternative for Low-Power Wind Turbines, 2025 IEEE 43rd Central America and Panama Convention (CONCAPAN XLIII), 2025, https://doi.org/10.1109/CONCAPAN66820.2025.11512528.