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AMPLIAÇÃO E APROFUNDAMENTO DE CONHECIMENTOS NAS ÁREAS DAS ENGENHARIAS 3

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APRESENTAÇÃO

Caro(a) leitor(a)

Como definir a engenharia? Por uma ótica puramente etimológica, ela é derivada do latim *ingenium*, cujo significado é "inteligência" e *ingeniare*, que significa "inventar, conceber".

A inteligência de conceber define o engenheiro. Fácil perceber que aqueles cujo oficio está associado a inteligência de conceber, dependem umbilicalmente da tecnologia e a multidisciplinaridade.

Nela reunimos várias contribuições de trabalhos em áreas variadas da engenharia e tecnologia. Ligados sobretudo a indústria petroquímica com potencial de impacto nas engenharias. Aos autores dos diversos trabalhos que compõe esta obra, expressamos o nosso agradecimento pela submissão de suas pesquisas junto a Atena Editora. Aos leitores, desejamos que esta obra possa colaborar no constante aprendizado que a profissão nos impõe.

Boa leitura!

João Dallamuta

Henrique Ajuz Holzmann

Rennan Otavio Kanashiro

CAPÍTULO 1

PROPOSAL OF A CONCEPT FOR MODELING SMALL WIND TURBINES

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ABSTRACT: As the wind energy surge in the global energy scenario, small wind turbines start to receive more attention from researchers, as they focus on improving its efficiency and lowering its costs. This work presents a concept to quantify and optimize the energy conversion of small wind turbines. The main proposal of this concept is to alter the turbine's design goal, from the nominal power output curve design scope to a time-based energy conversion analysis. This can be done by studying the turbine dynamic response in all possible operational scenarios. The basis of a modified Blade Element Momentum (BEM) theory algorithm developed for the proposal is presented. Also, a first consideration of applying Additive Manufacturing (AM) to the turbine blades production is made.

KEYWORDS: Small wind turbine, Blade element momentum theory, Additive manufacturing.

PROPOSTA DE CONCEITO PARA O PROJETO DE AEROGERADORES DE PEQUENO PORTE

RESUMO: No momento em que a energia eólica cresce no cenário de energia global, aerogeradores de pequeno porte começam a receber mais atenção de pesquisadores, com o foco na melhora da eficiência e redução de custos. Esse trabalho apresenta um conceito para quantificar e otimizar a conversão da energia de aerogeradores de pequeno porte. A proposta principal desse conceito é de modificar o objetivo de projeto, passando do escopo baseado na curva de potência nominal para um escopo de análise temporal de conversão de energia. Isso pode ser feito através do estudo da resposta dinâmica do gerador em todas as condições operacionais. A estrutura de um algoritmo baseado na teoria do elemento de pá desenvolvida para essa proposta é apresentada. Uma primeira consideração da aplicação de manufatura aditiva para a fabricação das pás é feita.

PALAVRAS-CHAVE: Aerogerador de pequeno porte, Teoria do elemento de pá, Manufatura aditiva.

1 I INTRODUCTION

Wind energy is one of the fastest-growing green energy sources on the planet, setting production records in 2014 and 2015. As the most committed countries keep their investments, new names are appearing in this energy field, GWEC (2016), raising the expected power potential to 800GW by 2021, Figure 1. Furthermore, the research field on the topic is also experiencing a big expansion, from structural, manufacturing, aerodynamic, and application perspectives, as presented in Tummala et al. (2016) and Chehouri et al. (2015).

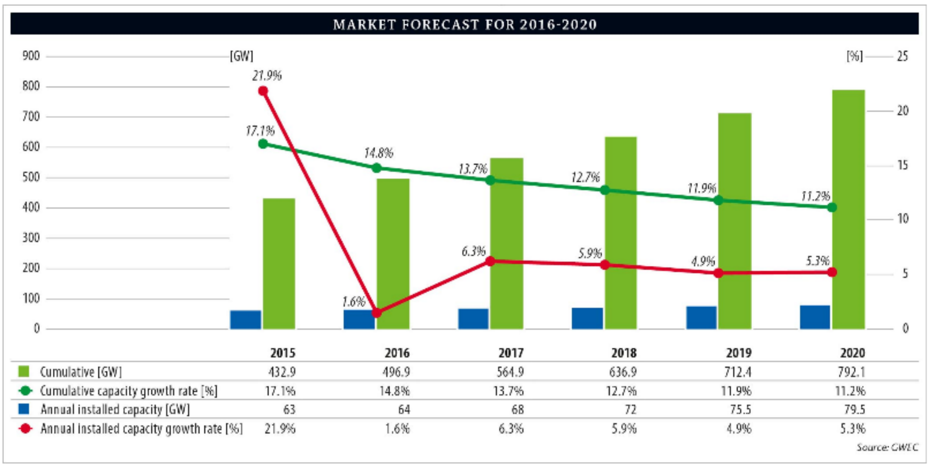

Figure 1 - Wind energy market forecast for 2016 to 2021, GWEC (2016)

Wind turbines are divided into several classes according to their power output for a defined wind speed, varying from less than a kilowatt to several megawatts. The focus of this work is to evaluate and propose a method to increase the energy conversion and minimize the Cost Of Energy (COE) of small wind turbines, which equates the amount of energy converted by the turbine to its cost of production, as considered in Sunderland et al. (2016). According to ANEEL (2012), a small wind turbine is that with a nominal power output up to 100kW, however, this work will aim turbines with power output up to 5kW. This class of wind turbines is commonly used in urban and rural areas, regions where the wind pattern is mostly not deeply studied and suffers major influence from the surroundings.

Wind turbines have been mostly designed to have a high power output for a specific wind speed - usually the most frequent wind speed of the working location -, this is acceptable for places where the wind pattern is reasonably constant and well comprehended, cases encountered by the megawatt on and off-shore wind turbines. But, to harvest the most energy in low-speed turbulent environments, the project methodology of the wind turbine must be redefined Wood (2004). A time-based energy conversion analysis must replace the maximum nominal power output concept. This means that the turbine must not only have a good performance for a specific and generally high wind speed but also be efficient for lower speeds and additionally for sudden speed changes.

Improving the turbine's performance in wind gusts means that it must have a good short-time dynamic response. In other words, the turbine must have a fast reaction to wind-speed changes, hence, a fast acceleration. This implies that the moment of inertia has a crucial role during the project, as it is inversely proportional to the acceleration. Therefore, the shape and material of the turbine blade highly influence its dynamic response.

It is evident that the turbine manufacturing cost influences the COE. The blade's complex geometry, which must comply with both structural, aerodynamic, and inertia requirements, makes them the most expensive part of the wind turbine. One of the proposals of this work is to evaluate the application of additive manufacturing to produce the blades. The increasing development of this technology, such as bigger, cheaper, and more precise machines combined with new design techniques may be a part of the solution for lowering the COE.

The most common methods for modeling wind turbines are the Blade Element Momentum (BEM) theory and other Computer Fluid Dynamics (CFD) methods Bai and Wang (2016). The BEM theory is based on dividing the blade into 2D airfoil sections and integrating their aerodynamic effects along its span. A downside of this method is that the 3D effects must be eventually implemented, however, the application of high fidelity models return good quality results in a short amount of computational time Du and Selig (1997), Elgammi and Sant (2017), Breton et al. (2008). Other CFD methods can give detailed and precise results, including direct 3D analysis, flow visualization, and wake patterns, but for so require longer computational time, which may preclude the application optimization techniques to the model.

In this work, a modified BEM algorithm is developed to be used with an optimization strategy for the modeling of small wind turbines.

2 I NUMERICAL APPROACH

The BEM method is based on dividing the turbine's blade into airfoil sections and summing their aerodynamic effects according to their radial position. Hence, the basis of the calculations is the airfoil's 2D aerodynamic data. For low angles of attack, this data can be acquired by different methods and software. But, for high angles of attack and low Reynolds numbers, a commonly faced condition by small wind turbines, this procedure becomes a cumbersome part of the method, situation addressed on Section 2.1.

One advantage of the BEM method, however, is the relatively low computational costs compared to other CFD methods. This fact allows it to be used in combination with optimization algorithms. For this, it must have high fidelity results, and so, several correction models must be integrated during the calculations. These models intend to insert the 3D correction factors to the 2D aerodynamic calculations. The development and study of such methods are still a very exploited area in the wind turbine research field.

The major change on the algorithm in development is that, for simulating and optimizing the turbine short-time dynamic response, it needs to be structured to analyze its temporal behavior, from the initial state - no angular speed -, to a final desired condition - optimal angular speed or the equilibrium state -, instead of simply calculating the power output for a defined wind speed. This temporal analysis is done by dividing the turbine motion into two stages, an idling period in which it produces little or no power and accelerates slowly and a working period, in which the turbine has fast acceleration and a high power output, Figure 2. This discretization allows for a better understanding of the turbine motion and also of how these stages influence the overall energy production.

In Figure 2, it can also be seen that for the turbine to have a constant power output for a defined wind speed, a fixed and controllable angular speed must be set. This is a crucial aspect of wind turbine projects which is also widely studied, as in Kusiak et al. (2010) and Simani (2015).

Also in Figure 2 the effects of the uncertain 2D aerodynamic data are noticed. The lack of precise data for the high angles of attack and low Reynolds number, especially in the starting period, results in abrupt variations of the blades torque and consequently of the turbine power in between the time-steps.

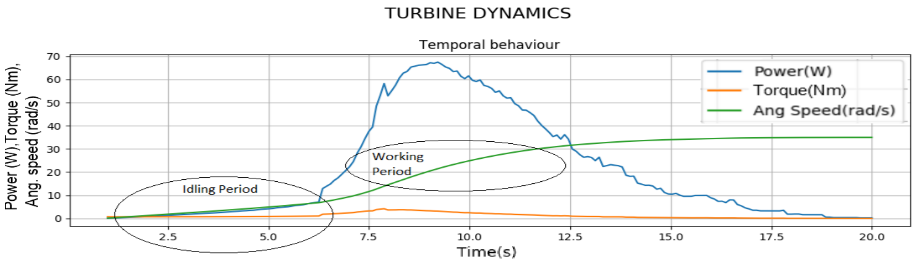

Figure 2 - Turbine dynamic response for a fixed defined wind speed, highlighting the idling - low acceleration and power - and working - high acceleration and power - stages on the angular speed curve. Figure generated by the algorithm in development

The basic structure of the algorithm consists of, for each time-step of the simulation, calculating the turbine's torque, angular acceleration, angular speed, and mechanical power.

The power available in the wind is given by:

$$P_a = 0{,}5\rho S V^3$$

Where ρ is the density of the air, S the wind turbine area, and V the wind speed. The optimal relation between the power extracted by the turbine and the power available in the wind, is 59,3% called the Betz-Joukowsky limit, van Kuik et al. (2015). This means that the optimal turbine will have a power output of 0,593 · $0{,}5\rho SV^3$.

The power of the wind turbine can be expressed as:

$$P_i = (T_i - T_r) \cdot \omega_i$$

where T_i is the sum of the blades torques, T_r is the sum of the resistive torques, for example, the generator cogging torque, and ω_i is the angular speed. The latter is defined as:

$$\omega_i = \alpha_i \cdot \delta_t + \omega_{i-1}$$

being δ_t the time-step, α_i the angular acceleration, and ω_{i-1} the angular speed of the previous step. As for the angular acceleration, it is calculated as:

$$\alpha_i = \frac{T_i - T_r}{I}$$

where I is the second moment of inertia of the turbine.

Therefore, for each time-step of the simulation, turbine data such as 2D aerodynamics, 3D corrections, induction factors, and torque, must be recalculated.

These procedures are described in the following sections.

2.1 2D aerodynamic data

As previously stated, for each time-step of the simulation and for each airfoil section, new data such as Reynolds number, angle of attack, Cl and Cd must be acquired. Considering this and to maintain a reasonable time for the simulation, the 2D aerodynamic coefficients are pre-calculated using the Xfoil software and stored separately in a text file. Hence, during the simulations, the algorithm must merely read the text files containing the data.

The 2D coefficients are simple to acquire when referring to usual situations, that is, low angles of attack up to the stall angle. However, during the operation of a small wind turbine, the airfoils will face very high angles of attack, up to 90° - tip airfoils when the turbine is still. To tackle these cases where the software is unable to return acceptable results, methods were developed to extrapolate the coefficients to high angles of attack, Viterna and Janetzke (1982). Yet, some combinations of angles of attack and Reynolds numbers can result in cases where there may be voids of data, as the software fails to converge and return results. These data voids are a known deficiency of the algorithm and an issue difficult to overcome when it comes to small wind turbine design.

Even demonstrating some convergence issues, Xfoil has shown to be a suitable software for the calculations of the 2D aerodynamic data, Wata et al. (2011).

2.2 3D correction models

To use the 2D aerodynamic data in the calculations, some correction models must be applied. They aim to represent 3D effects, such as stall-delay Figure 3, dynamic stall, and tip-loss, giving the model higher fidelity.

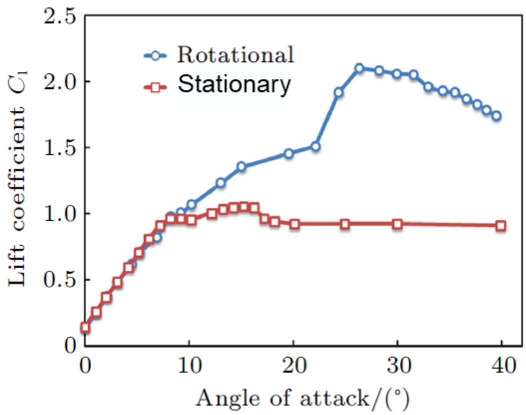

Figure 3 - Stall-delay effect, an example of how the rotational effects influence the 2D aerodynamic data - the latter labeled as statuary -, figure adapted from Wang (2012)

Several models have been developed, Du and Selig (1997), Elgammi and Sant (2017), Breton et al. (2008), Ning (2013), Shen et al. (2014), and work is still being done aiming to develop more exact wind turbine modeling methods. The main setback of these methods is that their effects are difficult to be measured experimentally, and when this is achievable, they tend to be biased by the one wind turbine being tested and end up not being suitable for other configurations of turbines.

Breton et al. (2008) compared some stall-delay methods, Shen et al. (2014) developed new methods for the tip-loss factor, Elgammi and Sant (2017) recently developed a new stall-delay method combined with their tip-loss factor. These novel approaches show an insight on how they are tending to get more exact as the researches on the field grow in importance.

One of the goals of this work is to gather some of the developed methods and apply the most suitable ones, remembering that they are ought to be used in an optimization process. As the methods have to be used in every time-step of the simulation, not only high fidelity results but also the computational cost is important when selecting the ones to be implemented in the algorithm.

2.3 Induction factors

Another crucial characteristic of wind turbines, which is also a 3D effect, is the occurrence of induction factors. These change the flow characteristics and ultimately alter the fluid direction over the airfoil sections. This is a consequence of the influence of the wakes created by the blades on the incoming flow, van Kuik et al. (2015).

In Figure 4, it can be seen how the induction factors α and α' act on altering the flow behavior. Ω the angular speed, *r* the airfoil radial position, U_∞ the wind speed, and the ϕ resultant flow angle.

As well as 3D corrections, methods have been developed to accurately calculate the values of the induction factors, Ning (2013), Guntur and Sørensen (2014).

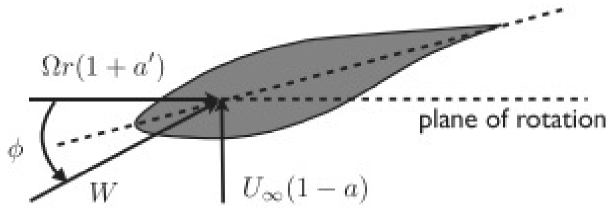

Figure 4 - Induction factors acting on a rotating airfoil section, is the axial induction factor and the radial induction factor, Ning (2013)

2.4 Torque calculation

The turbine torque is the sum of the blades torque minus the resistive torques. The blade torque can be expressed as the summation of the airfoil sections torque:

$$blade_{torque} = \sum_{i=1}^{n} PT_i \cdot \text{position}_i$$

The position_i is the distance of the current airfoil to the turbine axis of revolution, while PT_i is the airfoil tangential force, which is directly related to its aerodynamic forces, as seen in Figure 5. *L* is the lift force, perpendicular to the wind direction and *D* the drag force parallel to the wind direction. Both derived from the aerodynamic coefficients:

$$\begin{cases} L = 1/2 \rho C_l c W^2 \\ D = 1/2 \rho C_d c W^2 \end{cases}$$

being *p* the air density, *c* the airfoil chord and *W* the wind speed

PT is the tangential force, acting parallel to the rotation plane, and *PN* is the normal force, perpendicular to the rotation plane. These are related to the lift and drag forces as shown in:

$$\begin{cases} PN = L\,cos(\Phi) + D\,sin(\Phi) \\ PT = L\,sin(\Phi) - D\,cos(\Phi) \end{cases}$$

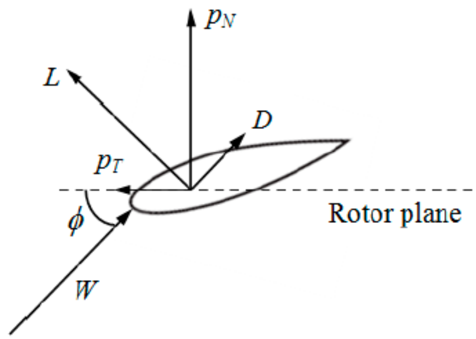

Figure 5 - Force diagram on an airfoil section. is the lift force, perpendicular to the wind direction. is the drag force parallel to the wind direction. is the tangential force. is the normal force. Zhu et al. (2017)

The modeling of the resistive torques that act in a wind turbine is not a simple task to execute as they are related to the type of generator, electrical connection, and bearing selection. For the small wind turbine class, the generator resistive torque is one that can highly influence the turbine's performance, Pourrajabian et al. (2014) and Wood (2004), and thus should be given special attention during the simulations.

2.5 Validation

To test and validate the developed algorithm, the results were compared with data of wind turbine models from the literature. As the great majority of cases available follow the nominal power output project concept, the validation was made by comparing a *Power X Wind speed* curve instead of a dynamic response curve, Figure 2. This is achievable on the algorithm by capturing the power value correspondent to the angular speed used in each test.

To ensure the algorithm's applicability to a wide range of turbines categories, it was compared with turbines of different sizes. The first model, Figure 6 and Figure 7, has 0.45m rotor diameter and 25W nominal power output. The second, Figure 8, a 38.5m rotor diameter and 105kW nominal power output.

Figure 6 depicts the comparison between the algorithm's result and the model from Lanzafame et al. (2016). The original work mentioned that, due to wind tunnel blockage effects, the measured data was underestimated. No resistive torques were implemented in the solution given by this work algorithm, and the efficiency between the mechanical and electric conversions was defined as 100%, yet another reason for the difference in the results. In Figure 7, with 85% energy conversion efficiency, the results are more compatible, still, the implications of the blockage effects on the experimental data and the no implementation of further losses models on the algorithm can be seen.

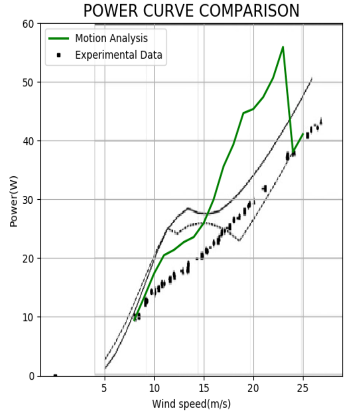

Figure 6 - Comparison between the algorithm's result and the test case from Lanzafame et al. (2016). The green curve represents the output of the algorithm with a 100% energy conversion efficiency and the points represent the experimental data. The dark curves are the results from the algorithm developed in the reference work.

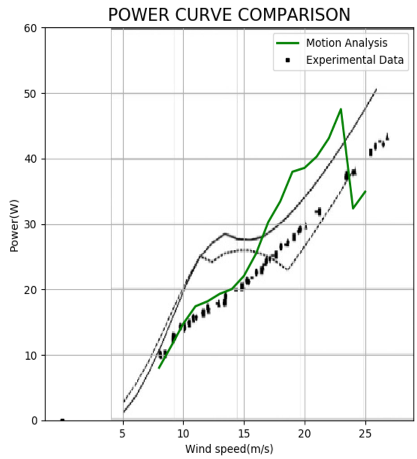

Figure 7 - Comparison between the algorithm's result and the test case from Lanzafame et al. (2016). The green curve represents the output of the algorithm with 85% energy conversion efficiency and the points represent the experimental data. The dark curves are the results of the algorithm developed in the reference work

In Figure 8, the algorithm was compared against an experimental case from Viterna and Janetzke (1982). In this case, the authors presented a model for the compensation of the system losses. With this model, high accuracy could be achieved by the algorithm. Furthermore, the comparison was performed up to the nominal wind speed, in which the curves stabilize at constant power.

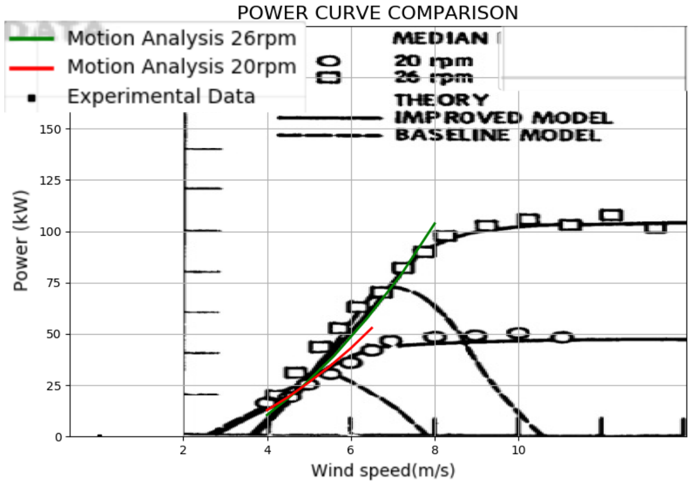

Figure 8 - Comparison between the algorithm's result and the test case from Viterna and Janetzke (1982). The green and red curves represent the output of the algorithm and the points represent the experimental data. The dark curves are the results from the algorithm developed in the reference work

The results show good agreement with the experimental data and highlight the importance of properly defining the losses that occur on the models.

3 I ADDITIVE MANUFACTURING

Given the recent developments in this technology, Additive Manufacturing (AM) is transforming the way mechanical parts are designed. Now, they are not restricted anymore to the constraints of machine tools or molding dependent techniques, which were a central part of the design process of wind turbine blades.

In AM, the design phase has increased flexibility, as complex parts can be manufactured easier and faster. Furthermore, new manufacturing concepts are being implemented during the design of mechanical parts, Comotti et al. (2017), such as different infill methodologies, topology optimization, and also a multi-material approach.

When considering wind turbines, as well as the small wind turbine category, the blades are their most expensive part. Their complex geometry pushes standard manufacturing methods - e. g. machine tools for metals and molding techniques for composite materials - to their limits. And also, the limitations of such manufacturing methods impede the design of more complex blades.

The use of AM to produce the blades can not only allow for the development of more elaborate geometries but also improve its structural components and ultimately create a model with high performance and low moment of inertia. Another point that may be improved is the total time that it is necessary to manufacture a blade, Bassett et al. (2015), faster AM processes should lead to shorter manufacturing times and reduce the COE.

4 | CONCLUSION

The preliminary version of the simulation algorithm showed good results and highlighted the importance of the correct modeling of the different losses that may occur on wind turbines. Further testing and validation are still necessary before optimization techniques can be applied for the design of small wind turbine models. Also, a model for calculating the COE, considering the features of AM must be developed. For so, an accurate study must be performed to evaluate the total impact of AM on the small wind energy scenario.

The results of the algorithm in development allowed for a deeper understanding of the turbine dynamic response, presenting the possibility to explore and optimize all work conditions of small wind turbines and with this increase its time-based performance.

The future work is to manufacture a small wind turbine model suing AM, to measure the turbine dynamic response curve on a wind-tunnel (the same delivered by the algorithm) allowing the further development of the algorithm, and to qualitatively and quantitatively evaluate the use of AM for the production of the blades.

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