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Efficiency Optimization in Medium Power Wind Turbines: an Innovative Mechanical Pitch Control System

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Abstract – *The paper illustrates the design of a new mechanical system for propeller blades pitch calibration in medium power wind turbines. The peculiarity of this system is its capacity of adjusting through a feedback control system, which allows the wind turbine to capture the maximum amount of energy from the wind. In this work an axial drive system was studied by means of racks capable of linearly adjusting the pitch of all wind turbine propeller blades in an intrinsically synchronous way, with an advantage over the traditional methods of propeller blades pitch calibration. For different wind speeds the system adjusts the blades angle of incidence in order to reduce the rotation speed and keep the system as close as possible to the pre-established design conditions generating maximum energy with a high efficiency. The manuscript examines the main analyses and simulations conducted during the design phase. These show that the proposed method allows to reach higher efficiencies with a greater intrinsic stability compared to the traditional pitch control mechanisms in medium power wind turbines. The experimental results on the first prototypes confirm the efficiency increase.* ***Copyright © 2022 The Authors.***

Keywords: *Propeller Blades, Pitch Calibration, Medium Power Wind Turbines, Racks, Linearly Adjusting*

Nomenclature

ω	Angular speed
d_c	Distance from the rotation center
F_a	Axial load
F_c	Centripetal force
K	Shape factor
m	Mass of the blade
M_b	Maximum bending moment
n	Rotor rotation speed
R	Radius
Ni Cr Mo	Nickel-chromium-molybdenum
S235JR	S is for structural steel, "235" represents the minimum yield strength (MPa) for the steel thickness ≤ 16 mm, "JR" indicates the quality grade related to Charpy impact test energy value at room temperature (20 °C)

I. Introduction

Wind power has increased in installed capacity by 20–30% each year for the past 5 years, indicating commercial viability with proper citing and regulatory framework [1]. Consequentially, wind energy has received considerable attention, due to its vital role in combating the energy crisis and global climate change; it has grown so to become the most important source of non-conventional renewable energy [2]. Indeed, it is essential that the supply of this electricity is safe, reliable, sustainable, and environmentally friendly, reducing CO_2 emissions into the atmosphere and the use of fossil fuels. Renewable energies, and wind energy, offer a significant contribution to this end [3]. Wind energy research dates to the last century, but the efforts to improve the performance of wind turbines are still considerable worldwide. Advances in blade aerodynamics and wind resource evaluation are remarkable [4]. Currently, the wind power sector is thus the fastest growing renewable energy sector and contributes significantly to reducing greenhouse gases and achieving the emission reduction targets set by the Kyoto Protocol and Paris Agreement [5]. Particularly, the use of systems for varying the pitch of the propeller in wind turbines, also acting through the aid of feedback control systems, is well known by now [6]-[8]. Indeed, thanks to these mechanisms installed inside the turbine hub/nacelle, a quantity of energy which is greater than that of the static systems lacking this calibration can be produced. In wind turbines, the angle of incidence of the wind on the blades plays a key role. In recent years, several studies have been conducted on the advantages of the blade pitch calibration in wind turbines [9], [10] in order to limit power in situations of high wind speeds; optimizing the energy production for low winds improves the effect relative to structural loads, which becomes a more important topic when increasing the size of the turbine [11], [12]. Among the various types of variable pitch wind turbines, pitch control is

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particularly critical in small-medium sized wind turbines (max 50 kW) in which the space available for the mechanical control system is very limited [13]-[15].

Considering this, although wind power generation is a mature technology and the levelized cost of electricity is low, further improvements in its design can be still realized in these terms [16]. In the present study, the authors focused on the proposal of an optimal solution for adjusting the pitch of the propellers for medium-small size wind turbines (max 50 kW), in order to reach a more accurate calibration than the traditional calibration methods of the pitch can otherwise provide.

The studied mechanism allows a linear adjustment of the angle of incidence and, therefore, of the pitch during the entire movement of the first adjustment organ. The attention was mainly addressed to the analysis of the mechanical aspects of this application and the structural performance of the entire structure of the wind turbine.

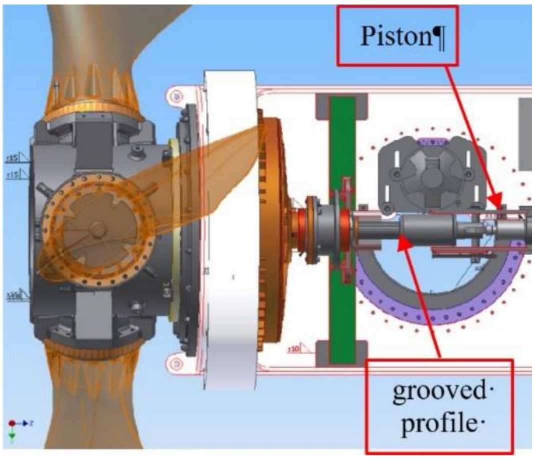
The study led to the construction of about 20 wind turbines with a power of 50 kW which were installed in various areas of Southern Italy, to test their actual operation.

The study is divided into four sections. Section I is the introduction. Section II is devoted to the design of an innovative pitch control system. Section III highlights the results and the discussions; finally, in Section IV conclusions are drawn from data gathered.

II. Design of Innovative Pitch Control System

The work started by designing the conceptualization; subsequent sizing of an innovative gear transmission system to adjust the propellers pitch was designed. By using computational numerical methods, as developed, and described in detail in their recent work [17]-[19], the authors reproduced the virtual Finite Elements Model (FEM) of the gear transmission and analysed the different possible configurations of the system components. In particular, the Mesh-Morphing method was employed to perform the sizing of the linear translational actuator and the hydraulic piston. The 3D parametric model of the whole mechanical adjustment unit was illustrated in Fig. 1(a) and in Fig. 1(b). The main parts of the system can be identified in the piston (Fig. 1(a)), the three racks and the three pinions (Fig. 1(b)). The three solidary racks at the piston translated along the main axis of the turbine connected to the generator by means of a grooved profile. In Fig. 2 an isometric view of the mechanical adjustment unit in section is shown. The list of the main components constituting the adjustment unit was depicted in Table I.

Turbines are generally subject to wind loads that are not particularly excessive and variable according to a probabilistic trend as shown in Table II; consequently, their performance is influenced by the wind speed entering their rotor. Typically, this quantity is not available since the wind speed is measured at the nacelle behind the turbine rotor, providing a lower value [20]. The data illustrated in Table II particularly refers to the locality of "Cava dei Modicani" in the province of Ragusa, Sicily (Italy), where the axial load and the overturning axial moment were calculated based on the variable wind speed [21], [22] to which the turbine was subject. The data, initially calculated analytically, was then experimentally verified on the first prototypes built. The moments indicated in Table II were 3 at 120° from each other arising from the overturning moments of the blades at the considered wind conditions. In the sizing of the structure, the maximum value of that moment was used with respect to the worst case in which all the load weighed on a single propeller. The mechanical components shown in Table I were considered as subjected to two different types of stress: a radial stress due to the overturning moment (1), and an axial one due to the centripetal force (2) which was incident on the blades during the rotation of the rotor.



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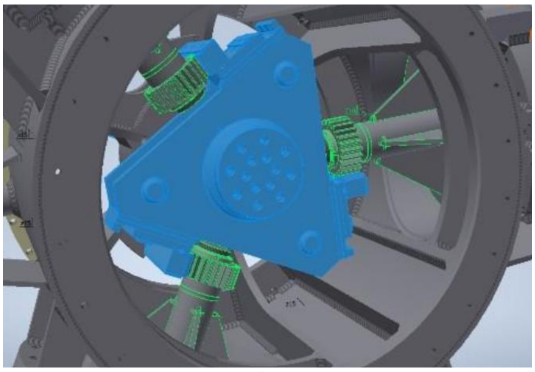


(b)

Figs. 1. Assembled in section of the mechanical adjustment unit

TABLE I
ADJUSTMENT UNIT COMPONENTS

Component	Quantity	Material
Hydraulic Piston	1	Alloy steel
Pinion	3	S235JR
Rack System	3	S235JR
Hub	1	S235JR
Rotor	1	S235JR
Radial Bearings	4	
Axial Bearings	3	

TABLE II
ADJUSTMENT UNIT COMPONENTS

Wind Speed [m/s]	Axial Load [N]	RPM	Wind Probability [%]	Overturning Moment [N m]
0	0.00	0	0.00%	0.00
1	23.95	9	6.14%	43.90
2.5	149.66	15	12.99%	274.37
3	215.51	21	14.29%	395.10
4	383.13	27	15.27%	702.40
5	598.64	33	14.35%	1097.50
6	862.041	39	12.15%	1580.41
7	1173.33	44	9.39%	2151.11
8.5	1727.53	48	5.47%	3167.14
9	1939.59	48	4.38%	3555.92
10	2394.56	48	2.67%	4390.02
12	3448.16	48	0.79%	6321.63
14	4693.33	48	0.18%	8604.44
16	6130.07	48	0.03%	11238.46
18	7758.37	48	0.004%	14223.67
20	9578.23	48	0.003%	17560.09

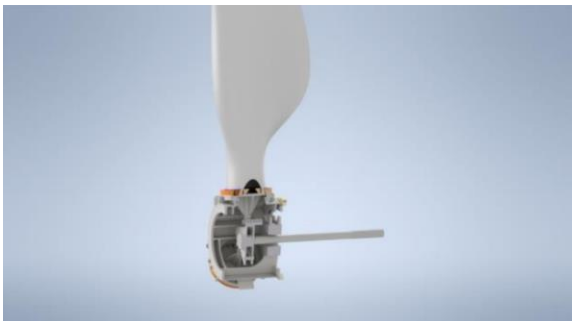


Fig. 2. Isometric view of the mechanical adjustment unit: section

Specifically, considering that:

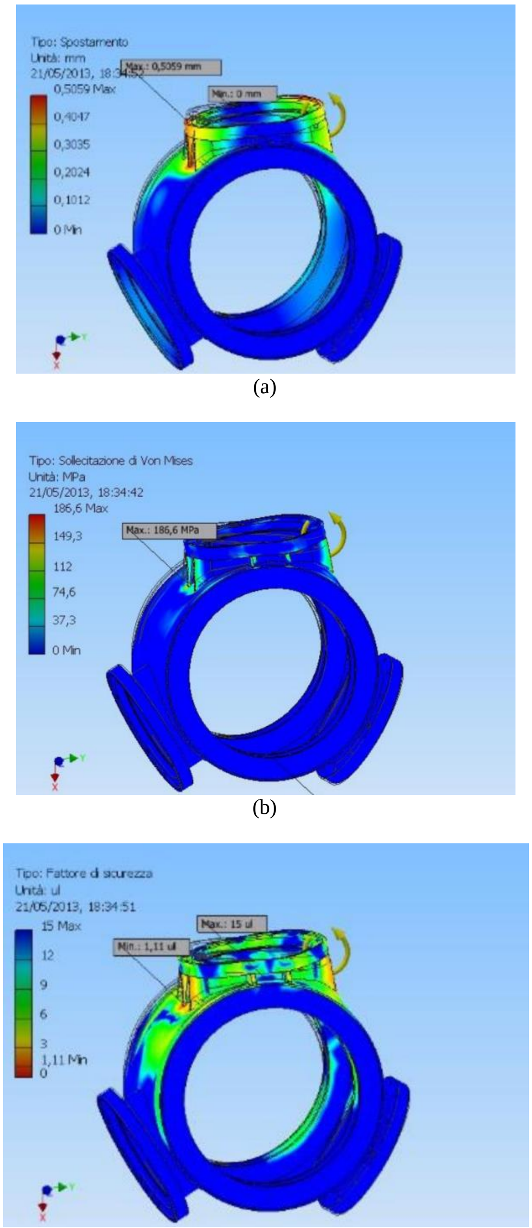
- The mass of the blade was estimated at 400 kg;
- The rotor rotated at maximum 67.2 rpm;
- The point of application of the loads on the blade, with an acceptable approximation, was distant from the center of rotation dc = 3.75 m;
- The share of the axial load (F_a) acting on the blade was 22 kN with a wind of 53.5 m/s. The maximum bending moment to which the blade was subject was calculated as:

$$M_b = F_a \times d_c = \sim 83 \text{ kN m} \quad (1)$$

$$F_c = m \times \omega^2 \times R = = 400 \times 7.03^2 \times 3.75 = \sim 74 \text{ kN} \quad (2)$$

II.1. Structural Verifications

Among the numerous results obtained in the various static and dynamic resistance tests performed both on all components and on the system, the tensions and deformations derived on the hub and on the rotor were the following ones. Maximum equivalent stresses, calculated using the von-Mises criteria, were found to be equal to 186.6 MPa in Figs. 3. It is important to note that since these values were less than the material's yield value (207 MPa), the wind turbine hub could operate in perfect safety even under extreme stress circumstances, without enduring any substantial changes impacting its operation and performance.

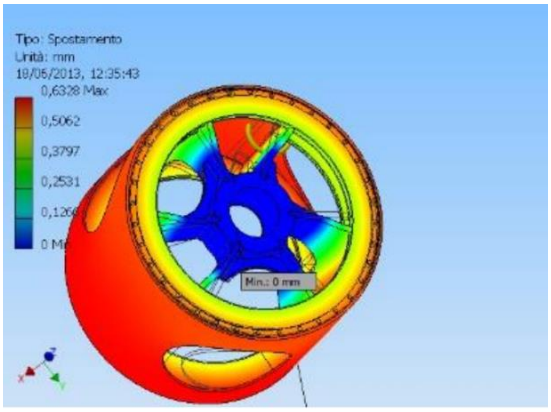


(a) (b) (c)

Figs. 3. Stress analysis on the turbine hub in static conditions: (a) displacement; (b) stress; (c) safety coefficient

The steel used for both hub and rotor analyses was a type of mild steel with a low yield strength sigma coefficient. The tests performed with this material permitted to ensure that with the type of alloy steel 38 Ni Cr Mo 4 (NCD4) used to produce the hub mounted on the shaft, having a yield sigma equal to 850 MPa, they were still reliable and fell within safety limits [23]-[26].

For the rotor casing and all the remaining components of the turbine, an S235JR steel (old FE360) with a yield strength of 235 MPa was employed. The values of maximum equivalent stresses, evaluated according to the von-Mises criterion, were found to be equal to 131.5 MPa in Figs. 4.



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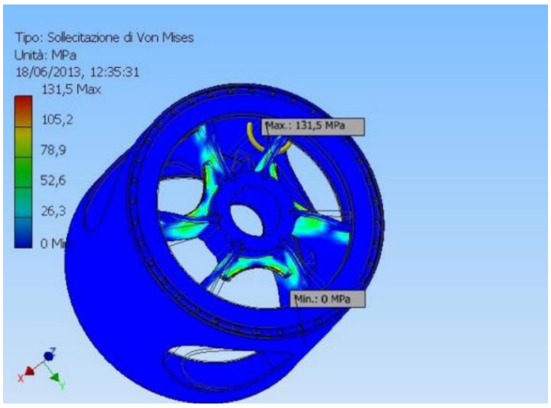

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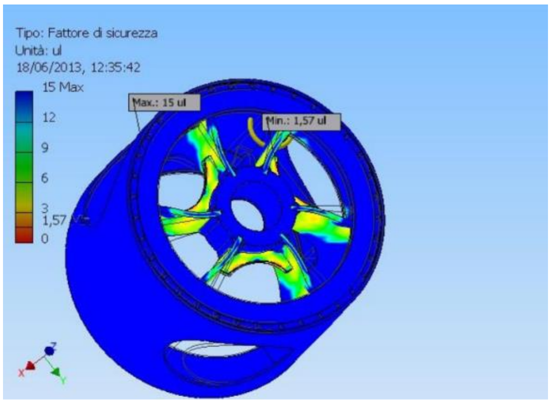


(c)

Figs. 4. Stress analysis on the turbine rotor in static conditions: (a) displacement; (b) stress; (c) safety coefficient

II.2. Weibull Wind Speed Calculation

As shown in Table III, wind speed probability was calculated as a Weibull curve defined by the average wind speed and a shape factor, K. To facilitate piece-wise integration, the wind speed range was subdivided into "bins" of 1 m/s in width (Column 1). For each wind speed bin, the instantaneous wind turbine power (W, Column 2) was multiplied by the Weibull wind speed probability (f, Column 3). This cross product (Net W, Column 4) was the contribution to the average turbine power output by wind speeds in that bin. The sum of these contributions was the average power output of the turbine on a continuous 24-hour basis. This model included a mathematical idealization of the wind speed probability. It was interesting to note that the validity of this assumption was limited as the time under consideration (i.e., the wind speed averaging period) was reduced. This model can be considered as the best used with annual or monthly average wind speeds. Using this model with daily or hourly average wind speed, data was not recommended because the wind would not follow a Weibull distribution over short periods. Hub Average Wind Speed was calibrated for wind shear and adopted to calculate the Weibull wind speed probability. Air Density Factor was the reduction from sea level performance.

Average Power Output was the average continuous equivalent output of the turbine. Daily Energy Output was the average energy produced per day. Annual and Monthly Energy Outputs were calculated using the Daily value. Percent Operating Time was the time the turbine should be producing some power. Below are inserted the Weibull results (Table IV) and a graph (Fig. 5), depicting the probability of having a certain wind speed value in a year.

TABLE III
WEIBULL PERFORMANCE CALCULATIONS

Wind Speed Bin [m/s]	Power [kW]	Wind Probablity [%]	Net kW @ V
0	0.0	0.00%	0.000
1	0.0	6.14%	0.000
2.5	1.2	13.00%	0.158
3	1.9	14.29%	0.277
4	4.8	15.27%	0.727
5	10.1	14.35%	1.456
6	18.1	12.15%	2.200
7	30.4	9.39%	2.855
8.5	50.5	5.47%	2.762
9	50.0	4.38%	2.190
10	50.0	2.67%	1.333
11	50.0	1.51%	0.754
12	50.0	0.79%	0.397
13	50.0	0.39%	0.195
14	50.0	0.18%	0.089
15	50.0	0.08%	0.038
16	50.0	0.03%	0.015
17	50.0	0.01%	0.006
18	50.0	0.00%	0.002
19	50.0	0.00%	0.001
20	50.0	0.00%	0.000
21	50.0	0.00%	0.000
22	50.0	0.00%	0.000
23	50.0	0.00%	0.000
24	50.0	0.00%	0.000
25	50.0	0.00%	0.000

TABLE IV
WEIBULL CALCULATION RESULTS

Results	
Hub Average Wind Speed [m/s]	5.00
Air Density Factor	0%
Average Output Power [kW]	16.12
Daily Energy Output [kWh]	386.9
Annual Energy Output [kWh]	141.23
Percent Operating Time	69.1%

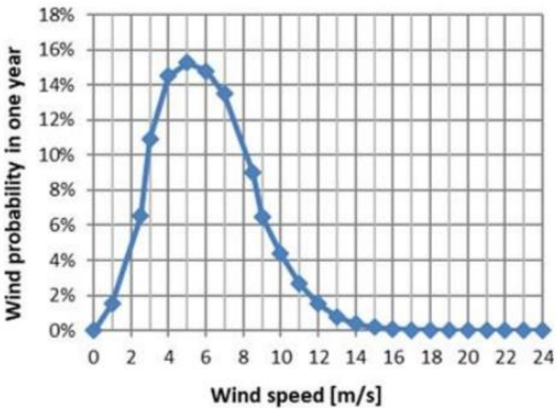


Fig. 5. Wind probability in one year
(Cava dei Modicani, Ragusa, Sicily)

III. Results and Discussions

III.1. Power Analysis in Turbine with the New Mechanical Pitch Control System

Generally, turbines are subject to variable wind loads entering their rotor, which can alter their performance.

This study tries to find a suitable solution for adjusting the pitch of the propellers in small to medium-sized wind turbines, which consists in dimensioning an innovative gear drive system using a virtual Finite Element Model (FEM). Specifically, for the wind distribution examined (area of "Cava dei Modicani" Ragusa, Sicily), the average power values produced by the turbine endowed with the new mechanical pitch control system can produce were compared with those obtained with the traditional control system and those obtained without any control system. The data, that was initially calculated analytically, was verified experimentally on the first constructed prototypes and relative performance was reported graphically (Fig. 6).

The control system developed made it possible to reach the maximum power value recommended for turbine operation faster (only at 6 m/s) and to keep it stable over a wide range of speed variations. Thus, with the new system, up to 53.5 m/s wind speed, the rotation speed of the electric generator was kept constant (48 rpm); the turbine worked under optimal conditions and produced maximum power (50 kW). In addition, the maximum equivalent stresses applied to the hub and rotor, calculated using the von-Mises criterion, were lower than the yield value of the material used. As a result, the hub of the wind turbine guaranteed safe operation even under extreme stresses.

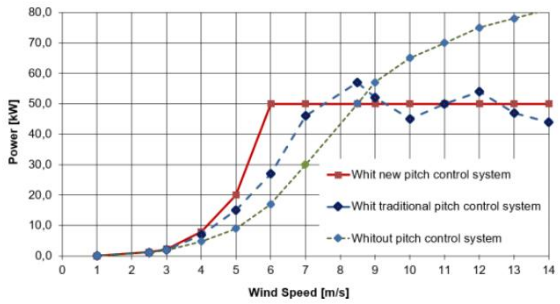
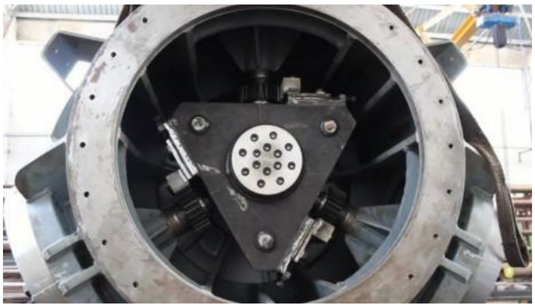


Fig. 6. Power developed by the wind turbine
as a function of wind speed

With conventional control systems, on the other hand, the maximum power was generally stabilized at around the optimum value. Without the pitch control system, the situation was even worse; it was not possible to stabilize the power output at the optimum value. Power continued to increase asymptotically as wind speed increased. In conclusion, the adoption of the proposed new control system had the advantage of being inherently stable and ensuring linear pitch calibration. In this way, an optimisation of the efficiency of the power produced by the turbine over the measured wind variation range was achieved. Fig. 7(a) shows a picture of the constructed mechanical pitch control system, while Fig. 7(b) shows the installation of the complete wind turbine.



(a)

(b)

Figs. 7. (a) Detail of the pitch control system built;
(b) Installation of the complete wind turbine

IV. Conclusion

In this work a new mechanical system designed for propeller blades pitch calibration in medium power wind turbines (50 kW) was presented and discussed. The innovative mechanical pitch control system here analysed was characterized by the capacity of adjusting itself through a feedback control system. This enabled the wind turbine to capture the maximum amount of energy from the wind. It arises that compared to the traditional systems currently on commerce, the proposed new system had a linear pitch calibration and intrinsically guaranteed the synchronism between the blades. For different wind speeds the system adjusted the blades angle of incidence reducing the rotation speed and maintaining the system as close as possible to the preestablished design conditions. In the future, this innovative mechanical system will be installed on all wind turbine model, horizontal and vertical axis, medium-power and high-power with the concern of further optimizing the design conditions. Lighter and at the same time stronger metal materials will be used to generate the maximum possible energy with high efficiency.

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References

[1] Tarfaoui, M., Nachtane, M., and Boudounit, H. (September 19, 2019). Finite Element Analysis of Composite Offshore Wind Turbine Blades Under Operating Conditions. *ASME. J. Thermal Sci. Eng. Appl.* February 2020; 12(1): 011001. doi: https://doi.org/10.1115/1.4042123

[2] Shourangiz-Haghighi, A., Diazd, M., Zhang, Y., Li, J., Yuan, Y., Faraji, R., ... & Guerrero, J. M. (2020). Developing more efficient wind turbines: A survey of control challenges and opportunities. *IEEE Industrial Electronics Magazine*, 14(4), 53-64.

[3] Alcayde A, Hernandez-Escobedo Q, Muñoz-Rodríguez D, Perea-Moreno A-J. Worldwide Research Trends on Optimizing Wind Turbine Efficiency. *Energies*. 2022; 15(18):6559. doi: https://doi.org/10.3390/en15186559

[4] Castillo, A.D.; Jauregui-Correa, J.C.; Herbert, F.; Castillo-Villar, K.K.; Franco, J.A.; Hernandez-Escobedo, Q.; Perea-Moreno, A.-J.; Alcayde, A. The Effect of a Flexible Blade for Load Alleviation in Wind Turbines. *Energies* 2021, 14, 4988.

[5] Navadeh N, Goroshko I, Zhuk Y, Etminan Moghadam F, Soleiman Fallah A. Finite Element Analysis of Wind Turbine Blade Vibrations. *Vibration*. 2021; 4(2):310-322. doi: https://doi.org/10.3390/vibration4020020

[6] D Muljadi, Eduard, and Charles P. Butterfield, 2001. Pitch-controlled variable-speed wind tur-bine generation. *IEEE transactions on Industry Applications* 37.1: 240-246

[7] Gao, Richie, and Zhiwei Gao, 2016. Pitch control for wind turbine systems using optimization, estimation and compensation. *Renewable Energy* 91: 501-515

[8] Larsen, Torben J., and Tor D. Hanson, 2007. A method to avoid negative damped low fre-quent tower vibrations for a floating, pitch-controlled wind turbine. *Journal of Physics: Conference Series*. Vol. 75. No. 1. IOP Publishing

[9] Moutis, Panayiotis, et al, 2009. Primary load-frequency control from pitch-controlled wind turbines. *2009 IEEE Bucharest PowerTech*. IEEE.

[10] Navarrete, E. Chavero, et al, 2019. Expert control systems implemented in a pitch control of wind turbine: A review. *IEEE Access* 7: 13241-13259.

[11] Bossanyi, E. A., 2003. Wind turbine control for load reduction. *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology* 6.3: 229-244.

[12] Schubel, Peter J., and Richard J. Crossley, 2012. Wind turbine blade design. *Energies* 5.9: 3425-3449.

[13] Pérez, Jesús María Pinar, et al., 2013. Wind turbine reliability analysis. *Renewable and Sustainable Energy Reviews* 23: 463-472

[14] Polinder, Henk, et al., 2013. Trends in wind turbine generator systems. *IEEE Journal of emerging and selected topics in power electronics* 1.3: 174-185

[15] Hansen, Martin Otto Laver, et al., 2006. State of the art in wind turbine aerodynamics and aeroelasticity. *Progress in aerospace sciences* 42.4: 285-330

[16] Bošnjaković M, Katinić M, Santa R, Marić D. Wind Turbine Technology Trends. *Applied Sciences*. 2022; 12(17):8653. doi: https://doi.org/10.3390/app12178653

[17] Babič, M., Petrovič, D., Sodnik, J., Soldo, B., Komac, M., Chernieva, O., ... & Calì, M., 2021. Modeling and Classification of Alluvial Fans with DEMs and Machine Learning Methods: A Case Study of Slovenian Torrential Fans. *Remote Sensing*, 13(9), 1711.

[18] Calì, M., Ambu, R., 2022. A mesh morphing computational method for geometry optimization of assembled mechanical systems with flexible components. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 16(2), 575-582.

[19] Calì, M., Hajji, B., Nitto, G., Acri, A., 2022. The Design Value for Recycling End-of-Life Photovoltaic Panels. *Applied Sciences*, 12(18), 9092.

[20] Carullo, A., Ciocia, A., Malgaroli, G., & Spertino, F. (2021). An innovative correction method of wind speed for efficiency evaluation of wind turbines. *Acta IMEKO*, 10(2), 46-53.

[21] Tavner, Peter, et al., 2006. Influence of wind speed on wind turbine reliability. *Wind Engineering* 30.1: 55-72.

[22] Menezes, Eduardo José Novaes, Alex Maurício Araújo, and Nadège Sophie Bouchon-neau Da Silva, 2018. A review on wind turbine control and its associated methods. *Journal of cleaner production* 174: 945-953.

[23] Mishnaevsky, Leon, et al., 2017. Materials for wind turbine blades: an overview. *Materials* 10.11: 1285.

[24] Gao, Zhiwei, and Xiaoxu Liu, 2021. An overview on fault diagnosis, prognosis and resilient control for wind turbine systems. *Processes* 9.2: 300.

[25] Amirat, Yassine, et al., 2009. A brief status on condition monitoring and fault diagnosis in wind energy conversion systems. *Renewable and sustainable energy reviews* 13.9: 2629-263

[26] Calì, M., Oliveri, S., Application of an Effective SIMP Method with Filtering for Topology Optimization of Motorcycle Tubular Frame, (2017) *International Review of Mechanical Engineering (IREME)*, 11 (11), pp. 836-844. doi: https://doi.org/10.15866/ireme.v11i11.13770

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