EXPERIMENTAL RESEARCH OF ENERGY CHARACTERISTICS OF VAWT IN A WIND TUNNEL

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Functional dependencies between the wind speed, RPM, current strength and voltage of wind turbines represent the basic indicator of their energy efficiency. In this sense, a series of tests of horizontal-axis and vertical-axis wind turbines were carried out in the Laboratory for Aerotechnics, the "Miroslav Nenadović" Wind Tunnel of the Faculty of Mechanical Engineering, University of Belgrade. In this paper, results of one such test are presented, where the observed functional dependencies showed the justification of using wind turbines as a source of electrical energy. The work is focused on a vertical-axis wind turbine with non-standard type airfoil blades of different dimensions and poor finishing of the same. The dimensions of the wind turbine are adapted to the dimensions of the working part of the wind tunnel with an integrated constant consumer of electrical energy and a digital acquisition chain. The results of the wind turbine test from the unloaded state to the maximum load point to the optimal exploitation trend in terms of the efficiency of the wind turbine.

Key words*: wind tunnel, VAWT, energy efficiency, acquisition*

1. Introduction

Wind power is a popular, sustainable, renewable energy source that has a much smaller impact on the environment than burning fossil fuels. It is estimated that the worldwide electricity capacity from wind is 769 227 MW in the year of 2021, according to the International Renewable Energy Agency (IRENA) data. The share of electricity capacity from wind is increasing in the last years in Serbia (see Fig. 1). In 2021. the capacity to produce energy from wind in Serbia was 398 MW.

Wind power is one of the fastest-growing renewable energy technologies. Small onshore wind farms can feed some energy into the grid or provide power to isolated off-grid locations. Electricity is obtained from wind through wind turbines with horizontal or vertical axis of blade rotation [2]. Horizontal axis wind turbines (HAWTs) are mainly used in large wind farms since they have higher eficiency compared to the vertical axis wind turbines (VAWTs), and consenquently faster return of the investment [3]. On the other side, vertical axis wind turbines are insensitive to wind direction change, they have better behavior with turbulent or disturbed flow and have less noise emissions [4,5]. Also, HAWTs are simpler mechanically than a horizontal-axis type, since they do not require any yawing mechanism to keep them pointed into the wind. In addition, the generator is located at the ground level, which makes maintanence and repair of the turbine easier [6]. All these qualities make VAWTs suitable for urban area installation. There are several types of VAWTs, considering the geometry of the blades,

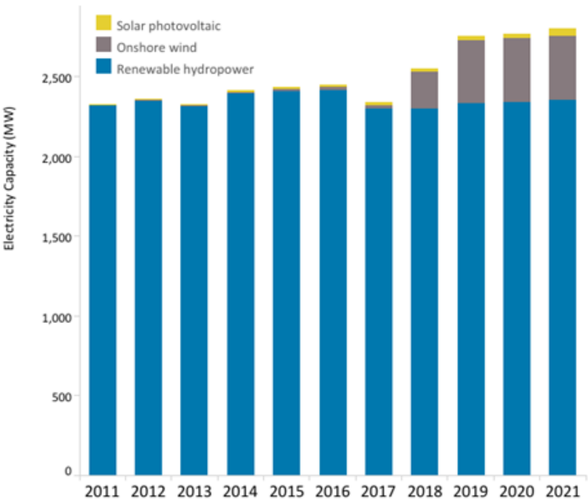


Figure 1. Electricity capacity from renewable energy sources (excluding bioenergy) trends in Serbia [1].

as shown in Fig. 2. The most popular nowdays is the H-Darrieus type – a straight-bladed VAWT. This type of vertical axis wind turbine has untwisted blades with constant cross section, that are relatively easy for fabrication and extrusion. However, the constant cross section blade is not a rule in constucting vertical axis wind turbines. In this paper, we will present experimental results of a non-standard blade VAWT from a wind tunnel testing.

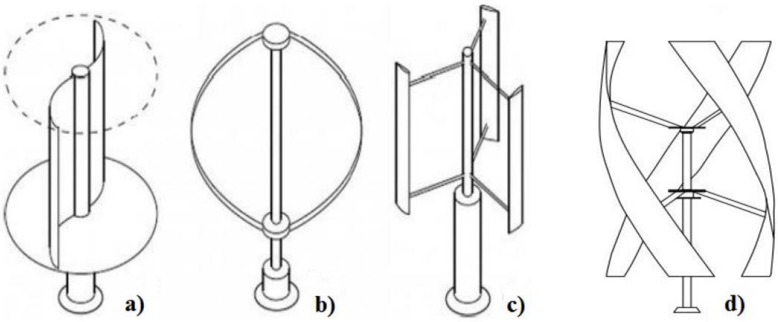


Figure 2. Different types of vertical axis wind turbines: a) Savounius, b) Darrieus-rotor, c) H-Darrieus, d) Helix shape [7].

There are different type of parameters that influence the performance of a vertical axis wind turbine. Analysis of the degree of utilization of wind as a renewable energy source poses questions related to the geometry and method of energy distribution to researchers. In this sense, the main controversy is the choice of horizontal or vertical wind turbines, that is, in which way the degree of utilization will be optimal. Many wind turbine researches are focused on experimental determination of vertical axis wind turbine performance evaluation in a wind tunnel facility. In that sence, the effects of gusts on a vertical axis wind turbine was the subject of [8,9]. They have subjected the VAWT to a step change in wind velocity. In [10] an experimental test a VAWT within the urban environment to assess the effects of unsteady wind on aerodynamic performance. Temporal variation in speed and direction was quantified and compared to a base case wind tunnel performance. Chong et al. [11] performed wind tunnel tests and CFD computations on a new device integrated with VAWT aimed at improving its performance. Experimental research on the influence of the unsteady wind on the VAWT perfomance was the subject of [12].

The authors of this paper focused on the analysis of the operation of vertical axis wind turbines with experimental confirmation and analysis of the obtained data. The paper shows the direct proportional dependence of the speed of the undisturbed current field and the energy characteristic of the alternating current generator. In the work, it is possible to see the minimum values of the speed of the undisturbed current field and the number of revolutions of the vertical wind turbine, as well as the optimal values of the speed of the flow of the undisturbed current field and the power of the electric current generator. The authors especially point out that the experiment was carried out under controlled conditions, i.e. in a Prandtl-type wind tunnel on a scale of 1:1, where the "problems" of the similarity theory were eliminated, especially regarding the Reynolds number and the thermodynamic characteristics of the undisturbed flow field.

2. Description of the wind tunnel facility and used equipment

Subsonic wind tunnel SB-1 built as an underground facility in the period of 1952/1957, is located in the Laboratory for aeronautics “Miroslav Nenadovic”. This is a wind tunnel of the Prandtl type i.e. with the return channel. The cross-section of the collector changes from the stilling chamber, where it is the largest, to the cross-section of the working part. This change in cross-section has the effect of accelerating the undisturbed flow field with minimal losses and local velocity deviations. Installed power of the wind tunnel is 200 kW, with a propulsion group consisting of one electric motor and a four-blade propeller of the Thunderbolt P47A aircraft.

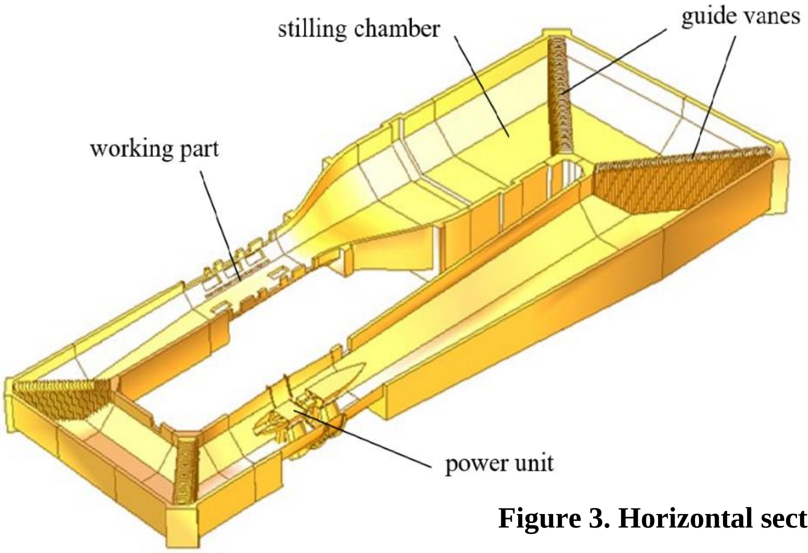


Figure 3. Horizontal section of the wind tunnel.

Figure 3 presents the horizontal section of the wind tunnel, with the characteristc parts of the same. The working part of the wind tunnel has the following dimensions: 2.90 x 2.10 x 6.0 m. The main purpose of the working part is to achieve as much homogeneous flow field as possible, with least possible turbulence, at a specific pressure and temperature, i.e. to create conditions as in free atmosphere.

The wind tunnel is equipped with electronic measuring equipment and is intended for both fundamental and exploitative industrial tests up to velocities of 116 m/s. The wind velocity (undisturbed flow field) is measured with a PCM-PFM 2 digital anemometer (Fig. 4a) connected to a stationary Pitot tube installed in the working part of the wind tunnel. The RPM of the vertical-axis wind turbine is monitored with OMRON photosensor presented in Fig. 4b.

a) b) c)

Figure 4. a) PCM-PEM 2 digital anemometer, b) OMRON-E3F2-DS30 photosensor and c) HBM QuantumX MX-840A central acquisition unit.

Data acquisition is performed with central acquisition unit QuantumX MX840A (Fig. 4c). All measuring devices are connected to this acquisition unit. The acquisition unit is equipped with a LAN and FireWire bus for distributing information to a higher order system (acquisition computer) as well as for expanding the number of measurement points by direct connection to several Quantum devices. HBM QuantumX MX840A is a multi-channel acquisition unit intended for static and dynamic parallel measurements. Thanks to the integration with a personal computer as a higher order system, the measurement process is extremely simple and the complete acquisition system is compact and small in size. This eight-channel acquisition unit provides 20000 measurements per second per channel with 24-bit resolution. All 8 A/D converters work synchronously and monitor the transformation of physical quantities into a digital signal in real time.

Figure 5. Analog rheostat.

The generator is loaded with an analog rheostat ranging from 0.03A to 30A by gradually changing the load range.

3. Methodology

Wind turbines energy efficiency testing basically represents the determination of the functional dependence between the input wind, geometric characteristics and output power from the generator. In this sense, the investigation is focused on measuring the associated power and voltage depending on the number of revolutions (RPM) of the wind turbine. Neither the wind turbine start-up limit values nor the values in the zone of lack of impuls, as a consequence of the generator's electrodynamic characteristics must be ignored. In the specific case, the vertical wind turbine is regularly connected to an alternating current generator, which, in turn, is connected to an industrial rheostat as a consumption simulator (see Fig. 6).

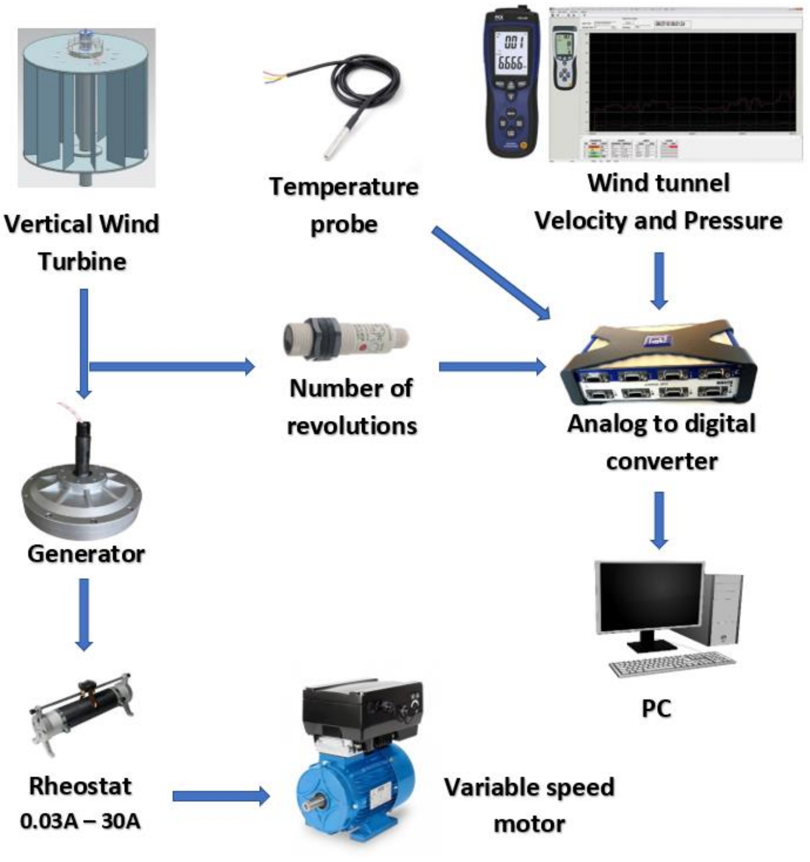


Figure 6. Schematic of experimental set up.

The basic idea is based on the change in the velocity of the undisturbed flow field in the wind tunnel with the idea of identifying the states of unloaded and loaded wind turbine. Flow velocities are within the range of safe norms up to 15 m/s, where the rheostat is loaded to a power of up to 30 A, respectively. With the exquisition analysis, it is necessary to determine at which wind velocity the wind turbine is started and at which wind velocity of the undisturbed flow field there is a maximum voltage not including „non-excitement“ zone. By experiment, it is necessary to determine the functional dependence for different resistances of the rheostat and, as such, show in the table as the final output the dependence of wind velocity-geometry of the wind turbine-output power and voltage of the same. In this sense, experiments were performed in the wind tunnel and the results were presented according to the previously defined procedure.

4. Results and discussion

The turbine on the test is presented in Fig. 7. This is a vertical-axis wind turbine with eight non-standard airfoil blades of poor finishing, whose profile is presented in Fig. 6, also. The dimensions of the wind turbine are 1330 x 1110 mm.

Figure 7. Vertical-axis wind turbine in the wind tunnel and turbine’s blade.

Figures 8 and 10 present the results of the vertical-axis wind turbine testing. Here are presented the time evolutions of RPM, frequency and voltage. The trends of RPM and frequency change are the same. This, in combination with the fact that the RPM and frequency of data reading on the acquisition device were separated, shows that the performed testing is valid.

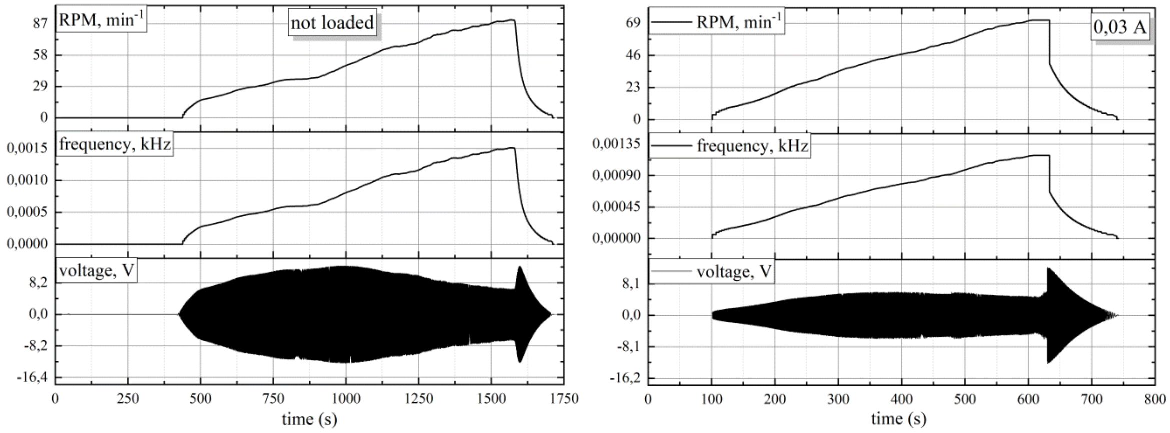


Figure 8. Results of non-loaded wind turbine, and for current of 0.03 A.

The RPM for the unloaded condition, as well as loads from 0.03 to 30 A indicate that the optimal velocity of the undisturbed flow field is in the range of 0-13 m/s, which is in accordance with generally accepted norms for wind turbines (both horizontal and vertical). The results indicate that there is space for the use of "excess" energy in the „non-excitement“ zone, where it is advisable to analyze the time determinants of that phenomenon, in accordance with the optimal degree of use.

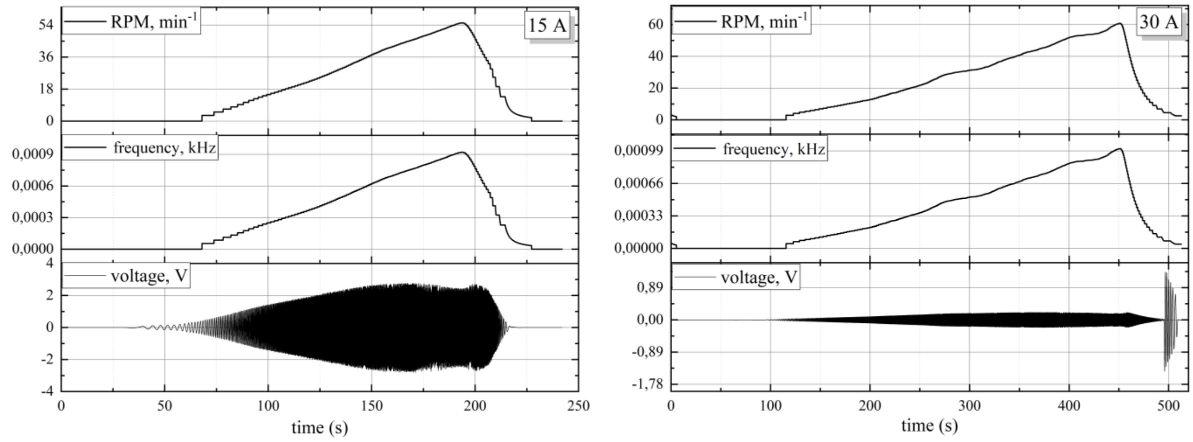
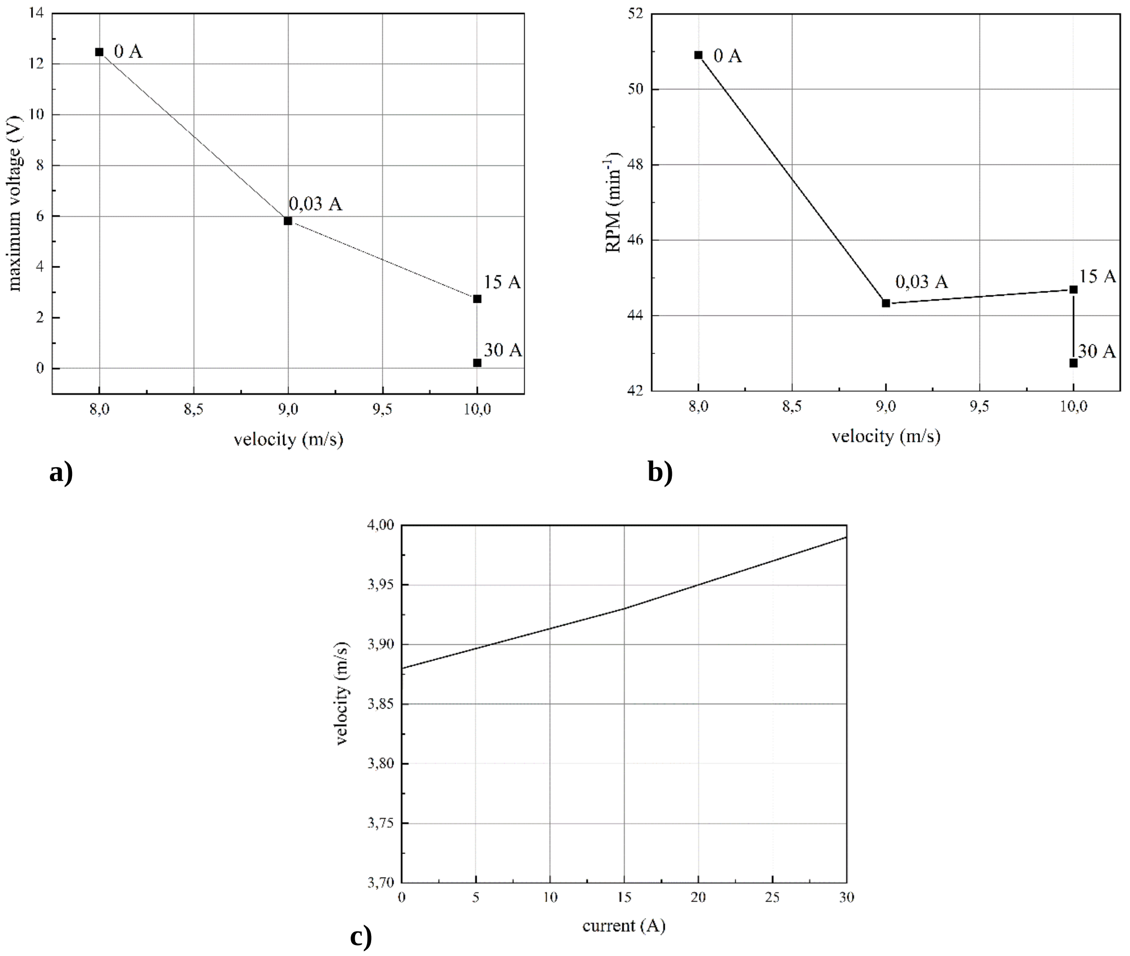


Figure 9. Results for currents of 15 A and 30 A.

It is interesting to note the linear dependence of the minimum starting limit of the wind turbine in relation to the loaded condition (Figure 11). In this sense, the vertical turbine start-up equation can be established, which goes beyond the scope of this paper. On the other hand, the voltage characteristic (alternating voltage where only positive voltage values are shown) has a mean value characteristic from 0 to 12 V for the values of the velocity of the undisturbed flow field with a mean velocity of 9 m/s (see



a)

b)

c)

Figure 10. Dependence of a) achieved maximum voltage and velocity, b) RPM and velocity at which maximum voltage is achieved and c) velocity at which the turbine starts to rotate depending on the wind turbine’s load.

Tables 1 and 2). Optimum voltage values were observed for wind turbine rotation numbers of 47 rpm at a value of 9 V. This practically means that for minimum rotation numbers it is preferable to limit the consumer to the lowest value and to accumulate as such over a longer period of time.

Mechanically and from the point of view of aerodynamics, it is evident that the use of wind turbines of this type is justified from the point of view of long-term exploitation. The diagrams show a tendency for the number of revolutions of the wind turbine to drop after turning off the wind tunnel, where the sudden increase in voltage corresponds to the number of revolutions of the wind turbine in the optimal mode, which confirms the justification of the measurement.

Table 1. Wind velocity and corresponding voltage and RPM on the VAWT for different loading (unloaded and 0.03 A).

Unloaded turbine				Load of 0.03 A			
time [s]	wind velocity [m/s]	voltage [V]	RPM [min^{-1}]	time [s]	wind velocity [m/s]	voltage [V]	RPM [min^{-1}]
0	0.00	0.0000	0.0000	24	0.91	0.0009	0.0000
55	1.00	0.0017	0.0000	28	2.01	0.0013	0.0000
68	2.00	0.0010	0.0000	44	3.01	0.0021	0.0000
256	3.00	0.0004	0.0000	95	3.88	0.7752	0.0000
433	3.71	1.6171	0.0000	95	**3.88**	0.7233	0.0026
439	**3.74**	1.5134	0.2942	97	4.00	1.0077	3.4722
555	4.00	7.1270	19.8200	166	5.00	2.7516	13.6871
669	5.00	10.1365	28.2289	212	6.00	4.0368	22.4210
869	6.00	11.7682	36.0635	268	7.00	5.0651	29.9296
958	7.00	12.4474	43.0224	316	8.00	5.6691	37.5055
1026	8.00	**12.4605**	50.9062	372	9.00	**5.8220**	44.3198
1087	9.00	11.0985	57.8825	431	10.00	5.5476	50.6662
1187	10.00	10.7083	66.1289	486	11.00	5.4187	57.6597
1278	11.00	9.6428	73.0080	528	12.00	5.2956	64.4838
1354	12.00	8.3345	79.4149	606	12.95	4.7394	5.5695
1499	13.00	7.0352	87.2565				

Table 2. Wind velocity and corresponding voltage and RPM on the VAWT for different loading (15 A and 30 A).

Load of 15 A				Load of 30 A			
time [s]	wind velocity [m/s]	voltage [V]	RPM [min^{-1}]	time [s]	wind velocity [m/s]	voltage [V]	RPM [min^{-1}]
20	1.00	0.0007	0.0000	30	1.00	-0.0009	0.0000
22	2.00	0.0012	0.0000	35	2.00	-0.0009	0.0000
36	3.00	0.0166	0.0000	62	3.00	-0.0008	0.0000
67	3.92	0.2970	0.0000	115	3.98	-0.0101	0.0000

71	**3.93**	0.3604	0.3434
85	5.00	0.5795	7.8577
103	6.00	0.7103	14.9792
122	7.00	1.6026	21.9791
138	8.00	2.3021	29.4870
153	9.00	2.5932	37.3614
170	10.00	**2.7472**	44.6867
187	11.00	2.4294	51.3900
192	12.31	2.4747	53.6158
197	9.91	2.2159	54.8442
199	8.09	1.8051	53.0238
206	5.03	0.5424	37.5293

115	**3.99**	0.0256	0.0130
126	4.00	0.0350	4.0981
171	5.00	0.0669	9.3218
206	6.00	0.0949	13.5070
245	7.00	0.1357	20.6941
277	8.00	0.1730	28.7255
325	9.00	0.1941	35.1304
359	10.00	**0.2044**	42.7420
391	11.00	0.2031	49.4714
437	12.00	0.1828	56.2715
447	12.63	0.1779	60.1899
452	11.65	0.1732	60.0500
463	5.01	0.1738	35.1122

The highlighted values in Tables 1 and 2 correspond to values of wind velocity at which the turbine starts to rotate (in the third column is the RPM value), and the highest achieved voltage depending on the wind turbine load from the rheostat. The turbine's load does not have great influence on the velocity at which it starts to rotate. As it can be seen from the tables, the difference between the velocity values for unloaded and different values of loaded turbine is of the order of measuring error. On the other side, the maximum value of the achieved voltage depends greatly on the turbine's load. It has the smallest value of the highest load of the turbine. It is also evident from these tables that even though the RPM is still increasing, the voltage starts to decrease. This corresponds to the problem that arises in the "non-excitement" zone, as explained earlier.

5. Conclusions

Testing wind turbines in real operating conditions is the primary task of engineers in the field precisely because testing resources are limited, and their results are subject to serious analysis. In this sense, the testing of wind turbines in wind tunnels represents a significant advance in the realization and definition of the functional dependence of the flow velocities of the undisturbed field and the energy characteristics of wind turbines. This paper clearly indicated the energy balance of a vertical-type wind turbine whose dimensions are limited to the working part of the wind tunnel and which can be multiplied by the method of similarity to wind turbines of larger dimensions. Of course, the entire test method can be applied to real wind turbines of both vertical and horizontal type with certain modifications of the test equipment and corrections related to the energy part as well as the way of measuring large powers. In this sense, the authors are of the humble opinion that the methodology of testing and determining the energy efficiency of wind turbines is also applicable in real cases of exploitation.

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