Optimization of Axial Wind Turbines Operation

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Abstract: *The operation of horizontal axial wind turbines was diversified through their applications in aero-energetic of variable speed of rotation. These situations are investigated and optimized in function of wind velocity, as intensity. Results are useful for wind power plants Marga and Ciugud designed and realized by a group of professors from the Hydraulic Machinery Chair, Faculty of Mechanical Engineering, University “Politehnica” Timişoara.*

Keywords: *Axial wind turbines, wind aggregates with variable speed of rotation, optimization of the operation in respect of wind velocity, aerodynamic profiles*

List of symbols

P – aerodynamic power.
ω – runner angular velocity.
N – runner blade number.
ρ – density.
C_P – lift coefficient
C_R – drag coefficient
r – runner current radius.
β – angle between relative velocity and the opposite of rotation velocity.
l - blade profile chord.
v – wind velocity.
n - runner speed of rotation.
i – profile angle of attack.
R – runner radius.

1. Introduction

Axial wind and hydraulic machines controls its operation through the rotation of their blades around the blades axis. Today through the progress of the electro-energetic systems it is possible to vary the speed of rotation of these machines. The classic axial hydraulic machines are able to rotate in the same time the wicket gates and runner blades in such a mode to obtain the maximum efficiency [9]. The classic axial wind turbines are controlled through the runner blades rotation in function of the wind velocity for assuring a maximum power [10]. In this paper it is investigated a different control modality of an axial wind turbine with fixed blades which is optimized through accord the speed of rotation of the aggregate to the wind velocity.

2. Wind aggregate calculus at nominal regime of operation

5 kW power plant wind aggregates in accord with the Marga and Ciugud projects [1] are designed for a nominal wind velocity of v_0 = 8.5 m/s and a speed of rotation of n_0 = 120 rot/min (for constant speed of rotation) and n_0 = 60 – 120 rot/min (for variable speed of rotation). The Ciugud blades geometry through aerodynamic profiles at different radiuses and their stagger angles of the grids are puts in evidence graphical for the tip profile of the blade in Fig. 1 and Fig. 3.

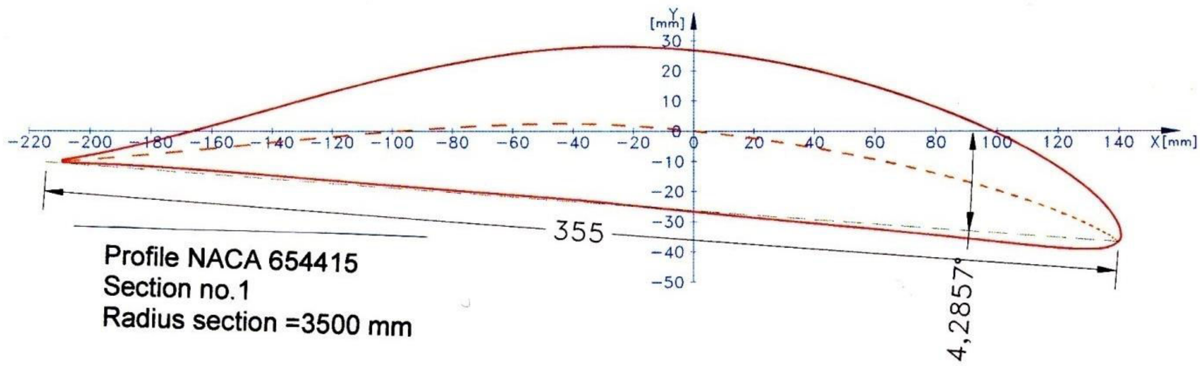

Fig. 1. Section through wind runner blade [1]

The investigation of the runner is with the two-dimensional blade theory based on fig. 2.

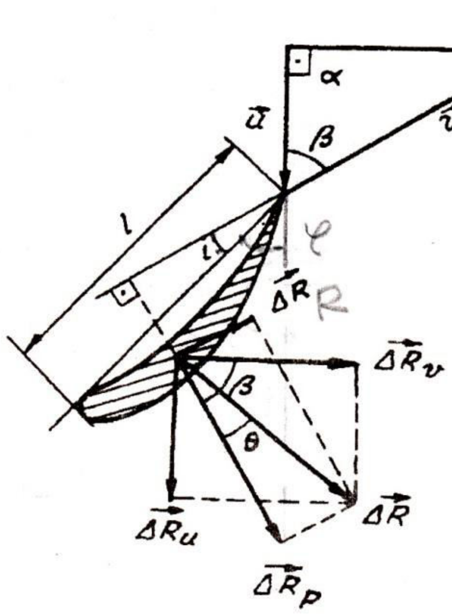

Fig. 2. Kinematic and dynamic of the elementary runner profile

There are calculated: rotation velocity, entrance angle of the wind on the runner and attack angle of the blade components profiles at different radiuses:

$$u = \omega \cdot r = \frac{\pi \cdot n}{30} \cdot r \tag{1}$$

$$\beta = arc\ tg\left(\frac{v_o}{u}\right) \tag{2}$$

$$i = \beta - \varphi \tag{3}$$

From the 28 elementary known sections of the wind runner blade it was chosen 3 representative sections for the hub, middle and tip of the blade. Data referring to blade chord "b" and the stagger angle of the profiles grid "φ" was extracted from [1]. Results are given in Table 1.

TABLE 1

Nominal values v_o = 8.5 m / s ; n_o = 120 rot / min.						
r	b	φ	Profile	u	β	i
m	m	grade	NACA	m /s	grade	grade
3.5	0.355	4.2857	654415	43.982	10.938	6.6523
2.5	0.525	7.600	654418	31.416	15.140	7.54
1.5	0.695	15.3333	654421	18.850	24.272	8.9387

Analytic connection between the angle of attack of the profile in function of the blade radius is:

$$i = 11.99488 - 2.4207 \cdot r + 0.2555 \cdot r^2 \tag{4}$$

with the mean error : $\varepsilon_m = 4.6259 \cdot 10^{-18}$. (5)

The rated regime rapidity is:

$$\lambda = \frac{u(at \quad r = 3.5\ m)}{v_o} = 5.174 \tag{6}$$

The value is smaller than the optimum value from literature $\lambda_{optim} = 6...8$ after [4].

3. Wind turbine operation at different values of the wind

For wind velocities between 5 and 9 m/s the results are in Table 2.

TABLE 2

Crt. no.	v_o	λ	r	b	φ	Profile	u	β	i	C_P	$C_R \cdot 100$
	m / s	-	m	m	°	NACA	m / s	°	°	-	-
1	5	8.796	3.5	0.355	4.2857	654415	43.982	6.4857	2.2	0.161	1.105
2			2.5	0.525	7.600	654418	31.416	9.0430	1.443	0.106	1.022
3			1.5	0.695	15.333	654421	18.850	14.8557	-0.4776	-0.035	0.099
4	6	7.330	3.5	0.355	4.2857	654415	43.982	7.7683	3.4826	0.255	1.337
5			2.5	0.525	7,600	654418	31.416	10.8125	3.712	0.271	1.390
6			1.5	0.695	15.333	654421	18.850	17.6564	2.3231	0.170	1.122
7	7	6.283	3.5	0.355	4.2857	654415	43.982	9.04312	4.7555	0.348	1.680
8			2.5	0.525	7.600	654418	31.416	12.5612	4.9612	0.363	1.746
9			1.5	0.695	15.333	654421	18.850	20.3726	5.0393	0.368	1.772
10	8	5.497	3.5	0.355	4.2857	654415	43.982	10.309	6.0233	0.440	2.134
11			2.5	0.525	7.600	654418	31.416	14.2866	6.866	0.502	2.498
12			1.5	0.695	15.333	654421	18.850	22.997	7.6637	0.560	2.888
13	9	4.887	3.5	0.355	4.2857	654415	43.982	11.565	7.2793	0.532	2.694
14			2.5	0.525	7.600	654418	31.416	15.986	8.386	0.613	3.279
15			1.5	0.695	15.333	654421	18.850	25.522	10.1887	0.745	4.414

From the Table 2 it is observed the large range of the attack angles and lift and drag coefficients. For the wind turbines with variable speed of rotation it is considered the minimum speed of rotation in Table 3.

TABLE 3

Nominal values v_o = 8.5 m / s ; n_o = 60 rot / min.						
r	b	φ	Profile	u	β	i
m	m	grade	NACA	m /s	grade	grade
3.5	0.355	4.2857	654415	21.99	21.1335	16.8478
2.5	0.525	7.600	654418	15.7079	28.4197	20.8197
1.5	0.695	15.3333	654421	9.4248	42.0459	26.7126

Analytic connection between the angle of attack of the profile in function of the blade radius is:

$$i = 39.15383 - 9.7349 \cdot r + 0.9605 \cdot r^2 \quad (7)$$

with the mean error: $\varepsilon_m = 8.0954 \cdot 10^{-18}$ (8)

Comparative analysis, of the results about attack angles from Table 1 and 3 shows that speed of rotation decrease produce greater attack angles and the separation of the flow by blade's hub. Data from NACA catalog [6], offer characteristic curves of the used profiles, from which here there are presented only the curves for the most uploaded, in Fig. 3.

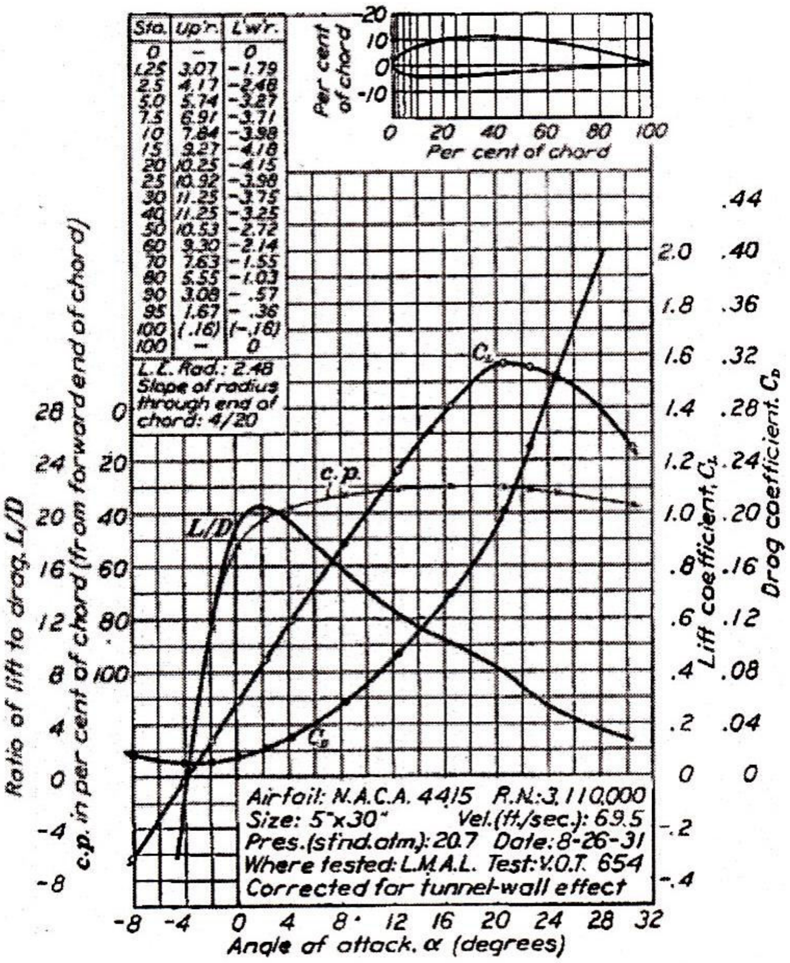

Fig. 3. Characteristic curves for the profile NACA 654415

4. Optimization of the operation regime

Considering the developed power in a wind turbine:

$$P = \frac{N \cdot \omega \cdot \rho}{2} \int_{r_0}^{R} \left\{ C_P(r) \cdot \sin\left[\beta(r)\right] - C_R(r) \cdot \cos(r) \right\} \cdot \left(\omega^2 \cdot r^2 + v^2\right) \cdot l(r) \cdot r\,dr \quad (9)$$

or

$$P = \frac{N \cdot \omega \cdot \rho}{2} \int_{r_0}^{R} \left[C_P(r) \cdot v - C_R(r) \cdot \omega \cdot r \right] \cdot \sqrt{\omega^2 \cdot r^2 + v^2} \cdot l(r) \cdot r\,dr \quad (10)$$

Knowing the usual values of the parameters along the blade and that the maximum power is extracted by the tip of the blade and also that:

$$\frac{C_P}{C_R} \cong 20 \quad ; \quad \frac{\omega \cdot R}{v} \cong 5 \quad ; \quad (11)$$

With these values it is deduced from relation (10) that the higher power is obtained for the greater lift coefficient C_P. The power depends on a lot of factors and the lift coefficient is accepted for different safety degrees in two-dimensional models, against the non-stable operation. It is considered the tip profile of the blade because the outside zone of the blade transfers large part of the power. To the axial wind turbine with fixed blades and variable speed of rotation it was calculated through a program "trail and error" the speed of rotation values of the aggregate in function of the wind velocity for an angle of attack imposed, therefore an adequate power and a safety degree in respect of flow separation at normal operation or gusts. So it was established for the outside profile NACA 654415 in function of the wind velocity "v" (in m/s) at the attack angle of i = 6^0, the optimum speed of rotation of the aggregate (wind turbine) "n" (in rot/min):

$$n = 14.25 \cdot v + 0.625 \quad (12)$$

At i = 10^0 $$n = 10.75 \cdot v - 0.125 \quad (13)$$

At i = 14^0 $$n = 8.933 \cdot v - 0.666 \quad (14)$$

The speed of rotation values calculated with these relations, depending from the wind velocity are introduced in the automation device of the power plant and acts upon the exciting device of the electric variable speed generating system [2], [3].

5. Conclusions

a) Modern wind aggregate often operate with variable speed of rotation acting on the electric generator. The automation device has an anemometer as the entrance transducer.
b) Exploitation strategy of the wind power plant imposes the aggregate speed of rotation modification law in function of wind velocity with different degrees of confidence with one of the formulas (12), (13) or/and (14).
c) In function of the wished power and the assumed in respect of the separation of the flow from the runner's blades it is chosen one of the above mentioned relations.
d) All the conclusions obtained in this article are valuable in the hypothesis of zero azimuth (yaw) angle or after the stabilization of the aggregate in the wind direction.
e) The validity of the results obtained through the relations (12), (13) and (14) can be verified on the base of measurements made on the actual automated system of the wind power plant from Ciugud which works with a program of maximum power searching of the axial wind turbine.

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