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PRELIMINARY DESIGN CALCULATIONS OF A SMALL WIND GENERATOR FOR THE SURROUNDINGS OF TOWN OF ZRENJANIN

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Abstract: Example calculations of a small wind turbine for selected electricity needs is presented. Based on some data about the wind conditions for the surrounding of the town of Zrenjanin and the required energy consumption for an individual consumer, the required electric power output of the wind generator, the average wind speed at the turbine level, the radius of the propeller and the rated speed of rotation are determined. The results of determining some basic parameters of the wind generator blade are also given. Some characteristics of the wind generator are presented.
Keywords: wind turbine, wind energy, design calculations, tip speed ratio

1. INTRODUCTION

The unstable fuel prices and of the energy resources in general, the problems related to the environmental pollution such as the release of harmful or toxic gases, the greenhouse effect, the total thermal pollution, etc. suggest the search for alternative "green" energy sources. Efforts to generate green energy may include a system of measures to use "free" energy sources, such as wind energy and solar energy by each individual consumer. The use of wind energy has been around for thousands of years, but it is currently very topical. In Serbia, there has been an increasing interest in the use of this type of energy in recent years, which is why the amount of scientific publications on the issue is increasing. The present work is an attempt to make a modest contribution to its enrichment together with the references to other sources of technical literature.

2. METHOD OF THE CONSTRUCTIVE CALCULATIONS - AN EXAMPLE SEQUENCE

— Assessment of energy needs

According to power wind generators can be divided into [1]: micro (*50-250 W*); small (*250 W-1 kW*); domestic (*1-50 kW*); medium (*50-750 kW*) and large (*> 750 kW*). Small-power wind generators do not, in principle, serve as a single source of energy, but rather to support energy needs, for example in single-family homes. Energy-intensive needs such as heating, cooking, hot water, production activities are provided by other sources - electricity, gas, timber and / or solar energy. Only the most basic for a comfortable and normal life of household appliances, such as lighting, TV, refrigerator, computer, etc., are powered by a wind generator. The power supply from a wind generator is shown in Figure 1.

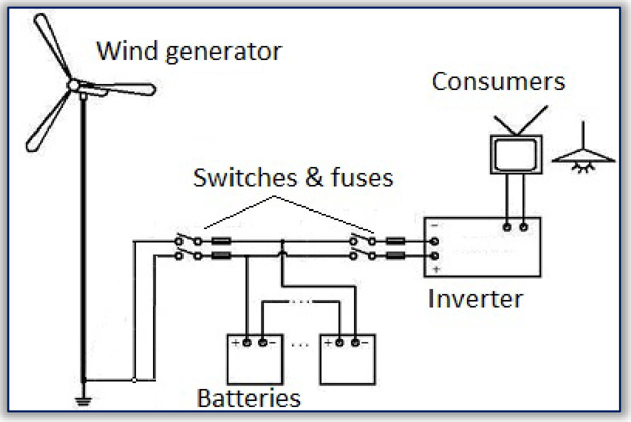

Figure 1. Wind turbine system

Table 1. Distribution of power and power consumption by electricity consumers in a home.

AC Consumers	Power P_i, [W]	Hours per day, h_i, [h]	Days of work in a week, n_i	Energy Ew_i,[Wh]
LED Lighting – bath	8	1,0	7,0	56
LED Lighting – Kitchen	15	2,5	7,0	262,5
LED Lighting – Bedroom	9	1,5	7,0	94,5
LED Lighting – Living room	32	4,0	7,0	896
TV	50	3,0	7,0	1050
Refrigerator	20	24,0	7,0	3360
Washing machine	500	1,5	2,0	1500
Laptop	20	4,0	7,0	560
Total	P = 654			E_{WEEK} = 7779

When there is sufficient wind flow, rechargeable batteries are charged (for example, *12 V*, *60 Ah* capacity connected in parallel). With consumers connected (TV, lamps, etc.), the DC *12 V* voltage from the batteries is converted to AC *220 V* via an inverter. As a first step in the preliminary calculations, an approximate estimate is made of the required power *P* and energy *E*, which should be met by the wind generator system [2]. Table 1 shows an example distribution of power and power consumption by electricity consumers over a period of one week.

The maximal instantaneous power of the consumers is:

$$P = \sum P_i = 8 + 15 + 9 + 32 + 50 + 20 + 500 + 20 = 654 \ \text{W} \tag{1}$$

The energy that consumers need in a week is:

$$E_{WEEK} = \sum P_i h_i n_i = 8 \times 1 \times 7 + 15 \times 2{,}5 \times 7 + \ldots + 500 \times 1{,}5 \times 2 + 20 \times 4 \times 7 = 7779 \ \text{Wh} \tag{2}$$

Some of the calculations below are given according to the methodology used in the EnergyBudgetWorksheet.xls file, which can be downloaded from [2]. The $E_{W.GEN}$ energy produced by the wind turbine for one week when using the AC users, due to the conversion efficiency from the wind turbine to the users is greater than E_{WEEK} and is calculated by the formula (k_E - loss factor; $k_E = 1.3$ for AC users; $k_E = 1.2$ for DC users):

$$E_{W.GEN} = k_E \times E_{WEEK} = 1.3 \times E_{WEEK} = 1.3 \times 7779 = 10113 \ \text{Wh} \tag{3}$$

Then in one day the wind generator must provide:

$$E_{D.GEN} = E_{W.GEN}/7 = 10113/7 \approx 1445 \ \text{Wh} \tag{4}$$

At this point, it is advisable to calculate the required number of $N_{R.BAT}$ rechargeable batteries:

$$N_{R.BAT} = INT\{[(E_{D.GEN}) \times (N_{D.AUTO})]/[(V_{NOM}) \times (D_{P.D}) \times (C_{NOM.B})] + 1\} \tag{5}$$

where $N_{D.AUTO}$ - number of days of autonomous operation of the system ($N_{D.AUTO} = 3.5$ days recommended), V_{NOM} - nominal voltage of the batteries and inverter used in the system (let $V_{NOM} = 12\ V$), $D_{P.D}$ - permissible degree of discharge of the batteries (let $D_{P.D} = 75\% = 0.75$), $C_{NOM.B}$ - nominal capacity of the batteries (let $C_{NOM.B} = 125\ Ah$, see [3]), *INT* - INTEGER function giving the largest integer less than the value of the argument. Then:

$$N_{R.BAT} = INT\{[(1445) \times (3{,}5)]/[(12) \times (0{,}75) \times (125)] + 1\} = 5 \tag{6}$$

— **Determination of the required rated power of the wind generator**

Here, the required power of the wind generator must be matched to the specific wind energy resource at the location where it will be installed. It is recommended that a so-called wind audit be prepared [5], taking into account such factors as the altitude of the wind generator, the density of the wind, the wind speed, the micro-relief of the surroundings, the geographical location (by the sea, in the mountains, etc.), influence of surface roughness [6]. Summarized the wind resource statistics for the area may also be used for an estimate. It is best to have specific measured values of wind speed and air density at the location of the wind turbine installation and the intended altitude of the wind turbine. The formula (7) from [12] for determining wind power could also be used to determine the average wind speed at the intended installation site .

$$W = (1/2) \times \rho \times A \times v^3 \tag{7}$$

where: ρ - wind density (It depends on barometric pressure and temperature. As the altitude and temperature increase, the air density decreases. In [9], the necessary dependencies are given by which it can be calculated ρ depending on the temperature and barometric pressure), *A* is the swept area of the blade, and *v* is the wind speed.

According to sources [4], [5], [6] in the vicinity of town of Zrenjanin (elevation above sea level *76 m*) in Vojvodina, at an altitude of *100 m*, the average annual wind speed is about *5 ÷ 6 m/s* and the average wind power flow is about $180\ W/m^2$ (*250* according [6]). Let accept the value of average wind power flow at elevation of *100 m* to be $P_P = 180\ W/m^2$. The density ρ of air at total elevation $z = 176\ m$ could be calculated [13] by formula (8):

$$\rho = \rho_0 \left(1 + \frac{cz}{T_0}\right)^{-\left(\frac{g}{cR}+1\right)} \tag{8}$$

where: $\rho_0 = 1{,}204\ kg/m^3$ [8] is air density at sea level and $p = 100\ kPa$ at 20 °C; $z = 176\ m$ – altitude; $c = dT/dz = 0{,}006$ [9],[10],[11] - temperature gradient with respect to altitude; R - the gas constant [7] and $R = 287\ J/kg\text{-}K$ for air; $g = 9{,}81\ m/s^2$; and.Then:

$$\rho = 1{,}204 \times \left(1 + \frac{0.006 \times 176}{293.15}\right)^{-\left(\frac{9.81}{0.006 \times 287}+1\right)} = 1{,}174\ , kg/m^3 \tag{9}$$

Thus, for the average wind speed for the Zrenjanin region at an altitude of *100 m*, we obtain:

$$v_0 = \sqrt[3]{\frac{2(W/A)}{\rho}} = \sqrt[3]{\frac{2(P_P)}{\rho}} = \sqrt[3]{\frac{2\times(180)}{1.174}} = 6.74 \ \text{m/s} \tag{10}$$

Since the wind generator is most likely to be located at an altitude *h* other than the height above the earth h_0 = *100 m* for which there are data on wind characteristics, the law of changing the wind speed in altitude could be used [14], [15]:

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^a \tag{11}$$

where: v_0 and h_0 are the known values of wind speed in m/s and given height above earth in *m*; *h* - planned generator height above earth in *m* (let *h* = 10 *m* for a small house or villa); *v* - demanded wind speed at new height (*m/s*); *a* is an empirical exponent: *a* = *0,1* for wide flat or water surfaces surroundings, *a* = 0,2 in the presence of separate high groups of facilities in the vicinity, *a* = *0,4* in the city center of tall buildings [15]. For Zrenjanin vicinities *a* = *0,1*. Then from (11):

$$v = v_0\left(\frac{h}{h_0}\right)^a = 6.74\times\left(\frac{10}{100}\right)^{0.1} = 5.357 \ \text{m/s} \tag{12}$$

Assuming the useful part of the winds [16] is the one with speeds in the useful range of *4.5* to *11.5 m/s*, then for an average wind speed of *5 m/s*, the percentage of time during which the winds have not too little speed or neither too big is about 70% [16] of total time during a day:

$$\text{(Time Useful)} = \text{(Total Time)} \times \text{(Percent of Useful Time)} = (24)\times(0.7) = 16.8 \text{ hours} \tag{13}$$

Then, for those 16.80 hours, more than $E_{D.GEN}$ = 1444,7 Wh must be generated, i.e. it should be looked for a wind generator with an approximate rated power greater than:

$$P = E_{D.GEN} / \text{(Time Useful)} = 1444{,}7 / 16{,}8 = 86{,}5 \text{ W} \tag{14}$$

So, it could be accepted rated power of *100 W* for this wind generator.

$$P = 100 \text{ W} \tag{15}$$

— **Tip speed ratio, output power, radius of the rotor of a wind generator**

In order to determine these parameters, it must be made clear in advance about the choice of type of wind generator, the rated rotational speed of the power generator, and so-called tip speed ratio *TSR* = λ. Generally wind generators are divided into vertical axial and horizontal axial ones. Those with a vertical axis have the advantage that they do not need to be directed in the wind direction, but in principle have a lower efficiency. That is why horizontal axes are now used, which are fast-moving (with one, two and three blades) and slow-moving (with more blades). The tip speed ratio λ is a basic parameter of the rotor of a wind generator that depends on its design (mainly the number of blades *B* of the blade) and is equal to the ratio of the peripheral speed of the blade end to the wind speed [17].

$$\lambda = \frac{\omega R}{v} \tag{16}$$

where ω is the angular velocity of the blade in *rad/s*, *R* - radius of the blade (of the swept area) in *m*, *v* - wind speed in *m/s*. Empirical data for the optimal value of tip speed ratio λ_{opt} are given in a number of sources [17], [18]. For example, in [17], these values are recommended - for a rotor with 1 blade λ_{opt} = 9; with 2 blades - λ_{opt} = 7; with 3 blades - λ_{opt} = 5; with 6 blades - λ_{opt} = 3; with 12 blades - λ_{opt} = 1,2. In [7] is recommended that a wind turbine with three blades would have an optimal tip speed ratio calculated by formula:

$$\lambda_{opt} = (1{,}25\cdots1{,}30)(4\pi/3) \approx (1.275)\times(4\times\pi/3) = 5{,}341 \tag{17}$$

To determine the required radius of the rotor, the equation for calculating the power output of the wind generator can be used [7]:

$$P = (1/2)\rho_{10}(\pi R^2)v^3 C_P \eta_G \eta_M \tag{18}$$

where *P* is the output power in *W* of wind rotor (here *P* = *100 W*); ρ_{10} - air density at *10 m* above earth surface (ρ_{10} = *1.188 kg/m³* see formula (9); ($\pi.R^2$) - swept blade area (m^2); *v* - wind speed in m/s at *10 m* above earth surface (here *v* = *5,357 m/s*); C_P – power coefficient (wind energy utilization coefficient). The maximum theoretical C_P value is *0.593*. For the best high-speed wheels: C_P = *0.42 ~0.46*. For multi-blade slow-speed wind wheels: C_P = *0.27 ~0.35*. Let C_P = *0.42*); η_M - efficiency of the mechanical and gear-motor matching gear - multiplier (if used η_M = *0.7 ~0.9*; if not used it η_M = *1*) Let η_M = *0.9*; η_G is the efficiency of the generator (automobile - *0.6*, of permanent magnets - *0.8*) (here the generator [19] is of permanent magnets and η_G = *0.8*). Then from (18) it follows:

$$R = \sqrt{(2P)/(\rho_{10}.\pi.v^3.C_P.\eta_G.\eta_M)} = \sqrt{(2\times 100)/(1.188\times\pi\times 5.357^3\times 0.42\times 0.8\times .0.9)} = 1.074 \;\; m \qquad (19)$$

From (16) for the rated rotational speed at $v = 5{,}357$ *m/s* it is obtained:

$$\omega = (\lambda_{opt}.v)/R = (5.341\times 5.357)/1.074 = 26.65 \quad rad/s \qquad (20)$$

3. DETERMINATION OF SOME AERODYNAMIC AND POWER CHARACTERISTICS.

The blade profiling involves determining the distribution of the angles of cross-sections placement, the distribution of the lengths of the chords of the sections, and also determining the power coefficient (coefficient of wind energy utilization) C_P for a particular operating mode - wind speed, tip speed ratio λ and rotation speed. Choosing a wing profile is also part of this process. The main dependencies and sequence of calculations are as given in [20] and are shown in short as follows:

- the blade is represented as a finite number of sections, spaced equally across the span;
- the *TSR* is determined for each section as a function of the current radius *r*:

$$\lambda_r = (\omega r)/v \qquad (21)$$

- the optimum relative wind angles $\varphi_{r,opt}$ of apparent wind (wind angles) are calculated (this is the flow angle which the effective flow velocity of a given section of the blade makes with the plane of rotation of that blade). These angles are determined according to [20,21] by formula (22) to achieve the maximum value of the power factor (Fig.2)

$$\varphi_{r.opt} = (2/3)\tan^{-1}(1/\lambda_r) \qquad (22)$$

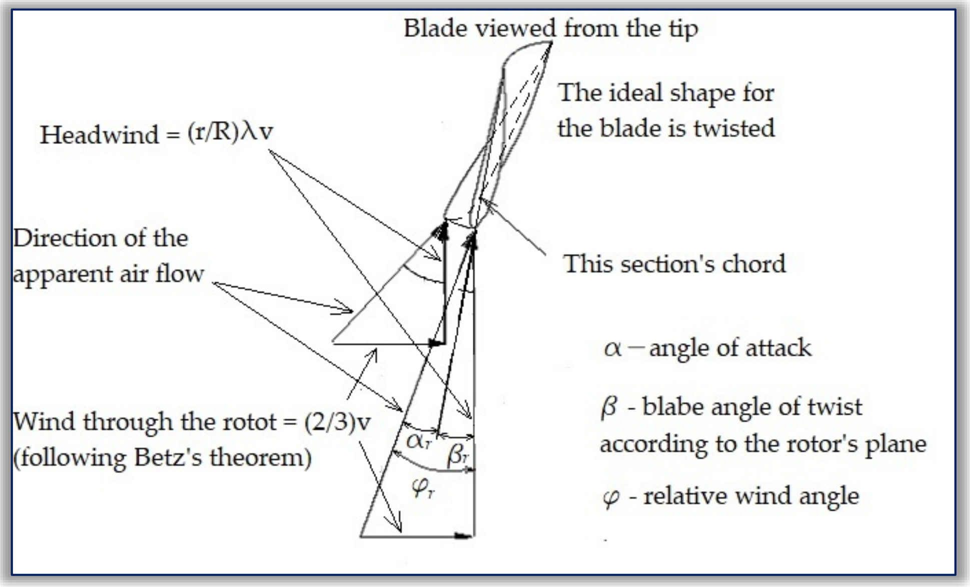

Figure 2. Section angles – angle of attack, blade angle, relative wind angle

- the tip loss factor is calculated for each considered section of the blade;

$$F_r = (2/\pi)\cos^{-1}\left\{\exp\left[\frac{-(B/2)[1-r/R]}{(r/R)\sin\varphi_{r,opt}}\right]\right\} \qquad (23)$$

This factor takes into account the change in the aerodynamic characteristics of the sections along the length of the blade. For approximate simplified calculations, $F_r = 1$ for $(r/R) < 0.97$ and $F_r = 0$ for $(r/R) \geq 0.97$ could be assumed.

- the distribution of the lengths of the chords along the length of the blade are determined, i.e. as a function of the radius *r*, by means of (24):

$$b_r = [8.\pi.r.F_r.\sin\varphi_{r,opt}.(\cos\varphi_{r,opt} - \lambda_r.\sin\varphi_{r,opt})]/\;[B.C_{yKmax}.(\sin\varphi_{r,opt} + \lambda_r.\cos\varphi_{r,opt})] \qquad (24)$$

More roughly the the distribution of the lengths of the chords along the length of the blade could be determined by (25):

$$b_r = [16.\pi.R.(R/r)]/[9.\lambda^2.B] \qquad (25)$$

- the distribution of the angles (so called blade angle) of twist of the chords along the length of the blade are determined by means of (26):

$$\beta_r = \varphi_{r,opt} - \alpha_{opt} \qquad (26)$$

— the power coefficient is determined using a sum approximating the integral $C_p = \frac{8}{\lambda^2}\int_{\lambda_h}^{\lambda} F_r \sin^2\varphi_{r,opt}(\cos\varphi_{r,opt} - \lambda_r \sin\varphi_{r,opt})(\sin\varphi_{r,opt} + \lambda_r \cos\varphi_{r,opt})(1 - \frac{1}{tg\varphi_{r,opt}.K_{max}})\lambda_r^2 d\lambda_r$ by means of (27):

$$C_p = \sum\left[\left(\frac{8(\lambda_r)^2.\Delta\lambda_r}{\lambda^2}\right)\right] F_r \sin^2\varphi_{r,opt}\left(\cos\varphi_{r,opt} - \lambda_r \sin\varphi_{r,opt}\right)\left(\sin\varphi_{r,opt} + \lambda_r \cos\varphi_{r,opt}\right)\left(1 - \frac{1}{tg\varphi_{r,opt}.K_{max}}\right) \quad (27)$$

The calculation of the values of above parameters is performed for the profiled part of the blade along its length from $r/R = 0.2$ (accepted here) to $r/R = 1$. Here λ_h (in the integral showed above) denotes the tip speed ratio in the section closest to the hub of the turbine rotor. In formula (26) α_{opt} denotes the optimal angle of attack of the correspond section of the blade. When designing the blade, this angle must correspond to the most advantageous, i.e. at maximum aerodynamic quality K_{max} (ratio of lift coefficient to drag coefficient) for the relevant profile. In formula (24) the coefficient C_{yKmax} denotes the lift coefficient at which maximum aerodynamic quality is ensured. The most frequently used profiles are from the NACA 44XX, NACA 230XX, NACA 63-2XX series.

At the determined wind speed, turbine speed and propeller radius, sample calculations were performed to design the blade. The profile NACA 4412 was chosen for the profile with the following characteristics (Figure 3) – Reynolds number $R = 280000$, lift coefficient $C_y = 1.05$ at maximum quality K_{max}, maximum aerodynamic quality $K_{max} = 42$ and angle of attack at maximum quality $\alpha_{opt} = 6°$ [22]. The distribution of chords is calculated by dependence (24). Figure 4 and Figure 5 present the results of the calculation of the angles of placement of the chords of the cross sections of the wind turbine blade and the lengths of the chords of the respective sections along the length of the blade, which was done using Microsoft Excel software.

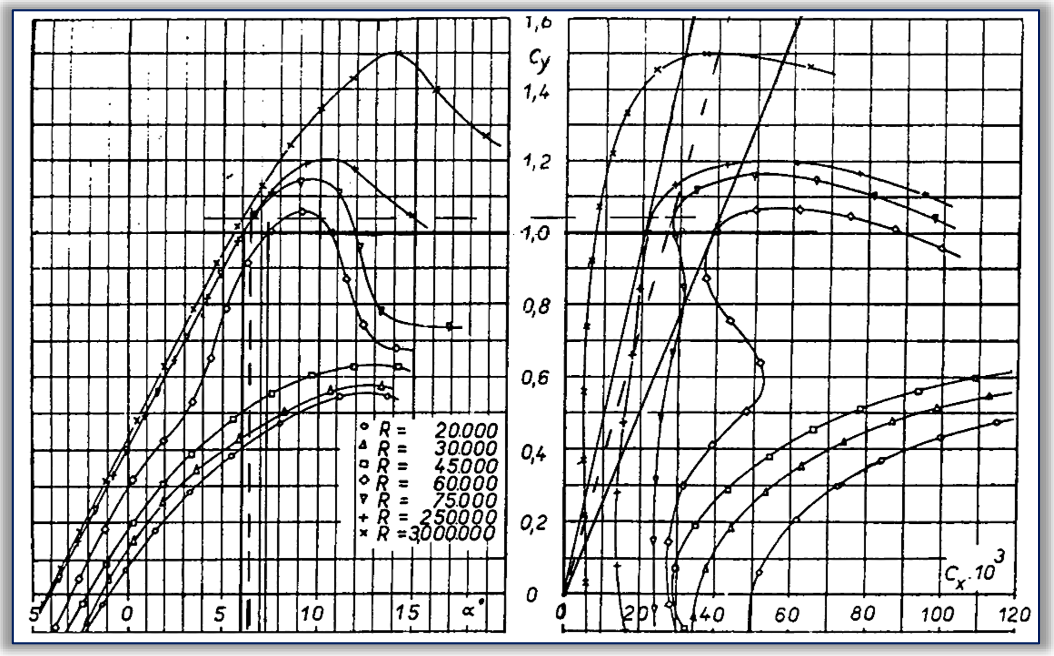

Figure 3. Graphs - aerodynamics characteristics of airfoil NACA 4412 [22].

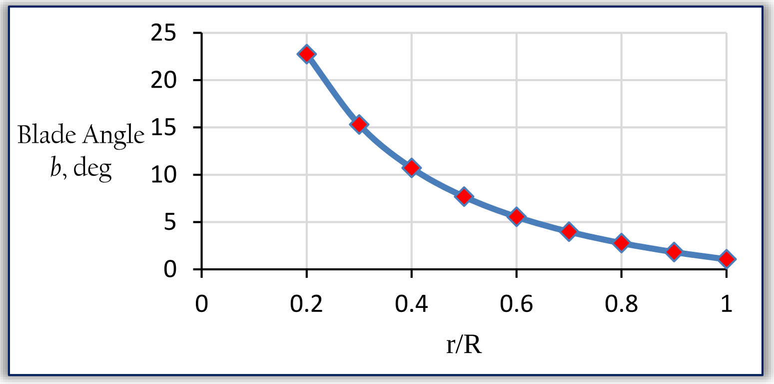

Figure 4. Blade angle distribution of twist of blade sections profile of designed wind turbine rotor along the length of the blade.

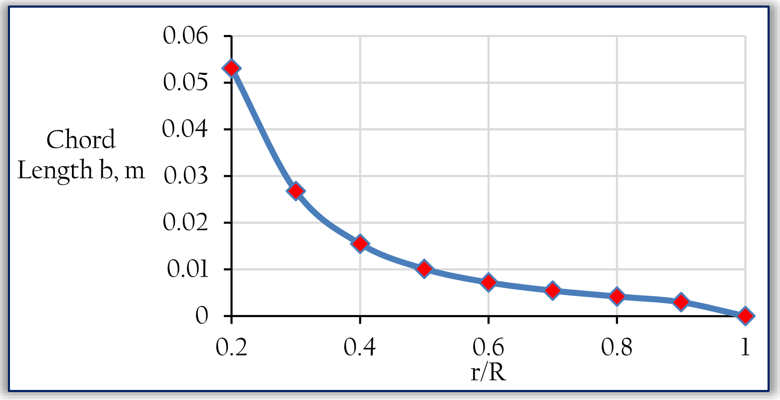

Figure 5. Chord length distribution of blade sections of designed wind turbine rotor along the length of the blade

Figure 6 shows the graph of the change of the power factor of the wind turbine at different modes of operation of the generator and at wind speed $v = 5.357\ m/s$

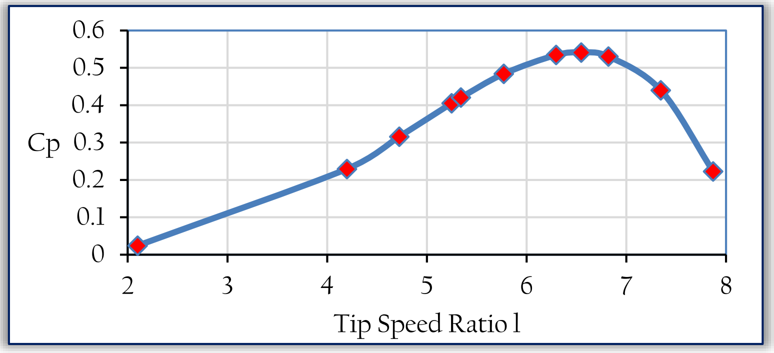

Figure 6. Graph of the change of the power factor C_p of the wind turbine at different modes of operation of the electric generator and at wind speed $v = 5.357 m/s$.

Figure 7 shows the change of the power of the designed wind propeller at different operating modes and wind speeds and comparison of powers at joint work with the alternator 145STK2M [23]. To match the operation of the wind turbine with the alternator, a multiplier with a gear ratio $i = 0.6211$ is placed between them.

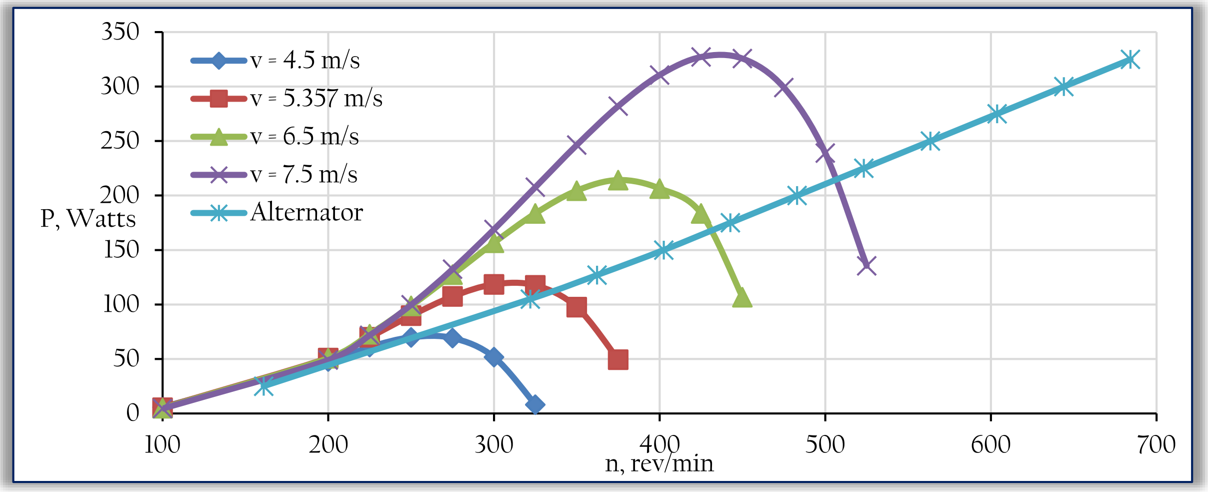

Figure 7. Comparison of the wind turbine power at different wind speeds and in cooperation with the alternator GL - PMG – 1000 [23].

4. CONCLUSION

A sequence of structural calculations for low power wind turbine with fixed type blades on the wind propeller is presented. It is applicable for determining some basic parameters such as power output, wind turbine radius, number of blades, blade profiling, etc. and to match the operation of the propeller-multiplier-generator system.

Note:

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