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THE REAL AND THE MAXIMUM POWER OF A WIND TURBINE, WHICH FUNCTIONS AT VARIABLE WIND SPEEDS OVER TIME

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Abstract: In this paper we determine the power given by a wind turbine, TV, the wind speed being variable over time. Identify the times at which the wind speed, V, has approximately the same value. Then calculate the useful power on TV, at those moments of time and, by interpolation, the coordinates of the operating point are deduced at (MPP) maximum power point, mechanical angular velocity (u_{OPTIM}), VUM, optimal and P_{TV-MAX}, the maximum power given by the TV. Using the coordinates of the MPP point the u_{OPTIM} (V) and P_{TV-MAX} (V) functions are recalibrated. It is shown that, in some operating points, the economic efficiency is over 25% lower compared to other operating points. It is shown that there are large differences between the values of the TV power, from those moments of time that have the same value of the wind speed. At the end of the paper an algorithm is presented for determining the energy efficiency of high power TV. The wind turbines from the Siliștea 2 location are analyzed, 141, Dobrogea, from the time interval 12:10 [h] –3:10 [h], from 11.01.2020.
Keywords: wind system, wind speed variable over time, wind turbine dynamics, maximum power points, operating point coordinates at maximum power, lower economic efficiency, Silistea 2 location, energy losses, the same value of wind speed, large differences between TV power values, algorithm for determining energy efficiency

1.INTRODUCTION

In this paper, the power given by a wind turbine, TV, from the location Siliştea 2, Dobrogea, [1,2,3,4], from the time interval 12:10 [h] – 3:10 [h], from dated 11.01.2020, in order to estimate energy losses, losses caused by high mechanical inertia and variable wind speed over time, [5,6,7,8].

The study is mainly based on values of wind speed, variable speed over time. In most works, [11,12,13,14], these aspects are treated at constant wind speeds and without efficient wind speed processing.

In areas where time variations in wind speed are significant, capturing maximum wind energy is a complex issue, with TV operation at the maximum power point not always possible, [5,6,7,8].

It is necessary to start from the knowledge of the wind speed, a speed that is variable in time, thus ensuring an optimal operation, from an energy point of view, of the wind installations, [2,3,4], mainly of TV.

The authors of the paper consider as essential, in obtaining useful and valid results, the analysis of the variation in time of the wind speed.

It treats the problem of operation in the maximum power point, MPP, of the TV, at mechanical angular speed, VUM, optimal, ω_{OPTIM}.

In this sense, a certain value of the wind speed is chosen and the time moments are identified that have approximately the same value, calculating, then, the useful power on TV, at those time moments.

It compares the values of the TV power, from those moments of time, with the maximum power of the TV, which is ordered to the maximum power point, MPP, at the respective value of the wind speed.

Therefore, the following two issues need to be addressed:

1) determining the power of TV, PT, at a given time and

2) determination of MPP, u_{OPTIM} and P_{TV-MAX} coordinates

The first problem, determining the power of the TV, is solved by measuring the basic quantities:

- ≡ V–wind speed;
- ≡ n– the generator speed of GE;
- ≡ P_{GE} – power at GE;

By measuring the generator speed at GE, n, the function n (t) is obtained.

It uses the momentum equation, [3,5,6,7], of form (1):

$$J\frac{du}{dt} = M_{TV} - M_{GE} \quad (1)$$

where:

- ≡ J–moment of total inertia,
- ≡ u–VUM at the shaft of the electric generator,GE,
- ≡ M_{TV}– the time given by the TV, relative to the GE shaft,
- ≡ M_{GE} – the electromagnetic moment given by GE.

By multiplication with u is obtained the ecuation (2) and (3):

$$J\frac{du}{dt}u = P_{TV} - P_{GE} \tag{2}$$

or:

$$J\frac{dn}{dt}n\left(\frac{\pi}{30}\right)^2 = P_{TV} - P_{GE} \tag{3}$$

where:

≡ n – rotational speed per minute;
≡ P_{TV} – the useful power given by the TV, related to the shaft of the electric generator;
≡ P_{GE} – the power given by GE, to the shaft;

All sizes are relative to the electric generator shaft.

At the local extreme points of the n (t) derived function $\frac{dn}{dt}$ is zero and it turns out that in these points, the power developed by the TV is equal to the power delivered by GE (4).

$$P_{TV-REAL} = P_{GE} \tag{4}$$

At the other points of the function n (t), where the derivative $\frac{dn}{dt}$, is not zero, the power developed by TV is calculated using the equation of motion, with the relation (5):

$$P_{TV-k} = P_{GE-k} + J\frac{n_k - n_{k-1}}{\Delta t}\left(\frac{\pi}{30}\right)^2 n_{k-1} \tag{5}$$

where:

≡ n_k – generator speed at GE at the time t_k;
≡ n_{k-1} – generator speed at GE at the time t_{k-1}, $\Delta t = t_k - t_{k-1}$;
≡ P_{TV-k}, P_{GE-k} – powers at the time t_{k-1},

The second problem, the determination of MPP coordinates, is solved by placing the operating points, previously determined, on the experimental characteristic of the TV power, ie on the graph of the P_{TV} function (u), for the value wind speed: V*, included in the range of speed values at which calculated the useful powers on TV, at those moments of time that have the values of the wind speed in the vicinity of V*.

To solve the two problems, only the basic quantities were measured: wind speed, generator speed at GE and GE power, and the mathematical models of TV, MM–TV, models that change over time, with limited validity, were not used.

The high mechanical inertia, through the high value of the total moment of inertia, J and the operation at variable wind speeds over time makes the operation of the TV in MPP, to be a complex problem, solvable with the technical data from a given wind system, [1, 3,5,6].

The dynamics of the TV is analyzed to what extent it works at the point of maximum power, over the analyzed time interval.

The results obtained, by simulation, are based on the mathematical models of TV, MM–TV, from [2,3,5,6].

Mathematical models of TV are used only as a guide, because they have a low degree of validity, they depend on weather conditions that change over time.

2. MATHEMATICAL MODELS FOR TV

The mathematical model of the TV allows the determination, as a guide, of the TV power and of the optimal mechanical angular speed of operation, u_{OPTIM}, so that the captured energy is maximum. The power given by TV is calculated with the relationship (6) [4,5,7,12]:

$$P_{TV} = \rho\pi R_p^2\, C_p(\lambda)V^3 \tag{6}$$

where:

≡ ρ–air density;
≡ Rp–pallet radius;
≡ Cp(λ)–power conversion factor;
≡ λ = uRp/V;
≡ V–wind speed;
≡ u–mechanical angular velocity,VUM

Power conversionn factor Cp(λ), is determined by the relationship (7):

$$C_p(\lambda) = c_1\left(\frac{c_2}{\Lambda} - c_3\right)e^{-\frac{c_4}{\Lambda}}, \tag{7}$$

where: $\frac{1}{\Lambda} = \frac{1}{\lambda} - 0.035$ = (V/(1. 5u) – 0. 035)

$c_1 - c_4$ are constant given in the catalog.

By replacement, the power conversion factor Cp(λ), is obtained in the form (8):

$$Cp(\lambda) = c_1\left(\frac{c_2}{\Lambda} - c_3\right)e^{-\frac{c_4}{\Lambda}} = c_1(c_2(V/(1.5u) - 0.035) - c_3)e^{-c_4((V/(1.5u) - 0.035)} \quad (8)$$

and the power given by the TV is calculated by the relationship (9):

$$P_{TV}(u,V) = \rho\pi R^2(\lambda)V^3 = 1 \quad (9.1)$$

or

$$P_{TV}(u,V) = k_1(k_2(V/u - 0.0525) - c_3)e^{-k_3(V/u - 0.0525))}V_3 \quad (9.2)$$

where: $k_1 = 1.225\pi 1.5^2 c_1$, $k_2 = c_2/1.5$, $k_3 = c_4/1.5$

For the wind turbine, TV, the experimental characteristics of the power are given by the construction company, [9,11,12,14], $P_{TV}(u,V)$, or of the torque, $M_{TV(u,V)}$, the latter also called experimental mechanical characteristics (10):

$$M_{TV}(u) = \frac{P_{TV}(u,V)}{u} = k_1\left(k_2\left(\frac{V}{u} - 0.0525 - c_3\right)e^{-k_3\left(\frac{V}{u} - 0.0525\right)}V^3/u \quad (10)$$

where: V –wind speed ; u – mechanical angular velocity,VUM;

Maximum value of the function $P_{TV}(u)$ is obtained for optimal VUM u_{OPTIM}, by derivation (11):

$$\frac{dP_{TV}}{du} = \frac{d}{du}\left(k_1k_2\left(\frac{V}{u} - 0.0525 - c_3\right)e^{-k_3\left(\frac{V}{u} - 0.0525\right)}V^3\right) = 0 \quad (11)$$

The result obtained demonstrates the direct connection between u_{OPTIM} and the wind speed. At wind speeds, V(t), time variables, the power varies between a minimum value and a maximum value depending on the VUM value u.

Finally, for MM–TV, it is obtained (12):

$$P_{TV}(u,V) = a(V/u - b)e^{-c(V/u)}V^3 \quad (12)$$

The maximum value of the $P_{TV}(u)$ function is obtained for the optimal VUM, u_{OPTIM}, by canceling the power derivative (13):

$$\frac{dP_{TV}}{du} = \frac{d}{du}a(V/u - b)e^{-c(V/u)}V^3 = 0 \quad (13)$$

resulting: $u_{OPTIM} = c/1+bc\ V$ or $u_{OPTIM} = k_0\ V$

where: k_0– the constructive constant of the turbine.

The value of the moment given by the TV, $M_T(u)$, is obtained from (14):

$$M_T(u,V) = P_{TV}(u,V)/u = a(V/u - b)^{e-c(V/u)}V^3/u \quad (14)$$

and the maximum value of the function $M_T(u)$ is obtained for VUM, u_{T-MAX}, by canceling the moment derivative (15):

$$\frac{dM_T}{du} = \frac{d}{du}a(V/u - b)^{e-c(V/u)}V^3/u = 0$$

resulting:

$$u_{T-MAX} = \frac{V}{b}\left(1 - 0.5\sqrt{b^2c^2 + 4} + 0.5bc\right) \quad (15)$$

With this value of VUM the maximum moment given by the TV is obtained, ecuation (16)

$$M_{T-MAX} = \frac{a(\sqrt{b^2c^2+4} - bc)}{2}e^{-\frac{bc}{1 - 0.5\sqrt{b^2c^2+4} + 0.5bc}}(b/1 - 0.5\sqrt{b^2c^2+4} + 0.5bc)^2V^2 \quad (16)$$

At optimal VUM, u_{OPTIM}, the value of the moment given by the TV is showen in (17):

$$M_{T(uOPTIM)} = \frac{a(1+bc)}{c^2}e^{-(1+bc)}V^2 \quad (17)$$

With the experimental data from the TV from Silistea location, [1], Dobrogea area, MM–TV was determined, in the form (18):

$$P_{TV}(u,V) = 1.984 \times 10^6(V/u - 2.6247 \times 10^{-2})e^{-58.617(V/u)}V^3 \quad (18)$$

By canceling the power derivative, the optimal VUM value is obtained, u_{OPTIM} (19):

$$\frac{dP_{TV}}{du} = \frac{d}{du}(1.984 \times 10^6(V/u - 2.6247 \times 10^{-2})e^{-58.617(V/u)}V^3 = 0 \quad (19)$$

or: $u_{OPTIM} = 23.091 \times V$.

Knowing the optimal VUM value is essential in operating the TV at maximum power, MPP, at u_{OPTIM}, figure 1. Replacing the optimal VUM value in $P_{TV}(u)$ the value of the maximum power, given by the TV, is obtained (20):

$$P_{TV-MAX}(V) = 3.0437V^3[kW] \quad (20)$$

In conclusion, the value of the maximum power given by the TV is directly proportional to V^3, wind speed cube.

3. CALCULATION OF WIND TURBINE POWERS

The variation of the wind speed, function V (t), was determined with the experimental data from the location Silistea 2, 141, Dobrogea, from the time interval 12:10 [h] –3:10 [h], from 11.01.2020 and which is can be found in table 1. In table 1 is presented the wind speed, power and generator speed at GE, from TV in Silistea 2 location 2.

Table 1. The wind speed, power and generator speed at GE in Silistea 2 location

t[min]	P_{GE}[kW]	t[min]	V[m/s]	t[min]	n[rpm]
0	101. 753	0	3. 870	0	811. 108
10	372. 442	10	5. 210	10	1171. 479
20	440. 728	20	5. 662	20	1261. 798
30	408. 718	30	5. 472	30	1232. 017
40	379. 155	40	5. 287	40	1200. 755
50	438. 860	50	5. 504	50	1259. 064
60	531. 630	60	5. 929	60	1334. 060
70	856. 017	70	6. 912	70	1551. 598
80	945. 798	80	7. 298	80	1601. 579
90	692. 932	90	6. 275	90	1455. 559
100	804. 745	100	6. 776	100	1533. 816
110	626. 852	110	6. 176	110	1411. 919
120	620. 315	120	6. 098	120	1405. 254
130	660. 848	130	6. 218	130	1434. 213
140	370. 412	140	5. 272	140	1167. 574
150	173. 482	150	4. 458	150	943. 540
160	357. 005	160	5. 143	160	1179. 103
170	268. 810	170	4. 867	170	1080. 667
180	290. 878	180	4. 988	180	1100. 648
190	494. 307	190	6. 255	190	1298. 889

— Real and maximum power calculation

On the analyzed time interval, two reference values of the wind speed are chosen, V_1^* si V_2^*.

▪ Case study 1 – at the reference wind speed, V_1^*

At times: A, B, C and D, figure 1, the wind speed values are approximately the same, being in its vicinity V_1^*.

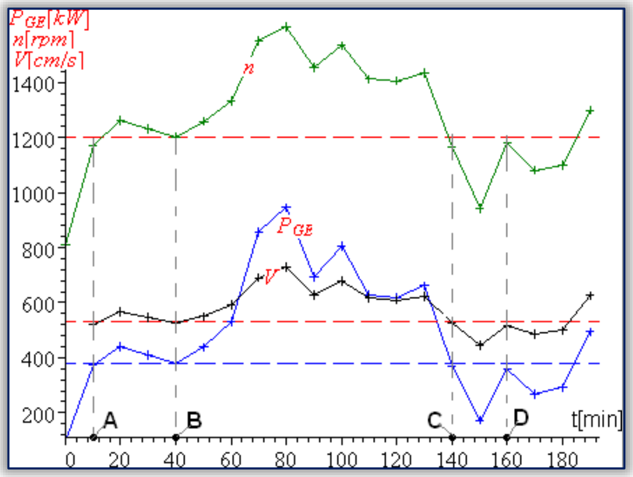

Figure 1. Wind reference speed, V* and variations over time in wind speed, generator speed and power at GE

At these times, the values of power and generator speed at GE are presented table 2:

Table 2. V – – – – – – – – – –PGE – – – – – – – – – –n

at the time:A	10	5. 210[m/s]	10	372. 442[kW]	10	1171. 479[rpm]	– V grows
at the time:B	40	5. 287[m/s]	40	379. 155[kW]	40	1200. 755[rpm]	V min.local
at the time:C	140	5. 272[m/s]	140	370. 412[kW]	140	1167. 574[rpm]	V decrese
at the time:D	160	5. 143[m/s]	160	357 [kW]	160	1179.103[rpm]	V max.local

The n / V ratio has the values:

$$\frac{n}{V} = \frac{1171.479}{5.21} = 224.85 \text{ at the time:A}$$

$$\frac{n}{V} = \frac{1200.755}{5.287} = 227.11 \text{ at the time:B}$$

$$\frac{n}{V} = \frac{1167.574}{5.272} = 221.47 \text{ at the time:C}$$

$$\frac{n}{V} = \frac{1179.103}{5.143} = 229.26 \text{ at the time:D}$$

When operating at maximum power, MPP, of the TV, the n/V ratio should have the same value.

Because the n/V ratio has different values, it results that, at these moments of time, it is not possible to capture a maximum wind energy.

Figure 1 shows that the local extreme points of the wind speed coincide with the local extreme points of the function n (t).

At the local extreme points of the n(t) derived function $\frac{dn}{dt}$ is zero and results from the equation of motion (21):

$$J\frac{dn}{dt}\, n\left(\frac{\pi}{30}\right)^2 = P_{TV} - P_{GE} \tag{21}$$

that, at these points, the power developed by the TV is equal to the power delivered by GE (21):

$$P_{TV-REAL} = P_{GE} \tag{21.1}$$

or

$$P_{TV-REAL} = P_{GE} = 5.287[kW] \text{ at the time: B} \tag{21.2}$$

$$P_{TV-REAL} = P_{GE} = 357.005[kW] \text{ at the time: D} \tag{21.3}$$

The ratio P_{TV}/V^3 has the values is presented in (22):

$$\frac{P_{TV}}{V^3} = \frac{379.155}{5.287^3} = 2.5656 \text{ at the time: B} \tag{22.1}$$

$$\frac{P_{TV}}{V^3} = \frac{357.005}{5.143^3} = 2.6244 \text{ at the time: D} \tag{22.2}$$

And, also the ratio n/V, does not have a constant value.

It also follows that, at these points, the TV operation is not at the maximum power point.

The TV power values, in points A and C, are calculated using the equation of motion, at J = 511.92 [kgm^2], with the relation (23):

$$P_{TV-k} = P_{GE-k} + J\frac{n_k - n_{k-1}}{600}\left(\frac{\pi}{30}\right)^2 n_{k-1} = 9.3564 \times 10^{-3}\,(n_k - n_{k-1})n_{k-1} + P_{GE-k} \tag{23}$$

where:

≡ n_k – the generator speed of GE at moment tk;

≡ nk–1– generator speed of GE at moment tk–1; Δt = tk – tk–1 = 600[s];

≡ P_{TV-k}, P_{GE-k} – powers at moment tk–1, this relations was used (24)

$$P_{TV-A} = P_{GE-A} + J\frac{n_k - n_{k-1}}{600}\left(\frac{\pi}{30}\right)^2 n_{k-1} = 9.3564 \times 10^{-3}\,(1261.798 - 1171.479)1171.479$$
$$+372442 = 3.73\text{x}10^5 \text{ [W] – power at moment A} \tag{24.1}$$

$$P_{TV-C} = P_{GE-C} + J\frac{n_k - n_{k-1}}{600}\left(\frac{\pi}{30}\right)^2 n_{k-1} = 9.3564 \times 10^{-3}\,(943.54\text{–}1167.574)1167.574$$
$$+ 370412 = 3.6796 \text{ x } 10^5\text{[W] – power at moment C} \tag{24.2}$$

In order to visualize the operating points, from the time moments: A, B, C and D, in relation to MPP, a reduction of these points is made at the reference speed, V_1^*, of a base point.

— Reduction to the reference speed V_1^* (base point).

Let this be the base point, the point at time B, with:

≡ wind speed: V_1^* = 5. 287[m/s];

≡ power TV: P_{TV-B} = 379. 155[kW];

≡ generator speed GE :n_B = 1200. 755[rpm];

- Specification 1: If the operating points, from time points: A, B, C and D, are in the MPP area, the value of the TV power is directly proportional to V^3, the wind speed cube.

Reduction of point A to base point B (25):

$$\text{–reduced power } P_{TV-RED-A} = P_{TV-A}\left(\frac{5.287}{5.21}\right)^3 = 3.7343 \text{ x } 10^5 \left(\frac{5.287}{5.21}\right)^3 = 3.9023\text{x}10^5[W] \tag{25.1}$$

$$\text{– low genererator speed } n_{RED-A}\left(\frac{5.287}{5.21}\right)^3 = 1188.8[rpm] = n_A \tag{25.2}$$

Reduction of point C to base point B (26):

$$\text{–reduced power } P_{TV-RED-C} = P_{TV-C}\left(\frac{5.272}{5.21}\right)^3 = 3.70412 \text{ x } 10^5 \left(\frac{5.272}{5.21}\right)^3 = 3.8379\text{ x}10^5[W] \tag{26.1}$$

$$\text{– low genererator speed } n_{RED-C}\left(\frac{5.272}{5.21}\right)^3 = 1181.5[rpm] = n_C \tag{26.2}$$

Reduction of point D to base point B (27)

$$\text{–reduced power } P_{TV-RED-D} = P_{TV-D}\left(\frac{5.143}{5.21}\right)^3 = 3.57005 \text{ x } 10^5 \left(\frac{5.143}{5.21}\right)^3 = 3.4341 \text{ x } 10^5[W] \tag{27.1}$$

$$\text{–low genererator speed } n_{RED-D}\left(\frac{5.143}{5.21}\right)^3 = 1163.9 \text{ [rpm]} = n_D \tag{27.2}$$

The coordinates of the operating points, from time points: A, C and D, reduced to base point B, are:

$$A(1188.8,\ 3.902\ 3\times 10^5)$$
$$B(1200.7,\ 3.79155\times 10^5)$$
$$C(1181.5,\ 3.837\ 9\times 10^5)$$
$$D(1163.9,\ 3.4341\times 10^5)$$

Table 3. The final values of power P_{TV} and n

n[rpm]	P_{TV}[MW]
D 1163. 9	0. 34341
C 1181. 5	0. 3837 9
A 1188. 8	0. 3902 3
B1200. 755	0. 379155

In tabel 3 we have the final values of power P_{TV} and n:

The highest value of power is at the time: A and the lowest at time D, the difference beeing $\frac{3.902\ 3-3.4341}{3.902\ 3}100\approx$ 12% and, therefore, at time D economic efficiency is 12% lower than at time A.

- Note 1: Observing the coordinates of the operating points, from the time moments: A and B, in the sense that we have (28):

$$n_{RED-A} = 1188.\ 8[rpm] < n_B = 1200.\ 755[rpm] \quad (28.1),$$
$$P_{TV-RED-A} = 3.\ 9023\times 105[W] > P_{TV-B} = 3.\ 79155\times 105[W] \quad (28.2)$$

it follows that, at time A, the operating point is, on the TV power characteristic, in the area $n<n_{OPTIM}$ and, at time B, the operating point is, depending on the power characteristic, in the area $n> n_{OPTIM}$ and therefore the operating point at maximum power, MPP, is between A and B $n_{RED-A}<n_{OPTIM}<n_B$.

A more detailed analysis is required, in the MPP area, to estimate the coordinates of the operating point at maximum power.

Using the coordinates of the operating points: A, B, C and D the MPP coordinates are deduce.

In figure 2 are placed, in detail, these operating points, on the TV power characteristic.

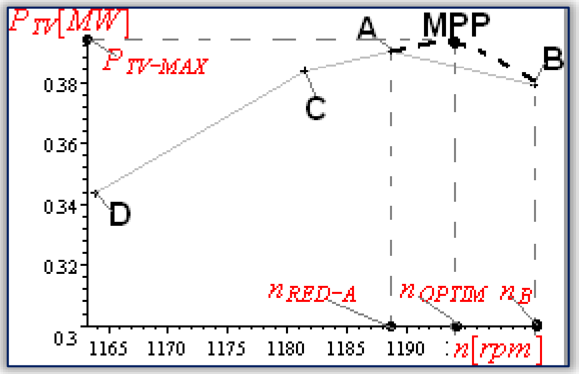

Figure 2. TV power characteristic with operating points: A, B, C and D.

By interpolation, the coordinates of the operating point at maximum power, MPP, are deduced (29):

$$MPP(1193.\ 9,\ 3.\ 934\times 10^5) \quad (29)$$

The coordinates of the MPP operating point are at the wind speed from time B, of value: V*= 5. 287[m/s].

With this value of the wind speed and using the coordinates of the MPP point, the functions are recalibrated. $u_{OPTIM}(V)$ and $P_{TV-MAX}(V)$, deduced with MM–TV in the form (30):

$$u_{OPTIM}(V) = 23.\ 091\cdot V \text{ VUM optim} \quad (30)$$

$P_{TV-MAX}(V) = 3.\ 0437V^3$[kW] maximum power optimal VUM value, at V*, is (31):

$$u_{OPTIM}(5.287)=\frac{2\pi}{60}n=\frac{2\pi}{60}1193.9=125.02[rad/s] \quad (31)$$

and it turns out (32):

$$k^*_{V-1}=\frac{u_{OPTIM}\,(5.287)}{5.287}=2.647, \text{ compared to the value in MM–TV} \quad (32.1).$$
$$k_V = 23.\ 091, \text{ the difference of } \frac{23.647-23.091}{23.647}100=2.3512\% \quad (32.2)$$

The value of the maximum power, at V*, is represented in (33):

$$P_{TV-MAX}(5.\ 287) = 3.\ 934\times 10^5[W] \quad (33)$$

And it results (34):

$$k^*_{p-1}=\frac{P_{TV-MAX}\,(5.287)}{5.287}=2.662 \quad (34)$$

compared to the value in MM–TV result (35):

$$kp = 3.\ 0437, \text{ the difference of } \frac{2.662-3.0437}{2.662}100=-14.339\% \quad (35)$$

Knowing the optimal VUM value is essential in operating the TV at maximum power, MPP, at u_{OPTIM}.

In figure 3 are placed, on the TV power characteristic, the operating points A, B, C and D, compared to MPP.

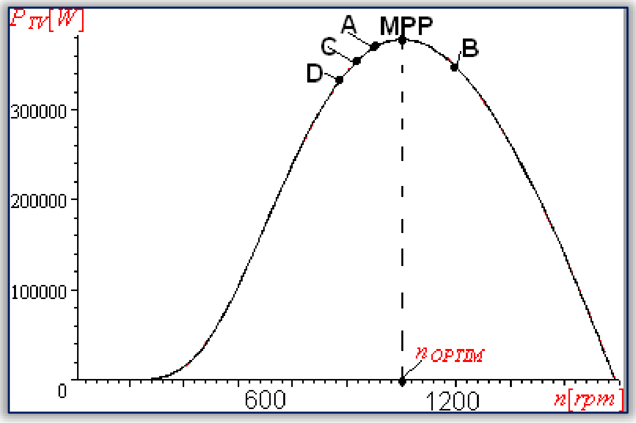

Figure 3. TV power characteristic with operating points: A, B, C and D

- Note 2: Power losses are at all operating points analyzed, however, the largest power loss is at time D, compared to MMP, the power difference being (36):

$$\Delta P_{TV} = P_{TV-MAX} - P_{TV-D} = 3.934 \times 10^5 - 3.4341 \times 10^5 = 49990\ [W] \quad (36.1)$$

or

$$\frac{3.934\times10^5 - 3.4341\times10^5}{3.934\times10^5}100 = 12.707\% \quad (36.2)$$

This loss of power is also found in the declining economic profitability of TV.

For a more detailed analysis of the values of TV powers, in order to estimate energy losses, some clarifications are required:

1) To determine the coordinates of the MPP point, the value of the optimal generator speed, n_{OPTIM}, must be in the range of values of the generator speeds of the operating points, from the time moments: A, B, C and D.

2) To have $n_{MINIM} < n_{OPTIM} < n_{MAXIM}$

where:

≡ n_{MINIM} minimum measured generator speed at GE;

≡ n_{MAXIM} maximum measured generator speed at GE, it is necessary to have operating points with lower generator speeds, below n_{OPTIM} and operating points with higher generator speeds, over $n_{OPTIM.;}$

3) The approximate value of n_{OPTIM} can be determined from the mathematical model of the TV, which allows the determination, as a guide, of the optimal mechanical angular speed of operation, u_{OPTIM};

4) From the obtained results it is observed the need to recalculate the factors k_V şi k_P, because the values obtained with MM–TV are much different from their real values, $\mathbf{k_V^*}$ şi $\mathbf{k_P^*}$.

Case study 2 – at the reference wind speed, $\mathbf{V_2^*}$ = 6. 098[m/s]

The reference wind speed, V*, was chosen at time t = 120 [min], because this time moment corresponds to a local minimum for the function n(t) and derivative $\frac{dn}{dt}$ it is zero, the power developed by the TV being equal to the power charged by GE (37):

$$P_{TV-REAL} = P_{GE} = 620.315[kW] \quad (37)$$

From the time variation of the wind speed, figure 1, the time moments are chosen: A, B, C, D, E and F, with the wind speed value in the vicinity of the reference speed value,V*.

At times: A, D and F, figure 4, the wind speed has the reference value: $\mathbf{V_2^*}$ = 6. 098[m/s], power and generator speed at GE, having values at the time A (38): P_{GE} = 609. 8[kW], n = 1390 [rpm]

$$\text{Power TV: } P_{TV-A} = 9.3564\times10^{-3}(1551.598 - 1334.06)1390+609800 = 6.1263\times10^5[W] = 612.63[kW] \quad (38)$$

At the time D (39):

$$P_{GE} = 620.315[kW],\ n = 1405.254[rpm] - n,\ V \text{ minim local, power TV:} P_{TV-D} = P_{GE} = 620.315[kW] \quad (39)$$

At the time F (40):

$$P_{GE} = 480\ [kW],\ n = 1270\ [rpm],\ \text{Power TV: } P_{TV-F} = 82.36[kW] \quad (40)$$

At times: B, C and E, figure 4, the wind speed has the value in the vicinity of the reference speed value, $\mathbf{V_2^*}$.

At the moment: B wind speed has the value: V_B = 6. 275[m/s] > V*, power and speed, at generator GE, having values P_{GE} = 692. 932[kW], n = 1455. 559[rpm] – n, V min.local.

By reducing to the reference speed V* is obtained (41): $n = 1455.559\left(\frac{6.098}{6.275}\right)^3 = 1414.5[rpm]$

$$P_{TV} = P_{GE} = 692.932\left(\frac{6.098}{6.275}\right)^3 = 635.93\ [kW] \quad (41)$$

At the moment: C wind speed has the value: V_C = 6. 176[m/s] > V*, power and speed, at GE, having values (42):

P_{GE} = 626. 852[kW], n = 1411. 919[rpm] – n, V power drops (42.1)

Power TV: $P_{TV-C} = 9.3564\times10^{-3}(1405 - 1411.919)1390 + 626852 = 6.2676\times10^{5}[W] = 626.76[kW]$ (42.2)

By reducing to the reference speed V_2^* is obtained (43):

$$P_{TV} = 626.76\left(\frac{6.098}{6.176}\right)^3 = 603.31[kW] \quad (43.1)$$

$$n = 1411.919\left(\frac{6.098}{6.176}\right) = 1394.1[rpm] \quad (43.2)$$

At the moment, the wind speed has the value (44):

$$V_E = 6.218[m/s] > V_2^* \quad (45)$$

power and speed, at GE, having values P_{GE} = 660. 848[kW], n = 1434. 213[rpm] – n, V maximum local.

By reducing to the reference speed V* is obtained (46):

$$n = 1434.213\left(\frac{6.098}{6.218}\right) = 1406.5[rpm] \quad (46.1)$$

$$P_{TV} = 660.848\left(\frac{6.098}{6.218}\right)^3 = 623.32[kW] \quad (46.2)$$

Figure 4 shows the time moments with the wind speed values in the vicinity of the reference speed value V_2^*.

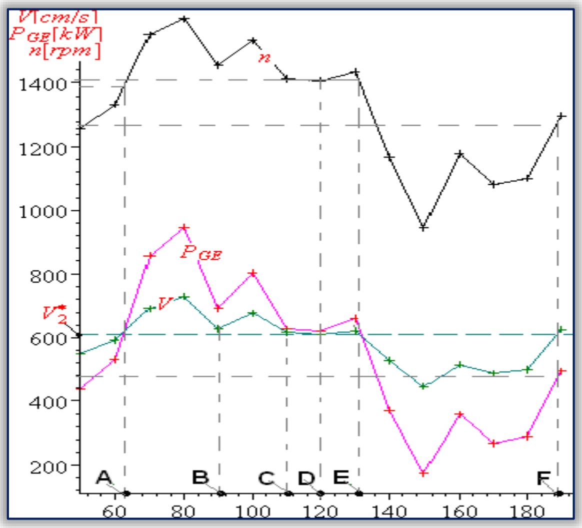

Figure 4.Moment of time with wind speed values in the vicinity of the reference speed value V_2^*.

Table 4. Coordinates of the operating points

n[rpm]	P_{TV}[MW]
F 1270.	482.36
A 1390.	612.63
C 1394.1	603.31
D1405.254	620.315
E 1406.5	623.32
B 1414.5	635.93

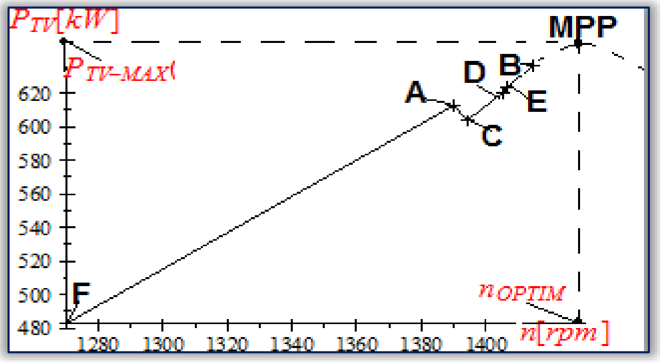

Figure 5. TV power characteristic with operating points: A, B, C, D, E and F

Coordinates of the operating points, from the time moments: A, B, C, D, E and F, reduced to the value of the reference speed V*, are represented in table 4.

The characteristic of the TV power, with the operating points: A, B, C, D, E and F, is given in figure 5.

- **Note 3:** Observing the placement of the operating points: A, B, C, D, E and F, compared to MPP, on the TV power characteristic, given in figure 5, it results that:

1) operating points: A, B, C, D, E and F are in the area: $n < n_{OPTIM;}$

2) The operating point at amximuum power, MPP,is at $n_{OPTIM} > n_B$ = 1414. 5[rpm];

3) the operating point at time B is closest to the MPP.

Under these conditions, the values of the proportionality factors k_V^* and k_P^* are:

$$k_V^* = \frac{u_{OPTIM}\,(6.098)}{6.098} > \frac{2\pi}{60}\frac{1414.5}{6.098} = 24.291 \text{ compare to } k_{V-1}^* = 23.647, \text{ deduced in Study of case 1}$$

$$k_P^* = \frac{P_{TV-MAX}\,(6.098)}{6.098^3} > \frac{P_{TV-B}}{6.098^3} = 2.8044 \text{ compare to } k_{P-1}^* = 2.662, \text{ deduced in Study case 1}$$

The highest value of power is at time: B and the lowest at time F, the difference being (47):

$$\frac{635.93-482.36}{635.93}100 = 24.14912\% \qquad (47)$$

and, therefore, at time F the economic efficiency is 24.14912% lower than at time B

Compared to MPP, the economic efficiency is even lower, by over 25%, because the value of TV power is, at time B, lower, compared to the value of TV power in MPP.

- Note 4: The loss of power results from the non–correlation of the power value at GE with the value of wind speed. From the wind speed and its derivative, the value of the power at GE can be determined, so as to achieve an operation in the optimal area, from an energetic point of view.

The following is an algorithm for determining energy efficiency.

— Algoritm for determinating energy efficiency

The algorithm for determining energy efficiency is based on the measured values of: wind speed, speed and power at GE.

- Stage 1

≡ a value is chosen from the measured values of wind speed,V*, at which energy efficiency is determined;

≡ time moments are identified t_k what are the values of the wind speed in the vicinity of the chosen value: V*;

≡ the function n (t) is generated by measuring, at a sampling step Δt, the speed, n, from the electric generator, GE;

- Stage 2

≡ the power developed by TV, P_{TV-K}, is calculated by measuring: speed, n and power, P_{GE}, at GE, at the time moments t_k, mentioned, in two variants:

a) at the local extreme points of the function n (t), where the power from GE is equal to that from TV: $P_{TV-REAL} = P_{GE}$;

b) in the other points, where the power developed by TV is the sum of the powers from GE, P_{GE-k} and inertial power, with the relationship (48):

$$P_{TV-k} = P_{GE-k} + J\,\frac{n_k - n_{k-1}}{\Delta t}\left(\frac{\pi}{30}\right)^2 n_{k-1} \qquad (48)$$

where:

≡ n_k,n_{k-1} – speeds at GE at times t_k and t_{k-1},

≡ $\Delta t = t_k - t_{k-1}$,

≡ P_{GE-k} – power at GE at the time tk.

- Stage 3

≡ is placed, on the characteristic of the TV power, the operating points, analyzed, F_K, of coordinates P_{TV-K} and n_k.

- Stage 4

≡ is analyzed, on the characteristic of TV power, $P_{TV}(n)$, operating points, F_K, compare to the maximum point, MPP.

≡ is calculated in the operating points Fk, power losses: $\Delta P_{TV} = P_{TV-MAX} - P_{TV-K}$.

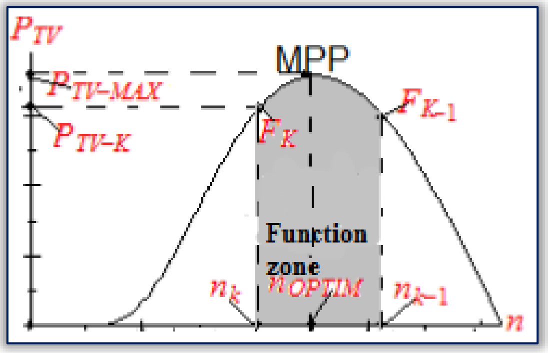

Figure 6. Characteristic of TV power at wind speed V*

Therefore, at a certain value of: wind speed, V*, from the measured values of: wind speed, speed and power at GE, the coordinates of the operating point at maximum power are determined, MPP,n_{OPTIM}, and P_{TV-MAX} and then calculated at operating points (Fk), power losses (ΔP_{TV}).

In this way, without using mathematical models, a study can be made on the energy efficiency of high power TVs.

4. CONCLUSIONS

The analysis of the operation of the wind turbine was based on direct measurements of the main basic quantities: wind speed, speed and power at GE. With these quantities the power given by a wind turbine, TV was determined, the wind speed being variable over time, identified the times at which the wind speed has approximately the same value. Calculated, then, the useful power at the TV, at those moments of time and, by interpolation, the coordinates of the operating point were deduced at maximum power, MPP. Using the coordinates of the MPP point, the functions u_{OPTIM} (V) and P_{TV-MAX} (V). It has been shown that, in some operating points, the economic efficiency is 12% lower compared to other operating points of the wind speed. At the end of the paper was presented an algorithm for determining the energy efficiency of high power TV. The wind turbines from the location Silistea 2, 141, Dobrogea, from 11.01.2020 were analyzed.

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