Energy efficiency of wind power plants in various wind condition

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Abstract. The present paper determines the optimum energy operation area of an electric wind power system, under time varying wind speed conditions. The determinations of the optimal area, from the energy point of view, is done based on experimental values from the Romanian black sea cost, Dobrogea area. The optimum operation area is defined by the optimal mechanical velocity, $\omega_{\text{OPTIM}}$. For this, the dependence between the wind speed, $v$, and $\omega_{\text{OPTIM}}$ are computed based on the current wind speed and the current mechanical velocity $\omega$. Due to the high inertia of the wind turbine (WT), the generators speed is not able to follow the changes of the wind speed. Knowing the optimum value $\omega_{\text{OPTIM}}$, the solution is to determine the load at the permanent magnet synchronous generator (PMSG) in order that the mechanical speed should timely reach his optimum.

1. Introduction

In situation of fast wind speed variations in time, due to the high values of the inertia moment, the speed at the wind turbine WT is not able to follow the fast-increasing wind speed [1], [2]. To obtain maximum output power on the WT, it is permanently necessary that the value of the mechanical angular velocity (MAV) [3] is correlated with the current wind speed value. Due the high inertia moment of a wind turbine, it is not permanently possible for wind power system (WPS) to operate in the maximum power point, MPP. Depending on the measured wind speed, $v$, the power at the permanent magnet synchronous generator (PMSG), $P_{\text{PMSG}}(v)$ and MAV, $\omega(v)$, at PMSG must be prescribed, so that a maximum power operation of the WPS will be achieved.

In the vast majority of wind turbines in operation, the control system presents, with regard to the described problem, two major shortcomings: (1) the power adjustment, PMSG is made only after the wind speed values, $v$, the equivalent value of the moment of inertia, $J$, is not taken into account. (2) at fast variations, in time, of the wind speed, MAV does not reach, in due time, the optimum value, $\omega_{\text{OPTIM}}$, due to the high $J$. Because the MAV does not reach, under the described condition, the optimum value, the wind turbines are not able to capture the maximum wind energy. When the wind speed varies significantly in time and given that the mechanical inertia of the big wind turbines is high,
capturing the maximum wind energy becomes a complex problem, difficult to be solved in practice [4], [5].

Due to the high mechanical inertia, to reach, in due time, the MAV condition, $\omega = \omega_{OPTIM}$, the load at the PMSG must be modified. Because $\omega_{OPTIM}$ value dependent on the wind speed, $v$, it is necessary that its value must change in close correlation with $v$. Due to the high mechanical inertia, the MAV modification is slow and, therefore, the mechanical angular velocity is not at the optimum value most of the time, $\omega \neq \omega_{OPTIM}$ [6], [7].

Estimating the value of the maximum power that can be developed by the WT, in conditions of varying wind speed over time, is particularly important in achieving an optimal adjustment of the entire system for the energy production. Some works, [8 - 10], propose the use of control algorithms, based on the wind speed measurement, to prescribe the optimum MAV in the MPP area.

2. Mathematical models

2.1. Determination of the wind turbine power, starting from the energy balance

From the energy balance of the wind turbine, [11] or by integrating the kinetic momentum equation,

$$\int \frac{d\omega}{dt} = M_{WT} - M_{PMSG}$$

multiplied with $\omega$, leads us to

$$\int \frac{d\omega}{dt} \omega = \omega \cdot M_{WT} - \omega \cdot M_{PMSG} = P_{WT} - P_{PMSG}$$

or, by integration (1), results

$$\int \frac{\omega_{k+1}^2 - \omega_{k}^2}{\Delta t} = \int_{t_{k}}^{t_{k+1}} P_{WT} - \int_{t_{k}}^{t_{k+1}} P_{PMSG} = P_{WTmedium} - P_{PMSGmedium}$$

where: $J$ – equivalent inertia moment; $\omega_{k}$ and $\omega_{k+1}$ - MAV at $t_{k}$ respective $t_{k+1}$ moment; $\Delta t = t_{k+1} - t_{k}$ - $P_{WT}$ medium – average power in the $\Delta t$ time frame; $M_{WT}$, $M_{PMSG}$ – moment of the wind turbine and the permanent magnet synchronous generator. Based on (3), in the $\Delta t$ time interval, the medium power at the wind turbine shaft, can be computed based on two basic sizes, current MAV and wind speed,

$$P_{WTmedium} = \frac{\int \omega_{k+1}^2 - \omega_{k}^2}{\Delta t} + P_{PMSGmedium}$$

2.2 Mathematical model of the wind turbine (MM-WT)

Starting from the classic form of the wind turbine mathematical model ([12], [13]) we obtain the optimum value for the mechanical angular velocity, by cancelling the derivative of the power, resulting

$$\omega_{OPTIM} = k_{\omega} \cdot v$$

2.3 Mathematical model of the permanent magnet synchronous generator (MM-PMSG)

To be able to analyses the behavior of the entire system, WT+PMSG, at variable wind speed, we appeal to the orthogonal mathematical model of the PMSG, described by [11-13]

$$\begin{cases}
-U\sqrt{3}\sin\theta = R_{I_d}I_d - \omega L_q I_q \\
U\sqrt{3}\sin\theta = R_{I_q}I_q + \omega L_d I_d + \omega \Psi_{PM} \\
M_{PMSG} = p_1 (L_d - L_q) I_d I_q + p_1 I_q \Psi_{PM} \\
P_G = R (I_d^2 + I_q^2)
\end{cases}$$

where: $U$ - stator voltage; $I_d$, $I_q$ - stator currents after $d$- and $q$-axis; $L_d$, $L_q$ - synchronous reactance after $d$- and $q$- axis; $\theta$ - load angle; $R$ - generator’s phase resistance; $\Psi_{PM}$ - flux permanent magnet; $p_1$ -
number of pole pairs, \( M_{\text{PMSG}} \) – PMSG electromagnetic torque. Neglecting in the above description, (6), the stator winding resistance, we obtain a simplified form of the mathematic model:

\[
\begin{aligned}
U\sqrt{3}\sin\theta &= \omega L_d I_q \\
U\sqrt{3}\sin\theta &= \omega L_d I_d + \omega \Psi_{PM} \\
M_{\text{PMSG}} &= p_1 (L_d - L_q) I_d I_q + p_1 I_q \Psi_{PM} \\
P_g &= R (I_d^2 + I_q^2)
\end{aligned}
\]  

(7)

The flux of the permanent magnet, \( \Psi_{PM} \), is determined by the operation without load, with the phase voltage \( U_0 \),

\[
3U_0 = \omega \Psi_{PM}
\]  

(8)

where \( \omega = 2\pi n \), \( n \) – shaft speed.

When the system operates under load, at the \( I_N \) current, eliminating \( \theta \) and approximating \( L_d = L_q = L_s \), we obtain from (7) a system of three equation,

\[
\begin{aligned}
3U^2 &= (\omega L_d I_q)^2 \\
I_N^2 &= I_d^2 + I_q^2 \\
p_1 I_q \Psi_{PM} \omega &= P_M
\end{aligned}
\]  

(9)

with the unknowns \( I_q, I_d, L_s \).

With the experimental data \( U = 400V, I = 618A, P = 736560W, n = 1430 \text{ RPM}, \omega = 2\pi \text{m/60} = 149.67\text{rad/s}, \Psi_{PM} = 130\text{Wb}, \nu = 6.39\text{m/s} \) and \( p_1 = 2 \) we obtain for \( L_s=0.214\text{H}, \) a very close value to the real one.

For a given value of the load, \( R \), with \( U = I \cdot R \), from the simplified equation system of the PMSG [14], the mechanical power results as:

\[
P_M = P_{\text{PMSG}} = R \Psi_{PM}^2 \frac{\omega^2}{\omega^2 L_s^2 + R^2}
\]  

(10)

The expression of the PMSG power, (10), at the \( t_k \) moment, depends on the MAV value at the \( t_k \) moment, \( \omega_k \), and the load resistance, \( R_k \).

3. Calculation of the optimum power at the permanent magnet synchronous generator

The optimum power at the generator, \( P_{\text{PMSG-OPTIM}} \), [15] is reached for the optimum mechanical velocity, \( \omega_{\text{OPTIM}} \), in the \( \Delta t \) time frame, \( \omega_{\text{OPTIM}} = \omega_k \):

\[
P_{\text{PMSG-OPTIM}} = P_{\text{WT-medium}} - \int \frac{\omega_{\text{OPTIM}}^2 - \omega_k^2}{2.\Delta t} \]  

(11)

When \( \omega_k \neq \omega_{\text{OPTIM}} \), the PMSG load must be changed to \( \Delta P_{\text{PMSG}} = \Delta W_{\text{kinetic}}/\Delta t \) corresponding to the kinetic energy \( \Delta W_{\text{kinetic}} = J(\omega_{\text{OPTIM}}^2 - \omega_k^2)/2 \). The power at the generator has to decrease / increase to:

\[
\Delta P_{\text{PMSG-OPTIM}} = \Delta P_{\text{PMSG-INITIAL}} - \Delta P_{\text{PMSG}}
\]

and the load resistance, \( R \), has to increase/decrease.

The power characteristics of the PMSG and the wind turbine at a wind speed of \( \nu = 10.28 \text{m/s} \) and a load resistance of \( R = 225 \Omega \) are computed and represented in Figure 1.

3.1 Calculation of optimal speeds and powers

Starting from experimental values [16], [17] we compute based on (13), the optimal speeds, Table 1.

\[
n_{\text{OPTIM}} = \frac{30}{\pi} 17.863 \cdot \nu.
\]  

(12)
Table 1. Experimental & computed values

| P (kW) | n (rpm) | v (m/s) | n_{OPTIM} (rpm) |
|--------|---------|---------|-----------------|
| 1617   | 1720.58 | 8.4     | 1432.9          |
| 2058.83| 1720.67 | 9.32    | 1589.8          |
| 2225.44| 1720.57 | 10.28   | 1753.6          |
| 1947.92| 1720.29 | 9.08    | 1548.9          |
| 1753.81| 1720.41 | 8.38    | 1429.5          |

Based on the synthetized values in Table 1, we observe that just for the wind speed of \( v = 10.28 \) m/s, the optimal value of the rotational speed (RPM) is higher than the measured one, at all other wind speed values, the optimum rotational speed is below the measured values.

Figure 1. Power characteristics of the wind turbine and permanent magnet synchronous generator

Due to the high values of the equivalent inertial moment, \( J \), the speed at PMSG cannot be modified in time in the same ratio as the average of the wind speed.

The load change at the PMSG has to be done considering the sign of the derivative of the wind speed at the \( t \) moment: in case it is positive, the PMSG load must increase and in case it is negative, the load should be reduced. Based on changes operated to the generators load, the wind energy system is brought to operate in the optimum area [18].

Case study. Considering \( \Delta t = 600 \) s and the inertial moment \( J = 36734 \) [kgm\(^2\)] we get

\[
\frac{\omega^2_{k} - \omega^2_{k-1}}{2 \cdot \Delta t} = 36734 \frac{n^2_k - n^2_{k-1}}{1200} \left(\frac{2\pi}{60}\right)^2 = 0.33\left(n^2_k - n^2_{k-1}\right)
\]  

(13)

Based on equation (13), we are able to compute the medium WT power from

\[
P_{WT - medium} = 0.33\left(n^2_k - n^2_{k-1}\right) + P_{PMSG - medium}
\]  

(14)

In the following, we analyse the optimal operation of the wind power system, in a 20 minute time frame.

The wind speed increases from 9.32 m/s to 10.28 m/s in 10 minutes, corresponding to the values in Table 1. Based on (12), the optimum mechanical angular velocity is for \( v = 9.32 \) m/s \( \omega_{OPTIM}(9.32) = 1589.8 \) RPM = 166.48 rad/s, compared with the one measured \( \omega_{MEAS}(9.32) = 1720.67 \) RPM = 180.19 rad/s and for \( v = 10.28 \) m/s \( \omega_{OPTIM}(10.28) = 1753.5 \) RPM = 183.63 rad/s, compared with the one measured \( \omega_{MEAS}(9.32) = 1720.57 \) RPM.
Because the two values are different, \( n_{\text{OPTIM}}(10.28) \neq n_{\text{MEAS}}(10.28) \), the load at the PMSG needs to be changed, with \( \Delta P_{\text{PMSG}} = \Delta W_{\text{kinetic}}/\Delta t \), corresponding to \( \Delta W_{\text{kinetic}} = J(\omega_{\text{OPTIM}}^2 - \omega_0^2)/2 = 36734(183.63^2 - 180.18^2)/2 = 2.305 \times 10^7 \) J. The power at the generator has to decrease to \( P_{\text{PMSG-OPTIM}} = P_{\text{PMSG-INITIAL}} - \Delta P_{\text{PMSG}} = (2058830 + 2225440)/2 - 2.305 \times 10^7/600 = 2.1037 \times 10^6 \) and the load resistance, \( R \), has to increase, \( R_{\text{OPTIM}} = 260 \Omega \).

When the wind speed decrease from 10.28 m/s to 9.08 m/s in 10 minutes, corresponding to the values in Table 1. Based on (13), the optimum mechanical angular velocity is for \( \nu = 9.08 \) m/s \( \omega_{\text{OPTIM}}(9.08) = 162.2 \) rad/s = 1548.9 RPM, compared with the one measured \( \omega_{\text{MEAS}}(9.08) = 180.15 \) rad/s = 1720.29 RPM.

Because the two values are different, \( n_{\text{OPTIM}}(9.08) \neq n_{\text{MEAS}}(9.08) \), the load at the PMSG needs to be changed, with \( \Delta P_{\text{PMSG}} = \Delta W_{\text{kinetic}}/\Delta t \), corresponding to \( \Delta W_{\text{kinetic}} = J(\omega_{\text{OPTIM}}^2 - \omega_0^2)/2 = 36734(162.2^2 - 180.18^2)/2 = -1.1287 \times 10^6 \) J. The power at the generator has to increase to \( P_{\text{PMSG-OPTIM}} = P_{\text{PMSG-INITIAL}} - \Delta P_{\text{PMSG}} = (1947920 + 2225440)/2 + 1.1287 \times 10^6/600 = 2.2748 \times 10^6 \) and the load resistance, \( R \), has to decrease to \( R_{\text{OPTIM}} = 212.26 \Omega \).

Based on the above results, we can conclude, in a first stage, that the generator load must be changed in relation to the wind speed and the inertial moment, so that the operating point approach the maximum power point (MPP).

### 3.2 Determination of the values of the wind energy captured under optimal conditions

The captured wind energy is maxims, when the system operates in the MPP, conditions that is similar with ensuring the optimum MAV, equation (13). We analyse the optimal operation of the wind power system and compute the energy yields in a 20 minute time frame [19 - 22].

The wind speed increases from 9.32 m/s to 10.28 m/s in 10 minutes, corresponding to the values in Table 1. Base on the power and RPM values, the average power of the wind turbine, applying the relationship (13), becomes for a \( \Delta t = 600 \) s time frame, \( P_{\text{WT-medium-1}} = 2142 \) [kW], the captured wind energy is \( E_{\text{WT-1}}(600) = P_{\text{WT-medium-1}} \cdot \Delta t = 1.2852 \times 10^6 \) J.

Considering the wind speed variation in the form \( \nu(t) = 9.32 + ((10.28-9.32/600)) \cdot t \), results the expression of the optimum MAV for this case by substituting the wind speed expression in relations (13), the maximum power of the wind turbine being

\[
P_{\text{WT-max}} = 2.2846 \cdot \nu^3. \tag{15}\]

Integrating the power in the \( \Delta t \) time frame of 600s, we receive the value of the captured wind energy, in optimal circumstances, \( E_{\text{WT-OPTIM-1}} = 1.2932 \times 10^6 \) J, higher value with 0.62% compared to the gained energy in the situation in which the system does not operate at the optimal MAV, \( E_{\text{WT-1}} \).

If the wind speed decrease from 10.28 m/s to 9.08 m/s in 10 minutes, corresponding to the values in Table 1, repeating the analysis and calculations steps previously passed through, for the wind speed variation in the form \( \nu(t) = 10.28 + ((9.08-10.28/600)) \cdot t \), we obtain the following results: \( E_{\text{WT-2}}(600) = 1.2518 \times 10^6 \) J, \( E_{\text{WT-OPTIM-1}} = 1.2481 \times 10^6 \) J. Based on the obtained results, we register an increase of the efficiency with 0.3%.

### 3.3 Optimal power calculation algorithm at the PMSG

The optimal area from the energy point of view, is defined through the optimal MAV, based on the measured wind speed \( \nu \) at the time moment \( t_k \). The value of the optimum power, \( P_{\text{PMSG-OPTIM}} \), is reached when the mechanical angular velocity, MAV, achieve the optimum, \( \omega_{\text{OPTIM}} \), in the time frame \( \Delta t = t_k - t_{k-1} \).

In the time frame \( \Delta t \), based on the measured MAV value, we compute the kinetic energy, \( \Delta W_{\text{kinetic}} = J(\omega_{\text{OPTIM}}^2 - \omega_0^2)/2 \).

In case of \( \omega_k \neq \omega_{\text{OPTIM}} \), the load of the permanent magnets synchronous generator must be changed with: \( \Delta P = \Delta W_{\text{kinetic}}/\Delta t \). The optimum value at the generator is \( P_{\text{PMSG-OPTIM}} = P_{\text{PMSG-INITIAL}} - \Delta P_{\text{PMSG}} \).
The steps of the described efficiency increase algorithm of the wind power systems, can be split in several steps:

Step 1: measure the generator power, \( P_{\text{PMSG-INITIAL}} \), the wind speed, \( v \) and compute the optimum mechanical angular velocity, \( \omega_{\text{OPTIM}} \);

Step 2: measure the mechanical angular velocity \( \omega_k \), and compute the kinetic energy, \( \Delta W_{\text{kinetic}} \).

Step 3: determining the optimum power at the generator, \( P_{\text{PMSG-OPTIM}} = P_{\text{PMSG-INITIAL}} - \Delta P_{\text{PMSG}} \).

Base on the above results, it is possible to compute an automation system that is able to assure the system operation in the optimal area from the energetic point of view, automation which is based on measured values of the main factors of influence, wind speed and mechanic angular speed.

Going through the analysis of several cases, it was possible to establish the basic sizes that lead to an optimal functioning of the wind power system, from the energy point of view.

Based on the measured wind speed values, we compute the optimum mecanical angular speed, \( \omega_{\text{OPTIM}} \), and measuring the MAV at the permanent magnets synchronous generator, the difference in power is determined, \( \Delta P_{\text{PMSG}} \), which is achieved through the control angle of the thyristors of the converter between the generator and the grid, Figure 2.

![Figure 2. Schematic representation of the proposed calculation steps to compute the optimum power at the wind turbines PMSG](image)

In this way, the estimation of the optimum permanent magnets synchronous generator power is strictly related to the evolution of the wind speed over time, relying on measured parameters and knowing the optimal mechanical angular velocity, \( \omega_{\text{OPTIM}} \).

4. Conclusions

In this paper we analyzed the way the wind power systems operate at maximum power if rapid changes of the wind speed over time exist. Using experimental data, we determined the mathematical models of the turbine, MM-WT and generator, MM-PMSG as well as the dependence of the optimum angular speed, \( \omega_{\text{OPTIM}} \), related to the current wind speed. By measuring the MAV and the power delivered by the synchronous generator with permanent magnets, we compute the value of the wind turbines power. The existing, measured values, have been compared with the optimal, computed, values from the energy point of view reported to the values of the captured wind energy.

To obtain maximum power, in a wind power system it is necessary that, permanently, the value of the mechanical angular velocity MAV must be correlated with the value of the wind speed. This correlation is done at chosen time intervals according to the values of the moment of inertia, \( J \) and the rapidity wind speed change in time.
At the end of the paper, the authors proposed an algorithm with the help of which it is possible
to determine the optimal power at PMSG, starting from the optimal value of the mechanical angular
velocity, \( \omega_{opt} \), which will be able to increase the efficiency of wind power plants [23].

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