

Optimal and stable energetic operation of wind power systems at variable wind speed

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Abstract. In the present paper we analyse the stable and optimal operation of wind power systems, WPS, composed of wind turbines, TV, coupled with synchronous generators with permanent magnets (SGPM), high power SGPM in the Dobrogea area, 4MW turbines manufactured at General Electric. Based on the experimental data, the wind turbine models MM-WT and the MM-SGPM permanent magnet synchronous generator are determined. Using these mathematical models, simulations are made of rapid variations in wind speed over time and the conditions for stable and energy-efficient EEA operation are highlighted. It mainly analyses the evolutions in time of power and speed from the generator, in direct connection with the change in wind speed over time. At the end of the paper is given a power calculation algorithm at SGPM, based on wind velocity measurements and VUM, ω , so that the operation is stable and energy optimal.

1. Introduction

Most articles in the specialized literature treats the operation of the wind power plants at constant wind velocities. In [1-3] it is proven that rapid wind speed variations in time, due to high values of the inertial moment, the wind turbine (WT) is not able to track this rapid change of wind speed over time. [1] shows a possible solution of how to maximize the power outcome of a WT. It is demonstrated, while [4], [5] highlights that it is always necessary to correlate the mechanical angular velocity (MAV) with the value of the wind speed.

The captured energy of a wind power system is maxim when each WT of the system operates in his maximum power point (MPP) [1], [4]. The optimal mechanical angular velocity (MAV) is computed, ω_{OPTIM} , based on the measured wind speed, for which the value of the wind turbine power results to be maxim, P_{WT-max} [1]. This means that permanently the MAV value has to be corelated with the wind speed value, at time intervals depending on the inertial moment, J , and the rapidity of the wind speed changes over time [7].

The main target of the wind turbine control strategy is to obtain the maximum energy yield, in given at significative variable wind speed. The question is to compute the systems load at wind turbine and electric generator, [1-7] to the obtain maxim energy outcome.



The main measurable parameters of the process are wind speed, v , produced electric power P_{SGPM} , and the mechanical angular velocity (MAV) measured at the generators shaft, ω . Based on these parameters, the load control at the generator can be assured.

The optimal at which the generator should operate, is give by the relation between the measured wind speed and, for this, the corresponding MAV, that can be reached and controlled by prescribing the electric power. In this way, an optimal and stable operation of the wind power system can be reached, at

$$\omega = k \cdot \omega_{OPTIM}. \quad (1)$$

The simulation results have been obtained using mathematical models of the wind turbine and the SGPM, determined in advance and based on them, on a given wind speed, result the optimum MAV, ω_{OPTIM} . [8-10]. The obtained results are used to ensure the operation of the wind power system in the maxim energetic area, at rapid wind speed changes.

The issue of capturing the maximum wind energy is complex, difficult to solve in practice when the wind speed varies significantly over time, the mechanical inertia of the wind power system being large, do not allow the generator RPM to be optimal from energy point of view. [11] The wind energy captured over the time interval Δt is found in the variation of the kinetic energies and the electricity generated by the SGPM, in Δt . The maximum power of the WT, $P_{WT}(\omega)$, is reached when the MAV is at his optimal value, ω_{OPTIM} , value which depends directly on the wind speed. The electricity produced by the wind power system depends on two basic sizes: the wind speed value in the time interval Δt and the MAV values, ω [5], [12]. Measuring the two sizes, wind speed, v , and current MAV, ω , we analyze the possibility of capturing the maximum wind energy: for operation in the maximum power point (MPP), the current MAV must be ω_{OPTIM} .

To implement an optimal control from energetic point of view power, in some papers [2], [13] control algorithms, use the wind velocity measurements [14] to prescribe the optimal RPM in the MPP area. Due to the large mechanical inertia, the changes which occur in ω are slow and, therefore, most of the time, $\omega \neq \omega_{OPTIM}$. At time variable wind velocity, the operation of the WT in the MPP area becomes a complex problem that is not always solvable in due time due to high mechanical inertia and rapid variations of the wind speed.

2. Mathematical description for SGPM and WT

2.1. SGMP mathematical model

In order to analyse the operation of the complete system (SGPM+WT), we use the orthogonal mathematical model for the synchronous generator with permanent magnet is used, described through the equations [3], [15],

$$\begin{cases} -U\sqrt{3}\sin\theta = R_1 I_d - \omega L_q I_q \\ U\sqrt{3}\sin\theta = R_1 I_q + \omega L_d I_d + \omega \Psi_{PM} \\ M_{SGPM} = p_1 (L_d - L_q) I_d I_q + I_q \Psi_{PM} \\ P_G = R(I_d^2 + I_q^2) \end{cases} \quad (2)$$

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; θ - load angle; R - generator's phase resistance; Ψ_{PM} - flux permanent magnet; p_1 - number of pole pairs, M_{SGPM} - SGPM electromagnetic torque.

As seen from (2), the electric power provided by the generator, $P_G(R, \omega)$, and the generators shaft moment, $M_{PMSG}(R, \omega)$, depend on the load resistance (R) and MAV (ω). Considering the values for the generator active power, RPM and wind speed synthesized in Table 1, result the parameter values: $R = 0.015[\Omega]$, $L_d = 0.0007[H]$, $L_q = 0.0008[H]$, $\Psi_{PM} = 130[Wb]$.

The generator operates at variable speeds, depending on the wind speed and the equivalent load resistance value. Substituting the above values in the SGPM equation system (2), we get the electric power, the mechanic power and the torque.

Table 1. Active power, RPM, wind speed

P (kW)	RPM (rot/m)	Wind speed (m/s)
736.56	1430.19	6.39
511.24	1268.38	5.58
497.53	1258.36	5.46
471.48	1234.86	5.25
410.86	1183.14	5.23
481	1244.3	5.56
500.7	1260.94	5.55
488.99	1251.33	5.46

2.2. WT mathematical model

The chosen model, [3], [16] allow us to estimate the reference of the angular velocity, ω_{ref} , such that the captured energy should be transformed as efficient as possible.

The power produced by a wind turbine, is described by:

$$P_{WT}(\omega, v) = \rho \pi R^2 C_p(\lambda) v^3, \quad (3)$$

where: v – wind speed, ω - mechanical angular velocity, $C_p(\lambda)$ - power conversion coefficient, R - blade radius, $\lambda = R\omega/v$, ρ - air density.

The producer give the experimental power $P_{WT}(\omega, v)$ or torque $\tau_{WT}(\omega, v)$ characteristics of wind turbine, the last being known as mechanical experimental characteristics:

$$\tau_{WT}(\omega) = \frac{P_{WT}(\omega, v)}{\omega}. \quad (4)$$

The maximum value for the produced power is achieved when the reference value of the MAV, ω_{ref} , reach the optimum value, ω_{OPTIM} , value resulted equaling the derivative with zero [9]:

$$\frac{P_{WT}(\omega, v)}{d\omega} = 0, \quad (5)$$

highlighting the direct link between the reference mechanical velocity, ω_{ref} , and wind speed, v .

At time variable wind speed, $v(t)$, the produced power varies between a minimum and a maximum, depending on the MAV value [17].

Based on the above remarks, the obtained mathematical model of the wind turbine (MM-WT) is:

$$P_{WT}(\omega, v) = a \left(\frac{v}{\omega} - b \right) e^{-c(v/\omega)} v^3. \quad (6)$$

The maximum value for the wind power turbine is obtained for the optimum mechanical angular velocity, canceling the derivative of the power (6), obtaining

$$\omega_{OPTIM} = k_0 \cdot v. \quad (7)$$

where $k_0 = c/(1+bc)$ – represents a constructive parameter of the turbine.

Knowing the dependence of the optimum MAV, ω_{OPTIM} , on the wind speed, v , is essential to capture the maximum wind energy. At ω_{OPTIM} the wind turbine operates in the maxim power point (MPP). Based on the measured wind speed, v , the optimum angular mechanical velocity, ω_{OPTIM} , is determined. To get maximum power from wind power systems, it is necessary that, the MAV should

be, all times, correlated with the wind speed, at time intervals established according to the inertial moment, J , and the rapidity of the wind speed change.

Analyzing the wind power system operating at a considered wind speed of $v = 5.45$ (m/s), in a 40 (min) time interval, with the data from Table 2,

Table 2. Active power, RPM, wind speed

P (kW)	RPM (rot/m)	Wind speed (m/s)
534.09	1286.88	5.75
508.75	1267.34	5.45
502.32	1261.59	5.46
495.07	1254.99	5.85
525.87	1277.99	6.46

we determined $\omega_{\text{OPTIM}} = 132.72$ [rad/s].

Based on equation (7) and considering the ratio between the optimum, ω_{OPTIM} , and maximum value of MAV, ω_{MAX} , [16], is equal with $2/3$, we obtain $cb = 2$, what leads us to $c = 73$ and, from here, to $b = 2.7 \cdot 10^{-2}$. Based on the measures wind turbine power at $v = 5.45$ (m/s), from equation (6) results the value for the a parameter: $a = 4563.7$.

Replacing the obtained values in the equation that describes the behavior of the wind turbine, (6), the result mathematical model for the wind turbine power (MM-WT) is

$$P_{WT}(\omega, v) = 4563.7 \left(\frac{v}{\omega} - 2.73 \cdot 10^{-3} \right) e^{-73(v/\omega)} v^3. \quad (8)$$

Canceling the wind turbine power derivation, $dP_{WT}/d\omega = 0$, the obtained solution is $\omega_{\text{OPTIM}} = 24.33 \cdot v$. The maximum value of the wind turbine power is obtained for ω_{OPTIM} and is $P_{WT-\text{max}} = 3.11 \cdot v^3$ [kW].

3. Optimum and stable operation from the energy point of wind power systems

At significant wind speed variation over time, the operation of the wind turbine in the Maximum Power Point (MPP) is at the stability limit and, based on the wind speed variation, the reach stable area, at $\omega > \omega_{\text{OPTIM}}$ or, the unstable area, $\omega < \omega_{\text{OPTIM}}$ [12].

The operation in MPP, without changing the injected power through the SGPM, the system lose stability if the wind speed decrease. To operate the wind turbine in the stable area, it is always necessary that the SGPM power must be correlated with the wind speed.

In the MPP area, the wind turbine power depends as $P_{WT-\text{max}} = 3.11 \cdot v^3$; this means that the SGPM power must be changed as follow:

- (1) if the wind speed decrease in a Δt time interval, with $\Delta v = v_{\text{initial}} - v_{\text{final}}$, the value of the SGPM power must be lowered in the same time interval, from the initial value, $P_{\text{SGPM-initial}} = 3.11 \cdot v_{\text{initial}}^3$ to the final value, $P_{\text{SGPM-final}} = 3.11 \cdot v_{\text{final}}^3 + J \cdot (\omega_{\text{initial}}^2 + \omega_{\text{final}}^2) / (2 \cdot \Delta t)$.
- (2) if the wind speed increase in the time interval Δt with Δv , the SGPM power must increase in the same time interval, from $P_{\text{SGPM-initial}} = 3.11 \cdot v_{\text{initial}}^3$ to $P_{\text{SGPM-final}} = 3.11 \cdot v_{\text{final}}^3 + J \cdot (\omega_{\text{initial}}^2 + \omega_{\text{final}}^2) / (2 \cdot \Delta t)$.

Analysing a dynamic process, we have to take in consideration the kinetic power, $J \cdot (\omega_{\text{initial}}^2 + \omega_{\text{final}}^2) / (2 \cdot \Delta t)$, to have a positive value when the wind speed decrease, because $\omega_{\text{initial}} > \omega_{\text{final}}$, and of negative value, when the wind speed increase, since $\omega_{\text{initial}} < \omega_{\text{final}}$.

To analyse those before exposed, we consider the situation in which the wind speed decreases from 5.75 m/s to 5.45 m/s, in a time frame, Δt , of 10 minutes.

At a wind speed of 5.75 m/s, v_{initial} , MAV's value is $\omega_{\text{OPTIM}} = 24.33 \cdot v = 139.91$ rad/s. In the initial point, A, Figure 1, at the wind speed of 5.75 m/s, to operate stable, MAV should be $\omega_A = 1.1 \cdot v = 153.9$ rad/s. For this MAV value, the wind turbine power (9) is 565.32 kW.

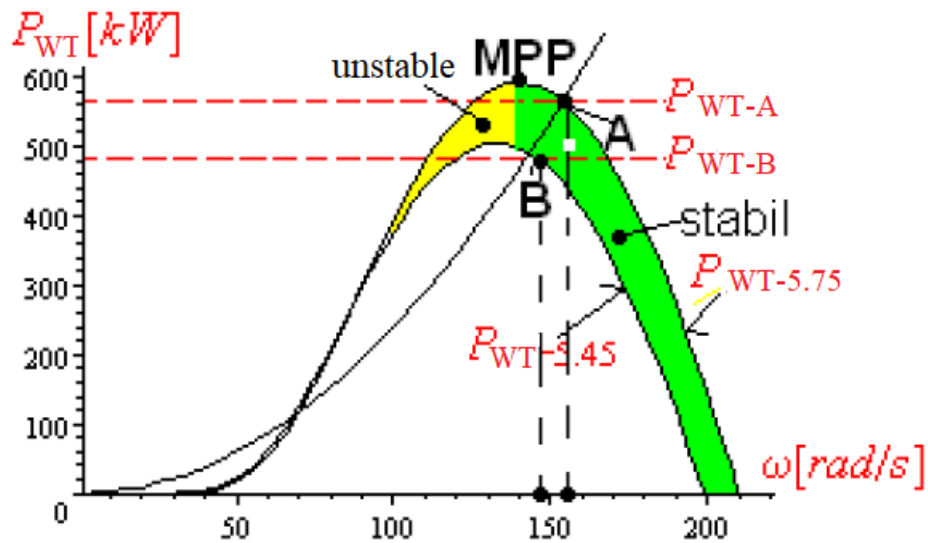


Figure 1. Displacement of the operating point on the wind turbine power characteristics

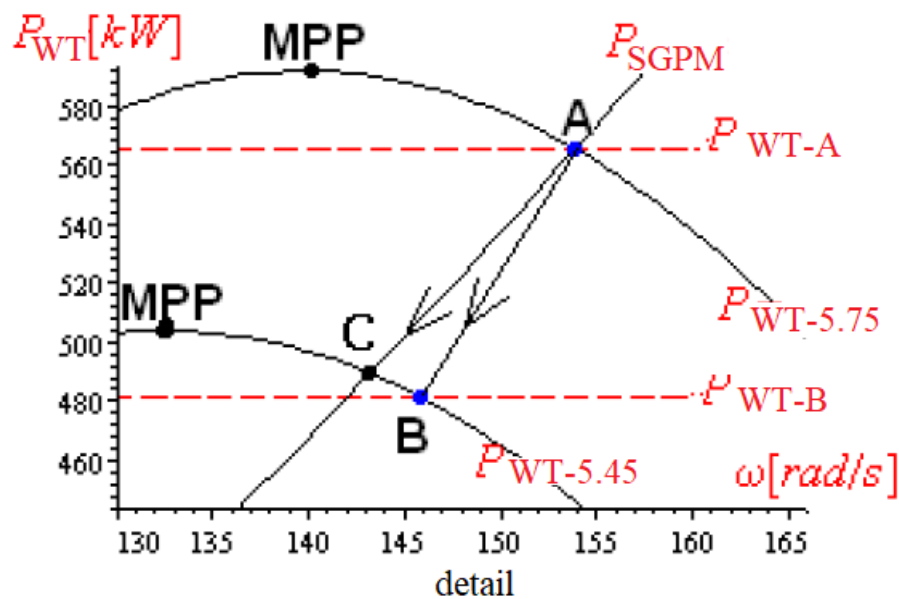


Figure 2. Displacement of the operating point on the wind turbine power characteristics (detail)

In point A, the operation being stable, the wind turbine power is equal with the SGPM power,

$$P_{SGPM-A} = \frac{16900R\omega^2}{R^2 + 0.04583\omega^2} = 565.23 \text{ kW}, \quad (9)$$

resulting the value for the SGPM load resistance, $R = 706.52 \Omega$.

At a slow variation of the wind speed from 5.75 m/s to 5.45 m/s, the displacement of the operation point tracks the path AC, Figure 1, on the SGPM power characteristics at $R = 706.52 \Omega$. Because the wind speed decrease in a 10-minute time interval, it is necessary to change the SGPM resistance load so after 10 minutes the operation point should arrive in point B, following the track AB, Figure 1.

Because in the performed analysis we consider the wind speed to decrease in 600s from 5.75 m/s to 5.45 m/s, the function that describes the wind speed evolution is

$$v(t) = 5.75 + [(5.45 - 5.75)/600]t. \quad (10)$$

In this condition, substituting the above values for the analyzed case study in the kinetic moment equation,

$$\begin{cases} 36734 \frac{d\omega}{dt} \omega = P_{WT}(\omega) - P_{SGPM}(\omega) \\ \omega(0) = 153.9 \end{cases}, \quad (11)$$

we obtain the MAV, ω , evolution, reflected in Figure 3.

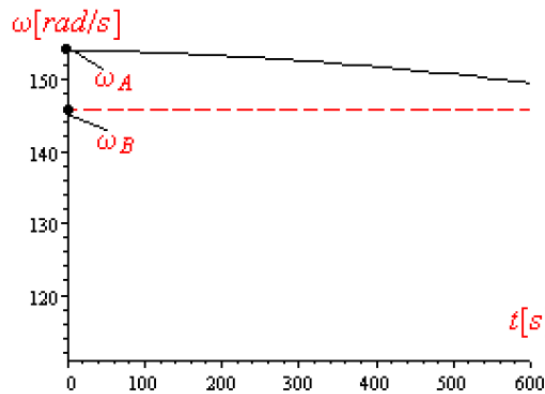


Figure 3. Time evolution of the mechanical angular velocity at $R = 706.52\Omega$

In the final point, B, Figure 1, at the wind speed of 5.45 m/s, to operate stable, the MAV should be $\omega_B = 1.1 \cdot \omega_{OPTIM} = 145.87$ rad/s. At this MAV value, the computed wind turbine power is $P_{WT-B} = 481.35$ kW.

For the operating point to reach B after 10 minutes, at an inertial moment, $J = 36734$ kgm², it is necessary to increase the SGPM load with ΔP , corresponding to the kinetic energy,

$$E_{Kinetic} = J \frac{\omega_A^2 - \omega_B^2}{2} = 1.9 \cdot 10^7 \quad (12)$$

and

$$\Delta P = \frac{E_{Kinetic}}{\Delta t} = \frac{1.9 \cdot 10^7}{600} = 33kW. \quad (13)$$

Therefore, the power of the SGPM must be: $P_{SGPM-imposed} = P_{SGPM-initial} + \Delta P = 598.417$ kW, corresponding to the load resistance at the SGPM, to which corresponds the SGPM load resistance $R = 667.27 \Omega$. Under those conditions, from the kinetic equation we get $\omega(600) = 147.52$ rad/s, compared with to the value in point B, $\omega_B = 145.87$ rad/s.

By imposing the load resistance of $R = 667.27 \Omega$ at the SGPM, the wind turbine does not reach in 10 minutes the operation point B, because $\omega(600) > \omega_B$. In order to operate after $\Delta t = 600$ s in point B, Figure 3, the power at SGPM is required to be $P_{SGPM-imposed} = 598.417$ kW.

Based on the obtained results, we can propose at this point a control algorithm to ensure the optimum operation of the wind power system from energy point of view [18-20].

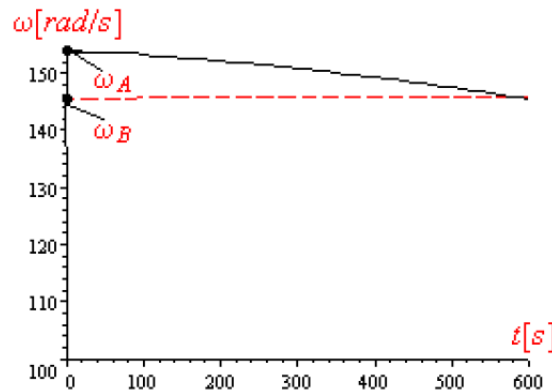


Figure 4. Evolution of the mechanical angular velocity at P_{SGPM} .
imposed = 598.417 kW

The proposed algorithm is based on the measured values, in Δt time intervals, for generator power P_{SGPM} , wind speed v and current mechanical angular velocity, ω .

In the initial point, at $t=0$, through the measured wind speed v , we are able to compute the optimal value for the MAV, $\omega_{OPTIM}(0) = k \cdot v(0)$. Based in this value, the next step has to assure a stable operation for the system, in the optimum area. For this, the MAV should be $\omega(0) = 1.1 \omega_{OPTIM}(0)$. Changing the generators load, the wind turbine is brought to $\omega(0)$.

In the final point, after an Δt time interval, based on the measured wind speed, we compute the optimal value for the mechanical angular velocity, $\omega_{OPTIM}(\Delta t) = k \cdot v(\Delta t)$, resulting $\omega_F(\Delta t) = 1.1 \omega_{OPTIM}(\Delta t)$.

We compare $\omega_F(\Delta t)$ with the measured value, $\omega(\Delta t)$, and compute the ΔP power, corresponding to the kinetic energy, and impose, finally, the SGPM power: $P_{SGPM-impose} = P_{SGPM-initial} + \Delta P$.

The above described steps of the control algorithm are synthesized in a flow chart, Figure 5.

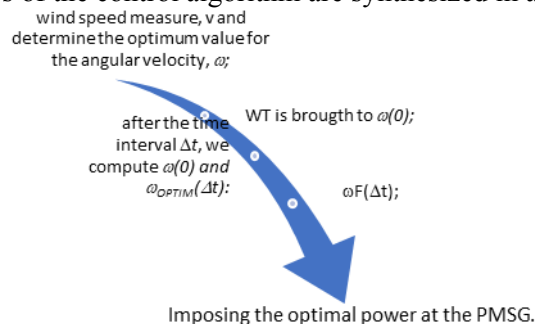


Figure 5. Proposed algorithm represented as flow chart

4. Conclusion

The present paper analyzed the stable and optimal operation of wind power systems.

Based on experimental data's, we compute the mathematic models for the Synchronous Generator with Permanent Magnet, MM-SGPM, and wind turbine, MM-WT that have been used farther in the simulation process, at rapid change of the wind speed, highlighting the circumstances that allow an optimum and stable operation of the wind power system. Based on the wind speed measurement, we determined optimal mechanical angular velocity at which the power of the wind turbine is maximum, showing that it is constantly necessary to correlate the MAV with the wind speed, at time intervals chosen according to the values of the inertia moment, J , and the frequency of the wind speed change.

Finally, the authors propose a power calculation algorithm for the SGPM, based on measured parameters, wind speed, v , and, M_{av} , ω , so that the obtained energy is maximum.

Increasing the efficiency of the wind power systems, it aims to reduce the dependence of this clean energy technology towards financial support schemes. [21-26]

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