Comparative analysis of two wind turbines with counter-rotating vs. fixed-stator electric generator

R Saulescu¹, M Neagoe² and N Cretescu²

¹Design of Mechanical Elements and Systems R&D Centre, Transilvania University of Brasov, Brasov, Romania
²Renewable Energy Systems and Recycling R&D Centre, Transilvania University of Brasov, Brasov, Romania

E-mail: mneagoe@unitbv.ro

Abstract. The paper presents a comparative study of two wind turbines with counter-rotating versus classical electric generator (with fixed stator). The wind turbines include a speed increaser that can operate with one or two counter-rotating outputs. The analytical modelling of the operating point of the wind turbines is firstly developed, based on the transmitting functions of the speed increaser and the mechanical characteristics of the wind rotor and the electric generator. The operating point is simulated, using the grapho-analytical method by reducing the mechanical characteristic of the wind rotor at the shaft of the electric generator rotor. This study highlights the advantage of higher efficiency for systems with parallel flow of the mechanical power as used in the wind turbines with counter-rotating electric generator.

1. Introduction
In the last years, new concepts of the wind turbines have been developed and presented in the literature. The studies on their performances focused on CFD analyzes for turbines with a single wind rotor that has 2 or more blades [1], on modelling and simulations of counter-rotating systems with two coaxial wind rotors that rotate in opposite directions [2], on systems with spatially arranged small wind turbines [3].

One method of increasing the energy performances of wind turbines is to ensure the optimum operating conditions of the electric generators at angular speeds near their nominal values, such as the implementation of differential speed increasers in single-rotor wind turbines and the use of a servomotor [4] or a variable speed transmission [5, 6].

Another method exploits the use of one degree of freedom (DOF) planetary transmissions with two inputs and two outputs [7] in turbines with two counter-rotating wind rotors and counter-rotating electric generator. They can significantly contribute to more power production by increasing the electric generator speed, as well as increasing the output torque by weighed summing-up the input torques generated by the counter-rotating wind rotors. Such a wind turbine with two counter-rotating wind rotors was tested experimentally [8]; the obtained results showed an increase of the extracted power by approximately 60% when a secondary wind rotor is used. A similar approach, but for a counter-rotating electric generator for implementation in urban wind turbines [9], highlighted its advantages of a lower starting torque and reduced noise.

Comparing the performances of technical systems allows their geometrical, kinematic or dynamic optimization, as well as of the kinematic or dynamic behaviour. Different comparative studies of wind
or hydro systems have been presented in literature, as on dynamics of various classical systems [10, 11], on behaviour of systems equipped with 1 DOF versus 2 DOF speed increasers [12, 13], or on systems containing fixed or mobile stator electric generators [14].

2. Problem formulation
The comparative study addressed in the paper considers two wind systems of single rotor - speed increaser - electric generator with rotating stator (Fig. 1a) versus fixed stator (Fig. 1b) types. The speed increaser is a 1 DOF planetary transmission composed by a mobile sun gear 1 and a fixed sun ring gear 4, two serial mounted satellites 2 and 4, and a carrier $H$ connected to the wind rotor $R$ and, for the dual-output system ($\omega_{SG} \neq 0$), to the generator stator $GS$.

![Figure 1. Structural scheme of the wind system with single rotor, planetary speed increaser, and counter-rotating (a) versus fixed-stator (b) electric generator.](image)

For the comparative analysis of the mechanical energy flow through the considered wind turbines, Fig.1, the operating point is modeled considering the mechanical characteristics of the wind rotor, the transmitting functions of the speed increaser and the mechanical characteristic of the electric generator. Moreover, the graph-analytical modeling of the operating point is done by reducing the wind rotor $R$ mechanical characteristic at the rotor $GR$ shaft of the electric generator. The operating point is expressed by the values of the input and output kinematic and static parameters, i.e. $\omega_R$, $\omega_{GR}$, $\omega_{GS}$ and $T_R$, $T_{GR}$, $T_{GS}$.

The single output wind turbine (Fig. 1b) can be considered a particular case of the wind turbine with counter-rotating generator (Fig. 1a), by breaking the connection with the speed increaser of the stator $GS$ and blocking it. The mechanical power flow into the speed increaser is depicted in Fig. 2, for both cases of 1 output ($\omega_{GS} = 0$) and 2 outputs ($\omega_{GS} \neq 0$).

![Figure 2. Generalized block scheme of the planetary speed increaser with one input and one/two outputs.](image)
The following assumptions are considered in the operating point modelling of the two considered wind turbines:

- a common mecanical planetary transmission (Fig. 1) is used, for which the constant values of the interior kinematic ratio $i_0$ and of the interior efficiency $\eta_0$ are known;
- identical wind rotors are used for both wind systems, i.e. the same mechanical characteristic is considered in the modelling;
- the fixed-stator and mobile-stator electric generators have the same mechanical characteristics.

The mathematical model derived for the wind turbine with counter-rotating generator allows to describe the system with a classical generator too, by changing the stator $GS$ state from mobile to fixed. For the systems shown in Fig. 1 and Fig. 22, the kinematic and static correlations are further presented and their energy performances are highlighted based on a numerical example.

3. The operating point modelling for the wind turbine with counter-rotating electric generator

The comparative study addressed in the paper considers two wind systems of single rotor - speed increaser - electric generator with rotating stator (Fig. 1a) versus fixed stator (Fig. 1b) types. The speed increaser is a 1 DOF planetary transmission composed by a mobile sun gear 1 and a fixed sun ring gear 4, two serial mounted satellites 2 and 4, and a carrier $H$ connected to the wind rotor $R$ and, for the dual-output system ($\omega_{GS} \neq 0$), to the generator stator $GS$.

According to the structural scheme shown in Fig. 1a, of the block scheme in Fig. 2 and of the working assumptions specified above, the mathematical correlations corresponding to a wind turbine with a single rotor – speed increaser – counter-rotating generator are further presented:

- Mechanical characteristic of the wind rotor:
  \[ T_R = -a_R\omega_R + b_R \] (1)

- Transmitting functions of the speed increaser:
  \[ \begin{align*}
  \omega_i &= \omega_H \left( 1 - i_0 \right) \\
  T_i &= -T_H^e \frac{\eta_0}{\eta_0 - i_0} = -T_H^{GR} = T_H^{GR} \frac{\eta_0}{i_0}
  \end{align*} \] (2)

- Mechanical characteristic of the counter-rotating electric generator, kinematic and static correlations between its stator and rotor:
  \[ \begin{align*}
  -T_{eg} &= a_G\omega_{eg} + b_G \\
  \omega_{eg} &= \omega_{GR} - \omega_{GR} \\
  T_{eg} &= T_{GR} = -T_{GS}
  \end{align*} \] (3)

where $eg$ designates the equivalent electric generator with fixed stator associated to the counter-rotating generator.

- Correlations wind rotor – speed increaser
  \[ \begin{align*}
  \omega_R &= \omega_H^e \\
  T_R - T_H^e &= 0
  \end{align*} \] (4)

- Correlations speed increaser – electric generator:
\[ \begin{align*}
\omega_i &= \omega_{GR} \\
-T_i + T_{GR} &= 0 \\
\omega_H &= \omega_{GS} \\
-T_H + T_{GS} &= 0
\end{align*} \] (5)

- Internal link correlations

\[ \begin{align*}
\omega_{H'} &= \omega_H \\
T_{H'} - T_{H} - T'_{H'} &= 0
\end{align*} \] (6)

Based on the correlations (1) – (6), the relations of the operating point (F) reduced to the generator rotor shaft are determined:

\[ \begin{align*}
\omega_F &= \left( b_G - \frac{b_R \eta_0}{i_0} \right) \left( a_G + \frac{a_R \eta_0}{i_0^2} \right)^{-1} \\
T_F &= -a_G \omega_F + b_G \\
P_F &= \omega_F T_F
\end{align*} \] (7)

4. The operating point modelling for the wind turbine with classic electric generator

By applying the same algorithm, the specific mathematical correlations for the particular case of using an electric generator with fixed stator (\(\omega_{GS} = 0\)) are:

- Transmitting functions of the speed increaser:

\[ \begin{align*}
\omega_i &= \omega_H (1 - i_0) \\
T_i &= -T_H - \frac{\eta_0}{\eta_0 - i_0}
\end{align*} \] (8)

- Mechanical characteristic of the electric generator with fixed stator and static correlation between its stator and rotor:

\[ \begin{align*}
-T_G &= a_G \omega_G + b_G \\
\omega_G &= \omega_{GR} \\
T_G &= T_{GR} = -T_{GS}
\end{align*} \] (9)

where \(G\) designates the electric generator with fixed stator.

- Correlations wind rotor – speed increaser:

\[ \begin{align*}
\omega_R &= \omega_H \\
T_R - T_H &= 0
\end{align*} \] (10)

- Correlations speed increaser – electric generator:

\[ \begin{align*}
\omega_i &= \omega_{GR} \\
-T_i + T_{GR} &= 0
\end{align*} \] (11)

Based on the expressions of the mechanical characteristics of the wind rotor, Eq. (1), and of the electric generator, as well as the kinematic and static correlations of the links between the wind rotor \(R\),
the generator rotor \( GR \) and the speed amplifier, the following relations related to the operating point (F) reduced to the generator rotor shaft have been established:

\[
\begin{align*}
\omega_F &= \left( b_G + \frac{b_G \eta_0}{\eta_0 - i_0} \right) \left( a_G + \frac{a_G \eta_0}{(1-i_0)(\eta_0 - i_0)} \right)^{-1} \\
T_F &= -a_G \omega_F + b_G \\
P_F &= \omega_F T_F
\end{align*}
\]

(12)

5. Numerical results and discussions

The relations of the kinematic and static parameters for the two analyzed cases are systematized, for comparison, in Tab. 1.

| Table 1. | The analytical expressions of the kinematic and static parameters. |
|-----------|---------------------------------------------------------------|
| Parameter | Relation | Relation |
| Speed increaser | | |
| \( i_a \) | \(-i_0\) | \(1-i_0\) |
| \( \eta_a \) | \(\eta_0\) | \(\eta_0(1-i_0)\) | \(\eta_0-i_0\) |
| Electric generator | | |
| \( \omega_{ge}; \omega_G \) | \(-\omega_g i_0\) | \(\omega_g(1-i_0)\) |
| \( T_{ge}; T_G \) | \(T_R \frac{\eta_0}{i_0}\) | \(T_R \frac{\eta_0}{\eta_0-i_0}\) |
| \( P_{ge}; P_G \) | \(-\eta_0 T_R \omega_R\) | \(-\frac{\eta_0(1-i_0)}{\eta_0-i_0} T_R \omega_R\) |

Based on relations (7) and (12), the parameters of the steady-state operating point for the two analysed wind turbines, characterised by a interior kinematic ration \( i_0 = 10 \) and interior efficiency \( \eta_0 = 0.857 \), are systematized in Tab. 2.

| Table 2. | Values of the steady-state operating point parameters |
|-----------|---------------------------------------------------------------|
| Input data: \( i_0 = 10 \), \( \eta_0 = 0.857 \), \( a_R = 35.2 \text{kNms} \), \( b_R = -605 \text{kNm} \), \( a_G = 0.4 \text{kNms} \), \( b_G = 35 \text{kNm} \) |
| \( \omega_R \) | \( T_R \) | \( P_R \) | \( \omega_{eg}; \omega_G \) | \( T_{eg}; T_G \) | \( P_{eg}; P_G \) | \( \eta \) |
| [rad/s] | [kNm] | [kW] | [rad/s] | [kNm] | [kW] | [%] |
| Fig. 1a | -12.4 | -169.3 | 2099.3 | 124.0 | -14.5 | -1798.0 | 85.7 |
| Fig. 1b | -13.3 | -136.4 | 1814.1 | 119.6 | -12.8 | -1530.9 | 84.4 |

These results are depicted in Fig. 4...6, where the mechanical characteristic of the wind rotor (Fig. 3) is reduced to the rotor shaft of the equivalent electric generator (in the first case, designated by \( T1(eg) = f1(\omega_{eg}) \)), and of the existing classical generator rotor (in the second case, \( T1(G) = f2(\omega_G) \)), respectively.
In order to facilitate direct comparison of the obtained results, the operating points of the two wind turbines are superposed in Fig. 6, according to the results depicted in Fig. 4 and Fig. 5.
By interpreting the values from Tab. 2 and Fig. 6, for the same specific parameters of the speed amplifier ($i_0 = 10$ and $\eta_0 = 0.857$), the following behavior in the steady-state is obtained:

- the wind system with one input and one output operates at a lower electric generator speed, comparing to the wind system with two outputs;
- the torques on the wind rotor shaft and on the generator shaft are smaller for the system with one input and one output, compared to the one with two outputs;
- the considered planetary transmission changes the direction of rotation, increases 9 times the input speed (in the case of the system with one output), respectively 10 times (for the dual-output system), while reducing the torque by 10.66 times (single-input system) and 11.67 times (dual-output system), respectively;
- the dual-output transmission has a better efficiency (85.7%) comparing to the single-output one (84.4%), i.e. higher by approx. 1.3%.

6. Conclusions
This paper presents a comparative study of the energy performance of two equivalent wind turbines, which integrates a single wind rotor, a 1 DOF speed increaser and an electric generator. For comparing the two wind systems, the same speed increaser is considered, which has two outputs connected to a counter-rotating generator (with mobile stator); by particularization, an output of the speed increaser can be disconnected from the generator stator and thus the wind turbine with classic electric generator (with fixed stator) can be obtained.

The numerical simulations of the steady-state mechanical response were developed in the assumption of the same input parameters (mechanical characteristics of the wind rotor, of the electric generator and the same speed amplifier), which allowed to highlight the following main conclusions:

- The wind turbines with counter-rotating generator are able to generate a higher power comparing to the wind turbines with classic generator, under the same wind conditions;
- Compared to the speed increaser with one input and one output, the dual-output speed increaser ensures a more balanced load of the transmission shafts; it ensures a constant efficiency, superior to the one with a single output.

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