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To cite this article: R Saulescu *et al* 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **147** 012090

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Performance analysis of a novel planetary speed increaser used in single-rotor wind turbines with counter-rotating electric generator

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Abstract. The paper presents a study on the kinematic and static performances of a new type of 1DOF (Degree Of Freedom) planetary speed increaser to be implemented in wind turbines, a transmission with three operating cases: a) one input and one output, b) one input and two outputs, in which the speed of the secondary output is equal to the input speed, and c) with one input and two outputs, where the secondary output speed is higher than the input speed. The proposed speed increaser contains two sun gears and a double satellite, allowing operation with an output connected to the fixed stator of a classic generator (case I) or with two counter-rotating outputs that drive a counter-rotating generator (with a mobile stator). A new variant of planetary transmission capable of providing the speed increase of the generator stator and, thus, the increase of the relative speed between the generator rotor and stator is obtained by the parallel connection of the speed increaser with a planetary gear. The three conceptual variants of planetary transmission are analytically modelled and comparatively analysed based on a set of kinematic and static parameters. The proposed transmission has higher performances compared to the same transmission with one input and one output, the increase of the kinematic amplification ratio and efficiency being achieved simultaneously.

1. Introduction

The use of speed increasers for higher performances of wind turbines was imposed by the increase of their production capacities; however, in the last decade, new types of speed increasers were adapted to better meet the functional requirements of the wind turbines implemented both in high power systems and for the built environment. The first step in these approaches has been to adopt a common terminology regarding gear mechanisms with mobile axes [1], in which the problem of the types of planetary transmissions depending on the number of inputs and outputs was discussed. Based on these approaches, [7] presents a methodology using graphs for the kinematic analysis of complex gear mechanisms, which include planetary gears (PU); an example of spur gear mechanisms optimization by applying a mathematical model for selecting the optimal solution based on the optimal speed ratio or the optimal position of the shafts axes is presented in [9].

A kinematic and dynamic model based on the transmission ratios and efficiencies, which is derived from a generalized model of the Ravigneaux type gear mechanisms is described in [10]. Two analytical methods for determining the efficiencies of the planetary gears are presented in [5], methods that use the equations of speeds and torques, namely the relations between powers and the speed ratio. This concept is further developed in [6] by describing a methodology for calculating the power



through the complex planetary transmissions consisting of planetary gears and a variable speed transmission, presenting the equation of power circulating through a branch by a kinematic approach.

A method for establishing the efficiency of planetary gears based on the screw theory is described in [8], while [12] presents an approach on modelling the efficiencies of power transmissions used in hybrid vehicles based on graph theory. A combined analysis of efficiency and transmission ratio [13] allows identifying transmissions with high gear ratios and high efficiencies, a useful approach in the design of planetary gears.

Thus, according to the previous models, the planetary gears can be addressed in two ways: as a separate stand-alone entity or as a subsystem of a complex system. A description of the planetary gears used in wind turbines is presented in [17], which proposes a type of 2 Degrees Of Freedom (DOF) planetary speed increaser controlled by a servomotor in order to obtain a constant speed at the generator. Starting from the idea of using 2DOF planetary gears as speed increasers, [3] proposes a kinematic and dynamic analysis of a counter-rotating wind system consisting of a bevel gear and a 2DOF planetary gear with improved efficiency. This approach is continued in [14] through a case study of a 1 kW wind turbine modelled by a dynamics algorithm based on the property of 2DOF planetary gears of summing two external motions for the speed increase at the generator. A model of a planetary speed increaser that is similar to the above solutions is described in [15, 16], which present a kinematic analysis and the efficiency compared to classical solutions; the kinematic and static performances of the planetary speed increaser are compared for two operating cases: with an input and an output or two inputs and one output.

The design and development of a counter-rotating generator that is integrated in wind turbines for urban areas [2], with higher performances than of a classical generator, containing mobile rotor and stator, represents a new approach of the 2DOF planetary transmissions that function with an input and two outputs. The use of these transmissions brings some advantages, like: the possibility of implementation into wind turbines with size constraints, as well as an increased efficiency due to the parallel connection of planetary gears. The paper analyses the performances of a type of 1DOF planetary speed increaser with an input and an output or an input and two outputs, which can be used in wind turbines.

2. Problem formulation

The paper refers to the comparison of kinematic and static performances of planetary speed increasers to be used in single-rotor wind turbines.

The paper proposes a new type of 1DOF planetary speed increaser usable in single-rotor wind systems with a counter-rotating generator, able to increase the energetic performances versus those of classical systems with one output. The proposed speed increaser is a spur gear transmission composed of two sun gears and a satellite with two gears in serial connection, which can function with an output (figure 1a) or two outputs, and in which the speed of the secondary output (connected to the mobile stator of the counter-rotating generator [2]) is equal to the input speed (figure 1b). The counter-rotating motions lead to the generator speed increase due to the summing up of rotor GR speed and stator GS speed (figure 1b).

Based on this concept, the authors propose another variant of speed increaser obtained by parallel connection of two PU: the first PU (1-2-3-4-H) is described in figure 1b, while the second PU with a double satellite gear (3-4-5-6-H) in figure 2c. This variant of speed increaser increases the output motion 6 (secondary) versus the input motion H , according to the speeds diagram from figure 2d.

According to figure 1, the transmission of the mechanical power from the wind rotor R to the generator, through the 1DOF speed increaser can be performed in two operating cases: with one output (figure 1e), which corresponds to the case of the generator with fixed stator, and with two outputs (figure 1f) in case of the counter-rotating generators (with mobile stator), in which the stator can rotate with the same speed or higher than the input speed. Therefore, three variants of planetary speed increasers are proposed in the paper:

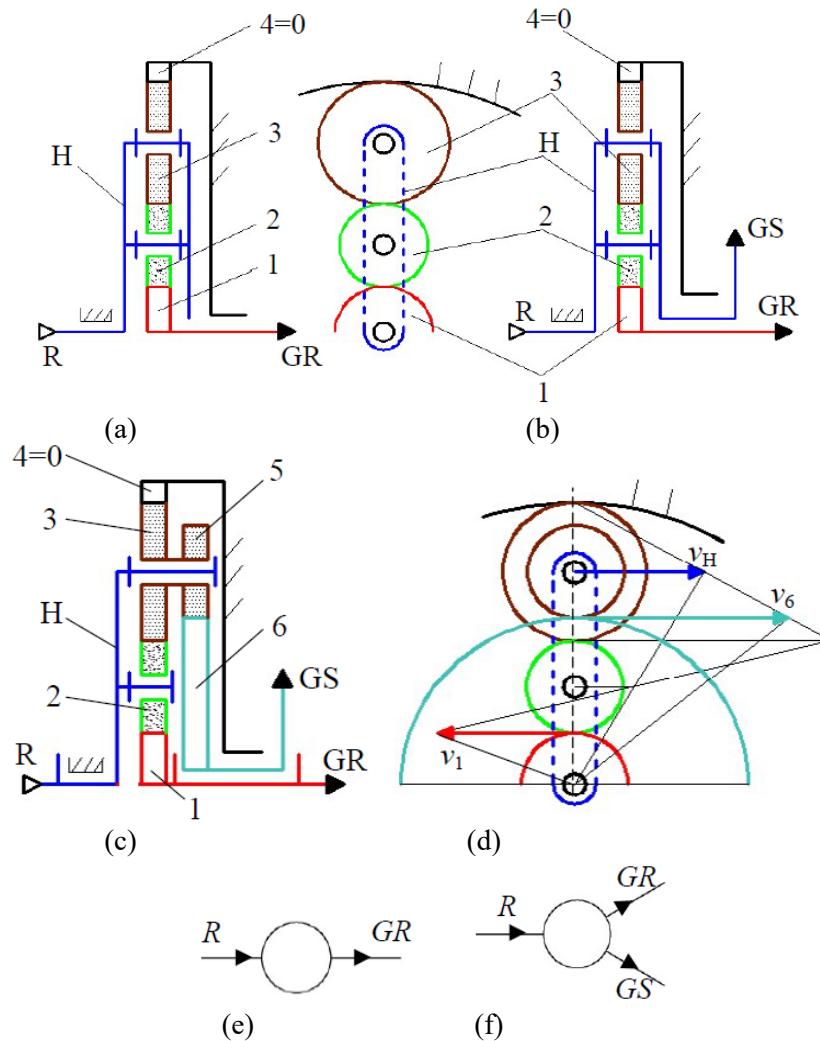


Figure 1. Kinematic schemes of a 1DOF planetary speed increaser with: (a) $L=2$; (b) $L=3$ and $\omega_{GS} = \omega_R$; (c) $L=3$ and $\omega_{GS} > \omega_R$; (d) speeds diagram for case (c); (e) block diagram associated to case (a); (f) block diagram associated to cases (b) and (c).

- Case I: speed increaser with one input and one output ($L=2$, $M=1$), and a generator with fixed stator, $\omega_{GS} = 0$ (figure 1a);
- Case II: speed increaser with one input and two outputs ($L=3$, $M=1$), and a counter-rotating generator with the speed of the stator equal to the rotor speed, $\omega_{GS} = \omega_R$ (figure 1b);
- Case II: speed increaser with one input and two outputs ($L=3$, $M=1$), the stator of the counter-rotating generator rotating with a speed higher than the input speed: $\omega_{GS} > \omega_R$ (figure 1c).

The kinematic and static analysis is further presented for the three variants of planetary speed increaser, their performances in case of using them in wind turbines being also highlighted.

3. Modelling the planetary speed increaser with one output (case I, figure 1a)

The 1DOF planetary transmission from figure 1 has two satellite gears in serial connection (2 and 3) and transmits the mechanical power generated by the wind rotor R to the rotor GR of the generator with fixed stator, multiplying the speed and changing its direction while reducing the torque.

The transmission functions and the properties of the planetary transmission were obtained in the kinematic and static analytical modelling by considering friction in the gear pairs.

3.1. Kinematic analysis

The transmission ratio of the planetary speed increaser, i_{H1}^4 is determined by relation (1) (figure 1a):

$$i_{H1}^4 = \frac{\omega_{H4}}{\omega_{14}} = \frac{\omega_{HH} - \omega_{4H}}{\omega_{1H} - \omega_{4H}} = \left(1 - \frac{\omega_{1H}}{\omega_{4H}}\right)^{-1} = \frac{1}{1 - i_{0I}} \quad (1)$$

where i_{0I} is the interior kinematic ratio of the planetary gear

$$i_{0I} = i_{14}^H = \frac{\omega_{1H}}{\omega_{4H}} = + \frac{z_4}{z_1} > 1. \quad (2)$$

The speed transmission function, relation (3), and the relation between the wind rotor speed (ω_R) and the speed of the generator rotor (ω_{GR}) can be written based on relation (1), where i_a is the amplification ratio:

$$\omega_{14} = \frac{\omega_{H4}}{i_{H1}^4} = \omega_{H4} \cdot (1 - i_{0I}) = \omega_{H4} \cdot i_a \quad (3)$$

$$\omega_{GR} = \omega_R \cdot i_a \quad (\omega_{GR} = \omega_{14}, \omega_R = \omega_{H4}) \quad (4)$$

where $i_a = i_{14}^H = 1 - i_{0I}$.

3.2. Static analysis

The static function of the speed increaser is obtained from the transmission energy equilibrium equation considering friction [4]:

$$\omega_{H4} T_H \eta_{H1}^4 + \omega_{14} T_1 = 0, \quad (5)$$

where the efficiency of the planetary speed increaser $\eta_a = \eta_{H1}^4$ depends on the transmission internal efficiency $\eta_0 = \eta_{14}^H = \eta_{12} \eta_{23} \eta_{34}$ [4]:

$$\eta_{H1}^4 = \frac{-\omega_{14} T_1}{\omega_{H4} T_H} = \frac{-T_1 / T_H}{\omega_{H4} / \omega_{14}} = \frac{\overline{i_{H1}^4}}{i_{H1}^4} = \frac{1 - i_{0I}}{1 - i_{0I}^x}, \quad (6)$$

where

$$x = \text{sgn}(\omega_{1H} T_1) = \text{sgn}\left(\frac{\omega_{1H} T_1}{-\omega_{14} T_1}\right) = \text{sgn}\left(\frac{i_{0I}}{1 - i_{0I}}\right) = -1. \quad (7)$$

The dependence of the input torque (T_H) on the output torque (T_1), or between the wind rotor (T_R) and generator rotor torques (T_{GR}), respectively is obtained from relation (6) as follows, relation (8):

$$T_1 = -i_{H1}^4 \eta_{H1}^4 T_H = -\frac{\eta_a}{i_a} T_H \quad \text{or} \quad T_{GR} = -\frac{\eta_a}{i_a} T_R. \quad (8)$$

4. Modelling the planetary speed increaser with two outputs and $\omega_{GS} = \omega_R$ (case II, figure1b)

The planetary transmission from figure 1a can function with two counter-rotating outputs, according to figure 1b, the main output being the generator rotor, as in the previous case; moreover, a secondary output is obtained by direct coupling of the input body H (the carrier) to the mobile stator of the electric generator. Thus, the generator speed is increased by increasing the relative speed of the rotor GR against the stator GS, the generator functioning in a more advantageous way, implicitly. In this

operating case, the kinematic and static analysis of the planetary speed increaser is based on the two power flows modelling: one from the wind rotor to the generator rotor (R-GR), and the second one from the wind rotor to the mobile stator of the generator (R-GS), by considering the properties of 1DOF mechanisms with 3 inputs and outputs regarding the distribution of speeds and summing of external torques, as well as the property of counter-rotating generator of having equal and opposite torques at its rotor and stator ($T_{GR} = -T_{GS}$).

4.1. Kinematic analysis

The speed of the counter-rotating generator, relation (10), defined as the relative speed of the rotor GR against the stator GS is obtained starting from the previous relation (1)-(4) established for the transmission with $M=1$ and $L=2$, which characterize the main power flow R-GR, and also considering relation (9):

$$\omega_{GS} = \omega_{H4} = \omega_R, \quad \omega_{GR} = \omega_{14}, \quad \omega_{GR-S} = \omega_{GR} - \omega_{GS}, \quad (9)$$

$$\omega_{GR-S} = \omega_{14} - \omega_{H4} = \omega_{H4}(1 - i_{0I}) - \omega_{H4} = -i_{0I}\omega_{H4} = (i_a - 1)\omega_R. \quad (10)$$

4.2. Static analysis

The energy equilibrium equation for the transmission with two outputs and considering friction can be expressed as follows:

$$T_R\omega_R\eta_a + T_{GR}\omega_{GR} + T_{GS}\omega_{GS} = 0 \Leftrightarrow T_R\eta_a + T_{GR}(i_a - 1) = 0. \quad (11)$$

As the planetary speed increaser is a 1DOF transmission with $L=3$, its efficiency can be given by relation (12) [11]:

$$\eta_a = (i_a - 1) \left(\frac{i_a}{\eta_{R-GR}} - \frac{1}{\eta_{R-GS}} \right)^{-1} = \eta_{0I} \quad (12)$$

where $\eta_{R-GR} = \eta_{H1}^4$ (relation (6)) and $\eta_{R-GS} = 1$ ($R \equiv H \equiv GS$).

The generator torque T_G , which conventionally is the torque on the generator rotor $T_G = T_{GR}$ is obtained from relation (11) and (12):

$$T_{GR} = -\frac{\eta_a}{i_a - 1} T_R = \frac{\eta_{0I}}{i_{0I}} T_R. \quad (13)$$

5. Modelling the planetary speed increaser with two outputs and $\omega_{GS} > \omega_R$ (case III, figure 1c)

The planetary speed increaser from figure 1c allows a higher speed at the secondary output (figure 1d, $v_6 > v_H$) by integrating the planetary gear 5-6 into the variant from figure 1b. This solution transmits the mechanical power generated by the wind rotor R to the electric generator through two power flows (similar to the previous case); the complex transmission consists of two planetary gears in parallel connection with a common input (the block diagram from figure 2), being characterized by a wind rotor assembled on the carrier (H), the generator rotor connected to the shaft 1, and the mobile stator to shaft 6.

The complex planetary speed increaser (figure 1c) has three sun gears (1, 6 and 4) and is composed of two 1DOF planetary gears (PU-I and PU-II) with a common input (H). According to the block diagram from figure 2, the two isolated planetary gears from the complex transmission are characterized by the following kinematic and static equations:

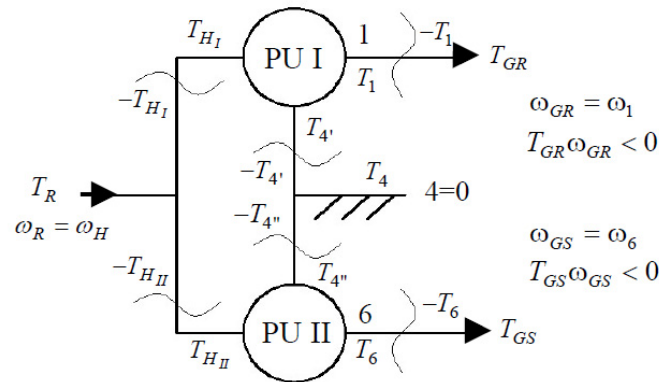


Figure 2. The block diagram of the planetary speed increaser obtained by parallel connection of two 1DOF planetary gears.

$$PU - I : \begin{cases} i_{14'}^{H_I} = i_{0I} = \frac{\omega_{1H_I}}{\omega_{4'H_I}} = \frac{z_4}{z_1} \\ \omega_1 - \omega_{4'}i_{0I} - \omega_{H_I}(1 - i_{0I}) = 0 \\ T_1 + T_{4'} + T_{H_I} = 0 \\ T_1 i_{0I} \eta_{0I}^x + T_{4'} = 0 \end{cases} \quad (14)$$

$$PU - II : \begin{cases} i_{64''}^{H_{II}} = i_{0II} = \frac{\omega_{6H_{II}}}{\omega_{4''H_{II}}} = -\frac{z_5}{z_6} \frac{z_4}{z_3} \\ \omega_6 - \omega_{4''}i_{0II} - \omega_{H_{II}}(1 - i_{0II}) = 0 \\ T_6 + T_{4''} + T_{H_{II}} = 0 \\ T_6 i_{0II} \eta_{0II}^w + T_{4''} = 0 \end{cases} \quad (15)$$

The planetary speed increaser is characterized by the following correlations for the internal links between the planetary gears, for the external links, relation (16)...(19), and between the rotor and stator of the electric generator, relation (20), which are obtained based on the power and coaxial torques equilibrium equations:

$$R = H_I = H_{II} \begin{cases} \omega_R = \omega_{H_I} = \omega_{H_{II}} = \omega_H \\ T_R - T_{H_I} - T_{H_{II}} = 0 \end{cases} \quad (16)$$

$$1 = GR \begin{cases} \omega_1 = \omega_{GR} \\ T_{GR} - T_1 = 0 \end{cases} \quad (17)$$

$$6 = GS \begin{cases} \omega_6 = \omega_{GS} \\ T_{GS} - T_6 = 0 \end{cases} \quad (18)$$

$$4 = 4' = 4'' \begin{cases} \omega_{4'} = \omega_{4''} = \omega_4 = 0 \\ T_4 - T_{4'} - T_{4''} = 0 \end{cases} \quad (19)$$

$$\begin{cases} \omega_R T_R \eta_a + \omega_{GR} T_{GR} + \omega_{GS} T_{GS} = 0 \\ \omega_{GR-S} = \omega_{GR} - \omega_{GS} \\ T_R + T_{GR} + T_{GS} + T_4 = 0 \\ T_{GR} = -T_{GS} = T_{GR-S} \end{cases} \quad (20)$$

These correlations allow establishing the kinematic and static transmission functions of the complex speed increaser.

5.1. Kinematic analysis

The amplification ratios for the two PU, relation (21) and (22), to be used in establishing the dependence between the speeds of the wind rotor and counter-rotating generator, relation (23), are obtained based on the kinematic equations for the two PU and on the internal and external correlations:

$$i_{1H_I}^{4'} = \frac{\omega_{14'}}{\omega_{H_I 4'}} = \frac{\omega_{1H_I} - \omega_{4'H_I}}{-\omega_{4'H_I}} = 1 - i_{0I} \quad (21)$$

$$i_{6H_{II}}^{4''} = \frac{\omega_{64''}}{\omega_{H_{II} 4''}} = \frac{\omega_{6H_{II}} - \omega_{4''H_{II}}}{-\omega_{4''H_{II}}} = 1 - i_{0II} \quad (22)$$

$$\omega_{GR-S} = \omega_{14'} - \omega_{64''} = (i_{0II} - i_{0I}) \omega_R \quad (23)$$

5.2. Static analysis

The efficiency of the planetary transmission is determined on the basis of the efficiencies of the two PU:

$$\eta_{H_I 1}^{4'} = \eta_{R-GR} = \frac{-\omega_{14'} T_1}{\omega_{H_I 4'} T_{H_I}} = \frac{-T_1 / T_{H_I}}{\omega_{H_I 4'} / \omega_{14'}} = \frac{\overline{i_{H_I 1}^{4'}}}{i_{H_I 1}^{4'}} = \frac{1 - i_{0I}}{1 - i_{0I}} = \frac{1 - i_{0I}}{1 - i_{0I} \eta_{0I}^x} \quad (24)$$

$$\eta_{H_{II} 6}^{4''} = \eta_{R-GS} = \frac{-\omega_{64''} T_6}{\omega_{H_{II} 4''} T_{H_{II}}} = \frac{-T_6 / T_{H_{II}}}{\omega_{H_{II} 4''} / \omega_{64''}} = \frac{\overline{i_{H_{II} 6}^{4''}}}{i_{H_{II} 6}^{4''}} = \frac{1 - i_{0II}}{1 - i_{0II}} = \frac{1 - i_{0II}}{1 - i_{0II} \eta_{0II}^w} \quad (25)$$

where

$$x = \text{sgn}(\omega_{1H_I} T_1) = \text{sgn}\left(\frac{\omega_{1H_I} T_1}{-\omega_{14'} T_1}\right) = \text{sgn}\left(\frac{-\omega_{1H_I}}{\omega_{1H_I} - \omega_{4'H_I}}\right) = \text{sgn}\left(\frac{-i_{0I}}{i_{0I} - 1}\right) = -1 \quad (26)$$

$$\eta_{0I} = \eta_{14'}^{H_I} = \eta_{12} \eta_{23} \eta_{34} \quad (27)$$

$$w = \text{sgn}(\omega_{6H_{II}} T_6) = \text{sgn}\left(\frac{\omega_{6H_{II}} T_6}{-\omega_{64''} T_6}\right) = \text{sgn}\left(\frac{-\omega_{6H_{II}}}{\omega_{6H_{II}} - \omega_{4''H_{II}}}\right) = \text{sgn}\left(\frac{-i_{0II}}{i_{0II} - 1}\right) = -1 \quad (28)$$

$$\eta_{0II} = \eta_{64''}^{H_{II}} = \eta_{65} \eta_{34} \quad (29)$$

The transmission efficiency, relation (31) and the correlation between the torques on the wind rotor and generator, relation (32) are obtained similar to case II and taking into account the power equilibrium equation, relation (30):

$$T_R \omega_R \eta_a + T_{GR} \omega_{GR} + T_{GS} \omega_{GS} = 0 \Leftrightarrow T_R \eta_a + T_{GR} (i_{0II} - i_{0I}) = 0 \quad (30)$$

$$\eta_a = \frac{i_{0II} - i_{0I}}{\frac{1-i_{0I}}{\eta_{R-GR}} - \frac{1-i_{0II}}{\eta_{R-GS}}} = \frac{i_{0II} - i_{0I}}{i_{0II} - i_{0I}} = \frac{(i_{0II} - i_{0I})\eta_{0I}\eta_{0II}}{i_{0II}\eta_{0I} - i_{0I}\eta_{0II}} \quad (31)$$

$$T_{GR-S} = T_{GR} = -\frac{\eta_a}{i_{0II} - i_{0I}} T_R = \frac{1}{i_{0II} - i_{0I}} T_R = \frac{\eta_{0I}\eta_{0II}}{i_{0II}\eta_{0I} - i_{0I}\eta_{0II}} T_R. \quad (32)$$

6. Comparative analysis. Discussions

The relations for the kinematic and static parameters for the three variants from figure 1 are systematized in table 1, followed by a numerical example of a wind turbine containing a speed increaser with an amplification ratio $i_a = 80$ and an efficiency of the spur gear of 0.95.

Table 1. The main kinematic and static parameters for the variants from figure 1

Numerical solution for $i_a = 80$ and $\eta_{12} = \eta_{23} = \eta_{34} = \eta_{65} = 0.95$

<i>Planetary increaser type</i>	<i>Figure 1a</i>	<i>Figure 1b</i>	<i>Figure 1c</i>
<i>Criterion</i>			
Internal kinematic ratio			
i_{0I}	$+\frac{z_4}{z_1} (=81)$	$+\frac{z_4}{z_1} (=80)$	$+\frac{z_4}{z_1} (=57)$
i_{0II}			$-\frac{z_5}{z_6} \frac{z_4}{z_3} (= -23)$
Internal efficiency			
η_{0I}	$\eta_{12}\eta_{23}\eta_{34} (=0.8573)$	$\eta_{12}\eta_{23}\eta_{34} (=0.8573)$	$\eta_{12}\eta_{23}\eta_{34} (=0.8573)$
η_{0II}			$\eta_{65}\eta_{34} (=0.9025)$
Kinematic ratio			
$i_a = \frac{\omega_{GR-S}}{\omega_R}$	$1 - i_{0I} (= -80)$	$-i_{0I} (= -80)$	$i_{0II} - i_{0I} (= -80)$
$i_{aR-GR} = \frac{\omega_{GR}}{\omega_R}$	$1 - i_{0I} (= -80)$	$1 - i_{0I} (= -79)$	$1 - i_{0I} (= -56)$
$i_{aR-GS} = \frac{\omega_{GS}}{\omega_R}$	0	1	$1 - i_{0II} (= 24)$
Static ratio			
$\bar{i}_a = \frac{T_{GR}}{T_R}$	$\frac{\eta_{0I}}{i_{0I} - \eta_{0I}} (=0.0106)$	$\frac{\eta_{0I}}{i_{0I}} (=0.0107)$	$\frac{\eta_{0I}\eta_{0II}}{i_{0I}\eta_{0II} - i_{0I}\eta_{0I}} (=0.0108)$
Efficiency			

$$\eta_a = -i_a \cdot \bar{i}_a \quad \frac{(i_{0I} - 1)\eta_{0I}}{i_{0I} - \eta_{0I}} (=0.8558) \quad \eta_0 (=0.8573) \quad \frac{(i_{0I} - i_{0II})\eta_{0I}\eta_{0II}}{i_{0I}\eta_{0II} - i_{0II}\eta_{0I}} (=0.8698)$$

According to table 1, the variants with a counter-rotating generator ($L=3$) have superior performances versus those of the variant with classical generator ($L=2$): the interior kinematic ratios are reduced and the efficiencies are higher at the same value of the amplification kinematic ratio.

To limit the inertial effects, the speed of the mobile stator is recommended to be lower than the speed of the generator rotor; in the case of the transmission from figure 1c and limiting the speed of the stator GS at the third part of the rotor GR speed ($i_{aR-GS} = 0.429i_{aR-GR}$), the diagram from figure 3 allows establishing the interior kinematic ratio i_{0II} as function of i_{0I} .

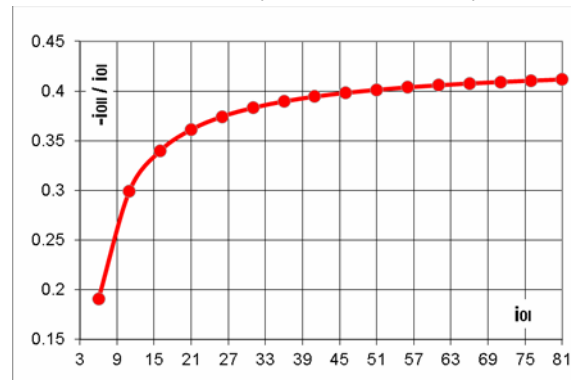
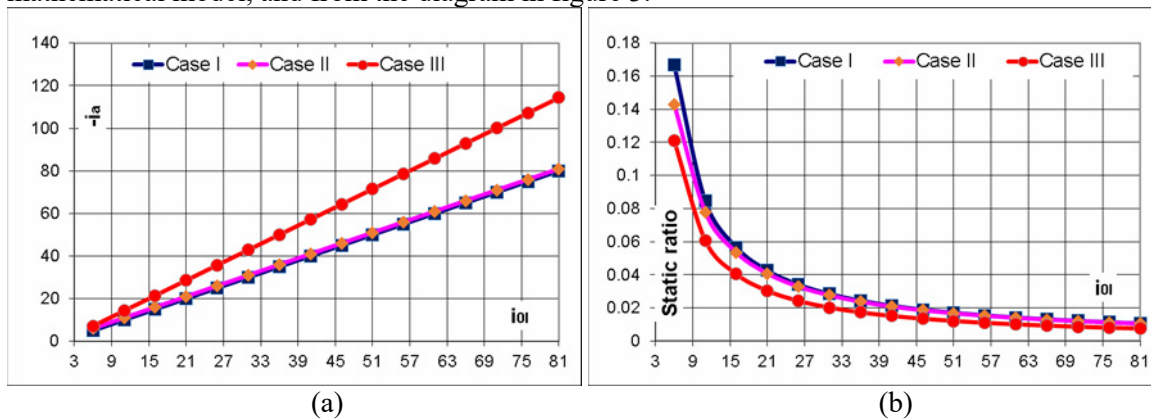


Figure 3. The variation of the ratio i_{0II}/i_{0I} as function of i_{0I} for the planetary speed increaser from figure 1c (case III) with $i_{aR-GS} = 0.429i_{aR-GR}$.

The kinematic amplification ratio i_a (figure 4a), the static ratio \bar{i}_a (figure 4b) and the efficiency (figure 4c) for the three operating cases are expressed as functions of i_{0I} , starting from the previous mathematical model, and from the diagram in figure 3.



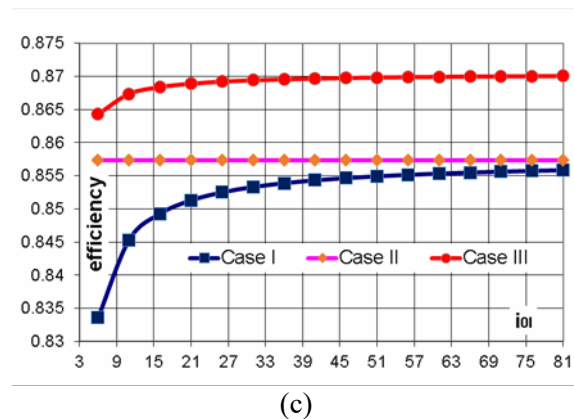


Figure 4. The variation of kinematic and static parameters of the planetary speed increaser for the three operating cases as function of the interior kinematic ratio of PU-I: (a) the amplification ratio i_a ; (b) the static ratio \bar{i}_a ; (c) the efficiency η_a .

Similarly, the variation of the kinematic amplification ratio for the two power branches are represented in figure 5 as function of i_{oi} .

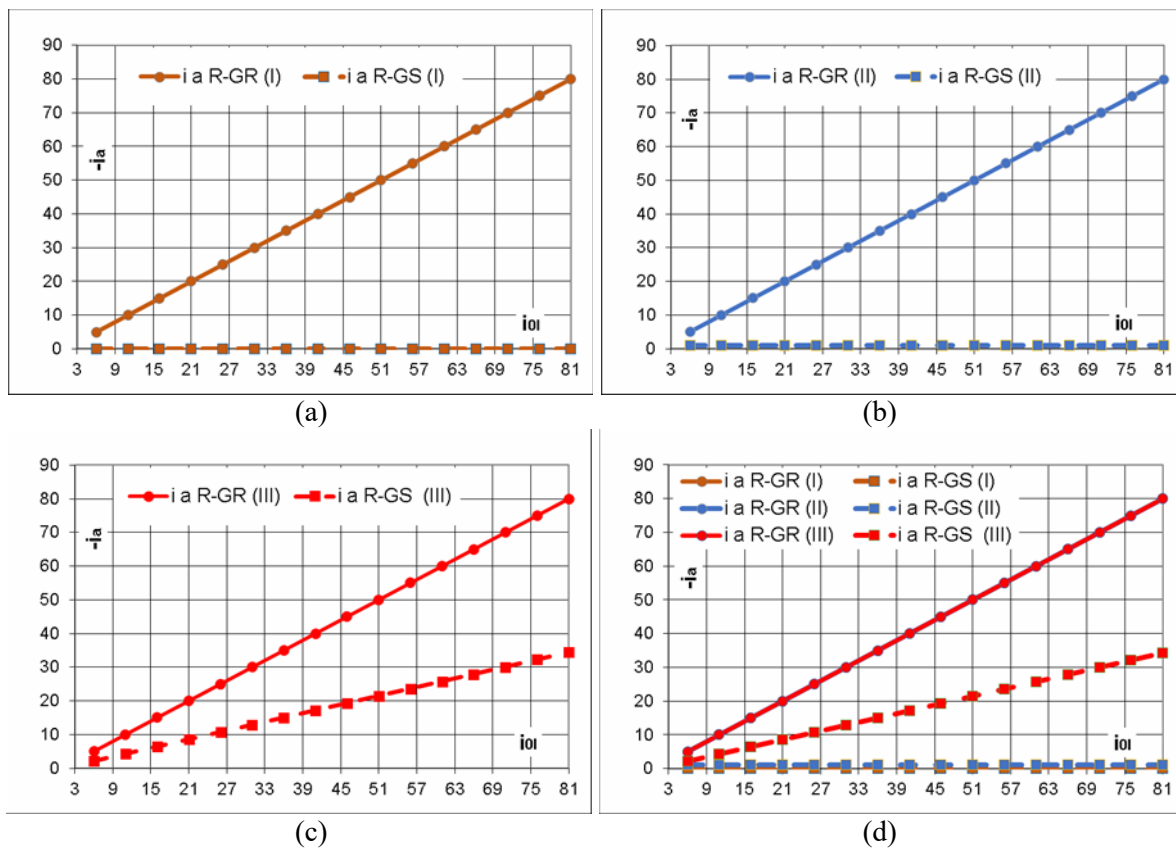


Figure 5. The kinematic transmission ratios from the wind rotor to the generator rotor (i_{aR-GR}), and to the generator stator (i_{aR-GS}) for the planetary transmissions: a) case I; b) case II; c) case III; d) the previous cases superposed.

The comparative analysis of the diagrams from figure 4 and 5 outlines that the most favorable solution is the transmission with two PU in parallel connection, due to the following advantages:

- the interior kinematic ratio of the second PU tends to be stabilized at a limited value with the increase of the PU-I interior kinematic ratio, e.g. $i_{0II}/i_{0I} \rightarrow 0.41$ for $i_{aR-GS} = 0.429i_{aR-GR}$, figure 3;
- the absolute increase of the amplification ratio i_a with i_{0I} is higher than for the cases I and II (figure 4a), while the static ratio \bar{i}_a has a more pronounced decrease compared to the other cases, decrease that tends to stabilize at higher values of the amplification ratio, figure 4b;
- at the same total amplification ratio i_a , the variant with two PU in parallel connection has smaller dimensions, the transmission ratios being lower compared to the other cases, table 1;
- the efficiency of the speed increaser from case III is higher than the efficiencies of cases I and II, and increases with the increase of the PU-I interior kinematic ratio, figure 4c; it is highlighted that the transmission from case II has a constant efficiency, equal to the internal efficiency of PU-I;
- the use of a generator with mobile stator increases the kinematic amplification ratio, being dependent on the relative speed between the generator rotor GR and stator GS: the stator speed is null in case I; in the second case, the stator speed is equal to the input speed, while in case III, the stator speed is higher depending on the transmission ratio of the second PU, $|i_{0II}| > 1$, table 1 and figure 5;
- for the same static ratio \bar{i}_a , the transmission with two PU in parallel connection and with one input and two outputs has a higher efficiency and smaller overall dimension compared to the other two cases; e.g. the results for $\bar{i}_a = 0.02$ are: case III: $i_{0I} = 33$, $i_a = -45$, $\eta_a = 0.8694$ compared to case I: $i_{0I} = 46$, $i_a = -45$, $\eta_a = 0.8546$.

The speed increasers containing planetary transmissions in parallel connection are characterized by higher performances compared to those of transmissions in series connection. The use of planetary transmissions in parallel with a counter-rotating output allows higher efficiencies and smaller overall dimensions. For instance, according to Table 1, an increase with approx. 1% of the efficiency and a decrease of the radial dimension with approx. 40.3% is obtained for an amplification ratio $i_a = 80$: case III - $i_{0I} = 57$ and $\eta = 0.8698$, compared to case II: $i_{0I} = 80$ and $\eta = 0.8573$.

The variant from case III brings more advantages for small amplification ratios, which makes it recommendable for low-power systems, including those installed in the built environment. For instance, for $i_{0I} = 11$ the following results are obtained in case I: $i_a = -8$, $\eta_a = 0.842$; in case II: $i_a = -9$ and $\eta_a = 0.857$; in case III: $i_a = -11.43$, $\eta_a = 0.866$; thus, for the same radial dimension, both the amplification ratio and the efficiency are increased (increase of approx. 42 % for the amplification ratio and of approx. 2.8 % for efficiency) in case III compared to the case of a classical generator (case I).

7. Conclusions

The paper presents an algorithm for the analysis of a new type of 1DOF planetary transmission used as speed increasers in wind turbines, considering three of operating cases: with one input and one output ($L = 2$, $M = 1$), with one input and two counter-rotating outputs, the input being fixed to the secondary output ($L = 3$, $M = 1$), and with two counter-rotating outputs in which the speed of the secondary output is amplified relative to the input speed ($L = 3$, $M = 1$). Depending on the required power on the generator shaft, the proposed algorithm determines the parameters of mechanical power on each branch separately, corresponding to the transmission outputs. The algorithm allows dimensioning a planetary speed increaser by taking into account the possibility of establishing the interior kinematic ratios and the amplification ratio, implicitly, considering ratios that are recommended between the generator stator and the rotor speeds. A speed increase of the generator rotor relative to the stator and, thus, a more advantageous operation of the generator are obtained due to the use of a generator with mobile stator; the variant of planetary transmission obtained by coupling two parallel PU (case III) achieves higher transmission ratios and a higher efficiency compared to the cases with one PU and one

output (case I) or two outputs (case II). The results are useful in the synthesis of speed increasers with high performances to be integrated in wind turbines, providing speed amplification, higher efficiencies and reduced dimensions.

8. References

- [1] Arnaudov K, Genova P, Dimitrov L 2005 For an unified and correct IFToMM terminology in the area of gearing *Mechanism and Machine Theory* **40** pp 993-1001
- [2] Booker J D, Mellor P H, Wrobel R, Drury D 2010 A compact, high efficiency contra-rotating generator suitable for wind turbines in the urban environment *Renewable Energy* **35** pp 2027-2033
- [3] Climescu O, Săulescu R, Jaliu C 2011 Specific features of a counter-rotating transmission for renewable energy systems *Environmental Engineering and Management Journal* **10** pp 1105-1113
- [4] Diaconescu D V, Duditză F I 1994 Wirkungsgradberechnung von zwangsläufigen Planetengetrieben. Teil II: Weitere Beispielrechnungen und Vorteile *Antriebstechnik* **33** 11 pp 61-63
- [5] del Castillo J M 2002 The analytical expression of the efficiency of planetary gear trains *Mechanism and Machine Theory* **37** pp 197-214
- [6] Gomà Ayats J R et al. 2011 Power transmitted through a particular branch in mechanisms comprising planetary gear trains and other fixed or variable transmissions *Mechanism and Machine Theory* **46** pp 1744-1754
- [7] Gomà Ayats J R, Diego-Ayala U, Minguella Canela J, Fenollosa F, Vivancos J 2012 Hypergraphs for the analysis of complex mechanisms comprising planetary gear trains and other variable or fixed transmissions *Mechanism and Machine Theory* **51** pp 217-229
- [8] Laus L P, Simas H, Martins D 2012 Efficiency of gear trains determined using graph and screw theories *Mechanism and Machine Theory* **52** pp 296-325
- [9] Marjanovic N et al 2012 A practical approach to the optimization of gear trains with spur gears *Mechanism and Machine Theory* **53** pp 1-16
- [10] Mathis R, Remond Y 2009 Kinematic and dynamic simulation of epicyclic gear trains *Mechanism and Machine Theory* **44** pp 412-424
- [11] Miloiu Gh, Duditză F I, Diaconescu D V 1980 Modern Mechanical Transmissions (in Romanian) (București: Ed. Tehnica)
- [12] Pennestrì E, Mariti L, Valentini P P, Mucino V H 2012 Efficiency evaluation of gearboxes for parallel hybrid vehicles: Theory and applications *Mechanism and Machine Theory* **49** pp 157-176
- [13] Salgado D R, del Castillo J M 2014 Analysis of the transmission ratio and efficiency ranges of the four-, five-, and six-link planetary gear trains *Mechanism and Machine Theory* **73** pp 218-243
- [14] Săulescu R, Jaliu C, Munteanu O, Climescu O 2014 Planetary Gear for Counter-rotating Wind Turbines *Applied Mechanics and Materials* **658** pp 135-140
- [15] Săulescu R et al. 2016 Structural and Kinematic Features of a 2 DOF Speed Increaser for Renewable Energy Systems *Applied Mechanics and Materials* **823** pp 367-372
- [16] Săulescu R et al. 2016 Comparative Analysis of Two Wind Turbines with Planetary Speed Increaser in Steady-State *Applied Mechanics and Materials* **823** pp 355-360
- [17] Zhao X, Maißer P 2003 A novel power splitting drive train for variable speed wind power generators *Renewable Energy* **28** pp 2001-2011

Acknowledgments

This work was supported by UEFISCDI and the PNII Partnership program through the project no PN-II-PT-PCCA-2013-4-0726 Sim-PhotoAd.