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COMPARATIVE ANALYSIS OF PLANETARY TRANSMISSIONS TO BE USED IN RES

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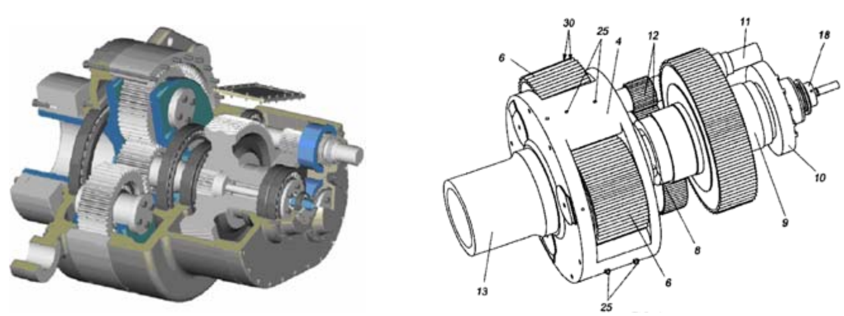
Abstract: *The paper main objective is to compare three planetary speed increasers to be used in renewable energy systems, especially in wind and small hydro applications. The comparison is meant to identify the proper solutions that fulfils the requirements for this kind of applications: to have an efficiency as good as possible, to increase up to 5 times the speed of the turbine shaft to the generator(for hydro systems) and up to 10 times (for wind turbines), to have reduced overall dimensions and technological costs.*

Key words: *speed increaser, efficiency, multiplication ratio, renewable energy systems (RES).*

1. Introduction

The majority of the turbines used in wind and hydro applications reach their maximum efficiency at much lower speeds than the generators do; therefore, it is necessary to use different types of transmissions that ensure the transmission of the mechanical power from the turbine to the generator, transforming its parameters in the same time. The range in which the turbine angular speed must be increased is 3-5 times for small hydro plants [2], [8] and 6-10 times for wind turbines [6].



a)   b)

Fig. 1. *a) Typical speed increaser configurations used in wind turbines Henderson transmission* [7]; *b) Muntala transmission* [10]

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There are many solutions in the literature that are used to increase the turbine speed, like: belts, gears, chains and, rarely friction transmissions (see Figure 1) [2], [4], [6-8], [10]. Each type has its advantages and disadvantages:

- the belt transmissions are used especially in micro and mini hydro applications due to the lower technological costs, but their efficiency is relatively small;
- gear transmissions have a better efficiency, but the technological costs and overall dimensions increase with the transmission ratio;
- friction transmissions are rarely used in RES applications, due to their lower efficiency, which is caused by the slippage between the two wheels in contact, which creates heat that requires a cooling system to make the transmission working effectively.

Two basic types of speed increasers are the most used is RES, and namely parallel shaft and planetary transmissions. In comparison, the planetary transmissions present several significant advantages: the input and the output shafts are coaxial, they have reduced radial and axial dimensions for high multiplication ratios and, in most cases, multiple power flows imply reduced load on each gear. Due to these advantages, the planetary transmissions have relatively light and compact structures.

In order to obtain higher values of the transmission ratio, multiple stages of different types (planetary sets, gear pairs) are placed in series. This configuration increases the multiplication ratio, but in the same time increases the overall dimensions, weight and technological costs and decreases the efficiency of the transmission because of the high number of gears and bearings.

The paper objective is to compare three representative planetary speed increasers to be used in renewable energy systems, especially in wind and micro hydro applications. Two of them are already used in renewable energy systems (see Figure 1), [7], [10]. Firstly, the two transmissions are analyzed comparatively in terms of multiplication ratio, efficiency, overall dimensions and technological costs. Then, the winning solution is compared to the planetary chain speed increaser that is proposed by the authors [3]. The aim of the comparison is to find the proper speed increaser to be used in a micro hydro plant to be implemented near Braşov.

2. Comparative Analysis of Henderson and Muntala Transmissions

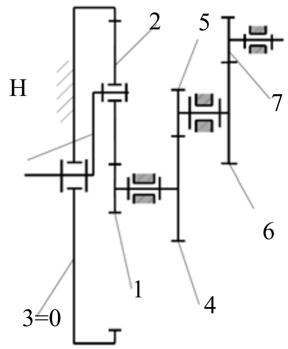
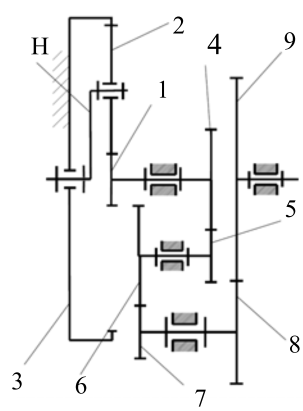
The first step in the analysis consists in defining the transmissions structural and kinematical aspects. The corresponding structural schemes of the two transmissions from Figure 1 are presented in Table 1 (where the input element is the carrier H). The planetary transmissions (see Table 1) contain a planetary set (consisting of a fixed sun gear 1, a satellite gear 2, a mobile sun gear 3 and a carrier H) and several gear pairs. The relations for the internal kinematical ratio i_0, the transmission ratio i_{H3}^1, the internal efficiency η_0 of the planetary set, and the kinematical ratios and efficiencies of the gear pairs, for the two speed increaser from Figure 1a and b are also presented in Table 1 [1], [5].

In the comparative numerical simulations of the multiplication ratio i and efficiency η, the following premises and notations are used:

- d_1, d_2 and d_3 are the diameters of gears 1, 2 and 3, respectively; the relations between them are taken from Figure 1a and b, which are scale drawings;
- the internal efficiencies of the gear pairs are considered $\eta_{12} = \eta_{23} = 0.98$, [3];
- the internal efficiency of the friction transmission from the Muntala transmission is $\eta_{89} = 0.80$, [1];
- the transmission ratios of the gear pairs are calculated by using the gears diameters.

Assuming that the two planetary sets have similar dimensions and comparing the

Comparative analysis of Henderson and Muntala gearboxes Table 1

The type	**Structural scheme**	**The multiplication ratio (*i*) and the efficiency (η) for:**
1. Henderson transmission		• The planetary set: $i_0 = i_{13}^H = \frac{\omega_{1H}}{\omega_{3H}} = -\frac{d_3}{d_1} = -2.25$, $i_{H3}^1 = \frac{\omega_{H1}}{\omega_{31}} = \frac{-\omega_{1H}}{\omega_{3H}-\omega_{1H}} = \frac{1}{1-1/i_{13}^H} = \frac{1}{1-1/i_0} = 0.307$, $\eta_0 = \eta_{13}^H = \eta_{12}^H \cdot \eta_{23}^H = 0.98 \cdot 0.98 = 0.9604$, $\eta_{H3}^1 = \frac{-\omega_3 T_3}{\omega_H T_H} = \frac{-T_3/T_H}{\omega_H/\omega_3} = \frac{(i_0-1)\cdot\eta_0}{i_0\eta_0-1} = 0.972$; • The gear pairs: $i_{45} = -\frac{d_5}{d_4} = i_{67} = -\frac{d_7}{d_6} = 0.914,\ \eta_{45} = \eta_{67} = 0.98$; • The transmission: $i_{H7} = i_{H3}^1 \cdot i_{45} \cdot i_{67} = 0.257,\ i = \frac{1}{i_{H7}} = 3.88$, $\eta = \eta_{H7} = \eta_{H3}^1 \cdot \eta_{45} \cdot \eta_{67} = 0.933$.
2. Muntala transmission		• The planetary set: $i_0 = i_{13}^H = \frac{\omega_{1H}}{\omega_{3H}} = -\frac{d_3}{d_1} = -0.55$, $i_{H3}^1 = \frac{\omega_{H1}}{\omega_{31}} = \frac{-\omega_{1H}}{\omega_{3H}-\omega_{1H}} = \frac{1}{1-1/i_{13}^H} = \frac{1}{1-1/i_0} = 0.357$, $\eta_0 = \eta_{13}^H = \eta_{12}^H \cdot \eta_{23}^H = 0.98 \cdot 0.98 = 0.9604$, $\eta_{H3}^1 = \frac{-\omega_3 T_3}{\omega_H T_H} = \frac{-\frac{T_3}{T_H}}{\frac{\omega_H}{\omega_3}} = \frac{(i_0-1)\cdot\eta_0}{i_0\eta_0-1} = 0.974$; • The gear pairs: $i_{45} = -\frac{d_5}{d_4} = i_{67} = -\frac{d_7}{d_5} = -0.387,\ \ i_{89} = -\frac{d_9}{d_8} = -2$, $\eta_{45} = \eta_{67} = 0.98,\ \eta_{89} = 0.80$; • The transmission: $i_{H9} = i_{H3}^1 \cdot i_{45} \cdot i_{67} \cdot i_{89} = -0.107,\ i = \frac{1}{i_{H9}} = -9.31$, $\eta_{H7} = \eta_{H3}^1 \cdot \eta_{45} \cdot \eta_{67} \cdot \eta_{89} = 0.748$.

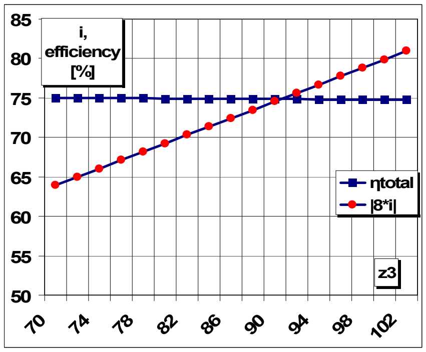


Fig. 2. *Numerical simulations of the multiplication ratio and efficiency for the Muntala transmission*

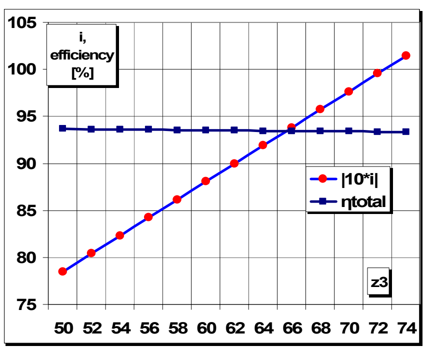


Fig. 3. *Numerical simulations of the multiplication ratio and efficiency for the Henderson transmission*

results from Table 1 it results that the Henderson transmission has a higher efficiency and smaller dimensions than Muntala transmission.

The numerical simulations of the multiplication ratio and efficiency for the two transmissions from Figure 1 are presented in Figures 2 and 3. The simulations are made in the following conditions:

- the diameter of gear 1 is considered constant, while the diameter of gear 3 varies;
- the following correlations between the gears diameters are considered: $d_2 = (d_3 - d_1)/2$, $d_4 = d_6 = d_3 \cdot 0.8$, $d_5 = d_7 = d_1$ (taken from the scale drawings in Figure 1);
- the teeth numbers can be calculated by keeping the proportions of the fixed axes transmissions and considering the same gears module.

By analyzing the diagrams from Figures 2 and 3, it can be observed that for similar values of the multiplication ratio, the Henderson transmission (Figure 1a) has a far better efficiency than Muntala transmission. Therefore, the Henderson transmission will be further compared to the planetary speed increaser with deformable element (Table 2) that was proposed by the authors in [3].

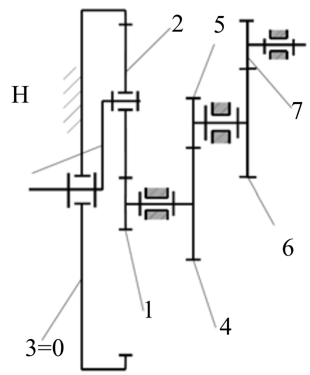
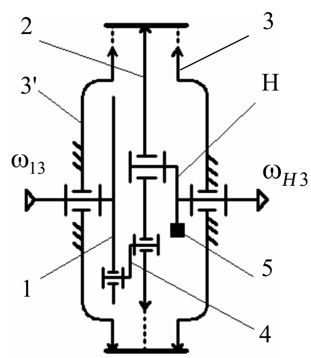
3. Comparative Analysis of Henderson and Chain Transmissions

A very important drawback of the transmissions from Figure 1 is that their use in small hydro applications requires relatively large radial dimensions, and, consequently, increased technological costs and weight. Considering this fact, the authors proposed a new speed increaser with deformable element [3]. The notations used in Table 2 for the speed increaser are: 1 - input disk, 2 - satellite gear, 3, 3' - sun gears, 4 - connecting rods, 5 - counterweight, 6 - chain on three courses, H - carrier.

Further, the characteristics of the Henderson transmission will be compared to the planetary speed increaser with deformable element from Table 2. As a working hypothesis, it was considered that the two transmissions are used in micro hydro applications; therefore, their multiplication ratio can vary between 3 and 5.

In the analysis of the planetary chain speed increaser it was considered that the teeth number of the satellite gear (z_2) is constant and less than the teeth number of the sun gear 3, which varies. The relations used in the numerical simulations of the multiplication ratio and efficiency (see Figures 4 and 5) are presented in Table 2, [1], [5]. Imposing the multiplication ratio in the micro hydro domain, the analysis aims

Comparative analysis of Henderson gearbox and Planetary Chain Transmission Table 2

The type	Structural scheme	The multiplication ratio (i) and the efficiency (η) for:
1. Henderson transmission		• The planetary set: $i_0 = i_{13}^H = \frac{\omega_{1H}}{\omega_{3H}} = -\frac{z_3}{z_1}$, $\eta_0 = 0.9604$, $i_{H3}^1 = \frac{1}{1-1/i_0}$, $\eta_{H3}^1 = \frac{(i_0-1)\cdot\eta_0}{i_0\eta_0-1}$; • The gear pairs: $i_{45} = -\frac{z_5}{z_4}$, $i_{67} = -\frac{z_7}{z_6}$, $\eta_{45} = \eta_{67} = 0.98$; • The transmission: $i_{H7} = i_{H3}^1 \cdot i_{45} \cdot i_{67}$, $i = \frac{1}{i_{H7}}$, $\eta_{H7} = \eta_{H3}^1 \cdot \eta_{45} \cdot \eta_{67}$.
2. Planetary speed increaser with deformable element		$i_0 = i_{13}^H = \frac{\omega_{1H}}{\omega_{3H}} = i_{12}^H \cdot i_{23}^H = (+1)\left(+\frac{z_3}{z_2}\right)$, $i_{1H}^3 = \frac{\omega_{13}}{\omega_{H3}} = \frac{\omega_{1H}-\omega_{3H}}{-\omega_{3H}} = 1 - i_0$, $i = \frac{1}{i_{1H}^3}$, $\eta_0 = \eta_{13}^H = \eta_{12}^H \cdot \eta_{23}^H = 0.995 \cdot 0.95$, [3], [9], $\eta = \eta_{1H}^3 = \frac{-\omega_{H3}T_H}{\omega_{13}T_1} = \frac{-T_H/T_1}{\omega_{13}/\omega_{H3}} = \frac{1-i_0\eta_0^{-1}}{1-i_0}$.

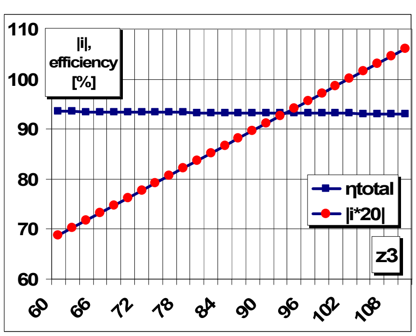


Fig. 4. *Numerical simulations of the multiplication ratio and efficiency for the Henderson transmission*

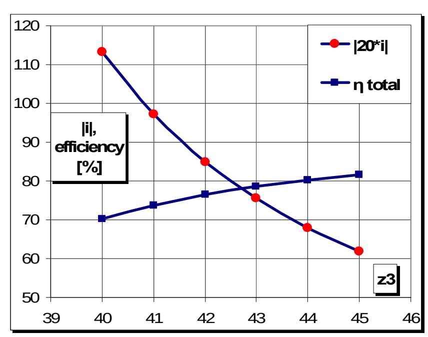
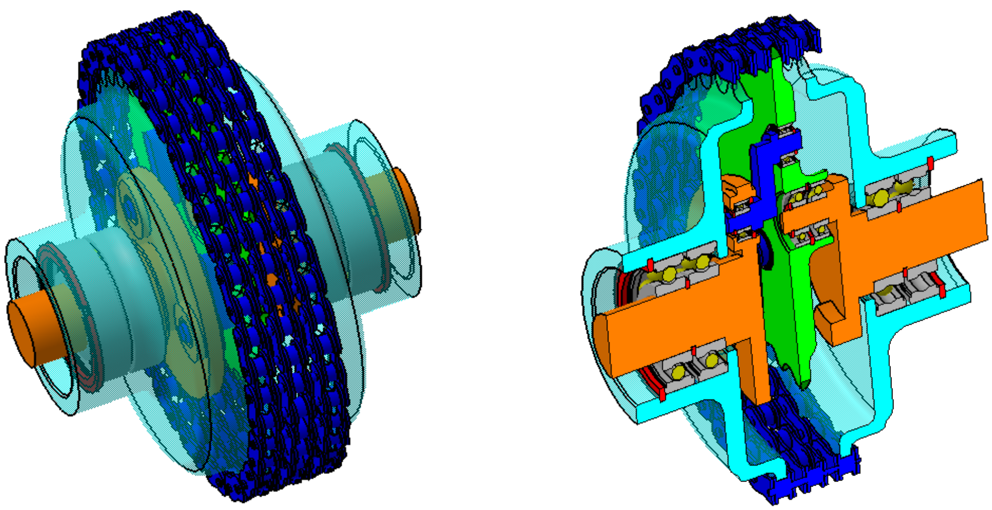


Fig. 5. *Numerical simulations of the multiplication ratio and efficiency for the chain planetary speed increaser*

to present its influence on the overall dimensions and efficiency.

The diagrams from Figures 4 and 5 highlight the fact that the Henderson transmission has a better efficiency for the same multiplication ratio, but its overall dimensions and cost are much higher than those of the chain transmission. Because in the micro hydro applications the technological cost of the speed increaser is the most important factor, the planetary speed increaser with deformable element is a better option than Henderson transmission. Therefore, this speed increaser will be implemented in a small scale micro-hydro station to be developed on Ghimbăşel River, near Braşov. With this purpose, a 3D model of the chain speed increaser and the technical documentation was developed using modern CAD/CAE software, namely Dassault Systems CATIA and Autodesk Inventor. This model is presented in Figure 6.



a) b)

Fig. 6. *The virtual model of the speed increaser proposed by the authors: a) isometric view; b) section view*

The most intense stressed parts were tested with FEA in CATIA. The following premises were used in the finite element analysis:

- the calculated maximum input torque is 15 Nm;
- the material is steel, ASTM A-36, Yield Strength S_y = 250 Mpa.

The results of the FEA analysis (see Figures 7 and 8) show that the parts of the speed increaser were properly designed, the maximum stress being 90 MPa, which means that the safety factor of the respective part is about 1.3.

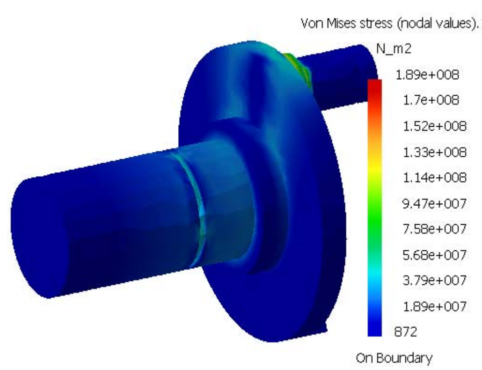


Fig. 7. *The results of FEA on the input shaft*

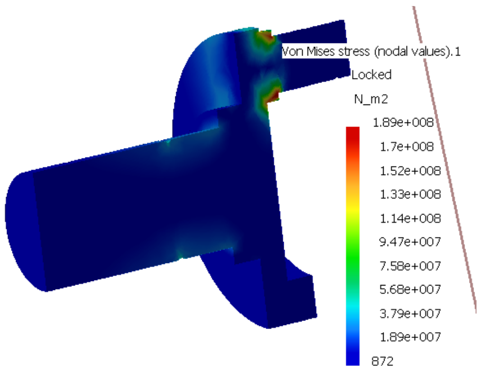


Fig. 8. *Section view for the results of FEA on the input shaft*

4. Conclusions

The paper presents the comparative analysis of three planetary speed increasers used in renewable energy systems with the aim to identify the proper solutions for a micro hydro plant that will be developed near Braşov. The following conclusions can be stated from the comparative analysis of the simulation results for the multiplication ratio and efficiency:

- transposing the transmission multiplication ratio in the same interval (8-10.5), the overall structural dimensions and complexity of the Henderson transmission are much lower, and the efficiency is higher than for the Muntala transmission;
- the comparison between the Henderson transmission and the planetary speed increaser with deformable element, for the same interval of the multiplication ratio (3-5) highlight the fact that Henderson transmission has a better efficiency, but the overall dimensions are considerably larger and the costs are much higher;
- as for micro hydro applications, a smaller cost is preferable to a higher efficiency, the speed increaser with deformable element will be further developed to be included in a micro hydro plant on Ghimbăşel River;
- the 3D model of the proposed transmission is then developed using modern CAD software (Dassault Systems CATIA, AutoDesk Inventor); resistance testing with FEA (Finite Element Analysis) are made for the most intense stressed parts;
- the testing results demonstrates that the chain speed increaser proposed by the authors is viable and can be manufactured to be implemented in the micro hydro station.

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