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IMPROVING THE ENERGY EFFICIENCY OF WIND TURBINES USING HYDRAULIC DRIVE

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Abstract: The article presents a variant of hydrostatic transmission in open circuit that replaces the classical mechanic transmission; for both variants are analyzed parameters such as energy efficiency, power, lost power, etc. Hydrostatic transmission has specific advantages that are deriving from positioning the generator on the ground such as: nacelle mass reduction that will reduce the price of the construction and the simplification of the energy transmitting chain. Energy transmitting and summing from multiple wind turbines is much easier.
Keywords: wind turbines, hydrostatic transmission, mechanical transmission, energy efficiency

INTRODUCTION

In 2020, the electricity obtained from the conversion of wind power covered 6.38% of the total consumption worldwide. Small wind turbines can produce a power of 400 watts up to 100 kW. The average wind speed from the geographical location determines how much wind power a turbine can convert (***, Small Wind Turbine & Generators to Power Your Home, 2020). Most of this energy production is obtained with horizontal axis wind turbines. For this type of turbine, the location of the electric generator in the turbine platform leads to a significant increase in the mass of the platform, and implicitly the mass of the pillar supporting the turbine. In addition, the maintenance of the turbine becomes more difficult with the increase of the rotor diameter and the height of placement.

The platform (excluding the rotor) represents between 20 ... 35% of the total weight of a large turbine reaching in some cases the order of hundreds of tons. In the case of the VESTAS V90 turbine, the platform weighs 75 tons, the rotor 40 tons, and the tower 152 tons (***, Renewables 2020 Global Status Report, 2020). In August 2021, the largest offshore wind turbine with a capacity of 16 MW was launched; for this turbine, the nacelle has a weight of 37 T / MW, considered very competitive. In the case of small turbines (< 100 kW), even if we do not have such weights, the same values are kept as a percentage. Other research has shown that in offshore turbines, one of the main issues is gearbox failure, with current designs requiring replacement or capital intervention every 4 years. With the gearbox contributing to around 10% of turbine cost (Buhagiar, T. S., 2013), such frequent replacements are very detrimental to the overall viability of offshore wind energy conversion. Danop Rajabhandharaks states in his thesis (Rajabhanharaks, D., 2014) that it is not uncommon for a gearbox to fail on average every 5 years, while the designed lifetime of a wind turbine is typically about 20 years. On the other hand, there are wind turbines that have appeared in the last decades that differ from the classic solutions, and fall into the category of unconventional wind turbines; they have different shapes, are arranged vertically or horizontally at different heights, and in terms of power they usually fall into the category of low power turbines (below 100 kW).

Reducing the weight of the platform, and implicitly the weight of the support pillar, would be easy to achieve if the electric generator were located on the ground and the tower would support only the rotor and a few other auxiliary elements. Maintenance would also be much easier to achieve. As for the unconventional turbines, they are located in the most diverse places, and the reduction of the suspended mass and reduction of the gauge is likely to simplify the construction and improve the visual impact. While in the turbines with vertical axis located on the ground or near the ground, the generator has small dimensions and weight, in those placed on buildings or bridges, the location on the ground of the generator significantly simplifies the construction.

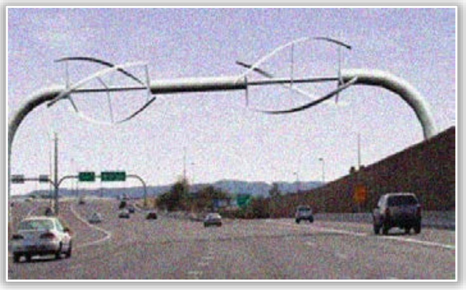

Figure 1 – Unconventional wind turbines (***, https://www.whirlopedia.com/index.php/unconventional–wind–turbines)

For all these problems the solution is the hydrostatic transmission of energy from the rotor to the generator, also giving up the gearboxes that multiply the reduced rotor speed (5...40 rpm) to make it compatible with that of the generator (1500...3000 rpm); by an intelligent use of some classic–and–modern hydraulic components, high performance hydrostatic transmission can be achieved.

MATERIALS AND METHODS

In addition to the advantages mentioned above, the research undertaken by the authors aimed to establish energy efficiency in two transmission variants: a classic variant and a hydrostatic transmission variant. Beside the main purpose of the research related to efficiency, the aim was to adjust the drive speed of the electric generator and the transmission response to the input parameter variation (wind speed mainly). In this phase, the research was performed by numerical simulation (by using Simcenter Amesim software), to reduce material costs and research time.

Hydrostatic system is consisting of a variable speed motor that represents the turbine blades, connected to a planetary speed multiplier that increases the hydrostatic pump speed up to 2000 rev/min. The hydrostatic pump is connected in an open circuit, which includes also: a hydraulic orifice that adds flow rate losses in the system; a hydraulic pressure relief valve that opens if the pressure in the system is higher than 150 bar; a hydraulic motor that drives the load pump; a hydraulic pressure relief valve. Generator is represented in this simulation by the load pump. The power sensors and the speed sensor collect the data, and then the difference between output power and input power is calculated and displayed on a chart. The same data from the sensor is divided and the result represents the efficiency of the transmission. Speed sensor measures generator speed, the data is transmitted for comparison in the comparator where the value from the sensor is compared with a reference value and then the error signal is transmitted to the PID regulator that adjusts pump displacement in such way that output speed remains constant. The reason is the necessity to maintain a constant frequency of 50 Hz.

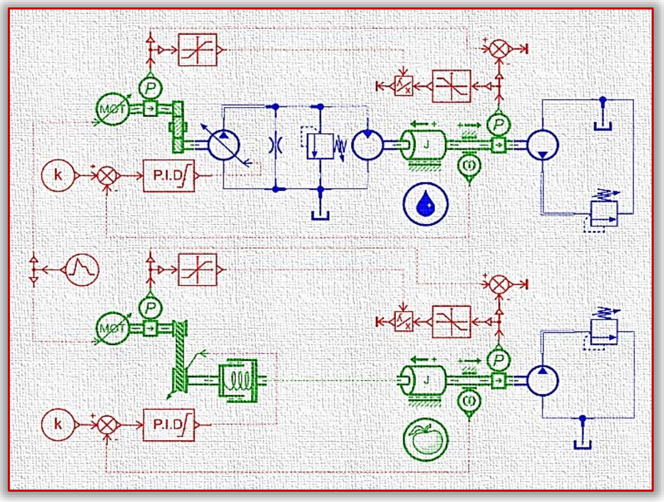

Figure 2 – Simulation Network

Mechanical transmission has in componence the same variable speed motor that is connected to a continuously variable speed multiplier that increases the speed up to 1470 rev/min. The output of the speed multiplier is connected by a flexible coupling to the load pump. The sensors from the mechanical transmission are placed in the same place as in the hydrostatic transmission, the PID regulator does the same thing as the PID regulator from the hydrostatic transmission; the difference is the parameter that is adjusted.

Table 1. Simulation parameters

Component	Hydrostatic transmission	Mechanical transmission
Variable speed motor (turbine blades)	Speed: 25. . . 100 rev/min	
Speed multiplier	Planetary $i_R = 20$	Continuously variable $i_M = 60$
Hydraulic pump	Displacement: 112 cm^3/rev Variable displacement	–
Hydraulic pressure valve	Relief valve 150 bar	
Hydraulic motor	Displacement: 35 cm^3/rev Fixed displacement	–
Hydraulic oil	HEP46	–
Moment of inertia	0.1 $kg{\cdot}m^2$	
Hydraulic load pump	Displacement: 35 cm^3/rev	
Hydraulic load pressure valve	Cracking pressure 120 bar	
PID regulator	$k_p = 3$ $k_i = 3750$ $k_d = 0.0016$ saturation range: 0 – 1	$k_p = 180$ $k_i = 3800$ $k_d = 0.0018$ saturation range: 0 – 60

RESULTS

The comparison between a hydrostatic transmission and a mechanical transmission by simulation leads to the following results that will be discussed next. In the following graphs, hydrostatic transmission is denoted as HT and mechanical transmission is noted as MT. The parameters have been monitored and calculated in order to ensure a fair comparison between the two transmissions.

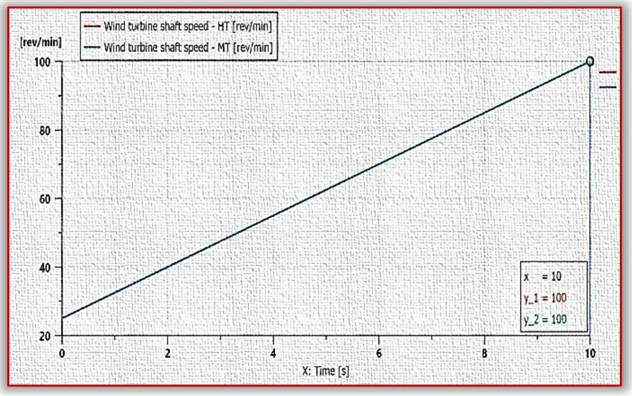

Figure 3 – Wind turbine shaft speed variation over time

Wind turbine shaft speed variation for HT and MT is shown in Figure 3. The two shafts speeds have the same variation as one can see on the graph.

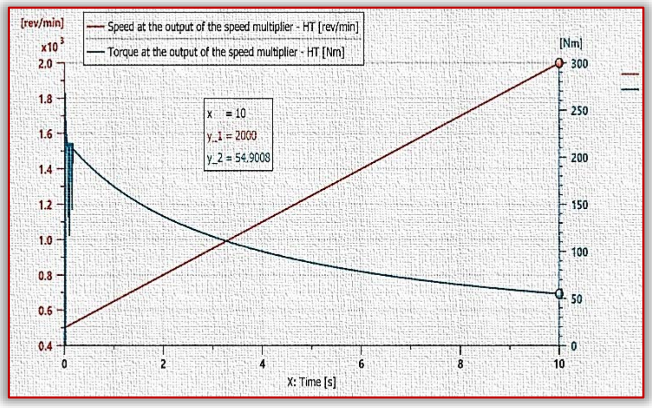

Figure 4 – Variation of the speed and torque at the output of the planetary speed multiplier (HT)

Variation of the speed and torque at the output of the planetary speed multiplier for HT, Figure 4, shows that the speed increase and simultaneously the torque decreases. The speed at the output of the multiplier increases because the input of the multiplier increases too due to the variation of the wind turbine shaft speed and because the torque decreases. The planetary multiplier provides the necessary speed for which the hydraulic pump has a good efficiency and good stability because the mass distribution of the transmission is even.

Variation of the speed and torque at the output of the continuously variable speed multiplier for MT, Figure 5, shows the output value of both parameters remains constant, the only parameter that varies is speed at the input of the multiplier. However, as is well known this type of transmission is capable to operate at a constant speed while the speed of the shaft may vary.

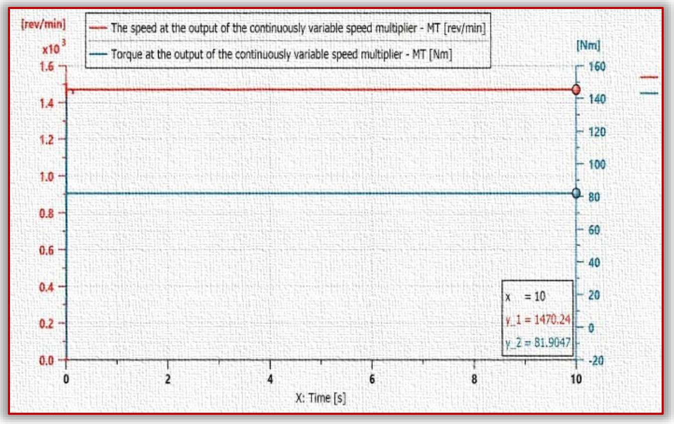

Figure 5 – Variation of the speed and torque at the output of the continuously variable speed multiplier (MT)

Variation of the pump flow rate, internal and external flow losses are shown in Figure 6, and as one can see the open circuit pump flow rate, after a short oscillation caused by the PID regulator, stabilizes. After the speed of the output multiplier shaft speed reaches 500 rev/min and the hydraulic pump enters in the speed zone where it begins to have good efficiency, the flow rate stabilizes. Of course, as in any hydraulic system, there are some internal losses in the hydraulic pump as well as in other system components and certainly, there are external losses too; both type of losses do not exceed 5.56 L/min.

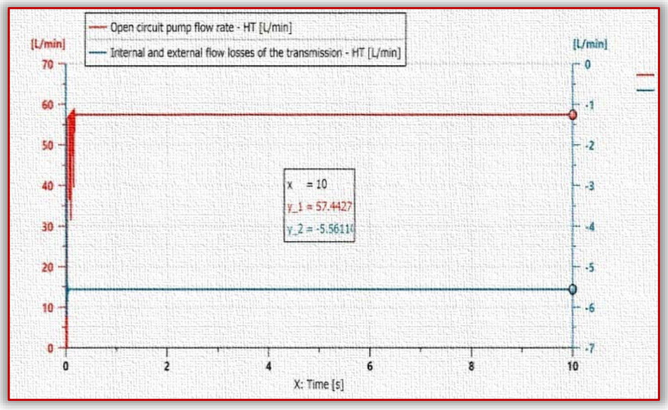

Figure 6 – Variation of the pump flow rate and internal and external flow losses (HT)

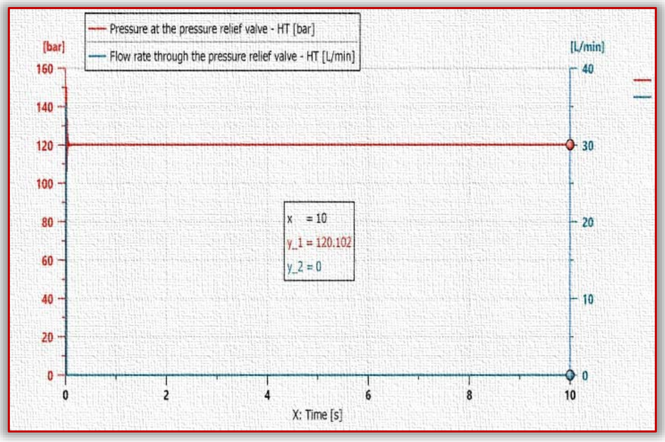

Figure 7 – Pressure and flow rate variation through the pressure relief valve (HT)

To ensure that pressure in the system has the set value and the flow rate through pressure relief valve remains zero, the values of these parameters are verified during the entire simulation. As it is shown in Figure 7, the pressure at the relief valve is 120 bar and the flow rate through the pressure relief valve is 0 L/min, meaning that it remains closed. The relief valve will open when the pressure reaches 150 bar.

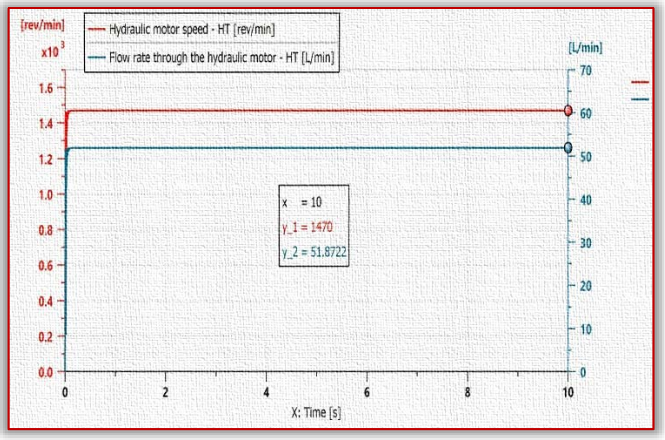

Figure 8 – Variation of the hydraulic motor speed and flow rate through the hydraulic motor (HT)

Variation of the hydraulic motor speed and flow rate is showed in graph in Figure 8; after a short period of variation in the beginning, the parameters become constant during the rest of the simulation. Speed of the hydraulic motor is monitored with a sensor that sends the value that is measured to the comparator that compares the set value with the output value of speed from the hydraulic motor. Based on the error that the PID regulator receives, it adjusts its output according with the input and makes correction in order to obtain at the HT the desired speed.

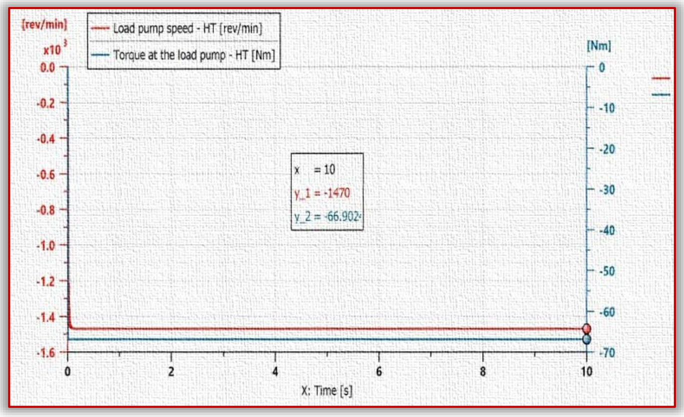

Figure 9 a) – Variation of the load pump speed and torque at the load pump (HT)

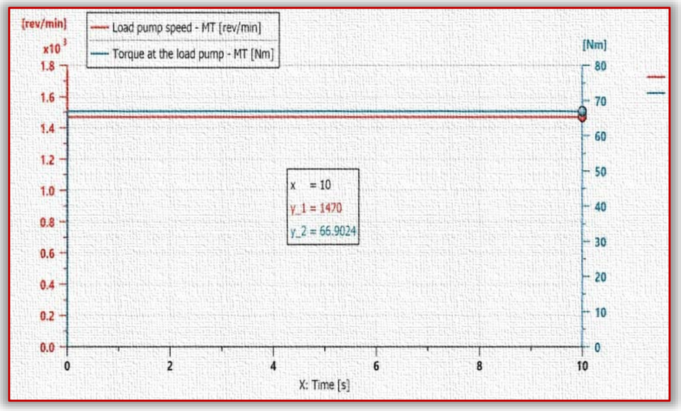

Figure 9 b) – Variation of the load pump speed and torque at the load pump (MT)

Figure 9 a) is the graph for the variation of the load pump speed and torque for hydrostatic transmission and Figure 9 b) shows the graph for the variation of load pump speed and torque for mechanical transmission. The two transmissions have the same values for these two parameters that are presented in the graphs, which means that frequency is the same, and constant for both transmissions.

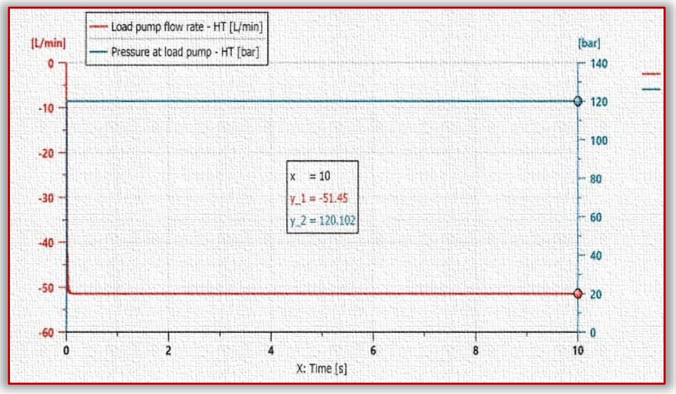

Figure 10 a) – Variation of the load pump flow rate and pressure at the load pump (HT)

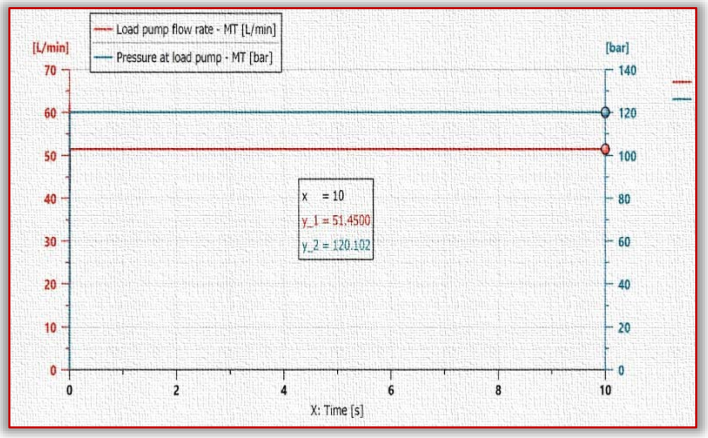

Figure 10 b) – Variation of the load pump flow rate and pressure at the load pump (MT)

Figure 10 a) shows the variation of the flow rate and pressure for the load pump of the hydrostatic transmission and Figure 10 b) shows the variation of the flow rate and pressure for the load pump of the mechanical transmission. Both pumps have the same values of the parameters during the simulation and that means that they generate the same power.

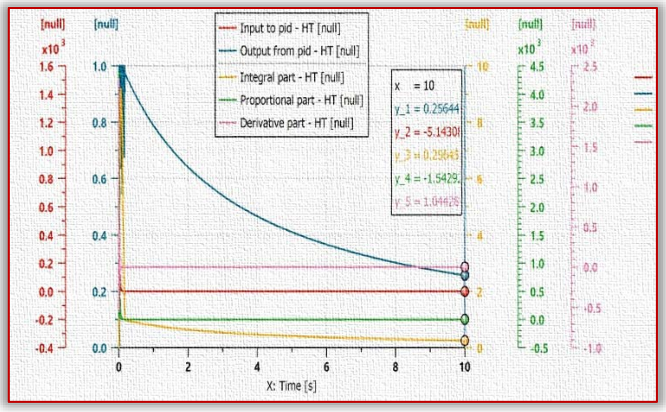

Figure 11 – a) PID regulator parameters (HT)

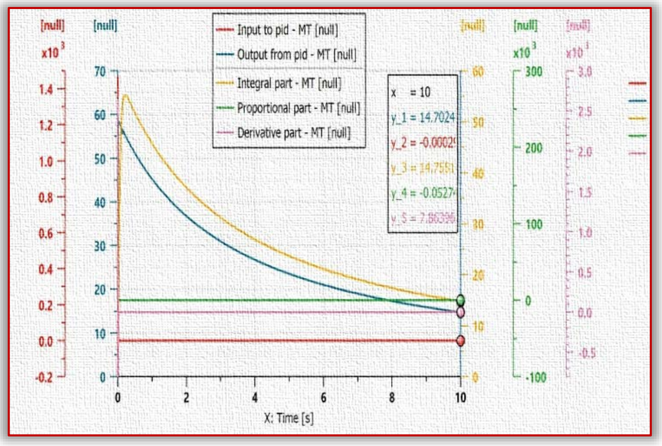

Figure 11 – b) PID regulator parameters (MT)

The graphs in Figure 11 a) and Figure 11 b) show the PID regulator variation of the parameter for HT and MT during the simulation. The PID parameters were calculated with Ziegler – Nichols method before they were introduced in the simulation parameters. Ziegler – Nichols method consists in finding a k_u gain by increasing the proportional gain, k_p, until output of the control loop remains stable. After finding the k_u, period, T_u, can be found too by measuring the difference between two oscillations. With those two parameters the PID regulator parameters can be calculated. For this simulation, it has been chosen Ziegler–Nichols method with no overshoot.

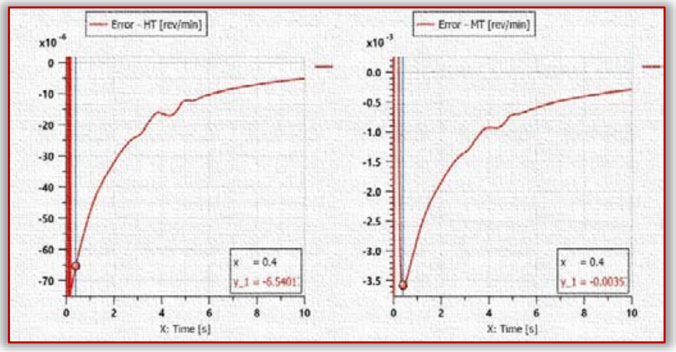

Figure 12 – Error variation for HT and MT

The speed error can be seen in Figure 12 for both transmissions. Comparing the two graphs, one can say that the hydrostatic transmission is more precise than the mechanical transmission because the speed error that enters in the PID regulator of the hydrostatic transmission is 55 times smaller than at the mechanical transmission.

Figure 13 shows the power consumption for HT and MT during the conversion of the wind power to electricity; even if the two transmissions have different power consumption the output power that is produced remains the same. Figure 14 proves that both transmissions have the same output power.

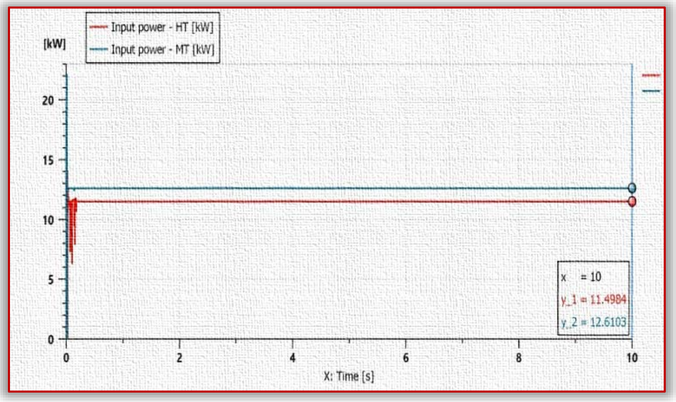

Figure 13 – Input power variation for HT and MT

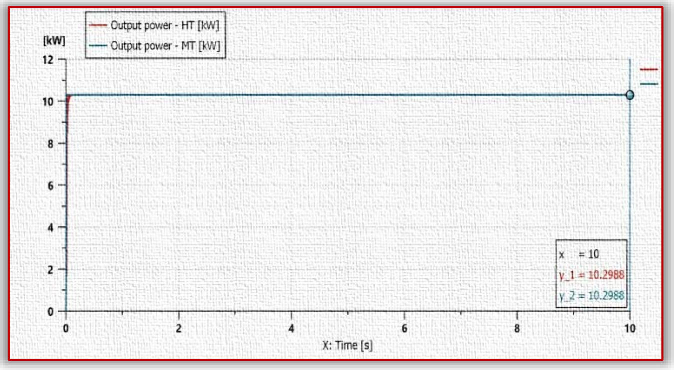

Figure 14 – Output power for HT and MT

The lost power, Figure 15, is bigger for the mechanical transmission because of the friction in bearings. The friction generates heat and causes premature wear of the transmission. Hydrostatic transmission does not lose that much power because the components are permanently immersed in fluid and, as we know, the fluid has lubrication proprieties.

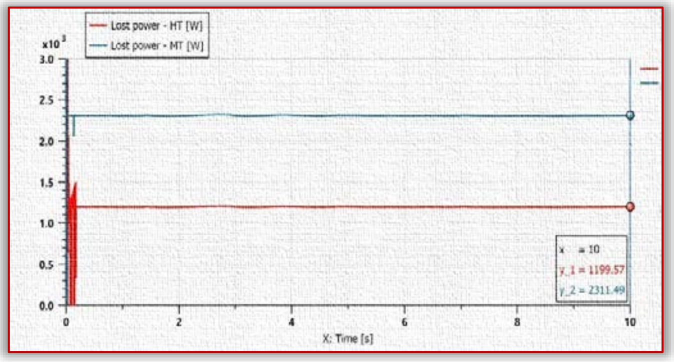

Figure 15 – Lost power for HT and MT

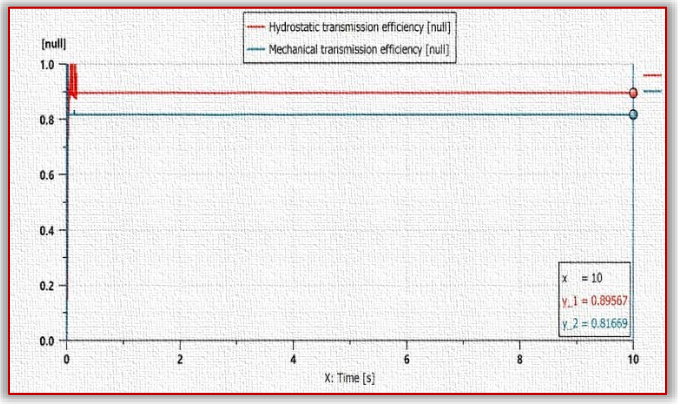

Figure 16 – HT and MT efficiency

Figure 16 shows that HT has a higher efficiency than MT, which makes this transmission better than the other; even a small difference of efficiency means a lot in the current situation that we are today when almost everything uses energy. HTs are more reliable and more compact than MTs that need a lot of space for the gearbox to fit.

CONCLUSIONS

≡ Hydrostatic transmission is by 8% more efficient than mechanical transmission.

≡ PID regulator was introduced in the system to maintain constant the output speed for both transmissions, speed that is proportional to the frequency of the generators.

≡ The speed regulation in the hydrostatic transmission is more precise than the one in the mechanical transmission.

≡ Hydrostatic transmission is easy to control and they can perform in various weather conditions.

≡ Hydrostatic transmission adapts easy to the changes of the input parameters such as wind speed fluctuations.

≡ Hydrostatic transmissions are more reliable than mechanical transmissions.

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