Development of a System for the Usability of Forest Residues for Electric Energy Production

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Abstract. Forest residue mass from timber harvests is a renewable resource that can be used for electrical utility production. Under this context, this work presents the development of a system for harnessing forest residues. The system consists in several different parts, constituting a complex mechanical-hydraulic-electrical coupling system. With the development of this system, forest residues and derivatives can be used through thermoelectric plants to produce electric energy.
In this paper, the proposed system, due to its specific structure, supports a wider range of forest residues that can be processed, i.e., mixed residues of different sizes and shapes can be used simultaneously. In addition, this solution may allow to skip pre-processing fragmentation.

Key words

Biomass; Forest residues; Electric Energy; Renewable resource.

1. Introduction

An important part of the electric supply is derived from coal fire plants. However, these power plants pollute the environment with toxins and contribute to the greenhouse effect, contributing to the rise of the global temperatures [1]. However, instead of using coal for the production of electrical energy, other products like biomass could be used. In fact, the use of biomass for the production of electrical energy is considered a renewable resource harvested from a several types of sources, such as brush, willow matter, crops, waste, timber, and forest residues [2,3]. The use of wood is a promising feedstock since it can be obtained from multiple sources. On other hand, wood biomass is less expensive when compared with fossil fuels, being the amount of carbon dioxide emitted during the burning process typically 90 % less and, in addition, wood contains minimal amounts of sulfur and heavy metals. Due to this, forest detritus has been proposed to be used for the electrical energy production [4-7].

The residues for biomass plants are characterized by their dimension, moisture content and proportion of silica. Usually, the final product of the residues to be used in biomass power plants is generally accomplished through fragmentation processes. The residues are crushed and smashed between the rotating and fixed parts of a cutting machine, remaining in a closed cycle until a suitable size of the fragments are achieved. The systems used in the processes of fragmentation can be driven by internal combustion engines or by electric motors. Systems that use internal combustion engines are less efficient, however they can be installed in deforestation fields, for primary treatment of the trees branches, bushes and roots. Primary treatment involves the partial fragmentation of material in order to facilitate the accommodation of the same in heavy container vehicles. Regarding the machines that operate with electric motors, their use will be difficult in deforestation zones due to the lack of a power supply. In industrial environment the machines driven by electric motors are more advantageous due to its high efficiency and clean operation since they do not emit greenhouse gases into the atmosphere.

Under this context, this paper presents the development of a chipping machine for forestry residues which are pre-fragmented. The development of this machine will undergo several phases that determine its technical characteristics. The development of this machine is based on the following factors: amount of fragmented material in output discharge, operating safety, equipment life and ease of maintenance. It is necessary to emphasize the first

factor since it will be decisive for the size of the machine and hence their power consumption.

2. Proposed System

The proposed system consists essentially in three very distinct parts: the mechanical, the hydraulic and the electric.

A - Machanical Part

The mechanical part is responsible by the fragmentation of forest or industrial residues. This fragmentation is achieved by the inertia of a rotating cylinder in order to cause fragmentation of residues. In fact, this fragmentation is due to the cutting blades mounted on the cylinder and fixed blades as shown in Fig. 1.
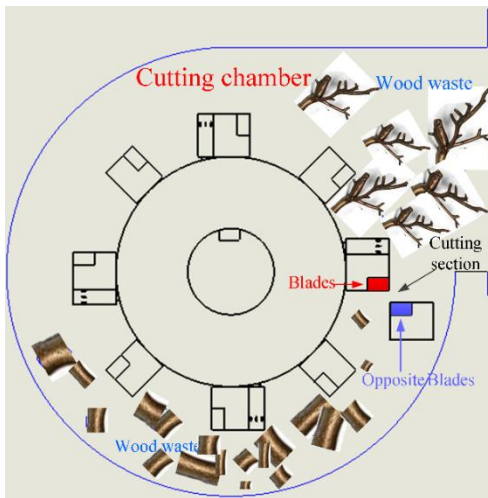

Fig. 1. View of the cutting chamber and of the cutting cylinder.

The residues that entering into the cutting chamber are pushed by blades placed on the rotating cylinder to the counter blades where they are crushed. The distance between the two cutting elements (blades and counter-blades) should be between 0.3 mm to 0.4 mm. Fig. 2 shows the cutter cylinder, being visible the location of the cutting blades. The characteristics of the cutting cylinder are shown in Table I.

Table I: Main characteristics of the cylinder and pulley

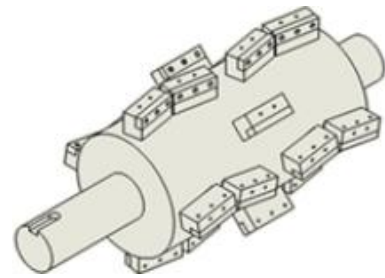|	Cylinder	Pulley
Diameter (m)	0.8	1.7
Weight (kg)	7911	1260
Volume (m^3)	1	0,16
Surface (m^2)	20.5	6,2
Moment of inertia (kgm^2)	729	289

Fig. 2. Cutting Cylinder.

Fig. 3 shows a view of the cutter cylinder where it is visible the brackets for the blades, the support of the opposite blades and sieve. The sieve separates the cutting chamber from the discharge chamber and is intended to set the maximum size for the crushed material.
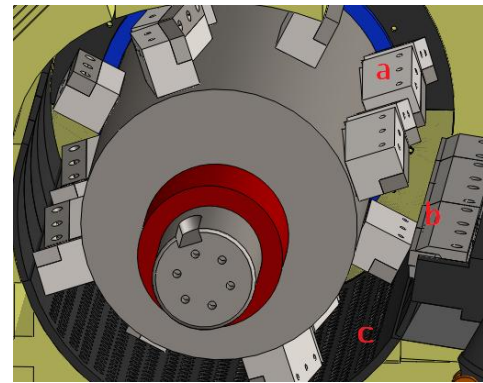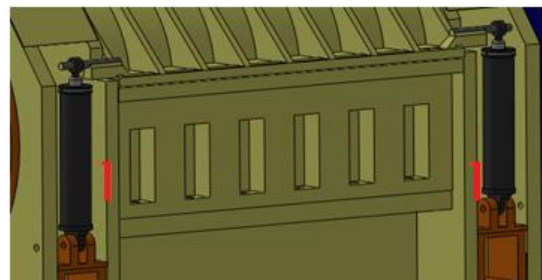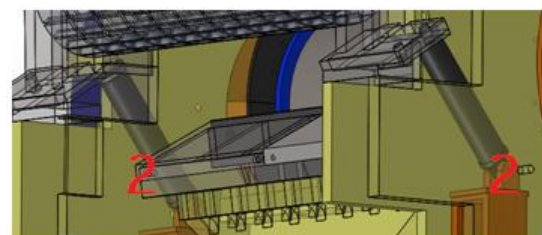

Fig. 3. View of the cylinder incorporated in the system: (a) Support of the blades (b) support of the opposite blades (c) sieve.

B - Hydraulic Part

The hydraulic system is designed to drive four hydraulic jacks, two in the front door and two in the rear door. The hydraulic jacks are solely used during the maintenance to the interior of the machine.

a)   Rear door

b)   Front door
Fig. 4. Hydraulic Jacks.

The hydraulic system has a safety valve which is activated when the system pressure reaches 150 bar. There are flux controllers that in case of overloading during the expansion block the flux in the opposite direction. In the case of any failure of electrical nature there is the neutral position in the valves that control the direction of the flux, in order to immediately lock the oil in both directions. This eliminates the possibility of the doors fall in case of blackout.

The technical data of the hydraulic system are:
- Maximum operating pressure: 150 bar
- Displacement: 82 cm³/rev
- rpm: 1200 (hydraulic pump motor)

C - Electrical Part

The operation of the proposed solution depends mainly on of the electrical part. The electrical part of the system comprises four electric motors M_1, M_2, M_3 and M_4 that are described below.

The residues are placed inside of the cutting chamber by a conveyor belt in driven by electric motor (M_2) and the help of the feed cylinder driven by the motor (M_4). The residues are fragmented by the cutting cylinder, which is driven by electric motor (M_1). After the fragmentation, the residues are driven out of the machine by a conveyor belt out through the motor (M_3).

In Fig. 5 is shown the electric motor M_1 and the transmission system of the motor to the load (cutting cylinder). The transition system comprises two pulleys, one with a smaller size that is placed on the motor shaft, and the other one with larger size that is placed on the load shaft.

Motor M_1 provides mechanical energy to the cylinder that fragments the biomass (forestry or industrial) to later be used in biomass power plants for the production of the electricity.
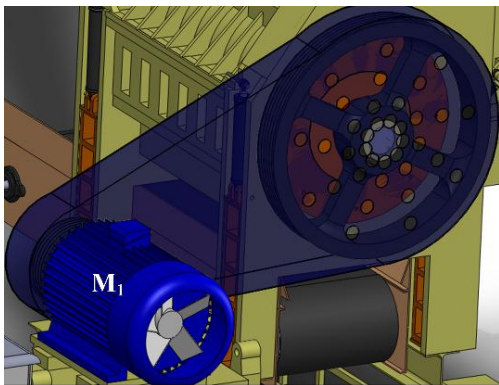

Fig. 5. View of the M_1 motor and transmission system.

The main characteristics of the cutting cylinder and pulley are presented in Table I.

Fig. 6. illustrates the transportation system of the residues for the cutting cylinder, where is visible the cutting cylinder, the feed cylinder, the feed chamber, the conveyor belt and the motor M_2. The feed conveyor belt is intended to put the biomass in the cutting chamber. Motor M_2 is designed to drive the conveyor belt that carries the biomass from the feed chamber to the cutting chamber.
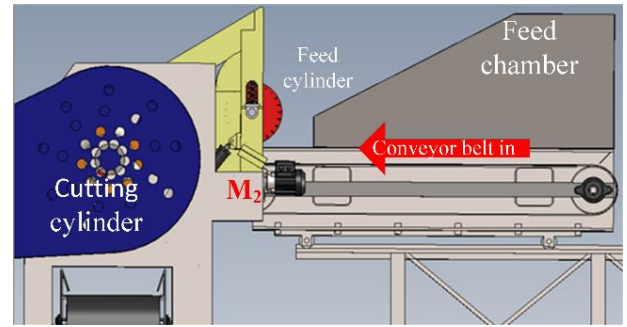

Fig. 6. System for the transportation of the residues for the cutting cylinder.

In Fig. 7 is represented the view of the transportation system where is visible the feed cylinder and motors M_3 and M_4. The electric motor M_3 is intended to drive the conveyor belt that carries the already fragmented biomass. The motor M_4 is intended to drive the feed cylinder.
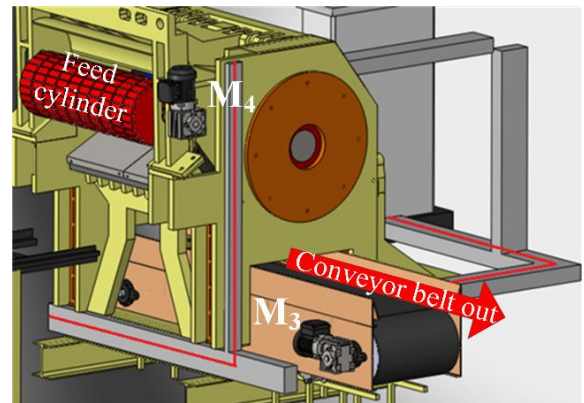

Fig. 7. Transportation system of the residues after passing the cutting cylinder.

3. Sizing of the Electric Motors

As described, this system requires several electric motors. For the sizing of the motors is necessary to take into consideration the load torque, T_{load} (Fig. 8), [8].
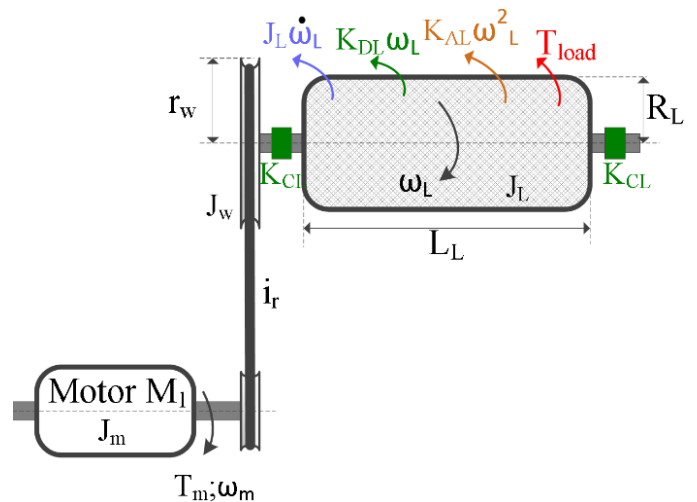

Fig. 8. Equilibrium of binaries in a system with elastic coupling.

The load torque of the motor is given by:

$$T_m = J_t \frac{d\omega_m}{dt} + T_r + T_{load} \qquad (1)$$

where:

T_r - Resistant torque associated to the frictions: static, viscous and turbulent

T_{load} - Load torque

The total inertia momentum can be calculated as follows:

$$J_t = J_m + J'_{L+w} \qquad (2)$$

where:

J_t - Total inertia momentum seen from the motor shaft

J_m - Inertia momentum of the motor

J'_{L+w} - Inertia momentum of the load (cylinder) seen from the motor shaft and Inertia momentum of the pulley (reduction gear) seen from the motor shaft

For a homogeneous cylinder with specific mass μ the inertia moment can be given by:

$$J_L = \int_0^{L_L} \int_0^{R_L} \int_0^{2\pi} r_L{}^2 \, \mu \, r_L d\theta dr_L dl_L = \frac{1}{2}\pi L_L R_L{}^4 \mu \qquad (3)$$

Where the cylinder mass is:

$$M_L = \mu\pi R_L{}^2 L_L \qquad (4)$$

Taking into account the mass of the cylinder the inertia moment is given by:

$$J_L = \frac{1}{2}R_L{}^2 M_L \qquad (5)$$

The gear ratio of the reduction gear box can be given by the following expression:

$$i_r = \frac{\omega_m}{\omega_L} \qquad (6)$$

The inertia moment of the load (cylinder) seen from the motor shaft is given by:

$$J'_L = \frac{1}{\eta_r}\frac{1}{i_r^2}J_L \qquad (7)$$

where η_r is the efficiency of the reduction gear box.

Regarding the biggest pulley that is integrated in the reduction gearbox, the inertia moment can be calculated by:

$$J_w = \frac{1}{2}r_w^2 M_w \qquad (8)$$

Making the reduction of this moment of inertia to the motor shaft, the new following expression is obtained:

$$J'_w = \frac{1}{2}\frac{r_w^2}{i_r^2}M_w \qquad (9)$$

The resistive torque is inherent in each type of load and can have various origins. The resistant binaries considered are the following:

Resistant torque due to static friction or Coulomb

This torque is associated with dry friction, causing higher resistant torque in the transition from rest to motion. This torque can be given by:

$$T_r = \begin{cases} +K_C & for\ \omega > 0 \\ -K_C & for\ \omega < 0 \end{cases} \qquad (10)$$

Resistant torque due to viscous friction

This torque is proportional to the velocity and is given by:

$$T_r = K_{D_L}\omega_L \qquad (11)$$

Resistive torque associated with the turbulent flow of the fluids

This torque is described approximately by a quadratic function given by:

$$T_r = K_{A_L}\omega_L{}^2 \qquad (12)$$

The gear ratio is given by the inverse of the torque, affected by the efficiency of the gearbox, η_r. According to this the following relationship is obtained:

$$i_r = \frac{1}{\eta_r}\frac{(T_{L+w}+T_{load})}{T_m} \qquad (13)$$

The torque seen from the motor shaft can be determined by:

$$T_m = \frac{1}{\eta_r}\left[\frac{J_{L+w}\dot{\omega}_L + K_{D_{L+w}}\omega_L + K_{A_{L+w}}\omega_L{}^2 + K_{C_{L+w}}}{i_r} + T_{load}\right] \qquad (14)$$

The torque seen from the motor shaft as function of the motor speed is given by:

$$T_m = J'_{L+w}\dot{\omega}_m + K'_{D_{L+w}}\omega_m + K'_{A_{L+w}}\omega_m{}^2 + K'_{C_{L+w}} + T'_{load} \qquad (15)$$

where the inertia moment of the cutting cylinder and pulley seen from the motor shaft is given by equations (7) and (9), and linear and quadratic coefficients of friction are given respectively by:

$$J'_{L+w} = \frac{1}{\eta_r}\frac{1}{i_r^2}J_{L+w} \qquad (16)$$

$$K'_{D_{L+w}} = \frac{1}{\eta_r}\frac{1}{i_r^2}K_{D_{L+w}} \qquad (17)$$

$$K'_{A_{L+w}} = \frac{1}{\eta_r}\frac{1}{i_r^3}K_{A_L+w} \qquad (18)$$

$$K'_{C_{L+w}} = \frac{1}{\eta_r}\frac{1}{i_r} \qquad (19)$$

$$T'_{load} = \frac{T_{load}}{\eta_r i_r} \qquad (20)$$

The angular acceleration seen from the motor shaft is $\dot{\omega}_m = 7.1 \; rad/s^2$.

The power of the motor is given by:

$$P_m = T_m \omega_m \qquad (21)$$

For the operation of the machine under no load, the torque caused by the cylinder, by the pulley and by the torque due to static friction is 4532.7 Nm. During the operation process, the load torque is not constant since it depends of the type of material that is being processed. Thus, it was considered an increase of load torque by 20 %, which is equivalent to consider for the resistance torque a value of 5439.2 Nm. For a transmission ratio, $i_r = 2.8$, and an efficiency of the transmission system of 85 %, resistant torque from the point of view of the motor shaft, M_1 is approximately 2285 Nm.

Considering the motor speed of 993 rpm, the power of the motor M1 should be greater than 236.6 kW.
According to this, the selected motor to drive the system was an ABB motor Ref. M2CA 355 MA, whose main features are listed in table II.

Table II. – Characteristic of the electric motor.

	units	M_1	M_2	M_3 & M_4
Power	kW	250	2.2	4
Current In	A	472	4.9	8.7
Weight	kg	1550	27	45
Speed	rpm	993	1430	1430
Efficiency (100% load)		95.4	86	84
Power factor (cosφ)		0.8	0.8	0.8
Moment of inertia	kgm^2	10.5	53x10^{-4}	98x10^{-4}
Nominal Torque	Nm	2404	15	26.9
Manufacturer		ABB	SEW-Eurodrive	
Reference		M2CA 355 MA	D(F)V100M4	DRE100M4

4. Control System

The electric actuators that are used in the system are controlled via a programmable logic controller (PLC). The PLC that can be used to implement this part of the system is a Siemens S7-200 with CPU 224 or equivalent. This PLC allows the expansion of both digital and analog inputs/outputs. The analog ports allow to control the electrical drives connected to the electric motors. This PLC has 10 digital inputs and 14 digital outputs. This PLC may be connected to a source of 230 V, 50 Hz and has a DC source of 24 V. The PLC receives signals from different sensors of the system or the communication network Profibus DP and processes these signals according to the algorithm previously defined and providing their signs on the output ports. Fig. 9 shows the simplified scheme for the connections to this PLC.
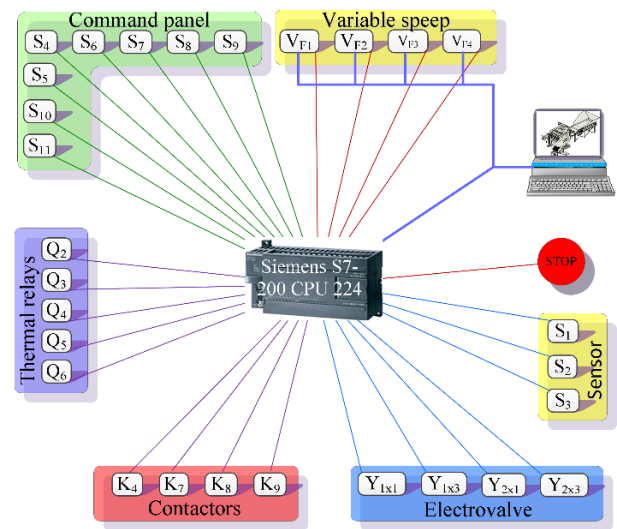

Fig. 9. Simplified scheme of the integration of the sensors with the PLC.

The variables used in the programming of the PLC are:

S_4 - Stop
S_5 - Start
S_6 - Button: Open the front door
S_7 - Button: Close the front door
S_8 - Button: Open the back door
S_9 - Button: Close the back door
S_{10} - Security key: Hydraulic pump
S_{11} - Operating Mode Selection
Q_2 - Thermic relay of the transformer 230V/24V
Q_3 - Thermic relay of the motor M_1
Q_4 - Thermic relay of the motor M_2
Q_5 - Thermic relay of the motor M_3
Q_6 - Thermic relay of the motor M_4
K_4 - Contactor: motor M_2
K_7 - Contactor: motor M_1
K_8 - Contactor: motor M_3
K_9 - Contactor: motor M_4
Y_{1x1} - Electrovalve: Direct direction of the front door
Y_{1x3} - Electrovalve: Inverse direction of the front door
Y_{2x1} - Electrovalve: Direct direction of the rear door
Y_{2x3} - Electrovalve: Inverse direction of the rear door
V_{F1} - Electrical drive for motor M_1
V_{F2} - Electrical drive for motor M_2
V_{F3} - Electrical drive for motor M_3
V_{F4} - Electrical drive for motor M_4
S_1 - Detector: Front Door
S_2 - Detector: Back Door
S_3 - Detector of presence of the sieve
Stop - Emergency stop

5. Conclusion

In this work it was presented the development of a system for the usability of forest residue biomass for electric energy production. The proposed system essentially consists in three very distinct parts, the mechanical, the hydraulic and the electric. The mechanical part is responsible by the fragmentation of forest or industrial residues. The hydraulic system is designed to drive the four hydraulic jacks, two in the front door and two in the

rear door. Finally, the electric system comprises four electric motors. These motors are used to provide mechanical energy to the cylinder that fragments the biomass and to the belts.

The proposed solution can be a step forward among the biomass processing systems since it accepts mixed residues of different sizes and shapes, and may allow to skip pre-processing fragmentation.

This solution focused over various areas of planning, however some of them were not extensively explored and has to be tested outside the virtual environment. An endurance test of the material regarding the fragmentation is essential for the determination of the load torque, and hence the choice of the main engine.

Furthermore, the electrical system can be completed with a level sensor mounted on the inner wall of the grinding compartment, an inductive sensor mounted on the shaft of the cutting cylinder and an inductive sensor mounted on the shafts of the drums of the conveyor belts. Nevertheless the developed machine fulfill the requirements that initially was predicted, thus its design can serve as a starting point for the construction of a testing prototype.

Acknowledgement

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