A didactic prototype to estimate the electric power produced by an angular motion

R. Castillo Meraz*, R.C. Martínez Montejano, I. Campos-Cantón and M.F. Martínez Montejano
Coordinación Académica Región Huasteca Sur (CARHS)
Universidad Autónoma de San Luis Potosí (UASLP).
Km. 5 Carretera Tamazunchale-San Martin, Zip Code 79960.
Tamazunchale, San Luis Potosí, México.
**e-mail: raul.castillo@uaslp.mx*

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This paper describes the design and implementation of an experimental system that estimates the electric power that can be produced by the angular motion showing the fundamental principles of mechanical-into-electrical energy conversion, which are the operation main basis of electromechanical devices such as wind turbines. Some theoretical concepts related with curricular subjects such as Electric mchenary, Physics, Renewable Energies, Power Electronics and Microcontrollers, were verified by Science students that participated in this project achievement. The main aim of this work is to show a simplified system development for didactic applications that can be mounted at indoor conditions and can be constructed from a set of basic and cheap electrical components.

Keywords: Electric Power; Electric Motor; Mechanical Power; Synchronous Generator; Wind Energy.

Este trabajo describe el diseño y la implementación de un sistema experimental de tipo didáctico que puede estimar cuanta potencia eléctrica se produce por un movimiento angular, mostrando así, los principios fundamentales de la conversión de energía mecánica en eléctrica los cuales son básicos para el análisis de la operación de dispositivos electromecánicos como lo son los aerogeneradores. En este trabajo se muestran algunos principios básicos relacionados con las asignaturas de Máquinas Eléctricas, Física, Energías Renovables, Electrónica de Potencia y Microcontroladores. Durante el desarrollo de este trabajo, estos principios fueron verificados por estudiantes de licenciatura quienes participaron en el desarrollo y caracterización de este prototipo. El objetivo principal de este artÃculo es el de mostrar el desarrollo de un sistema simplificado para aplicaciones didácticas que puede ser implementado en condiciones controladas de laboratorio y puede construirse a partir de elementos sencillos y económicos.

Descriptores: Potencia Eléctrica; Motor Eléctrico; Potencia Mecánica; Generador Síncrono; Energía Eólica.

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1. Introduction

During 2015, the world's energy tendency has changed drastically due to the collapse of oil prices leaving a better outlook for the renewable energy market. Almost half of the new global power generation capacity installed in 2014 was based on renewable sources [1].

Additionally, the world energy demand is projected to grow by 37% to the year 2040 [2]. This poses a real challenge to the world community because it is fundamental to increase the energy generation worldwide, but also requires that this energy does not impact even more the critical environmental conditions of the earth.

The renewable sources are an ideal option to deal with this problem. Nowadays, the wind energy is the most used renewable energy type (only below hydroelectric energy) and has been growing exponentially for the past decades. This fact is due to some advantages versus other renewable sources, like the high energy conversion high efficiency (compared to the photovoltaic cells) and his 24-hour generation.

In this context it is necessary to promote the study of this energy type at universities; it is also required to develop educational projects (with low cost) that help students understand their operation and learning about renewable energies and its relation with other subjects like Electrical Machinery. Recently works had been focused on this topic [3,4].

The main motivation for this project development was the demonstration of the relation between the wind and the electric power, through an experimental and didactic prototype for engineering and science students, in order to introduce them to this renewable energy systems due to wind turbines recent popularity, which are devices capable to convert wind energy into electrical energy.

This paper focuses on a didactic system that is based on the wind turbines energy conversion principle and was designed for helping undergraduate students to understand this principle and power conversion.

The advantages of this system are that can be constructed from a simple and cheap set of electrical and mechanical components that does not requires special conditions like three phase sources, electrical isolation or similar stuff; its development and operation can be done at indoor conditions without interferences and its start up can be easily done by undergraduate students. On the other hand, its principal disadvantage consists that is a simplified system; power losses due to mechanical friction, leakage currents or other similar facts are not considered on this prototype.

An overview of this work is shown here: In the first section, a basic introduction is presented. A wind power and power transformation theoretical development is made on section two. On the third section, the experimental system implementation is presented. A set of results are shown on the fourth section. Finally, the discussion and conclusions are presented on the fifth section.

2. Theoretical development

A theoretical framework is considered in this section: on the first subsection, the wind power theoretical development is presented. On the second subsection, the elements for the energy conversion are shown. Finally, the link between the wind linear speed v and the angular speed ω is explained, and the relation between the input power *P* and the output P_{gen} (electrical power) is presented.

2.1. Wind power theoretical development

Considering a system as shown in Fig. 1, and according to classical mechanics, the kinetic energy of a system of particles with mass Δm moving with a speed *v* is given by [5]:

$$E_k = \frac{1}{2}\Delta m v^2 \tag{1}$$

Therefore, we can define the available mechanical power P on a mass air flow Δm and a time Δt as:

$$P = \frac{E_k}{\Delta t} = \frac{1}{2}v^2\frac{\Delta m}{\Delta t} \tag{2}$$

Definition 2.1 *The fluid flow mass with density ρ through an area A and speed v is given by:*

$$\dot{m} = \frac{\Delta m}{\Delta t} = \rho A v \tag{3}$$

Applying definition 2.1 to Eq. (3), the wind power can be written as follows:

$$P = \frac{1}{2}\rho A v^3 \tag{4}$$

Where:

- ρ = Air density [kg/m^3]
- A = Transverse area [m^2]
- v = Wind speed [m/s]

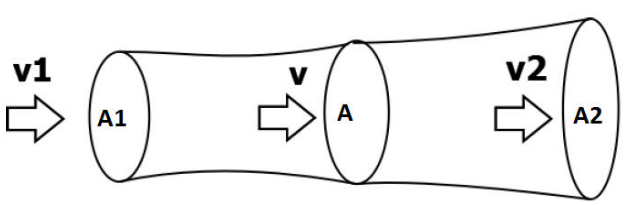


FIGURE 1. Model of an air flow across an area.

However, Eq. (4) is the available mechanical power generated by any wind flow, but an expression to know how much power can be extracted from the wind is needed. On Fig. 1 we can appreciate that the input speed (v_1) is different to the output speed (v_2). Taking an average speed, the average mass flow is given by:

$$\dot{\overline{m}} = \rho A\left(\frac{v_1+v_2}{2}\right) \tag{5}$$

Similarly, a kinetic energy change is given between v_1 and v_2 by:

$$\Delta E_k = \frac{1}{2}m\left(v_1^2 - v_2^2\right) \tag{6}$$

Considering Eqs. (5) and (6), the Eq. (4) can be rewritten as follows:

$$P_e = \frac{1}{4}\rho A\left(v_1+v_2\right)\left(v_1^2-v_2^2\right) \tag{7}$$

Where P_e is introduced in order to represent the extracted power from the wind. Eq. (7) can be reordered as follows:

$$P_e = \frac{1}{2}\rho A v_1^3\left[\frac{1}{2}\left(1+\frac{v_2}{v_1}\right)\left(1-\frac{v_2^2}{v_1^2}\right)\right] \tag{8}$$

Definition 2.2 *The Betz's Coefficient C_p indicates that the power could that be extracted of a wind flow is given by:*

$$C_p = \left[\frac{1}{2}\left(1+\frac{v_2}{v_1}\right)\left(1-\frac{v_2^2}{v_1^2}\right)\right] \tag{9}$$

According to the definition 2.2, the maximum power extracted from the wind occurs when $v_2/v_2 = 1/3$ and $C_p = 0.59$. So, Eq. (8) can be written as follows:

$$P_e = \frac{1}{2}\rho A v_1^3 C_p;\ 0 \le C_p \le 0.59 \tag{10}$$

This important result ensures that the maximum power that can be extracted will be $(16/27) \approx 0.59$ from the total available wind power.

2.2. Elements for the power conversion

The basic elements inside of a low-power wind turbine can be appreciated in Fig. 2 and they are described as follows:

- *Low speed shaft.* This part is attached to the blades and the rotor, and has low angular speed.
- *Gear system.* It is responsible for increasing the rotational speed of the low velocity shaft, and is the link between the low and high velocity shafts.
- *High speed shaft.* This part is attached to the electrical generator; its rotational speed is high and some thousands of revolutions per minute (RPM) could be reached.
- *Electrical Generator.* This part converts mechanical energy into electrical energy.

Some simplifications are considered in this work:

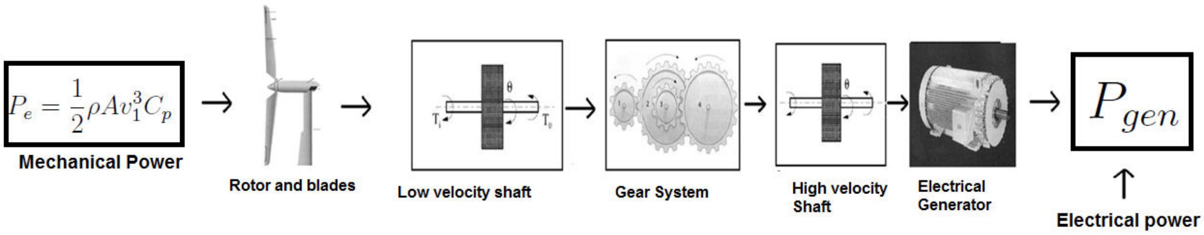


FIGURE 2. Basic elements for the power conversion of a low-power wind turbine.

1. All the mechanical power outside the blades and rotor is transmitted to the low speed shaft.

2. Power losses due to mechanical friction are depreciated.

3. Gear system is considered as a frictionless system and is represented with a pair of pulleys and a rubber band. According to the mechanical machinery, the relation between pulleys is:

$$\frac{\omega_2}{\omega_1} = \frac{d_1}{d_2} \tag{11}$$

   Where ω_2, ω_1 are the rotational speeds of the big and small pulleys respectively. Similarly, d_2, d_1 are the diameters of the big and small pulleys.

4. The electrical generator has an efficiency denoted by η. This parameter denotes how much mechanical power is converted to electrical power[7]. Asynchronous generators has high efficiencies $(0.8 \leq \eta \leq 0.9)$ and synchronous generators has a lower efficiencies $(0.5 \leq \eta \leq 0.7)$ [8].

2.3. Relation of the input power and the output power

Definition 2.3 *The relation between the linear wind speed and the rotational speed of the low speed shaft is given by the Tip Speed Ratio denoted by [6]:*

$$\lambda = \frac{\omega_1 R}{v} \tag{12}$$

Where:

- λ = Tip Speed Ratio (TSR)
- ω_1 = Rated angular speed of the low speed shaft
- R = Radius of the swept area
- v = Rated wind speed

This parameter can be calculated with the technical data of the wind turbine.

If the angular speed ω_1 is known, also the angular speed ω_2 can be calculated with Eq. (11); similarly, if the electrical generator efficiency is also known, the electric power at the output, can be calculated.

Finally, considering a frictionless system, the generated electrical power P_{gen} is given by the product of the two types of efficiency and can be calculated as follows:

$$P_{gen} = C_p \eta P \tag{13}$$

Where:

- P_{gen} = Electric Power [W]
- C_p = Mechanical efficiency
- η = Electrical efficiency
- P = available wind power [W]

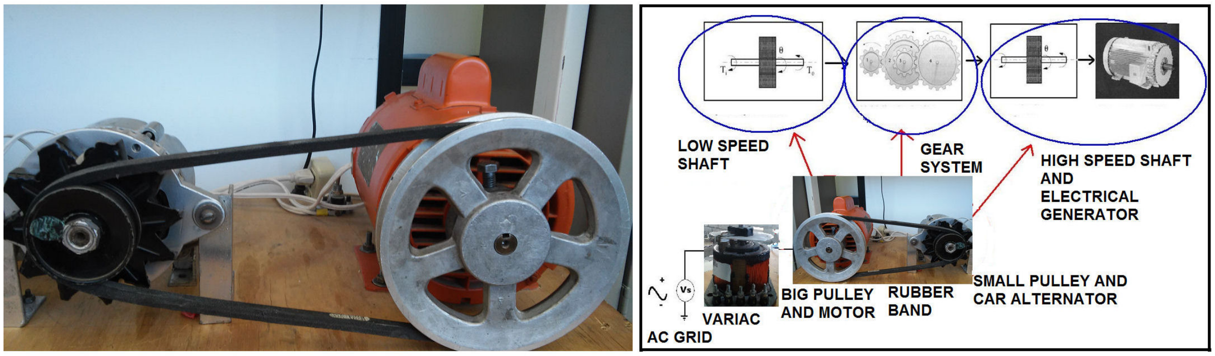
3. Implementation of the experimental system

This section describes each part of this experimental system and, then, an analogy between the system developed and a commercial wind turbine was done. In every stage of this implementation, undergraduate students were involved in order to apply the theoretical knowledge that they obtained on their classes.

The low velocity shaft rotation was emulated with an alternate current (AC) motor. The motor angular speed can be controlled with a variable transformer (VARIAC) connected between the motor and the AC grid. A big pulley is attached to this motor and these 3 parts (AC motor, VARIAC and big pulley) emmulate the behaviour of the low speed shaft. Then

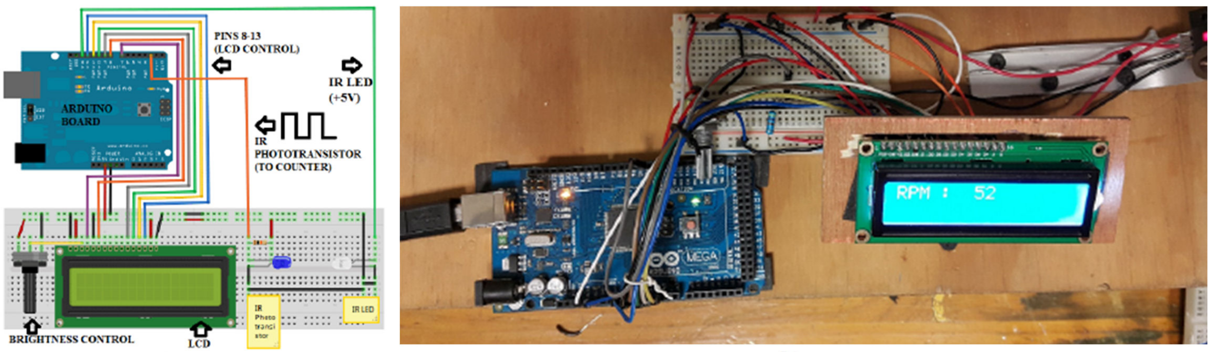
TABLE I. Comparative table of elements of the experimental system and a wind turbine.

Element of the system	Technical characteristics	Part of the wind turbine
Variable Transformer	STACO, 120 Vrms, 60 Hertz, 5 A	Low speed shaft
Electrical Motor	SIEMENS, 373 W, 1740 RPM max	Low speed shaft
Pulleys and Rubber Band	Aluminium, 1:4 ratio	Gear system
Car alternator	HITACHI, 12 V DC, 50 A max.	Electrical Generator



a) b)

FIGURE 3. a) Experimental system b) Analogy between the experimental system and a simplified wind turbine



a) b)

FIGURE 4. a) Digital tachometer schematic b) Real tachometer.

FIGURE 5. Experimental system with the safety protocol.

a rubber band connects the large pulley with another small pulley emulating the gear system. The ratio between the pulleys is 1:4. Finally, that small pulley is attached to a simple car alternator changing mechanical power into electrical power. Basically, this car alternator is a synchronous generator and needs a battery or DC source to operate. These parts are shown on Fig. 3 and a summary table with the characteristics of those parts is shown on Table I.

To know the angular velocity, a RPM counter of was implemented a on ARDUINO platform (Fig. 4). A pair infrared led and photo transistor was used to detect one revolution; then this digital pulse was sent to a digital counter on the ARDUINO board [10]. Using some programming code, it is simple to calculate the RPM and this number is sent to a Liquid Crystal Display (LCD).

To guarantee students safety that will operate the system, an acrylic wall with a list of cautions was mounted at the system's frontal side as can be seen on Fig. 5.

The recommendations to operate this system are explained as follows:

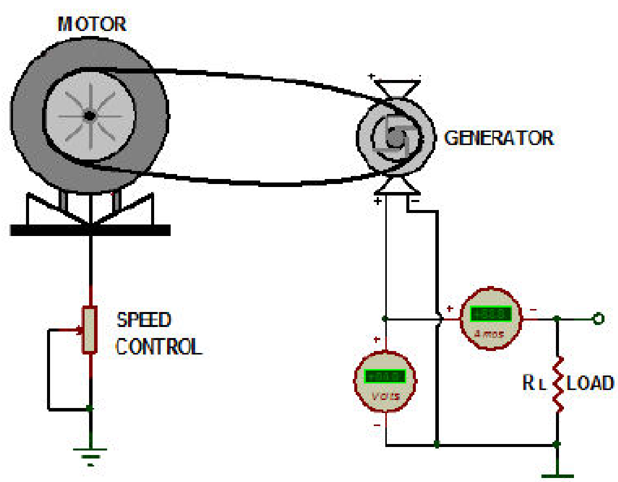


FIGURE 6. Schematic for the measurements of the prototype.

TABLE II. Table of measurements for the prototype

Motor RPM	Generator RPM	Voltage [V]	Current [A]	Electric Power [W]
85	340	3.94	0.87	3.42
116	462	6.27	1.24	7.76
162	649	7.3	1.45	10.61
243	972	9.27	1.85	17.12
250	1000	9.46	1.89	17.85
500	2000	19.83	3.95	78.4
575	2300	24.76	4.94	122.2
625	2500	28.7	5.72	164.16
750	3000	41.5	8.2	340.3

TABLE III. Comparison between angular speeds and output electric power

Motor RPM	Generator RPM	Electric Power [W]	Turbine RPM	Turbine Electric Power [W]
625	2504	164	142	152
651	2597	190.5	355	192
677	2710	220.9	497	218
705	2802	256.2	711	258
730	2915	297	853	298
765	3012	344	1066	348

The system will be operated by two students at the same time. It is very important not to wear any pendant accesories to avoid them be pulled by the pulleys or rubber band. It is also important for the students to wear safety glasses.

4. Experimental Results

In order to verify the system performance, current and voltage measurements were taken (Table II) according to the schematic showed on Fig. 6.

As expected, not significantly electric power could be obtained from low angular speeds (below 1000 RPM); but from 1000 RPM, electric power increases exponentially.

Then, for knowing the system quality of the developed system, a comparisson with a commercial low-power (Fig. 7) wind turbine was done and the results are shown on Table III. It should be mentioned that the SUNSOL-TEC turbine has a $C_p = 0.27$ and $\lambda = 4.29$.

In order to establish a relation between our prototype and the commercial turbine, the least squares method was used and the result is shown on Fig. 8.

This linear relation results on:

$$\omega_{\text{motor}} = 0.1379\omega_{\text{turbine}} + 604.24 \tag{14}$$

Finally and according to the Eq. (13), the relation between the electrical power of the turbine was:

$$P_{\text{gen}} = 0.243P \tag{15}$$

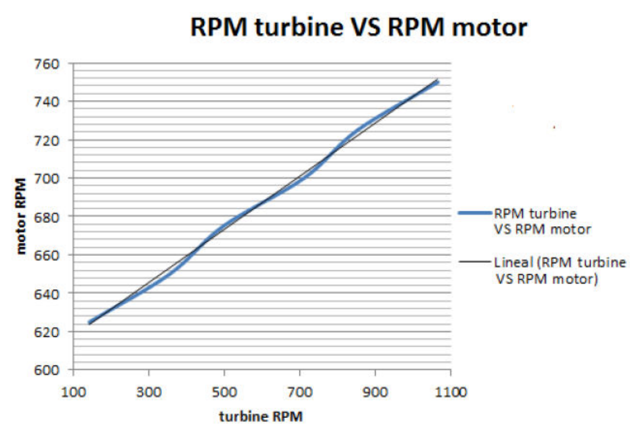


FIGURE 8. Graphic of the least squares method.

And for the experimental system was:

$$P_{\text{gen}} = 0.146P \tag{16}$$

5. Conclusions

A system that converts mechanical power into electrical power was presented on this paper and a comparison with a commercial low-power wind turbine was made. The system can be implemented at indoor conditions in scholar laboratories for related subjects with electrical machinery, power electronics, physics, microcontrollers and renewable energies.

The first results on Table II indicates that the electrical generator is not efficient at angular speeds below 1000 RPM.

This is due to the fact that is a synchronous machine and has an efficiency of $\eta = 0.54$ (according to the technical data). But, in order to minimize the project economical cost, this element was used because is easy to acquire and cheaper than the asynchronous generators.

As expected, the car alternator typical behaviour was confirmed: Low electric generation for speeds below 1000 RPM and acceptable electric generation for 2000-3000 RPM. Theoretically and according to the manufacturer, this alternator can generate 50 Ampere at 10,000 RPM.

On Table III, a similar electrical power could be appreciated but the difference is that the system needs more RPM to reach the power generated by the commercial turbine. A rank from 625 to 765 RPM (at low speed shaft) is needed to emulate the behaviour of the turbine (that has $\eta = 0.8$); Eqs. (15) and (16) show this fact.

On the other hand, with some cheap electrical elements, a basic power conversion system was made. The low-power wind emulator total cost was about of 190 U.S. dollars with new components. Using pre owned parts, the total cost can be about 85 U.S. dollars; this is a very reasonable cost compared with commercial low-power wind turbines whose price ranges around 400 U.S. dollars (In Mexico, SUNSOL-TEC turbine had a cost of 440 U.S. dollars).

As future work, we will implement a larger pulley and powerful motors to emulate the low speed shaft and probably less RPM at the low speed shaft could be needed to reach similar behaviour of the commercial turbine; but this implies that the total cost will be higher.

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