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Design and Manufacturing of a System That Generates Renewable Energy from A Permanent Magnet Generator

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Abstract: The most efficient electric generators to use in low power wind turbines are those of permanent magnets, this being one of the most expensive components of wind turbine. In this work, a prototype of a synchronic generator of axial flow was designed and built, based on Neodymium-Iron-Boron permanent magnets to be installed in low power wind turbines (less than 0.5 KW). The work was based on the following premises: 1) Designing and specification of the electrical and mechanical components of the generation system for wind turbines. 2) Building the power generation system, 3) Realizing tests and measurements of the constructed prototype. All the parts of the generator (rotor, stator, AXIS, base and coils) were designed and built using the following machinery: pantograph, grinder, bench drill, bench sander, tin soldering iron, winder, industrial dryer, rotating lathe. The result was a three-phase axial generator with 12 pairs of poles, with 24 magnets located in a rotor of 165 mm diameter and 9 coils connected in a star shape, offset by 40 degrees from one another. The tests yielded a maximum voltage test of 7.6 Volt at 500 rpm, obtaining a linear relationship between voltage and rotational speed. Although, this design is very low power, its construction allowed to obtain the necessary experience and knowledge-know how- for the development of future electric generators for low power wind turbines in the alar profile research group.

Key words: permanent magnet, generator, stator, rotor, wind turbine

1. Introduction

The model of the current economic development around the world is based on the intensive use of fossil energetic resources mainly in the underdeveloped countries.

These fuels are not renewable, they are finite and so the reservoirs are depleted progressively.

On the other hand, their extraction, processing, and combustion increase the proportion of greenhouse effect and release toxic gases to the atmosphere.

In order to find a solution to this problem, a Project called "social wind turbine" has been created. The aim of the Project is to develop wind turbine of horizontal axis, low-powered and manufactured from reused materials to be installed in poor communities. In order to achieve this goal, a wind turbine prototype has been manufactured and installed in the National University de Tres de Febrero in Villa Lynch. This prototype will be used to adjust the design variables. This project has been approved by the university (Code 32/17 521).

The aim of this project is to design and manufacture the electrical energy generator system in a laboratory scale. To make it reproducible, the design has some features: easy manufacture, assembly, installation and operation. Making the prototype more accurate will give poor communities access to safe and reliable electric power.

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2. Materials and Methods

The paper starts with the design of the generation system. At this stage, equations, criteria, materials and assumptions necessary to get the design variables are presented.

A permanent magnet generator has been proposed to turn the mechanic energy obtained into electrical energy.

In this type of generator, the magnetic flux goes through the coils in a parallel direction to the axis device. This device consists of two rotors and one stator. Both rotors are joined by a longitudinal axis and the stator is installed in a fixed base. The copper wire coils are in the stator, there the tension is generated by the magnetic field rotors. The magnets are displayed to let the magnetic flux go from one rotor to another. The magnetic flux goes through the coils as the rotors turn round. In this way, the sinusoidal voltage is induced in the coils [1]

For the development stage, the paper "Axial Flux Permanent Magnet Generator Design for Low Cost Manufacturing of Small Wind Turbines" [2] was used as a reference. After the realisation of the calculations in the design stage, the values for the manufacturing of the laboratory scale generator were obtained as shown in the data Table 1.

2.1 Number of Poles and Coils

The number of poles in a generator is directly related to the frequency of the voltage we want to generate. The nominal frequency determines the pole pairs p, and so the total number of magnets.

$$p = \frac{120\, f_{nom}}{n_{nom}} \tag{1}$$

$$0.5 = \frac{2Q}{3p} \tag{2}$$

The permanent selected magnets are rectangular and of Neodymium-Iron-Boron (NdFeB). It is possible to reuse the magnets in the hard discs to reduce the cost in the manufacturing generation system and at the same time to positively contribute to the environment.

Table 1 List of symbols [1].

ai	pole arc to pole pitch ratio
Bmg	magnetic flux density on magnet surface (T)
Bp	peak value of the fundamental component of airgap flux density (T)
Br	remanent magnetic flux density (T)
Cpmáx	maximum power coefficient
Cq	heat coefficient (W/cm^2)
dc	copper diameter (mm)
Din	generator inner diameter (mm)
Dout	generator outer diameter (mm)
Ef	electro-magnetic force (V)
fnom	generator nominal frequency (Hz)
G	mechanical clearance gap (mm)
Hc	coercive field strength (A/m)
hm	permanent magnet thickness (m)
hr	back iron thickness (m)
IAC	nominal AC current (A)
IACmax	maximum AC current (A)
Jmax	maximum current density (A/mm^2)
kd	inner to outer radius ratio
kf	coil fill factor
ksat	saturation factor
la	active length (m)
laug	average coil length (m)
lec	end-turn length (m)
Is	generator inductance (mH)
N	generator RPM
Nc	number of turns per coil
nnom	nominal RPM
Nphase	number of turns per phase
P	number of pole pairs
Pair	aerodynamic power (W)
Pnom	generator nominal power (W)
PCU	ohmic losses (W)
pcu	copper density (kg/m3)
Q	number of coils per phase
Q	total number of coils
Rc	coil resistance (Ω)
Rin	inner radius (m)
Rout	outer radius (m)
R turb	wind turbine diameter (m)
Sc	copper crosection (mm^2)
SPM	permanent magnet surface area (m^2)
tw	stator axial thickness (m)
vw	wind speed (m/s)
wc	coil side width (m)
wm	permanent magnet radial width (m)
H	generator efficiency
λopt	optimum tip speed ratio
µ0	vacuum permeability (Wb/(A·m))
µrrec	recoil permeability
Ρ	air density (kg/m^3)
ρcu	electrical resistivity of copper (Ω m)
Φmax	maximum magnetic flux (Wb)
ωe	electrical speed (elec.radians)

The number of coils (Q) can be calculated from the Eq. (2). The appropriate pole pair for coil combinations for a three-phase system is shown in Table 2.

Table 2 Pole-coil combinations [1].

8-6	12-9	16-12	20-15	24-18

The combination 12-9 was used. The coils will be connected in a three- phase system using a star connection. The coils should be separate by 120° electric degrees regarding the other phase.

2.2 Axial Dimensions of the Generator

The Axial dimensions of the generator include the mechanical clearance gap (*g*), the thickness of the stator (*tw*), the thickness of the rotor discs (*hr*), and the thickness of the magnets (*hm*) as shown in Fig. 1.

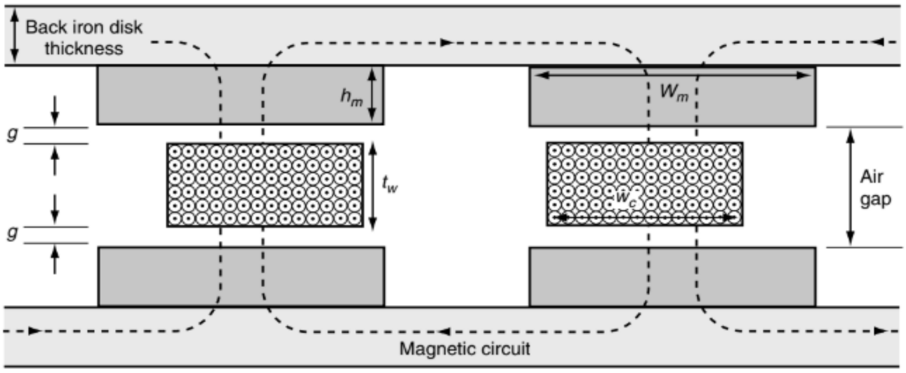


Fig. 1 Axial dimensions of the generator (rotor disks and magnets, stator coils and clearances).

The mechanical clearance gap (*g*) is one mm.

Magnets Dimensions

thickness (h_m): 3 mm; width (w_m): 10 mm; length (l_a): 20 mm

2.3 Rotor Disc Thickness

The rotor discs thickness that makes the rotors should be reduced to as much as possible to avoid increases in the total weight of the generator, but at the same time it should not be reduced too much in order to withstand the attractive magnetic forces pulling the two rotors discs together and thus ruining the mechanical clearance gap damaging the generator.

Also magnet saturation is possible in the iron disc if it is chosen too thin. Nevertheless we can use a general rule which indicates that the thickness of the rotor should be the same as the thickness of the magnets. The diameter selected for the rotors is 16.5 cm.

2.4 Axial Coil Thickness (t_w)

The *tw* can be calculated through the equation 3 which results from the analysis of the magnetic circuit while assuming no magnetic flux density leakage. The magnetic flux density near the magnet surface B_{mg} is usually set about *br/2*, where the remanent magnetic flux density *Br* and coercive field strength *hc* are characteristic values of the magnet that are related to its grade and can be easily extracted from neodymium magnet data sheets. Other variables are $k_{sat} = 1$ due to the coreless stator and μ_0 the vacuum permeability.

$$B_{mg} = \frac{Br}{2} = \frac{B_r}{1+\mu_{rrec}\frac{(g+0.5t_w)}{h_m}k_{sat}} \quad (3)$$

$$\mu_{rrec} = \frac{1}{\mu_0}\frac{B_r}{H_c} \quad (4)$$

Due to the fact that the magnets are NdFeB N40, the equation can be rewritten for the stator thickness (t_w) as:

$$t_w = 2h_m - 2g \quad (5)$$

$$t_w = 2\,(3\,mm) - 2(1\,mm) = 4\,mm$$

2.5 Number of Turns per Coil (N_c)

Using basic equations for the electromagnetic induction and assuming an almost sinusoidal magnetic flux density, the required turns per coil can be calculated using Eq. (6).

$$\Phi_{max} = B_{mg} * w_m * l_a \tag{6}$$

$\Phi_{max} = 0.64T * 0.01m * 0.02m = 1.28\times10^{-4}$Wb

The number of turns per coil *Nc*, is calculated using 7 where k_w is a winding coefficient equal to 0.95, *Q* is the number of coils per phase, *n* is the *RPM* at cut-in and ef is the corresponding induced voltage during the the cut-in.

$$N_c = \frac{\sqrt{2}E_f}{q*2\pi*k_w*\Phi_{máx}*n*\frac{p}{120}} \tag{7}$$

$$Nc = \frac{\sqrt{2}*12V}{3*2\pi*0.95*1.28\text{x}10^{-4}\text{Wb}*160rpm*\frac{12}{120}}$$

$$Nc = 462.74\ vueltas$$

2.6 Coil Width (w_c)

Given the number of turns per coil N_c and the axial stator thickness t_w, the coil leg width w_c is calculated in 8 for a value of the heat coefficient *cq* that is equal to 0.3 W/cm^2 and where $I_{ACmáx}$ is the maximun generator current and *p* is the electrical resistivity of copper.

$$w_c = \frac{I_{AC\,máx}*N_C}{\sqrt{\frac{2*cq*k_f*t_w}{\rho}}} \tag{8}$$

The fill factor *(kf*) of the coils could be about 0.55 due to the fact that construction of the coils is manually done.

2.7 Heat Coefficient cq and Maximun Current Density J_{max}

Along with the heat coefficient *cq*, the maximun current density J_{max} of the winding must be cosidered as shown in 14.

This is possible after realising the Eq. (9) for I_{ACmax} where in the place of I_{AC}, I_{ACmax} is used which is the maximun current used produced momentarily in a gust of wind which is 10% more powerful than the nominal potential P_{nom}. So 15 has to be calculated for the copper cross-sectional area.

$$I_{ACmáx} = \frac{1.1*P_{prom}}{3*E_{fnom}*\eta} \tag{9}$$

To know the value of I_{AC} it is necessary to calculate E_{fnom}, which is obtained from the following equation:

$$E_{fnom} = \frac{n_{nom}}{n_{cutin}} * E_{fcutin} \tag{10}$$

$$E_{cutin} = \frac{E_f+1.4}{\sqrt{3}*1.35} = \frac{12\ V+1.4}{\sqrt{3}*1.35} = 5.74\text{ V} \tag{11}$$

$$n_{nom} = \frac{60*v_w*\lambda_{nom}}{2\pi*R_{turb}} = \frac{60*10\frac{m}{s}*7}{2\pi*1.5m} = 445.63\text{ rpm} \tag{12}$$

$$n_{cutin} = \frac{60*v_{cutin}*\lambda_{cutin}}{2\pi*R_{turb}} = \frac{60*3\frac{m}{s}*8.75}{2\pi*1.5m} = 167.11\text{ rpm} \tag{13}$$

As it is shown in the Eqs. (11), (12) and (13) it was assumed an E*f* of 12 V, a minimun wind speed of 3 m/s and a nominal wind speed of 10 m/s. On the other hand, a value of λ_{cutin} of 8.75 was used, a value of λ_{nom} *of 7* and *a* R_{turb} of 1.5 m.

$$E_{fnom} = \frac{445.63\ rpm}{167.11\ rpm} * 5.74\ V$$

$$E_{fnom} = 15.28\ V$$

Supposing that η = 0.9 then the value of $I_{acmáx}$ can be calculated

$$I_{ACmáx} = \frac{1.1 * 35\ V}{3 * 15.28\ V * 0.9} = 0.933\ A$$

Once the value of $I_{ACmáx}$ is known, the side width of the coil can be calculated with the Eq. (8).

$$w_c = \frac{0.933\ A * 462.74\ rpm}{\sqrt{\frac{2 * 3000\frac{W}{m^2} * 0.55 * 0.00371428m}{0.0000000168\ \Omega\ \text{m}}}}$$

$$w_c = 0.01598\ m$$

A standard approach for the design of the small wind turbine would be a value for the current density of 6A/mm^2 without this value being restrictive. The structure of the generator, with the rotating discs working as fans cooling the winding system allows high current density values.

$$J_{máx} = \frac{I_{ACmáx}}{S_c} \tag{14}$$

2.8 Copper Diameter (d)

The copper cross-sectional area *sc* and the diameter of the copper wire dc which will be used, it is obtained from Eq. (15) and (16) respectively.

$$s_c = \frac{k_f*w_c*t_w}{N_c} \tag{15}$$

$$s_c = \frac{0.55 * 0.01598 \text{ m} * 0.00371428\text{m}}{462.74\ rpm}$$

$$s_c = 7{,}0569\text{x}10^{-8} m^2$$

$$d_c = \sqrt{\frac{4 * s_c}{\pi}} \tag{16}$$

Substituting the value *sc* in the previous equation, the value of the copper wire diameter is obtained.

$$d_c = \sqrt{\frac{4 * 7{,}0569\text{x}10^{-8} m^2}{\pi}}$$

$$d_c = 2.997x10^{-4} m$$

With the result obtained in Eq. (15) $J_{máx}$ of the Eq. (14) is obtained.

$$J_{máx} = \frac{I_{ACmáx}}{S_c} = \frac{0.933\ A}{7{,}0569\text{x}10^{-8} mm^2}$$

$$J_{máx} = 13221102.75\ \frac{A}{mm^2}$$

The form of the coils: It is a general rule that the inner form of the coils has to have the same dimensions as the magnets

The generator radio: Using all the variables obtained previously, the diameter of the steel discs can be calculated.

$$R_{in} = \frac{(2Q * w_c) + (p * w_m)}{2\pi} \tag{17}$$

$$R_{in} = \frac{(2 * 9 * 0.01598521181 \text{ m}) + (12 * 0.01\ m)}{2\pi}$$

$$R_{in} = 0.0648 \text{ m}$$

$$D_{out} = D_{in} + 2l_a \tag{18}$$

$$D_{out} = (2 * 0.0648 \text{ m}) + (2 * 0.02\text{m})$$

$$D_{out} = 0.1697 \text{ m}$$

2.9 Generation System Manufacturing

2.9.1 Materials (Table 3)

2.9.2 Machinery (Table 4)

Table 3 Materials and dimensions.

Parts	Components	Quantity	Dimensions
Rotor	Magnets	24	l_a: 20 cm w_m:10 cm h_m: 3 mm
	Low carbon steel plate	2	D_{out}: 165 mm h_r: 3 mm
Stator	Paraffin	250 g	-
	Copper wire	500 g	d_c: 0.3 mm
	Tape	-	-
Axis and Base	Wood plank	1	Long: 170 cm *Width:* 20 cm *Thickness:* 4 cm
	Ball bearings	2	Diameter (in): 12 mm *Diameter (out)*: 32 mm
	Threaded rod	1	Diameter (out):12 mm
Others	Nut	8	Diameter (in): 12 mm
	Screws	11	Diameter: 4 mm
	Washers	8	Diámeter (in): 12 mm

Table 4 Machinery and application.

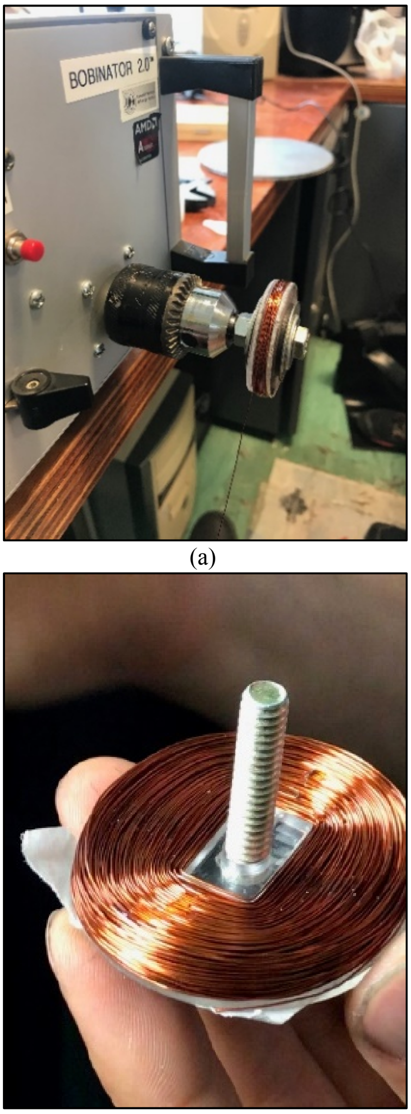
Machinery	**Application**
Pantograph	Circular cutting of steel plates for the rotor
Grinder	Edge rounding
Drill press	Circular cutting of acrylic plates and wood drilling
Pencil soldering iron (low power)	Cable welded
Oscilloscope	Obtaining the sinusoidal curves
Gaussimeter	Magnetic field measurement
Rotating lathe	Shaft rotation
Industrial dryer	Paraffin casting
Winder	Winding of copper wire

2.10 Stator Manufacturing

The stator manufacturing started with the winding up of the copper wire of 0.3 mm diameter. This was realised with a winder which possess a turns counter and let us set different speeds for the winding up.

A device that works as a winding mold was developed; it allows to keep the right dimension of the coil (thickness and width) and it also gives it the right size as shown in the Fig. 2.

As it was mentioned in the design stage, the inner form of each coil has to be the same as the form of the magnets that's why an acrylic mold was inserted.



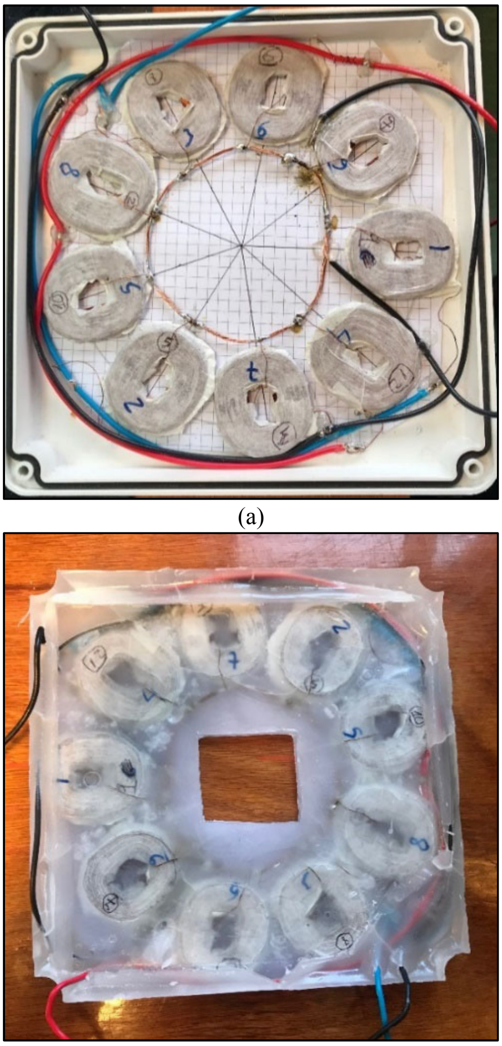
(a)

(b)

Fig. 2 (a) Winding process, (b) Inside of the coil.

The winding process was done at different speeds based on the forms the coils were taking and it finished when the device showed 462 turns. Twelve coils were made and nine were selected. The coils whose inductance values were similar, were selected.

Then the coils were placed in a rectangular plastic mold and covered with paraffin. A circumference was realised manually. This circumference was devided in 9 parts to ensure the right place of the coils. Then a neutral circular wire was placed in the center of the mold and the initial ends were joined to each coil. Once the ends were linked, the three-phase connection started.



(a)

(b)

Fig. 3 (a) Three-phase connection, (b) Stator embedded in paraffin.

The coils 1, 2, 3 constitute the first phase (blue wire), 4, 5, 6 the second phase (red wire) and 7, 8, 9 the third phase (black wire). Later 250 paraffin grams were heated until it became liquid and this was put in the mold to form the stator.

The result was a stator of 19.6 cm wide, 19.6 cm long and 6.1 cm thick.

2.11 Rotors Manufacturing

For the manufacturing of the rotors, a low carbon steel plate was used. The plate was cut with a pantograph and two discs (165 mm in diameter and 3 mm thick) were obtained. Every measurement was calculated in the design stage.

Three drillings were made in each disc. One in each centre (12 mm in diameter) and the other two were made to join both discs so that they could reach the same speed. The location of the twelve magnets was drawn to fix them in the right position, well aligned. After that the magnets were inserted alternatively.

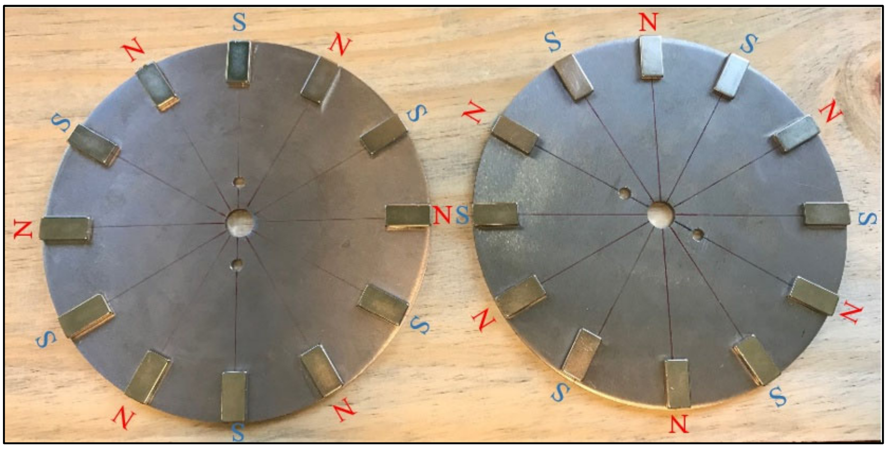


Fig. 4 Rotors with permanent magnets.

2.12 Assembly and Installation

Once the rotors and the stator were built, the Assembly of the Generation System was started. The rotors were placed on a longitudinal axis and the stator (between the two rotors) on a fixed base. Also one of the phases was connected to 4 led lights to check the operation of the generator.

2.13 Costs

For the manufacturing of the energy generator system based on permanent magnets, reused materials were used. Not all the materials were reused because of the lack of time to collect them.

2.14 Measurement of the Magnetic Field

For the measurement and detection of the electromagnetic fields a Gaussmeter was used to measure the magnetic influence produced by the permanent magnets. The unit of measurement obtained was kG. Before the measurement of magnetic field, the equipment was calibrated.

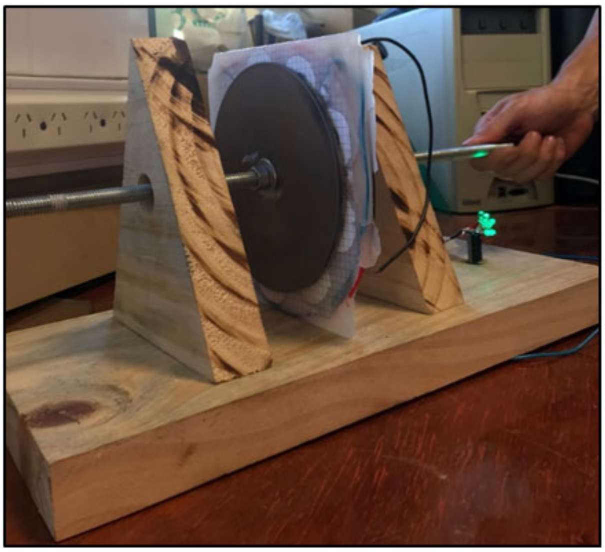


Fig. 5 Permanent magnet generator.

Table 5 Costs of manufacturing.

	Components	Quantity	Cost / Obtaining
Rotors	Neodymium-Iron-Boron (NdFeB) magnets	24	$383
	Steel plates	2	Reused
Stator	Paraffin	250g	$42
	Copper wire	500g	$371
Axis and base	Wood plank	1	Reused
	Threaded rod	1	Reused
	Ruleman	2	$100
Others	Nuts	8	Reused
	Washers	8	Reused
	Screws	11	Reused
Total	-----------------------	------------	$896

Once the equipment was calibrated, the sensor was put on the magnets and the measurement was realised. The value of the magnetic field obtained was -2.63 kG at the temperature of 24ºC.

2.15 Resistance and Inductance of the Phases

Once the manufacturing of the stator was finished, the values of R and L of each phase were measured at 100 hz.

2.16 Sinusoidal Curve

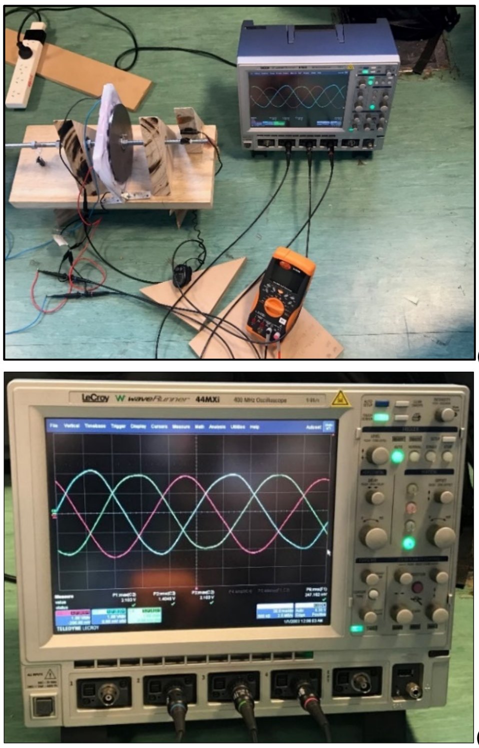
A three-phase system is the set of three monophases which are outphased at 120º.

2.17 Electrical Tests

To measure the tension and the revolutions per minute (rpm) the generator was connected to a voltmeter and a tachometer. Consequently an axis was joined to a drill to make it turn around to measure at different speeds.

2.18 Tension vs RPM

To obtain the graph of tension with load based on the rpm, one phase was connected to three resistors of 1 ohm each. Knowing that the power is Tension^2/Resistance, it was multiplied by three to get the delivered power to the three loads.



(a)

(b)

Fig. 6 (a) Connecting the generator to the oscilloscope, (b) Sinusoidal curve.

Table 6 RPM vs. voltage.

Data	Rpm	Volt (V)	Power (W)
1	25	0.456	0.6238
2	138	0.4789	0.6880
3	145	0.4653	0.6495
4	147	0.4892	0.7179
5	149	0.4813	0.6949
6	151	0.4891	0.7177
7	162	0.6404	1.2303
8	213	0.7746	1.8000
9	236	0.7869	1.8576
10	240	0.7822	1.8355
11	243	0.7912	1.8780
12	246	0.9067	2.4663
13	266	0.9297	2.5930
14	286	0.953	2.7246
15	290	0.9224	2.5525
16	295	0.9425	2.6649
17	311	1.0594	3.3670
18	333	1.09	3.5643
19	338	1.0966	3.6076
20	343	1.1003	3.6320
21	360	1.345	5.4271
22	413	1.4111	5.9736
23	449	1.4287	6.1236
24	459	1.4759	6.5348
26	472	1.5359	7.0770
27	493	1.6091	7.7676
28	500	1.5999	7.6790
29	515	1.5446	7.1574
30	493	1.4975	6.7275
31	486	1.5626	7.3252

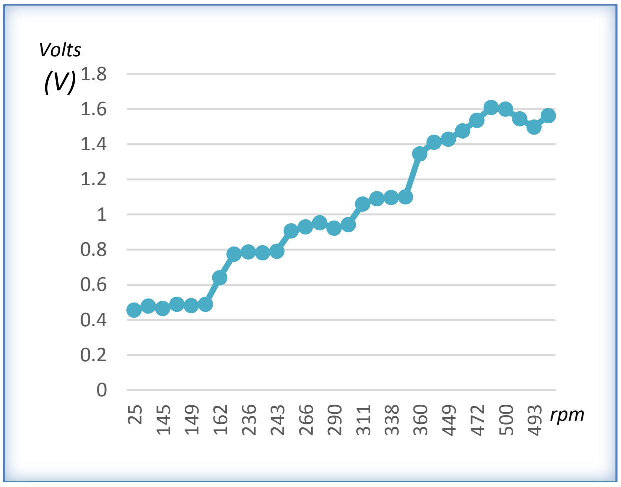


Fig. 7 Volts vs. rpm.

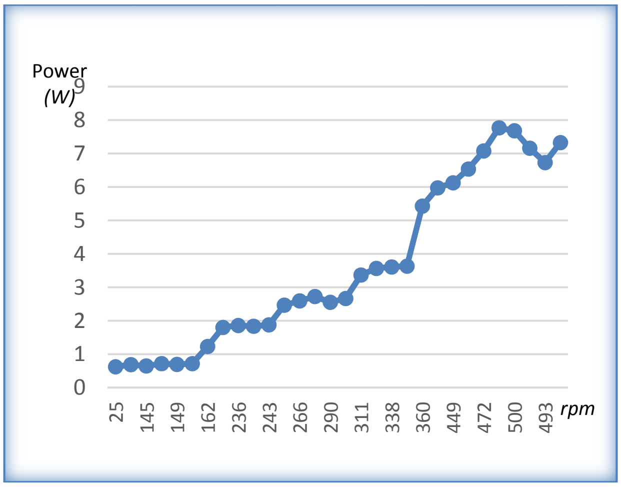


Fig. 8 Potencia vs rpm.

The maximun voltage obtained was 1.6091 V at 493 rpm giving out the maximun power of 7.76 W.

3. Results and Discussion

The generation of energy based on the application of the Faraday-Lenz law using permanent magnets is a good alternative to be installed in the wind turbine prototype located in Villa Lynch.

The current development from its proposed small scale represents a potential solution to the crisis that is currently overwhelming us around the world in reference to exhaustion of the natural resources and the global warming.

The stages of design, manufacturing and measuring done during the current work meant an incentive to continue doing research on the exploitation of wind resources.

This development let us identify the methods which better adapt to low budgets and short time lapses in the manufacturing.

It is clear that the power achieved with this prototype is not enough to meet the energy needs of the university. However, considerable quantities of energy could be obtained by increasing the scale and by optimizing the operation variables in future developments.

3.1 Aspects to Improve

It is important to use the appropriate materials to keep the main features and structural integrity intact. Next, some aspects of the generator are detailed to be improved, which will be useful to optimize the design variables.

Stator: A 3D printer is a good alternative for the manufacturing of the stator. A good option for the winding process is to use a precision coiler so as not to get a lot of space between the copper overlapping layers. Thus, the width of the coils will be reduced approaching the design values

Rotors: The use of the most quantity of magnets in the rotor can mean an important improvement for the generator because the magnetic field would be intensified.

Base and ball bearings: A good choice for the base would be the use of a satellite panel with honeycomb structure because it is resistant and light. However, it is difficult to acquire this material. The support of the ball bearing can be obtained from a 3D printer to reduce its size and weight.

3.2 Future Works

The development of the energy generation system based on permanent magnets was very important to know in detail the design and manufacturing process of these types of generators. Based on this work, the necessary adjustments will be made so that the generation system to be installed in the prototype located in Villa Lynch will not have mechanical or electric defects before it starts operating.

From this starting point, a future job will be to implement the proposed aspects to improve and then to propose a storing energy system through batteries. Once this system is optimized, the installation of this device in the university is the next step. To get more energy, solar panels can also be installed.

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