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Characterization of an axial flow generator for applications in wind energy

Caracterización de un generador de flujo axial para aplicaciones en energía eólica

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Abstract

The use of unconventional energy resources in recent years has developed mainly with the intention of reducing the use of fossil fuels to obtain electricity. When talking about electricity generation at medium and small scale, the global trend while taking advantage of wind energy, is the use of permanent magnet generators. Axial flow generators are the most often available: the main feature of these generators is their ability to deliver electrical power at low revolutions, with an acceptable efficiency. In this research project two types of axial flow generators were characterized; one with coils in series and another with coils in parallel, with the intention of evaluating the performance of each one. The design starts from the determination of the magnetic flux, number of revolutions, number of poles, number of coils, output voltage and electrical losses, to then carry out the contrast through the data acquisition of amperage and voltage with respect to the theoretical calculation; the purpose is to establish the efficiency of each of the configurations. It was established that the series generator has characteristics that make it a configuration that has an efficiency greater than that of the generator in parallel.

Keywords: Generators, flow, axial, energy, wind, efficiency.

Resumen

El aprovechamiento de los recursos energéticos no convencionales en los últimos años se ha desarrollado principalmente con la intención de disminuir el uso de combustibles. A mediana y pequeña escala la tendencia mundial, cuando se habla de generación eléctrica utilizando la energía eólica, es el uso de generadores de imanes permanentes. Los generadores de flujo axial son lo que se encuentran con mayor frecuencia a disposición. La principal característica de estos generadores es su capacidad de entregar energía eléctrica a bajas revoluciones, con una eficiencia aceptable. En este proyecto de investigación se caracterizaron dos tipos de generadores de flujo axial; uno con bobinas en serie y otro con bobinas en paralelo, con la intención de valorar el rendimiento de cada uno. El diseño parte de la determinación del flujo magnético, número de revoluciones, número de polos, número de bobinas, voltaje de salida y pérdidas eléctricas, para luego realizar el contraste a través de la toma de datos de amperaje y voltaje con respecto al cálculo teórico; la finalidad es establecer la eficiencia que presentan cada una de las configuraciones. Se estableció que el generador en serie posee características que lo convierten en una configuración que tiene una eficiencia mayor que la del generador en paralelo.

Palabras clave: generadores, flujo axial, imanes permanentes, energía eólica, eficiencia.

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1. Introduction

The growing demand for fossil fuels, together with the reduction of their reserves, has unleashed a continuous increase in prices that affects the world economy. In addition, the use of these fuels produces gases, such as carbon dioxide (CO_2), whose greenhouse effect causes an increase in the temperature of the planet's surface [1].

According to the WWEA in its September 2016 newsletter, at the end of 2014 the installed capacity of small-scale wind registered more than 830 MW worldwide. This represents a growth rate of 10.9% in relation to 2013, when 749 MW were registered. The year 2013 was 10.3% higher than the total of 678 MW installed in 2012.

China accounts for 41% of global capacity, the United States 30% and the United King-dom 15%. At the end of 2014, a cumulative total of at least 945 000 small wind turbines were installed worldwide. This represents an increase of 8.3% (7.4% in 2013) compared to the previous year, when 872 000 units were registered [2]. It is estimated that the capacity in the mini-wind industry by 2020 could sup-ply 50 000 MW worldwide [1].

To help reduce costs and minimize maintenance as much as possible, many wind turbine developers employ direct-drive (without gearbox) permanent magnet generators (PMG) as long as they have a mechanically simple generator design. Several permanent magnet generator topologies can be used [3].

A suitable design for a generator with central stator axial flow is based on two rotor pieces that are lateral-ly fixed to the axis of the machine. This configuration of two air gaps has the advantage of canceling the lon-gitudinal forces on the stator. In addition, this topology minimizes the dispersion inductance [4].

The goal of this project is to characterize PMG axi-al flow in two configurations of coils, one in series and the other in parallel using iron-boron-neodymium magnets, to determine the efficiency of each of them.

1.1. Design features of an axial flow generator

It consists of a pair of thin iron disks that revolve around an axis perpendicular to it, and in whose contour a set of magnets is placed, which in turn creates a magnetic field parallel to the axis of rotation as shown in Figure 1. The axial arrangement for cutting the magnetic field is parallel to the winding. This kind of arrangement allows an excitation of the electrons without friction and magnetic opposition. The cut made is of 180° producing fewer losses than with radial generation [5].

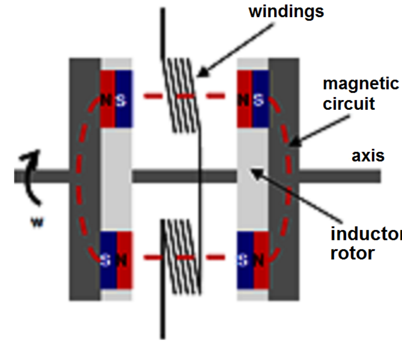

Figure 1. Transverse view of an axial generator.

1.2. Coils with an air core

The conductor is rolled up on a hollow support which is then removed, resulting in something that looks similar to a spring. It is utilized in elevated frequencies. A variant of the previous coil is called a solenoid, which differs in the insulation of the coils and the presence of a support that does not necessarily have to be cylindrical. It is utilized when several turns are required. These coils can have intermediate sockets. In such cases, they can be considered as two or more coils on the same support and connected in a series.

Each coil produces a voltage depending on how they are connected, which can be of two types: in series and in parallel. The series connection consists of joining the end of the first coil with the beginning of the next so that the voltages are added. On the other hand, in parallel connections the ends are connected to each other and the resulting voltage is the same as that of a coil, with the difference that twice the current can be obtained. It is inevitable that the output voltage of each coil will be slightly different in parallel configu-rations, which leads to the generation of eddy currents that waste energy [6].

Figure 2 shows the connection of three coils in se-ries for each phase, and a stator composed of nine coils in total, therefore it is a three-phase generator. A remarkable advantage of this generator is that the recti-fier only requires three cables [6].

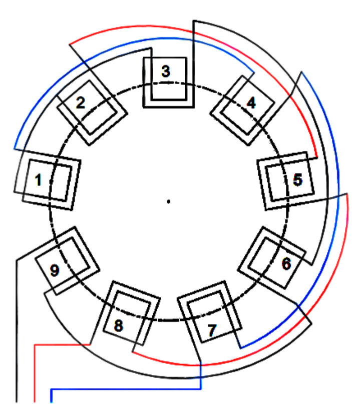

Figure 2. Wiring diagram of coils in series.

Figure 3 shows ten cables, each connected in parallel to its respective coil; the number of output cables de-termines the location of the rectifier, since if there are too many cables the movement of the generator at the end of the tower is limited, which implies that the rec-tifier must be located next to the generator and this causes maintenance problems. The number of phases is not a problem for rectification since the bridge con-nections can be varied to rectify up to two phases for each one [6].

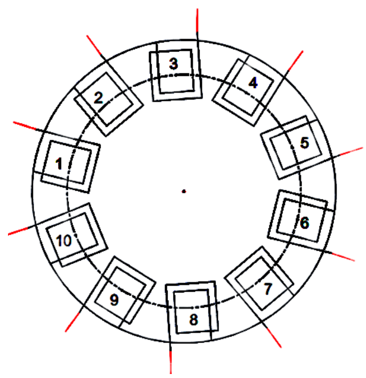

Figure 3. Connection diagram of parallel coils.

1.3. Permanent magnets

The basic compound in the permanent magnets used in this research is Neodymium-Ironboron (NdFeB), which has low resistance to corrosion due to its coating with thin layers of nickel and chromium to isolate the base material from the environment, overcoming the disad-vantage of demagnetization at lower temperatures like other com-pounds [7]. Magnets with a high degree of magnetiza-tion are required, which make it possible to place sev-eral magnets in each rotor [8, 9]. In addition, the polar-ization direction must be relevant to this purpose; hence, neodymium grade 40 (N40) magnets were se-lected.

2. Materials and methods

Figure 4 shows the scheme for determining the magnetic flux density through Equation 1, applicable to rectangular magnets [10].

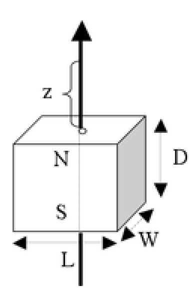

Figure 4. Scheme for the application of the flow density formu-la.

The magnetic flux density is determined as:

$$B = \frac{Br}{\pi}\left[tan^{-1}\left(\frac{LW}{2z\sqrt{4z^2+L^2+W^2}}\right) - tan^{-1}\left(\frac{LW}{2(D+z)\sqrt{4(D+z)^2+L^2+W^2}}\right)\right] \tag{1}$$

Br = Remanence field independent of the geometry of the magnet (1.26 T, which is obtained from the magnet's physical data).

z = Distance on the axis of symmetry of a polar surface (10.5 mm which is half the distance to which the magnets are separated in each rotor).

L = Length of the parallelepiped (46 mm).

D = Thickness of the parallelepiped (10 mm).

W = Width of the parallelepiped (30 mm).

Substituting the data in the equation we have:

$$B = 0,137\ T$$

To check the calculated data, simulations were performed in the FEMM software as shown in Figure 5.

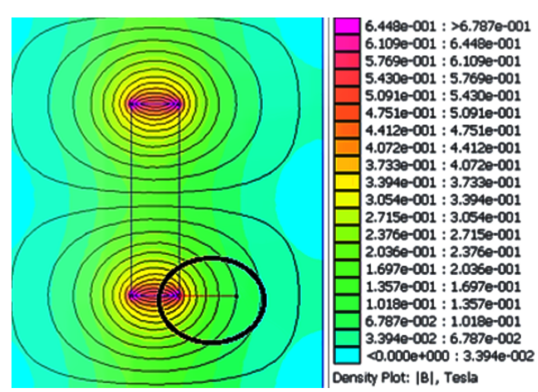

Figure 5. Simulation of the flux density of a magnet side view.

In the software, 0.1357 T is obtained, which is very close to the calculated value and is used for the design. When adding a low carbon steel plate, Figure 6 shows that the flow values practically doubled due to the effects of magnetic concentration and isolation of steel.

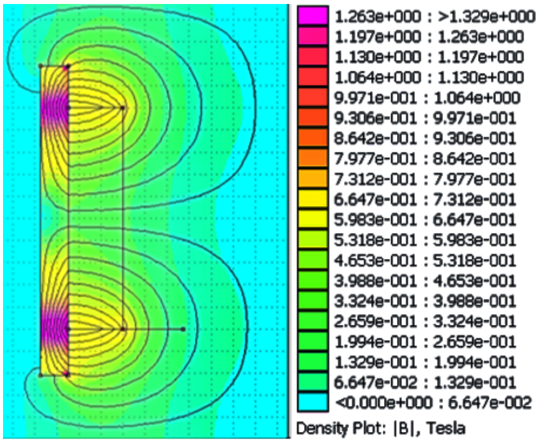

Figure 6. Simulation of the flux density of a magnet glued to a steel plate, side view.

Finally, the two-plate system with facing magnets is analyzed as shown in Figure 7, to obtain the total flow.

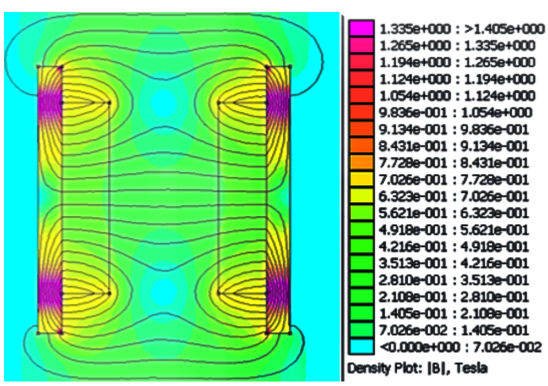

Figure 7. Simulation of the flux density of two plates with facing magnets, side view.

The flux between the plates is 0.5621 T (approximately half of the remaining flux), which confirms the proposed rule [6]: «If there are magnets in both disks and the gap between them is roughly equal to the combined length of the magnets, B will be half of the remaining flux».

2.1. Determination of the number of revolutions for operation

To determine this value, it is necessary to obtain the peak speed ratio, which is the index of the rotational speed of the blades in relation to wind speed, as indicated in equation (2).

$$\lambda = \frac{\omega r}{v} \tag{2}$$

Where:

λ = Peak speed ratio (a recommended value of 7 will be used for all calculations).

ω = angular velocity (rad/s).

r = Blade radius (m) (a value of 1.5 is used for all calcula-tions).

v = Wind speed (m/s).

Equation (3) [11] is used to determine the speed in r.p.m.

$$N = \frac{30\lambda v}{r\pi} \tag{3}$$

2.2. Determination of the number of poles

According to [12] the number of poles is calculated with equation (4) where f stands for electric frequen-cy:

$$p = \frac{4 \cdot f \cdot r \cdot \pi}{\lambda \cdot v} \tag{4}$$

Using equation (4), Table 1 is obtained, setting a maximum frequency of 60 Hz available in the electric network.

From Table 1 we conclude that the higher the frequency, the more poles are needed. In addition, if the wind speed is low, a greater number of poles is necessary to obtain the required frequency. Taking into ac-count the recommendation in [6], a number of 24 poles (12 in each rotor) is chosen, which guarantees an adequate distribution of the magnets in the rotors. The value of operation frequency does not have to be high since direct current that lacks frequency is obtained in the rectification.

Table 1. Physical data of magnets

V. of 2 m/s		V. of 4 m/s		V. of 6 m/s	
Freq. (Hz)	# of poles	Freq. (Hz)	# of poles	Freq. (Hz)	# of poles
10	13,46	10	6,73	10	4,49
20	26,93	20	13,46	20	8,98
30	40,39	30	20,2	30	13,46
40	53,86	40	26,93	40	17,95
50	67,32	50	33,66	50	22,44
60	80,78	60	40,39	60	26,93
V. of 8 m/s		V. of 10 m/s		V. of 12 m/s	
Freq. (Hz)	# of poles	Freq. (Hz)	# of poles	Freq. (Hz)	# of poles
10	3,37	10	2,69	10	2,24
20	6,73	20	5,39	20	4,49
30	10,1	30	8,08	30	6,73
40	13,46	40	10,77	40	8,98
50	16,83	50	13,46	50	11,22
60	20,2	60	16,16	60	13,46

2.3. Determination of the number of coils

According to [6] the number of coils is a function of the available poles:

$$N_B = \frac{3N_p}{4} \tag{5}$$

Where:

N_B = Number of coils.

N_P = Number of rotor poles.

The ratio is: 3 coils for each 4 pairs of poles, applying equation (5) a number of 9 coils is obtained; this distribution guarantees that 3 magnets are synchronized with 3 coils at the same time [11], allowing the induced electromotive force (emf) to add up.

In order to make the comparison between generators with different coil connections, the decision to test another generator with 10 coils all connected in parallel was made. This arrangement is proposed by [6] and guarantees that a battery can be charged with this generator.

2.4. Number of turns per coil

The dimensions of the coil are determined by the measurements of the magnet, since the coil must provide a hollow section for the passage of the magnetic field. As the coils have an air core with support, an inductance of 1 mH is considered for this dimensioning.

$$n = \sqrt{\frac{lL}{\mu A}} \tag{6}$$

Where:

n = Number of turns.

l = Coil length (0.013 m).

L = Inductance (1 mH).

μ = Permeability of the core ($4\pi \times 10^{-7}$ Hm^{-1}).

A = Cross section area ($1{,}2 \times 10^{-3}$ m^2).

For reasons of space and packaging, AWG 14 wire with a diameter of 1.63 mm has been used for the construction of the coils [6].

Table 2 shows the necessary parameters for the construction of the stator.

Table 2. Stator parameters

	Number of poles (p)	Number of colis (Nc)	Number of turns per coil (n)
Generators in series	24	9	93
Generators in parallel	24	10	67

2.5. Coil distribution

The built stator must allow the screws connecting the rotors to pass through, leaving the central part empty and circular in shape. For this, [6] recommends the use of an «island» that is nothing more than a circular sec-tion of wood as shown in Figure 8. The diameter of the island (DIS) is 13 cm.

Figure 8. Location of coils.

The finished stator can be seen in Figure 9, the foot of the coils is located 1 cm from the hole. From these measurements, the magnets are placed on steel discs so that their perimeter coincides with the internal spaces of the coils.

Figure 9. Stator

2.6. Distribution of magnets

The 12 magnets are distributed symmetrically in each rotor disk, where their diameter is in function of the diameter of the island as shown in Figure 10, the distance to the foot of the coils, and the width of the coils (AB). Therefore, the diameter at the foot of the mag-nets (DIM) expressed in centimeters is:

$$D_{IM} = D_{IS} + 2 \cdot A_B + 2 \quad (7)$$

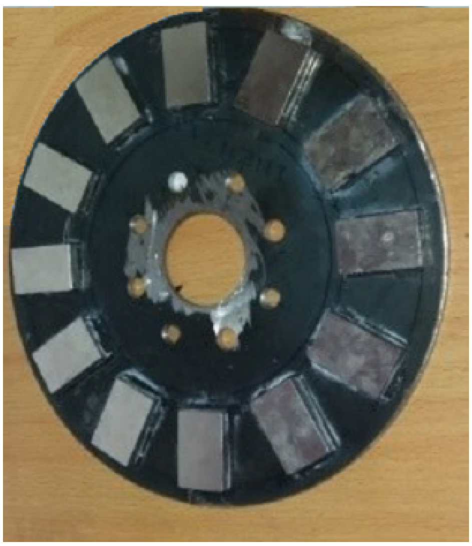

Figure 10. Location of magnets

2.7. Determination of electrical losses

- **Losses due to resistance in the series generator coils:**

The resistance measured in two phases or 6 coils is 2.2Ω, therefore the resistance per coil is 0.37Ω. To deter-mine the resistance in the stator according to [6] it is considered that 2 phases are always working and it follows that the resistance in the stator is:

$$R_E = 2 \cdot N_B \cdot R_B \quad (8)$$

Where:

R_E = Resistance in the stator.

R_B = Resistance per coil.

Resulting in a stator resistance of 2.22Ω.

- **Losses due to resistance in the parallel generator:**

The resistance per coil is 0.26Ω and, due to its configu-ration, this is the resistance of the stator because only one coil works at a time.

- **Losses due to resistance in the coils:**

The resistance of the coil turns prevents the current from flowing completely free, since every material has some electrical resistance. This can help determine if the materials are good or bad conductors, which is evaluated by means of equation:

$$P_B = I^2 \cdot R_E \quad (9)$$

Where:

P_B = Loss power in the coils.

I = Intensity of current circulating in the windings.

- **Losses in the rectifier:**

After the energy collection at the ends of the coils, the following step is the rectification process, from alternating to direct. The rectification method chosen for this application is full wave, with rectifier bridges. Three bridges were used for the series generator, and five for the parallel generator. The intention is to take full advantage of the alternating current generated. Each phase is distributed for four diodes which reduc-es the heating and, therefore, its wear. The only disad-vantage of this arrangement is the voltage drop of 1.4 volts for the two generators.

$$P_R = I \cdot V \quad (10)$$

Finally, the total electrical losses (P_E) are:

$$P_E = P_B + P_R \quad (11)$$

$$P_E = I^2 \cdot R_E + I \cdot V \quad (12)$$

The greater the losses, the lower the efficiency, but in order to determine this, generation trends must be analyzed.

2.8. Determination of efficiencies

The output power (P_S) is obtained from the measured voltage and amperage, the efficiency (η) is determined by the net power output and losses. The generator must provide the net power value plus the losses, therefore:

$$\eta = \frac{P_S}{P_S + P_E} \quad (13)$$

3. Results and Discussion

The voltage and current intensity data were obtained by operating each of the generators at different angular velocity values (in r.p.m.), rotating the rotors in the mandrel of a lathe as shown in Figure 11. To load the generator, a rheostat was used with different resistance values connected to its output.

Figure 11. Assembly of the generator on the lathe.

Through this arrangement the voltage and amperage data were obtained simultaneously with the help of two multimeters connected as seen in Figure 12.

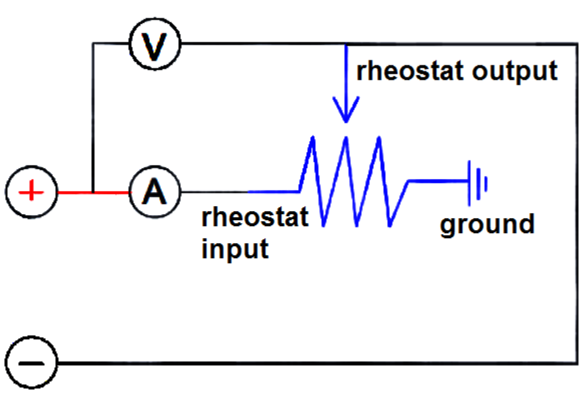

Figure 12. Connection scheme

With the obtained data, graphs are made taking into account that all the values are in function of the angu-lar velocity, since the generation variations depend on it.

Figures 13 to 15 show the graphs with the data of the parallel coil generator:

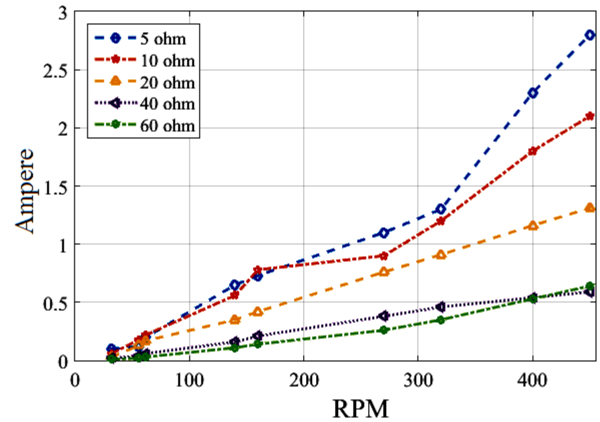

Figure 13. Current intensity at different values of resistance.

The variation of intensity is proportional to the an-gular velocity as shown in Figure 13, which shows that with a higher resistance of the load and a greater angu-lar velocity, the amperage decreases.

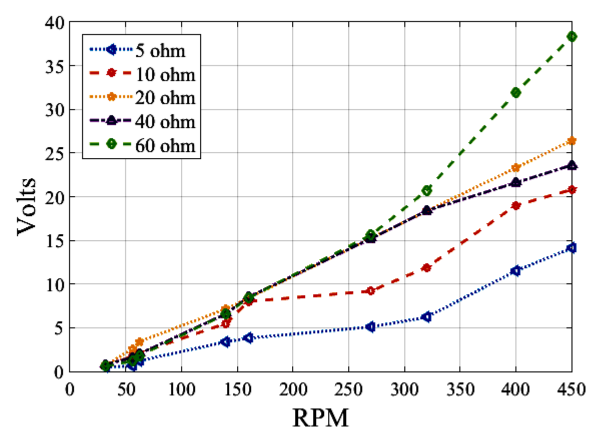

Figure 14. Electromotive force at different resistance values.

Since the voltage is proportional to the current according to Ohm's law, an increase in voltage is observed in Figure 14 as the value of the resistance in-creases, being more significant at high angular velocities.

Figure 15 shows the behavior of the generator power versus its angular velocity. Up to 250 r.p.m. there is no significant increase in power. When the speed of the rotors increases, the power increases. This increment is more evident at low resistance.

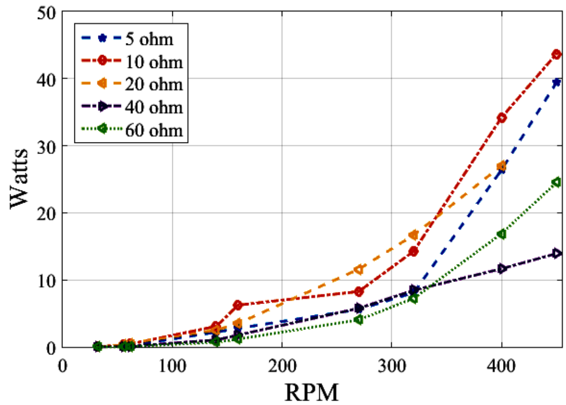

Figure 15. Powers at different resistance values.

Figures 16 to 18 show the graphs with the serial coil generator data.

The behavior of the amperage is increasing in all cases as shown in Figure 16 and it should be noted that the lower the resistance the greater the amperage.

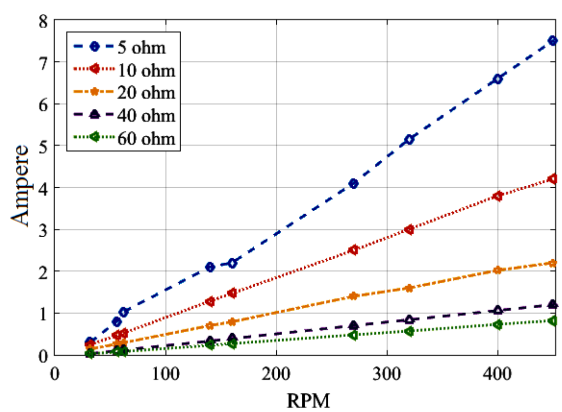

Figure 16. Amperages at different resistance values.

Figure 17 shows that there are important variations in the voltage values. If you take 100% growth, both in resistance and in angular speed, the voltage has a 120% growth at the same load.

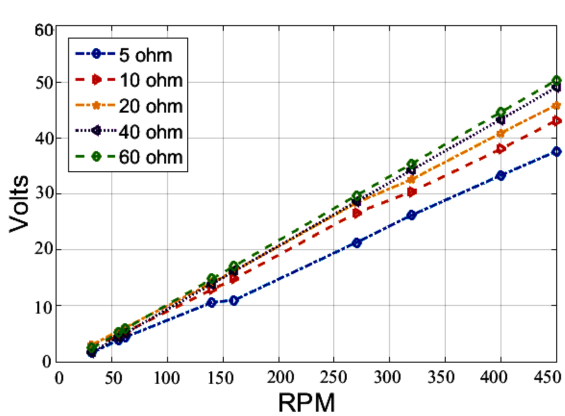

Figure 17. Voltages at different resistance values.

This is a very favorable feature for this generator because, although its amperage changes remarkably as seen in Figure 16, the behavior of the voltage is linear.

The increase in resistance prevents the free passage of current as can be seen in Figure 18.

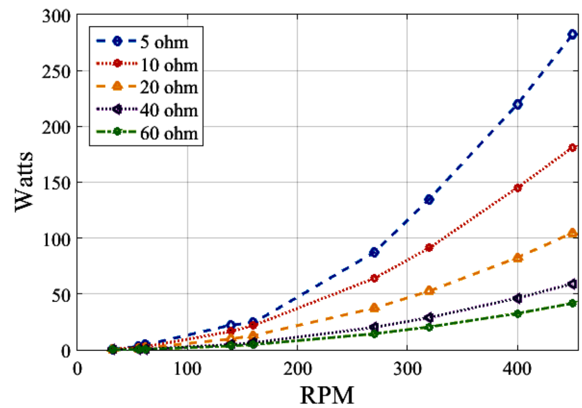

Figure 18. Powers at different resistance values.

This causes the power to be lower at high load de-spite the increase of angular speed in the generator.

In Figures 19 to 22 the theoretical and experimental characteristics of the series and parallel generators are compared. The value chosen for the resistance is 5Ω, which generates sufficient amperage or current, as well as the voltage at angular speeds common in the use of wind microgenerators. In addition, it is necessary to overcome the resistance caused by a charge controller, the wiring and the batteries to be charged.

Although the parallel coil generator has one more coil than the series generator, the difference in voltages can be clearly seen in Figure 19.

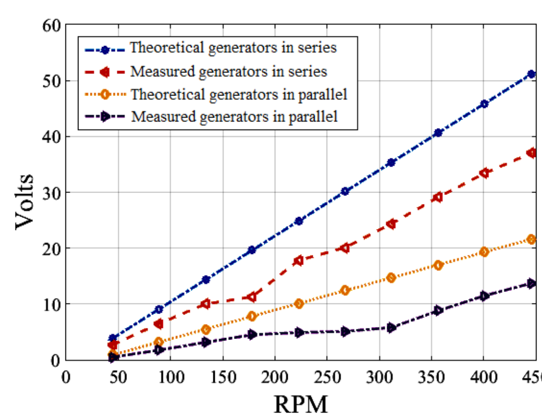

Figure 19. Comparisons of theoretical and measured voltages.

This is because, in the series generator, the three coils act as one because of their connection, with the difference that three pairs of magnets act at the same time. This causes the voltage to be much higher than in the case of the parallel coil generator, where only one coil acts at a time with a pair of magnets.

As can be seen in Figure 20 the series generator ex-ceeds the parallel generator in providing greater amperage. This allows the battery to be charged quickly for energy storage, or their number could be increased.

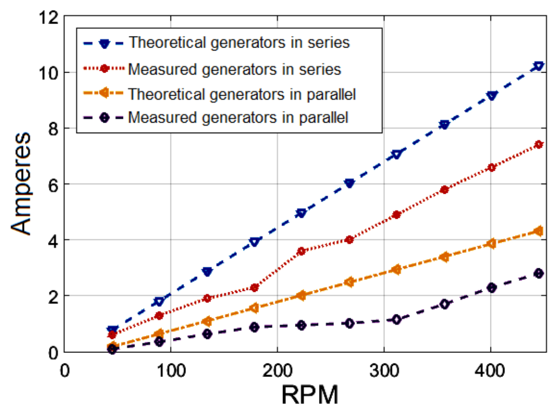

Figure 20. Comparisons of theoretical and measured amperage.

The powers determined in Figure 21 are no more than the reflection of the voltage and amperage values, therefore, they are directly proportional.

In the case of power, the measured values tend to behave quadratically.

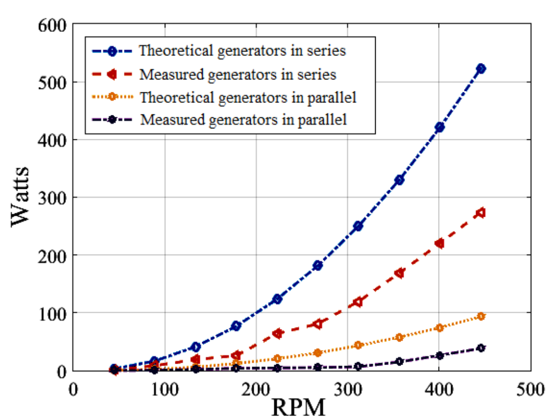

Figure 21. Comparisons of theoretical and measured powers.

The amperage and voltage obtained in both tests of the series coil generator are greater and imply that its power is also greater.

Regarding the efficiency of the generators, Figure 22 shows that although the parallel generator is exceeded in voltage and amperage by the series generator, it is more efficient.

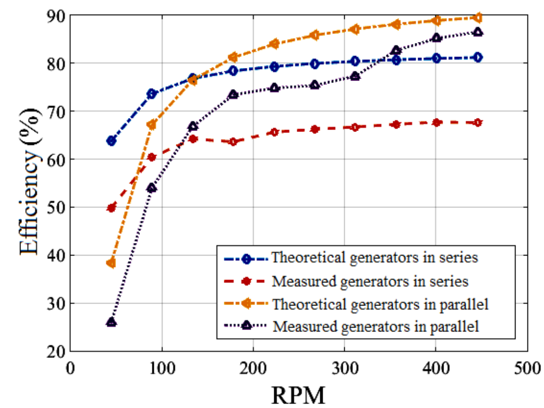

Figure 22. Comparisons of theoretical and measured efficiency.

This fact is reasonable since, in the series generator, the resistances per phase add up, causing more losses; the parallel generator only has one resistance per phase.

These qualities must be considered in their selection, taking energy requirements into account. If high voltages and amperages and a reasonable efficiency are needed, a series generator must be selected; but if what is sought is greater stability of voltage and am-perage at low revolutions with greater efficiency, the parallel generator is the appropriate choice.

4. Conclusions

The main parameters for the dimensioning of an axial flow generator are the selection of magnets, determination of the field density, number of poles, number of coils, number of turns per coil, wire gauge for the coils, and symmetric distribution of magnets and coils.

The dimensions of the discs for the rotors and the stator measurements are determined by the arrangement of the coils: the larger they are and the greater their number, the larger the discs and therefore the stator.

This study shows that the best configuration for the connection of coils is in series, as in enables the best use of the distribution of magnets, and has the quality of adding the f_{em} of each group of coils. However, the series generator has higher losses, which indicates that it will have more heating problems than the parallel generator.

Axial flow generators provide very good voltages and amperage at low revs. This highlights the benefits that these generators have for applications in wind energy despite the fact that there is a low or limited wind potential.

If you compare the theoretical results with the experimental ones, the axial flow generators are adequate for small-scale electricity generation. If a three-phase generator is tested in a place where the average wind speed is between 4 to 8 m/s, with rotor speeds of 220 to 450 rpm, the amperage reached ranges from 3 to 7 amps. In addition, if during the day there are 4 to 8 hours with this wind speed, this results in 18 to 24 ampere-hours in the day, which represents a quarter of the total amperage of a common 100 Ah battery.

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