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Comparative Assessment of a Horizontal Small Wind Turbine with Ball and Magnetic Bearings on the Starting

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This article describes a mathematical model of a horizontal wind turbine of 500 W with a NACA 2418 airfoil type during the start-up condition for two proposed systems. The first one considers a wind turbine system where the friction moment is given by ball bearings. The second one proposes the replacement of the ball bearings by magnetic bearings called maglev wind turbine. The latter is a technology based on electromagnetic field to levitate a shaft. The magnetic bearing has the features of non-mechanical contact, non-mechanical friction, minimizing the damping in the wind turbine. The results under a wind speed of 8 m/s show that there is an increase in power by 7.2 % generated by a wind turbine with magnetic bearings, besides under a condition of 4 m/s the start-run time is 8.96 s quicker for the maglev wind turbine. Finally, it also confirms that the maglev wind turbine can operate with a speed similar at 3 m/s.

1. Introduction

The use of wind energy as a renewable source of energy for electricity production has been increasing over the past 20 years. This has created huge machines and forced investors to look for areas with high wind availability, commonly found in remote areas, far away from the consumer. This also causes high investments in construction machinery. The study of low-capacity wind turbines had been scarce, but in recent years, the development of new designs of low capacity, allowed to settle in metropolitan areas, which has increased their commercial demand. This is due to the concept of distributed generation, which represents a low installation cost of this equipment for rural zones, and it has a potential usage in urban homes in Mexico by the concept of grid interfacing.

The use of magnetic bearings (MB) has been increasing over the past five years, (Schweitzer, 2009 and Chiba, 2005) because the efficiency has increased, due to the magnetism applied in different machines such as trains and air conditioned machines. The McQuay Company presents a MagLev Chiller with a 30 % efficiency greater compared capacity machines without maglev technology. Sanza Kazadi et al. (2008) mentioned that the development of magnetic bearings has sought to increase the efficiency of the machines, reducing problems of vibration, noise, friction and maintenance. Even though, the magnetic bearing has been researched for 25 y, it can be considered recent, and there are many applications that are not studied yet. For example, currently in the literature of wind turbines are no more than two years old, publications regarding maglev wind turbines. Kumbernuss et al. (2012) describes a vertical axis wind turbine with magnetic bearing. So far, all revised paper are about developed or proposed levitation systems in the last 2 y. Projects have proven to be feasible, but there is still a need to compare the typical systems with the magnetic ones. The use of magnetic bearings could help to increase the performance of the wind turbines at low wind speed. Then, the wind turbines could be used in the cities, where the wind speed is low. This paper compares the theoretical performance of a wind turbine with ball bearings to one with magnetic bearings.

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2. Wind turbine system description

The comparative study between the ball bearing and magnetic ones takes into account three subsystems (see Figure 1). The first is the aerodynamic subsystem on the blade; the second one is the mechanical, and the last one is the electrical. For the blade aerodynamic a previously established methodology to blade design (see Figure 2) was used, which is described in detail by Rosales and Cerezo (2010). The features for the design are a wind turbine of 500 W (P_{wt}) with a TSR (λ) of 8 for an airfoil NACA 2418. The main data obtained from these parameters of design is the radius (r), that is it divided in 15 ribs, the pitch angle (Θ_p) and a total radius (R). As important mechanical considerations were taken into account a friction bearing (M_r) ETN9 SKF-6207, which can be used on the wind turbine shaft. Also the force called cogging (F_{cog}) was considered, this force is created by a permanent magnet generator (PMG), the sum of the latter two (M_r, F_{cog}) will be known as resistive torque (Q_r). Effects like the weight of the generator (PMG), and the shaft seals are not considered in the model.

2.1 Blade aerodynamic

For the starting time of the wind turbine it was considered the methodology proposed by Ebert and Wood in 1997. The input variables of the solution algorithm are the data entry of the blade geometry, density (ρ) of blades, wind speed (U), desired nominal operating λ, number of blades and polar graphs where the desired profile shows the angle of attack (α) and lift and drag coefficients, resistive torque (Q_r) that is the turbine torque necessary to start spinning that is generated by the cogging of the permanent magnet generator, and the ball bearing friction.

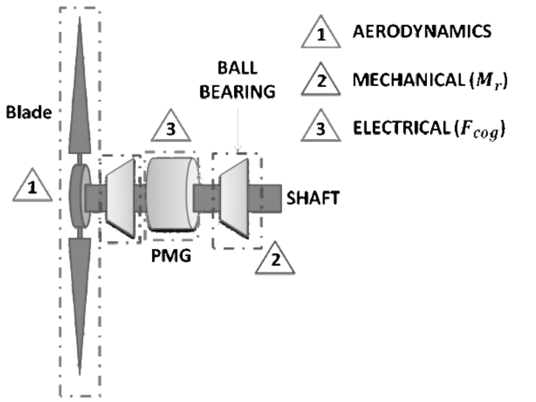

Figure 1: Schematic configuration of a wind turbine

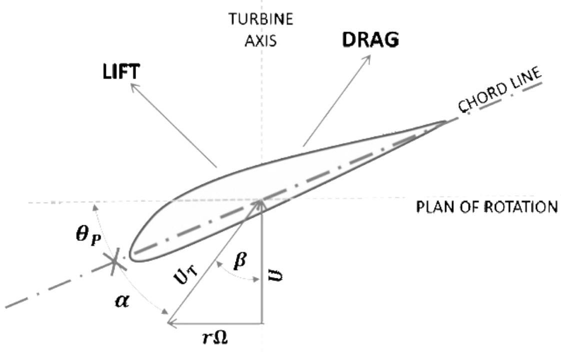

Figure 2: Blade element, velocities and forces

The parameters of study to calculate the power for the wind turbine are the number of blades that are 3, the density of blade with 550 kg/m^3, a cogging with 0.5 Nm, the mechanical friction 0.8 Nm, the sum of cogging and mechanical friction offer the total starting torque (Q_r), that is 1.3 Nm, the inertia moment of the blade is 1.6 Nm, the profile used for the blade of the wind turbine is the NACA 2418.

Equation 1 was used for calculating the moment of inertia (J) of the blades, where N is the number of blades, ρ_b is the air density, A is the area of the surface of the blade, R is the total radius of the blade, c is the length of the chord per section divided in r, and Θ_p is the pitch angle.

Equation 2 was used for calculation of revolution per minute (RPM) from its angular velocity (Ω), and the Equation 3 was used to calculate the power (P) transmitted to the shaft from the blades. In this case T is the torque over the shaft.

$$J = N\rho_b AR^5 \left[\int (cr)^2 dr + \frac{A}{12} \left(\int c^4 cos^2\theta_p dr + A^2 \int c^4 sen^2\theta_p dr \right) \right] \quad (1)$$

$$\Omega = RPM \left(\frac{\pi}{30} \right) \quad (2)$$

$$P = \Omega T \tag{3}$$

2.2 Wind turbine starting time

In this paper *starting* means the time period beginning when the blades are stationary and finishing when the wind turbine reach their λ of design.

To calculate the starting time of the wind turbine, it is necessary to calculate the λ_r of design. Also, a wind speed (U) should be supposed. From Equation 4 can be noticed that there is an inverse relationship between variables.

$$\frac{U}{\Omega \mathrm{r}} = \frac{1}{\lambda_r} \tag{4}$$

The wind speed (U) on a blade element (U_T) is calculated from the following expression:

$$U_T = \sqrt{U^2 + (r\Omega)^2} = U\sqrt{1 + \lambda_r^2} \tag{5}$$

In a wind turbine without pitch control to adjust the angle of attack (α), it is necessary to calculate an angle of attack on every (U_T), dependent of time is given by the next correlation:

$$k_\alpha = \frac{|\dot{\alpha}|}{2U_T} \tag{6}$$

Where:

$$\dot{\alpha} = \frac{d\alpha}{dt} \tag{7}$$

Besides, the Equation 8 is used to calculate $\dot{\alpha}$ over the blade, when the Ω is accelerating ($\dot{\Omega}$):

$$\dot{\alpha} = \frac{d\alpha}{dt} = \frac{-rU}{r^2\Omega^2 + U^2}\frac{d\Omega}{dt} \tag{8}$$

On the other hand, to estimate the initial torque to spin the blades, the next equation is used:

$$T = J\dot{\Omega} = J\frac{d\Omega}{dt} \tag{9}$$

This expression has the disadvantage that is used only on horizontal wind turbines and when there is not a dragging force on the blade. The main contribution to the torque is the lift force. This effect could be noticed in Equation 10 when in a time equal to zero the λ_r is also zero, because the C_d could be eliminated and only the C_l exists in a first instant.

The coefficient of torque is obtained from Equation 10, requiring the blade and wind features, like wind velocity (U), wind density (ρ), and radius on the tip of the blade (R). Also this could be calculated from the speed ratio (λ_r) in each section of the blade with their own lift and drag coefficients.

$$C_q = \frac{2T}{\rho U^2 \pi R^3} = \frac{N}{\pi}\int_{rh}^{1} [1 + \lambda_r^2]^{1/2}[c_l - \lambda_r c_d]crdr \tag{10}$$

Equation 10 is solved when the wind turbine reaches the tip speed ratio, the system has already started, this means that λ is equal to λ_r. To know how the ball bearing affect the starting of the wind turbine, the Equation 11 is used, this describes how the speed ratio is affected by a resistive torque (Q_r) that decreases the starting.

$$\frac{d\lambda}{dt} = \frac{R(Q - Q_{r})}{JU} \tag{11}$$

2.3 Magnetic bearing

This technology consists of a set of electromagnet able to levitate the rotor for the wind turbine at a certain distance from a surface. This system commonly uses the configuration showed on Figure 3 applied for a wind turbine. This magnetic bearing system (MBS) consist of two radial MB, one axial MB, a gap sensor and a controller, which receives the position of the shaft and adjusts the magnetic force on the MB to readjust the shaft location.

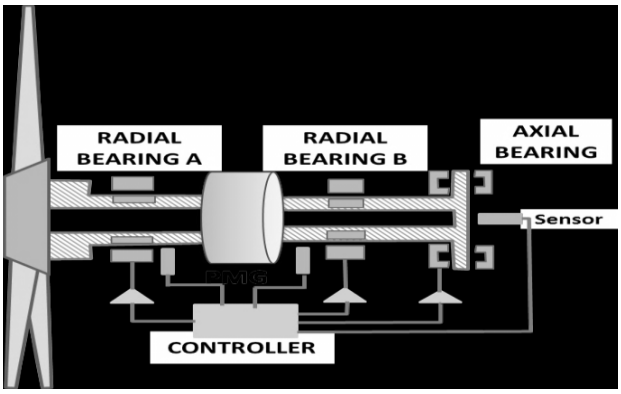

Figure 3: Schematic configuration of a horizontal magnetic bearing system

2.4 Friction on starting

To determine the contribution to the resistive torque of the mechanical bearing SKF-6207 ETN9 (see Figure 1), the expression 12 is used. The resistive force (M_r) is the necessary torque to roll a bearing, and it is calculated as follows:

$$M_r = M_{rr} + M_{sl} + M_{seal} + M_{drag} \tag{12}$$

Where M_{rr}, M_{sl}, M_{seal} and M_{drag} are the rolling, sliding, seals and drag friction, respectively.
The rolling friction is the resistance generated by the bearing roll and it is calculated with:

$$M_{rr} = G_{rr}\,(vn)^{0.6} \tag{13}$$

Where G_{rr} is a constant that depends on the kind of bearing, average diameter of bearing, axial and radial load, cinematic viscosity (v), and n is the spin velocity.
The sliding friction is calculated from Equation 14, where μ_{sl} is the friction coefficient dependent of the lubrication used, and the G_{sl} that depends on the kind of bearing, average diameter of bearing, axial and radial load.

$$M_{sl} = \mu_{sl} G_{sl} \tag{14}$$

Seal Friction is calculated with the following expression:

$$M_{seal} = K_{s1} {d_s}^{\beta} + K_{s2} \tag{15}$$

K_{s1} is a second constant that depends on the kind of bearing, K_{s2} is a second constant that depends on the kind of seal, d_s is the diameter of contact between the seal and the surface, β is an exponential number determined by the kind of bearing and seal.
Drag friction is calculated by the friction offered by a fluid, the kind of lubricant and bearing, in this case a ball bearing. The variables that are involved on drag friction are the level of lubricating (V_m), a constant related with the bearing (K_{ball}), the average diameter (d_m) and the spin speed (n). Drag friction is showed in the following expression:

$$M_{drag} = V_m K_{ball}\, d_m{}^{5} n^2 \tag{16}$$

3. Results

The Figure 4 shows the model for the starting time and its analytical result to achieve a given wind turbine λ in a determined time. In all cases, the λ design is 8, so it is considered that the starting time is when the wind turbine reaches that value. The simulation compares 3 different wind speeds (4, 6 and 8 m/s) with 2 different Q_r, one for the maglev wind turbine with 0.5 Nm and the ball bearing wind turbine with 1.3 Nm, for each speed. The difference on starting time for a wind velocity of 4 m/s, is 8.96 s for the difference between a Q_r = 0.5 and Q_r = 1.3 Nm, and 0.84 s for a wind velocity of 8 m/s as is shown in Table 1. Figure 5 is the result of the RPM acquired for both wind turbines. According to the analytical results with magnetic bearings, the time for reaching the design RPM is less in the maglev wind turbine that in the ball bearing wind turbine. In Figure 5 it is important to notice that at 8 m/s the RPM are stable at 950 RPM, this happens because the model considers only the lift force during this time period, and the drag force is not considered. Results are listed in Table 1. In the table, RPM are revolution per minute; Resistive Torque is 0.5 Nm for maglev wind turbine and 1.3 Nm for ball bearing wind turbine, the time difference is always better for the maglev wind turbine.

Table 1: Starting time for different wind velocity and RPM for resistive torques

Wind velocity (m/s)	RPM	Resistive Torque (Q_r)		Time Difference (s)
		0.5 Nm	1.3 Nm	
8.00	507.51	23.92 s	24.76 s	0.84
6.00	380.63	32.42 s	34.35 s	1.93
4.00	253.75	51.06 s	60.02 s	8.96

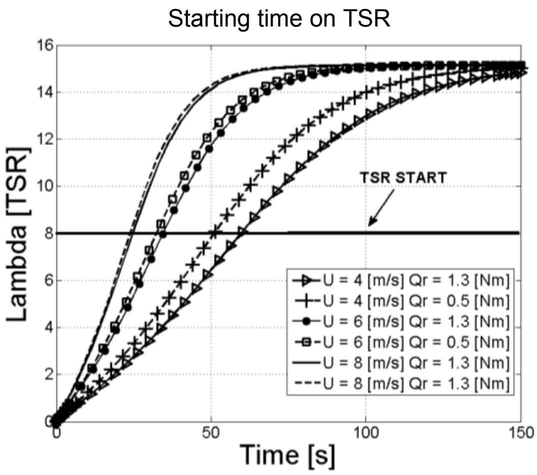

Figure 4: Starting time from different wind speed

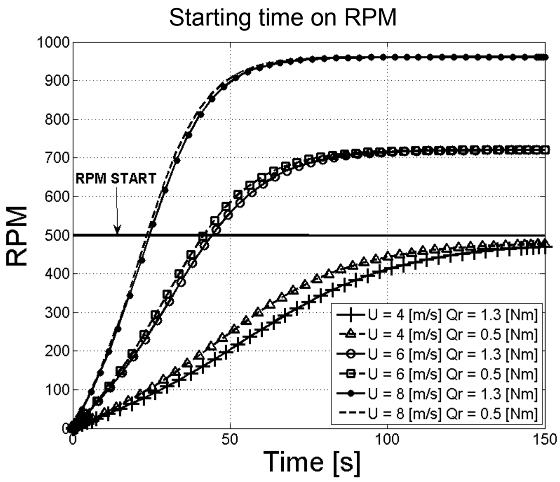

Figure 5: Starting time from different wind speed for a 500 W wind turbine

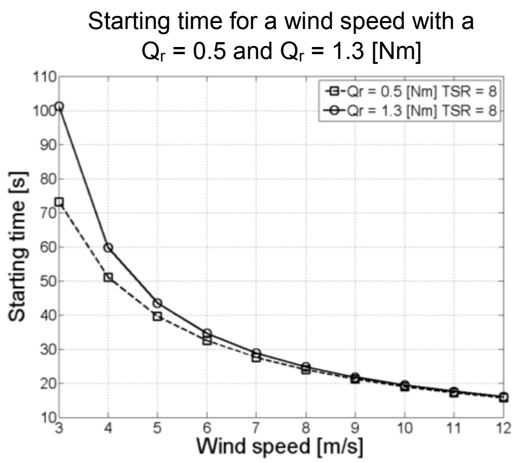

Figure 6: Starting time to different wind velocities

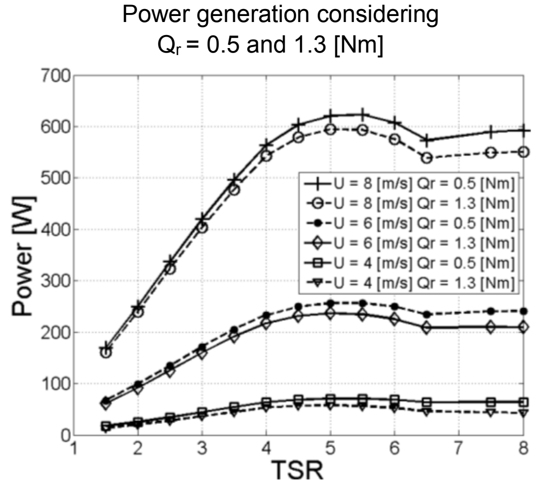

Figure 7: Power generation at different λ

Figure 6, is the analytical result of different starting times, where different conditions of constant wind was simulated. The minimum starting speed is ascertained at a wind velocity of 3 m/s for both wind turbines. Moreover, according to the analytical results, speeds below 6 m/s has a time difference greater than 3 s.,

until we have a difference of up to 8.96 s at 4 m/s to boot, which is important for urban zones where the wind resource viability is limited.
Figure 7 depicts that as λ increases, there is a power difference generated by the traditional wind turbine (ball bearing) and the maglev turbine (magnetic bearing), where the maglev generates 592.8 W, and the typical turbine 550.3 W with a velocity of 8 m/s. At a velocity of 4 m/s the wind turbine with magnetic bearing gives 63.94 W and the wind turbine with ball bearing indicates 42.68 W. Excess power that starts at a λ of 5 is due to the same aerodynamics of the blade that will be accelerating to present different angles of attack, so different coefficients of lift (C_l) and drag (C_d). On the other hand, in a λ of 6.5 for all cases is assumed that a phenomenon called "stall" is presented, where the lift and drag coefficients show a decrease in power and torque due to acceleration of the blade itself.

4. Conclusion

It was compared and analysed two systems where the first is a wind turbine with ball bearings that provides a resistive torque (Q_r) of 1.3 Nm and the second with magnetic bearings considering that $Q_{r\,=}$ 0.5 Nm.

1. For wind speeds of 8 m/s, with a λ of 8 the difference of seconds in starting time for both systems is 0.84 s, which is a non-significant time. However, the power generated by the wind turbine with magnetic bearing is 592.8 W, when with a ball bearing is 550.3 W, which means the efficiency increases to 7.2 % by adding the magnetic bearings.
2. For wind speeds of 4 m/s, with a λ of 8 the difference in starting time for both systems is 8.96 s, which becomes a significant time, if we consider the intervals of time that take gusts of wind. Unlike the time, the power generated for ball bearing is 42.68 W and the magnetic bearing is 63.94 W which gives an efficiency of 33.2 %.
3. Several wind speed conditions were analysed. In all three cases, the wind turbine with magnetic bearing reached first the design λ than ball bearings. This was due to the decrease in the resistive torque. The time for starting was 23.92, 32.42 and 51.06 s for 8, 6 and 4 m/s with magnetic bearing.
4. The stall effect indicates that the blade design could be improved, changing the angle of attack or the design TSR, or adding a pitch control to the wind turbine.

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