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Research Article

Design and Development of Low Friction More Efficient Magnetically Levitated Wind Turbines

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Abstract

Nonconventional energy resources are the alternative forms of energy resources which can combat the deficiency of depleting sources of energy. Although there are various forms of nonconventional energy resources, the potential utilization of these resources is a major issue. In the present work, efficient utilization of wind energy is considered. A novel magnetic levitation (Maglev) wind turbines are designed and developed to reduce the contact friction in bearings supporting the wind turbine shaft. Both the vertical and horizontal configurations of wind turbines are designed and developed. Rear earth neodymium permanent magnets are used to support the wind turbine shaft both axially and radially depending upon the wind turbine configuration. Performance analysis of these Maglev wind turbines is carried out to determine the startup wind velocity, rotational speed at various wind velocities, time taken to stop rotation and electric power generated at different wind velocities. Results shows that the resistance offered by Maglev vertical and horizontal wind turbines is 35 % and 16 % less compared to conventional wind turbines respectively. Therefore, higher rotor speeds in Maglev wind turbines generated about 10 to 15 % more electric power at a recorded wind velocity of 6.7 m/s.

Keywords: *Wind energy; Maglev wind turbine; neodymium permanent magnet; vertical and horizontal configurations.*

1. Introduction

Renewable energy resources are the natural resource which can replenish with the passage of time. The renewable resources are a part of earth's natural environment and the largest components of its ecosphere (Twidell and Weir, 2006). The examples of renewable energy resources are; solar energy, wind energy, tidal energy, geothermal energy, biomass etc. which is used for producing electricity, direct heating, cooling and direct cooking purposes. Among all other renewable energy resources global electric power produced from the wind energy is largest and it is about 2.9 % in 2013. India is the sixth largest country in the world with 27 GW of renewable power capacity and only the wind energy is having 80 % of this renewable power capacity (REN21. 2014). Wind energy is the best alternative source of energy for India and therefore its utilization for the power generation shall increase in near future. However, the conversion efficiency of wind energy to electrical energy from the available conventional wind turbines is less than 30 % and the minimum wind velocity required to run these turbines is 5.5 m/s (20 km/h) (Sidhu K. S. 2012). Therefore, increasing the efficiency of the wind turbines is the present need.

Wind turbine is a device which converts the kinetic energy of moving air into mechanical energy that can be either used directly to run the machine or to run the generator to produce electricity (Twidell and Weir, 2006). Wind turbines are broadly classified into two categories based on their axis of rotation as; horizontal axis and vertical axis wind turbines. Horizontal axis wind turbines are more popularly used because they can be installed to any elevated heights to take the advantage of higher wind velocity. However, it requires gearing and generator to be installed at the top of the tower. Furthermore, this type of wind turbine requires the yawing mechanism to follow the wind flow direction. Now a day vertical axis windmills are gaining popularity because of their advantages such as; capability of catching the wind from all directions, therefore, no need of yawing mechanism, gearing system and electric generator can be positioned on ground, and hence can be easily accessible for maintenance, lower wind velocity for start up, low noise etc. However, this type of wind turbine needs very large space to generate high torque for the main shaft as they are installed at ground level where wind

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velocity is low. Furthermore, the rotational torque from the wind varies periodically within each cycle, and thus unwanted power periodicities appear at the output and guyed tower support is complex (Twidell and Weir, 2006).

In order to improve the performance of the wind turbines, most of the work has been done in the literature for the wind turbine blade profile modification (Xiong *et al.*, 2007, Grujicic *et al.*, 2010, Cheng *et al.*, 2010, Liu & Janajreh, 2012, Wei *et al.*, 2014) and effective steering control for horizontal configuration (Zhang *et al.*, 2004, Hong *et al.*, 2012). Furthermore, the vertical axis wind turbines blades profile, blade pitch angle and guide vanes have been considered for the performance enhancement (Takao *et al.*, 2009, Chong *et al.*, 2012, Li *et al.*, 2014, Roh & Kang, 2013, Yoo *et al.*, 2013, Brusca *et al.*, 2014). However, by reducing the contact friction of the rotor at its supports by providing the contact free frictionless magnetic bearings is the new direction to improve the performance of wind turbines. Therefore, in the present work, rear earth neodymium permanent magnet bearings are used to support the shaft of horizontal and vertical axis wind turbines. The performance analysis of these Maglev wind turbines is carried to determine the startup wind velocity, rotational speed at constant wind velocities, time taken to stop rotation and electric power generated at different wind velocities.

2. Design and Development

Both the horizontal and vertical configurations of wind turbines are considered for the design and development. Sectional views of the proposed magnetically levitated wind turbines are shown in Figs. 1 and 2. Rear earth neodymium permanent magnets are used to construct the radial and axial bearings. These bearings are used to support the wind turbine shafts. The detailed design of the wind turbines is explained in the following sections.

2.1 Design and Development of wind turbine frames

Wind turbine frame mainly consists of blades and supporting structure. Number of blades decides the solidity (solidity is the ratio of the total area of the blades at any one moment in the direction of the airstream to the swept area across the airstream.) of the wind turbines. Large solidity machines start easily with large initial torque; however, soon reach maximum power at small rotational frequency. Small solidity devices may require starting, but reach maximum power at faster rotational frequency. Thus large solidity machines are used for water pumping even in light winds. Small solidity turbines are used for electricity generation, since fast shaft rotational frequency is needed. In the present work for both horizontal and vertical windmill three blades are considered. Aspect ratio is another parameter considered especially in the design of vertical axis wind turbines. The aspect ratio of this particular wind turbine is defined as the ratio between blade length and rotor radius. The aspect ratio variations of a vertical-axis wind turbine cause Reynolds number variations, which strongly influences the turbine performance. With the decrease in the aspect ratio Reynolds number rises and it improves wind turbine performance. In the present work, optimum aspect ratio 1.5 is considered for the vertical axis wind turbine design. Blades of vertical axis wind turbine are made from stainless steel sheet of 3 mm thick and fitted to the wooden disk and supporting metallic frame is made using V- channel. For the horizontal axis wind turbine table fan rotor is used and it is fixed on the wooden frame.

2.2 Design and development of magnetic bearings

Magnetic levitation for the wind turbine rotors is created by using neodymium magnets. For the vertical axis wind turbine two ring magnets are used to support the rotor axially and for the horizontal configuration ring magnets and square magnets are used to create a pair of permanent magnet radial bearings to support the rotor at two places. The dimensions of the magnets used and their arrangement for the rotor axial support (thrust bearing) and radial support (radial bearing) are described in Figs. 3 and 4. For the axial bearing two ring magnets of same size are arranged one over the other with like poles facing each other. This results in the generation of repulsive force and it is used to support the rotor, which is placed over the top magnet. For the radial magnetic bearing six brick magnets are arranged circumferentially to the ring magnet with same polarity faces of the brick magnets facing the similar polarity face of the ring magnet as illustrated in Fig. 4.

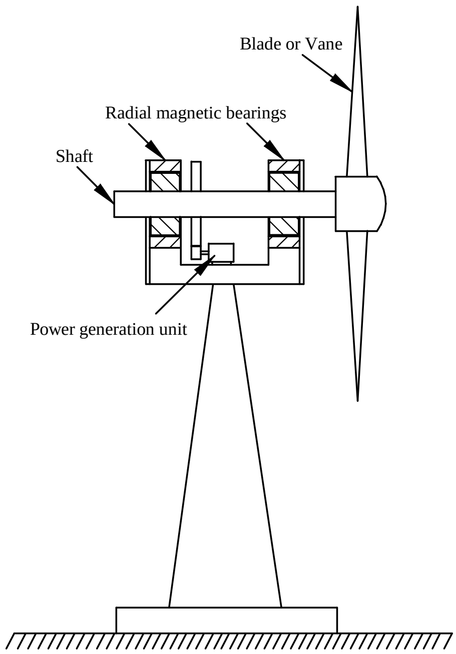

Fig. 1 Magnetically levitated horizontal axis wind turbine

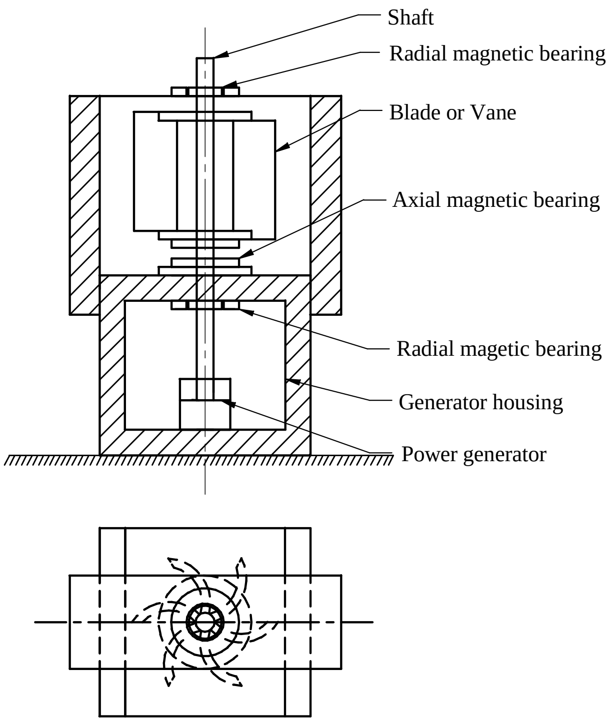

Fig. 2 Magnetically levitated vertical axis wind turbine

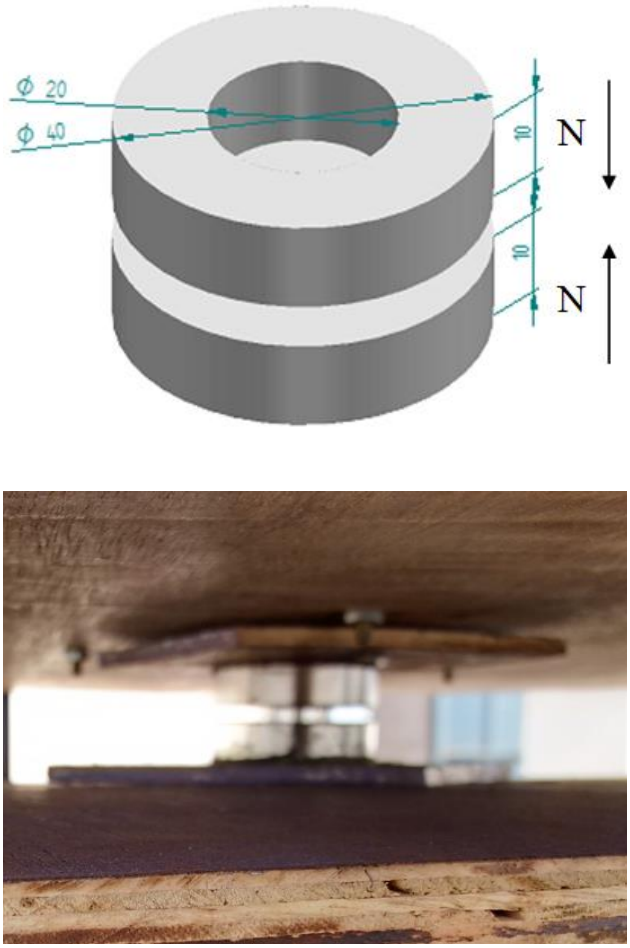

Fig. 3 Arrangement of the ring magnets for axial bearing

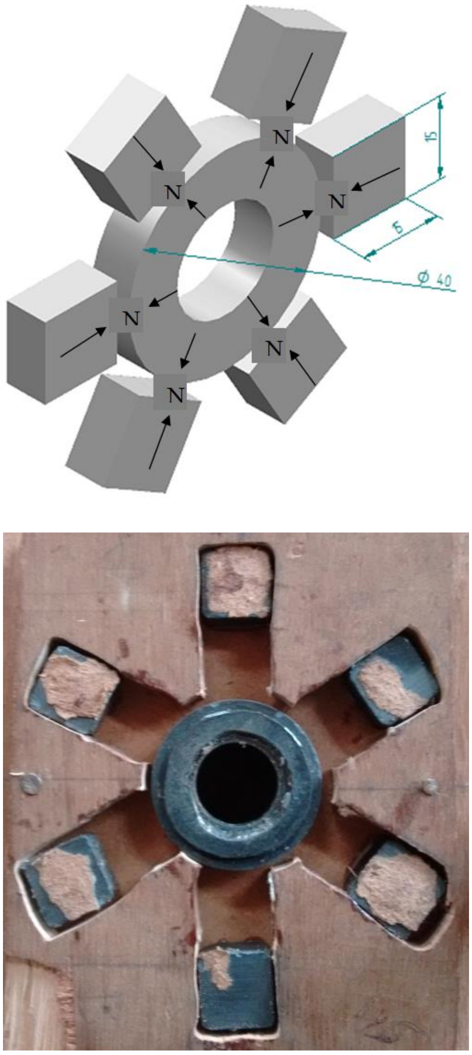

Fig. 4 Arrangement of the magnets for radial bearing

Numerical analysis is carried out to determine the amount of repulsive force generated by the magnets. Ansys R11® software is used for the numerical analysis. Neodymium magnet (NdFeB 37 MGOe) with coercivity 950 kA/m and relative permeability 1.048 and PLANE 13 element with axisymmetric option is used in the analysis. Further, the contour plots for the flux density developed in the air-gap of the axial and radial magnetic bearing with 5 mm air-gap are shown in Figs 5 and 6 respectively. The average flux density developed at the center of the air-gap is considered for the calculation of repulsive force generated.

The repulsion force between two neodymium magnets is given by Eq. (1)

$$F = \frac{B^2 A}{2\mu_o} \tag{1}$$

where B is the magnetic flux density at the center of the air-gap between the two magnets, A is the pole face area, and μ_o is the permeability of air and its value is $4\pi \times 10^{-7}$ N/A^2.

Similarly the analysis is carried with different air-gaps and the repulsive force generated in both the configurations of magnetic bearings is tabulated in Table 1. In the present work, the vertical and horizontal axis wind turbine rotor weighs 7.8 kg and 2.5 kg, respectively. When this load is supported by the bearings, the axial and radial configuration air-gaps comes out to be 4.6 mm and 7.6 mm, respectively (Fig. 7).

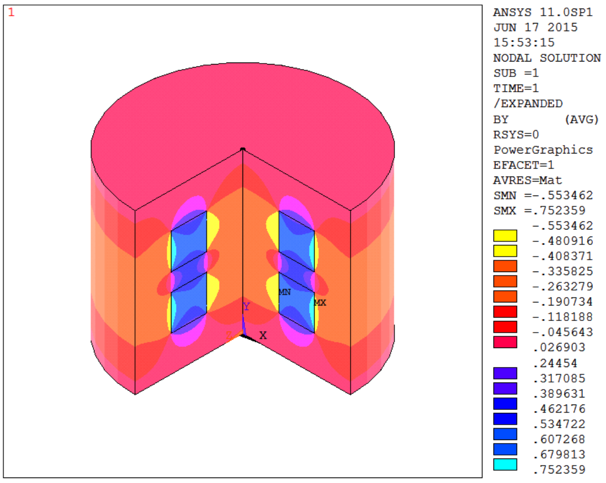

Fig. 5 Flux density distribution in axial magnetic bearing

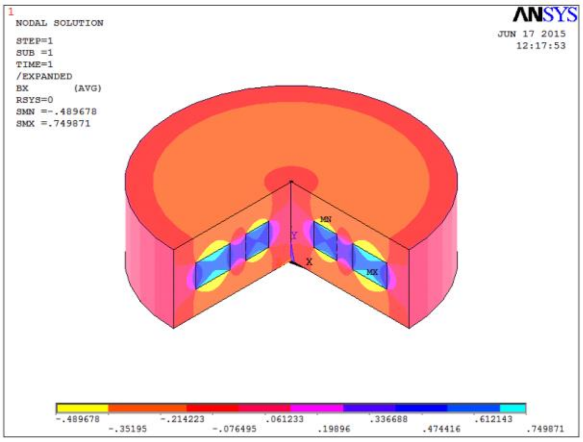

Fig. 6 Flux density distribution in radial magnetic bearing

Table 1 Repulsive force generated in magnetic bearings

Air-gap (mm)	Magnetic flux density (T)		Repulsive force (N)	
	Axial	Radial	Axial	Radial
1	0.65	0.70	158.43	123.78
3	0.53	0.54	105.33	75.40
5	0.42	0.43	66.15	49.10
7	0.34	0.34	43.35	31.27
9	0.25	0.24	23.43	15.12

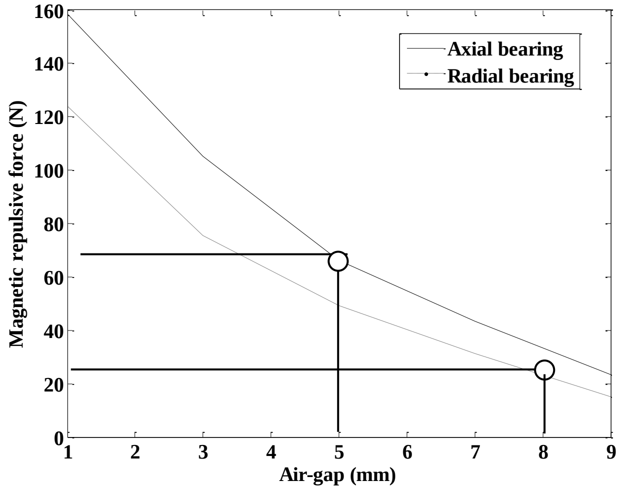

Fig. 7 Magnetic repulsive force generated in bearings at different air-gaps

2.3 Design and development of electric generator

To generate electrical power from the mechanical power, an electric power generator is designed and developed. The Minimum electric potential of 14 V at 300 rpm rotor speed is considered for the generator design, so that a 12 V battery can be used to store electric power. Now the number of turns required in the stator coils is determined by using Eq. (2).

$$N = \frac{Vdt}{(dB \times A)} \tag{2}$$

where V is the electric potential, A is the pole face area, dB is the change in flux density and dt is the change in time. For the rear earth neodymium permanent magnet (NdFeB 37 MGOe) the change in flux density per unit time is taken as 0.7150 and the disc magnets of 30 mm diameter are used for the rotor.

Therefore, the area of the pole is calculated by using Eq. (3).

$$A = \pi D^2/4 \tag{3}$$

For 300 rpm speed of the rotor that is 5 rps gives dt equals to 0.2 s for every time flux lines to pass through each coil.

Now Eq. (2) gives 5490 turns for the coil. In the present work 4 coils are considered in the stator. Therefore we get 1373 turns in each coil. Electric power generator with stator and rotor is shown in Fig. 8. Eight neodymium disc magnets are arranged circumferentially on a disc to make the rotor and four coils are arranged circumferentially to make the stator.

Electric power generated by the generator is given by Eq. (3).

$$P = V \times I \quad (4)$$

where I is the electric current generated and it is given by the relation (4)

$$I = V/R \quad (5)$$

where R is the stator winding resistance and it is calculated by using Eq. (5)

$$R = \frac{\rho L}{a} \quad (6)$$

where ρ is the resistivity of the copper wire, L is the length of the wire used in stator and a is the cross sectional area of the copper wire.

In the present work, 29 gauge (0.287 mm) copper wire with resistivity 1.68×10^{-8} Ωm is used for the stator winding. Each coil with 1373 turns measures 165 m and for four coils the length of the wire is 660 m. The electric resistance of the stator is found to be 171 Ω which is calculated by using Eq. (6).

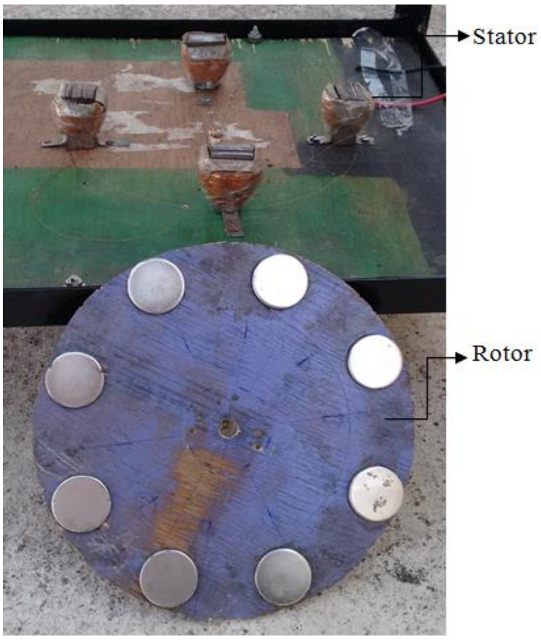

Fig. 8 Stator and rotor of the electric generator

2.4 Fabricated model of wind turbines

The dimensions of both the horizontal and vertical axis magnetically levitated wind turbines are shown in Figs. 9 & 10, respectively. Further, the Figs. 11 & 12 show the fabricated models for both the horizontal and vertical axis magnetically levitated wind turbines, respectively.

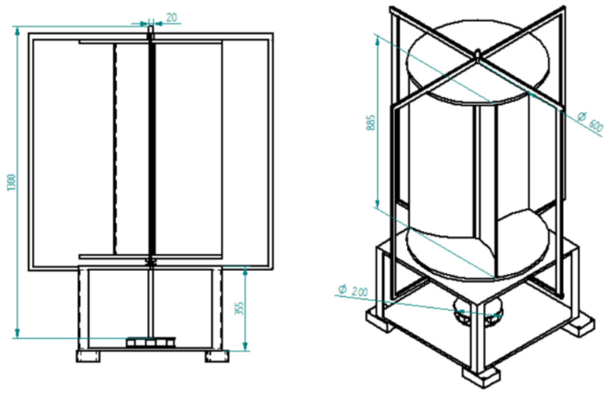

Fig. 9 Assembled view of vertical axis wind turbine with dimensions (in mm)

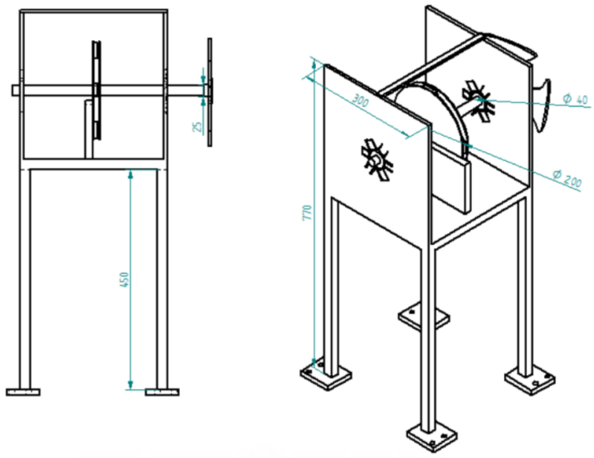

Fig. 10 Assembled view of horizontal axis wind turbine with dimensions (in mm)

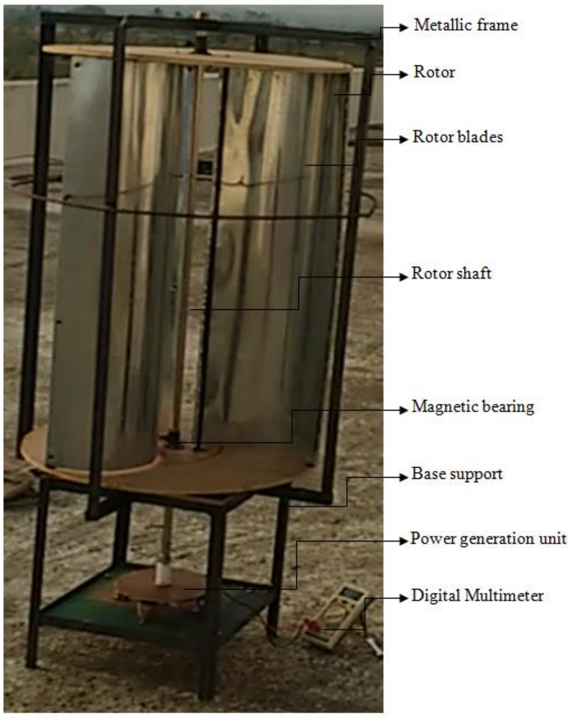

Fig. 11 Fabricated model of magnetically levitated vertical axis wind turbine

Fig. 12 Fabricated model of magnetically levitated horizontal axis wind turbine

3. Performance analysis

Performance study of the designed Maglev windmills is carried out to determine the starting wind velocity, rotational speed and electric power generated at various wind velocities and time taken to stop the rotation completely. Thereafter, the comparison is done with the conventional windmill supported on frictional contact ball bearings.

3.1 Performance analysis of vertical axis wind turbine

Both the magnetically levitated and frictional contact thrust bearing supported vertical axis wind turbines are operated at various wind velocities and the rotor speed and electric power generated are recorded as given in Table 2. It can be observed from the Table 2, that the minimum wind velocity required to start the wind turbines is about 1.5 m/s. At this wind velocity Maglev wind turbine rotates at about 66.67% higher speed and it produces 2.33 times more electric power compared to frictional contact wind turbine. Further, the Figs. 13 and 14 shows that rotor speed variation vertical axis wind turbine and electric power generated in vertical axis wind turbine with respect to wind velocity, respectively. It is seen from the Figs. 13 & 14 that, the increase in the wind velocity, the frictional contact wind turbine performance also increases. However, Maglev wind turbine shows still better performance. At the recorded maximum wind velocity of 6.7 m/s Maglev wind turbine rotates at 9 % higher speed and also generates 15 % more power compared to frictional contact wind turbine. Further, a study is conducted to know the friction offered by both the turbines by recording the time taken by the turbines to stop from certain speed. The data recorded in Table 3 shows that time taken by the Maglev vertical axis wind turbine is 40% and 30% more than the frictional contact wind turbine to stop from the rotor speed of 50 and 100 rpm, respectively. Therefore the friction offered by the magnetic levitation is about 35 % less compared to frictional contact thrust bearing.

Table 2 Performance of vertical axis wind turbines at different wind velocities

Wind velocity (m/s)	Maglev vertical axis wind turbine			Frictional contact wind turbine		
	Speed (rpm)	Electric		Speed (rpm)	Electric	
		Potential (V)	Power (W)		Potential (V)	Power (W)
1.5	85	3.6	0.07	51	2.2	0.03
2.4	128	5.8	0.19	89	4	0.09
3.2	162	7.5	0.32	126	5.6	0.18
4.6	232	10.7	0.67	192	8.7	0.44
5.5	261	12.1	0.85	231	10.7	0.67
6.7	303	13.8	1.12	278	12.8	0.95

Table 3 Time taken to stop the vertical axis wind turbines

Wind turbine rotor speed (rpm)	50	100
Time taken by Maglev vertical axis wind turbine (s)	56	94
Time taken by frictional contact wind turbine (s)	40	72

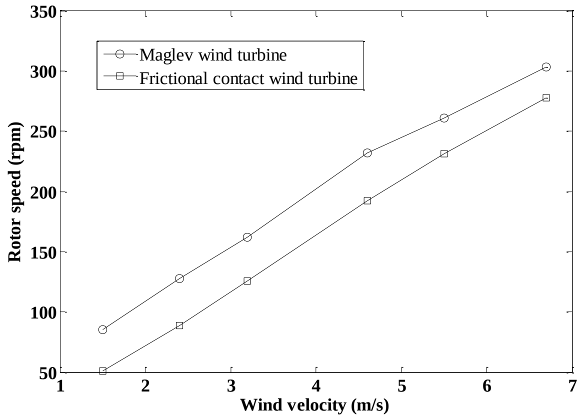

Fig. 13 Rotor speed variation in vertical axis wind turbine with respect to wind velocity

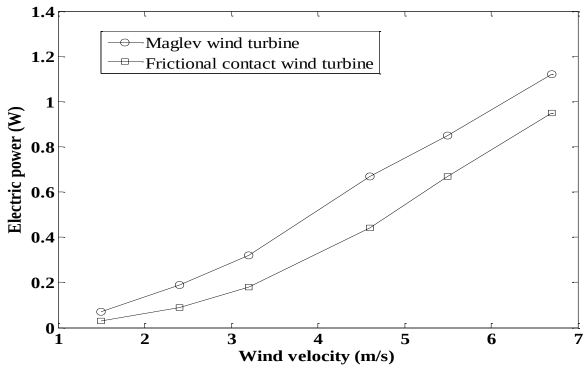

Fig. 14 Electric power generated in vertical axis wind turbine with respect to wind velocity

Table 4 Performance of horizontal axis wind turbines at different wind velocities

Wind velocity (m/s)	Maglev horizontal axis wind turbine			Frictional contact wind turbine		
	Speed (rpm)	Electric		Speed (rpm)	Electric potential (V)	
		Potential (V)	Power (W)		Potential (V)	Power (W)
1.8	41	1.6	0.015	25	1.1	0.007
2.2	58	2.6	0.039	47	2.1	0.026
3.2	97	4.3	0.108	83	3.7	0.080
4.4	145	6.5	0.247	135	6.1	0.217
5.6	193	8.8	0.452	182	8.2	0.392
6.8	241	11.1	0.720	232	10.6	0.657

Table 5 Time taken to stop the horizontal axis wind turbines

Wind turbine rotor speed (rpm)	50	100
Time taken by Maglev horizontal axis wind turbine (s)	14	22
Time taken by frictional contact wind turbine (s)	12	19

3.2 Performance analysis of horizontal axis wind turbine

Similarly in this section the performance study is carried out for the horizontal axis wind turbines. It can be observed from Table 4 that at the recorded minimum wind velocity of 1.8 m/s the Maglev horizontal axis wind turbine rotates at 64 % higher speed and generates 2.14 times higher power compared to the frictional contact radial bearings supported horizontal axis wind turbine. The rotor speed and electric power of the horizontal axis wind turbine with respect to wind velocity is plotted in Figs. 15 and 16, respectively. It is found that with the increase in wind velocity both the wind turbines shows improved performance, however, Maglev wind turbine performance is much better than the frictional contact wind turbine. At a recorded maximum wind velocity of 6.8 m/s the Maglev wind turbine has given 4 % higher rotor speed with 9.6 % higher power generation compared to frictional contact wind turbine. Frictional resistance offered by both the turbines is also studied and results are recorded in Table. 5. Maglev wind turbine offers 16 % less friction compared to the frictional contact radial bearings supported horizontal axis wind turbine.

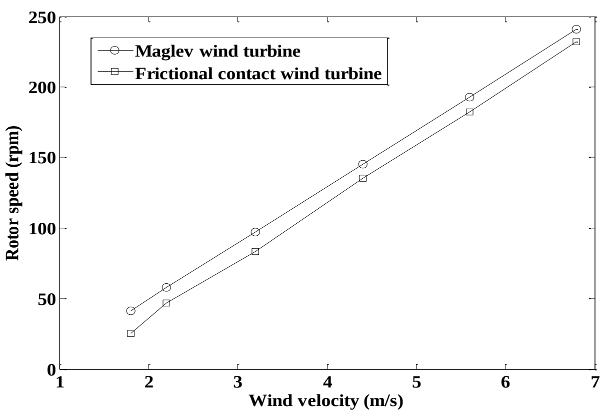

Fig. 15 Rotor speed variation in horizontal axis wind turbine with respect to wind velocity

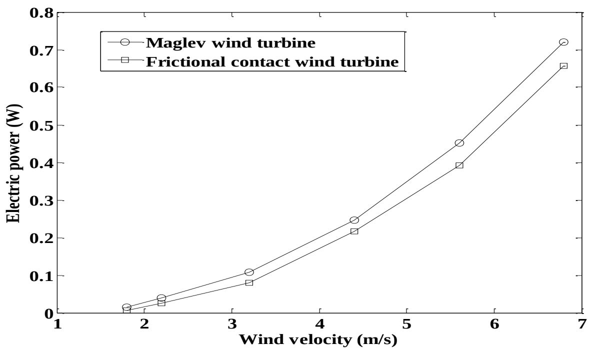

Fig. 16 Electric power generated in horizontal axis wind turbine with respect to wind velocity

Conclusions

The permanent magnet bearings supported Maglev vertical and horizontal axis wind turbines are designed and developed in this work. The performance of these designed wind turbines are compared with the frictional contact ball bearings supported wind turbines. Further, the performance measures considered are, staring wind velocity, rotor speed at various wind velocities, electric power produced and the resistance offered by the wind turbines for their rotation. From the performance study following conclusions are derived:

- Maglev wind turbines require lower wind velocity for startup and also they show better performance at lower wind velocities. Maglev vertical and horizontal wind turbines required respectively 1.5 and 1.8 m/s wind velocity for startup. They have generated respectively 2.33 and 2.14 times higher power compared to the frictional contact vertical and horizontal wind turbines at lower wind velocities.
- With the increase in the wind velocity, the power generated by both Maglev and frictional contact wind turbines improves. However, the Maglev wind turbines show better performance. Maglev

vertical axis wind turbine generated 15% more power compared to frictional contact wind turbine at the recorded maximum wind velocity of 6.7 m/s. Whereas, Maglev horizontal axis wind turbine generated 9.6 % more power compared to frictional contact wind turbine at the recorded maximum wind velocity of 6.8 m/s.
- Frictional resistance offered by the Maglev wind turbines is lower than the conventional frictional contact wind turbines. Frictional resistance offered by the Maglev vertical and horizontal axis wind turbines is 35 % and 16 % lower than the conventional frictional contact wind turbines, respectively.

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