Modelling and Development of Passive Permanent Magnetic Bearing for a Small Cross Flow Vertical Axis Wind Turbine

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Abstract- Mechanical frictional resistance offered by the conventional ball bearings prevent the self starting ability of vertical axis wind turbine at low wind speed regimes. This is overcome with use of passive permanent magnetic bearings. The present study focuses on optimizing the axial force and stiffness by analysing different arrangements of stacked rings of passive permanent magnetic bearings for a small cross flow vertical axis wind turbine using COMSOL Multiphysics software. Three different passive permanent magnetic bearing configurations are stacked with axial and radial magnetisations while the Configuration 3 is stacked only with axial magnetisation. Among all, Configuration 1 shows the highest value of stiffness and maximum axial force exerted by the outer ring magnet on the inner magnet. Therefore, Configuration 1 is chosen for fabrication and implementation in a cross flow VAWT. Rotational speed tests are carried out. The rotational speeds of cross flow VAWT with passive permanent magnetic bearings increased by around 2.36 to 3.28 times the speed of the VAWT with ball bearings. The test results showed that the use of permanent magnetic bearings would lead to a significant improvement in the performance of cross flow VAWT.

Keywords Passive permanent magnetic bearings, zero friction, vertical axis wind turbine, rotational speed.

1. Introduction

The demand for energy from renewable sources is increasing due to increase in the world's energy consumption and environmental issues. However, the energy produced from the renewable energy sources is much less compared to traditional non-renewable energy sources. Therefore, there is a need to develop right technologies for harnessing the renewable energy sources effectively. The wind turbine running at nominal speed is capable of generating more power within a small place in comparison with all other renewable energy sources [1]. Even though horizontal axis wind turbine is preferred for its high power generation capability, the present focus is towards developing innovative turbine blade design for medium and small sized vertical axis wind turbine for generating power in urban Indian homes. But, this small sized vertical axis wind turbine needs further improvement in its design for efficient use in urban Indian home rooftops. Generally, ball bearings are used in the wind turbines to reduce friction. The energy losses by using these ball bearings can't be made zero. Therefore, it is important to reduce these energy losses in order to increase the efficiency of the wind turbine. Replacing the ball bearings with magnetic bearings could be considered as one of the ways in improving the performance of the vertical axis wind turbines [2]. A magnetic bearing supports the load based on magnetic levitation and it supports the moving parts without any physical contact. Magnetic bearings based on its operation, are classified as passive magnetic bearing and active magnetic bearing. Passive magnetic bearing operates based on the repulsive forces between the permanent magnets. On the other hand, active magnetic bearing works on the attractive forces between the electromagnet (coil and core) and ferromagnetic material [3].

Among different permanent magnetic bearing technologies, the passive permanent magnetic bearing is chosen. Passive permanent magnetic bearings (PPMB) are safe, ease in use, noiseless, no mechanical wear, allows frictionless relative motion, low maintenance cost, lubrication free and it do not require any external power source for its operation [3]. However, stability is a major issue faced in using a passive permanent magnetic bearing. This is mainly due to allowing all its six degrees of freedom to move freely. This issue in stability is overcome by preventing the axial movement of passive permanent magnet bearing with carbide tip sharp point. This approach allowed the remaining other five degrees of freedom in a stabilized magnetic state [3, 4]. This development in the passive permanent magnet bearing is used for fabricating one of the permanent magnetic bearing which is used to support the cross flow VAWT from the top. Also, the advancements in use of rare earth magnetic materials enable us to use it for magnetic bearings involving mechanical systems [5].

In general, stiffness and force are the main design parameters considered in design of permanent magnet bearings. Various researchers [6, 7] used analytical approach involving mathematical expressions and finite element analysis to analyze these parameters.

Using a typical arrangement, viz., a shaft held by PPMBs, the forces acting in magnetic levitation of a passive permanent magnetic bearing system was analytically investigated by Roberto Bassani [8]. Ravaud *et al.* [9] calculated the force and stiffness between rings of permanent magnets which was axially magnetized using semi-analytical expressions. The arrangement represented a typical PPMB. Colombian model was used in all these calculations. The authors reported an optimized ring dimensions to provide a large stiffness as well as large force. Also, the air gap dimension between relative positioning the rings defined the magnitude of force.

Hamler *et al.* [10] analysed the rotating and fixed part of the PPMB for high-speed rotary elements. The investigation of magnetic conditions were carried out using 3D finite element method and the performance of the magnetic bearing was found using Maxwell stress method. Furlani *et al.* [11] carried out a three dimensional analysis of radially polarized permanent magnet cylinders. The outcome of the study was verified by using 3D finite element analysis. Earlier, Bruno Azzerboni *et al.* [12] analytically studied the distribution and strength of the magnetic field in massive conductor systems.

Optimization studies were carried out involving parameters like inner radius of outer and inner rings, air gap, number of ring pairs and axial offset to identify the stack structure having maximum axial force and stiffness. Recently, Siddappa *et al.* [13] analyzed an axially magnetized stack structured having 'n' number of ring pairs of passive permanent magnetic thrust bearing using 3D generalized mathematical model. Earlier, Siddappa and Soumendu [14] developed a generalized 3D mathematical model for permanent magnetic bearing with 'n' number of ring pairs in order to analyze the stiffness and force in axially, radially and perpendicularly magnetized bearing. Subsequently, Siddappa *et al.* [15] developed a mathematical model to estimate the stiffness and force for ring magnets with radial polarizations. 3D Finite element analyses were carried out to validate the accuracy of these optimization methods. Ravaud *et al.* [16] carried out studies to optimize the stiffness and force of ring magnet pairs with radial polarization using semi-analytical expressions involving Colombian model. Curvature effect was also taken into consideration in this study. By considering the magnet curvature, the precise position of maximal force exerted between two ring magnets can be obtained. Again, air gap between the relative positions of rings decided the strength of the force. Recently, Huachun Wu *et al.* [17] used FEM analysis to optimize the geometric parameters of a permanent magnetic bearing for use in the VAWT at low wind speeds.

The stiffness and force of the PPMB of a rotating shaft with a pair of axially polarized ring magnets as well as stacked structured rings were analytically studied using mathematical model by Valerie and Guy [18]. Yonnet *et al.* [19] investigated different stacked structures namely conventional stacking and stacking with rotating magnetization direction involving PPMBs. Stacked structures showed improved stiffness and stiffness of stacking with rotating magnetization direction improved by a factor of two compared to conventional stack. Using finite element method, Sun Jinji *et al.* [20] studied the characteristics of stiffness and force of the passive axial magnetic bearing with segmented Halbach magnetized array. Also, Ravaud *et al.* [21] analytically established that Halbach structures were more efficient and the magnitude of stiffness and force were increased by twofold.

Only few researchers have experimentally investigated the effect of arrangement of polarized ring magnets on the stiffness and force of these passive permanent magnetic bearings. Jan Kumbernuss *et al.* [2] analytically studied a magnetic levitated bearing system for the vertical axis wind turbine using Ansoft: Maxwell software. The bearing system generated magnetic force to support the weight of the turbine. A prototype was developed using low cost pre charged ferrite magnets and experiments were conducted. Based on the experimental outcome, the authors suggested that air gap between the stator and rotor plays a major role in defining the performance of the bearing system in a VAWT.

Elkin Rodriguez *et al.* [3] analytically as well as experimentally conducted investigations on a VAWT using two different configurations (with stacking i.e, layers of ring permanent magnets stacked with specific magnetization pattern and without stacking i.e., single layer ring permanent magnets with specific magnetization pattern) of radial passive permanent magnetic bearings. The results obtained through experimental studies were compared with the simulation results. The stacked structure showed a better behaviour for both dynamic test (i.e., magnetic bearings attached to the rotating shaft to study its dynamic behaviour) and static test (i.e., magnetic bearings tested at stationary condition to understand behaviour). The prototype PPMB delivered a force of 160 N.

An axial type passive permanent magnetic thrust bearing for a VAWT was analyzed by Yi Hua Fan *et al.* [22] for different air gaps ranging from 1 mm to 5 mm. Using Maxwell equations and finite element analysis software JMAG, the PPMB with an air gap of 2 mm was found to exert force of 225.60 N. The experimental results showed that the rotational speed of passive magnetic bearing increased by 10% in comparison with roller bearings of same wind speed. Also, the system with PPMB rotated at a lower wind speeds compared to contact type bearing. On the other hand, Kriswanto and Jamari [23] conducted both analytical and experimental investigations on a horizontal axis wind turbine (HAWT) using PPMBs. Simulations were carried out using COMSOL Multiphysics software. The HAWT with PPMB rotated at a lower wind speed of 1.40 m/s to produce torque of 0.043 Nm. The HAWT with ball bearing rotated only at a wind speed of 4.40 m/s. The rotational speed of the HAWT system with PPMB increased by 87.40% compared to HAWT with ball bearing. Similarly, studies based on permanent magnetic generators using permanent magnets were carried out by several researchers [24-32]. Recently, Micha Premkumar *et al.* [33] analyzed the influence of air gap variations (7.50 mm to 12.5 mm in steps of 2.50 mm) on the performance of the PPMB system in a VAWT using COMSOL Multiphysics. The investigations revealed the necessity of minimum air gap between ring magnets to produce larger axial force and stiffness.

The presence of non-contact type passive permanent magnetic bearing eliminates mechanical friction and reduces the VAWT starting torque thereby improving the capability of VAWT to rotate at low rated wind speeds (i.e., 4 to 5 m/s). Also, the wind energy utilization of the VAWT system would improve along with increased life cycle and power generation efficiency due to reduced energy losses. Based on the literature review, it is understood that only few researchers have investigated the effect of arrangement of polarized ring magnets on the stiffness and force of these passive permanent magnetic bearings in vertical axis wind turbine. Therefore, the focus of this present study is to optimize the axial force and stiffness using different stacked ring configurations as shown in Figure 1, so as to use the PPMB in a cross flow vertical axis wind turbine (VAWT).

The present work focuses on analyzing the possible magnetization arrangements using COMSOL Multiphysics software® [23, 34] to obtain the maximum stiffness value and axial force exerted by PPMB using an array of ring magnets for using it in a cross flow VAWT. The simulation uses magnetic field physics to model the magnetic field. Based on the simulation outcome, the PPMB prototype is developed and it is tested in an experimental test rig comprising a VAWT. Rotational speed test is carried for VAWT with PPMB and it is compared to a VAWT with ball bearing.

2. Design of Passive Type Permanent Magnetic Bearings

The permanent magnetic bearing made of neodymium magnets for the rotor and ferrite magnets for the stator of ring type for different configurations is made and these configurations consisting of magnets with radial and axial magnetisation is shown in Figure 1.

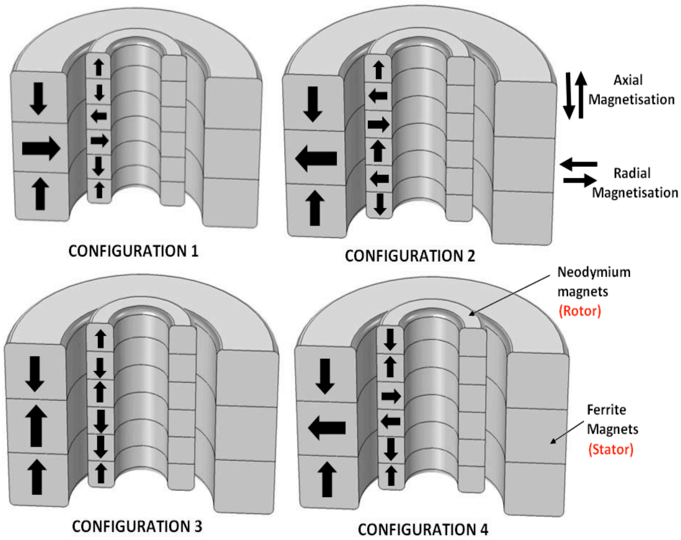


Fig. 1. Stacked ring configurations used for analysis of PPMB at the bottom end

The Configurations 1, 2 as well as 4 are designed by using axial and radial magnetisations while the Configuration 3 is designed with only axial magnetisation. Regarding the dimensional details, six neodymium magnets in the rotor is having an inner radius of 10 mm, outer radius of 20 mm, height 10 mm with Remanent flux density of 1 T. Remanent flux density, also called as residual flux density, is one of the magnetic properties of permanent magnet. It is the value of magnetic flux density which remains in a magnetized body even after the applied magnetic field strength is brought to zero. The three outer ferrite magnets which are used in the stator is having its inner radius as 27.50 mm with its outer radius 50 mm, height 20 mm and having a Remanent flux density of 0.35 T. An air gap of 7.50 mm is maintained between the ring magnets [33]. The arrangement of various PPMBs as shown in Fig. 1 is made by keeping the outer ferrite magnet and the inner neodymium magnet in a concentric manner thereby causing the repulsive reaction force of these two magnets to centre by itself relatively with respect to each other in the magnet assembly.

The configurations as represented in Figure 1 is chosen for making the PPMB which is used to support the cross flow VAWT at the bottom side. The PPMB which is used to support the cross flow VAWT at the top is having six neodymium magnets for the rotor with one ferrite magnet for the stator in order to reduce the cost of the magnetic bearing. A provision is made for keeping another two ring of ferrite magnets for the future works. The passive permanent magnetic bearing configuration used at the top is shown in Figure 2. This bearing's inner magnets are placed as per the Configuration 1 as seen in Figure 1.

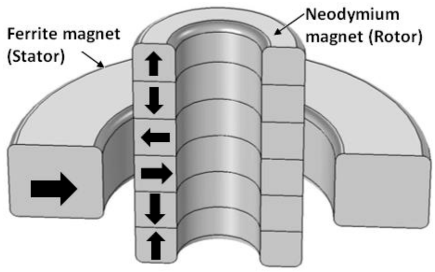


Fig. 2. Configuration used for analysis of PPMB at the top

3. Mathematical Modelling

Several approaches like two dimensional approach, Colombian model [7, 13-16] finite element method [7, 10], etc., are available to find the magnetic field created by the permanent magnets. In order to study the magnetic bearings either the force, stiffness exerted is to be calculated or the two dimensional equations is to be solved to determine the magnetic fields produced by the ring permanent magnet [12-14]. In the permanent magnet bearing, the rotor magnet is on the shaft and the stator magnet is kept inside the housing. Due to repulsive reaction among the stator and rotor magnets, the shaft of the cross flow VAWT remains at a levitated position. The three dimensional Colombian model [7, 13-16] is used in this present study to find the force exerted in these permanent magnets. The axial field exerted by this permanent magnet is expressed as

[illegible] (1)

where

[illegible] (2)

The axial force is determined by using the equation

[illegible] (3)

Two methods are available in COMSOL Multiphysics software® [34], to calculate the electromagnetic forces and torques. Maxwell stress tensor method [10, 22] is the most general method which is used in the magnetic fields interface by the force calculation feature. This feature integrates the Maxwell stresses which are solved just outside the selected domain(s) and all over the entire outer boundary of the selected domain as these are the domain(s) moving together as a single mechanical system. The force computed by this method is sensitive to the grid size as this approach is based on surface integration. A proper mesh refinement is to be carried out while carrying out the study to compute the torque or force using this method.

Lorentz force method is another method which is used to compute the magnetic force on a non-magnetic current carrying domain. Lorentz force is expressed as F = B x J, where B is the magnetic flux density and **J** is the current density. In an electrically conducting domain, the Lorentz force method is accurate in calculating the force as this approach evaluates it in the volume rather than on the boundaries. In this present study, the Maxwell stress tensor method [10, 22] is used to calculate the force. COMSOL Multiphysics software calculates the total magnetic force on an object by integrating the vector expression given below as

$$f = n\cdot T = -1/2\, n(H.B) + (n.H)B^T \qquad (4)$$

where n is the outward normal vector, B is the magnetic induction, H is the magnetic intensity and T is the Maxwell stress tensor over the object's outer boundaries. Amphere's law feature is used to model the magnets i.e., the direction magnetization (radial and axial) [11, 23]. The force obtained for different permanent magnet configurations are shown in Figure 5.

It is known that passive magnetic bearing exerts a radial restoring force when the system is excentered which is characterized as stiffness. Thus, the negative of the derivative of total magnetic force with respect to the position is referred as the magnetic stiffness (K_Z). By this definition, the axial magnetic stiffness (K_Z) of the permanent magnetic bearing is expressed as

$$K_Z = -\, dFz/dz \qquad (5)$$

where Fz is the total axial magnetic force on the magnetic bearing. This approach calculates the magnetic stiffness in the axial direction only. In order to increase the stiffness, the magnetic bearings are stacked from top to bottom. The total stiffness obtained is approximately equal to $K_n = (2n-1)K_z$ where n is the number of elementary bearings stacked. A complete 3D model is required to calculate the magnetic stiffness in the radial direction as well as the coupled stiffness coefficients. The stiffness of different configurations is discussed later as shown in the Figure 7. After mathematical manipulations, the above expression can be reduced as represented in the equation 6 and 7.

[illegible] (6)

where

[illegible] (7)

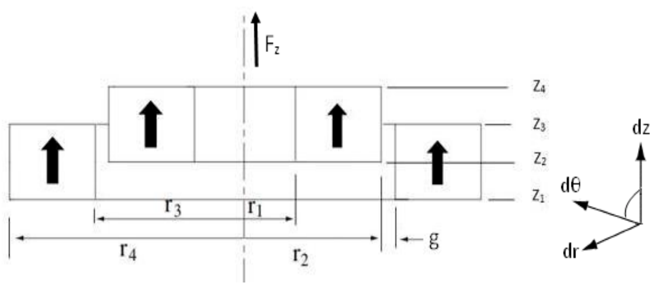


Fig. 3. Cross section view of the stacked ring permanent magnets with axial polarization

Table 1. Dimensions of the permanent magnets and its flux density values

Symbol	Description	Value
[illegible]	Inner magnet Remanent flux density	1 T
[illegible]	Outer magnet Remanent flux density	0.35 T
h_o	Outer magnet thickness	20 mm
h_i	Inner magnet thickness	10 mm
r_4	Outer magnet's outer radius	50 mm
r_3	Outer magnet's inner radius	27.5 mm
r_2	Inner magnet's outer radius	20 mm
r_1	Inner magnet's inner radius	10 mm
g	Air gap between the ring magnets [33]	7.50 mm

The dimensional detail of the ring passive permanent magnet used in this present study is given in Table 1 and the schematic cross sectional view of these stacked ring permanent magnets representing stator and rotor is shown in Figure 3.

Meshing is carried out using the tools available in COMSOL Multiphysics software [34]. Free triangular mesh is created for the magnet as well as the computational domain. To ensure the accuracy of the simulation, the mesh is refined with finer elements in the computational domain near the magnet as shown in Figure 4.

Figure 4(a) shows the meshing arrangement for the bottom and top permanent magnetic bearing and a closer view of these meshes in the magnet is shown in Fig. 4(b). The resulting meshes of the top permanent magnetic bearing and bottom permanent magnetic bearing consists of about 8599 elements and 9396 elements respectively. The number of nodes for the top PPMB and bottom PPMB are 4485 and 4896 respectively. In this present study to carry out the analysis, one of the physical interface namely magnetic field interfaces is chosen and appropriate boundary condition are enforced.

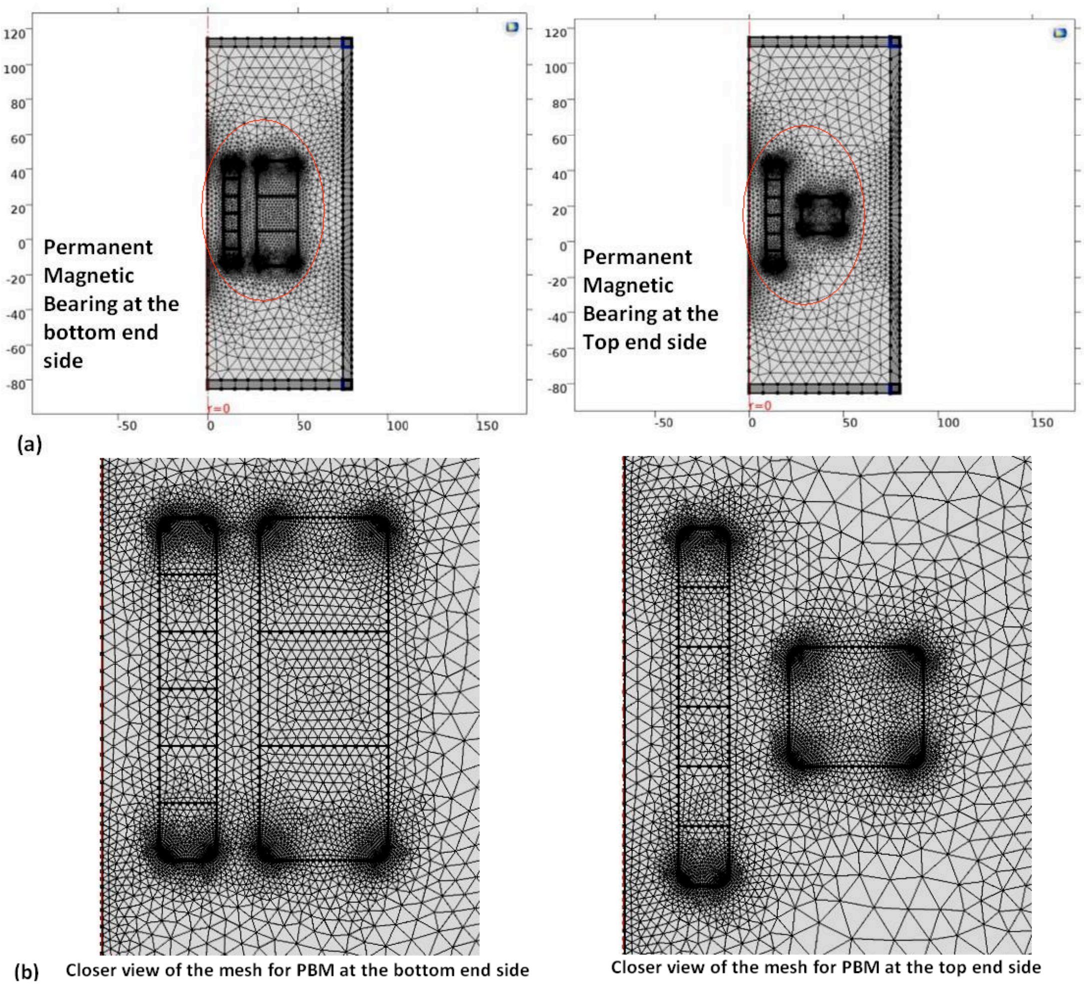


Fig. 4. (a) Mesh of the bottom PPMB and top PPMB domain **(b)** Closer view near the permanent magnets

4. Results and Discussion

The characterization of passive permanent magnetic bearing viz., varying its axial, radial and rotational position is essential in order to understand the force generated and stiffness due to interaction of magnetic flux before it is used in the cross flow VAWT. Four different bottom PPMB configurations namely, Configuration 1, Configuration 2, Configuration 3 and Configuration 4 are compared. All these configurations consists of two inner neodymium magnets and an outer ferrite magnet and these combine into as a single set of permanent magnetic bearing. These stacked ring PPMB configurations are compared and discussed here.

Figure 5 shows the axial force exhibited by these configurations. The x axis represents the axial distance of the rotor magnets with respect to the stator magnets (dZ) and the y axis represents the axial force in Newton exerted by the rotor magnets on the stator magnets. As can be seen in Figure 1, the Configuration 1, 2 and 4 comprises both axial and radial polarization. Configuration 3 consists both of inner and outer magnets magnetized in axial direction only. The maximum axial force exerted by the outer ring magnet on the inner magnet in Configuration 1 PPMB is 176 N (refer Fig. 5a). Similarly, the maximum axial force exerted by Configuration 2 PPMB and Configuration 4 PPMB is 98 N and 63 N respectively (refer Fig. 5b and 5d). Configuration 3 with axial magnetization gives a least axial force of 38 N (refer Fig. 5c). On comparing all these configurations, it is clear that Configuration 1 PPMB gives the best output with maximum axial force of 176 N and this Configuration 1 PPMB is used to support the cross flow VAWT at the bottom side.

The axial load that the PPMB is to withstand is 80 N. This includes the weight of the aluminium shaft, couplings, cross flow VAWT, etc. As per the simulation results, it is possible to lift the axial load using the bottom end PPMBs and the top PPMB has no load to bear. Therefore, the top PPMB is used only to provide support to the shaft of the cross flow VAWT. This is the reason behind to consider the top PPMB with only one outer ferrite magnet. Due to repulsion among the ring magnets, the inner neodymium magnets self aligns itself between the ferrite magnets and the axial load of 80 N is supported easily.

As Configuration 1 exerts the maximum axial force on the inner magnet, this configuration is selected to support the cross flow VAWT at the top end. The maximum axial force exerted for this magnetic bearing with one ferrite outer magnet and six inner neodymium magnets as can be seen in Figure 6 is 36 N.

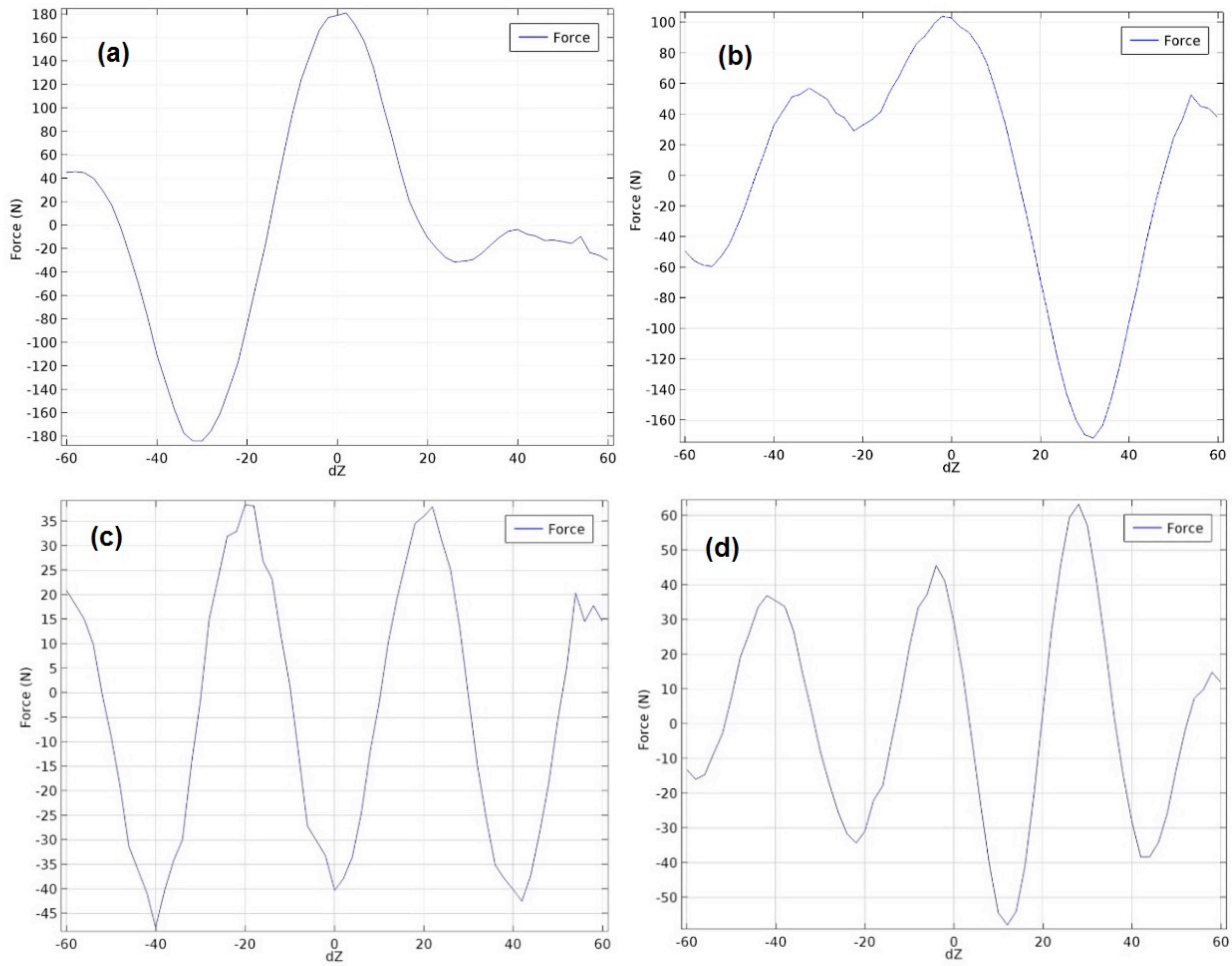


Fig. 5. Variations of axial force exerted by different PPMB configurations

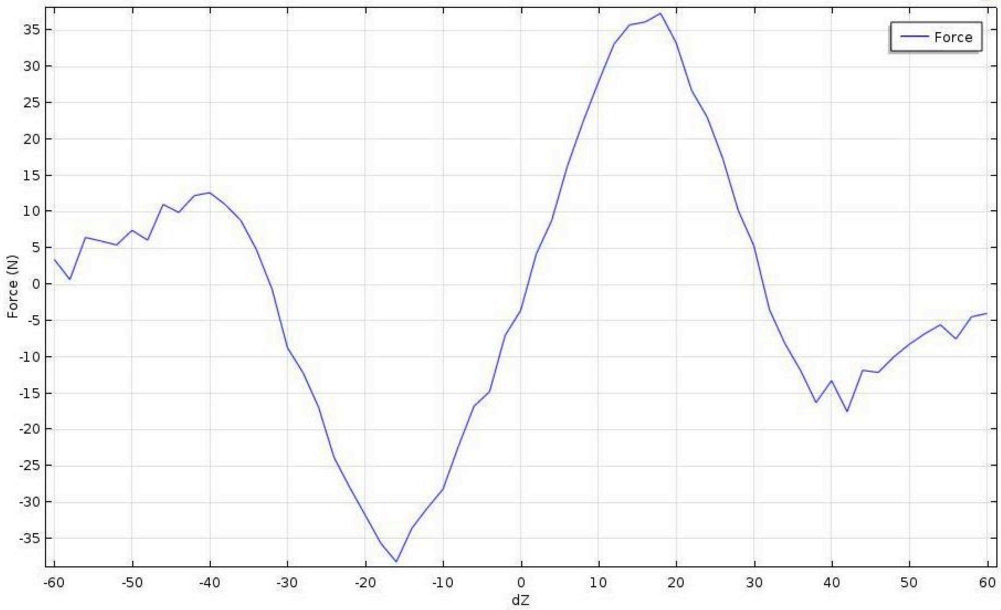


Fig. 6. Variation of axial force exerted by the magnetic bearing supporting the VAWT at the top

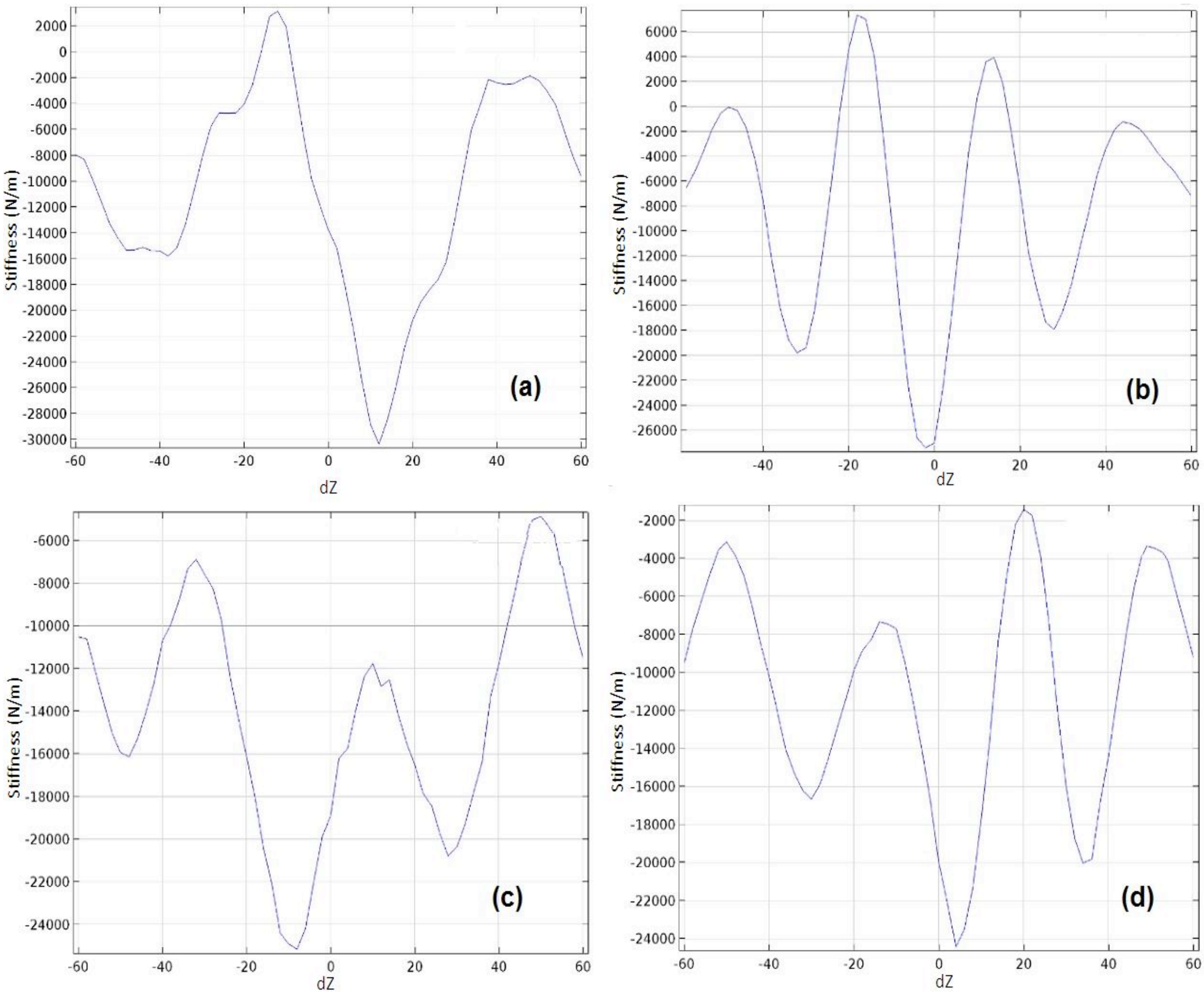


Fig. 7. Variations of stiffness for different configurations of bottom side PPMB

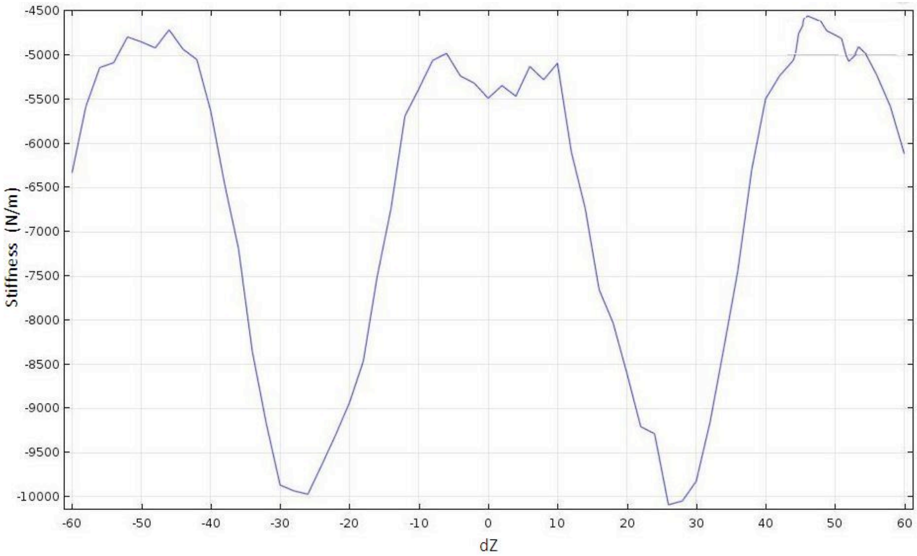


Fig. 8. Variations of stiffness for top PPMB

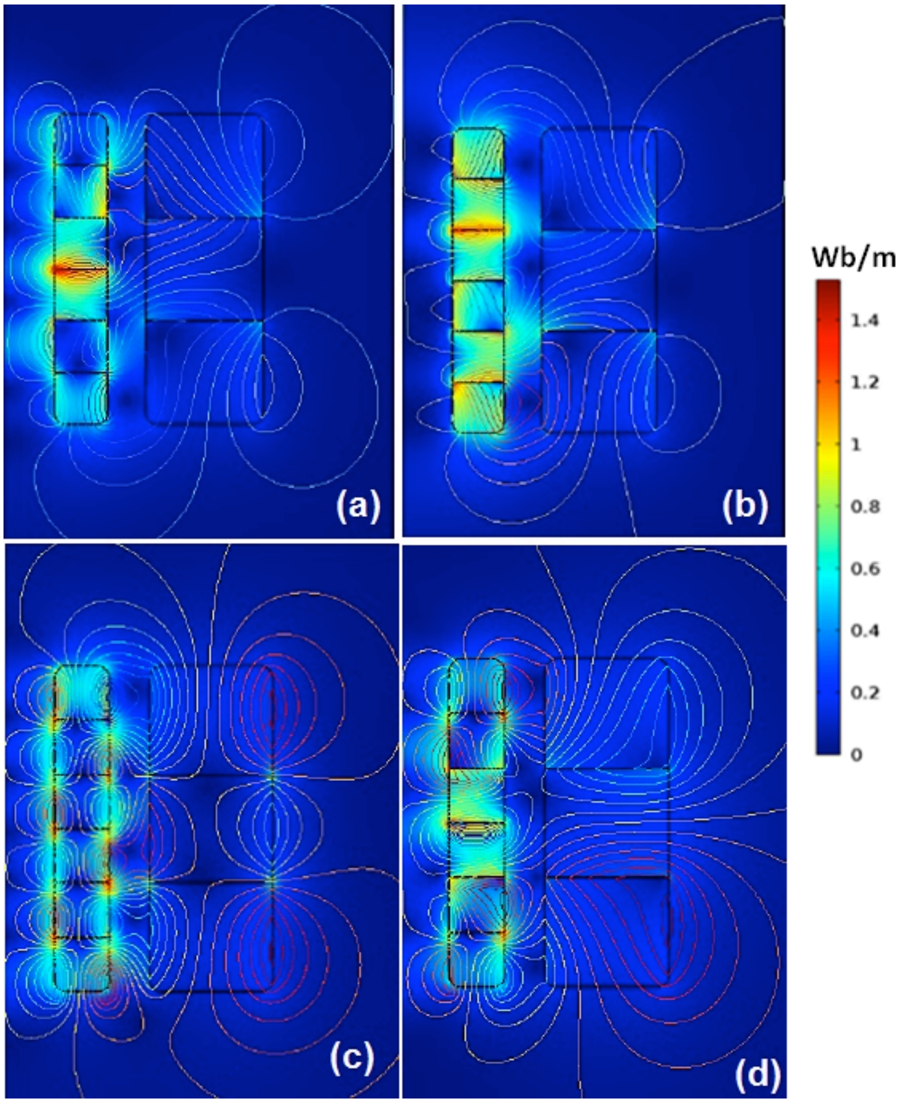


Fig. 9. Magnetic field contours due to interaction of flux between the rotor and stator of different bottom end PPMB configurations

The stiffness of these configurations is represented in Figure 7. The x axis represents the axial distance of the rotor magnets with respect to the stator magnets (dZ) and the y axis represents the stiffness in N/m. As can be seen in Figure 7(a), the Configuration 1 gives the maximum stiffness of 30000 N/m. Configuration 2 which is a combination of axial and radial magnets with perpendicular polarization gives a maximum stiffness of 26800 N/m (refer Fig. 7b). Configuration 3 which is having only axial configuration and Configuration 4 having a combination of axial and radial magnetization gives a maximum stiffness of around 24800 N/m (refer Fig. 7c and 7d). Therefore, Configuration 1 which gives the highest value of stiffness is selected for the fabrication of bottom side PPMB to be used in cross flow VAWT. The stiffness exhibited by the top side PPMB is shown in Figure 8.

The contour of the magnetic field for different configurations due to the interaction of flux between the rotor and stator of the PPMB is shown in Figure 9. As can be seen in the Figure 9(a) and 9(b), the Configurations 1 and 2 show the magnetic array repulses in which the magnetic flux lines are observed to be mostly slanted. Therefore, these PPMB configurations interact in both the horizontal and vertical directions. This causes a vertical force in the rotor so that the rotor is pushed away. This phenomena is good as it reduces the load on the thrust bearings of the cross flow VAWT. The Configuration 3 (refer Fig. 9(c)) reveals the magnetic array repulses which are observed parallel to the axis of the bearing. Hence, it leads this configuration to interact only in radial direction. The Configuration 4 (refer Fig. 9(d)) shows the magnetic array repulses which are found to be mostly perpendicular with respect to the axis. Therefore, this leads the Configuration 4 to interact mostly in vertical direction. The magnetic field contour due to interaction of flux between the rotor and stator of the PPMB located at the top end of the cross flow VAWT (refer configuration as seen in Fig. 2) is shown in Figure 10. The magnetic field is observed to be confined in the bearings.

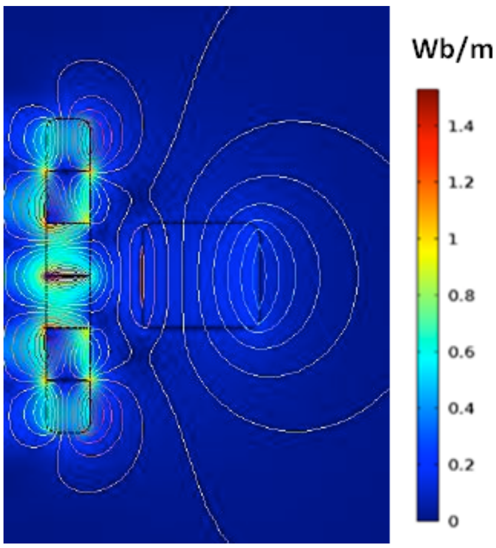


Fig.10. Magnetic field contours due to interaction of flux between the rotor and stator of top end PPMB configuration

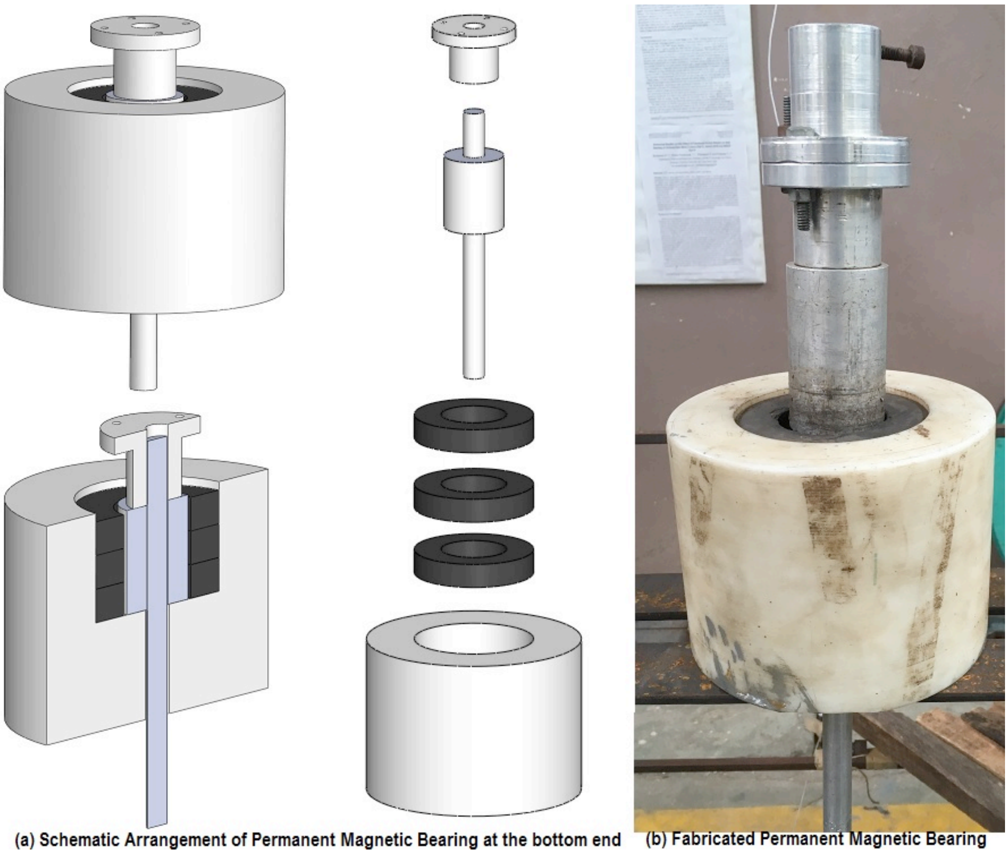
Hence, based on the selection criteria of PPMB in this present simulation study, it is found that Configuration 1 shows the highest value of stiffness and maximum axial force exerted by the outer ring magnet on the inner magnet. Therefore, Configuration 1 is chosen for fabrication and implementation in a cross flow VAWT.

4.1. Passive Permanent Magnetic Bearing For a Cross Flow VAWT and its Rotational Speed Test

The actual fabricated passive permanent magnetic bearing used at the bottom of the VAWT as well as its schematic arrangement is shown in Figure 11. As seen in the Figure, it is made by keeping the outer ferrite magnet and the inner neodymium magnet in a concentric manner. The inner neodymium magnets is fixed to the shaft of the cross flow VAWT. An outer casing arrangement supports the outer ferrite magnet. The stability of this PPMB is ensured by keeping a constraint in its axial direction thereby allowing the remaining five degrees of freedom in a stabilized magnetic state. Similarly, the PPMB at the top end of the VAWT is fabricated and its actual as well as schematic arrangement is shown in Figure 12. These PPMBs are installed at the top end and bottom end of the cross flow VAWT in the experimental setup as seen in Figure 13.

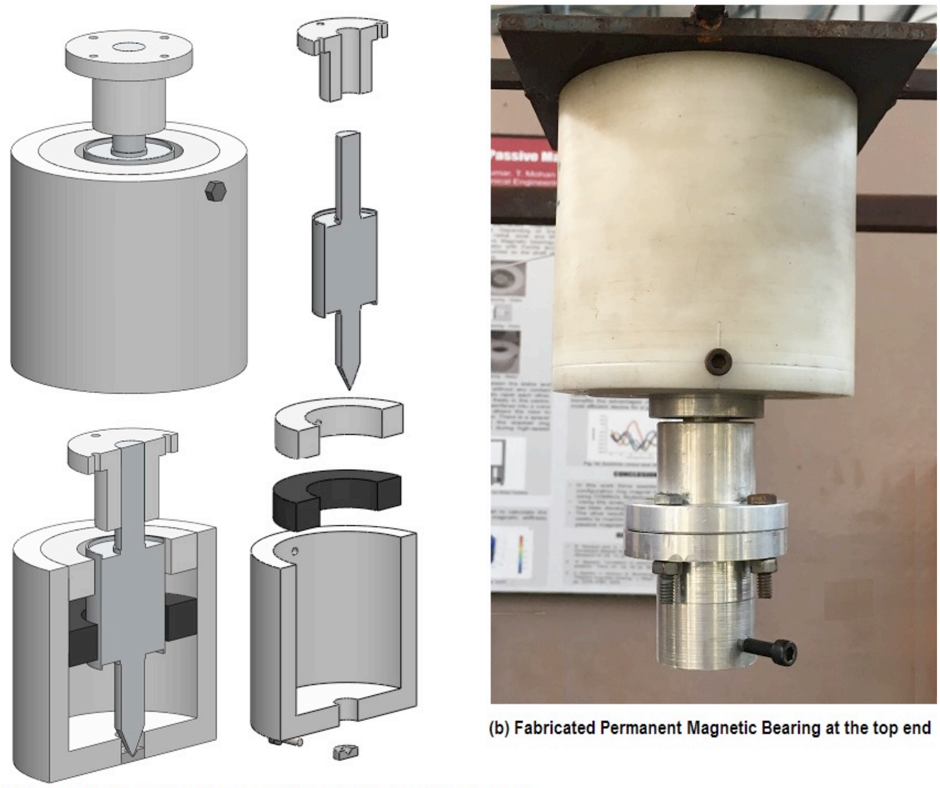
The axial load that the PPMBs have to withstand is 80 N. This includes the weight of the aluminium shaft, couplings and the cross flow VAWT. As per the simulation results obtained using COMSOL Multiphysics software, it is possible to lift the axial load using the bottom end PPMB and the top end PPMB has no load to bear. Therefore, it is only used to support the VAWT from the top. Due to repulsion between the ring magnets, the inner neodymium magnets self aligns itself between the ferrite magnets and the axial load to be lifted comfortably. This is also realised during this experimentation.

Experimental investigations are carried out in the laboratory by generating the low rated wind velocities varying from 4 m/s to 11 m/s using axial fan. Cup type anemometer and non-contact type photo electric sensor is used to measure the wind velocity (V) and rotating speed of the cross flow VAWT (N) respectively. These measured data are recorded using NI© data acquisition system with Labview© software through a data logger interfaced with the computer. Table 2 lists the rotational speeds of the cross flow VAWT with the proposed PPMBs and rotational speed of this VAWT with conventional ball bearings at both the ends. On comparing the data, it is observed that the rotational speeds of the cross flow VAWT with PPMBs increased by around 2.36 to 3.28 times the rotational speed of the VAWT with conventional ball bearings at both the ends. The rotational speeds of cross flow VAWT using PPMB in this present study is also compared with the earlier work done by Kriswanto and Jamari [23] as shown in Table 3. As the frictional resistance offered is considerably reduced in these PPMBs, the use of this PPMB in the cross flow VAWT would lead to a significant improvement in the performance of VAWT and also its ability to self-start and rotate at low rated wind velocities.



(a) Schematic Arrangement of Permanent Magnetic Bearing at the bottom end (b) Fabricated Permanent Magnetic Bearing

Fig. 11. Schematic arrangement and actual fabricated PPMB used at the bottom end of VAWT



(b) Fabricated Permanent Magnetic Bearing at the top end

(a) Schematic View of the Permanent Magnetic Bearing at the top end

Fig. 12. Schematic arrangement and actual fabricated PPMB used at the top end of VAWT

Fig.13. Experimental setup of the tested prototype PPMB with cross flow VAWT

Table 2. Rotational speed test of the cross flow VAWT with PPMB at no load condition

Wind speed, V (m/s)	**Maximum rotational speed of the cross flow VAWT, N (rpm)**	
	With conventional ball bearings	**With PPMBs**
4	89	292
5	100	304
6	121	338
7	148	392.50
8	174	411

Table 3. Comparison of rotational speed of VAWT using PPMB with earlier study

Rotational Speed of PPMB	
Present Study **PPMB in a Cross Flow VAWT System**	**Kriswanto and Jamari [23]** **PPMB in a HAWT System**
Rotational speed of VAWT with PPMB enhanced by 2.36 to 3.28 times on comparing a VAWT with ball bearing for a wind velocity ranging from 4 m/s to 8 m/s	Rotational speed of HAWT with PPMB increased by 2.10 to 3.39 times compared to HAWT with ball bearing for a wind velocity varying from 4.40 m/s to 8.40 m/s

5. Conclusion

The focus of this present study is to optimize the axial force and stiffness using different stacked ring configurations of passive permanent magnetic bearings. The different arrangements of stacked rings of passive permanent magnetic bearings for a small cross flow VAWT are analytically investigated using COMSOL Multiphysics software. Three different PPMB configurations are stacked with axial and radial magnetisations while the Configuration 3 is stacked only with axial magnetisation. Among all, Configuration 1 shows the maximum values of axial force exerted and stiffness. Therefore, this configuration is chosen for fabrication and it is implemented in a small cross flow VAWT. It is tested using an experimental setup at low rated wind velocities. The data derived from the experimental results showed that the rotational speeds of the cross flow VAWT with passive permanent magnetic bearings increased by around 2.36 to 3.28 times the speed of the VAWT with conventional ball bearings. Based on this study, it could be concluded that the use of this passive permanent magnetic bearings in the cross flow VAWT would lead to a significant improvement in the performance of VAWT and also its ability to self-start and rotate at low rated wind velocities.

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