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Dynamic Analysis of 650 W Vertical-Axis Wind Turbine Rotor System Supported by Radial Permanent Magnet Bearings †

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Abstract: This paper presents a comprehensive dynamic analysis of a 650 W vertical-axis wind turbine (VAWT) rotor system, focusing on the impact of radial permanent magnet bearings (PMBs) on its performance. Through optimization of PMB capacity and stiffness using multi-ring radially magnetized stack structures, the study explores their influence on modal frequency, vibration amplitude, and system stability. The research progresses through steps, initially analyzing the rotor system with deep groove ball bearings (DGBs), considering the bearing span length, and transitioning to a hybrid bearing set (HBS) with PMBs. Ultimately, the rotor system entirely relies on radial PMBs, as investigated through finite element analysis (FEA). The results reveal significant improvements in critical speeds (5.75–9.81 percent higher than operational speeds), emphasizing the influence of bearing stiffness on system dynamics and stability. The study's insights offer valuable contributions to the understanding and design optimization of VAWT rotor systems supported by PMBs, enhancing the efficiency and reliability of wind energy conversion systems.

Keywords: rotor dynamic; wind turbine; PMB; hybrid bearing set; modal analysis

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1. Introduction

Renewable energy sources like wind have enormous potential since they are indigenous, limitless, and environmentally benign. The energy issue and the global warming caused by greenhouse emissions can only be solved by increasing wind power usage. Conventional mechanical bearings are now used for most wind turbine rotor support; however, these bearings need frequent maintenance and lubrication owing to the high dynamic stresses they are subjected to in wind turbines' harsh operating environments. This significantly raises the price of producing electricity using wind. Heat is produced in mechanical bearings due to frictional forces between the balls and the outer and inner races, and this heat contributes to thermal expansion, which in turn impacts the lubrication performance. A rotor bearing may thus fail before its time if frictional forces are miscalculated. If a wind turbine bearing failed, the whole rotor system would be destroyed. Combining magnetic bearings with traditional bearings is a practical solution to the problem of their excessive influence on the rotor system [1,2]. The block Lanczos method and Ansys modal response tools are used to perform the free vibration analysis of the Darrieus-type VAWT system. Five blades and two bearings fitted over the vertical rotor are considered for the modeling, and linear analysis is carried out to ease the computation. The presented analysis method gives faster solutions with simplified VAWT system designs [3,4]. Several optimum design methods were studied for VAWT based on Antarctic and offshore deep-water moving platforms. The blade and rotor parameters were analyzed to understand their influence on wind power efficiency using different FEA simulation tools [5–8].

Bekinal et al. [9] designed and developed axial PMB to support the rotor axially, along with foil bearings for complete passive levitation. Three ring pairs used to develop the PMB are arranged in the Halbach pattern and are perpendicularly magnetized. The experiment was conducted on a rotor-bearing system to analyze the complete levitation and the system was stable at 40,000 rpm. Gireesha et al. [10–12] analyzed vertical spindle systems supported by HBS for dynamic and harmonic responses. Machine tool spindles experienced chatter vibrations due to thrust force during cutting operations, which leads to the failure of the spindle-bearing system. The practical applications and benefits of using PMBs in VAWT rotor systems include reduced friction, enhanced durability, and the potential for reduced maintenance requirements, leading to improved overall performance and a longer service life.

In the present work, dynamic analysis is performed on a VAWT rotor-bearing system supported by different combinations of HBS to study the feasibility of radial PMBs in such applications.

2. Modeling of the Wind Turbine Rotor

The 650 W Darrieus H-type vertical rooftop wind turbine system considered in the present study consists of a stepped shaft, supported by two sets of DGBs, and a hub with blades. The model includes the main shaft and two main bearing sets. To calculate bearing load variations, the primary bearings must be included in the turbine rotor system. The generator rotor, main shaft, and hub with blades are the key parts and system characteristics of the wind turbine rotor investigated in this study. The primary construction of a VAWT rotor is seen in Figure 1.

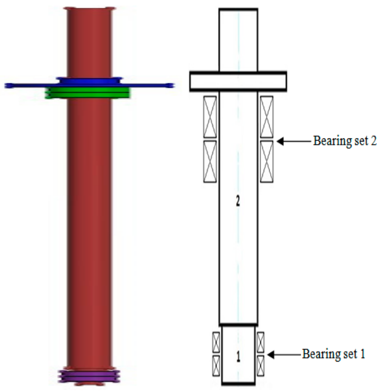

Figure 1. VAWT rotor schematic model.

The rotor system of a VAWT is represented by the mechanical and geometrical features shown in Table 1. Three masses are considered in the study, one rotor self-mass and two bearing set masses at bearing set locations 1 and 2. The bearing set is indicated here as the two identical and isotropic bearings. Both sets of bearings are designed to take the axial and radial loads. It is assumed that both the bearings are isotropic with their own stiffness and damping coefficients.

The dimensional and load rating details of these bearings [13,14] are tabulated in Table 2. The SKF 6305-2Z type of DGB's are used at bearing set 1 and the SKF 6012-2Z type of DGB's are used at bearing set 2. Later, the work is carried out by replacing front and rear DGB's with PMB's separately to achieve HBS.

The stiffness parameters of these conventional bearings are computed using the equations given by Gargiulo, as below [15]. The contact angle (α) is considered to be zero for deep groove ball bearings. The radial and axial stiffness parameters are listed in Table 3.

Table 1. VAWT rotor dimensions.

Description	Value (mm)
Length of the rotor	1297
Bearing span length	989
Rotor diameter at Element 1	25
Rotor diameter at Element 2	60
Maximum diameter of hub	189
Minimum diameter of hub	68

Table 2. VAWT bearing details.

Description	Units	Bearing Set 1	Bearing Set 2
Inner diameter (d)	mm	25	60
Outer diameter (D)	mm	62	95
Length (B)	mm	17	18
Number of balls (Z)	--	07	14
Dynamic load rating (F)	kN	23.4	30.7

Table 3. VAWT rotor-bearing stiffness.

Description	Units	Bearing Set 1	Bearing Set 2
Radial Stiffness	N/m	24.6955×10^7	42.1009×10^7
Axial Stiffness	N/m	24.6955×10^7	42.1009×10^7

Stiffness characteristics have a considerable influence on the performance of both conventional and magnetic bearings. Stiffness has a direct impact on load-bearing capacity, damping, and overall stability in conventional bearings. The high stiffness of these bearings improves the load-carrying capacity and decreases vibrations, which is critical in heavy equipment applications. In magnetic bearings, stiffness determines the levitation force and rotor stability. Changing the magnetic stiffness of a system impacts its responsiveness to shocks, affecting its control and stability. Because of their customizable stiffness characteristics, magnetic bearings provide improved controllability and higher accuracy, allowing precise control over the levitation and stability of rotating systems and revolutionizing various high-precision applications.

PMBs are non-contact bearings; only two magnetized rings are sufficient to achieve simple PMB. One magnetized ring is placed on the stator and the other on the rotor to create a basic PMB, as illustrated in Figure 2. Bearing stiffness is achieved through an outer-ring force applied on the inner ring. In the present work, axially polarized multi-rings are stacked to achieve radial PMB and are optimized to suit the geometry of the VAWT rotor at two different locations with the help of mathematical models developed in our earlier efforts [16,17]. To improve the radial stiffness of PMB, multi-rings are mounted in opposite directions, as shown in Figure 3. The optimized geometrical dimensions and stiffness parameters of PMB in proportion with the conventional mechanical bearings used in the VAWT rotor are given in Table 4. These bearings are employed in the rotor. Materials of the magnet grade NdFeB N45 are used in PMBs with a Br value of 1.34T. The axial length of each ring is 5 mm. Figures 4 and 5 show the relationship between the number of ring pairs and the radial force and stiffness.

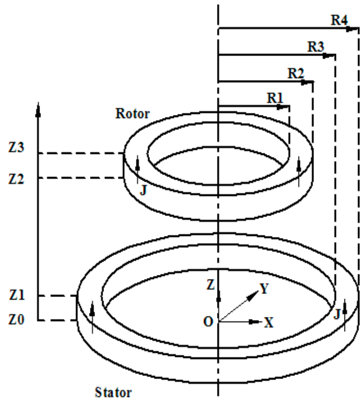

Figure 2. Configuration of radial PMB.

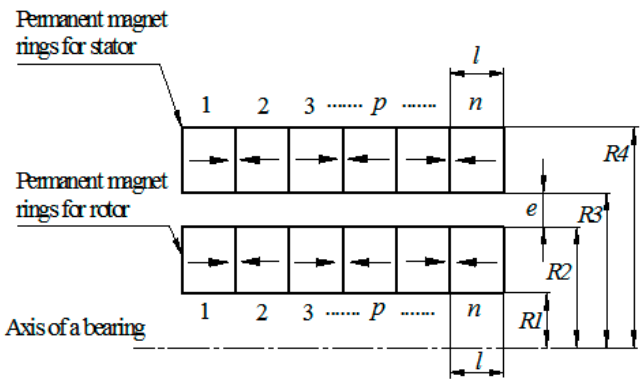

Figure 3. Multi-ring radial PMB.

Table 4. Geometrical dimensions of PMB for VAWT rotor.

Parameter	Units	PMB at Bearing 1		PMB at Bearing 2	
		Inner Ring	Outer Ring	Inner Ring	Outer Ring
Inner diameter	mm	D1 = 22	D3 = 53.6	D1 = 40	D3 = 84.8
Outer diameter	mm	D2 = 51.2	D4 = 64	D2 = 82	D4 = 96
Air gap	mm	g = 1.24		g = 1.4	
Axial air gap	mm	ag = 0.6		ag = 0.7	
Number of ring pairs (n)	--	6		5	
Total length	mm	L = 20			

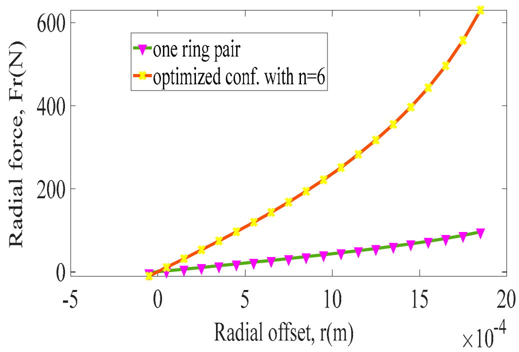

Figure 4. Fr vs. r, radial bearing maximum performance comparison.

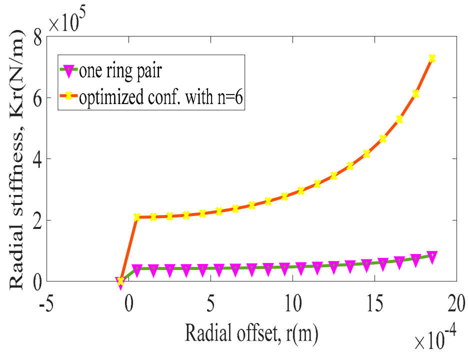

Figure 5. Kr vs. r, radial bearing maximum performance comparison.

According to Earnshaw's theorem, in radial magnet bearing, the axial stiffness is equal to twice of its radial stiffness [18]. Table 5 shows the stiffness results of the VAWT rotor PMB. The VAWT rotor system is made of steel with 200 GPa of modulus elasticity and is modeled using the CAD modelling CATIA V5 tool. Then, the Ansys workbench rotor dynamic response tool is used to analyze the dynamic parameters by converting the CAD model into an FE model and applying the relevant boundary conditions.

Table 5. PMB stiffness values.

Permanent Magnet Bearing	Units	At Bearing 1	At Bearing 2
Radial stiffness	N/m	3.385×105	4.527×105
Axial stiffness	N/m	-6.77×105	-9.054×105

In the FE model, conventional DGB bearings are supported with a coefficient of friction of 0.015, and frictionless support is used for radial PMB; also, corresponding bearing stiffness properties are inserted. The motion of the rotor element is constrained along the x- and z-axes to compensate for the shear effect due to the rotor twist motion, and rotation along the y-axis is kept free [19–21].

The rotor dynamic response of the VWAT rotor-bearing system is performed to establish mode shapes, rotor dynamic frequencies, critical speeds, and the Campbell stability diagram.

3. Results and Discussion

Initially, analysis was performed on a VAWT rotor supported by conventional DGB sets; later, DGB sets were replaced by radial PMBs at location 1 and 2, making a HBS-supported rotor system. The rotor dynamic parameters, such as mode shapes, rotor frequencies, critical speeds, and stability parameters, are extracted and studied for all the combinations of the rotor-bearing system.

3.1. Finite Element Basic Formulation

The rotor dynamic analysis using FEA involves creating a detailed 3D model of the VAWT rotor with HBS and PMBs, applying loads and constraints, and conducting dynamic simulations to assess its structural behavior and stability at critical speeds. The results help evaluate the feasibility of using the proposed bearing systems and identify potential resonance issues. The second-order hexa mesh is used in the analysis. The rotor dynamic response of the VWAT rotor-bearing system is determined to establish mode shapes, rotor dynamic frequencies, critical speeds, and the Campbell stability diagram. The limitations and challenges of implementing PMBs in VAWT rotor systems, such as magnetic field interactions, stability under varying loads, and design complexity, were addressed in the analysis by employing advanced FEA techniques capable of handling dynamic simulations and accurately modeling magnetic properties to ensure structural integrity.

3.2. FEM Results

Speeds up to 30,000 rpm follow the initial 0 rpm in the numerical analysis. Wind turbines supported by DGBs at bearing 1 and 2 receive their natural frequencies first. Wind turbines using a hybrid bearing system (HBS) are analyzed after that to establish their natural frequencies. Simply switching out one DGB set for a PMB yields HBS. In HBS, the study uses DGB in bearing set 2 and PMB in bearing set 1, corresponding to the bottom and top of the rotor, respectively. Table 6 shows the expected wind turbine bearing assembly rotor dynamic frequencies obtained from the Ansys rotor dynamic module. The mode shape at the first natural frequency of all bearing combinations is shown in Figures 6 and 7, and the Campbell stability graph for the rotor supported by DGB is shown in Figure 8. The critical speeds may be determined by analyzing the Campbell diagrams of frequency vs. speed. The rotor critical speeds (in revolutions per minute) for various bearing configurations in wind turbines are listed in Table 7. All possible bearing configurations have critical speeds significantly above the operation speed (450 rpm); hence, the system is robust.

Table 6. Rotor dynamic frequencies (Hz).

Natural Frequencies	DGB at Bearing 1 and 2	PMB at Bearing 1	PMB at Bearing 2
1	175.05	73.64	43.17
2	382.33	254.79	189.64
3	565.88	565.77	565.85
4	615.27	613.89	613.20

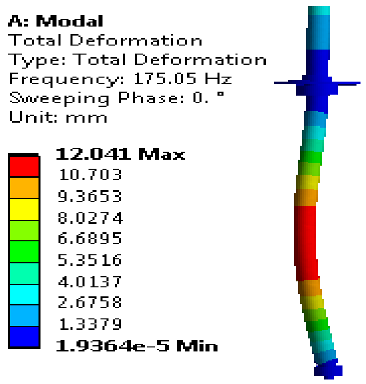

Figure 6. First mode shape for DGBs at bearing set 1 and 2.

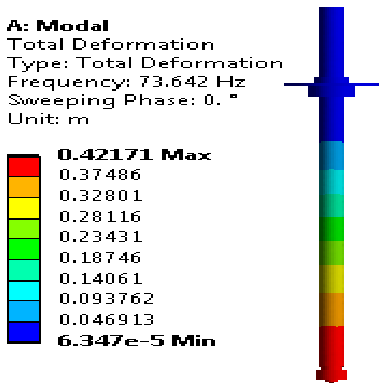

Figure 7. First mode for PMB at bearing set 1.

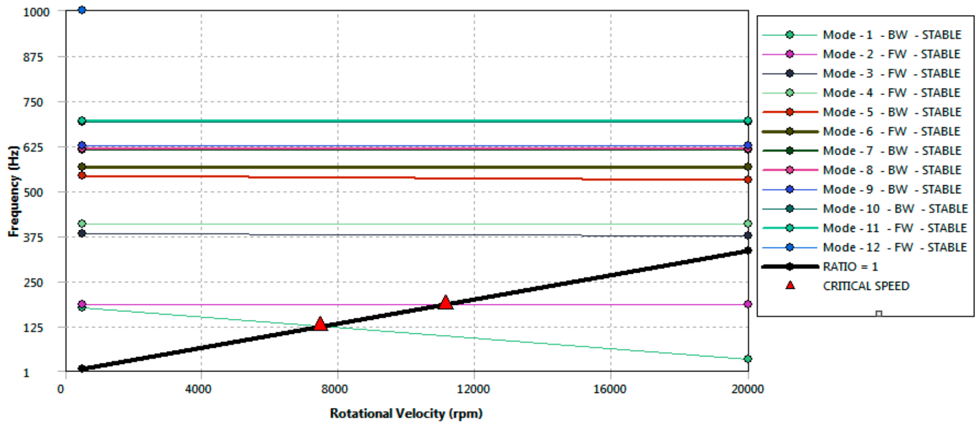

Figure 8. Campbell diagram for DGBs at bearing set 1 and 2.

Table 7. Critical speeds of wind turbine rotor-bearing system.

Rotor-Bearing Combinations	First Critical Speed (rpm)
Both the bearings as DGB	7466
PMB at bearing 1	4416
PMB at bearing 2	2590

3.3. Maglev Wind Turbine Rotor

The present work is extended to study the effect of complete levitation achieved through PMBs at bearings 1 and 2, thus making the rotor system a maglev wind turbine rotor system. Complete levitation is widely studied due to its high reliability, low maintenance, and low loss. Achieving complete levitation in VAWTs through PMBs could be significantly beneficial. The turbine's efficiency may improve by eliminating mechanical bearings and reducing friction, resulting in increased electricity generation and reduced maintenance requirements. Additionally, the VAWT could experience a longer lifespan and enhanced start-up performance, especially in low-wind conditions. Noise levels might be reduced, but implementing PMBs would require complex engineering and control systems, potentially increasing costs. Furthermore, the technology's scalability for large VAWTs remains challenging, and magnetic interference and safety considerations must be carefully addressed. Although promising, magnetic levitation for wind turbines is still experimental and requires further research and development for practical and widespread implementation. Table 8 shows the maglev wind turbine bearing assembly rotor dynamic frequencies obtained from the Ansys rotor dynamic module.

Table 8. Rotor dynamic frequencies of maglev wind turbine rotor (Hz).

Rotor Dynamic Natural Frequencies	PMB at Bearing 1 and 2
1	37.166
2	185.47
3	450.53
4	613.19

The rigid and flexural modes of the rotor system are investigated in this paper. Figures 9 and 10 depict the modes of the rotor system as studied using ANSYS. The stability of the rotor–PMB bearing system for the maglev wind turbine rotor is investigated, and the system is found to be stable in all modes, with a first critical speed of 2230 rpm, far from the operational speed. Several significant differences emerged in the dynamic response comparison between the rotor system supported by DGBs and the hybrid bearing set (HBS) backed by PMBs. The HBS–PMB combination demonstrated superior load-carrying capacity, enabling the rotor to operate effectively at higher rotational speeds without compromising structural integrity. Additionally, the HBS–PMB system exhibited reduced friction losses due to the magnetic support, leading to improved overall efficiency and reduced energy consumption. On the other hand, the DGB-supported system showed limitations in load capacity, making it less suitable for high-speed applications. The presence of mechanical contact in DGBs resulted in higher friction, causing energy losses and potential wear over time. Furthermore, the HBS–PMB arrangement displayed better stability, as the absence of direct contact between bearing components reduced the risk of vibration-induced resonance and allowed for smoother operation. The study's findings indicate that adopting HBS with PMBs offers substantial advantages over traditional DGBs in VAWT rotor systems. The enhanced load capacity, reduced friction, and improved stability of the HBS–PMB combination can significantly optimize the dynamic response and overall performance of wind energy conversion systems. These insights contribute to the broader field of wind energy and can guide the design and optimization of other types of wind turbines to achieve higher efficiency, longer service life, and reduced maintenance requirements.

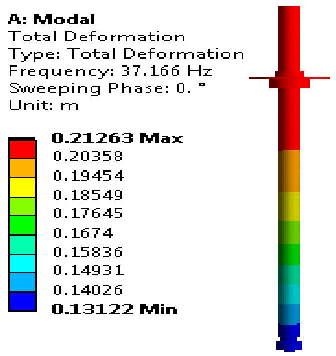

Figure 9. First rigid mode shape.

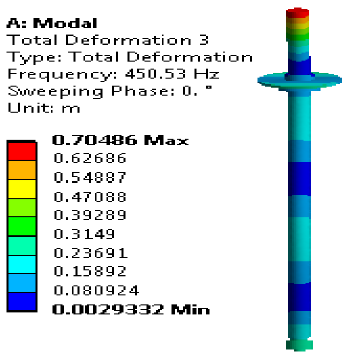

Figure 10. First flexural mode shape.

4. Conclusions

Radial PMB is designed considering the geometrical and mechanical proportions of the VAWT rotor and conventional bearing combinations. The rotor dynamic parameters are analyzed for the VAWT rotor and different bearing combinations using DGB and radial PMB by placing PMB at different bearing locations.

The following conclusions were drawn based on the study:

- The modal frequencies of the rotor system are in good agreement with conventional DGB when PMBs are used away from blade mass and are too far when PMBs are used near the hub.
- The rotor-bearing system of VAWT is stable at chosen mode frequency ranges for all combinations of bearings.
- The critical speeds of the rotor system are in close agreement with conventional DGB when PMBs are used at bearing location 2, i.e., at the top pole, but come down nearly half when PMBs are used at bearing location 1, i.e., at the bottom pole.

- The maglev rotor of VAWT is analyzed by supporting radial PMBs at both bearing locations and the critical speed is more than four times the operating speed.

Author Contributions: G.R.C. and S.I.B. conceived the presented idea. G.R.C., S.I.B. and M.D. developed the methodology. S.I.B. designed and optimized the radial PMB. G.R.C. performed the FEA analysis and prepared the original draft of the paper. S.I.B. and M.D. reviewed and edited the final writing of the present article. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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