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Analysis of Hybrid Windmill

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Abstract

Hybrid energy system with the combination of multiple energy generation process has gained much attention nowadays due to its reliability and increased flexibility. This study carried out is an analysis of a hybrid windmill with and without blades. The proposed model consists of two systems. The first system is a vertical axis wind turbine (VAWT) system. The second is a bladeless wind turbine or Vortex wind turbine system. Here the overall analysis helps to visualize the proposed model and eliminate the errors and mistakes like aeroelastic instability and aerodynamic resonance that exists in the previous models. The simulations and flux density diagrams of the systems is visualized to support the main study of the hybrid system. The flux density analysis and the structure design of permanent magnet was done using Ansys software. The structure design and CFD analysis for the two systems was done using Solidworks.

Keywords: VAWT, Vortex Windmill, Vortex Induced Vibration, Finite Element Analysis, CFD, Turbine, Permanent Magnet Synchronous Generator

1. Introduction

The traditional methods of harnessing wind energy have become obsolete due to various limitations, such as low efficiency and reliability. This happen as, they are often located in remote areas, which can make it difficult and expensive to transport electricity to the places where it is needed most. Additionally, wind speeds can be inconsistent, which can lead to fluctuations in energy output that can make it difficult to maintain a steady supply of power. Finally, conventional wind turbines can be noisy and visually unappealing, which can make them unpopular with local communities and limit their use in areas where aesthetics are a

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priority. Therefore, researchers have been exploring new techniques to optimize wind energy production. Two modern wind turbines, namely the Vertical Axis Wind Turbine (VAWT) and the Vortex Windmill, have emerged as promising alternatives. The principle of operation of a wind turbine involves converting wind energy into electrical energy using the aerodynamic force generated by the rotor blades. The blades' rotation is powered by the difference in air pressure between the two sides of the blade as air passes over them, generating lift and drag forces. The rotor spins as the lift force overcomes the drag force. Depending on the type of generator used, the rotor may be connected directly to the generator in a direct drive system or indirectly through a gearbox. The conversion of wind-induced aerodynamic force into generator rotation produces electricity. This study presents an analysis of these two modern wind turbines.

The study discusses the analysis of two modern wind turbines, the VAWT and the Vortex Windmill. One of the primary challenges associated with these turbines is optimizing their efficiency and reliability. To address this challenge, the study has performed an in-depth analysis of the aerodynamic stability of the turbines, focusing on the interaction between the rotor and the surrounding flow field. The analysis revealed that the VAWT has better aerodynamic stability than the Vortex Windmill due to its symmetrical blade configuration. Furthermore, The impact of various design modifications, such as introducing auxiliary blades, on the turbines' performance were also analysed. The results showed that the introduction of auxiliary blades enhanced the stability and efficiency of the both turbines. Additionally, control systems of the turbines, particularly the yaw control mechanism, and proposed improvements were evaluated to optimize the turbines' stability and lifespan. In conclusion, the analysis provides valuable insights into the design and operation of VAWT and Vortex Windmill turbines, enabling us to develop optimal wind energy production systems.

2. Literature Survey

Precise aerodynamic modelling is crucial for wind turbines to generate maximum electricity from wind. The free body diagram of forces ensures strong power harvesting configurations and helps practical engineers determine the ideal wind turbine size based on various parameters. The angle of attack of the turbine blades is used to cut through air flow, extracting power from the wind. This results in a continuous push on the turbine blades, generating momentum and rotation around an axis that produces power based on wind speed and atmospheric conditions. This article provides insights into how the aerodynamic design impacts the turbine's output. [1]

A surface-mounted permanent magnet synchronous generator design with concentrated windings is presented. The device is made for a wind turbine with a vertical axis and variable speed direct drive. The price of active material is one of the design process's optimal criteria. The surface mounted PM machines are among the most appealing options for wind power applications due to their high efficiency, high torque density, and simple scaling. The cost of the active material must be kept to a minimum, particularly for permanent magnets. The induced voltage and air gap flux density have minimal harmonic contents, according to the data reported here. Due to the extremely low cogging torque and minimal radial forces, there is also likely to be little magnetic noise. [2]

Computational fluid dynamics is the best approach for analysing aerodynamic flow in wind turbines (CFD). To use this approach to examine how the turbine enclosure affects the static torque properties of a vertical axis wind turbine (VAWT) with straight blades. The programme Ansys CFX is used to carry out analyses. The study initially ran turbine simulations without an enclosure. The next stage was to determine the enclosure's size that would improve the turbine's torque. Based on the analysis's findings, the enclosure at wind speeds of 5 and 10 m/s, increased average torque was chosen. It is done to determine how the enclosure's impact on turbine torque varies at two different wind speeds. [3].

The vortex wind generator is made of a hollow, conical-shaped bluff body that is meant to be positioned vertically on the ground. Due to the vortex shedding fluid phenomena, the body of this bluff body vibrates when the air flows over it. Electrical energy may be created from the body's vibrational energy. In their study,they first choose all of the design parameters using Ansys Fluent software to visualize the Von Karman effect. To attain the maximum lift force produced by the planned body, a mathematical model is then built. To quantify the recovered vibration energy for further conversion, a comprehensive model is created as the last stage and evaluated under various operating situations. [4].

A bladeless wind turbine wind power generation system has been designed for the coastal side, which uses vortex-induced vibration to produce power. The turbine's body experiences this vibration when wind flows around the circumferential mast. A crankshaft is used to turn a pulley, which in turn rotates a DC generator to generate power. To evaluate the efficiency of this system, a comparison was made between the proposed and existing power outputs. It was found that the proposed bladeless wind turbine model achieved the highest efficiency of approximately 46%. [5]

This research paper focuses on dynamic modeling of four distinct configurations of vortex-induced vibration for a bladeless wind turbine (BWT). BWTs are made up of a bluff body attached to a flexible framework in the flow field, with differences in the bluff body's form and mounting system for each configuration. These BWTs experience varying lift forces due to periodically shedding vortices, and the researchers develop a nonlinear distributed-parameter model using the Euler-Bernoulli beam theory and Galerkin process. To compare the results of the dynamic model, a 3D CFD-FEM numerical simulation is employed. The researchers investigate the impact of wind speed on the induced lift force, turbine deflection, and power generation for all four BWT configurations. The study confirms that the amplitude of BWT vibrations increases considerably when the vortex shedding is synchronized with the structural oscillations. [6]

A series of experiments were carried out to investigate the vibration generated by vortices in tapered cylinders that were allowed to oscillate in the crossflow direction while maintaining a constant mass ratio. The maximum amplitude of the crossflow oscillations was approximately uniform for all taper ratios and was comparable to that of a uniform cylinder with the same mass ratio. As the taper ratio decreased, the lock-in range for the reduced velocities was found to increase. To ensure the reliability of the findings, tests were conducted with cylinders positioned vertically in the water tunnel test section, with their diameter facing both upward and downward. [7]

3. Wind Parameters

Wind characteristics are crucial to wind turbine design because they determine the amount of energy that can be harnessed from the wind. By carefully analysing the wind data for the site, turbine designers can optimize the turbine design to maximize energy output and efficiency.

Table 1. Wind Parameters (in location of Coimbatore)

Property	Value
Average wind speed	4-6 m/s
wind direction	Southwest
Wind gusts	Up to 30 m/s during cyclones
Coriolis effect	As Coimbatore is located in the Northern Hemisphere, winds will generally deflect to the right of their intended path.
Pressure gradient	Can vary depending on the weather patterns affecting the region

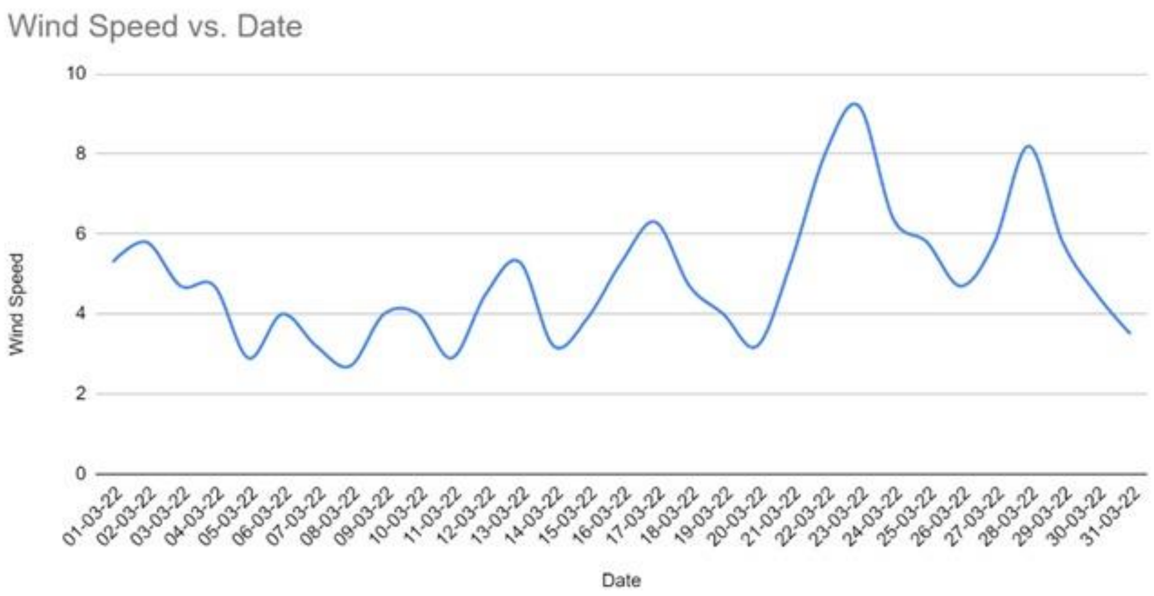

Figure 1. Wind analysis for the month March,2022

The data provided on the wind parameters of our college is used for designing a wind turbine that can withstand the worst-case scenario of wind velocity. It is important to note that the data was collected over a month (March 2022), which indicates mixed conditions throughout the day. The data shows that the wind speed ranges with an average of 4.15 m/s. This indicates that the wind speed is relatively low, which may pose a challenge in designing a wind turbine that can generate sufficient power. However, the data also shows that the wind direction is predominantly from the Southwest, which may provide an opportunity to design a wind turbine that is optimized for this direction.

Overall by analyzing the wind speed, direction, and variability patterns, it is possible to design a wind turbine that can generate sufficient power while withstanding the worst-case scenario of wind velocity.

4. Vertical Axis Wind Turbine

The conversion of wind kinetic energy to mechanical energy is the principle behind the operation of a Vertical Axis Wind Turbine (VAWT) used for generating electricity. The rotor blades of the turbine are supported by a vertical central shaft, which can be arranged in either a straight or helical configuration. When the wind passes through the blades, they rotate around the central axis, turning the rotor that is linked to a generator that converts the mechanical energy into electrical energy.

VAWTs are omnidirectional and can capture wind from any direction, making them useful in urban and suburban environments where wind direction can be unpredictable. However, they have some disadvantages compared to Horizontal Axis Wind Turbines (HAWTs), such as lower efficiency due to lower wind speeds and higher turbulence, and higher maintenance costs due to their more complex mechanical design.

Overall, VAWTs, particularly with a three-bladed design using NACA 0018 air foil shape, can be an effective and efficient solution for small-scale wind power generation in areas where space and noise considerations are important.

Computational fluid dynamics (CFD) is a numerical technique used to predict fluid flow by solving the governing equations. Engineers use computer programs to solve problems iteratively, resulting in visualizations of expected velocity, pressure, and temperature. This helps to understand the performance of the turbine and how it behaves under various wind velocities.

Here, the study modeled and analyzed the Vertical Axis Wind Turbine in Solid works. The CFD analysed model is given below.

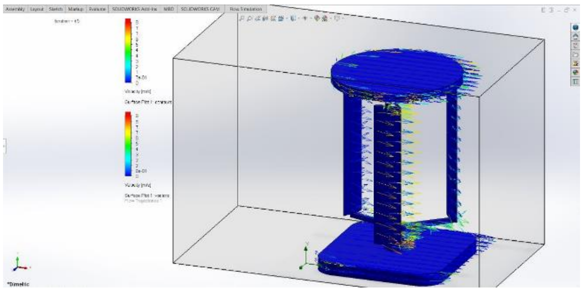

Figure 2. Flow trajectory surface magnitude plot

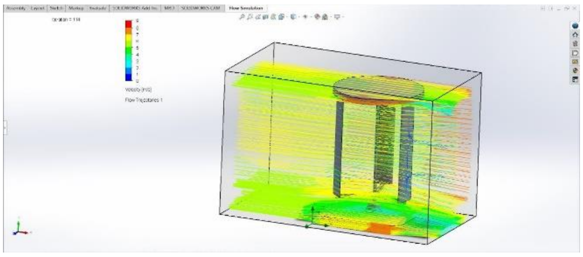

Figure 3. Flow trajectory surface streamline plot

Table 2. Aerodynamic parameters for VAWT

Case - Wind Speed	Ω	C_D	C_L	L_{rr}
2 m/s	1.002	0.28	0.94	0.6
4.5 m/s	2.006	0.30	1	0.58
9 m/s	3.025	0.37	1.25	0.55

The provided table displays integral properties of flow for a vertical axis wind turbine when the frequency of external forcing matches the natural frequency of the turbine. The table includes three different amplitudes of the forcing, and shows the mean drag coefficient (CD), lift coefficient (CL), and recirculation zone length (Lrr). It is observed that the mean drag coefficient (CD) does not differ significantly (less than 5%) from the unforced scenario for any of the three cases. However, a small increase in CD is observed for amplitudes of **Ω** = 1.002 and 3.025, while a decrease is observed for **Ω** = 2.006, as compared to the non-rotational reference value. The table provides insight into the aerodynamic behaviour of the VAWT under external forcing.

After analyzing the model of Vertical Axis Wind Turbines (VAWT), it has been concluded that attaining a low mean drag coefficient (CD) is essential for efficient energy conversion, while maximizing the lift coefficient (CL) is crucial to generate enough lift force for electricity production. The length of the recirculation zone (Lrr) is also an important factor to consider, with a shorter zone being preferable to avoid turbulence and increase efficiency. A comprehensive understanding of the integral flow properties of VAWTs can aid in the design and optimization of VAWT systems for better performance and efficiency. Thus, it is imperative to analyze and evaluate these factors in the model of VAWTs to improve their overall effectiveness and sustainability.

The aerodynamic stability of vertical axis wind turbines (VAWTs) is a crucial aspect that determines their performance and reliability. The unique configuration of VAWTs presents several challenges in achieving stable operation. One of the primary concerns is the interaction between the rotor and the surrounding flow field, which can cause various types of instabilities. For instance, the rotor can experience vertical or horizontal vibrations due to unsteady flow conditions, leading to increased loads and reduced power output.

To improve the aerodynamic stability of VAWTs, researchers have explored various design modifications, such as introducing winglets, endplates, or auxiliary blades. These devices can alter the flow pattern around the rotor and enhance the pressure distribution, leading to improved stability and efficiency. However, the optimal design of such devices depends on several factors, such as the blade geometry, wind speed, and turbulence intensity.

Another important factor that affects the stability of VAWTs is the yaw control system. Yaw misalignment can cause unbalanced loads on the rotor and tower, leading to fatigue damage and reduced lifespan. Therefore, an efficient yaw control mechanism is essential to ensure stable and safe operation of VAWTs. Several techniques have been proposed to improve the yaw control, such as using passive or active systems, or combining both approaches.

In conclusion, the aerodynamic stability of VAWTs is a complex and challenging issue that requires careful consideration in the design and operation of such devices. Further research is needed to investigate the optimal design and control strategies to achieve reliable and efficient VAWTs for sustainable energy production.

5. Permanent Magnet Synchronous Generator (PMSG)

A device that transforms mechanical energy into electrical energy through the generator's primary mover is known as a synchronous generator, which is also commonly known as an alternator. Its name is derived from its rotation speed, which matches the speed of the field at the generator's stator, also known as synchronous speed. Unlike an induction generator, which does not require an external source, a synchronous generator uses an external dc source for excitation. However, the Permanent Magnet Synchronous Generator operates differently, as it does not need a DC source connected to the machine. Instead, a permanent magnet stator is utilized to generate a uniform magnetic field along the rotor's axis.

To convert mechanical power generated by the Vertical Axis Wind Turbine (VAWT) into electrical energy, a Permanent Magnet Synchronous Generator (PMSG) is used. The VAWT acts as the primary mover for the PMSG, and the rotor of the PMSG consists of permanent magnets that produce a field for excitation. This eliminates the need for an external supply source for the generator. The excitation field is provided by neodymium (permanent) magnets, and the term "synchronous generator" means that the rotor and the magnetic field provided by the permanent magnets rotate at the same speed. Unlike other generators, it does not require any external supply for excitation.

Table 3. Design Requirements and constraints

Parameter	Description
Rated power (kW)	0.25
Rated speed (rpm)	2500
Base speed (rpm)	100
Air Gap length (mm)	0.2
Cooling system	Natural air convection
Cogging torque (Nm)	around 1%
Outer diameter (mm)	<0.5 m
Minimum shaft diameter (mm)	> 0.13 m
Efficiency (%)	around 94%

Table 3 presents the design specifications and restrictions for the generator, including an air gap distance of 1.5mm, a rated power of 0.25 kW, and a base speed of 100 rpm. The shaft must be able to withstand high torque, which necessitates a minimum diameter to ensure that the generator operates safely and stably.

Table 4. Independent parameters in Machine Geometry

Stator tooth width	B_{ts}
Stator yoke height	h_{rs}
Rotor yoke height	h_{rr}
Stator slot height	h_{ss}
Air gap diameter	D
Magnet thickness	l_m
Number of poles	p
Number of stator slots	Q_s
Magnet angle	α
Air Gap length	δ

Table 4 illustrates the design parameters of the generator, which are utilized as independent variables in optimizing the machine's structure and reducing the cost of active material. Various machine configurations are assessed to determine the fundamental air gap flux density and air gap diameter.

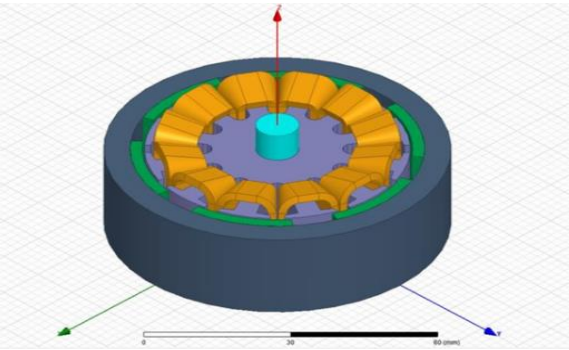

Figure 4. 3D Model of outer Rotor PMSG

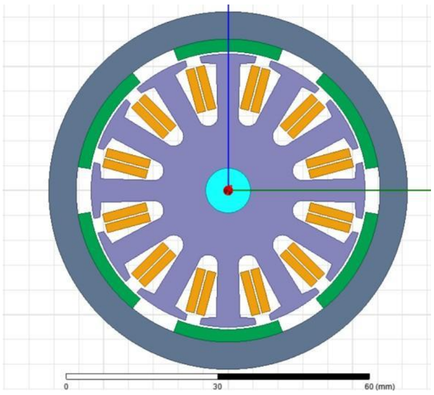

Figure 5. 2D Model of Outer Rotor PMSG

It should be noted that the cost of magnets plays a crucial role, as observed in a prior project. Moreover, the cost of magnet coating is considered in the price estimation and is calculated based on smaller volumes for small-scale production. While designing the machine, considerable efforts are put into reducing the permanent magnet volume as much as possible.

The magnetic design of the machine is given priority after determining the air gap diameter and air gap flux density values. To calculate the magnet thickness, the following equation can be used:

$$B_m = B_{r,m} \frac{1}{1 + \mu_r \frac{\delta_e}{l_m}}$$

The calculation of magnet thickness can be performed using the following formula, which takes into account the maximum air gap flux density (B_m), the remanent flux density of the magnet at operating temperature ($B_{r,m}$), the relative permeability of the magnet (μ_r), the effective air gap length (δ_e), and the thickness of the magnet (l_m). Once the magnet thickness is determined, the stator and rotor yoke height and stator tooth width can be determined using the following equation:

$$h_{rs} = \frac{\alpha B_m D}{p k_j B_{rs}}$$

$$h_{rr} = \frac{\alpha B_m D}{p k_j B_{rr}}$$

$$b_{ts} = \frac{\alpha B_m \tau_s}{k_j B_{ts}}(1 - \frac{2\delta}{D})$$

The equations mentioned previously incorporate two factors - the stacking factor k_j and the slot pitch τ_s. The slot pitch is essential in determining the design constraints on the flux density in different parts of the machine. By taking these constraints into account, the slot geometry can be calculated.

4.1. Finite Element Analysis of PMSG

The finite element method is a numerical approach for resolving engineering field problems that uses differential equations applied over areas and restricted by boundary conditions (FEM).

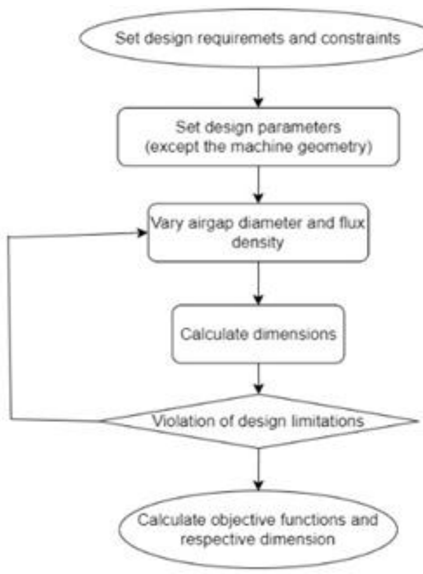

Figure 6. Flowchart showing the optimization procedure of PMSG.

The finite element method involves discretizing the overall structure by representing complex things with a limited set of units and nodes that connect them. Proper boundary conditions are selected to find a suitable solution to the model. FEM has been widely used to tackle engineering challenges due to its accessibility and accurate results, and it has recently gained widespread acceptance as a generic approach for designing and studying various permanent magnet devices.

Figure shows the optimization procedure for the PMSG as a flowchart. In the initial step, the design requirements and constraints are identified. In the subsequent step, design

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parameters such as the properties of the selected material, winding parameters, etc., are introduced.

This paper utilized ANSYS Maxwell's finite element analysis (FEA) software program to resolve magnetic and electric field problems. The FEM design of the PMSG includes various parameters such as the outer and inner diameters of the stator and rotor, air gap, PMs' length, width, and thickness, slot size, and winding data, in addition to the structure type, material selection, and model geometry.

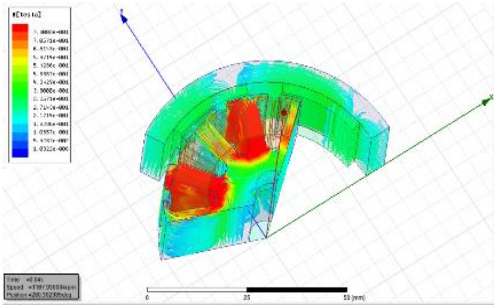

Figure 7. Flux Magnitude Vector of PMSG

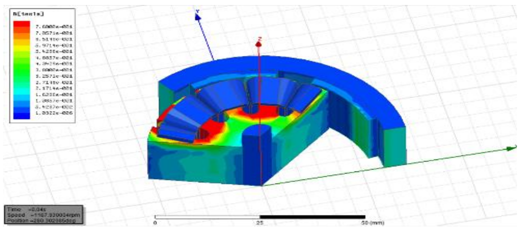

Figure 8. Magnetic Flux Density of PMSG

Numerous solutions, including electrostatic, magnetostatic, and transient solvers, are available for ANSYS Maxwell 2D. A static electric field may be understood using an electrostatic solver, and a static magnetic field can be seen using a magnetostatic solver. The designer may view and examine the magnetic fields, energy, flux, and many other machine model characteristics at different time steps using a transient solver. Due to the symmetry of the model's structure, 2D is employed in the study. To cut down on the number of finite components and shorten simulation times, it can be analyzed in 1/8 of the entire model.

The generator's geometry was designed, a finite element model was created, and the model's various areas were given different material qualities. Prior to doing the finite element solution using the solvers, the boundary conditions are applied, and meshing is finally constructed.

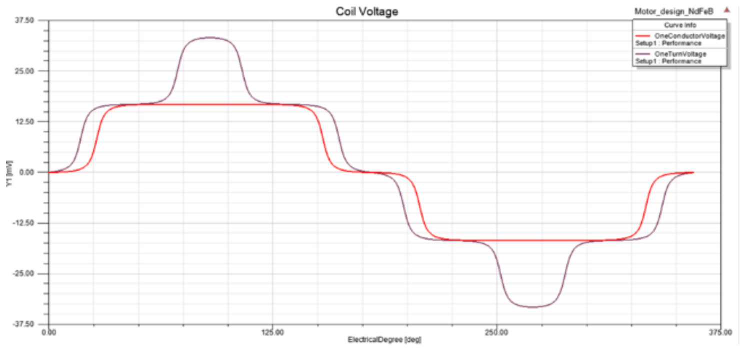

Figure 9. Winding Voltage

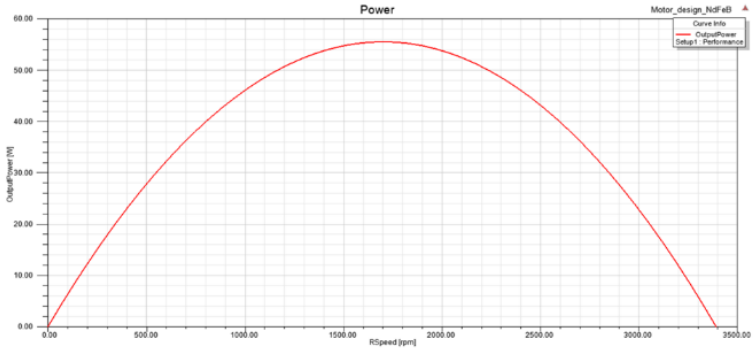

Figure 10. Power Curve

Table 5. performance comparison between PMSG and DFIG

Parameter	PMSG	DFIG
Rated speed	50-200 RPM	300-600 RPM
Rated voltage	50-300 V	690-6900 V
Rated current	10-100 A	1-10 A
Cut-in speed	2-3 m/s	2-3 m/s
Cut-off speed	10-15 m/s	35-40 m/s
Efficiency	Higher efficiency (up to 98%)	Lower efficiency (up to 98%)
Power density	Higher power density (up to 8kW/kg)	Lower power density (up to 8kW/kg)
Maintenance	Lower maintenance	Higher maintenance

It can be observed from the above fig, shows that the steady state response of PMSG. The coil voltage per conductor value in steady state is 35V with pronounced losses. This validates the worthiness of the model.

6. Vortex Wind Turbine

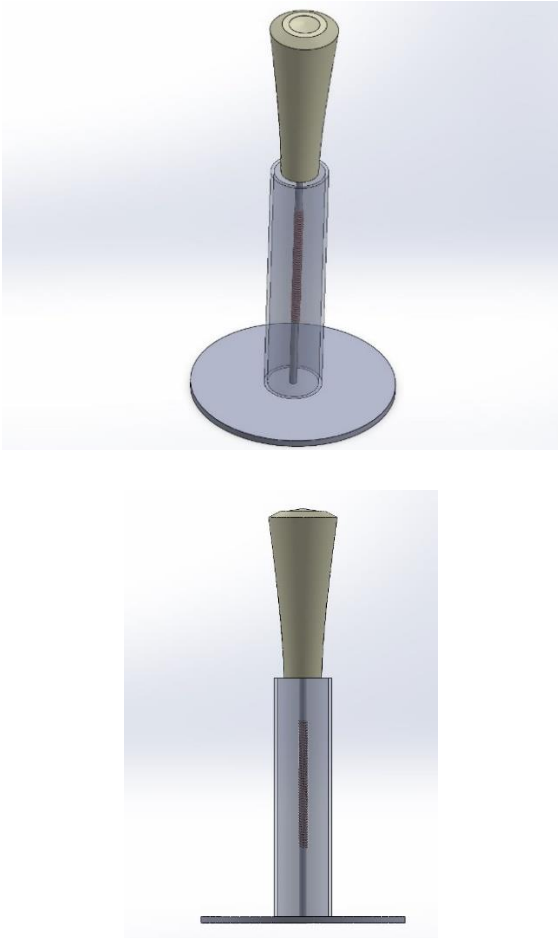

Figure 11. Model of Vortex Windmill

For a vortex windmill, it uses the vorticity principle to produce a voltage. When the wind flows over a tapered structure with a specific velocity, vortices are created at the trailing end. Vortices is nothing but a whirling force is created on the other side of the mast, due to this mast follows the Karman's path. This whole phenomenon is known as vortex shedding. Due to this Vibration is induced, which causes the whole setup to oscillate. This oscillatory motion is converted into electricity by using the coil which is wound on the rod.

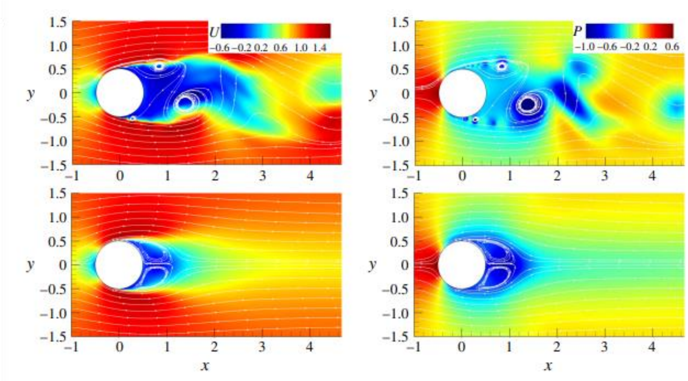

Figure 12. CFD simulation for Vortex windmill

The movement of the fluid in this system is controlled by the repeated shedding of vortices from the upper and lower parts of the cylinder. At the subcritical Reynolds number analyzed, the separation of the flow is smooth, and the change occurs in the shear layer downstream. The fluid recirculation strengthens this change. The vortices produced in the shear layer merge with adjacent ones, creating significant vortex structures that interact with their counterparts on the opposite side of the cylinder. This activity is almost periodic since the incoming flow intermittently adds more streamwise momentum to either the top or bottom of the cylinder, as depicted in the figure.

Table 6. Aerodynamic parameters for different rotational amplitude with constant forcing frequency, f=1

Case - Wind Speed	Ω	C_D	C_L	L_{rr}
1.5 m/s	1.002	1.27	0.45	0.67
3.5 m/s	2.006	1.29	1.18	0.38
4.2 m/s	3.025	1.24	1.08	0.18

Table has been provided which shows the integral properties of the flow when the frequency of external forcing matches the natural vortex shedding frequency.

The magnetic arrangement for suitable flux linkage can be modeled and analyzed using ANSYS Maxwell.

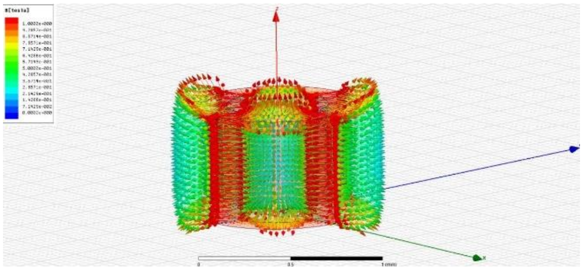

Figure 13. Magnetic Flux density Distribution - Vector plot

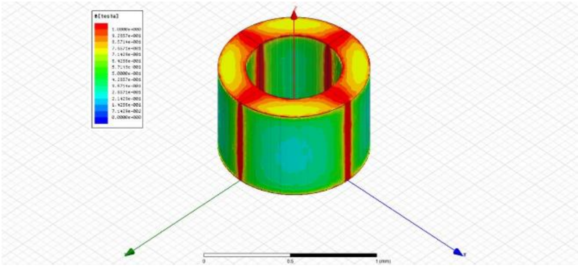

Figure 14. Magnetic Flux density Distribution - Magnitude plot

Here, the simulation result shows the maximum flux density along the axis. From this model we can obtain the maximum induced voltage.

In contrast, electromagnet magnetic field produced by an electromagnet can be easily controlled and adjusted. This is because the strength of an electromagnet's magnetic field depends on the amount of current flowing through the coils, which can be easily varied by adjusting the input voltage or current.

Figure 15. Magnetic Flux inducing in Electromagnet

Table 7. Field strength for respective supply voltage

Input voltage (V_{in}) Electro-magnet supply	Generated Voltage (V_{out})	Current (A)	Output Magnetic Field Strength (Tesla)
5	0.09	0.2	1.1303×10^{-6}
10	0.40	0.4	2.2606×10^{-6}
15	1.05	0.6	3.3909×10^{-6}
20	1.32	0.8	4.5212×10^{-6}
25	1.51	1	5.6515×10^{-6}
30	1.74	1.2	6.7818×10^{-6}
32	2.13	1.3	7.3469×10^{-6}
36	2.41	1.5	8.9121×10^{-6}
39	2.73	1.6	9.9470×10^{-6}
40	3.04	1.65	1.0265×10^{-5}
43	3.21	1.75	1.0992×10^{-5}
48	3.32	1.9	1.2446×10^{-5}
50	3.57	2	1.3003×10^{-5}
60	3.94	2.4	1.5604×10^{-5}
70	4.27	2.8	1.8206×10^{-5}

In generator design, electromagnets can suffer in terms of efficiency, complexity, and reliability compared to permanent magnets. Electromagnets require a constant supply of electrical energy to maintain the magnetic field, which can lead to energy losses and reduce the overall efficiency of the generator. In contrast, permanent magnets do not require any external power source and can maintain a constant magnetic field, which can improve the efficiency of the generator.

7. Conclusion

This paper utilizes ANSYS Maxwell software to develop and analyze a hybrid windmill and PMSG model in both 2D and 3D. The simulation results demonstrate the performance of both the windmill and motor. Furthermore, the effectiveness of FEM for electromagnetic field analysis of Permanent Magnet Synchronous Generators is demonstrated, providing designers with insights to choose better PM materials to enhance generator design.

8. Future Works

This paper has a lot of scope for expansion and hardware of higher range can be explored and motors of higher ratings can be used. By exploring various mathematical models, the proposed system could be further perfected. In the proposed system, electromagnets have been used considering the cost constraints. If expanded, neodymium magnets could be implemented which would increase the efficiency of the system. the analysis of the vortex windmill could be expanded to improve the structure's efficiency.

Another prospect which could be looked into is the collection and incorporation of the system's data into a database. The setting up of hybrid windmills could be extended across various cities and the collected data could be fed into the cloud. The collected data can also be used for monitoring the windmills. Multiple data centers can be established this way and the data center network formed can be controlled by a central data center.

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