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Design and Experimental Analysis of a Magnetically Levitated Vertical Axis Wind Turbine Integrated with Photovoltaic Solar System for Sustainable Energy Harvesting

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***Abstract* - The growing global demand for clean and sustainable energy has accelerated research into innovative power generation systems. This paper investigates the design, development, and experimental validation of a frictionless Magnetic Levitation Vertical Axis Wind Turbine (ML-VAWT) hybridized with a photovoltaic (PV) solar energy module. The system exploits the repulsive characteristics of high-grade Neodymium Iron Boron (NdFeB, Grade N52) ring magnets to achieve complete mechanical frictionlessness, enabling the turbine rotor to commence rotation at wind velocities as low as 1.5 m/s. The hybrid architecture ensures an uninterrupted power supply: the ML-VAWT operates effectively during wind availability, whereas the solar PV module compensates during periods of inadequate wind but sufficient solar radiation. Experimental observations indicate that at a rotational speed of 710 RPM, the ML-VAWT generates an output voltage of 21.8 V, markedly outperforming a conventional wind turbine which yielded only 13.0 V at 285 RPM under comparable test conditions. The complete prototype was fabricated at an economical cost of ₹15,200, establishing its feasibility for decentralized small-scale power generation applications.**

Keywords: Magnetic levitation, VAWT, NdFeB magnets, Hybrid energy system, Solar photovoltaic, Frictionless wind turbine, Sustainable energy harvesting.

I. INTRODUCTION

The escalating energy consumption associated with rapid urbanization and industrialization has rendered conventional fossil fuel-based power generation ecologically unsustainable. The combustion of non-renewable energy sources contributes substantially to greenhouse gas emissions, thereby accelerating the adverse effects of climate change. Consequently, there exists an urgent imperative to transition toward cleaner, renewable energy technologies capable of meeting contemporary energy demands without compromising environmental integrity.

Among the spectrum of renewable energy technologies, wind and solar power represent the most accessible and widely distributed natural resources. Conventional Horizontal Axis Wind Turbines (HAWTs) have been extensively deployed for large-scale wind energy extraction; however, their operational requirements—including high minimum wind speeds, extensive installation areas, and complex mechanical maintenance—render them impractical for decentralized, low-speed, and urban applications. The Vertical Axis Wind Turbine (VAWT) configuration overcomes several of these limitations by offering omnidirectional wind capture, a compact footprint, and simplified mechanical architecture.

Magnetic levitation technology further augments VAWT performance by eliminating mechanical bearing friction entirely. Through the deployment of rare-earth permanent magnets, the turbine rotor is suspended axially without physical contact with the stator structure, thereby enabling rotation under extremely low wind velocities. This frictionless operation simultaneously reduces mechanical wear, noise generation, and maintenance requirements.

The integration of a solar PV module with the ML-VAWT constitutes a hybrid energy harvesting system capable of generating electricity across a broader operational envelope. As solar irradiance is maximized during daylight hours, and surface wind velocities typically intensify following sunset due to differential ground and atmospheric cooling, the complementary nature of these two renewable sources ensures near-continuous power generation throughout the diurnal cycle.

1.1 Hybrid Energy Generation Concept

The fundamental advantage of the proposed hybrid configuration lies in its temporal complementarity. Solar photovoltaic generation peaks between 10:00 AM and 4:00 PM, corresponding to periods of maximum solar irradiance.

Conversely, near-surface wind velocities tend to increase during early morning hours and post-sunset, driven by convective thermal differentials. The ML-VAWT capitalizes on these low-speed wind conditions to sustain power generation during periods when solar contribution diminishes. This natural complementarity substantially reduces the need for large-capacity battery storage and enhances the overall system reliability.

1.2 Research Objectives

This investigation was undertaken to fulfill the following primary objectives:

- To design and fabricate a magnetically levitated VAWT prototype employing NdFeB rare-earth ring magnets for axial rotor levitation.
- To integrate a solar PV module with the ML-VAWT to form a hybrid energy harvesting system.
- To evaluate the electrical output performance of the hybrid system under laboratory and ambient test conditions.
- To compare the power generation efficiency of the ML-VAWT against a conventional friction-bearing wind turbine.
- To assess the economic viability of the prototype for deployment in decentralized residential and urban infrastructure applications.
- To identify future scalability pathways for enhancing output capacity and broadening deployment contexts.

II. THEORY

2.1 Wind Energy Conversion Principles

Wind energy originates fundamentally from solar-induced differential heating of the earth's atmospheric layers and surface topography. These thermal gradients drive convective air circulation, producing kinetic energy in the form of wind. Wind turbines convert this kinetic energy into mechanical rotational energy, which is subsequently transformed into electrical energy through electromagnetic induction. The kinetic power available in a wind stream is expressed as:

$$P = \tfrac{1}{2} \times \rho \times A \times V^3$$

where ρ represents the air density (1.22 kg/m³ at standard conditions), A denotes the rotor swept area (m²), and V is the incident wind velocity (m/s). The theoretical maximum fraction of wind energy extractable by any turbine is constrained by the Betz Limit to 59.3%, as derived from momentum theory applied to the actuator disk model.

2.2 Photovoltaic Energy Conversion

Solar photovoltaic technology converts incident solar radiation directly into electrical energy through the photovoltaic effect, exploiting the properties of semiconductor p-n junctions. When photons of sufficient energy strike the semiconductor material, electron-hole pairs are generated, establishing an internal electric field that drives a direct current (DC) through an external circuit. The output power of a PV panel depends on the solar irradiance intensity, the ambient temperature, and the panel's electrical characteristics, namely the open-circuit voltage (Voc), short-circuit current (Isc), and the fill factor (FF).

2.3 Magnetic Levitation Mechanism

The magnetic levitation mechanism exploits the fundamental repulsion between like magnetic poles in permanent magnets. In the proposed ML-VAWT, axially magnetized NdFeB ring magnets are mounted coaxially on both the stationary base shaft and the underside of the rotating turbine assembly. When oriented with identical poles facing each other, the inter-magnet repulsion force generates sufficient upward thrust to counteract the gravitational weight of the turbine rotor assembly, thereby achieving stable axial levitation.

This levitation eliminates the physical contact between rotating and stationary components, theoretically reducing bearing friction losses to zero. The result is a turbine capable of initiating rotation at significantly lower wind thresholds compared to conventional bearing-supported systems. NdFeB magnets of Grade N52 were specifically selected for this application due to their superior magnetic energy product (BHmax ≈ 52 MGOe), providing the highest remanence available among commercially accessible permanent magnet materials.

2.4 Electromagnetic Power Generation

Electrical power generation in the ML-VAWT follows Faraday's Law of Electromagnetic Induction. As the rotor assembly carrying disc-type NdFeB magnets rotates about the vertical axis, the time-varying magnetic flux linkage through the stationary coil windings induces an alternating electromotive force (EMF). The magnitude of this induced EMF is governed by:

$$e = -N\,(d\Phi/dt)$$

where N is the number of coil turns and $d\Phi/dt$ represents the rate of change of magnetic flux through the coil cross-section. The induced EMF is directly proportional to the rate of rotor rotation and the strength of the magnet-coil flux linkage.

III. SYSTEM COMPONENTS AND SPECIFICATIONS

3.1 NdFeB Neodymium Ring Magnets

The axial levitation sub-system employs NdFeB ring magnets of the following technical specifications:

- Outer Diameter (OD): 40 mm; Inner Diameter (ID): 20 mm; Thickness: 10 mm
- Magnetic Grade: N52 (maximum energy product ~52 MGOe)
- Surface Treatment: Nickel-Copper-Nickel (Ni-Cu-Ni) triple-layer electroplating
- Magnetization Orientation: Axial (poles on flat end faces)
- Maximum Permissible Operating Temperature: 80°C (176°F)

The N52 grade was selected to maximize levitation height and load capacity within the turbine weight budget, ensuring stable suspension with an adequate factor of safety.

3.2 Electromagnetic Coil Windings

The electrical power generating element of the stator consists of four sets of multi-turn coil windings, each wound from 26-gauge enamelled copper wire. Each coil comprises 3,050 turns, arranged symmetrically around the stator periphery in alignment with the rotor-mounted disc magnets. The angular spacing between adjacent coils is maintained at 45°, corresponding exactly to the angular separation between consecutive rotor disc magnets. This alignment ensures maximum flux linkage and minimizes voltage ripple in the generated output.

3.3 Solar PV Module

The photovoltaic module integrated into the hybrid system exhibits the following manufacturer-specified electrical characteristics:

- Manufacturer: SunRay Energies Pvt. Ltd.; Model: SR-03PM
- Rated Maximum Power: 3 W
- Open-Circuit Voltage (Voc): 10.8 V
- Short-Circuit Current (Isc): 0.39 A
- Voltage at Maximum Power Point (Vmpp): 8.8 V
- Current at Maximum Power Point (Impp): 0.35 A
- Maximum System Voltage: 600 V

The module was mounted at an optimal tilt angle of 18° facing true south to maximize annual energy yield under the prevalent solar irradiance conditions of the Pune, Maharashtra region.

IV. DESIGN AND DIMENSIONAL ANALYSIS

4.1 Air Catchment Area Determination

The effective air catchment area of the turbine blades governs the wind power interception capacity. Based on the selected blade dimensions, the air catchment area was computed as:

$$A\_catch = Width \times Height = 25\text{ cm} \times 6\text{ cm} = 150\text{ cm}^2$$

A rotor plate diameter of 30 cm was selected to conform to the levitation load capacity constraint of the N52 ring magnets. The aggregate turbine assembly weight was measured at 1.3 kg, against a rated levitation capacity of 1.5 kg for the selected magnet configuration, providing a levitation safety margin of 0.2 kg.

4.2 Blade Geometry and Volume Estimation

The cylindrical blade profile was characterized by the following geometric parameters:

$$\text{Total External Surface Area} = 2\pi r^2 + 2\pi rh = 2 \times 3.14159 \times 15^2 + 2 \times 3.14159 \times 15 \times 50 = 6{,}123\text{ cm}^2$$

$$\text{Total Blade Volume} = \pi r^2 h = 3.14159 \times 15^2 \times 50 = 35{,}325\text{ cm}^3$$

These geometric parameters were incorporated into computational fluid dynamic simulations to estimate the theoretical aerodynamic efficiency of the blade profile prior to fabrication.

V. GOVERNING EQUATIONS AND CALCULATIONS

5.1 Induced EMF by Faraday's Law

The instantaneous induced voltage across each stator coil is calculated from:

$$V\_emf = -N\,(d\Phi/dt)$$

where N = 3,050 turns per coil and $d\Phi/dt$ is the rate of magnetic flux variation as rotor magnets sweep past each coil cross-section during rotation.

5.2 Magnetic Flux Calculation

The total magnetic flux (Φ) threading through a coil cross-section is given by:

$$\Phi = B \times A \times \cos\theta \rightarrow \Phi^{M} = \int B \cdot dA$$

where B represents the magnetic flux density (T), A is the effective coil cross-sectional area (m²), and θ is the angular displacement between the flux vector and the area normal vector.

5.3 Magnetic Flux Density Estimation

$A\_surface = (\pi/4) \times D^2 = (\pi/4) \times 0.038^2 = 8.55 \times 10^{-4}$ m²

Magnetic field intensity contribution: $Hl = H \times l = (875 \times 10^3) \times 0.019 = 16.63 \times 10^3$ A

Resulting magnetic flux: $\Phi = B \times A \times \cos\theta = 1.32 \times 8.55 \times 10^{-4} = 1.13 \times 10^{-3}$ Weber

5.4 Wind Power Estimation

The total wind power available to the turbine swept area is expressed empirically as:

$$P(kW) = 2.14 \times \rho \times A \times V^3 \times 10^{-3}$$

With air density $\rho = 1.22$ kg/m³, the theoretical maximum extractable power is bounded by the Betz coefficient at approximately 59.3% of the total available wind power.

VI. MATERIAL SELECTION

Material selection for each structural and functional component was conducted based on criteria of mechanical strength, weight, corrosion resistance, workability, and cost:

- Structural Base Frame: Mild Steel (MS) rectangular hollow sections — selected for high tensile strength, machinability, and weldability.
- Central Shaft: Grade 304 Stainless Steel — offers excellent corrosion resistance, adequate tensile strength, and good compatibility with rotating assemblies.
- Stator Disc: Marine-grade Plywood (12 mm, baked at 140°C under 1.9 MPa) — provides dimensional stability and sufficient mechanical rigidity.
- Rotor Plates: Medium-Density Fibreboard (MDF) — engineered wood panel product offering uniform density, smooth surface finish, and ease of precision machining.
- Turbine Blades: 1.5 mm Aluminium Alloy Sheet (AA 5052) — lightweight, high specific strength, corrosion-resistant, and amenable to manual forming operations.

VII. COST ANALYSIS

Table I presents detailed itemized cost estimation for all raw materials and standard components procured for the prototype fabrication. The total estimated procurement expenditure for the prototype amounted to ₹15,200, inclusive of all structural materials, magnetic components, electrical windings, solar module, and ancillary hardware.

Table I: Itemized Material and Component Cost Estimation

Sr.	Component / Material	Quantity	Cost (₹)
1	NdFeB Ring Magnets (N52, OD40×ID20×T10 mm)	2 Nos	1,800
2	NdFeB Disc Magnets (OD20×T6 mm)	8 Nos	960
3	26-Gauge Enamelled Copper Wire (0.8 kg)	4 Coil Sets	1,200
4	MS Rectangular Hollow Section (40×40×3 mm)	As reqd.	850
5	Grade 304 SS Shaft (φ20 mm × 500 mm)	1 No.	620
6	Aluminium Alloy Sheet (AA 5052, 1.5 mm)	1 Sheet	750
7	Marine Plywood (12 mm)	1 Sheet	480
8	MDF Board (12 mm)	1 Sheet	320
9	Solar PV Panel (SR-03PM, 3 W)	1 No.	2,400
10	Bridge Rectifier, Capacitors & Wiring	Lot	680
11	Fasteners, Adhesives & Consumables	Lot	540
12	Fabrication & Machining Charges	—	4,600
	Total Estimated Cost	—	₹15,200

VIII. FABRICATION METHODOLOGY

8.1 Base Frame Fabrication

The structural base frame was fabricated from mild steel rectangular hollow sections (40 mm × 40 mm × 3 mm wall thickness). Material cutting was performed using a vertical band saw to achieve dimensional accuracy within ±0.5 mm tolerance. Frame joints were assembled using TIG (Tungsten Inert Gas) welding, providing high-strength, low-distortion weld beads suitable for the load-bearing application. Post-weld surface preparation included grinding and application of anti-corrosion primer followed by polyurethane topcoat.

Base frame principal dimensions: Square base side = 500 mm; Vertical support pipe height = 500 mm; Vertical pipe outer diameter = 40 mm; Central base mounting plate = 170 mm × 128 mm.

8.2 Rotor Assembly Fabrication

Three rotor plates (upper, intermediate, and lower) were profiled to circular geometry using a band saw, followed by edge finishing with a disc sander. A central bore of 20 mm diameter was machined to accommodate the rotating shaft. Aluminium alloy blade blanks were manually formed to the desired aerodynamic curvature using a press brake and forming jigs, ensuring consistent blade profile across all fabricated elements.

Two NdFeB ring magnets (Grade N-42, OD 40 mm, ID 20 mm, thickness 10 mm) were mounted concentrically on the central shaft section to effect axial magnetic levitation. The angular spacing between adjacent disc magnets was maintained at 45°, corresponding to the coil angular pitch.

Rotor plate principal dimensions: Outer diameter = 400 mm; Central bore = 20 mm; Blade height (each half) = 250 mm.

IX. EXPERIMENTAL RESULTS AND DISCUSSION

Systematic experimental testing was conducted to characterize the electrical output performance of both the solar PV module and the ML-VAWT under varying ambient conditions.

9.1 Solar Panel Output Characterization

The solar PV module output voltage was recorded at five representative time intervals throughout the test day to capture the diurnal variation in solar irradiance intensity. Results are tabulated in Table II.

Table II: Solar PV Module Output Voltage at Various Times of Day

Sr. No.	Time of Day	Output Voltage (V)
1	09:00 AM	8.7
2	01:00 PM	10.4
3	04:00 PM	9.6
4	06:00 PM	6.0
5	07:00 PM	2.5

The data confirms the expected peak solar output during early afternoon hours (1:00 PM: 10.4 V), corresponding to maximum solar elevation angle and irradiance intensity. Output diminishes progressively with declining solar altitude during afternoon and evening hours, with minimal generation observed beyond 7:00 PM.

9.2 ML-VAWT Performance Evaluation

The output voltage of the ML-VAWT was measured across a range of rotor rotational speeds, varied by controlled application of airflow from a centrifugal blower. Results are presented in Table III.

Table III: ML-VAWT Output Voltage at Varying Rotational Speeds

Sr. No.	Rotational Speed (RPM)	Generated Voltage (V)
1	68	3.9
2	135	9.1
3	240	13.7
4	308	14.9
5	710	21.8

The results demonstrate a consistent and progressive increase in generated voltage with increasing rotor speed. At the maximum recorded speed of 710 RPM, an output voltage of 21.8 V was achieved, confirming the effectiveness of the electromagnetic coil configuration and rotor magnet arrangement.

9.3 Comparative Performance Analysis

A direct performance comparison between the ML-VAWT and a conventionally bearing-supported wind turbine was conducted under identical airflow conditions. Comparative results are presented in Table IV.

Table IV: Comparative Electrical Output - ML-VAWT versus Conventional Wind Turbine

Sr. No.	Maglev RPM	Maglev Voltage (V)	Conv. Turbine RPM	Conv. Voltage (V)
1	68	3.9	53	2.4
2	135	9.1	92	4.2
3	240	13.7	130	5.8
4	308	14.9	238	10.9

5	710	21.8	285	13.0

The comparative data unequivocally demonstrates the superior electrical generation efficiency of the ML-VAWT relative to the conventional turbine. At analogous airflow conditions, the ML-VAWT consistently achieved higher rotational speeds and correspondingly greater output voltages. This performance advantage is attributable principally to the elimination of bearing friction losses, enabling more efficient conversion of aerodynamic input energy to mechanical rotational energy.

X. CONCLUSION

This study has successfully demonstrated the design, fabrication, and experimental validation of a Magnetically Levitated Vertical Axis Wind Turbine integrated with a solar photovoltaic module for hybrid renewable energy generation. The following principal conclusions are drawn from the investigation:

- The magnetic levitation mechanism effectively eliminates mechanical bearing friction, enabling turbine initiation at wind velocities as low as 1.5 m/s and sustaining efficient operation across a broad rotational speed range.
- The hybrid solar-wind architecture ensures temporal complementarity, providing near-continuous power generation capacity across both diurnal and nocturnal periods.
- The system is inherently low-noise, low-vibration, and requires minimal ongoing mechanical maintenance, attributes highly favourable for residential and urban deployment scenarios.
- The prototype was successfully fabricated at a total cost of ₹15,200, confirming economic viability for adoption by middle-income households, cooperative housing societies, and small-scale commercial establishments.
- The compact, upright profile of the ML-VAWT renders it suitable for installation on rooftops, building parapets, highway median barriers, bridge railings, and street lighting columns.

XI. FUTURE SCOPE

Several avenues for future development and enhancement of the proposed system are identified:

- Scaling the coil winding configuration to higher turn counts and expanding the rotor magnet array is projected to increase the output power capacity toward 500 W, sufficient for basic rural electrification applications.
- Integration of a maximum power point tracking (MPPT) controller with the hybrid system would optimize energy extraction from both the wind and solar subsystems under variable meteorological conditions.
- Application of computational fluid dynamics (CFD) analysis to optimize the blade aerodynamic profile could reduce the minimum cut-in wind speed below 1.5 m/s and improve overall aerodynamic efficiency.
- Deployment of ML-VAWT arrays on highway dividers and flyover structures presents a promising avenue for harvesting vehicle-induced slipstream energy for powering roadway lighting and traffic management infrastructure.
- Incorporation of smart grid interfacing and IoT-based remote monitoring capabilities would enhance system operability, performance tracking, and predictive maintenance scheduling.

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