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Increasing the operational capability of a horizontal axis wind turbine by its integration with a vertical axis wind turbine

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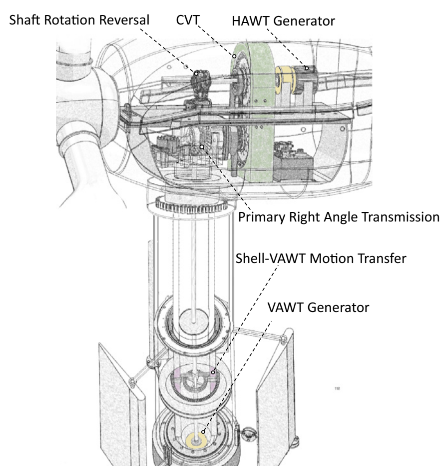
HIGHLIGHTS

- A new mechanism transfers torque from HAWT rotor to an integrated VAWT drive-train at high wind speeds.
- Operational range is improved for prototype-scale 12 kW HAWT-10 kW VAWT combination.
- A k-ω (SST) turbulence model suggests safe rotor clearance for the integrated system.
- Aerodynamic feasibility reveals effects of torque ripple on the combined power output.

GRAPHICAL ABSTRACT



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ABSTRACT

A major difficulty encountered by a horizontal axis wind turbine is the limit of aerodynamic torque that it can withstand at high wind speeds. A novel strategy is proposed to improve the operational capability of a prototype scale system by increasing its rated wind speed for power generation. This is achieved by integrating its drivetrain with that of a vertical axis wind turbine supported on a common tower. Excess torque is transferred from the horizontal axis rotor to the vertical axis rotor's drivetrain by coupling them using a continuously variable transmission. In this article, firstly, the concepts of motion transfer that facilitate this combined operation are discussed. A combination of a 12-kW horizontal axis rotor and a 10-kW vertical axis wind turbine is studied to estimate the increased benefit of increments in rated wind speed. Performance of this hybrid system is predicted at potential wind sites and is shown to exceed the standalone mechanical power output of both subsystems under different wind regimes. The critical criterion of the system's aerodynamic feasibility is then investigated. Turbulence modelling is performed for a configuration which involves a combination of the NREL Phase VI rotor and a NACA 0021 profiled vertical axis H-rotor. A 3-D simulation, using a validated k-ω (Shear Stress Transport) computational fluid dynamics model helps confirm the ability of both turbines to operate aerodynamically independent of each other. Further, by this methodology, a safe clearance between the two rotors is pre-determined. Analysis of turbulent flow scenarios reveals the characteristic effects of aerodynamic torque ripple experienced by the vertical axis wind turbine and its impact on combined power output. Parameters outlined in this article will be of assistance in the practical implementation of the integrated axes wind turbine.
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Nomenclature

HAWT	horizontal axis wind turbine
VAWT	vertical axis wind turbine
CFD	Computational Fluid Dynamics
NREL	National Renewable Energy Laboratory
TSR	Tip Speed Ratio
CVT	Continuously Variable Transmission
RANS	Reynolds Averaged Navier-Stokes (Equations)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
Rpm	revolutions per minute
Z_1,Z_2,Z_3,Z_4	tooth numbers of VAWT motion transfer gear-train
r	CVT ratio
u_{cH}	cut in wind speed for the HAWT
u_{HB}	rated wind speed for the HAWT
u_{VB}	rated wind speed for the VAWT
u_{FH}	furling wind speed for the HAWT
u_{FV}	furling wind speed for the VAWT
ω_H	angular speed of HAWT rotor
ω_{HB}	rated Angular speed of HAWT rotor
ω_V	angular speed of VAWT rotor
τ_{aH}	aerodynamic torque on HAWT main shaft
τ_{cH}	control torque exerted by HAWT generator
τ_{aV}	aerodynamic torque on VAWT central shaft
τ_{cV}	control torque exerted by VAWT generator
R	radius of rotor
ρ	density of air
λ	Tip Speed Ratio
C_p	coefficient of power
C_q	coefficient of torque
$P - P_\infty$	gauge pressure
A	projected area of rotor
v_∞	free stream wind speed
TKE	Turbulent Kinetic Energy

1. Introduction

Horizontal axis wind turbines (HAWTs) are the primary source of grid connected wind power [1]. A primary issue encountered is that at high wind speed nearing its wind rated speed, the HAWT's operation is stall regulated or pitch controlled to limit power generation by reducing lift on its blades [2]. This limits the optimal torque exerted and causes the wastage of a portion of potential mechanical power at a site. Therefore, to better facilitate energy capture from the three-bladed turbine, drivetrain modifications and control schemes are being designed and improved to maximize the power drawn at varying wind speed. More recently, research is veering towards the incorporation of artificial neural networks [3,4] which form a framework of learning algorithms which help correlate on-site wind data with the power coefficient and pitch angles. In particular, the adaptive neuro-fuzzy inference system (ANFIS) [5–7] is gaining popularity. On a broader scale, it can also assist in maximizing profit from empirical wind profiles for wind farms [8–10]. Feathering and pitch actuation models are also being improved to optimize the angle of attack of the wind and the instantaneous Tip Speed Ratio (T.S.R) of the HAWT. These are supported by soft computing techniques for power coefficient optimization [11,12] and Maximum Power Point Tracking (MPPT) algorithms [13,14] which enhance the synchronous power output from the turbine's grid-connected Permanent Magnet Synchronous Generator (PMSG) or Doubly-Fed induction Generator. Here, the use of the sliding mode control strategy [15–17] is a popular method which helps optimize the functioning of the turbine's drivetrain elements. While these strategies may assist in compensating for the limitations in the existing capability of the HAWT, attention must pivot towards the fundamental design of the three-bladed system.

To increase the mechanical power a HAWT can harness, changes in the design of the three-bladed rotor are being attempted. One imaginative method to draw more power is to access the stream of fast-flowing wind at higher altitudes by the crosswind motion of tethered wings [18,19]. Another bold approach entails radically increasing the swept area of the turbine. For example, a new design was tested by Vestas Wind Systems [20] wherein multiple 3-bladed rotors were supported at different eccentricities from a central tower to achieve a 900-kW output. While it is claimed that this reduces the Levelized Cost of Energy (LCOE) [21] and construction and transportation costs, the rotor overhang in such a configuration could be challenging. The key consideration for all such hybrid designs is that implementation at a megawatt-scale is governed by economy. This is compounded by the breakdown of critical components, thus increasing operational cost [22].

To improve the mechanical power output at the hub height of the HAWT, some improvements in the existing motion transfer mechanism within the nacelle have been undertaken. These include the use of direct-driven PMSGs which avoid the need of intermediate gearboxes. Also, to facilitate smooth gear ratio transition, the use of Continuously Variable Transmission [23–25] is being investigated. Contrary to a manual or a conventional automatic transmission, the operation of a CVT involves no torque interruption during change in angular speed. While CVTs have been investigated for active drivetrains in HAWTs to convert gusty wind power to stable alternating current for synchronous generation [26], practical designs which address optimum torque transfer and ability to raise rated wind speed haven't been adequately implemented.

With an apparently disparate purview, to harvest more energy near the ground surface, vertical axis wind turbines (VAWTs) too are being re-designed to up-scale their drivetrains. To save costs, intermediate gearboxes are avoided and instead, low solidity ratio models which facilitate low torque and high rpm central shaft rotation to optimize the use of alternators, are used [27]. Consequently, more effort has been directed to fabricate VAWTs of a 1–20 kW scale [28]. By arranging these turbines in arrays so they may mutually aid each other in rotation [29], it is claimed that they produce a higher aggregate of mechanical power. Unlike their horizontal axis counterparts, however, VAWTs cannot access the stream of fast flowing wind as they are located at a lower elevation, have a smaller swept area and suffer from turbulence at ground level.

In an attempt to address these difficulties, the author proposes a new mechanism for a prototype scale wind turbine system. This incorporates the use of a shell-type VAWT installed on the same support tower as the HAWT. This constitutes a strategy to optimize the power output of the HAWT in a unique way. A novel motion transfer mechanism comes into operation when the wind speed at the hub height of the HAWT approaches or exceeds its original rated wind speed. The modified HAWT drivetrain is designed to transfer the excess torque exerted on the HAWT's main shaft to the VAWT's central shaft. This further utilizes a CVT for a purpose removed of its normal purpose of power transmission from rotor to

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