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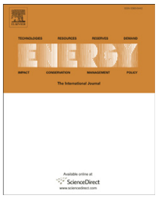

Multi-objective optimization of the design and operating point of a new external axis wind turbine

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A B S T R A C T

A new class of wind turbine termed the external axis wind turbine (EAWT) has been recently developed in response to the anticipated increase in global demand for renewable energy. The EAWT combines the high power output of the HAWT with the low installation and maintenance cost of the VAWT. This paper optimizes this EAWT to simultaneously maximize the power while minimizing power fluctuation and the time required to reach the optimal operating point. The multi-objective optimization on the EAWT using Genetic Algorithm is performed on a response surface that is generated using CFD simulations in OpenFOAM. The turbulence model and mesh-sizing for the CFD simulations are validated against previously published experimental results on a bluff body. The paper first optimizes the EAWT using steady state CFD simulations which are found to be not valid. The paper then optimizes the EAWT using transient CFD simulation with moving mesh, first for a single Reynolds number then for a wide range of Reynolds numbers. From the analysis, a blade count of 10 at an operational tip speed ratio of 0.32 is recommended. This paper is the first study on EAWT. To the best of authors' knowledge, this paper is also the first study on wind-turbines to optimize changing blade count and operating point to simultaneously maximize power, while minimizing power fluctuation and the time needed to reach peak operating point.

1. Introduction

There is a significant anticipated growth in wind energy. Current state-of-the-art wind turbines can be classified into horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) [1]. Under near laminar conditions, HAWTs are more efficient than VAWTs [2]. However, the wind thrust force on the tall tower towers used by HAWT, translate to a large moment at the base of the tower necessitating deep foundations. This results in a higher installation cost for HAWTs and HAWTs cannot be easily integrated onto buildings. VAWTs consist of blades mounted on a vertical rotating shaft at its center. The use of the center shaft limits the physical size of the VAWT and VAWTs are limited to small-scale and micro-scale energy generation [1]. SP Power Farm Group Ltd. (SPPF) has developed a new class of wind-turbines called External Axis Wind Turbine (EAWT) [3]. For the benefit of the reader, the innovations and salient features of the in the EAWT are briefly summarized here.

Technologically: The EAWT also rotates about a vertical axis but does not use a center shaft. Since the EAWT rotates about a vertical axis, the airflow is always perpendicular to the direction of rotation and the EAWT is omnidirectional. The turbine does not incorporate the weight bearing center axis. This allows for the design to be scaled up effectively as well as many new applications that have not been available in the wind industry before. Specifically, the external axis would allow for much larger turbines and the EAWT is expected to be capable of generating power in the range of few MW (which is comparable to medium HAWTs). The power take-off for the turbine can be customized to meet the requirements of the client, project, and application(s). The magnets and the power take-off, for instance, can be mounted on the circumference and EAWT can generate power without additional gearing mechanism. If applications require, ring and pinion, and/or cam and lever may be utilized.

Installation: The EAWT does not require a tall tower and the turbine can be housed within the structure; either purpose-built application like a wind farm or in a high rise building application, it will allow for the turbine to be constructed in the extremely windy areas on the planet. The turbine is designed to withstand 280 km per hour winds operationally and will be able to withstand

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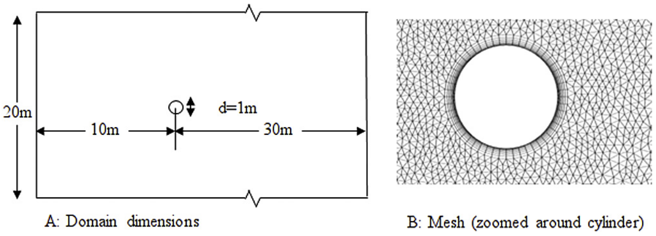
up to 480 km per hour winds. The purpose built wind farm turbine housing and structure can be built to a much higher Seismic rating, with current structures at more than 9.0 on the Richter scale.

Potential market: Once in full commercialization mode, the costs/price will be overall equal to or better than current commercial HAWTs. As the EAWT can be installed under persistently high wind conditions and earth quack prone zones, the EAWT has a significantly increased market potential. The EAWT would also be easy to install and maintain and due to the nature of the design, it allows for the opportunity to lease the equipment during the lifetime of the project. It at the end of the requirement (for instance in a mining application), the structure and turbine may be disassembled, containerized, and moved to a new location for the same or new application. The structure and housing will have a minimum life expectancy of over 100 years. Additionally owing to the external axis, the EAWT applies less concentrated structural load and can be incorporated into existing structures and skyscrapers. The ISO Standards will be applied to the required turbine components and power take off(s). As well the turbine system will be maintained, repaired or replaced as required to meet or exceed any or all life safety standards.

According to Betz Law, the coefficient of power, $C_p \leq 8/27$ for drag based wind turbines and $C_p \leq 16/27$ for lift based wind turbines [4]. Since the EAWT also rotates about a vertical axis, we will examine VAWT optimization in literature. VAWT can further be classified into lift based VAWT (VAWT-L) and drag based VAWT (VAWT-D). Sheldahl et al. [5] have experimentally investigated several NACA-00xx aerofoils for use in VAWT-L while Gharali et al. [6] and Ahmadi et al. [7] have investigated the aerodynamic performance of the aerofoil blades under dynamic flow condition. Experimental research has shown that vertical flap, known as Gurney flap, improve the lift coefficients of aerofoils [8]. Research has also show that outward dimples on the upper surface of the aerofoil to improve the lift coefficient of aerofoil [9]. Ismail et al. [10,11], have optimized a combination of Gurney flap and a dimple to improve VAWT-L torque. Researchers have also examined vortex capture using complicated blade profile [12] and studied vortex dynamics of VAWT-L [13]. Drag based VAWT are primarily used for its good starting characteristics, lower installation costs and, low operating speed [14]. The vast majority of drag based wind turbines are Savonius-VAWT consisting of two blades that have a “S” profile. Increasing the number of blades to beyond two blades has been found to result in lower efficiency in Savonius-VAWTs [15,16]. Researchers have evaluated various parameters such as blade profile, blade overlap and blade gap on VAWT-L performance [15–17]. Researchers have also used deflectors which in combination with optimal rotor has been shown to harness about 20% more power [15]. While Saha et al. [16,18], aim to optimize Savonius-VAWT power for semi-circular and twisted blades, they have not attempted to determine the optimal speed. Rather, they have used the maximum speed as a measure of efficiency.

This paper aims to maximize power while minimizing the time needed to reach peak operational point and power fluctuations (only for transient simulation base optimization) in EAWTs. The paper will use a Response Surface Analysis (RSA) based optimization. RSA involves evaluating a chosen objective function (in this case the average torque) at discrete points in the parameter space to generate a “response surface” [19]. The optimal distribution of the evaluation points can be achieved using the design of experiment (DOE) analysis [20]. Details on RSA can be found in literature on engineering optimization [19–30]. To ensure reliability, the turbulence models used in this paper are validated against the corresponding experimental results published in the literature. The objective of this study is to maximize the peak power of the EAWT while minimizing the time need by the EAWT to reach the peak power point by selecting the number of blades and the operating point. This is a classic muti-objective optimization and we cannot expect a single optimal point. Hence we will construct the Pareto surface [31], which represents the surface on which the family of optimal solutions. This paper is the first study on EAWT. To the best of authors' knowledge, this paper is also the first study to investigate changing blade count, and determining the optimal operating point to simultaneously maximize power, while minimizing power fluctuation and the time needed to reach peak operational point in wind-turbines.



A: Domain dimensions

B: Mesh (zoomed around cylinder)

Fig. 1. Domain for validation.

2. Simulation of EAWT

2.1. Turbulence model

The CFD simulation is solved using OpenFOAM, an open-source CFD software. Detailed description of governing equations for CFD are available in literature [32,33]. The EAWT will be simulated using 2D Reynolds number averaged Navier-Stokes (RANS) computational fluid dynamics (CFD). In using the RANS equations, it is necessary to use a model for the turbulence. In this paper we have used the SST k-ω (shear stress transport) turbulence model [34–36], with automatic wall function is used here to model the flow turbulent flow. The SST k-ω was chosen because it is a hybrid model that provides a larger weightage to the k-ω close to walls and a larger weightage to the k-ε model in the free stream thus allowing for better modelling of turbulence [32,33]. The simulation used Euler scheme for time derivatives, cell-limited Gauss Linear schemes for k, ω and ε, and Gauss Linear schemes for all other quantities. The CFD simulation also used linear interpolation scheme. The pressure was solved by Generalized geometric-algebraic multi-grid (GAMG) solver while all other quantities used a smoothSolver. A value of 10^{-6} was chosen residual convergence limit.

2.2. Validation of turbulence and establishing mesh independence

The VAWT is a drag based wind-turbine, hence the grid-spacing and turbulence model are to be validated for a bluff body. Zdravkovich [37] provides extensive experiments results on the pressure measurement, drag and wake oscillation frequency for a stationary bluff cylinder. Hence the turbulence model and mesh are being validated against the results in Zdravkovich [37]. For the validation study, we choose a cylinder of diameter $d = 1\ m$, domain height of $20m$, with a length of $10m$ upstream of the cylinder and a length of $30m$ downstream of the cylinder as shown in Fig. 1A. We choose a mesh size of $0.025 \times d$ on the surface of the cylinder and used a mapped a boundary layer mesh close to the surface of the cylinder and free mesh elsewhere in the domain as shown in Fig. 1B. This resulted in a mesh with approximately 1.01×10^5 cells. Transient simulations were run for an inlet velocity of 1.56 m/s (corresponding to $Re = 0.96 \times 10^5$) using an adjustable time step method