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A Pareto optimal multi-objective optimization for a horizontal axis wind turbine blade airfoil sections utilizing exergy analysis and neural networks

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ABSTRACT

In this study a multi-objective genetic algorithm is utilized to obtain a Pareto optimal set of solutions for geometrical characteristics of airfoil sections for 10-meter blades of a horizontal axis wind turbine. The performance of the airfoil sections during the process of energy conversion is evaluated deploying a 2D incompressible unsteady CFD solver and the second law analysis. Artificial neural networks are trained employing CFD obtained data sets to represent objective functions in an algorithm which implements exergetic performance and integrity characteristics as optimization objectives. The results show that utilizing the second law approach along with Pareto optimality concept leads to a set of precise solutions which represent minimum energy waste, maximum efficiency, and topmost stability. Furthermore, enhanced rotor performance coefficients are observed through a BEM study which compares conventional designs with the second law obtained configurations. Exergy analysis is believed to be an efficient tool in the optimal design of wind turbine blades with the capability of determining the amount of lost opportunities to do useful work.

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1. Introduction

Depleting sources of fossil fuels and the environmental issues associated with utilizing them have made development of alternative and clean energy sources and their effective employment a considerably rapid process (IEA, 2013). Wind energy market is experiencing a significant growth which stands out among renewable energy technologies and is expected to extend even in a more substantial way. Horizontal Axis Wind Turbines (HAWTs) have been demonstrated to be the transcendent machine tools in extracting the energy from the wind (Hau, 2006; Gipe, 2004); these machines possess a number of advantages when compared with Vertical Axis Wind Turbines (VAWTs), such as higher energy efficiency, more mechanical stability, less sensitiveness to off design conditions, etc. Thus, effective extraction of the wind stream energy with less energy waste, obtaining a comprehensive understanding of the energy conversion phenomena, and economic analysis of these systems have become an area of concern for technology leaders as well as an area of interest for researchers (Mehta et al., 2014; Arroyo et al., 2013; Castellani and Vignaroli, 2013; Castellani and Garinei, 2013; McKenna et al., 2014; Jung and Kwon, 2013; Jha, 2010; Burton et al., 2011; Wood, 2011). In this regard, optimization of geometrical properties of wind turbine blades has been investigated using various approaches. The design of a HAWT rotor blade is a complex task consisting of trade-off decisions. The objective of this procedure can usually be addressed as finding the optimum performance for a range of specified conditions (Burton et al., 2011).

Benini and Toffolo (2002) optimized HAWT blades using the BEM theory along with an evolutionary algorithm. In their study a multi-objective optimization algorithm was employed for designing the blades of a stall-regulated HAWT. The BEM theory analyzed the flow field around the airfoil while the evolutionary algorithm selected the decision variables.

Jureczko et al. (2005) used aerodynamic characteristics along with modifying the composite material of the blade in order to optimize the wind turbine blade. The complexity of the problem of determining the optimum shape of the blade and the best composite material became the incentive to use multi-criteria optimum design approach. The aerodynamic analysis was based on the BEM theory and the effect of the blade material on the dynamic properties was evaluated using a Finite Element Model (FEM). A genetic algorithm was employed to conduct the optimization.

Vitale and Rossi (2008) devised a computational method for the design of wind turbine blades. They developed and introduced a computer code for blade design of HAWTs with low capacities, which provided the possibility of obtaining optimum wind turbine blade

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Nomenclature

A	Area $[m^2]$
a	Axial induction factor
a'	Tangential induction factor
c	Chord length $[m]$
C_p	Specific heat $[kJ/kgK]$
$\dot{E}x$	Exergy rate $[kW]$
$\vec{F}$	External body force
H	Energy
I	Unit tensor
$\dot{m}$	Mass flow rate $[kg/s]$
k	Thermal conductivity $[W/m^2K]$
P	Static pressure $[Pa]$
Q	Heat $[J]$
r	Radius $[m]$
R	Gases constant $[J/Kmol]$
Re	Reynolds number
S	Source term
t	Time $[s]$
T	Temperature $[K]$
U	Undisturbed velocity $[m/s]$
$\vec{\nu}$	Velocity component $[m/s]$
V	Free stream velocity $[m/s]$
y^+	Turbulence wall Y Plus

Greek Letters

α	Angle of attack [deg]
β	Twist angle [deg]
ε	Exergy efficiency
μ	Dynamic viscosity $[kg/ms]$
ρ	Density $[\mathrm{kg}/m^3]$
Ω	Rotational speed $[rad/s]$
τ	Shear stress $[N/m^2]$
φ	Approach (flow) angle [deg]

Subscripts

0	Reference condition
at	Atmosphere condition
D	Drag
dest	Destruction
eff	Effective
in	Inflow
L	Lift
Loss	Loss
m	Mass
out	Outflow
ph	Physical
product	Products
rel	Relative
work	*Work*
x	Streamwise direction
y	Vertical direction

shape. The Blade Element Momentum (BEM) theory was used in the algorithm of fluid dynamics analysis. The software made developing various designs for many different conditions affordable.

Leung et al., (2010) obtained the optimum design of the rotor of a small wind turbine by using Computational Fluid Dynamics (CFD) analysis. The objective of this study was performance evaluation of small wind turbines which usually extract energy from low speed wind streams. The study investigated the variation of the performance of micro wind turbine with different design parameters. The results showed that the performance of high-solidity wind rotors is more desirable than that consisting of low-solidity rotors.

The overall efficiency of a wind turbine might depend on several contributing factors, such as generator performance, the ratio of the gear box system and the height of the hub from the ground, which are not investigated in this study. Generally, with specified wind distribution and at a given range for rotational speed of the rotor, the most important issue to address will be selection of the airfoils and their geometrical properties along the blade (Jha, 2010; Burton et al., 2011; Wood, 2011; Cengel and Boles, 2006).

Typically, common design methodologies employ the first law of thermodynamics for wind power system analysis and design (Benini and Toffolo, 2002; Jureczko et al., 2005; Vitale and Rossi, 2008; Leung et al., 2010). Through these methods a theoretical maximum efficiency can be predicted, but the loss of opportunities to produce more useful work is not evaluated. According to Dincer and Rossen (2012), to provide an efficient and effective use of the energy sources, it is essential to consider both the quality and quantity of the energy used to achieve a given objective. In this regard, the second law of thermodynamics deals with the quality of energy and it simply analyzes degradation of the energy during a process, entropy generation and the lost opportunities to do work (Dincer and Rossen, 2012; Dincer et al., 2014). Entropy-based design and exergy analysis have been shown to identify the maximum theoretical capability of energy system performance in various applications, by employing the fact that higher levels of entropy generation are associated with a lower level of useful energy (Dincer and Rossen, 2012; Dincer et al., 2014; Koroneos et al., 2003).

Therefore, exergy analysis together with stability characteristics can be considered as an advantageous tool for optimal design of geometrical parameters of wind turbine rotors. In this study a Mmulti-objective genetic algorithm (MOGA) is utilized to obtain a Pareto optimal set of solutions for chord lengths and flow angles for the airfoil sections of 10-meter blades of a HAWT rotor. The objective functions in this algorithm are exergy efficiency of the section, loss of exergy around the airfoil, and the solidity of the airfoil section. First, performances of three different NREL Dan Somers' airfoil families are evaluated using an incompressible unsteady CFD solver and second law approach which leads to selection of an airfoil family for blade investigations. CFD simulations are conducted in order to evaluate exergy efficiency and the resultant dissipated exergy around the airfoil under various flow conditions of the section's radius, chord length and flow angle. Neural networks are trained in order to enable predicting the values of exergy efficiency and exergy loss under un-investigated flow conditions and section radii. In the next step trained neural networks along with the section's solidity are deployed as objective functions in MOGA to achieve Pareto optimal sets of solution tailored for each of the blade sections. Moreover, power coefficients of the rotors designed by the second law approach are compared with the power coefficients representing rotors designed utilizing conventional methods.

2. Second law analysis via CFD

CFD has emerged as an expeditious tool for apprehending cognition of the flow field in various engineering problems including wind engineering, a few exhibits are flow analysis

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