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Multi objective optimization of horizontal axis tidal current turbines, using Meta heuristics algorithms

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ABSTRACT

The performance of horizontal axis tidal current turbines (HATCT) strongly depends on their geometry. According to this fact, the optimum performance will be achieved by optimized geometry. In this research study, the multi objective optimization of the HATCT is carried out by using four different multi objective optimization algorithms and their performance is evaluated in combination with blade element momentum theory (BEM). The second version of non-dominated sorting genetic algorithm (NSGA-II), multi objective particle swarm optimization algorithm (MOPSO), multi objective cuckoo search algorithm (MOCS) and multi objective flower pollination algorithm (MOFPA) are the selected algorithms. The power coefficient and the produced torque on stationary blade are selected as objective functions and chord and twist distributions along the blade span are selected as decision variables. These algorithms are combined with the blade element momentum (BEM) theory for the purpose of achieving the best Pareto front. The obtained Pareto fronts are compared with each other. Different sets of experiments are carried out by considering different numbers of iterations, population size and tip speed ratios. The Pareto fronts which are achieved by MOFPA and NSGA-II have better quality in comparison to MOCS and MOPSO, but on the other hand a detail comparison between the first fronts of MOFPA and NSGA-II indicated that MOFPA algorithm can obtain the best Pareto front and can maximize the power coefficient up to 4.3% and the produced torque on stationary blade up to 57.9%. The geometries of the first and last members of the Pareto front of MOFPA are compared to each other. These members which produce the maximum power coefficient and the maximum produced torque on stationary blade have hyperbolic and constant chord distributions, respectively.

1. Introduction

High energy consumption is one of the serious problems in the world today. Recently, this question has taken on not only economic, but also ecological and social importance [1]. Renewable energies which offer a great amount of free energy for most countries of the world can be one of the potential solutions for reducing fossil fuels consumption and emissions. Today, at different points of the world, various renewable energy convertors are being used to trap the free energy. Tidal current which is one of the forms of ocean energy, is vast, reliable, regular and the most predictable energy resource [2]. Various global studies have shown that tidal current energy has large potential as a predictable sustainable resource for commercial scale generation of electrical power [3].

Tidal current energy is much easier and cheaper to extract using tidal current converters, with less harmful environmental effects compared to tidal barrages [3,4]. Many devices are being studied for tidal current energy conversion although most are designed around horizontal axis turbines, known as horizontal axis tidal current turbines (HATCT) [5]. The design and operation of HATCT are similar to those of a horizontal axis wind turbine [3,6]. There are however a number of fundamental differences in the design and operation of the HATCT, which will require further investigation, research, and development [7]. These include changes in force loadings and Reynolds numbers, different stall characteristics, depth of immersion and the possible occurrence of cavitation [7,8].

Many developments have taken place in field of horizontal axis marine current turbines during the recent years, moving from model testing to prototype development and installation [3]. Bahaj et al. [5] designed a test model of HATCT for the purpose of studying the characteristics of turbine power and thrust for a different range of RPM, flow speed and hub pitch angle. The

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Nomenclature

B	number of Blades
C_D	drag coefficient
C_L	lift coefficient
C_P	power coefficient
C_1	first acceleration factor in MOPSO algorithm
C_2	second acceleration factor in MOPSO algorithm
D	drag force (N)
G_{best}	global best solution in MOPSO algorithm
K	constriction factor in MOPSO algorithm
L	lift force (N)
P	power (W)/pressure (Pa)
P_{best}	individual best solution in MOPSO algorithm
Q	torque (N m)
R	radius (m)
TSR	tip speed ratio
U_∞	free stream velocity (m/s)
V_{total}	relative velocity (m/s)
a	axial induction factor
a'	tangential induction factor
c	Chord (m)
f	tip loss factor
g_*	global best solution in MOFPA algorithm
h	depth of immersion of turbine(m)
p_a	switch probability
r	local radius (m)
s	levy step size
Ω	rotational speed (rad/s)
α	angle of attack (°)
β	local pitch angle (°)
γ	scaling factor
ϵ	random numbers drawn from uniform distribution
λ	tip speed ratio/Levy exponent
ρ	density (kg/m^3)
σ	Solidity/cavitation number
ϕ	Local inflow angle (°)
ω	Inertia weight in MOPSO algorithm

Subscripts and superscripts

r	local property
t	tip
h	hub
atm	atmospheric
v	vapor
max	maximum
min	minimum
$'$	local property

experimental measurements were carried out in both a cavitation tunnel and a test tank. Myers and Bahaj [9] studied the power output performance characteristics of a horizontal axis tidal current turbine. Numerical and experimental studies on hydrofoils for tidal current turbines were carried out by Goundar et al. [10] and the design of a high performance and cavitation free hydrofoil HF-Sx was presented. An HATCT was designed by Goundar and Ahmed [3] by using HF10XX hydrofoils. Batten et al. [7] developed a blade element momentum (BEM) model for the hydrodynamic design of tidal current turbines and compared the results with experimental data. These results showed that the theoretical predictions were in a good agreement with experiments. Also Batten et al. [8] used the same BEM theory in order to design possible horizontal axis tidal turbines for the tidal flows around Portland Bill. Lee et al. [11] studied different computational methods for performance analysis of horizontal axis tidal current turbines and compared the results of CFD and BEM theory. Wu et al. [12] designed high-efficient blades of tidal current turbine by using Schmitz method. The designed blade increases the startup torque, improves the total performance of the turbine and decreases the thrust coefficient. Lawson et al. [13] applied genetic algorithm for optimization of the blade twist angle and chord length distribution along the span. The optimization objective for the blade design process was to maximize power generation over a range of flow speeds from 0.5 m/s to 3 m/s [13]. Few studies exist on different optimization algorithms which can be utilized in finding the global optimum design of marine current turbines.

The performance and the efficiency of an HATCT mainly depend on the geometry and the design parameters of the turbine blades. These parameters entail diameter, pitch or twist and also the chord distribution across the blade span, blade section and etc. Therefore, the optimum performance of an HATCT can be obtained by an optimized geometry. There are several parameters that can describe the performance of the turbine, for example, the power coefficient, the startup torque, the startup time, weight and etc. In reality, optimization of all these parameters, for achieving the overall optimum design, is required. These kinds of problems are called multi objective optimization problems. Solving the optimization of multi objective problem requires synchronized satisfaction of different objectives. Thus, Meta heuristic algorithms were established and evolved through the 20th century in an effort to solve multi-objective issues at random [14]. A suitable way to a multi objective quandary is to inquiry a collection of routes, each of them convinces the objectives at a satisfactory degree away being overcome by another route [15]. Cai et al. [16] applied multi objective particle swarm optimization for environmental/economic dispatch. Duan et al. [17] optimized the thermodynamic design of Stirling engine using multi objective particle swarm optimization algorithm. Ahmadi et al. [18] applied non dominated sorting genetic algorithm (NSGA-II) for thermodynamic modeling and multi objective optimization of a new multi generation energy system. Ahamdi et al. [19] applied non dominated sorting genetic algorithm for thermo-economic optimization of Stirling heat pump. Also, Recently, multi objective optimization of diverse thermodynamic and energy systems were employed in different field of science [20,21]. One of the features of Meta heuristic algorithms is the capability of including the influence of all variables on the objective function, at the same time. These algorithms can be utilized with BEM theory for the purpose of obtaining the optimum geometry of HATCTs. Genetic algorithm has been used with BEM theory in many studies. For example, Pourrajabian et al. [22] used the genetic algorithm for optimization of the chord and twist distribution across the blade span of a micro scale horizontal axis wind turbine. The power coefficient and the startup time were objective functions in this study.

According to the attention of engineers and scientists to the evolutionary or Meta heuristics algorithms, in this research study, it is aimed to evaluate the performance of four different multi objective optimization algorithms in combination with blade element momentum (BEM) theory for the purpose of achieving the optimum design of HATCTs. For this purpose the presented turbine by Bahaj et al. [5] is selected. The selected algorithms are the second version of non-dominated sorting genetic algorithm (NSGA-II), multi objective particle swarm optimization algorithm (MOPSO), multi objective cuckoo search algorithm (MOCS) and also the multi objective flower pollination algorithm (MOFPA). Two of these