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Multiobjective optimization of wind turbine blades – performance evaluation of some optimizers

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Abstract

In this paper, a comparative study of multiobjective meta-heuristics (MOMHs) for optimum design of a wind turbine blade with shape and size design variables is presented. The design problem is posed to maximize annual energy production and minimize energy cost. Aerodynamic analysis of a horizontal-axis wind turbine is achieved by using the standard numerical method, blade element momentum theory. Total lift and drag coefficients are calculated by using the XFOIL program. Several well established MOMHs are used to solve the design problem. The results obtained from several MOMHs are compared based on the hypervolumn indicator. Based on this study, the performance of several MOMHs on solving optimization of a wind turbine blade is investigated and the optimum design is obtained.

***Keywords**:* Multiobjective Evoluationary optimization, Wind Turbine Blades design, Meta-heuristics, Blade element momentum theory

1. Introduction

Wind energy is one of the biggest ecological energy resources, which can be harvested by using a wind turbine [1,2]. Several countries have been using such an energy device effectively but it seems to be the reverse when applied in Thailand because of the low inland wind speed. However, windmill project in the country is still possible in the east and south coasts. It has also been unofficially reported that a small wind turbine can be used with suitable output in some areas of Nakhon Ratchasima province. The coasts wind turbine plant is the other option. The use of wind turbine at low wind speed is possible in Thailand. However, for a reasonable investment, a greater turbine blade is needed in order to produce the lower-energy wind from a larger inflow area without increasing the cost of the rotor [3]. With such a wind turbine, many working problems and unwanted situations could be inevitable. The conceptual, primary and detailed design steps as well as the testing and manufacturing process need to be taken with caution. The optimization is clearly close to the most important implements for this work.

Optimization problems are normally assigned to find the solution of the design that gives the optimum design objective (either maximum or minimum) while satisfying all design constraints [4]. Basically, there often include multiobjectives to be optimized and the problem is called multiobjective optimization. Multiobjective evolutionary algorithms are some of the most popular optimizers for this kind of problem. The benefits in using such methods are that they are simple to use, require on functional derivatives, hardly stall for the duration of the search, and most prominently can explore the Pareto optimum set within one optimization run. For the case of wind turbine blade design, as a wind turbine is a highly complex system, all possible design/optimization principles should be taken into concern. Some design principles are: the value of annual power production (to be maximized) [5], total running cost (to be minimized), dynamic instability (to be constrained), dynamic stall (to be minimized), natural frequency (to be constrained), fatigue (to be constrained) and static disappointment (to be constrained).

This paper presents performance assessment of some MOMHs for the conceptual shape design of a wind turbine blade. The design problem is to find blade shape such that optimizing two objective functions, the annual energy production density and energy cost. Aerodynamic analysis of a horizontal-axis wind turbine is accomplished by using the blade element momentum theory, where 2D lift and drag coefficients are calculated using the XFOIL program [6] The optimizers used for benchmarking include MOPBIL, MODEMO, MORMOHS, MORNSGA, MORPS, RPBILDE and UPSEMOA. The program is developed by using the MATLAB computing language.

2. Design problem

A multiobjective design problem can be defined as: Min: $f = \{f_1(x),\ldots, f_m(x)\}$

Subject to

$g_i(x) \leq 0$

$h_i(x) = 0$

where

x is the vector of n design variables

f_i are the m objective functions

g_i are inequality constraints

and h_i are equality constraints.

The objective functions are in general conflicting to each other. For example, in structural optimization, minimising structural mass usually causes structural stiffness reduction but increasing the stiffness leads to a heavier structure. The set of optimum solutions of the design problem is called a Pareto front. A number of optimization methods can be used to solve this problem and some of them are MOEAs (also known as the population-based methods). The most advantageous feature of MOMHs is that it can search for the Pareto front of a multiobjective design problem by using only one optimization run while the other approaches use many runs for solving.

The main concept of exploring Pareto optimum points by using MOMHs is that, on each generation, while a new population is created, non-dominated solutions are selected and continued to the next generation. The term "non-dominated solutions" defines the local Pareto solutions between the members of the current population and the previous non-dominated solutions. For more details, see references [6 -9]. MOMHs are often generated to solve unconstrained optimization; however, they can be applied to tackle constrained problems by using a penalty function technique. Also, the non-dominated classification scheme for constrained optimization given in reference [9] is found to be greatly efficient and effective. A three-blade horizontal-axis wind turbine is selected for design experiment in this investigation. The bi-objective design problem, which is similar to the presented problem, is defined as.

Find: blade geometry such that
max f_1 & min f_2
Subject to
design variable constraints

where
$$f_1 = \frac{AEP}{R^2} \quad (1)$$
$$f_2 = COE = \frac{TC + BOS}{AEP} FCR + O \& M \quad (2)$$

AEP = annual energy production
COE = cost of energy
R = tip radius of the blade
TC = the turbine cost which is set to be proportional to blade weight

The first objective is set to find the blade that gives maximum density of annual energy production as imposed in [10]. The second objective is the most normally used design norm when considering economic present i.e. the cost of energy in [9]. All of the parameters used to calculate the COE value are the same values as given in previous problem. The design variables determine the blade shape comprising blade chord distribution, airfoil thickness distribution and the pitch angles of the blade elements. Fig. 1 illustrates the design variables. The airfoil cross-section used here is the NACA44XX series where XX is the integer indicating the airfoil thickness, which is also set as one of the design variables.

The blade is divided into 30 elements. On each blade element, the chord length, airfoil thickness (XX) and the pitch angle have to be assigned. The blade shape is controlled by these parameters. The constraints for the design variables are as follows give in conference [11].

- The thickness (XX number) at the i^{th} element must be larger than or equal to the thickness at the $(i+1)^{th}$ element.
- The chord length at the i^{th} element must be smaller than or equal to the length at the $(i+1)^{th}$ element for $r < 0.2R$
- The chord length at the i^{th} element must be larger than or equal to the length at the $(i+1)^{th}$ element for $r \geq 0.2R$
- The pitch angle at the i^{th} element must be larger than or equal to the angle at the $(i+1)^{th}$ element.
- The blade length is in the range of 1.5 m to 3.0 m
- The domain of the element pitch angle is [30°, 60°]
- The maximum chord length at r = 0.2R is set to be in the range of [0.2 m, 0.3 m]
- The root chord length is set to be in the range of [0.1m, 0.2 m]
- The tip chord length is set to be in the range of [0.1m, 0.2 m]
- The hub radius is Rhub =0.1 m.
- The airfoil thickness number is set to be in between 10 to 50.
- The airfoil thickness of the first element is larger than 24.

Fig. 2 shows an arbitrary design solution whereas the corresponding wind turbine is shown in Fig. 3.

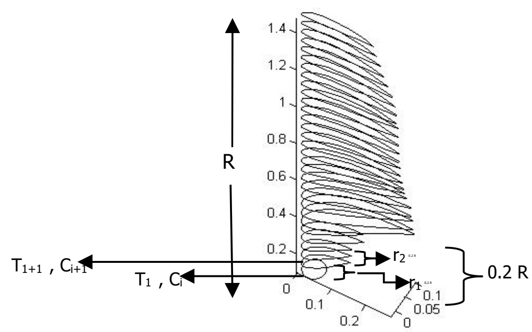

Fig. 1 Design variable

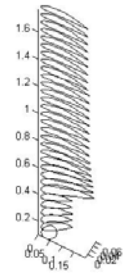

Fig. 2 specific design solution

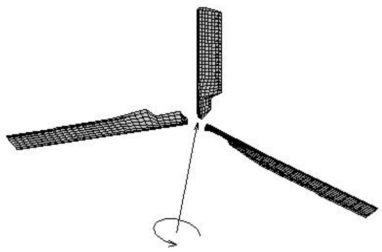

Fig. 3 Resulting wind turbine

3. Objective Function Assessment

The analysis of wind turbine aerodynamics is executed by using the blade element momentum theory (BEM) taken from reference [12]. The technique, even if remaining in suspect and controversy, usually gives acceptable calculation results in many applied design cases. The algorithm is appropriate for an optimization process because it is easy to use and, most essentially, requirements lower calculation time. The concept of BEM is shown in Fig. 4 where the blades are divided in to a number of elements. Given that θ is an element pitch angle, α is an element local angle of attack and φ is an element flow angle, the forces acting at a specific element can be calculated using the 2-dimensional aerodynamic theory as

$$\Delta T = \Delta L\cos\varphi - \Delta D\sin\varphi \qquad (3)$$

$$\frac{\Delta Q}{r} = \Delta D\cos\varphi + \Delta L\sin\varphi$$

where the force components are:

L = lift
D = drag
T = thrust
Q = torque.

When considering the induced flow impacts and taking hub and tip losses into account, the axial and tangential induction factors (expressed as a and a' successively) as well as hub and tip losses (F_{hub} and F_{tip}) are integrated into the aerodynamic model, after some manipulation, leading to the relations

$$dT = 4\pi r\rho U(1-a)aFdr$$

$$dQ = 4\pi r\rho U\Omega(1-a)a'Fdr \qquad (4)$$

where F is the product of hub and tip loss factors. The calculation process is carried out to find the thrust and torque on the elements.

The difficulty in this calculation method is the definition of the induction factors a and a'. In this paper, the computational steps presented in [12] (with slight improvement) are used i.e.

1. Starting with the initial guesses of a and a
2. Compute φ from $U_\infty(1-a)$ and $\alpha = \theta - \varphi$
3. Compute
4. Compute $F = F_{tip}, F_{hub}$ where

$$F_{tip} = \frac{2}{\pi}\cos^{-1} e^{\frac{-B(R-r)}{2r\sin\phi}}$$ and

$$F_{hub} = \frac{2}{\pi}\cos^{-1} e^{\frac{-B(r-R_{hub})}{2r\sin\phi}}$$

5. Find a_{new} and a'_{new}. If $C_T > 0.96F$ where

$$a_{new} = \frac{18F - 20 - 3\sqrt{C_T(50-36F) + 12F(3F-4)}}{36F-50}$$

otherwise

$$a_{new} = \left[1 + \frac{4F\sin^2\phi}{\sigma'(C_1(\alpha)\cos\phi + C_d(\alpha)\sin\phi)}\right]^{-1}$$

and

$$a'_{new} = \left[-1 + \frac{4F\sin\phi\cos\phi}{\sigma'(C_1(\alpha)\sin\phi + C_d(\alpha)\cos\phi)}\right]^{-1}$$

6. If a_{new} and a'_{new} converge, stop. Otherwise, set $a = a_{new}$ and $a' = a'_{new}$ and go to step 2.

The details of all parameters assumed in the computational steps are given in reference [13]. Having Received the induction and loss factors, the sum thrust, torque and therefore power at a given wind speed can be success. The gluey effect on the flow over 2D airfoil sections is taken into the analysis. Lift and drag coefficients are provided by using XFOIL at the pre-process give in conference [13]

The annual energy production can be computed using the formula

$$AEP = \int_{u_{\min}}^{u_{\max}} w(u)Power(u)du \qquad (5)$$

where

u = wind speed

$Power(u)$ = the power a wind turbine can produce at a wind speed u in [14]

$w(u)$ = Weibull distribution which can be expressed as

$$w(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{(k-1)} e^{-\left(\frac{u}{c}\right)^k} \qquad (6)$$

In this work, k is set to be 2 and c is set to be 6, which is quite tall for Thailand wind energy. The flowchart for function assessment and rotor aerodynamic required in the pre-process to give 2D lift and drag coefficients at all feasible values of the blade angles of attack and airfoil thickness. The plots of lift and drag coefficients against the angles of attack of the all kinds of NACA44XX airfoils used in this paper are given in Fig. 6 and analysis is exponential in Fig. 5. MATLAB is used as the main performer. The use of XFOIL is 7. The BEM analysis and the *AEP* and *COE* computation along with the optimization method are coded using MATLAB technical calculating language.

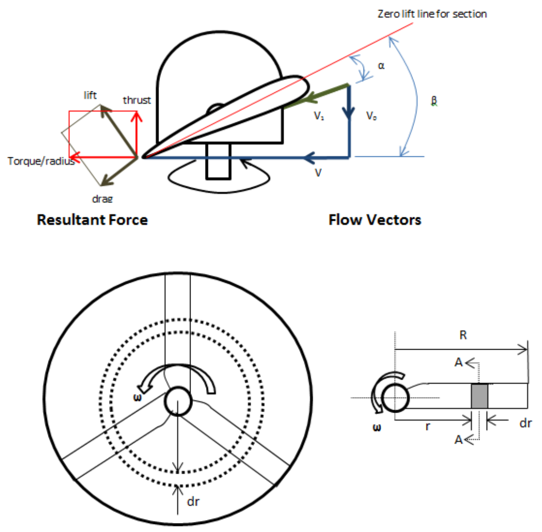

Fig. 4 BEM illustration [15]

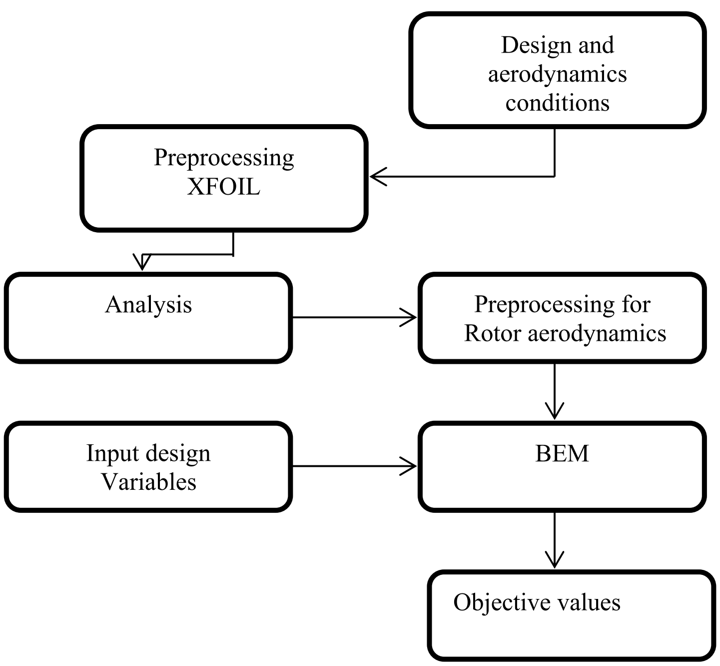

Fig. 5 Flowchart for function evaluation

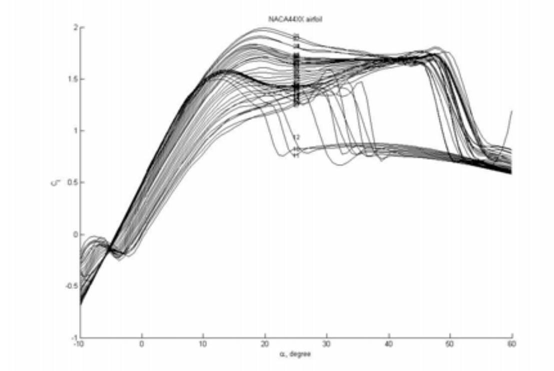

Fig. 6 C_l with angle of attack of NACA44XX

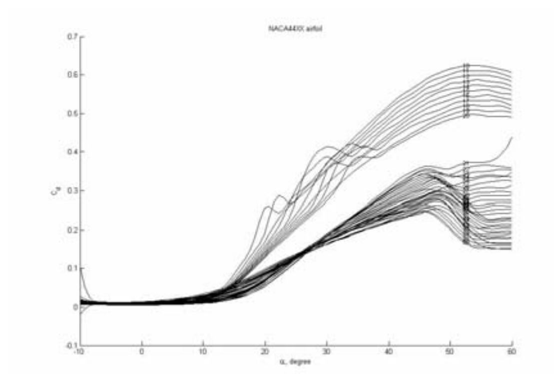

Fig. 7 C_d with angle of attack of NACA44XX

4. Numerical Experiment

The proposed many-objective design problem will be solved by several MOEAs including:

- Multiobjective Population-Base Incremental Learning (PBIL) [16]
- Differential Evolution for Multiobjective Optimization (MODE) [17]
- Multiobjective Harmony Search (RMOHS) [18]
- Non-Dominated Sorting Genetic Algorithm II (NSGA-II) [19]
- Multiobjective Particle Swarm Optimization (MORPSO) [20]
- Hybrid real code population based incremental learning and differential evolution algorithm (RPBILDE) [21]
- Unrestricted Population Size Evolutionary Multiobjective Optimization Algorithm (UPS-EMOA) [22]

Each method is run to solve the problem five times. The population size is set to be 200 while the number of iterations is 250. The hypervolume indicator will be used to measure the optimizers' performance.

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The hypervolume is the volume (for 3D) or area (for 2D) covered by non-dominated solutions and measured with respect to a defined reference point (as shown in Fig.8), which can be calculated as follow,

$$HV = \sum_{i=1}^{n} Vi \qquad (7)$$

where

HV = Hypervolume

V_i = Volume or area of a hypercube, that is created by the ith non – dominated solution and reference point [23].

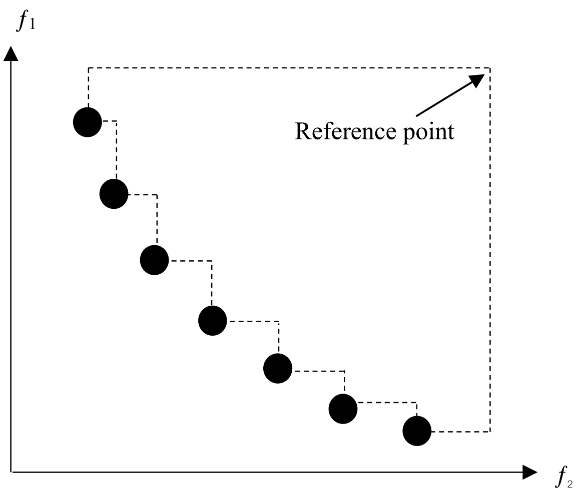

Fig. 8 Area to calculate HV [25]

5. Design Results

Having performed all the optimizers for solving the problem 5 times, the results as the values of the hypervolumes are given in Table 1. Based on the hypervolume indicator, the higher value the better algorithm. Thus, MOPBIL is superior to the other while the second best is RPBIL-DE. The best Pareto front for each algorithm is shown in Fig. 10 and the best Pareto front obtained from this study is illustrated in Fig. 11. Some optimal solutions are selected to display in Fig. 12. It is seen that we can have various blade shapes within one optimization run.

Table. 1 Hypervolume values

	Hypervolume values					
Algorithm	Run 1	Run 2	Run 3	Run 4	Run 5	Average
MODE	27.23	26.45	27.27	27.40	28.19	27.31
MOHS	16.28	16.42	15.87	15.99	16.94	16.30
RPBIL-DE	28.59	29.01	28.72	28.69	29.02	28.81
NSGA-II	27.48	28.00	28.08	28.31	28.51	28.08
MOPSO	17.67	16.84	16.62	16.52	18.77	17.28
MOPBIL	**29.92**	**30.10**	**29.54**	**29.75**	**29.61**	**29.78**
UPSEMOA	28.63	27.84	27.35	29.49	28.84	28.43

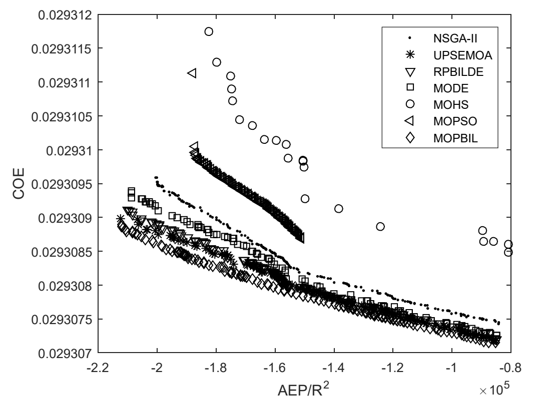

Fig. 10 Best Pareto front obtained from each algorithm

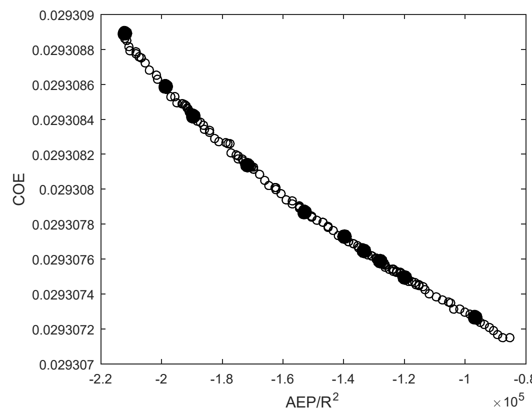

Fig. 11 Pareto fronts of best run of MOPBIL

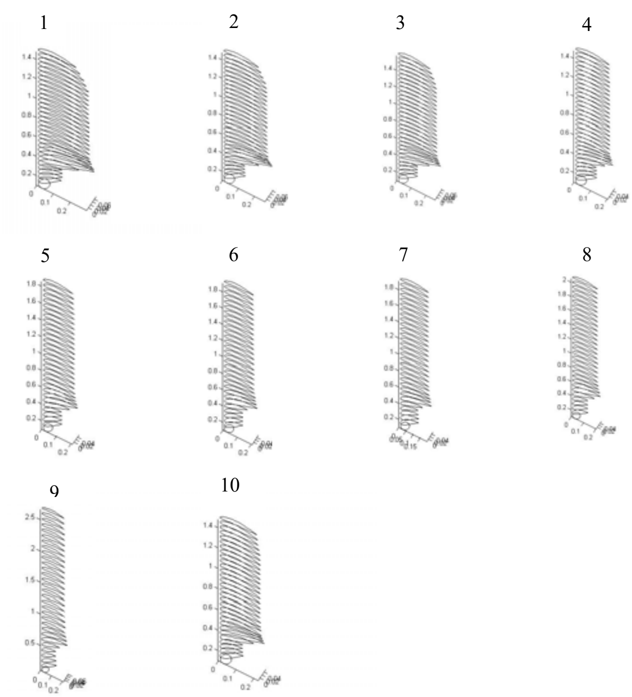

Fig. 12 some of blade geometries as the black dots in Fig.11

6. Conclusions Discussion and Future Work

Comparative performance of the various MOMHs for multiobjective optimization design of a wind turbine blade is successfully conducted in this work. The design is posed to find the blade geometry which maximize annual energy production and minimize energy cost. The hypervolume indicator is used to verify the search performance of the MOMHs. It was found that, the MOPBIL optimizer is one of the best methods for providing population diversity in multiobjective design. The decision making can be made so that the selected blade can be designed in the next step.

7. Acknowledgement

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