WIND FARM LAYOUT OPTIMIZATION USING COMBINED AREA DIMENSIONS AND DEFINITE POINT SELECTION TECHNIQUES

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To My beloved parents, and my daughters Hania and Tayyiba for their enduring love,
sacrifice, patience, encouragement and best wishes.

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ABSTRACT

The current wind turbines are the biggest rotating machines on earth, operating in the lowest part of the earth boundary layer. The layout scheme of wind farms is a challenging job to researchers having many design objectives and constraints due to the multiple wake phenomenon. The far wake effect is more prominent in wind farm layout design problems than the near wake effect. At present, wind energy industry is facing major design constraints in boosting power output. Most of the existing approaches focused only on the positioning of the wind turbines within the wind farms. They did not consider the effect of the shape of wind farm area on power output. This research proposes a novel method to find the optimized dimensions of the wind farm shape where maximum area could face the free stream velocity. This is achieved by developing an area dimension method which rotates the wind farms up to 180 degree. Afterward, a novel method called Definite Point Selection (DPS) is developed to place the turbines in order to operate at their maximum efficiency, while providing the obligatory space between adjacent turbines for operation safety. The positions within the wind farm facing zero wake effect can be identified by using DPS method. It is observed that the combined area dimension and DPS techniques are more effective than the previous approaches. Jensen's wake model is used to calculate the wake effects among wind turbines as existing literatures illustrate that the Jensen's far wake model is a good choice acceptably for the solution of layout problem. A wind farm of 2 km x 2 km area is divided into 10 x 10 cells for case study. Three different wind scenarios i.e. constant wind speed with uniform direction (Case 1), uniform wind speed with variable direction for equal probability of occurrence (Case 2) and variable wind speed with variable direction for unequal probability of occurrence (Case 3) are considered for the application of proposed methods. The proposed layouts are simulated to place different number of wind turbines in all wind scenarios. The optimized layout operates with efficiency of 99.15%, 96.9% and 93.9% for Case 1, Case 2 and Case 3 respectively. Results show that power output of the wind farm by using the same area in different dimension has increased even with identical number of wind turbines. The proposed method is useful for onshore as well as offshore wind farms.

ABSTRAK

Turbin angin semasa adalah mesin berputar terbesar di dunia, yang beroperasi di kawasan paling rendah di lapisan sempadan bumi. Skim susun atur ladang angin adalah satu pekerjaan yang mencabar untuk para penyelidik yang mempunyai objektif reka bentuk banyak dan kekangan akibat fenomena berbilang keracak. Kesan keracak yang jauh ini adalah lebih menonjol dalam ladang angin masalah reka bentuk susun atur daripada kesan keracak yang dekat. Pada masa ini, industri tenaga angin sedang menghadapi kekangan reka bentuk utama dalam meningkatkan kuasa keluaran. Kebanyakan pendekatan yang sedia ada hanya memberi tumpuan kepada usaha membangunkan turbin angin dalam ladang angin. Mereka tidak mengambil kira kesan bentuk kawasan ladang angin pada kuasa keluaran. Penyelidikan ini mencadangkan satu kaedah baru untuk mencari dimensi optimum bentuk ladang angin di mana kawasan maksimum boleh menghadapi halaju arus bebas. Ini dicapai dengan membangunkan satu kaedah dimensi kawasan yang berputar ladang-ladang angin sehingga 180 darjah. Selepas itu, satu kaedah baru dipanggil Pemilihan Titik Tentu (DPS) dibangunkan untuk meletakkan turbin untuk beroperasi pada kecekapan maksimum, manakala menyediakan ruang yang wajib antara turbin bersebelahan untuk keselamatan operasi. Kedudukam dalam ladang angin menghadapi kesan keracak sifar boleh dikenal pasti dengan menggunakan kaedah DPS. Adalah diperhatikan bahawa kawasan dimensi gabungan dan teknik DPS adalah lebih berkesan daripada pendekatan yang sebelumnya. Model keracak Jensen digunakan untuk mengira kesan keracak antara turbin angin sebagai literatur menggambarkan bahawa model keracak jauh Jensen adalah pilihan yang baik boleh diterima bagi penyelesaian masalah susun atur. Sebuah ladang angin di kawasan 2 km x 2 km dibahagikan kepada 10 x 10 sel-sel untuk kajian kes. Tiga senario angin yang berbeza iaitu kelajuan angin yang berterusan dengan hala tuju seragam (Kes 1), kelajuan angin seragam dengan arah ubah untuk kebarangkalian kejadian yang sama (Kes 2) dan kelajuan angin berubah-ubah dengan arah ubah untuk kebarangkalian kejadian yang tidak sama (Kes 3) dipertimbangkan untuk penggunaan kaedah dicadangkan. Susun atur yang dicadangkan adalah simulasi untuk meletakkan beberapa jenis turbin angin dalam semua senario angin. Susun atur dioptimumkan beroperasi dengan kecekapan 99.15%, 96.9% dan 93.9% untuk Kes 1, Kes 2 dan Kes 3 masing-masing. Hasil kajian menunjukkan bahawa kuasa keluaran ladang angin dengan menggunakan kawasan yang sama dalam dimensi yang berbeza telah meningkat walaupun jumlah nombor turbin angin adalah sama. Kaedah yang dicadangkan adalah berguna untuk daratan dan juga untuk ladang angin luar pesisir.

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LIST OF ABBREVIATIONS

ACO	-	Ant Colony Optimization
AMPL	-	A Mathematical Programming Language
BPSO	-	Particle Swarm Optimization
CF	-	Capacity Factor
DPS	-	Definite Point Selection
DE	-	Differential Evolution
ENDOW	-	Efficient Development of Offshore Wind farm
EWTS	-	European Wind Turbine Standards
ECN	-	Energy research Centre of the Netherlands
EV	-	Eddy Vescosity
FlaP	-	Farm Layout Program
GA	-	Genetic Algorithm
GGA	-	Global Greedy Algorithm
MIL	-	Mixed Integer linear
NPC	-	Net Present Cost
NSE	-	Navier Stokes Equations
PSO	-	Particle Swarm Optimization
PEVM	-	Parabolic Eddy Viscosity Model
PBL	-	Planetary Boundary Layer
QIO	-	Quadratic Interpolation Optimization
RANS	-	Reynolds-averaged Navier Stokes
SA	-	Simulated Annealing
SE	-	Stochastic Evolution
Sim E	-	Simulated Evolution
TMSI	-	Turbine-site Matching Index
UO	-	University of Oldenburg
UPMW	-	Universidad Polytecnica de Madrid Wakefarm
WF	-	Wind farm
WT	-	Wind turbine
WFLO	-	Wind farm layout optimization

WAsP - Wind Atlas Analysis and Application Program
WINDOPS - Wind Online Performance Surveillance

LIST OF SYMBOLS

α - Wake decay constant
γ - Divergence angle
ρ - Air density
θ - Diagonal angle of area
ϕ - Rotational angle
u_o - Free stream wind velocity
u_1 - Wake velocity at downward distance
D - Rotor diameter
z - Hub height
Z_0 - Surface roughness
C_T - Thrust coefficient
A_{shadow} - Wake shadow cone
P_t - Totall energy produced
P_{rated} - Rated power output
C_t - Cost per annum
C_i - Installation cost
C_{ij} - Cost of cables
C_p - Power coefficient
A - Rotor swept area
t - Life time of project
R_w - Wake radius
r_d - downstream radius of wind turbine
r_r - Wake radius just behind of wind turbine
a - Axial induction factor
s - Wind sector
v_{co} - Cut out wind velocity
v_{ci} - Cut in wind velocity
N_t - Total number of wind turbines
c - Weibull scale parameter
k - Weibull shape parameter

p_v	-	Probability density function of wind
U_o	-	Free stream flow passing through disc
p_b	-	Pressure drop at point b
p_c	-	Pressure drop at point c
A_c	-	swept area of rotor disc
A_w	-	surface crossection of stream tube after disc
A_o	-	surface crossection of stream tube before disc
m_s	-	mass flux on the sides of stream tube
T	-	Thrust force
B_t	-	Payback period of wind farm
P_i	-	Total power of ith wind turbine
ICC	-	Normalized initial capacity cost

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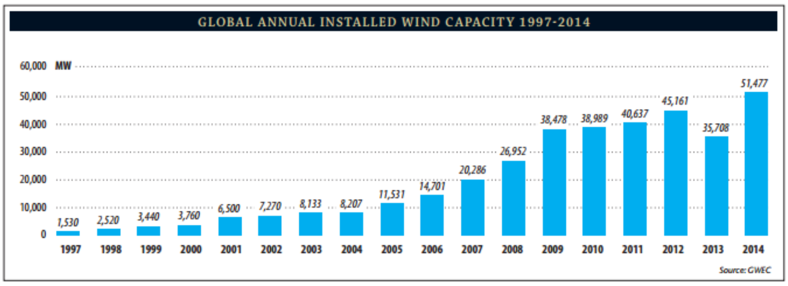
CHAPTER 1

INTRODUCTION

1.1 Background of study

Due to depletion of the fossil fuels, leading to acute scarcity of energy production from the conventional source, there is an upsurge in utilization of the non conventional energy resources like wind, biogas, solar etc [1]. One of the profligate developing sources of energy among sustainable and renewable is the wind energy source [2, 3]. Wind energy installation has experienced a tremendous increase in the past years. At the same time, related research activities have flourished in the past decade [4]. According to the Global Wind Energy Council 2015 Report [5], it has become the fastest growing energy source in the world with a steep increase in development from 2009 to date. Figure 1.1 shows the global installed wind capacity from 1997 to 2014. In 2004, the total world wide wind capacity was 14,781 MW but in 2014 the capacity became 51,477 MW [5].

Due to rapid development of wind turbine technology and increasing size of wind farm, 4 GW in construction now, 40 GW by 2020, and 150 GW by 2030 are planned to construct, meaning many large wind farms [6, 7]. Now wind power plays a significant role in the power production of developing countries as well as in developed countries [8–15]. This increasing demand for wind energy has given way to a shift from single turbine installation to multi megawatt installations consisting of a large number of clustered wind turbines called ’Wind Farms’. The main task of a wind farm is to get maximum possible power by using minimal area with less number of wind turbines [16, 17].



Source: GWEC

Figure 1.1: Global Annual Installed Capacity from 1996 to 2014 [5]

1.2 Problem statement

The problems can be formulated into three points.

- The wind farm area dimension is a crucial parameter that is not mentioned by wind energy community. In other words, except the relative positions of the wind turbines in the installation site, the boundaries of the installation area also affect the overall electricity production. In literature an unavailability of wind farm area dimension model has been observed.
- Careful planning of the geometrical arrangement of wind turbines in the wind farm can minimize the wake effects and increase the farm efficiency in terms of power production. However, the question, “where to install the turbines”, is not a trivial one. The wind flow inside the farm (evolution of wakes) depends on the wind speed and direction, as well as on the wind turbine specifications.
- Wind direction varies with time making it challenging to arrange turbines in a manner such that they can escape, wakes of upstream turbines for a majority of their operational time. At the same time, the determination of the wind farm output for a given layout is also not straight forward, since wake effects, wind variations and turbine responses need to be carefully considered. Advanced numerical methodologies are, therefore, necessary to optimize the arrangement of turbines in the wind farm, a process more commonly known as Wind Farm Layout Optimization (WFLO).

1.3 Research objectives

The objectives of this research are:

1. To model wind farm area dimension which ensures the maximum width of wind farm perpendicular to the mean wind direction and investigate its effect on the total output power of a wind farm.
2. To develop a new technique named ’Definite Point Selection (DPS)’ which identify the zero wake effect points within the wind farm. The DPS is based on an idea of installing the wind turbines in a form of group, while no one turbine laying in the wake of other wind turbine.
3. To explore the validation of the DPS algorithm applying it on different wind scenarios with varying number of wind turbines installation and verify by comparing with previous relative research work.

1.4 Significance of research

The present research offers a paradigm move in wind farm layout optimization problem. A momentous research work has been done (and is on-going) in the wind farm design literature. However, the most researches in this field focused only the placement of wind turbine within some given boundaries of the wind farm. In contrast, present research introduces the new concept of two level optimization. First, to identify and analyze the impact of land area and land shape on the optimization of wind farm layout, an area dimension method is proposed to get the optimal area dimension of wind farm. This can provide novel insights into the role of farm land shape in the wind farm layout design. Second to explore the zero wake effect points within the wind farm area for wind turbine placement. For this, a novel method called Definite Point Selection (DPS) is developed to place the turbines in order to operate their maxima, while provided the obligatory space between adjacent turbines for operation safety. The implementation of such novel concepts present significant modelling and design challenges that have been appropriately addressed in this research. In addition, this research takes three different type of wind scenarios, constant wind speed with constant direction, variable wind speed with variable wind direction for equal probability of occurrence and variable wind speed with wind direction for unequal probability of occurrences. In order to explore the effectiveness of the developed techniques ‘wind farm area dimension and DPS algorithm’, these techniques are applied on each wind scenario with varying number of wind turbines installation and are validated by comparing the outcomes with previous relative research work.

1.5 Scope of study

In order to achieve the objective of the research, the scope of research will be carried out: The total area of wind farm is fixed which is equal to $2\,km \times 2\,km$ and divided into cells of same size for wind turbine installation. This dimension is chosen based on the benchmark in the literature for comparative study purposes. This type of discrete siting is convenient for the realization of optimal method. As the wind turbine type matters, only horizontal axis are considered, and all having same rotor radius, hub height and power curve characteristics. It is also assumed that the turbine nacelle is fully controlled and can move the rotor towards the wind direction. The obligatory distance between wind turbines in the columns and rows is accepted to be around five rotor diameters (5D), the wind farm area is discretized by equal number of cells. The layout is simulated to work on different wind farm layouts for the maximum power output. It seems good to understand the impact of multiple shadowing of turbines on one another in the farm in different wind conditions. The proposed layout technique is equally valid for onshore as well as offshore wind farms.

1.6 Organization of thesis

This thesis is organized into five chapters, namely the introduction, literature review, research methodology, results and discussion, and conclusion and future recommendations.

Chapter 1 provides information on the background of study, problem statement, objectives and scope of research.

Chapter 2 analyzes the status of wake effect in wind farm, discusses its significance on the energy yield and structure of the problem will be defined. This chapter also reviews the optimization methods used in Wind Farm Layout Optimization (WFLO). The important finding from the previous work will be used as a guideline in this research.

Chapter 3 aims to focus the wind farm modelling which includes cost model, wake model, power and efficiency modelling. In this chapter, the novel methods of influence of wind farm area on power yield and Definite Point Selection (DPS) for wind turbine positioning are proposed. This chapter also presents the implementation of the proposed methodology in different wind scenario.

Chapter 4 discusses and compares the results of proposed research finding with the previous work for three wind scenarios; constant wind speed with uniform direction, uniform wind speed with variable direction and variable wind speed with variable direction.

Chapter 5 concludes the discussion of the work undertaken and highlights the contributions of this research. Several suggestions are recommended for possible directions of future work.

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