EXPERIMENTAL AND SIMULATION STUDY ON THE AERODYNAMIC PERFORMANCE OF A COUNTER ROTATING VERTICAL AXIS WIND TURBINE

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ABSTRACT

The Darrieus H-rotor has gained much interest in the last few decades as among the reliable devices for wind energy conversion techniques, for their relatively simple structure and aerodynamic performance. In the present work, development and aerodynamic performance predictions of a unique contra-rotating VAWT have been studied through experimental and computational approaches as it has yet to be applied to a VAWT. The main purpose of this study is to develop and investigate the practicality of employing the contra-rotating concept to a VAWT system while enhancing its conversion efficiency. The simulation study was performed using three-dimensional computational fluid dynamics (CFD) models based on K-omega shear stress transport (SST) model. The computational work covers a wider range of simulation processes compared to the experiment which includes a parametric study based on the axial distance between the two rotors and blade height. The performance evaluations of the current models were established in terms of key aerodynamic parameters such as torque and power. The systematic analysis of these quantities showed the usefulness of the contra-rotating technique on a VAWT system and the ability to extract additional more than threefold power over the entire operating wind speeds covered. The system has also improved the inherent difficulties of the Darrieus rotor to self-start. The results also demonstrated a significant increase in terms of conversion efficiency for both power and torque compared to a single-rotor system of a similar type. A maximum of 43% and 46% of power and torque coefficients were respectively possible with the current dual-rotor system. The simulation results indicate that smaller axial distance tends to enhance the performance output of the system relatively better compared to a larger distance. However, in terms of the blade height, longer blades generated the highest amount of power. It is anticipated that this current technique could revolutionize wind energy harvesting strategies and would find applications in a wide range of sites that are characterized by low and moderate wind regimes and particularly be useful in the urban environment where turbulence is high.

ABSTRAK

Darrieus H-rotor telah mendapat banyak minat dalam beberapa dekad yang lalu sebagai antara alat yang boleh dipercayai untuk teknik penukaran tenaga angin, kerana strukturnya yang sederhana dan prestasi aerodinamik. Kajian yang dijalankan ini melibatkan proses kerja ramalan perkembangan dan aerodinamik turbin angin paksi menegak kontra-berputar unik (VAWT) yang telah dikaji secara eksperimen dan kaedah komputasi. Tujuan utama kajian ini adalah untuk membangun dan menyiasat keberkesanan penggunaan konsep kontra-berputar kepada sistem VAWT sambil meningkatkan kecekapan penukarannya, kerana sehingga kini ia masih belum diaplikasikan untuk digunakan pada VAWT. Kajian secara komputasi dilakukan dengan menggunakan model dinamik bendalir tiga dimensi (CFD) berdasarkan Persamaan *K-omega shear stress transport (SST)*. Kerja komputasi merangkumi pelbagai proses simulasi yang lebih meluas berbanding eksperimen yang merangkumi kajian parametrik berdasarkan jarak paksi antara kedua-dua rotor serta ketinggian bilah. Penilaian prestasi bagi model kajian ini diperkukuhkan dari segi prestasi aerodinamik utama dalam parameter seperti tork dan kuasa. Analisis secara sistematik melalui pendekatan eksperimen dan komputasi telah menunjukkan keberkesanan teknik kontra-berputar pada sistem VAWT dan keupayaanya untuk mengekstrak tambahan lebih daripada tiga kali ganda kuasa seluruh kelajuan angin yang beroperasi. Sistem ini juga telah berupaya mengurangkan kesulitan yang dihadapi oleh pemutar Darrieus untuk mula berputar sendiri. Hasilnya juga menunjukkan peningkatan ketara dari segi kecekapan penukaran untuk kedua-dua kuasa dan tork berbanding dengan sistem satu-pemutar dari jenis yang sama. Maksimum 43% dan 46% pekali kuasa dan tork masing-masing mungkin dengan sistem dwi-rotor semasa. Keputusan simulasi komputer menunjukkan bahawa jarak paksi yang lebih kecil cenderung untuk meningkatkan output prestasi sistem yang lebih baik berbanding dengan jarak yang lebih besar. Walau bagaimanapun, jika dibandingkan dari segi ketinggian bilah, didapati bahawa bilah yang lebih panjang menjana kuasa yang lebih tinggi. Diharapkan teknik ini akan merevolusikan strategi penuaian tenaga angin dan akan

dapat diaplikasikan dalam pelbagai kawasan yang mempunyai tiupan angin perlahan dan sederhana, dan khususnya berguna di persekitaran bandar di mana terdapat intensiti pergolakan tinggi angin.

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LIST OF SYMBOLS AND ABBREVIATION

Acronyms

AEP	Annual energy production
CFD	Computational fluid dynamic
CRWT	Contra-rotating wind turbine
HAWT	Horizontal axis wind turbine
H-Rotor	VAWT with straight blades
KE	Kinetic energy
NACA	National Advisory Committee For Aeronautics
PVC	Polyvinyl chloride
RPM	Revolution per minute [N]
SRWT	Single rotor wind turbine
TSR	Tip-speed ratio [λ]
RANS	Reynolds-Averaged Navier-Stokes
SST	Shear stress transport
VAWT	Vertical axis wind turbine

Latin symbols

A	Projected area of rotor [m^2]
c	Blade chord [mm]
C_t	Torque coefficient
C_p	Power coefficient of the turbine
D	Rotor diameter [m]
F	Force [N]
g	Gravity [m/s^2]
H	Blade height [m]
k	Turbulence kinetic energy [$m^2\ s^{-2}$]

m	Mass [kg]
P	Pressure [N/m^2]
P_{ext}	Extractable power [W]
P_w	Actual power [W]
P_T	Theoretical wind power [W]
R	Rotor radius [m]
Re	Reynolds number based on chord length, c
r_{shaft}	Radius of the shaft [m]
r_{rope}	Radius of nylon string [m]
S	Spring balance reading [Kg/m^2]
T_m	Actual rotor torque [Nm]
T_T	Theoretical torque [Nm]
U	Tip speed [m/s]
V	Free stream velocity (Wind speed) [m/s]
W	Weight of the load [Kg/m^2]

Greek symbols

ε	Turbulence dissipation rate [m^2 s^{-3}]
σ	Turbine's solidity [-]
ρ	Fluid (air) density [kg/m3]
μ	Fluid viscosity [kg/(s.m)]
ν	Kinematic viscosity [m^2/s]
ω	Specific turbulence dissipation rate [s^{-1}]
λ	Tip-speed ratio [-]

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The generation of electricity has commonly been accomplished through the combustion of fossil fuels. However, fossil fuels power plants to some extent pollute the environment by producing contaminating emissions and the supplies of these energies have been predicted to finish in a few decades of time. Thus, the use of fossil fuels has to be limited and the use of renewable energies should be encouraged. Renewable energies such as the wind, solar, wave and thermal are abundant and will always be there as long as the world exists. The usage of these energies does not contribute significantly to the pollution problems or to the extinction of the Earth natural resources. As such, their implementation is highly favorable for the purpose of saving the world while serving human beings.

Wind power, in particular, has been proven to be a promising sustainable alternative energy future, due to its free availability and clean character. Hence, it has drawn more attention recently in response to numerous environmental and social challenges (Sutherland, Berg, Ashwill, 2012). Many studies including Delucchi & Jacobson (2011) suggest that in order to address the current significant problems such as climate change, greenhouse gas (GHG) emission and energy insecurity, there needs to be a major change to energy infrastructure, i.e. from fossil fuel based to renewables. Consequently, the recent years witnessed a rapid development of wind power all over the world. A total of 456 GW wind power capacity was achieved across the globe by mid of 2016 and expected to reach 666.1 GW by the end of 2019 (Tummala *et al.*, 2016; WWEA, 2016). Furthermore, a recent projection made by International Energy

Agency (IEA) also reported that renewable energy sources surpassed the coal sources in 2015 and became the largest source of electricity capacity in the world (IEA, 2016).

The fast growing population in developing countries and their lack of access to electricity supply particularly in rural or remote areas cause some of these nations face the challenge to generate more energy sources and to establish a new form of energy supply structure in an effort to meet current and future increasing electricity demands. Permanent electricity supply is considered as one of the major factors responsible for sustainable economic and social development of a nation (Mohammed, Mustafa, and Bashir, 2013). Thus, currently, a great deal of extensive research on wind energy is taking place almost all over the world for the exceptional benefits that wind energy could offer.

Currently, there are two main typical trends stand out towards wind energy generation mechanism. The first one is being established predominantly in developed countries where a trend towards offshore wind energy harvesting is taking place. In a response to the emerging needs towards the replacement of the conventional power plants to 100% renewable energy based sources in the coming few decades. While the other is largely found in developing countries where wind energy is yet to be fully regarded as a source of reliable energy. In the latter case, the trend is pertaining to a low-speed wind turbine (LSWT) due to the lower strength of the wind in most of those regions. Particularly in the equatorial countries, unlike the solar energy, the strength of the wind decreases near the equator.

Another reason behind adopting LSWT is owed to the fact that the current existing European wind turbine is not feasible in all regions across the globe, typically the equatorial zones such as Malaysia, Chad, etc. for its high designed cut-in speed of more than 5 m/s, in order to be adequate commercially (Wahab *et al.*, 2008) . The equatorial regions are characterized with an annual average wind speed of less than 5 m/s. Nevertheless, wind energy could successfully be harnessed in almost every corner of the world if a proper siting and an appropriate wind turbine design for such locality are made (Wahab, Ramli and Tong, 1997; Wahab, Ramli and Tong, 2008).

Although there exist numerous techniques to harvest wind energy, the current study seeks to adopt the counter rotating technology (Figure 1.1) which requires two sets of rotors that are eventually rotating in opposite direction to each other while harvesting the kinetic energy from the air. One of the advantages of this system is more energy could be generated compared to a single-rotor wind turbine (SRWT) (Appa 2002; Shen *et al.*, 2007; Habash *et al.*, 2011).

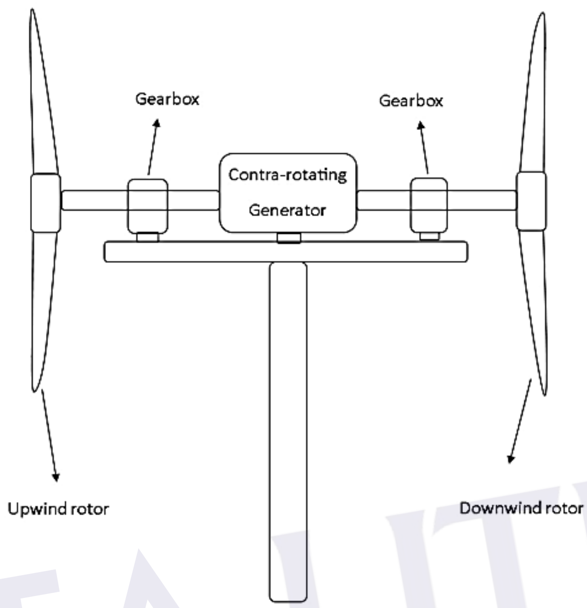

Figure 1.1: Typical counter-rotating HAWT

Prior to fabricating the prototype of the current counter rotating wind turbine, a computational model is designed first using a CAD modeler (SOLIDWORKS), and then simulation process is undertaken using ANSYS FLUENT in an effort to verify the feasibility and reliability of the model and to decide the appropriate geometrical features of the proposed prototype. Next, the prototype is built and tested so as to verify and evaluate its effectiveness and output performance. The performance analysis of the counter rotating wind turbine (CRWT) from the two distinct study methods (lab experiment and numerical simulation) is established, which includes the output of the model in terms of aerodynamic coefficients such as power coefficient and torque coefficient. At the end, a comparison between the simulated results and that from the lab tests is performed for validation purposes.

1.2 Research problem statement

Fossil fuel has been the source of energy and satisfying the need for electrical energy demand for centuries. However, the current increasing energy demand more than ever before and the problems associated with the fossil fuels such as finite amount, greenhouse gas (GHG) emissions, climate change, high cost, air pollution, land surface damage, etc. have triggered stakeholders to look for other sources of sustainable energy. Wind energy, in particular, is one of the fastest growing and widely used renewable sources today to produce electricity for its clean, freely available, renewable, highly efficient and economically viable characteristics.

Today, wind energy conversion technologies development is growing rapidly all over the world so as to realize all the advantages that wind energy could serve. However, the existing successful European wind turbine is not feasible for some regions or countries. That is due to the operating speed this wind turbine is designed for. The annual average wind speed in many countries including the equatorial region is in the range of 3-6 m/s which is far less than the minimum wind speed the European wind turbine operates.

Moreover, high oil price in some countries forces the majority of the population to rely upon wood for fuel particularly in rural areas, which is very polluting. This is partly because it is not economically viable for governments to provide electric supply grid in the rural areas where population distribution is scattered. As a result, an adequate wind turbine for such locations is needed in order to satisfy people’s demand for low-cost energy without polluting the environment. It is envisaged that by building a suitable wind turbine, wind energy could be used as a source of generating electricity in the region with relatively lower cost compared to the leading existing propeller-type horizontal axis wind turbine (HAWT).

Furthermore, the conventional single-rotor turbine can extract only about one-third of the available wind energy which is far behind the Betz limit (59.3%) and increase to 64% for dual-rotor system, according to the momentum theory by (Newman, 1983). These limits are independent of the design of the wind turbine and cannot be exceeded; provided that the rotor is non-shrouded (Schubel & Crossley, 2012). The remaining huge amount of energy escapes without being harnessed. Thus the counter-rotating and contra-rotating are typically used to extract the amount of wind stream at the wake that escaped from a SRWT.

Over the years, some of the efforts or strategies embraced by researchers to enhance the performance of a SRWT were achieved by improving blade design, generator performance, increasing rotor size and/or tower size to access greater wind speeds at higher altitudes or by incorporating gearbox and lubrication in the system rather than looking for new innovative techniques to increase the efficiency of the wind turbine. Despite studies for such parameters are already well established and been put in place. Not to mention the associated high engineering cost involved, as the rotor alone constitutes almost 80% of the total cost of a wind turbine, let alone the visual, acoustic, radar and environmental impacts.

Large rotors also create several problems such as blade surface stresses, vibratory loads, loading noise due to aerodynamical and gravitational loads and require wide space and strong wind to operate. Thus in the current study, a new concept is being adopted which is believed to increase the rotational speed by incorporating a contra-rotating system that does not implicate any of the aforementioned techniques while improving the performance of a wind energy converter.

While the application of the counter rotating technique is widely spread on HAWT, to the best of author's knowledge no known work has been found on vertical axis wind turbine (VAWT) thus far. This study is therefore set out to develop and evaluate the performance of a new design of a counter-rotating VAWT through wind tunnel testing and numerical simulations. Unlike the leading/existing counter rotating HAWT, the current design is an alternative type which is a VAWT.

A Wind turbine with vertical-axis rotation is believed to operate in a lower wind speed range compared to the HAWT. It can also accommodate wind from any direction while coping with the turbulence. Moreover, the novelty and innovation of the current design revolve around the fact that the mechanism of operation in the present contra-rotating design is, it spins in the vertical axis and does not require two shafts or a contra-rotating generator to achieve opposite rotation of the two rotors, but one of the shafts is attached to the generator itself so that both; the generator and the rotor spin together in a counterclockwise direction, while the other (main) rotor is attached to the shaft in order to rotate in a clockwise direction.

As the main rotor turns the shaft, the second rotor spins the generator so that the magnetic coil (stator winding) inside the generator receives more rotational speed relative to the shaft since both rotors rotate in two opposite directions. Maintaining opposite rotation of the two rotors is of paramount importance in order to avoid zero output due to the fact that the torque produced from the two rotors may cancel out each other if they operated in the same direction. The proposed concept is somewhat similar to the contra-rotating helicopter; however, in this case, the torque is generated solely by the wind alone and not from the generator/motor as in the helicopter.

1.3 Research objectives

The aim of this study is to propose and develop an effective, easy to fabricate and low-cost contra-rotating wind turbine with vertical axis for electricity generation. Thus, this thesis embarks on the following objectives while achieving the aim of this research:

(i) To study the practicality of employing the contra-rotating technique on a VAWT in terms of power and torque outputs,
(ii) To design and fabricate a VAWT with a contra-rotating concept,
(iii) To characterize the variations of wind on the performance of a contra-rotating VAWT in term of aerodynamic coefficients and self-start characteristics,
(iv) To determine the most appropriate axial distance between the two counter-rotating rotors as a means of enhancing wind energy conversion efficiency of the proposed system.

1.4 Scope of the research

The scopes of this research are set forth as follows:

(i) The counter rotating rotors' model is a vertical-axis type,
(ii) The airfoil profile is a symmetrical NACA four-digit i.e. NACA 0021 series airfoil,
(iii) Semicircle tubes are used to enable the self-start characteristics of the airfoil,
(iv) The diameter of the proposed prototype model is 80 cm for both counter-rotating rotors,
(v) The 3D geometrical models are developed using the CAD modeler; SOLIDWORKS,
(vi) The computational simulations are performed using ANSYS FLUENT v16.1,
(vii) The hybrid K-omega shear stress transport (SST) model is used as the turbulence viscosity model,

(viii) For validation: the simulated and experimental results are compared.

1.5 Research significance

This study significantly embarks in an effort to utilize wind energy for electricity generation through a novel design of a counter rotating wind turbine. As the majority of the existing studies on wind turbines are focused more on either, improving the blade parameters such as the solidity, chord length, thickness etc. or on the generator performance, rather than looking for new innovative techniques to enhance the performance of the wind turbine. Thus, a novel wind turbine design especially meant for improving the performance efficiency of VAWTs is established which is expected to contribute to the enhancement of the traditional harvesting techniques. This particular CRWT would be the first of its kind to come up with two sets of blades; one rotates clockwise and the other in a counter-clockwise direction while maintaining the shaft to rotate in only one direction.

Furthermore, this research also significantly contributes to the utilization of green technology energy resources. As wind turbines are believed to be in an excellent position to offer clean and efficient power generation which conventional heat engines find it difficult to compete. The proposed new technique also contributes to the provision of a new knowledge/approach of harvesting wind energy through the rotation of the generator itself alongside one of the rotors while maintaining the shaft to rotate in only one direction. The interesting part of the current concept is that the existing VAWT could also easily adapt this technique to enhance the conversion efficiency of their system since it does not require the provision of another generator.

Thus, it is anticipated that this current approach would revolutionize the wind energy harvesting strategies and could find application in a wide range of wind turbine sites that are characterized by relatively low and moderate wind speed regimes and particularly be useful in the urban environment where turbulence intensity is high. Thus, the research entitled "Experimental and simulation study on the aerodynamic performance of a counter rotating vertical axis wind turbine" is crucial.

1.6 Research structure outline

The proposed outline of this research is presented in this section. The overall structure of the thesis comprises six main chapters, including this introductory chapter. The detailed elements of this study have been documented in these six chapters as presented below:

(i) **Chapter 1: Introduction:** This chapter while giving a background of the research equally establishes the research problem and coin the research problem, aim and objectives. Furthermore, the scopes as well as the significance of the research are also contextualized in this chapter.

(ii) **Chapter 2: Literature Review:** This chapter provides a brief look on the previous studies pertaining to the classification of wind turbine technology in general while focusing more on the standing studies in VAWT. Subsequently, the chapter discusses the counter rotating concept and common airfoil designs and their selection criteria on VAWT applications and other topical issues such power curve. Each of these issues is discussed in detail before contextualizing it to suit this particular research. The chapter closes with an important method of wind turbine performance analysis which is the computational fluid dynamic (CFD) approach. Furthermore, justifications for any contextualization made are also established in the comprehensive summary provided in the final part of the chapter.

(iii) **Chapter 3: Research Methodology:** This chapter is set out to design the overall methodological process required for this research in the experimental approach. It basically presents the methods, approach, and strategy and/or research procedure, theory and calculation method. It then goes on to provide the appropriate experimental apparatus used while building the counter rotating prototype and the suitable equipment needed to evaluate its performance.

(iv) **Chapter 4: Computational Simulation:** Chapter 4 brings together the second approach adopted throughout the methodology of this work since there are two types of research methods undertaken in this research which are the experimental

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