THE DESIGN AND TESTING OF A WIND TURBINE FOR ELECTRICAL POWER GENERATION IN MALAYSIAN WIND CONDITIONS

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This fruit of my efforts,
I humbly dedicate to ……
my beloved family members (especially my grandmother);
who have truly shaped my life
and my wife;
who has influenced my life in a wonderful way.

God bless all of you

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ABSTRACT

Malaysia is situated in the equatorial zone and experiences low and unsteady wind speed. As a result, most of the existing wind turbines are not suitable for Malaysian application. High capital cost, low regional wind speed, incorrect matching between existing wind turbines and available wind speed as well as the level of technology are barriers to the use of wind energy conversion system. This project is a study on low cost, medium rotational speed, small scale stand-alone wind turbine for electrical power generation in low wind speed region. It involves designing, fabricating, testing and determining (blade and rotor configuration) a suitable wind turbine. A study on wind resources in Malaysia and the feasibility of its application showed that there is a possibility to utilise wind energy especially in the coastal areas and islands. The conceptual design of the wind turbine prototype was developed by considering the aspects of application requirements, configuration, functions and performance. The rotor blades were the most critical parts and they were analysed using aerodynamic theory. Wind turbine rotor models were fabricated and tested in a wind tunnel. The components and mechanisms were designed, built and analysed through computer-aided-design (CAD) modeling, theoretical calculation and computer software simulation. Various loads on the wind turbine structures were also examined. An indoor test rig was built for the testing of the wind turbine prototype, in order to obtain the power and torque coefficient at various tip speed ratio ($C_{Pmax} = 36.8\%$). The prototype was also field tested to verify its start-up speed and feasibility of power generation. It has demonstrated good strength, component integrity and yaw response in the field test. The findings suggested that the optimum performance of this innovative wind turbine (TSR = 2.7 - 4.0) falls in the operating range that matched with the available wind speed ($V_\infty = 2.2 - 7.0$ m/s) if the load matching is properly done. The work developed is sufficient for further investigation into the refinement of every sub-assembly of the system.

ABSTRAK

Malaysia terletak di zon khatulistiwa, dan mengalami kelajuan angin yang rendah dan tidak stabil. Oleh itu, kebanyakan kincir angin sedia adalah tidak sesuai untuk kegunaan di Malaysia. Kos kapital yang tinggi, halaju angin tempatan yang rendah, ketidak-sesuaian kincir angin sedia ada dan tahap teknologi merupakan halangan kepada penggunaan sistem penukaran tenaga angin. Kajian ke atas kincir angin kos rendah, berkelajuan putaran sederhana, berskala kecil dan beroperasi secara bersendirian telah dilaksanakan di dalam projek ini. Ia melibatkan rekabentuk, fabrikasi, pengujian dan penentuan (bilah dan konfigurasi rotor) kincir angin yang sesuai. Hasil kajian ke atas sumber angin di Malaysia dan kebolehlaksanaannya, tenaga angin didapati berpotensi untuk digunakan terutamanya di kawasan tepi pantai dan pulau. Rekabentuk konsep untuk prototaip kincir angin telah dibangunkan dengan mengambilkira aspek keperluan kegunaan, konfigurasi, cara berfungsi dan perilaku. Bilah rotor merupakan bahagian yang paling kritikal, dan telah dianalisa menggunakan teori aerodinamik. Model rotor kincir angin telah difabrikasi dan diuji dalam terowong angin. Komponen dan mekanisma telah direkabentuk, dibina dan dianalisa melalui permodelan CAD, pengiraan secara teori dan simulasi perisian komputer. Pelbagai beban ke atas struktur kincir telah dinilai. Sebuah kelengkapan pengujian dalam makmal telah dibina untuk menguji prototaip kincir angin bagi memperolehi pekali kuasa dan daya kilas pada pelbagai nisbah kelajuan hujung (C_{Pmax} = 36.8%). Prototaip ini juga diuji di lapangan bagi mengesahkan kelajuan permulaan dan kebolehlaksanaannya untuk penjanaan kuasa. Ia telah menunjukkan keupayaan yang baik, integriti komponen dan keupayaan untuk menukar arah rewangan dalam ujian lapangan. Hasil perolehan menunjukkan bahawa perilaku optimum kincir angin yang inovasi ini (TSR = 2.7 – 4.0) berada dalam lingkungan operasi yang berpadanan dengan kelajuan sumber angin yang ada (V_∞ = 2.2 – 7.0 m/s) jika imbangan beban dilakukan dengan betul. Hasil kerja ini juga memadai untuk penyelidikan lanjutan ke atas setiap bahagian sistem secara terperinci.

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A_{chord} - Blade area between b_i and b_o

A_{ring} - Annulus area between b_i and b_o

AOA - Blade section angle of attack

a - Axial induction factor

a' - Angular induction factor

B - Number of blade

b_i - Inner station span / R

b_o - Outer station span / R

Δb - Station span

c - Local blade chord

C_D - Blade section drag coefficient

C_F - Thrust coefficient

C_L - Blade section lift coefficient

C_P - Power coefficient

$C_{P'}$ - Section power coefficient

C_Q - Torque coefficient

$C_{q'}$ - Section torque coefficient

C_x or C_t - Blade section force coefficient (turbine plane)

C_y or C_n - Blade section force coefficient (axial)

D - Drag

G - Gear ratio

I_F - Excitation current (field current)

I_G - Output current of generator

i - Transmission ratio

L - Lift

$n_{cut\text{-}in}$ - Cut-in speed (rpm) of generator

n_G - RPM of generator shaft
n_r - RPM of wind turbine rotor shaft
P_{in} - Power input of generator
P_{out} - Power output of generator
P_{shaft} - Shaft power
Q_{shaft} - Torque at the shaft of the wind turbine rotor
Qstart - Starting torque of wind turbine rotor
R - Radius of the rotor / tip radius
r - Rotor radii
T - Blade tangential force
TSR - Tip speed ratio
U_G - Terminal voltage of the generator
u - Blade tangential speed
V - Wind speed
V_1 - Wind speed at upstream of rotor or initial velocity
V_2 - Wind speed through turbine rotor plane
V_3 - Wind speed at downstream of rotor or final velocity
V_{cut-in} - Cut-in wind speed
$V_{cut-out}$ - Cut-out wind speed
V_∞ - Free stream wind speed
w_∞ - Swirl velocity
α - Wind shear exponent
ϕ - Relative flow angle
η_{B-P} - Efficiency of belt-pulley
η_{Gr} - Efficiency of gear
η_G - Efficiency of the generator
$\eta_{G\,(E)}$ - Efficiency of the excitation of the generator
η_{Tr} - Efficiency of the transmission (friction loss)
λ - Tip speed ratio
ρ - Density of the air
Ω - Turbine angular velocity

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CHAPTER 1

THESIS INTRODUCTION

1.1 Introduction

This thesis describes the study of low cost, medium rotational speed (optimum tip speed ratio, $TSR_{opt} = 2.1 – 4.6$), small scale stand-alone wind turbine for electrical power generation in low wind speed regions ($V_{ave} < 2.50$ m/s) like Malaysia. As we know, wind energy has long been recognised as a potential source of free, clean and inexhaustible energy; and it could play an important role in contributing to small amount of energy requirements at the rural areas. The cost effectiveness of a wind energy conversion system (WECS) is a function of low initial costs, good energy production and high competing 'fuel' cost.

Malaysia is situated at equatorial zone and experiences low speed wind belt consisting of Southwest and Northeast Monsoons a year. Most of the areas in mainland experience low ($V_\infty < 4$m/s for more than 80% of total hours) and unsteady wind speeds. As a result, most of the existing wind generators ($V_{rated} = 9 - 15$ m/s) are not suitable for Malaysian applications since they are designed for high wind speeds which prevail in the USA and Europe. However, there is a potential for wind energy especially at the coastal areas and islands off the east coast of Peninsular Malaysia, if a suitable wind turbine design could be found. Sia (August 01, 1995) has reported that the wind speeds in islands of Perhentian, Redang and Tioman reach up to 5 or 6 m/s during monsoon months. So, wind energy could be an economically viable generation of electricity for isolated areas far away from national grid system, for the cost of laying electricity transmission cables and delivering fuel. Also, wind energy is particularly suitable for islands where pollution is a crucial issue. This technological innovation could safeguard the environment and curb overexploitation of country's rich natural resources. Oil spills are by far the most damaging of all coastal and river pollution. Major oil spills such as The December 19, 1976 Argo Merchant oil spill off Nantucket, Massachusetts (Figure 1.1), spillage of massive quantities of oil in the Persian Gulf as a results of the eight-year Iran-Iraq war and 1991 Persian Gulf War have led to disastrous ecological consequences (Erickson, 1992). Sea pollution due to oil sludge also occurred at coastal areas of Pengerang, Johor, Malaysia (Figure 1.2). It has caused an impact on the fishermen and was reported by China Press (June 26, 2005).

Figure 1.1 : The December 19, 1976 Argo Merchant oil spill off Nantucket, Massachusetts (Erickson, 1992)

(a) (b)

Figure 1.2 : The pollution issues at coastal areas of Pengerang, Johor, Malaysia (China Press, June 26, 2005).

Before significant benefits from the wind power could be realised, many technological and environmental problems had to be solved. Therefore, sufficient knowledge in WECS design, location of site, wind resources and load matching has to be gained. The use of small and medium size WECS rated at several hundreds of watts or a few kilowatts is gaining popularity for domestic and for small business and commercial use. According to Shepherd and Shepherd (1998), economic operation of small wind powered generators requires average wind speeds of 12 mph (5.36 m/s), being less stringent than for large system (requires higher cut-in speed, complicated drive train and control system). In Malaysia, Sia (August 01, 1995) reported that new technology can profitably harness winds as low as 3 m/s. According to the study on the potential of wind energy in Indonesia done by Notodisuryo (1990), wind velocity could reach more than 4 m/s in Indonesia. The speed is considered as sufficient for moving a small scale wind turbine which generates electricity ranging from 250 to 500 watts in villages located along the coast and islands. Moreover, the study of small wind turbine does not mean just for small amount of energy production. New Straits Times (April 20, 1999) has reported that twenty wind turbines in a 20 meters tall honeycomb-shaped configuration was used in Japan, and it was claimed that the cost of building and running this unique wind turbine generator is lower than that for a similar output large single wind generator (Figure 1.3).

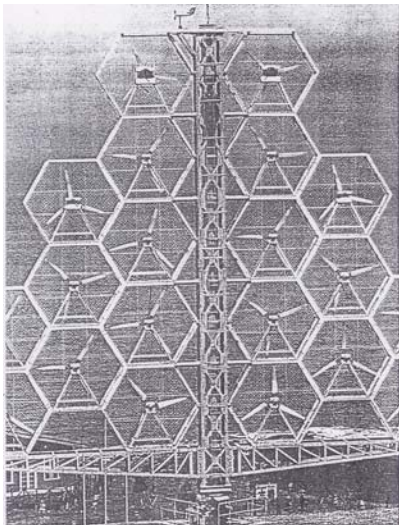

Figure 1.3 : Twenty wind turbines in a 20-meter-tall honeycomb-shaped configuration generate electricity in Kitahiyama, northern Japan (New Straits Times, April 20, 1999)

With only one 150 kW WECS installed at Pulau Layang-Layang, wind power technology is still considered to be in the initial stages of development in Malaysia. The research on wind energy at Universiti Teknologi Malaysia (UTM) has been started at Faculty of Mechanical Engineering (FKM), UTM since 1988. Most of the existing wind turbines were designed for the requirement of extreme wind speeds and involved high-tech design and fabrication. So, the design of the wind turbine for Malaysian wind conditions must be changed for better matching and optimised for higher output and/or longer operation hour at lower wind speeds. In this project, the design, fabrication, testing of a low cost wind turbine for electrical power generation (for lighting), which is suitable for Malaysian wind conditions has been carried out. The viability of the use of wind turbines to generate electricity is primarily dependent on its ability to operate under low wind speeds and the capital cost of the installation. So, the entire design concept aimed at good start-up behaviour with acceptable performance criteria, simplicity, reliability, automatic, relatively maintenance-free service and low cost in order to suit the requirements of the low-income groups in off the grid areas of developing countries such as Malaysia.

1.2 Problem Statement

Wind energy is one of the most available renewable energy in addition to solar and hydro energy. As reported by Xinhua in The Star (October 19, 1999), wind energy could provide 10% of the world's electricity requirement by 2020. The wind driven systems produce no pollutants and are environmentally safe. Synergy Power Corporation (1998) reported that eighty percent of the world's landmass has winds less than 5 m/s. Due to its geographical location, the overall potential of wind energy in Malaysia is not very promising. In general, maximum surface wind is 13 m/s and percentage of calm period (wind speeds < 0.3 m/s) is 20% to 50% depending on location (Abdul Majid Ismail, 2001). So, the main problem that hinders the progress of wind energy in Malaysia is the low wind speed. However, some locations (especially islands and coastal areas) could be suitable for wind power generation –'wind gate'. Some studies performed by UM, SIRIM, UPM and USM on the wind energy since 1983 indicate that some strategic places in the East Coast of Peninsular Malaysia have sufficient wind energy for utilisation (Chong and Mathews, 2001). But, a lot of issues need to be considered related to its remoteness in design stage (transportation, routine maintenance, weight and size of components, assembly and installation method, etc.).

Since most of wind energy development has been encouraged by the market stimulation in the developed world, primarily the Europe and USA, most of the wind turbines were designed for the requirement of high wind speeds ($V_\infty > 6$ m/s) which prevail in these regions. For low wind speeds regions like Malaysia, a different rotor design might be used to harness the wind power in a wide range of 2.0 m/s to 12 m/s wind speeds (to avoid the incorrect matching between the turbine design speed and the wind energy available). These wind turbines will also be designed for easy transportation (suitable for remote areas and islands), easy to erect and lower survival wind speeds, i.e. according to the wind speed in lower wind speed region (with a lower capital cost as a result). In order to generate electricity in low wind speeds (V_∞ less than 4 m/s is considered low for wind turbine generator application), the wind turbine must have high starting torque coefficient while still attaining sufficient running speeds.

It is also recognised that high cost (the total cost to purchase and install the complete wind energy system in order to provide desired operation of the system, including wind turbine, tower, power storage, control system, connections, installation cost, etc.) is the greatest barrier to the use of WECS. These costs must be reduced in order to make wind power cost-competitive with other power sources. A more robust design is also required to reduce the life cycle cost. However, it will further decline because of technical advance in wind machines, cost-cutting improvements in manufacturing techniques and environmental concerns. Moreover, wind power technology is straightforward (does not involve sophisticated processing of material, etc.). Because of that advantage, developing countries with their relatively cheap labour, might turn to building their own manufacturing capacity in the technology (Jayadec, 1995). The cost of wind energy is reduced if higher wind speeds available. According to Manwell *et al.* (2002), site with power density of 400 W/m^2 (V_∞= 8.5 m/s) is categorised as good site. For the capacity of 500 Watts and the average wind speed of 5 m/s, the electricity cost is around US$ 0.63 per kWh, and if the average wind speed increases to 6 m/s, the cost of electricity will be about US$ 0.29 per kWh (Notodisuryo, 1990).

The other important criterion that needs to be considered is the level of existing technology. The technology used must be able to be handled by local people (installation, operating, maintenance and repairing), and also the components / parts of the WECS could be obtained easily. Furthermore, the simple design also means that the technology could be transferred and wind turbine could be built in many countries utilising local material and manufacturing capabilities.

Another problem for the immediate economic development of wind energy is the competition from the very low-priced electricity usually available from national grid. So, at this moment wind energy is most suitable and viable to be applied at the islands where it is far away from main electricity grid and pollution is a critical issue.

1.3 Objective, Aim and Importance of Research

The objective of this research is to build a medium rotational speed wind turbine in order to generate small scale electrical power in Malaysian wind conditions. This involved designing, fabricating, testing and determining (blade and rotor configuration) a suitable wind turbine that is able to perform up to expectation at low wind speeds.

At this moment, there is still lack of awareness of the possibility of harnessing power from the wind, especially for our rural areas. This project is aimed to harness the wind energy available in Malaysia by producing a wind turbine that could be coupled with other existing WECS components (power transmission system, power generation system, power storage system, etc. that are available locally) for the Malaysian wind conditions. The power generated could be used in remote areas (far from main national grid and electricity distribution would be of prohibitive cost or would never be connected to the network). The main application of this WECS is to supply power for battery charging and lighting system and other applications such as powering communication network, lighthouse and beacon.

Taking into account budgetary constraints and inadequacy of technological infrastructure, a progressive development approach has been adopted for the development of small wind turbine for battery charging. The wind turbine construction should be more robust and relatively simple. The WECS designed is also aimed for easy transportation, installation, operation and management (highly skilled person and advanced technology are not required). The capital, operating and maintenance costs of the WECS designed must be affordable. Moreover, the technique, parts and components used must be easily obtained or fabricated locally. Thus, it is decided to use commercially available automobile alternator in the experimental prototype although low speed permanent magnet generator could be a better choice.

Besides, this research also provided a better understanding towards the knowledge, technical know-how and performance characteristics of wind turbine (coefficient of power, coefficient of torque, load matching, starting torque, cut-in speed, etc.) through wind tunnel tests, indoor testing and field tests conducted on wind turbine models and prototypes. The prototype built has provided a design concept to produce a wind turbine locally that is able to meet the requirements defined. The performance could be improved with further refinement and better matching could be done in future research (with particular application and site). So, the development of the small horizontal axis wind turbine is intended to meet the need for rural applications (with small amount of energy requirement), as well as to build up understanding and appreciation required for the development of larger and complex systems.

To sum up; an efficient (adapted to Malaysian wind conditions) and cost effective WECS is aimed for, with the design and production technique developed locally. The performance must be optimised and competitive with existing small wind turbines in market (Appendix C) in terms of total operating hour and energy gained if both wind turbines operate in Malaysian wind conditions. The long-term goal is the proliferation of wind energy applications in rural areas and the establishment of wind farm, capable of supplying local power to remote areas.

1.4 Research Scope and Methodology

This research has been divided into several parts / phases:

a) To perform literature review (parameter study, design approach, rotor blade aerodynamic design, component and structural design, test method and recent development).
b) To obtain and process the wind data recorded at UTM sites (Fakulti Kejuruteraan Awam, FKA and Balai Cerapan) and Senai Meteorological Station.
c) To identify, design and fabricate a low cost medium rotational speed wind turbine (model and prototype) and the supporting structure that is suitable for small scale electrical power generation (less than 1 kW output).
d) To design and construct the indoor testing facility, and to prepare the test parameter measuring equipment.
e) To test the wind turbine model and prototype by using wind tunnel and indoor testing facility, and evaluate the wind turbine rotor performance.
f) To conduct survey on suitable power generation system, power storage and lighting system, and perform load matching.
g) To conduct site testing of WECS (feasibility and functional test at real conditions).
h) Wind turbine performance data collection and analysis.

Phase I involved the feasibility study and development of conceptual design. It was initiated with the parameter study of existing wind turbines and generators in market (rotor diameter, cut-in speed, rated power, rotational speed, etc.) – Appendix C. The wind speed data was obtained from secondary resources, e.g. the average wind speed data furnished by Malaysian Meteorological Departments for weather stations in Malaysia (e.g. Senai wind speed data in 1995). Wind speed data from other publications was also reviewed to understand the wind variation in Malaysia. The evaluation of wind resources and calculation of wind energy at the selected sites

(Senai, Mersing and UTM Skudai) were also carried out. This information was used to study the feasibility of using wind turbine system in Malaysia. The machine / product requirements such as machine type and configuration, performance, application, estimated costs and other specifications were outlined. The design specification and conceptual design were developed for the machine functionality and its general arrangement. In this project, the energy demand was not specified since the wind turbine was designed for testing purpose only.

Phase II was the preliminary design stage and it involved building and testing experimental models. The rotor blades models and wind tunnel test rig were designed and fabricated. The wind tunnel test on the 1: 5 scale-down models has been conducted at the wind tunnel in Termo Lab., FKM, UTM. The results from wind tunnel tests are useful to compare the performance of various rotor blades combination, and they could be used to select optimal solution. But, the results were not encouraging due to scale-down factors (Reynold number and bearing friction). After the tests, wind turbine type, preliminary system and sizing were established. After performing load matching, a wind turbine rotor with 3 m diameter was designed to drive an automobile generator through belt-pulley RPM increaser (initial intention was a low speed permanent magnet generator (PMG) driven through gear box or a direct drive PMG). A survey on simple battery storage and lighting was carried out in order to obtain suitable one for testing purpose. After the WECS design was conceptualized, the detail design of every component could be performed.

In phase III which is the detailed machine / product design stage, the detail of functional components and mechanism were created and analysed through CAD, drawing, calculation and computer software simulation. Some of the critical components of the wind turbine were designed and analysed based on aerodynamics and structural analysis. The selection procedure of airfoil section and rotor blade design was performed, based on the information gained from literature review. In aerodynamic design; airflow, airfoil selection, blade twist, torque and power coefficient were considered. An existing Delta-wing rotor with maximum torque coefficient at zero tip speed ratio was chosen as starter rotor to aid start-up performance. Suitable airfoil for main rotor blade was reviewed (HK8556) for predicted Reynold number. The simplified airfoil profile (AE airfoil) designed was analysed using GAMBIT and FLUENT software. The aerodynamic design and performance analysis of the innovative rotor blade have been carried out. The tangential force and rotor drag prediction was based on the blade element momentum theory (BEM) / strip theory. In order to have a compromise between good starting behaviour and reasonable rotational speed, 6-bladed wind rotor with the combination of existing Delta blades and innovative blades (AE blades) was obtained. The overall system efficiency was then estimated and the rotor size (diameter) was calculated. Since the aerodynamics and structural analysis are related, it is more practical to develop them together. The various loads on the rotor and shaft were examined, and each member was designed to withstand the applied loads. COSMOS/Works software has been used to aid the structural analysis. The system design was also analysed for possible component interface, fabrication and operation problems. The various efficiencies and performance characteristics (coefficient of power and torque) were evaluated, and then the system efficiency was re-estimated. This was a challenging and time-consuming task because of the many complex interrelationships involved.

Phase IV involved the fabrication, installation and indoor testing of wind turbine prototype. A full-scale prototype (3 m diameter) was fabricated for indoor testing and field testing. Specialised tools and fixtures were also required to assist the installation, monitoring, maintenance and testing purposes. A low cost indoor test rig has been built to generate “wind” for indoor testing of wind turbine prototype. The purpose of the design and fabrication of this testing facility is to obtain some important aerodynamic characteristics of the wind turbine rotors designed, i.e. power coefficient, C_P and torque coefficient, C_Q at different tip speed ratio (TSR), before field testing. The starting behaviour of the wind turbine rotor could also be studied, by matching the wind turbine performance obtained with the applied load (generator’s characteristics curve). This test rig could provide a suitable testing facility (low cost and easy-to-assemble) for low wind speed wind turbine prototype. This indoor testing facility could eliminate some problems that would be faced in actual field tests. The results of the measurements have produced the necessary data for the evaluation of the rotor blade performance. Comparison of the performance results from this test method with design conditions (using BEM), indicates that this indoor testing facility can be used for wind rotor design verification and optimisation. For load matching purpose, the output power (shaft power) at various TSR and wind speed could be matched with the generator load curve.

In phase V, field test was carried out and it involved a lot of preparation works (building of tower and foundation, tower erection, maintenance platform, instrument set up, etc.). A suitable site for conducting field test was selected at Balai Cerapan, UTM Skudai based on the criteria set. The wind turbine design was tweaked and enhanced for better strength before field testing. The wind speed measurement equipment was set up for data recording. The wind speed data would be compared with the data from Senai Meteorological Station. The supporting structure / tilted tower was designed and fabricated for wind turbine installation. This prototype has been tested at Balai Cerapan UTM to study the feasibility of using wind power for electrical power generation. The measuring instruments (revolution counter, anemometer, slip ring and wiring for transmitting electrical signal from alternator) were mounted on wind turbine structure. The signals produced were transmitted to recorders / displays. The measured parameters were wind speed, number of revolution in certain period (RPM) and output power (battery charging ampere and voltage). The results obtained could be compared with theoretical prediction / design parameters. In field trial, the wind turbine was also monitored for its component strength and yaw response. In addition, the fabrication and maintenance costs of WECS have also been estimated.

Above approach was implemented in order to realise the localisation of wind turbine technology in Malaysia and the flow chart was given in Figure 1.4. General ideas and knowledge for completing a wind turbine have been outlined, with further refinement in every single stage could be done in future.

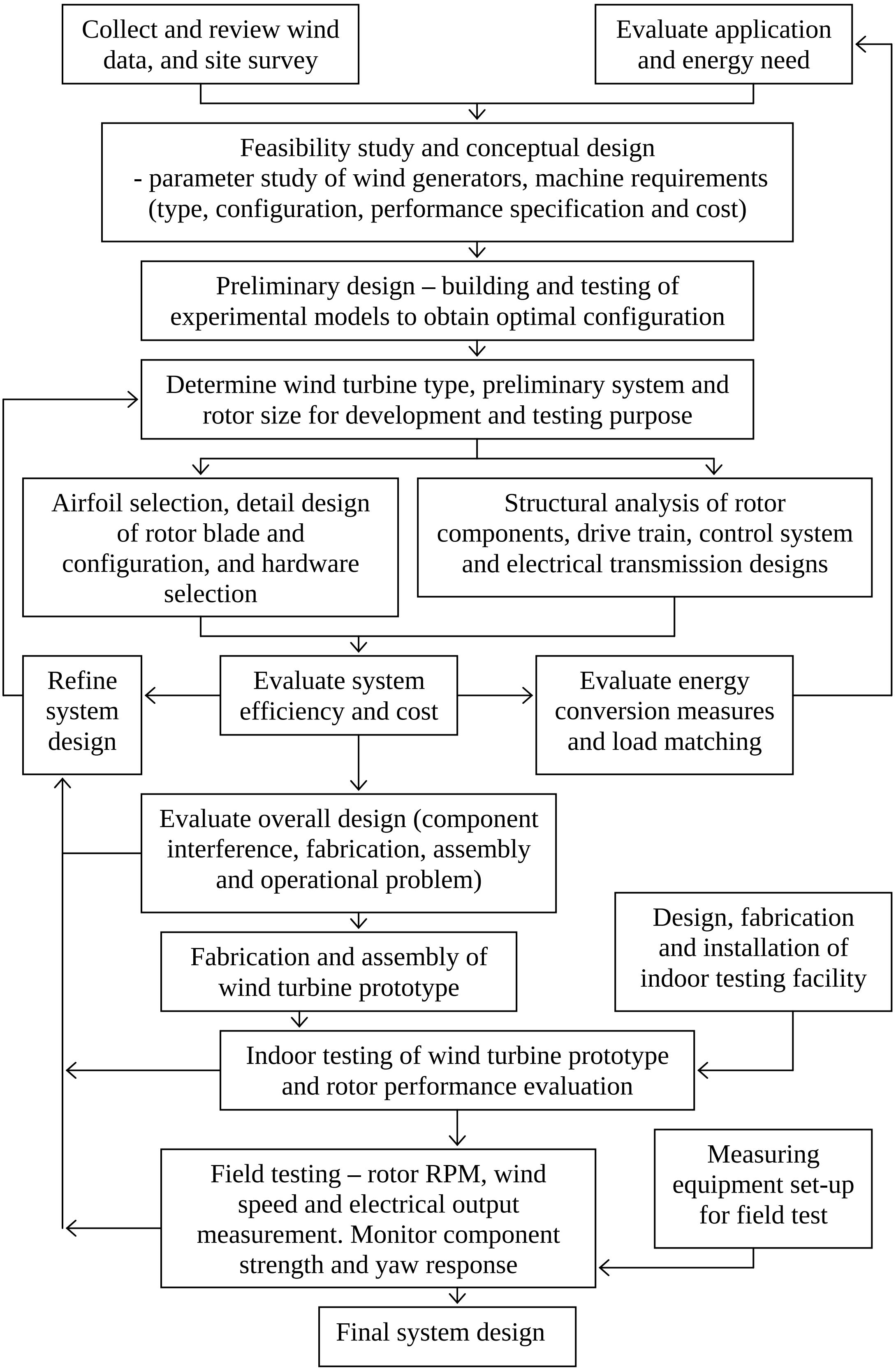

Figure 1.4 : Research methodology for wind turbine prototype design

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