



Faculty of Engineering

**Development of Axial-Flow Hydrokinetic Turbine Systems for Shallow
Tropical Rivers**

Tan Kheng Wee

**Doctor of Philosophy
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Development of Axial-Flow Hydrokinetic Turbine Systems for Shallow Tropical Rivers

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A thesis submitted

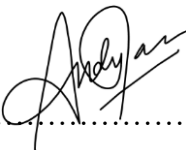
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(Renewable Energy System)

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



.....

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ABSTRACT

Currently, the majority population of the world without access to electricity are countries in the tropics. Although Malaysia was among the tropical country listed to achieve 100 % accessibility in 2015, the state of Sarawak still has about 5 % of its population that does not. Due to the uneconomical grid connection, the state government has implemented small-scale conventional Micro-Hydropower (MHP) and Solar Energy Systems (SES) because of their abundant resources. However, despite being the preferred choice, small-scale MHP is inapplicable in the area where the topography does not favour it. In the meantime, the off-grid rural communities rarely have the purchasing power to acquire expensive equipment manufactured in high-cost countries. Besides, few commercially available small-scale Hydrokinetic Turbines (HKT) were developed specifically for shallow rivers (less than 1 m), and their design might not be entirely suitable for tropical rivers. Subsequently, this research aimed to construct a low-cost axial-flow HKT acceptable for shallow rivers in the tropics and would produce 2 kWh of energy per day. Two prototypes are designed and built in this research. The first was to evaluate the concept of building an HKT solely with off-the-shelf materials while the second was to overcome the issues faced by the first. The second improved prototype, with a 0.585 m reprofiled fan rotor with swept-back blades as the turbine rotor, produced 92.29 W of power from a flow velocity of 1.26 m/s, and its estimated efficiency is 0.34. Therefore, it can generate more than 2 kWh per day and is considered sufficient for a typical rural household. Besides, the improved prototype only costs USD 750 and is a fraction of the cost of commercial HKT for shallow rivers. Nevertheless, the study also revealed the Smart Drive motor as a promising and versatile candidate to be used as a generator for small-scale HKT construction. It produces less noise and has lower cogging torque than the DC brushed motor used in the improved prototype. A basic guide is also

presented for small-scale HKT construction with the modified Smart Drive motor – with the 60 SP and 60P configuration – as an alternative generator.

Keywords: Affordable, hydrokinetic turbine, off-the-shelf materials, rural electrification, swept-back turbine rotor

Pembangunan Sistem Turbin Hidrokinetik Beraliran Paksi untuk Sungai Tropika yang Cetek

ABSTRAK

Pada masa kini, kebanyakan penduduk di dunia yang tidak mempunyai kebolehcapaian kepada tenaga elektrik adalah di kalangan negara-negara yang terletak di kawasan tropika. Walaupun Malaysia adalah di antara negara di kawasan tropika yang tersenarai untuk kebolehcapaian 100 % pada 2015, negeri Sarawak masih memiliki lebih kurang 5 % daripada penduduknya yang belum. Disebabkan oleh kos sambungan ke grid yang tidak ekonomi, kerajaan negeri telah melaksanakan sistem kuasa hidro mikro konvensional dan tenaga solar kerana memiliki sumber yang banyak. Walaupun sebagai pilihan utama, sistem kuasa hidro mikro tidak dapat diaplikasikan pada topografi yang tidak sesuai dengannya. Pada masa yang sama, masyarakat luar bandar yang di luar sambungan grid jarang memiliki kuasa membeli untuk mendapatkan peralatan mahal yang dihasilkan oleh negara-negara kaya. Tambahan pula, terdapat sangat sedikit bilangan turbin hidrokinetik yang dibangunkan khas untuk sungai yang cetek (kurang dari 1 m), dan reka bentuknya pula mungkin tidak sesuai untuk sungai di kawasan tropika. Seterusnya, kajian ini bertujuan untuk menghasilkan sebuah turbin hidrokinetik aliran paksi yang berkos rendah untuk sungai cetek di kawasan tropika serta dapat menjana tenaga 2 kWh setiap hari. Dua prototaip telah direka dan dibina di dalam kajian ini. Yang pertama bertujuan untuk penilaian pembinaan turbin hidrokinetik dengan hanya menggunakan bahan-bahan yang sedia ada di kedai manakala yang kedua adalah untuk mengatasi kelemahan yang didapati daripada yang pertama. Manakala untuk prototaip yang kedua, dengan penggunaan pemutar kipas bersaiz 0.585 m yang telah diprofil semula dan digunakan sebagai pemutar

turbin telah menghasilkan kuasa sebanyak 92.29 W dari arus sungai 1.26 m/s, dan memiliki kecekapan anggaran sebanyak 0.34. Ia mampu untuk menghasilkan tenaga elektrik lebih daripada 2 kWh setiap hari dan dianggap mencukupi untuk sebuah rumah biasa di luar bandar. Di samping itu, prototaip yang kedua hanya dibina dengan kos USD 750 dan jauh lebih rendah berbanding dengan kos turbin hidrokinetik komersil untuk sungai yang cetek. Namun begitu, kajian ini turut mendedahkan bahawa motor Smart Drive adalah merupakan calon yang berpotensi dan serba boleh untuk digunakan sebagai penjana untuk pembinaan turbin hidrokinetik berskala kecil. Ianya kurang hingar dan memiliki penuugalan kilas yang lebih rendah berbanding dengan motor DC berberus yang digunakan di dalam prototaip yang ditambah baik, dan satu panduan turut dibentangkan untuk pembinaan sebuah turbin hidrokinetik menggunakan motor Smart Drive yang diubah suai dengan konfigurasi 60SP dan 60P sebagai penjana.

Kata kunci: Bahan-bahan sedia ada, bekalan elektrik luar bandar, mampu milik, pemutar turbin disapu balik, turbin hidrokinetik

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LIST OF ABBREVIATIONS

AC	Alternating Current
Back-EMF	Counter-Electromotive Force
DC	Direct Current
DPG	Diesel-Powered Generator
ER-PMSM	External Rotor Permanent Magnet Synchronous Motor
HDPE	High-Density Polyethylene
HKT	Hydrokinetic Turbine
LEA	Local Electrical Authority
MHP	Micro-Hydropower
PMDCG	Permanent Magnet DC Generator
PMDCM	Permanent Magnet DC Motor
PMSM	Permanent Magnet Synchronous Motor
RES	Renewable Energy System
RPM	Revolutions per minute
SES	Solar Energy System
Solar PV	Solar Photovoltaic
TSR	Tip-Speed Ratio
UPVC	Unplasticised Polyvinyl Chloride

CHAPTER 1

INTRODUCTION

1.1 Study Background

According to the Our World in Data in 2016, only 87% of the world's population has access to electricity (Ritchie & Roser, 2020). The majority population without access are countries in central Africa and certain countries in Southeast Asia like Myanmar and Papua New Guinea. Malaysia was among the countries listed to achieve 100% accessibility in 2015 (The World Bank, 2022).

Malaysia is a federation comprising thirteen states and three federal territories. The state of Sarawak is the biggest, with a total land area of 124,450 km² – approximately 37 % of the total area of Malaysia – situated on the island of Borneo. It was reported about 48 % out of the 2.8 million population in Sarawak reside in rural areas (Yap et al., 2020) and live in 6,235 widely scattered villages (Shiun, 2016).

In 2017, according to Sarawak's Ministry of Utilities, the number of rural villages without access to electricity had been reduced to 1,623, involving 36,365 households, and are characterized into three categories under the State Rural Power Supply Program as shown in Figure 1.1. However, due to their small size of communities, scattered location, ruralness, and uneconomical grid connection, 5 % of Sarawak's population remains without access to 24-hour electricity from mains or solar power (Sarawak Energy, 2019). Therefore, due to these circumstances, the Local Electrical Authority (LEA) would turn to conventional Micro-Hydropower (MHP), Solar Energy Systems (SES) and even Diesel-Powered Generators (DPG) as a short-term solution to power up rural schools, clinics, administrative

offices or even small villages for several hours daily (Anyi et al., 2010; Fauzi Shahab, 2017; Saupi et al., 2018). Eventually, situations like this provide tremendous challenges to the state government as they involve huge costs to provide electricity to all the rural communities. The state government estimated RM 6.7 billion is needed to power up the entire Sarawak by 2025 (Toyat, 2018).

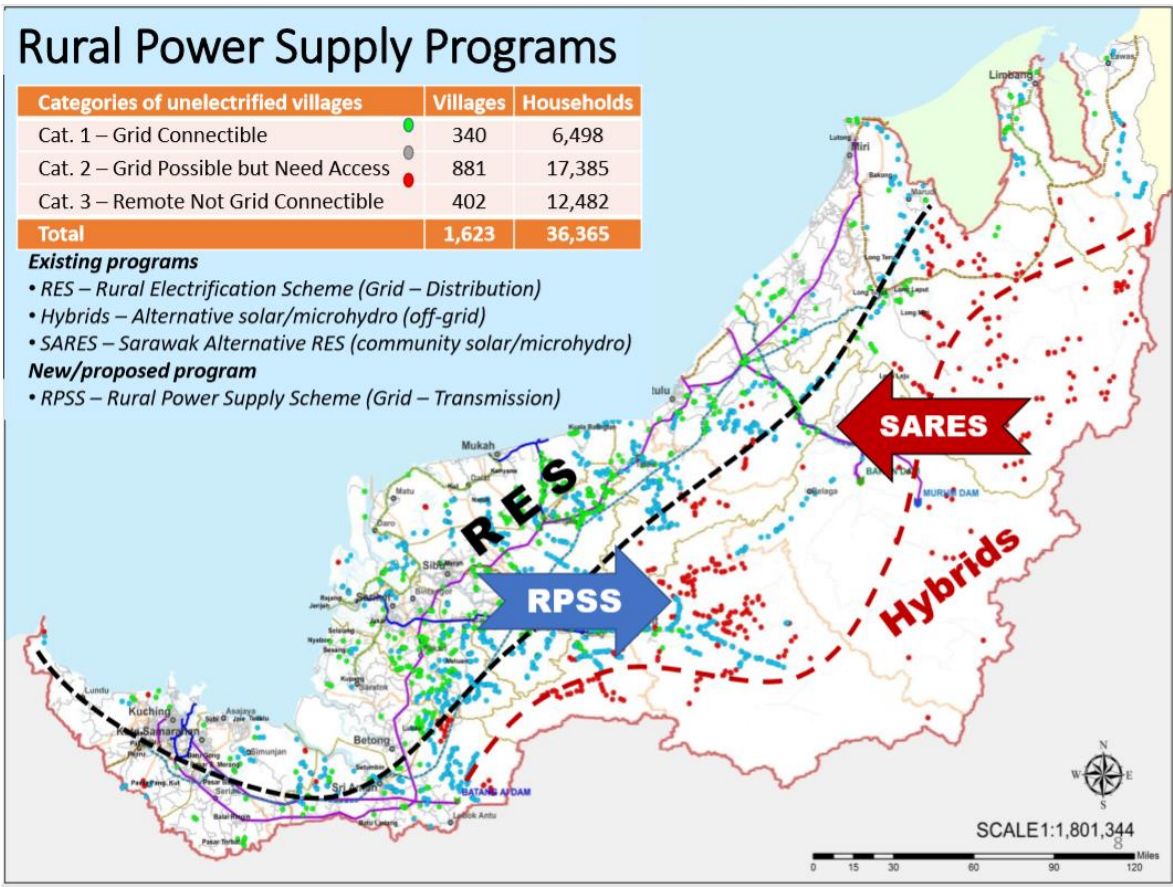


Figure 1.1: Categories of unelectrified villages (Fauzi Shahab, 2017).

Through Figure 1.1, the great concern would be category 3, which is considered remote and not grid connectable. From Figure 1.1, one can see that the majority of these villages (i.e., red dots) are scattered in the interior of Sarawak, particularly in the Rajang and Baram River basins, compared to Figure 1.2.

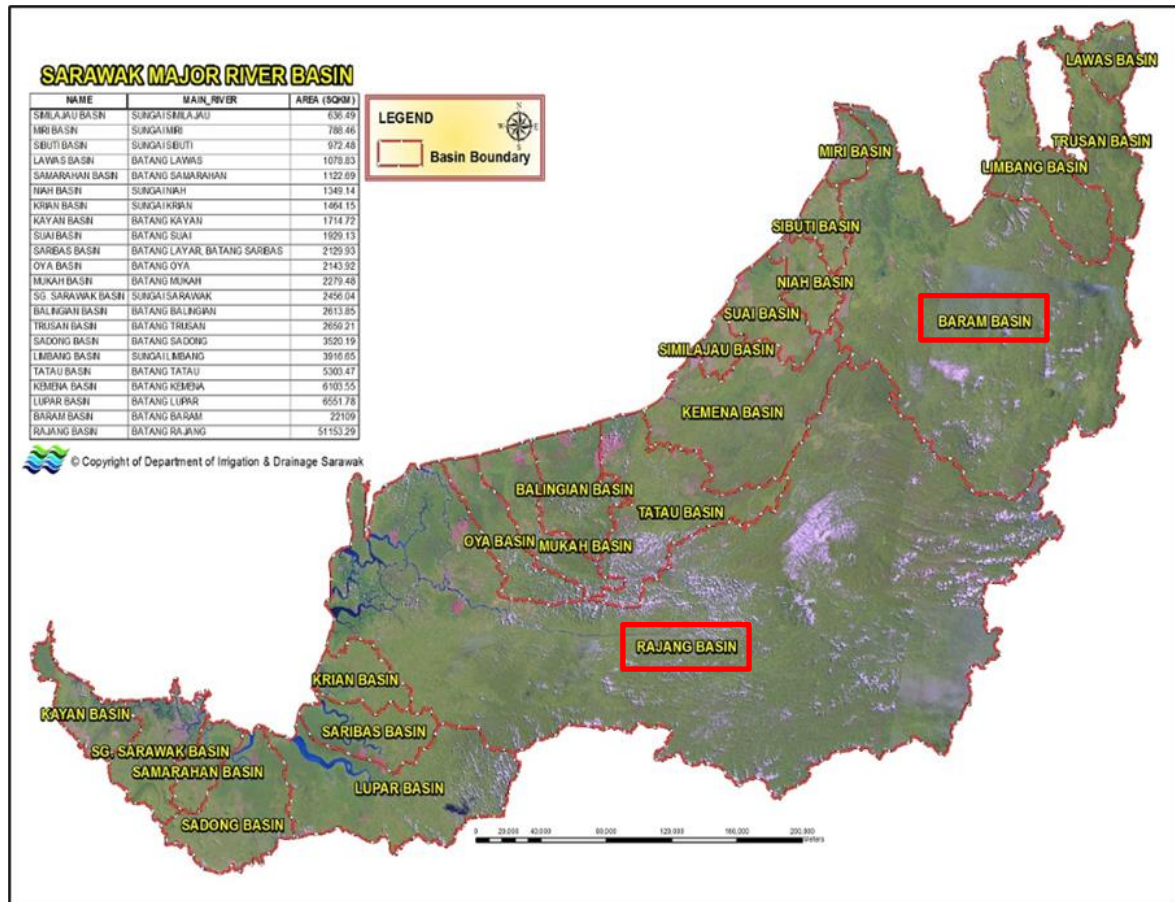


Figure 1.2: Sarawak 22 major river basins (DID of Sarawak, 2022a).

Sarawak receives an average annual rainfall of about 3850 mm, five times more than the world's average (Salleh et al., 2018). In addition, the hot and wet tropical climate has allowed a vast network of rivers to form and flow continuously throughout the year. The majority of the off-grid remote communities in Sarawak are located on the upper courses of rivers or tributaries because they rely on the river for water, food and transportation. Hence, MHPs have been considered the most suitable option for powering off-grid remote rural communities in Sarawak, where the topography is suitable (Anyi et al., 2010; Borhanazad et al., 2013; JOAS, 2015; Wan Zainal Abidin et al., 2009; Yeo et al., 2014).

By 2017, 103 villages had benefited from the MHP project implemented by the government and non-governmental organizations (Fauzi Shahab, 2017; Khengwee et al., 2017). The MHPs are known to be very reliable when properly maintained. Nevertheless, their design is very site-specific, requiring continuous flow from a water intake at a significant elevation above the turbine. When this is unavailable from the natural stream, a reservoir is needed, thus adding cost and significantly altering water, nutrient, and ecosystem dynamics and fluxes in river networks (Deemer et al., 2016). Furthermore, some recent studies also state that water reservoirs created by hydropower dams are significant producers of greenhouse gases (Deemer et al., 2016; Fearnside, 2016; Kate, 2017; Mooney, 2016).

Therefore, to overcome these circumstances, several researchers have suggested utilising Hydrokinetic Turbines (HKT) as an alternative for small-scale power generation in Sarawak due to their great potential (Aling et al., 2018; Anyi et al., 2010; Azrulhisham et al., 2018; Jamaluddin et al., 2018; Salleh et al., 2018; Saupi et al., 2018). However, until today, that suggestion has not materialised.

The only HKT project ever implemented is the Sustainable Hydrokinetic Renewable Energy (SHRE) by the Ministry of Works, Malaysia (a joint project with the Ministry of Energy, Green Technology and Water, Malaysia, and two other local universities) at Pelagus village in Kapit, Sarawak. The information is available on their Facebook page (Ministry of Works, 2018). The SHRE HKT prototype dimension is 15 m (width) x 45 m (length) in size and has eight cross-flow turbines. It has the potential to generate 40 - 60 kW of energy from an average flow velocity of 1.7 m/s. Unfortunately, until today, there was no information nor update available on the performance data of the HKT.

1.2 Problem Statement

From Figure 1.1, one can see that there are more than 12,000 households in Sarawak that are categorised as “remote and not grid connectible”. Compared with Figure 1.2, one can also see that most of these scattered off-grid villages are in the Rajang and Baram basins. This is because a vast portion of these two river basins receives the highest annual rainfall in Sarawak, between 4000 mm and 4800 mm (Sa’adi et al., 2019). This data agreed with the finding that the conventional MHP is the most suitable option for powering off-grid remote rural communities in this region. However, not all of these off-grid villages have a topography that favours the conventional MHP nearby to their villages, as highlighted by Anyi (2013). For example, the Long Busang village at the upper Balui River (i.e., a tributary of the Rajang River), where a suitable site for the MHP, is a few kilometres away.

On the other hand, the Balui River flowing next to the Long Busang village is relatively wide and fast-flowing but is less than a meter deep almost throughout the year. It usually contains sediment and a certain number of submerged debris such as dead leaves, grass, vines, etc. Larger and heavier debris such as tree branches or rotten tree trunks can be found floating down the river during flash floods. The Balui River is considered to have similar characteristics as the Balleh River (i.e., another tributary of the Rajang River) which have a flow velocity exceeding 1.5 m/s and offer a good opportunity for hydrokinetic power generation according to a study by Saupi et al. (2018).

The Long Busang village has more than 1200 people, mostly subsistence farmers and jungle produce collectors and depends on diesel-powered generators for a few hours of electricity every night. With this kind of livelihood, villagers hardly have the purchasing power to acquire expensive equipment manufactured in high-cost countries. Although the

HKT technology does not require extra costs for infrastructures such as penstock or powerhouse and has almost no environmental impact, the relatively high prices of highly customized commercial HKTs have hindered the advancement of this technology in the region. Currently, there are only three commercial small-scale HKTs that are designed for shallow rivers (less than 1 m) with the price ranging from USD 4,900 to 12,000. Aside from being high costs, these HKTs may not be entirely suitable for applications in tropical rivers. Furthermore, the highly customized HKTs may cause longer downtime due to the delay of spare parts for maintenance and repair.

1.3 Objectives

This research aims to have a better insight into the current status of the off-grid rural electrification in Sarawak and to develop an affordable and practical small-scale HKT suitable for shallow tropical rivers. To achieve this aim, the objectives are as follows:

- i. To investigate Sarawak's need for off-grid rural electrification. This will involve researching the energy sectors, the current situation for off-grid rural electrification, the list of renewable energy projects, and the potential and challenges of using renewable energy for off-grid rural electrification.
- ii. To design and build a small-scale HKT prototype suitable for shallow tropical rivers using readily available off-the-shelf materials mainly for proof of concept. The process will involve designing, constructing and field testing the prototype.
- iii. To design and build a small-scale HKT that costs less than USD 1000 (using readily available off-the-shelf materials) and can generate 2 kWh per day, to

meet the service level deemed sufficient for a typical rural household. The process will involve designing, constructing and field testing the improved prototype based on the lesson learned from the previous prototype.

- iv. To evaluate off-the-shelf/recycled motors suitable for small-scale HKT construction. The process will involve a case study on types of off-the-shelf/recycled motors/generators commonly used in small-scale Renewable Energy System (RES) construction. Another case study will look at the rewired Smart Drive motor as a generator for small-scale HKT construction and provide a fundamental guide for its design.

1.4 Hypothesis

The existing method of HKT construction normally involved highly customized parts to improve efficiency. These highly customized parts are costly and normally not readily available off-the-shelf. Besides, the delay of spare parts for maintenance and repair may cause longer downtime. Therefore, to save cost, this research will adopt the method of repurposing existing materials from off-the-shelf/recycled for the small-scale HKT prototype construction. The hypothesis of this research is as follows:

- i. Readily available off-the-shelf materials can be used to construct a hydrokinetic turbine to reduce the construction cost.
- ii. A swept-back type of industrial fan rotor can be used as a hydrokinetic turbine rotor for debris mitigation in tropical rivers.
- iii. Off-the-shelf/recycled motors can be used or modified as a generator in hydrokinetic turbine construction to reduce cost.

1.5 Scope

The scope of work for the small-scale HKT prototype is as follows:

- i. Design to operate on shallow tropical rivers (less than 1 m deep).
- ii. Construction using only parts/materials (i.e., rotor, transmission, generator, float, metal bars, etc.) from off-the-shelf. There will be no obstruction on flow to the turbine rotor (i.e., no mesh, no wire etc.), but must have protection from heavier debris (i.e., tree branches or rotten tree trunks). It will be a non-submerge type of turbine configuration and the turbine will sit on Pontoon.
- iii. Since there is no facility for testing the turbine at the university, and there are rivers nearby the university with similar characteristics to the Balui River flowing next to Long Busang, the prototype will be field tested at a suitable river in the Padawan district, Kuching, Sarawak.
- iv. Able to generate 2 kWh of energy per day (i.e., deemed sufficient for a typical rural household in Sarawak as depicted in Figure 1.3).

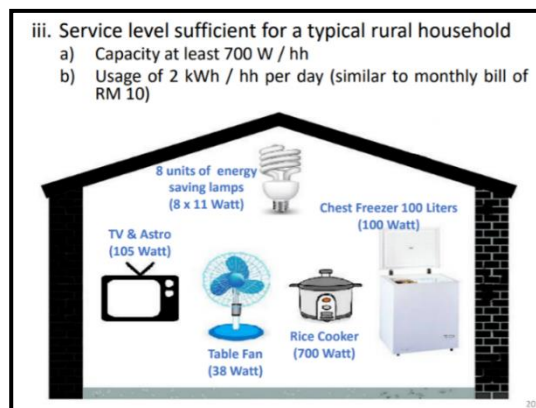


Figure 1.3: Service level deemed sufficient for a typical rural household (Fauzi Shahab, 2017)

1.6 Chapter Summary

This chapter has provided the study background, the problem statement, and the objectives of this research. The study background elaborates on the current situation of rural electrification in Sarawak. It highlights the need for an alternative method of providing access to electricity to off-grid rural and remote villages where topography does not favour the conventional MHP. The problem statement emphasised the issues involving the high cost of commercial HKTs, and the lack of design dedicated to shallow tropical rivers. Finally, the objectives outlined what the research is trying to achieve at the end of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter has two main parts. The first part involved Sarawak's need for off-grid rural electrification. This investigation will first review the current energy generation scenario and the current rate for off-grid rural electrification in Sarawak. Subsequently, the Renewable Energy System (RES) currently utilised with particular attention on Micro-Hydropower (MHP) and Solar Energy Systems (SES) would be described together with their potential and challenges. The second part will cover the Hydrokinetic Turbine (HKT) technology and focus on small-scale inland rivers HKT type. The study would also look into HKTs currently used for rural electrification and issues faced by HKTs in the tropical region. Lastly, the study will examine the method used to reduce the costs of HKT construction.

2.2 The Need for Rural Electrification in Sarawak

Sarawak is a large state that serves as a big catchment area for its annual estimated rainfall of 3850 mm (Salleh et al., 2018), which keeps the many rivers running. The abundant water resources denote great potential for producing reliable renewable energy – hydroelectric power. The Local Electrical Authority (LEA) has identified 50 sites with a total hydropower potential of 20 GW (Shirley & Kammen, 2015; Shiun, 2016). But until recently, only three have been fully developed (The Baleh hydroelectric power plant is expected to be commissioned by 2027) and contributed more than two-thirds of the total energy resources, as shown in Table 2.1. The other leading energy resources are coal which contributed 20.4%, and natural gas at 11.1% of the total power generation in the state.

Sarawak has about 1.5 billion tons of coal in its reserve from five mining sites (about 82% of the national total) and 40.9 trillion standard cubic feet of natural gas (Shiun, 2016).

Table 2.1: Energy Generation Scenario in Sarawak (Shirley & Kammen, 2015; Shiun, 2016).

Type	Plant	Capacity (MW)
Hydro	Batang Ai	108
	Bakun	2,400
	Murum	944
	Baleh	1285*
Coal	Sejingkat	210
	Mukah	248
	Balingian	600
Gas	Tanjung Kidurong	190
	Bintulu	310
	Miri	78
Mix (Gas, Diesel)	Tun Abdul Rahman	75
Diesel (off-grid)	Scattered in Rural Areas	50
Total		6,498

* Expected to be commissioned by 2027.

Although Sarawak has surplus power generated (energy demand of around 3,500 MW in 2017 (Sarawak Energy, 2017)), supplying the rural and non-rural small communities remains a great challenge and is very costly. The communities in these areas are usually of small scale and widely scattered. More than 50 % of these villages are estimated to have 50 or fewer households.

These communities have desired to have continuous electricity for so long, and all the ease it can bring in assisting their daily chores and much-needed refrigeration for their food, as long enjoyed by the urban dwellers. Besides that, more importantly, these people deserve to have development in infrastructure, improved amenities, increase in job and business opportunities – such as starting small or medium-scale entrepreneurship as emphasized by the state government for the rural communities – to enhance their standard of living (Jee, 2019).

According to Sarawak's Ministry of Utilities, the statistic for 2017 show that 1,623 rural villages involving 36,365 households in the state are still without access to 24-hour electricity. These off-grid rural villages are classified into three categories under the State Rural Power Supply Program: 1. Grid Connectible (340 villages), 2. Grid Possible but Need Access (881 villages), and 3. Remote Not Grid Connectible (402 villages) (Fauzi Shahab, 2017).

Due to these communities' small size, scattered location, and ruralness, the LEA declared that 5 % of Sarawak's population remain without access to 24-hour electricity in 2019 (Sarawak Energy, 2019). Hence, there is a slight misalignment with the World Bank's Global Electrification Database which shows Malaysia has achieved 100 % access to electricity since 2015 (The World Bank, 2022).

Currently, Sarawak has two major off-grid RES widely implemented in Sarawak for the off-grid rural electrification programs, namely the MHP and SES. Wind energy generation has been tried but failed miserably as wind resources at the equator are relatively poor (Anyi et al., 2010; Karunakaran et al., 2016; Shirley & Kammen, 2015).

2.2.1 Micro-Hydropower

The classification of hydropower plants is shown in Table 2.2. Large, medium and small-hydropower plants are used to feed the electricity grid, while the mini, micro and pico-hydropower plants are commonly used for standalone systems and electrification in rural/remote areas (Singh, 2009).

Table 2.2: Classification of hydropower plants (Singh, 2009).

Plant	Capacity
Large hydro	> 100 MW
Medium hydro	15 – 100 MW
Small hydro	1 – 15 MW
Mini hydro	100 kW – 1 MW
Micro-hydro	5 – 100 kW
Pico-hydro	< 5 kW

Although 48 % of people in Sarawak stay in rural areas and small communities, reliance on rivers for water supply, the source for food and transportation has made most of them choose to reside close to the rivers. Consequently, those who inhabited the river upstream or in the highlands will have the advantage of cleaner water and the possibility of using that resource to generate electricity through an MHP, as shown in Figure 2.1. Through the survey by LEA, the potential of MHP in Sarawak is estimated at 10.2 MW through 104 sites in eight divisions, and sadly, this information was no longer available on the LEA's website. Meanwhile, Table 2.3 lists the known site for 55 MHPs with a total generated power close to 1 MW installed throughout Sarawak for rural electrification in 2017. As can be seen from Table 2.3, not all MHP construction funding comes from the government.



Figure 2.1: A 10 kW MHP at a rural village in Sarawak (Bombastic Borneo, 2011).

Table 2.3: MHP installed in Sarawak for rural electrification.

Division	Village	Year	Capacity (kW)	Funding
Kuching	Kpg. Parang	2011	10	Community-based
	Kpg. Nyegol	2014	6	NGOs/ Private
	Kpg. Sting	2014	7.5	NGOs/ Private
	Kpg. Sapit	2015	6	NGOs/Private
	Kpg. Assum	2015	10	Government
Sri Aman	Kpg. Keranggas*	2010	N/A	Government
	Kpg. Wong Pandak	2010	N/A	Government

Table 2.3 continued

Sri Aman	Kpg. Sri Stamang 2	2011	18.3	Government
	Nanga Talong Engkari	2013	N/A	NGOs/ Private
	Rh Tapang Pungga	2014	8.3	NGOs/ Private
	Rh Laroh*	2015	3	Government
	Nanga Jambu	2017	15	Government
Sarikei	Rh Jawang Janting	2013 to 2015	112	Government
	Rh Michael Jantan			Government
	Rh Lugom Jengging			Government
	Rh Nyaiyang			Government
	Rh Suin Tebru			Government
	Rh Kedit Chundang			Government
	Rh Balang	2012	N/A	Government
	Rh Suing Ensan	2016	8	Government
Kapit	Long Lawen	2002	10	NGOs/ Private
	Kpg. Mudung Abun	2010	20	NGOs/ Private
	Rh Unyat Chupong	2015	8	Government
Miri	Kpg. Bario Asal	2009	40	NGOs/ Private
	Long Lamai	2013	15	NGOs/ Private
	Long Banga**	2014	320	Government
	Pa Ramapoh	2015	20	NGOs/ Private
	Long Kerangan	2015	10	NGOs/ Private
Mukah	Ulu Mukah	N/A	0.5	NGOs/ Private
Limbang	Buduk Nur	2004	7.5	Private

Table 2.3 continued

Limbang	Buduk Nur***	2008	30	Government
	Buduk Aru****	2006	10	Community-based
	Buduk Bui	2008	12.5	Government
	Long Langai	2010	15	Government
	Long Rusu	2010	35	Government
	Long Kerabangan	2012	10	NGOs/ Private
	Long Tanid	2012	12	NGOs/ Private
	Long Semadoh Naseb	2014	20	NGOs/ Private
	Buduk Nur	2015	20	Community-based
	Long Lidung	2015	7.5	NGOs/ Private
	Long Beluyu	2015	12	NGOs/ Private
	Long Resina	2015	10	NGOs/ Private
	Long Rutok	2015	N/A	NGOs/ Private
	Long Telingan	2016	20	Government
	Buduk Bui	2017	30	NGOs & Community-based
	Long Lidung	2017	5	NGOs/ Private
	Pa'Brunut	N/A	5	NGOs/ Private
	Punen Kelalan	N/A	3	NGOs/ Private
	Ulu Bol	N/A	3	NGOs/ Private
	Puneng Trusan	N/A	0.5	NGOs/ Private
	Long Langai	N/A	5	NGOs/ Private
	Long Lemumut	N/A	N/A	Government
	Long Ritan	N/A	N/A	Government

Table 2.3 continued

Limbang	Long Semadoh Rayeh	N/A	N/A	Government
	Long Remirang	N/A	N/A	NGOs/ Private
Total			911.6	

Source: Compiled by the author.

* MHP and PV hybrid

** MHP with Diesel backup

*** MHP failed

**** MHP Not operating

2.2.2 Solar Energy System

In Malaysia, the annual average daily solar irradiation was from 4.21 kWh/m² to 5.56 kWh/m² (Wirun et al., 2013 cited in Sufiah et al., 2017). The state of Perlis and Kedah in the northern region of Peninsular Malaysia and some areas of Sabah and Sarawak are known to receive the highest solar irradiations in Malaysia. All these four states receive more than 5 kWh/m²/day of solar energy throughout the year (Borhanazad et al., 2013; Shirley & Kammen, 2015), making it very attractive for solar energy applications. The LEA in Sarawak, which has pursued green technology for rural electrification programs for years, has recently intensified its effort by installing more SESs in the rural communities considered not grid connectible in years to come. By the middle of 2016, it was reported the LEA already had 18 Solar Photovoltaic (Solar PV) systems up and running (that serve 36 villages), 13 Solar PV systems (for 37 villages) are still under construction, while another 9 more Solar PV systems (for 14 villages) are in the planning stage. These SESs shall produce 9 to 10 MW of clean energy and are all funded by the government (Shiun, 2016). The rural electrification initiative in Sarawak achieved another milestone on October 25, 2016, when

the biggest solar project in Sarawak, named the Centralized Solar Hybrid System, as shown in Figure 2.2, was officiated in the highland of Bario. It has a capacity of 887 kW, and it serves a cluster of 9 villages with 233 households, shops and administrative offices. Eventually, the connection will be expanded to Arun Layun and Bario Asal to supply electricity to a total of more than 300 households (Borneo Post, 2016).



Figure 2.2: Centralized Solar Hybrid System in Bario, Sarawak (Borneo Post, 2016).

2.2.3 Renewable Energy Potential and Challenges

In 2016, the global small hydropower potential estimated was 217 GW and those already installed are estimated at 78 GW, an increase of 4 % compared to 2013 (UNIDO, 2016). Meanwhile, global solar energy generation continued to rise significantly to 227 GW in 2015, ten times the cumulative world capacity a decade earlier (REN21, 2016). Based on these facts, the LEA has chosen MHP and SES for rural electrification programs in Sarawak because it is the renewable technology that is being accepted and used worldwide.

In Sarawak's scenario, MHP usage has not reached its full potential. The MHP is renowned as cost-effective, needs less maintenance and has a longer life span compared to SES (Karunakaran et al., 2016). All of the MHPs installed in Sarawak (as listed in Table 2.2) have been in operation for more than five years, while the MHP at Long Lawen has been producing electricity since 2002 without fail (Aliran, 2017). There is only one MHP-Solar PV hybrid system reported to fail at Kpg. Keranggas (Borneo Post, 2015). However, an MHP is not the sort of plug-and-play type of system since each potential site is unique and requires careful designing and implementation to be successful. Moreover, an MHP requires a constant water source and cannot function during prolonged dry spells. Hence, a proper water reservoir combined with rationing of water usage is a must. Most MHP also requires a static head of 10 m or more, which means they are useless in an area with little or no elevation (Borhanazad et al., 2013). In the meantime, an MHP setting also requires expensive civil works and control systems. However, getting help from the community to be involved in civil construction and using locally manufactured components can reduce construction costs (Anyi et al., 2010; Karunakaran et al., 2016). Besides, training the locals and periodical checking of the system from the LEA or appointed agency can also reduce the maintenance cost. Furthermore, Jaringan Orang Asal Semalaysia (JOAS) team leader stated that "strong leadership and organised community are prerequisites in ensuring the success of an MHP project" (JOAS, 2015).

On the other hand, due to the constant higher daily solar irradiation in Sarawak throughout the year, the implementation of SESs in Sarawak is growing. The SES is also easier to install and more suitable for rural areas with small elevations or unsuitable water resources for MHP. Nevertheless, the SES do have setbacks in the tropical setting despite the benefits mentioned. Due to the tropical climate, high temperatures and humidity cause

the termination box to crack and the performance of solar panels to drop. Besides, the solar panel surface needs constant cleaning from various debris and growth to maintain its performance (Anyi et al., 2010; Borhanazad et al., 2013; Karunakaran et al., 2016). Currently, the principal concern for the SES is the overused battery without recharging if the sky is heavily clouded for days and causes the battery to have a shorter life span (Karunakaran et al., 2016). Despite that, the problem with a shorter life span is resolvable by equipping the SES with a backup diesel generator. Last but not least, training the locals would help maintain the system, and periodical inspection from the LEA or appointed agency will help keep the system in check.

2.3 Hydrokinetic Turbine

The energy from moving water can be harnessed through either the conventional hydrostatic or the hydrokinetic approach (Yuce & Muratoglu, 2015). In hydrostatic, water is usually accumulated in custom-made reservoirs to create the pressure head. An energy conversion system captures the potential energy of steady-flowing water to produce electricity (Khan et al., 2008). But in hydrokinetics, no reservoir is required. Instead, the kinetic energy of the continuously flowing water is directly converted into electricity by placing an HKT inside the water's path (Khan et al., 2009; D. Kumar & Sarkar, 2015; Lago et al., 2010; Laws & Epps, 2016; Yuce & Muratoglu, 2015).

In the conventional hydrostatic approach, the turbine used can be a reaction turbine or an impulse turbine. A turbine that generates power from the combination of pressure and moving water forces is called a reaction turbine (Kamran, 2021; Water Power Technologies Office, 2003). The propeller, Francis, and kinetic turbine are among the types of reaction turbines. Contrastingly, the Pelton and cross-flow turbine that only uses the force of the

water to move the rotor and discharges at atmospheric pressure is called an impulse turbine (Water Power Technologies Office, 2003).

In terms of terminology, the term HKT is a synonym with Water Current Turbine (WCT), Ultra-low-head Hydro Turbine, Free Flow/Stream Turbine, and Zero-Head Hydro Turbine (Khan et al., 2009). An HKT system can be specifically designed to tap into inland (rivers), tidal (estuaries and channels), and ocean (currents) as their natural resources (Laws & Epps, 2016). Currently, many concepts have been tested for harnessing hydrokinetic energy, as illustrated in Figure 2.3. They can be divided into two classes, the one that uses a turbine and the one without a turbine (Khan et al., 2009). Through decades of research, the turbine type remains the primary choice in this technology (Khan et al., 2009; Ladokun et al., 2013; Topaloglu et al., 2016). The axial-flow (horizontal axis) and cross-flow (vertical axis and in-plane) turbines are the most commonly used small-scale HKTs (Vermaak et al., 2014).

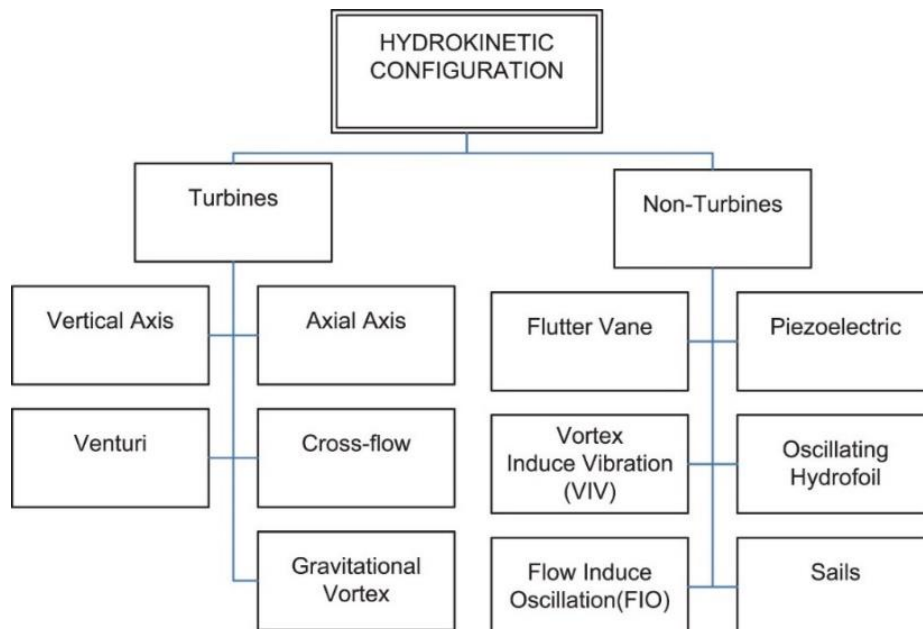


Figure 2.3: Classes of HKT (Ibrahim et al., 2021).

2.3.1 Design Principle

Although an HKT is considered a reaction turbine, the working principle is similar to a wind turbine. Furthermore, since water is approximately 800 times denser than air, the amount of energy generated by the HKT is much higher than the wind turbine under equivalent settings (Vermaak et al., 2014). Thus, the total power generated by an HKT system can be calculated using Equation 2.1. Where A is the turbine swept area (m^2), ρ is the water density (1000 kg/m^3), V is the flow velocity (m/s), and C_p is the turbine power coefficient or efficiency which has a theoretical maximum value of 0.593 (Betz limit), while η is the transmission system efficiency. The combination of $C_p\eta$, thus, represents the overall/water-to-wire efficiency of the HKT.

$$P = \frac{1}{2} A \rho V^3 C_p \eta \quad \text{Equation 2.1}$$

In the Wind Turbine theory, the Betz limit suggested a maximum of 59.3 % of energy is extractable from an undisturbed wind stream. In practice, when combined with the frictional losses and other mechanical imperfections, the energy extractable would drop to 35 to 40 % (Magdi. Ragheb & Raghed, 2011). Only highly efficient machines with low mechanical losses can get near the Betz limit, small-scale river turbine, on the other hand, usually has an efficiency of just 0.25 (Vermaak et al., 2014). In wind turbine design, another important concept is the optimal Tip Speed Ratio (TSR), which is the ratio of the speed of the rotor tip to the free stream wind speed. A rotor rotating too slowly will allow too much wind to pass through, while too fast will create too much drag. Thus, under these conditions, the wind turbine does not extract as much energy as it could. The rotor TSR depends on the blade airfoil profile used, the number of blades, and the type of wind turbine (Ragheb & Raghed, 2011). The TSR is a dimensionless factor calculated using Equation 2.2. Where V

is the wind speed (m/s), $v = \omega r$ is the rotor tip speed (m/s), r is the rotor radius (m), $\omega = 2\pi f$ is the angular velocity (rad/s), and f is the rotational frequency (Hz), (s^{-1}).

$$\text{TSR}, \lambda = \frac{v}{V} = \frac{\omega r}{V} \quad \text{Equation 2.2}$$

Since the optimal TSR depends on the number of blades, n , of the wind turbine, a smaller number of blades must spin faster to extract the maximum power from the wind and vice versa. According to Magdi. Ragheb & Raghed, (2011), the optimal TSR can be estimated using Equation 2.3. Therefore, for $n = 2$, the optimal TSR is calculated to be 6.28, while 4.19 and 3.14 are for the three-bladed rotor and four-bladed rotor respectively. Figure 2.4 shows maximum power extraction occurs at optimal TSR for a two-bladed rotor. The optimal TSR can be further improved by 25 to 30 % above these values with proper airfoil design (Ragheb & Raghed, 2011). Where n is the number of blades.

$$\lambda_{\text{optimal}} \approx \frac{4\pi}{n} \quad \text{Equation 2.3}$$

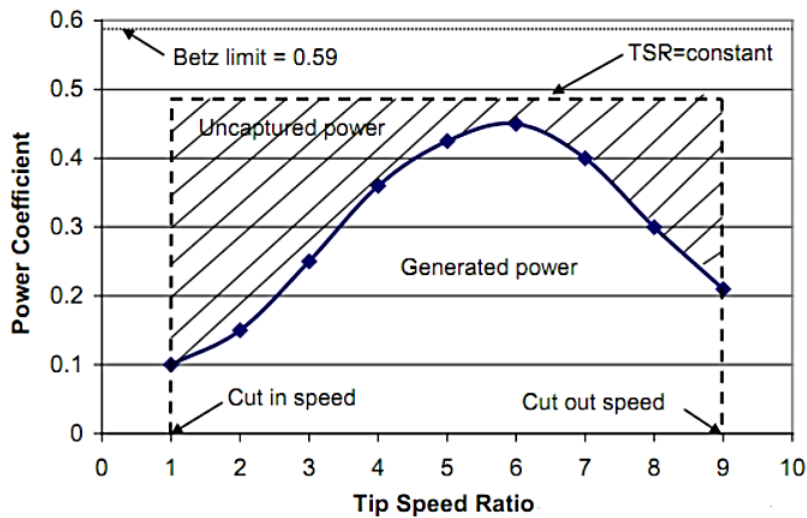


Figure 2.4 Power coefficient as a function of TSR for a two-bladed rotor (Magdi. Ragheb & Raghed, 2011).

2.3.2 Configuration

The axial-flow (horizontal axis) turbine and cross-flow (vertical axis and in-plane) turbine are two of the most commonly used in small-scale HKT (Sørnes, 2010; Vermaak et al., 2014). The key advantages of the axial-type turbine over a cross-flow turbine are its self-starting capability and optimum performance at higher rotor speeds, thus reducing gear coupling and generator matching (Khan et al., 2009; Vermaak et al., 2014), and increasing the power efficiency (Tian et al., 2018). Figure 2.4 shows the various arrangement of axial-flow and cross-flow turbines.

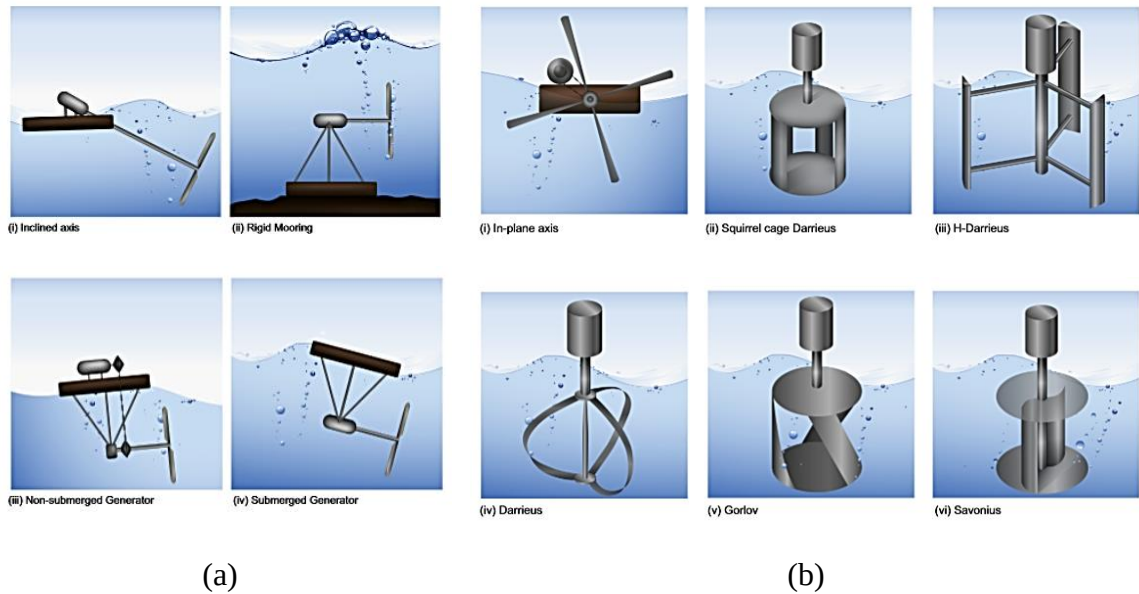


Figure 2.5: (a) Axial-flow turbines and (b) Cross-flow turbines (Vermaak et al., 2014).

2.3.3 Rotor

Figure 2.5 shows the type of wind turbine rotors and their typical efficiency. From Figure 2.5, one can see that the axial-flow wind turbine with 3-blades has the highest rotor power coefficient, C_p . Optimum performance is achieved between the Tip-Speed Ratio (TSR) of 6 to 8. Currently, most horizontal axis wind turbines operate with three blades as

standard as it's considered an ideal compromise between high energy yield and greater stability and durability of the turbine itself (Saoirse, 2018).

While the 2-blades wind turbine has a slightly lower efficiency, the optimum performance is achieved over a broader range of TSR of 8 to 14. From Figure 2.5, one can conclude that the two or 3-blades low-solidity turbines are more suitable to be operated at a higher speed. In contrast, turbines with higher solidity are more suitable for low RPM but high torque applications such as the Dutch Windmill and American Wind Turbine are used for pumping water.

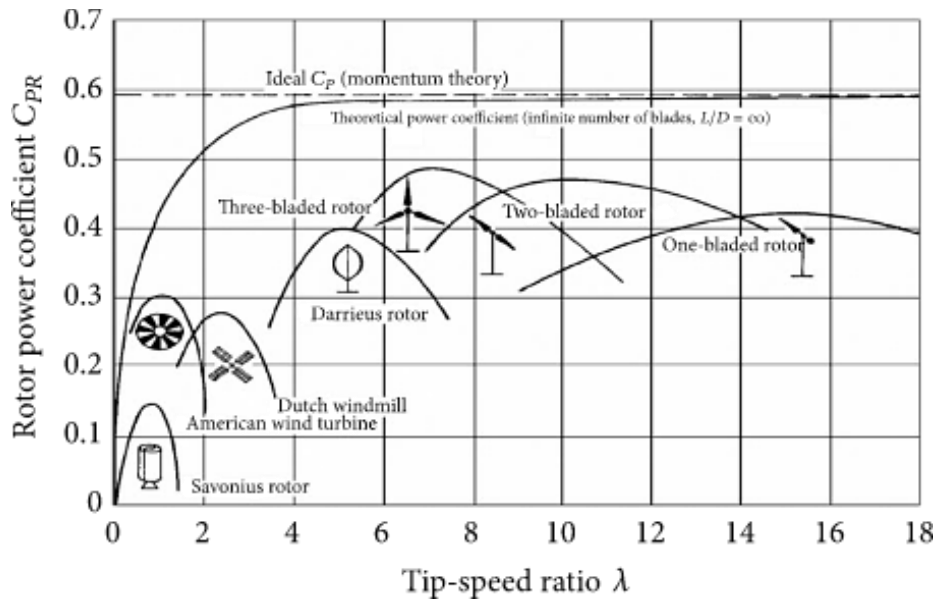


Figure 2.6: Typical performance of wind power machines (Sahim et al., 2018).

2.3.4 Electric Generator

Electric generators are devices that convert mechanical energy into electrical energy. HKT uses the same generator as conventional hydro and wind power generation. Generally, the two commonly used generators in the wind and hydrokinetic turbine systems are

synchronous and induction generators. Generators can mainly give Direct Current (DC) or Alternating Current (AC).

A DC generator is a machine that converts mechanical energy into direct current electricity. DC generators are equipped with a DC electric or permanent magnet excitation system and are generally expensive. Since DC is less efficient when transmitted across long distances, AC generators remain the most suitable for providing electricity to remote areas (Güney & Kaygusuz, 2010; Vermaak et al., 2014). However, according to Güney & Kaygusuz (2010), standalone systems can be divided into two categories, limited usage in a household or full supply for all equipment. Limited usage can include lighting, heating, and battery charging system. In this case, the DC generator is suitable for use.

In the meantime, with the advancement in power electronic conversion technology and demand to remedy the inadequacies of the national grid and in providing electricity to the rural communities, distributed generation (DG), which often utilises carbon-neutral renewable energy sources become the better solution (Burmester, Rayudu, Seah, & Akinyele, 2017). DG using DC sources (i.e., from solar) are common in micro- or nano-grid to supply electricity to remote communities. DC micro- or nano-grid powered by a DC source and low voltage DC (LVDC) distribution are more efficient as they have fewer power conversions (Burmester et al., 2017; Manandhar et al., 2016). Consequently, using a DC generator in the HKT system would allow easier integration with other DC sources such as solar energy for greater capacity in the rural setting.

In terms of the type of generator, the Permanent Magnet Synchronous Generator (PMSG) is commonly used in wind and HKT systems, as shown in Table 2.4. According to Gör & Kurt (2016), using PMSGs in low-speed applications is very usual. There are two

distinct groups, axial flux and radial flux PMSG. In the radial flux generator, the flux passes through the coils in the radial direction. If the flux passes perpendicular to the radial direction, this generator is known as an axial flux generator. Axial flux generators have a higher power-to-weight ratio, easy winding structure, and cooling advantages (Gör & Kurt, 2016).

Table 2.4: Type of generator used in wind and hydrokinetic turbine.

Author/Year	Paper Title	Type of generator	Application
Pop et al., 2013	Axial-flux vs. radial-flux permanent-magnet synchronous generators for micro-wind turbine application	Axial and Radial Flux PMSG	Wind Turbine
Davila-Vilchis & Mishra, 2014	Performance of a hydrokinetic energy system using an axial-flux permanent magnet generator	Axial Flux PMSG	Hydrokinetic Turbine
Tewari et al., 2015	Hydrokinetic Energy for Enlightening the Future of Rural Communities in Uttarakhand	PMSG	Hydrokinetic Turbine
Koko et al., 2015	Micro-hydrokinetic river system modelling and analysis as compared to wind system for remote rural electrification	PMSG	Hydrokinetic Turbine
Gör & Kurt, 2016	Preliminary studies of a new permanent magnet generator (PMG) with the axial and radial flux morphology	PMSG	Wind Turbine

Table 2.4 continued

Woods, 2017	Hydrokinetic Turbine Systems for Remote River Applications in Cold Climates	PMSG	Hydrokinetic Turbine
Røkke, 2017	Permanent Magnet Generators for Marine Current Tidal Turbines	PMSG	Hydrokinetic Turbine
Tian et al., 2018	Design, test and numerical simulation of a low-speed horizontal axis hydrokinetic turbine	PMSG	Hydrokinetic Turbine

2.4 Hydrokinetic Turbine for Rural Electrification

Table 2.4 listed some of the research projects on HKTs designed for rural electrification. Even though both vertical and horizontal axis turbines are considered primary choices for hydrokinetic energy conversion systems, from Table 2.4, one can see that most of the HKT designs chose the horizontal axis turbine due to its advantages over a vertical axis.

Since some of the rural communities reside in the upper river area where the river is shallow, many HKTs listed in Table 2.5 are inapplicable in terms of the sizes of their turbines and without debris mitigation which is considered essential in the tropical region. In addition, most systems are mounted on pontoons for easier retrieval during maintenance. Equally noticeable are the significant challenges these researchers encounter in the field as the system design does not achieve the intended output. The evidence is explicit in the system design by Woods from Canada that produced 590 W from a 5 kW system. Another system design by Chica from Colombia generated 127.89 W from a 1.5 kW system.

Table 2.5: List of HKT designs for rural electrification.

Author/ Year	Country	Turbine Type/ Axis	Size (m)	Water Velocity (m/s)	Power Output (W)	Efficiency	Mounting	Debris Mitigation	Diffuser	Rotor Solidity
Els et al., 2003	Brazil	6-blades/ Horizontal	0.8	2	1000	N/A	Suspended with long arm	With	With	High
Solari et al., 2008	Peru	3-blades/ Axial-flow	1.75	1	250	N/A	Furling from Pontoon	Without	Without	Low
Baumgart ner et al., 2010	USA	3-blades/ Horizontal	N/A	1.95	100 (designed) 70 (actual)	N/A	Pontoon	Without	With	Low
Quick, 2012	Japan	3-blades/ Horizontal	N/A	2	250	N/A	Suspended on a steel frame	Without	With	Low

Table 2.5 continued

Smart Hydro Power, 2021	Germany	3-blades/ Horizontal	1	1 to 2.8	250 – 5000 (designed)	N/A	Pontoon	With	With	Low
Ismail et al., 2015	Brazil	7-blades/ Vertical	0.5 (r) 1 (h)	2	1.6 (designed)	N/A	Pontoon	Without	Without	High
Woods, 2017	Canada	4-hydrofoil blades/ Vertical	1.52 (D) 0.76 (h)	2.12	5000 (designed) 590 (actual)	0.35	N/A	Without	Without	Low
Verterra Energy, 2019	USA	Cross Flow	3(D) 1(h)	3	8232.84	0.5	Riverbed	Without	N/A	N/A
Chica et al., 2018	Colombia	3-blades/ Horizontal	0.79	1.5 (designed) 0.625 (actual)	1500 (designed) 127.89 (actual)	0.54	Pontoon	Without	Without	Low

Table 2.5 continued

Waterotor , 2019	Canada	Savonius/ Cross-flow	N/A	1.78	1000	0.5	Riverbed	N/A	N/A	N/A
Idénergie, 2015	Canada	Darrieus/ Cross-flow	0.66 (h) 1.32 (w)	1 to 2.5	100 to 500 (designed)	N/A	Riverbed	N/A	N/A	N/A

2.4.1 Hydrokinetic Turbine for Shallow Rivers

Currently, there are few commercially available small-scale HKTs developed specifically for shallow rivers (less than 1 m), and it is hard to get price and performance data for them. Kirke (2020) surveyed available HKTs and found few suitable products available, although there were plenty of websites with enthusiastic sales pitches. Some were found only on YouTube presentations or websites with no performance or price data and no response to enquiries. Those able to operate in depths of 1 m or a little more are shown in Table 2.6, based on Kirke (2020). A further search found two more HKTs suitable for depths less than 1 m, the EcoCinetic and the Ibasei Cappa, and these are also shown in Table 2.6.

Table 2.6: HKT power output, required depth and prices current August 2020.

company	Rated power, (kW)	Flow velocity (m/s)	Power at 1 m/s (W)	Min depth (m)	Price, (USD)	Available?
New Energy Corp	5	3	0.185	1	50,000?	Yes
Smart Hydro	5	3.1	0.168	1.1	14,000	Yes
Idénergie	0.5	3	0.018	0.6	9,300	N/A
Green energy Hydrocat	0.183	1	0.183	NA	16,600	No
Waterotor	1	1.8	0.171	1.15	5,000	N/A
EcoCinetic	2	3	0.074	0.9	4,900	N/A
Ibasei Cappa	0.25	2	0.031	0.5	12,000	N/A

Notes:

1. New Energy: A price of \$50,000 negotiable for a complete 5 kW system was mentioned but not put in writing.

2. Smart Hydro price is for the turbine, generator and frame only. Other components for a complete system include (i) electrical cabinet, inverter & dump load \$9700, or (ii) Grid-connected inverter, controller, dump load, and fuse box \$3650 and (iii) 10 kWh, 48 V battery bank \$5550.
3. Some prices have been estimated from limited data gleaned from websites.
4. Power output at 1 m/s has been estimated on the assumption that power is proportional to the flow velocity cubed, but this may give an over-estimate as it does not allow for drive train friction and Reynolds number effects.
5. There is doubt as to whether some of the manufacturers tabulated above can actually supply.

The small-scale HKTs shown in Table 2.6 have prices ranging from USD 4,000 to 50,000 per unit, which is very expensive for a RES that produces only a few hundred watts compared to less than USD 500 for a wind or SES with a similar rated capacity (see Appendix A for URLs giving prices). However, it must be remembered that the average output from a solar or wind system will be only a fraction of the rated capacity, especially in high-rainfall tropical areas. Besides, with most components custom-made for each turbine, this will not help either in cost-cutting on maintenance and repair or reducing the possible longer downtime due to the unavailability of parts. Thus, to make the small-scale river HKT technology more compelling to a developing nation like Sarawak, Malaysia, a reduction in capital and operational costs while increasing affordability and sustainability should be the priority. Khan et al. (2008) suggested from the cost and performance point of view, it is desirable for river HKT design to apply simple design using off-the-shelf materials. This matter is again suggested by Laird et al. (2013) on marine HKT cost-reduction pathways, but to date, nobody has actually offered an affordable HKT.

2.4.2 Issues Faced

In developing countries of Asia and the Pacific, the main reasons for the low rate of rural electrification are because of scattered low-income consumers, high upfront equipment costs and decentralised electricity supply grids that are gradually being extended (Urmee et al., 2009).

Anyi et al. (2010) have made the following case for HKT on rivers in the humid tropics:

- i. It is usually uneconomic to provide mains power to small remote communities even when high voltage lines pass by a village. Instead, local authorities normally resort to Diesel-Powered Generators (DPG) which are noisy and require frequent maintenance and are often neglected in remote areas due to limited resources and know-how. Apart from that, fuel is expensive and difficult to bring into remote areas.
- ii. Neither wind nor sun provides reliable power in humid tropical regions with a lot of still and overcast weather. Towers attract lightning strikes, which can destroy electronic controls, fungus grows on solar panels, and the multiple electrical connections on photovoltaic arrays corrode away in hot, humid climates.
- iii. MHP is an attractive option in mountainous areas but is not possible in a flat country where there is little elevation.

Numerous companies around the world are now developing HKT to harvest tidal and river flows, but there are four major problems with most designs for rivers:

- i. Clogging by floating debris, especially in tropical rivers.

- ii. Turbines are typically designed for flow velocities in the order of 3 m/s, based on the best tidal sites, but flow velocities in most rivers most of the time are no more than about 1 m/s, so turbines deliver well below their rated power (Kirke, 2019, 2020).
- iii. River depths are typically less than 1 m in areas where the flow is fast enough to provide viable power density, but most turbines are designed for much greater depths (Ibid).
- iv. Off-grid remote communities in tropical regions rarely have the purchasing power to acquire expensive equipment manufactured in high-cost countries such as Germany, Canada and the United States, and long delays in the supply of replacement parts can lead to long downtime.

2.4.3 Hydrokinetic Potential for Rural Electrification in Sarawak

Sarawak receives an average annual rainfall of about 3850 mm, 1.5 times higher than Sabah and the Malaysian Peninsular and five times more than the world's average (Salleh et al., 2018). The enormous amount of rainfall coupled with a warm and wet tropical climate has allowed a vast river network in the state to flow continuously throughout the year. These river networks formed the 22 river basins, where the Rajang basin (51153.29 Km²) and Baram basin (22109 Km²) are two of the largest, as shown in Figure 1.2. These two river basins cover most of the interior of Sarawak and ironically also house the majority of rural communities without access to electricity, as shown in Figure 1.1 (i.e., red dots). In addition, Figure 1.1 also reviews that most of these rural communities in the Rajang and Baram basins reside relatively far from the state's power grid (i.e., purple line). As the people in the rural area depend on rivers as their source of water supply, food, and transport, this has caused them to reside along the rivers, as depicted by rainfall stations (i.e., red dot) in Figure 2.7 and Figure 2.8.

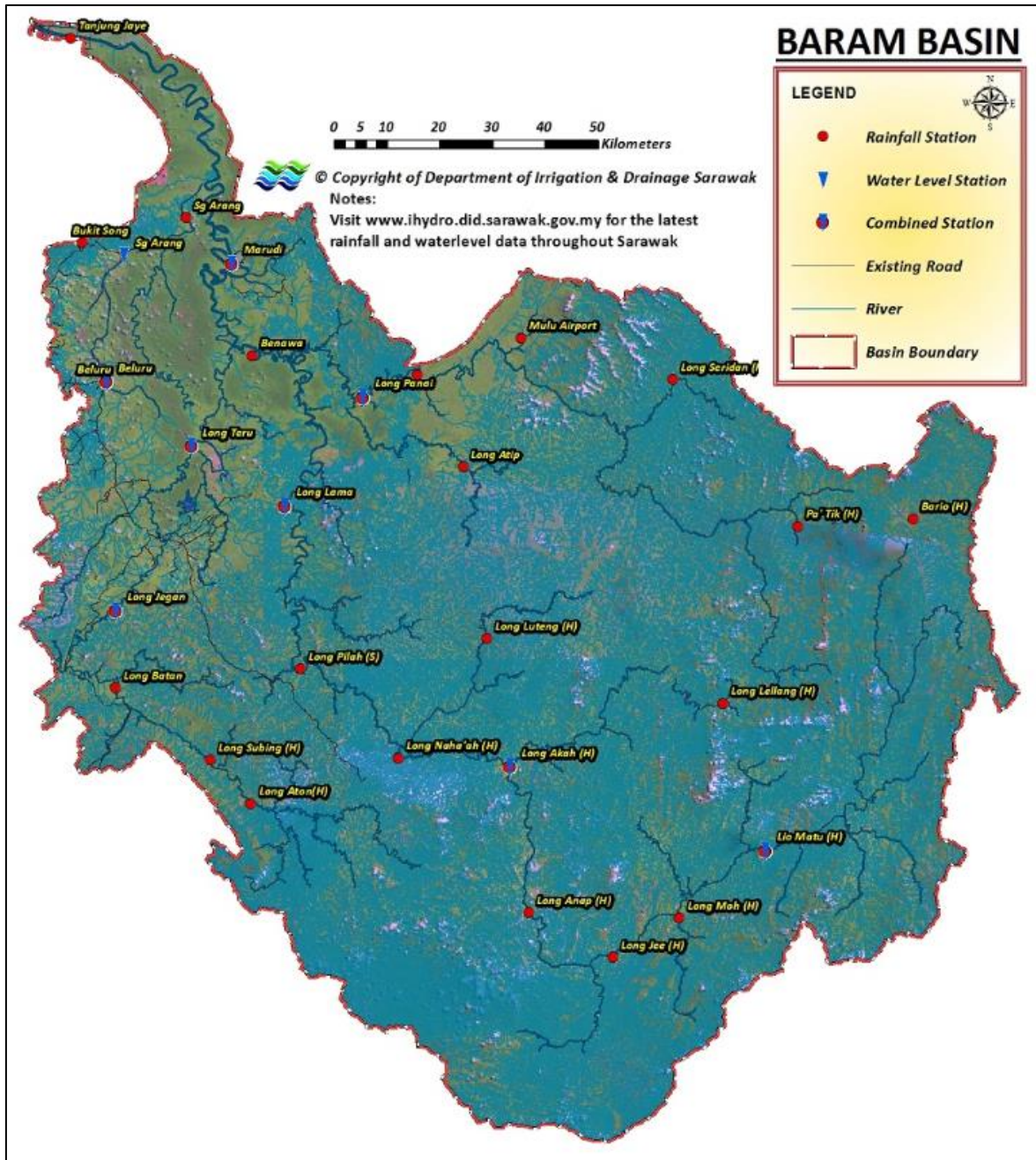


Figure 2.7: Rural communities reside along rivers in the Baram basin (DID of Sarawak, 2022b).

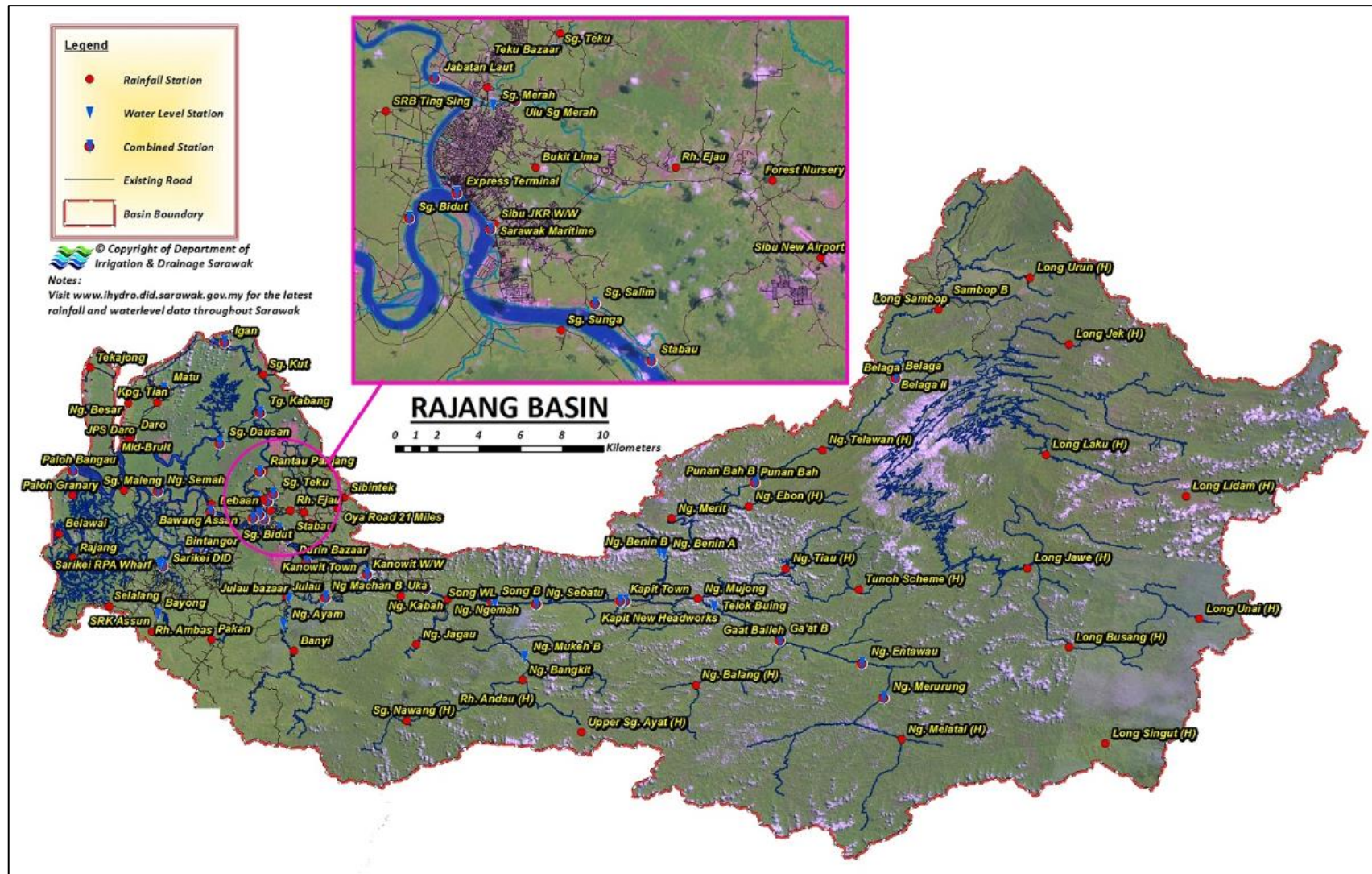


Figure 2.8: Rural communities reside along rivers in the Rajang basin (DID of Sarawak, 2022c).

Although there is no comprehensive study conducted on the actual potential for hydrokinetic power generation in Sarawak, some researchers from Malaysian universities have agreed that Sarawak has significant potential through their research publication, as seen in Table 2.7.

Table 2.7: Research on hydrokinetic potential.

Author/ Year	Institution	Paper Title
Behrouzi et al., 2016	UTM	Renewable energy potential in Malaysia: Hydrokinetic river/marine technology
Saupi et al., 2018	UPM	Hydrokinetic Energy Assessment in Unregulated River for Hydrokinetic Performance Analysis Studies in East Malaysia
Azrulhisham et al., 2018	UniKL, UNIMAS	Potential Evaluation of Vertical Axis Hydrokinetic Turbine Implementation in Equatorial River
Jamaluddin et al., 2018	UniKL	Potential of Portable Hydrokinetic Energy Turbine Design for Remote Communities in Sarawak
Aling et al., 2018	PMU	Potential Application of Hydrokinetic Turbine for Rural Electrification in Katibas Region
Salleh, Kamaruddin, & Mohamed-Kassim, 2018	USM	Micro-hydrokinetic turbine potential for sustainable power generation in Malaysia

2.4.4 Methods To Reduce Hydrokinetic Turbine Cost

HKT design and construction is an intricate process. Many researchers in Table 2.8 have chosen to tackle a specific part of the turbine to make the turbine more cost-effective. Lago et al. (2010) and A. Kumar & Saini (2014) have suggested using venturi systems to

increase the power density, while Laws & Epps (2016) proposed the usage of buoyant systems to reduce the cost of mounting systems. Besides, others have suggested improving the turbine blade design (Ismail et al., 2015; Kiran, 2014; Kirke, 2020; Norta et al., 2015), making the blade locally in rural communities (Anyi & Kirke, 2011; Chica et al., 2018), improving the generator design (Koko, 2014; Soemphol & Angkawisittpan, 2020), and improving the turbine's control system (Zhou, 2012). On the other hand, both Khan et al. (2008) and Laird et al. (2013) have suggested keeping the design simple. Building an HKT using currently available technologies or materials from off-the-shelf is desirable (Khan et al., 2008). In rural electrification, reliability should reign supreme, therefore, reduced efficiency is tolerable if reliability is significantly increased (reducing operational cost), as mentioned by Laird et al. (2013).

Table 2.8: Suggested method to reduce the cost of HKTs.

Author/ Year	The method suggested
Khan et al., 2008	1. Use of available technologies. 2. Simple design using off-the-shelf materials.
Lago et al., 2010	Use of venturi systems.
Anyi & Kirke, 2011	Making the blade locally in rural communities.
Zhou, 2012	Use Maximum Power Point Tracking (MPPT) control.
Laird et al., 2013	System Simplicity and Reliability.
A. Kumar & Saini, 2014	Use of venturi systems.
Koko, 2014	A balance between PMSG's pole pairs and gearbox ratio.
Kiran, 2014	Turbine blade design.
Norta et al., 2015	Use of Polyurethane turbine blade construction.

Table 2.8 continued

Ismail et al., 2015	Use of Savonius rotor.
Laws & Epps, 2016	Use Buoyant systems.
Chica et al., 2018	Making the blade locally in rural communities.
Kirke, 2020	Use of a modified version of the New Energetics orthogonal turbine.
Soemphol & Angkawisittpan, 2020	Building a low-speed permanent magnet generator using 3D-printed structures.

2.5 Chapter Summary

This chapter has reviewed that due to scattered rural communities and uneconomical grid connection, 5 % of the population of Sarawak still has no access to 24-hour electricity. The state government has devised plans to overcome this shortcoming, but it will cost billions of Ringgit Malaysia and take time to implement. Currently, short-term solutions include installing small-scale RES such as conventional MHP and SES. The conventional MHP is undoubtedly the best option for rural electrification in this region. Still is unfeasible on topography that does not favour it, while the SES has issues in the hot and humid tropical climate.

In those circumstances, hydrokinetic technology can serve as a promising alternative for rural electrification. Sarawak has great hydrokinetic potential, but having the rural communities residing in upper river areas requires suitable HKTs for shallow river application. Current small-scale HKTs on the market are too costly and may not be entirely suitable for tropical rivers due to debris and flash floods. In the meantime, most HKT-related research usually focuses on customizing a specific component (i.e., turbine rotor, generator,

control, etc.) which typically increases the complexity and costs. Meanwhile, very few researchers have suggested methods to reduce the cost of HKTs. Eventually, to date, nobody has offered an affordable HKT for rural electrification in the Tropics and this is the gap that this research seeks to address.

The advantages of a simple HKT design using currently available technologies and off-the-shelf materials will not only reduce the capital cost (as there are no intricate custom parts) but the operational cost (reducing the possible longer downtime due to the unavailability of custom parts) as well. Therefore, it shall be the focus of this research.

CHAPTER 3

MATERIALS AND METHODS

3.1 Overview

This chapter will explain in detail the materials and methods used in this study. First, a research framework and a flow chart will describe the phases and flow of the entire research work. The following section will relate to selecting a reference for the small-scale Hydrokinetic Turbines (HKT) design and a suitable site for the field test. Later, the design and construction of the two full-scale prototypes and their field tests began. Finally, the case studies on the off-the-shelf/recycled motor as the generator will be presented.

3.2 Research Framework and Flow of Study

This study consists of four phases, as shown by the research framework in Figure 3.1 and the flow chart in Figure 3.2. Phase 1 began with a review of the need for rural electrification in Sarawak. The focus would be on the Distributed Generation (DG) systems used for off-grid rural electrification in Sarawak, particularly the Renewable Energy System (RES), and their potential and challenges. Next is followed by a review of HKT types and design. The study focuses on inland river small-scale HKT and the issues of its application in off-grid rural electrification. Subsequently, the study has decided on a method to overcome the capital and running cost issues before selecting a river in an isolated area (with an existing off-grid community and a suitable condition for hydrokinetic power generation) as the reference for the small-scale HKT design. Since the field test would not happen in a rural area due to practicality, a suitable field test site nearby is necessary and crucial.

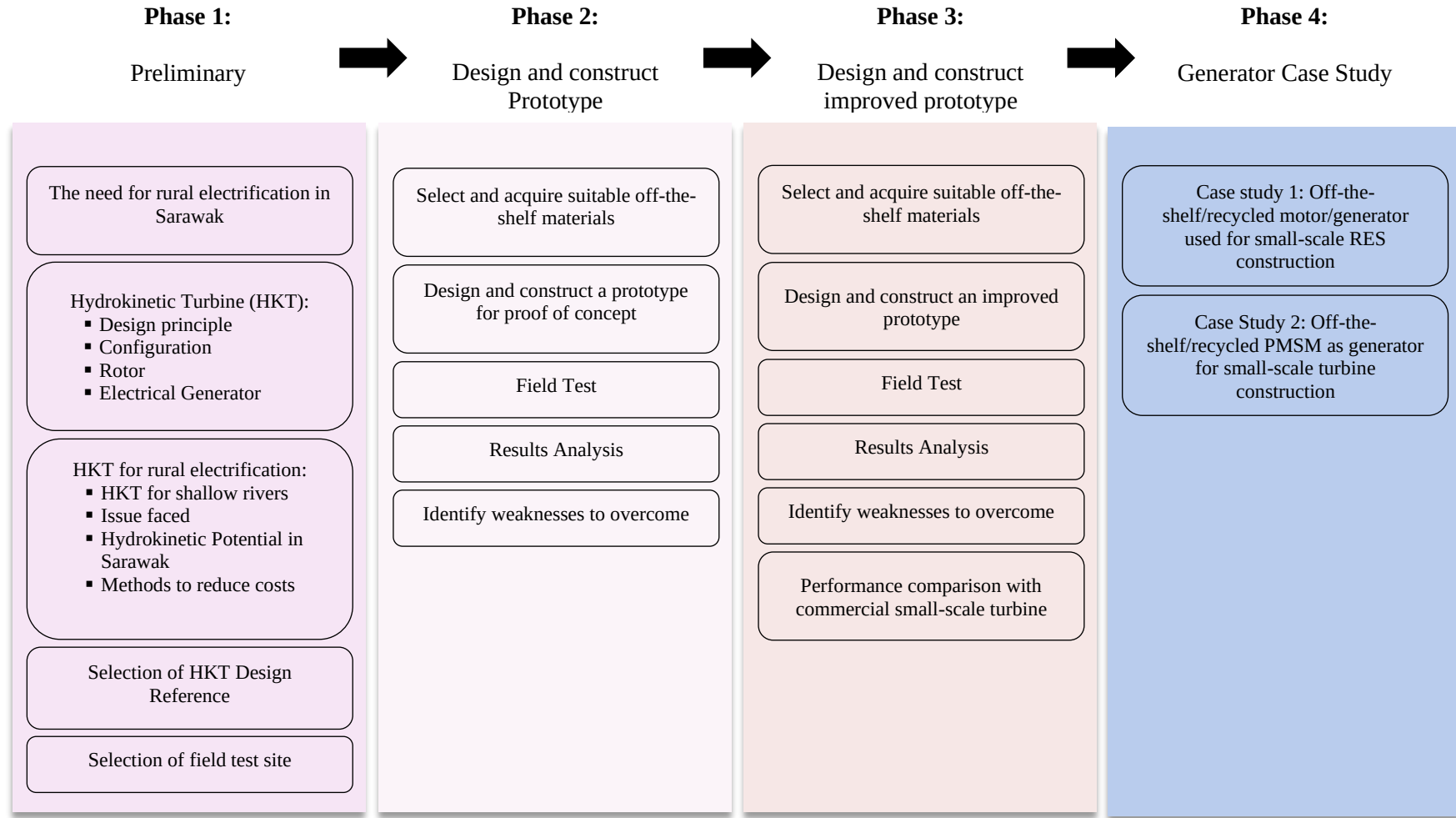


Figure 3.1: The Research Framework.

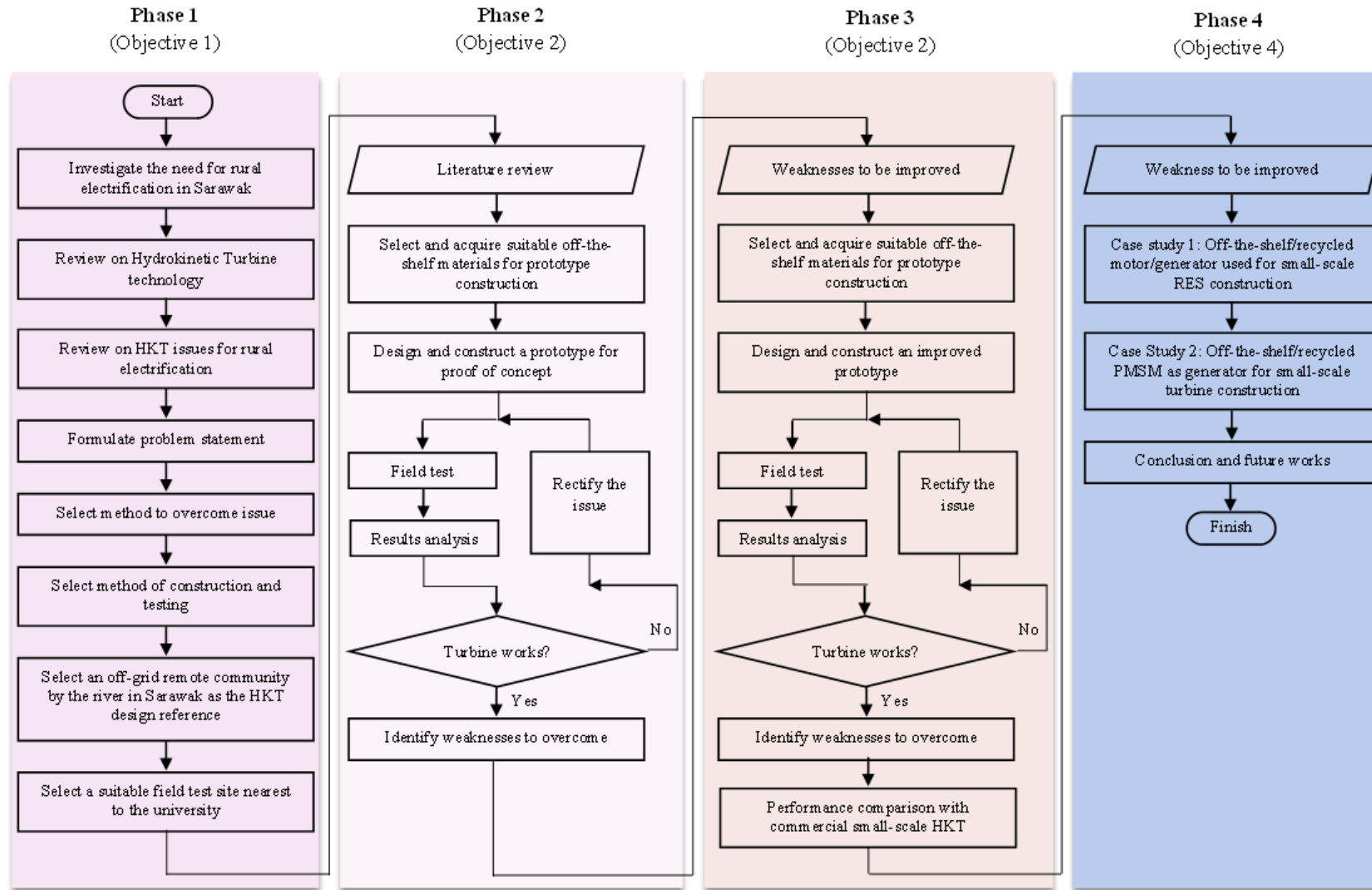


Figure 3.2: Study flow chart.

The study will design and construct a full-scale prototype in the second phase. It is mainly for proof of concept. The weaknesses from the prototype field test became the input for phase 3, which is the design and construction of an improved prototype. The objective of phase 3 is to come out with a prototype that works. Meanwhile, Phase 4 would focus on case studies of the generator used in the small-scale HKT construction. The case studies involved the off-the-shelf/recycled Permanent Magnet Synchronous Motor (PMSM) as the generator.

3.3 Selection of HKT Design Reference

Most off-grid rural communities in Sarawak reside in the upper course of the Rajang and Baram Rivers and their tributaries. An example is the Kenyah ethnic village known as Long Busang, located in the Rajang Basin. Figure 3.3 and Figure 3.4 indicate the aerial view of the area using Google Maps and the locality in the Rajang Basin.

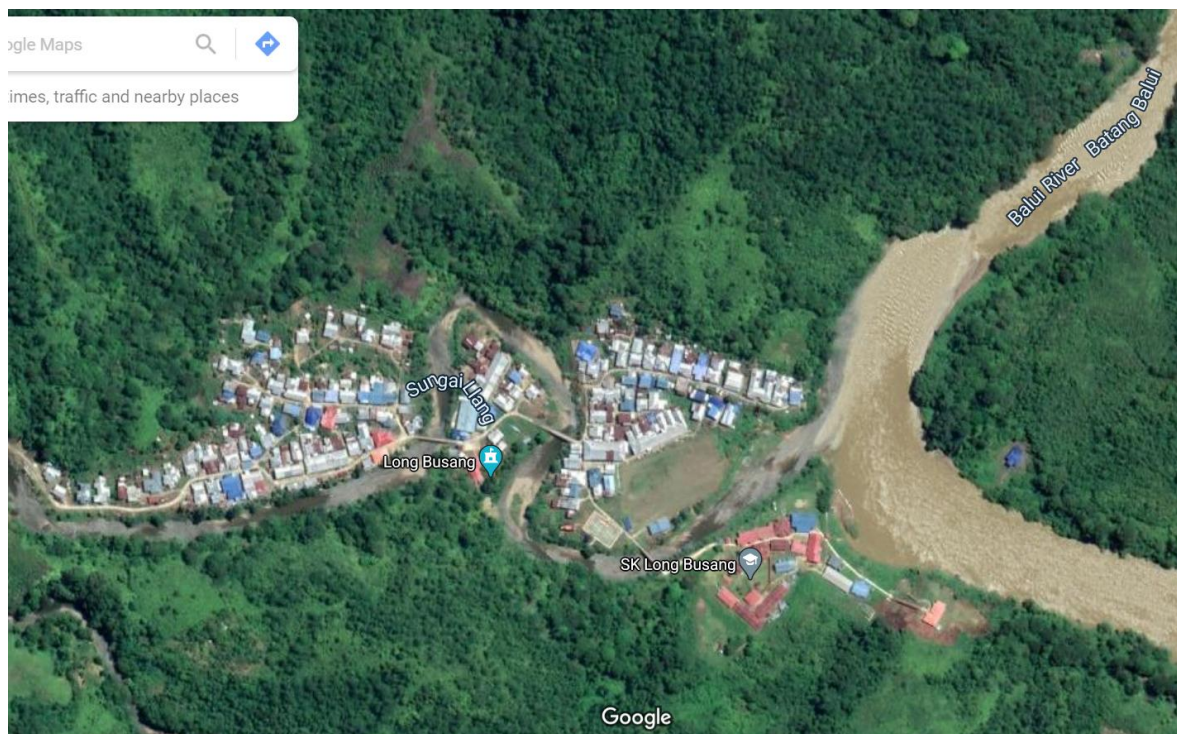


Figure 3.3: Long Busang village.

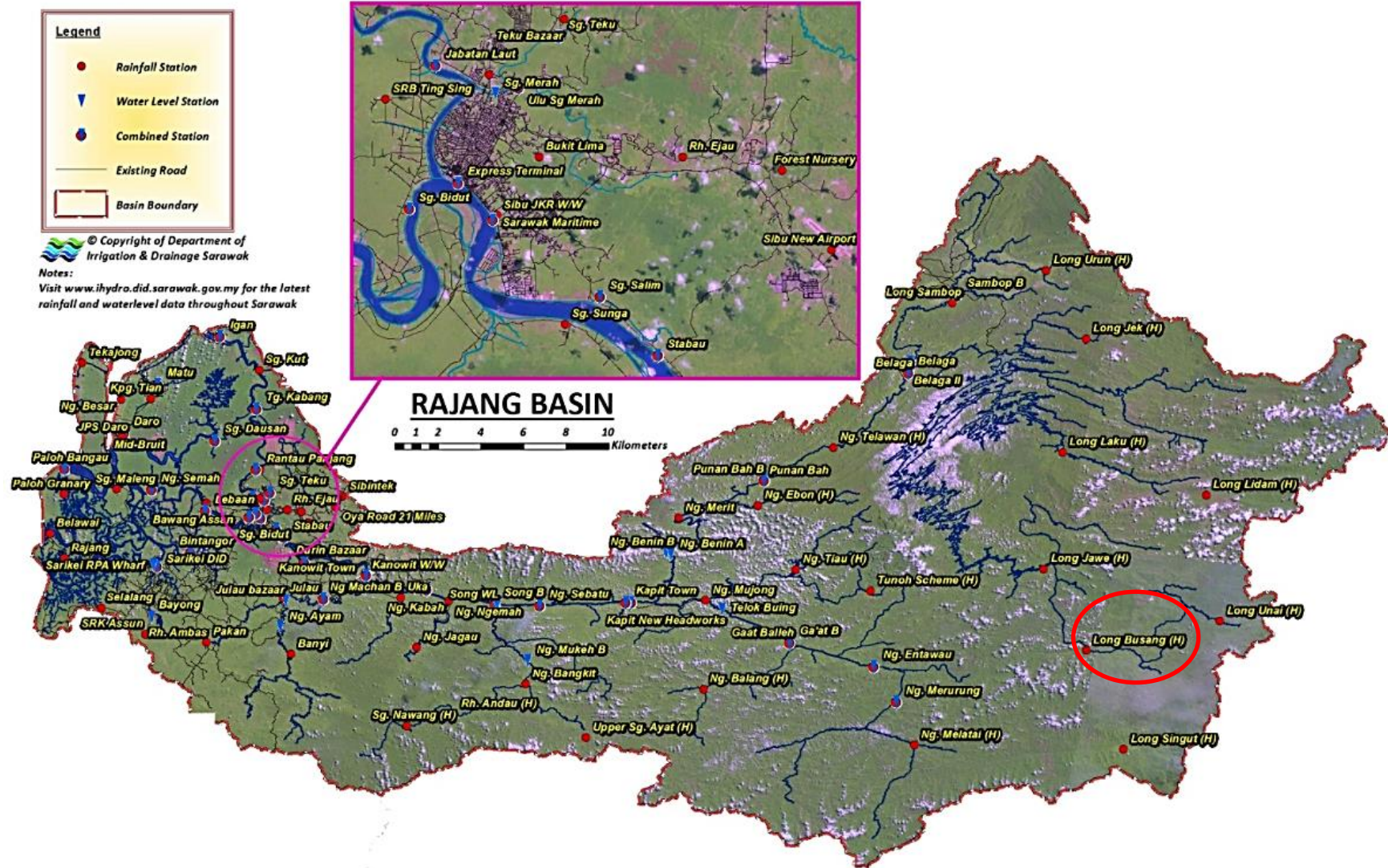


Figure 3.4: Locality of Long Busang in the Rajang Basin (DID of Sarawak, n.d.-b).

The journey from Bintulu to Long Busang would take 12 hours (3 hours on the road and 9 hours on a longboat) (Su Lin, 2015). Long Busang has a population of 1200, mostly subsistence farmers, fishermen, and jungle produce collectors. They depend on diesel generators for a few hours of electricity every night.

The Balui River flowing next to the village is relatively wide but is shallow (as river depth is usually less than a meter almost throughout the year). The estimated river flow velocity is between 1.0 to 1.5 m/s. The river usually contains a certain amount of suspended sediment, as can be seen in Figure 3.3. The river also carries submerged debris such as dead leaves, grass, and vines. Other than that, larger and heavier debris such as tree branches or rotten tree trunks can be found floating down the river during flash floods. Figure 3.5 shows a major flash flood at Long Busang in 2019, while over-logging and land-clearing activities caused a log jam at the upper reaches of the Balui River in 2017, as shown in Figure 3.6. The presence of submerged and floating debris beside the occasional flood provides additional difficulties to small-scale HKT design. First, the turbine rotor chosen must have the debris-shedding ability. Next is the floating debris mitigation, and lastly, a suitable turbine mounting technique for easy retrieval during a flash flood.

3.4 Selection of Field Test Site

Since the field test would not happen in the intended remote area due to practical reasons, there is a need to identify a suitable test site nearby with similar river characteristics. Consequently, there are two test sites surveyed. The first test site is near Danu village in the Padawan sub-district, Kuching division, around 45 Km from the university, as shown in Figure 3.7 and Figure 3.8.



Figure 3.5: Flash flood at Long Busang (Dayak Daily, 2019).



Figure 3.6: Log jam at the upper reaches of the Balui River (Lian, 2017).



Figure 3.7: First test site as indicated by the red marker.



Figure 3.8: Visual of the actual test site near Danu village.

While the second test site is near Suba Buan village in the Bau district, Kuching division, which is equally 45 Km from the university, as shown in Figure 3.9 and Figure 3.10. Both Figure 3.8 and Figure 3.10 show the river condition during a non-rainy season where the river should be shallow (less than 1 m deep). More importantly, both rivers have a similar flow velocity (estimated between 1.0 to 1.5 m/s) as the Balui River at Long Busang. After surveying the test sites for ease of accessibility, deployment, and recovery of the small-scale HKT is determined to do the field test at the river near Danu village.



Figure 3.9: Second test site as indicated by the red marker.



Figure 3.10: Visual of the actual test site near Suba Buan village.

3.5 Prototype for Proof of Concept

After the field test site was determined, the study began identifying suitable off-the-shelf materials for the prototype construction, mainly for proof of concept. The study would search for a suitable off-the-shelf rotor as the turbine rotor. Subsequently, the projected output power would determine the size of the generator. Thereafter, the turbine configuration, structure, transmission, mounting, and mooring would be designed and constructed. The prototype's design and construction process are divided into ten parts as illustrated in Figure 3.11 and explained in detail in the next section.

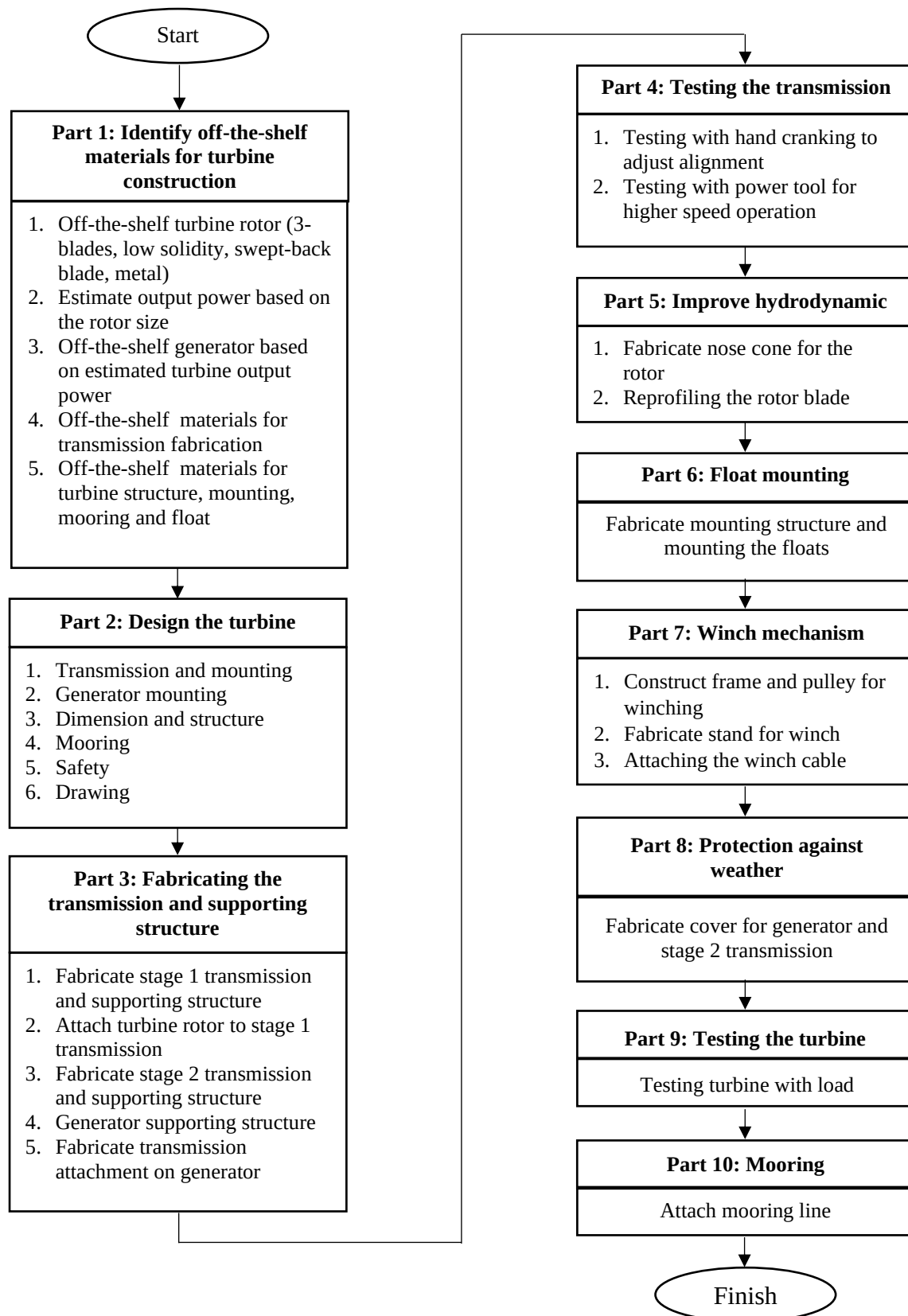


Figure 3.11: Flow chart for the prototype design and construction.

3.5.1 Design

Horizontal Axis HKT has a similar design and working principle as the Horizontal Axis Wind Turbine. Hence, the off-the-shelf rotor sought after would be a low-solidity type with 3-blades for higher speed operation. Meanwhile, a rotor with swept-back blades is preferred. The swept-back propeller has debris-shedding ability and is widely used in fishing boats, outboard engines, and wastewater treatment systems to avoid tangling with weeds and as suggested by Anyi & Kirke (2010). Examples of small-scale HKT using the swept-back propeller are the Smart Turbines (Smart Hydro Power, 2021) in Figure 3.12 and Flowwatt200 (Heliowatt, n.d.), as shown in Figure 3.13.

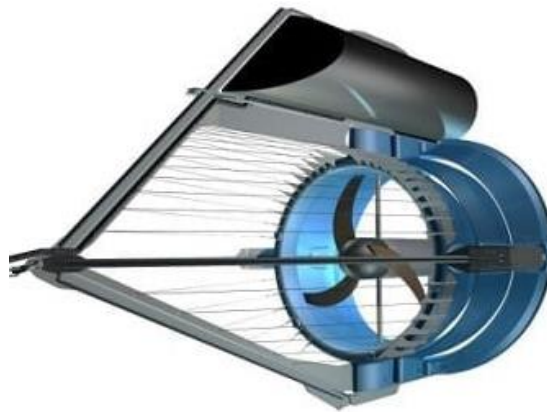


Figure 3.12: Smart Turbine (Engineering For Change, 2021).



Figure 3.13: Flowwatt200 (Heliowatt, 2021).

Since the power generated is directly proportional to the turbine rotor swept area, it is preferable to have a larger rotor. A 0.45 m diameter low solidity plastic fan rotor with three swept-back blades was chosen for the prototype construction, as shown in Figure 3.14. The fan rotor came from the KHIND brand 18" floor fan model FF1811. Unlike the conventional high-solidity plastic fan rotor, the fan rotor shown in Figure 3.12 has much thicker blades. With this fan rotor and the assumption of 0.20 overall turbine efficiency, the prototype would generate between 15.9 to 53.7 W with river flow velocity between 1.0 and 1.5 m/s shown in Figure 3.15. As small-scale river turbines usually have an efficiency of 0.25 (Vermaak et al., 2014), the 0.20 efficiency assumption should be reasonable.



Figure 3.14: Plastic fan rotor with three swept-back blades.

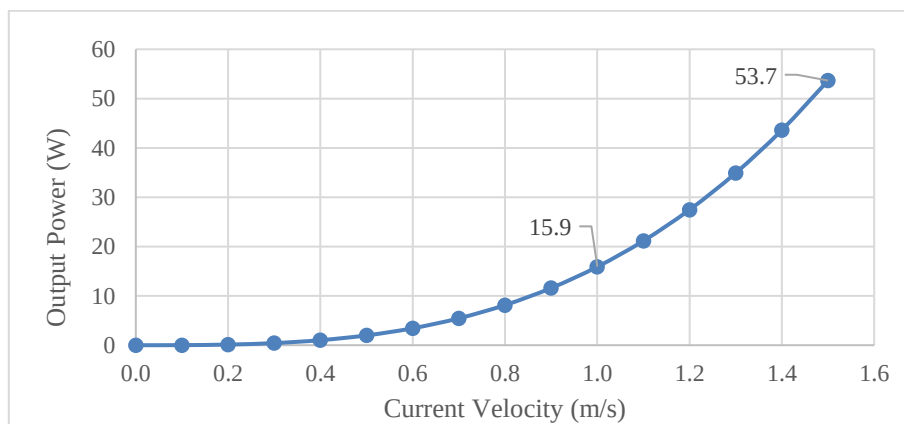


Figure 3.15: The predicted output power for the prototype.

Since the output power predicted is small, the study has decided to use a recycled Ryobi cordless drill DC motor as the generator for the prototype construction. The Ryobi cordless drill model used is shown in Figure 3.16. It has a rating of 18 V and 1300 maximum RPM. As for the transmission, the study has decided to use the long-shaft assembly from a conventional backpack brush cutter shown in Figure 3.17. The long shaft and additional gearcase are available as spare parts, and the modification needed for the inner driveshaft would be minimum.



Figure 3.16: Ryobi Cordless Drill.



Figure 3.17: A backpack brush cutter.

After acquiring the necessary part for the turbine rotor, generator, and transmission, the structure designing process eventually began. The prototype constructed would have a dimension of 1.52 m (h) $\times$ 1.77 m (w) $\times$ 3.40 m (l). Figure 3.18 and Figure 3.19 show drawings for the prototype. The swingable section on the prototype (for housing the

generator, transmission, and turbine rotor) would ease transportation and deployment to the field test site. Besides, a retracted position would enable simple access to the turbine rotor for maintenance whenever needed. The construction of the swingable section of the turbine utilizes hollow steel bars (size of 25 mm x 25 mm and 25 mm x 50 mm) to reduce its weight. Alternatively, the construction of the support frame for the swingable section utilizes 50 mm angle steel bars. In the meantime, a 50 mm galvanized round steel bar is used as the pivot shaft. Differently, the front pulley frame and floats mounting construction utilize smaller 40 mm angle steel bars. As for the aquaculture aerator, High-Density Polyethylene (HDPE) floats, two floats can support the weight of 60 Kg (as in the aerator paddle wheel device). Therefore, four floats are needed to support the prototype's estimated weight of 100 Kg.

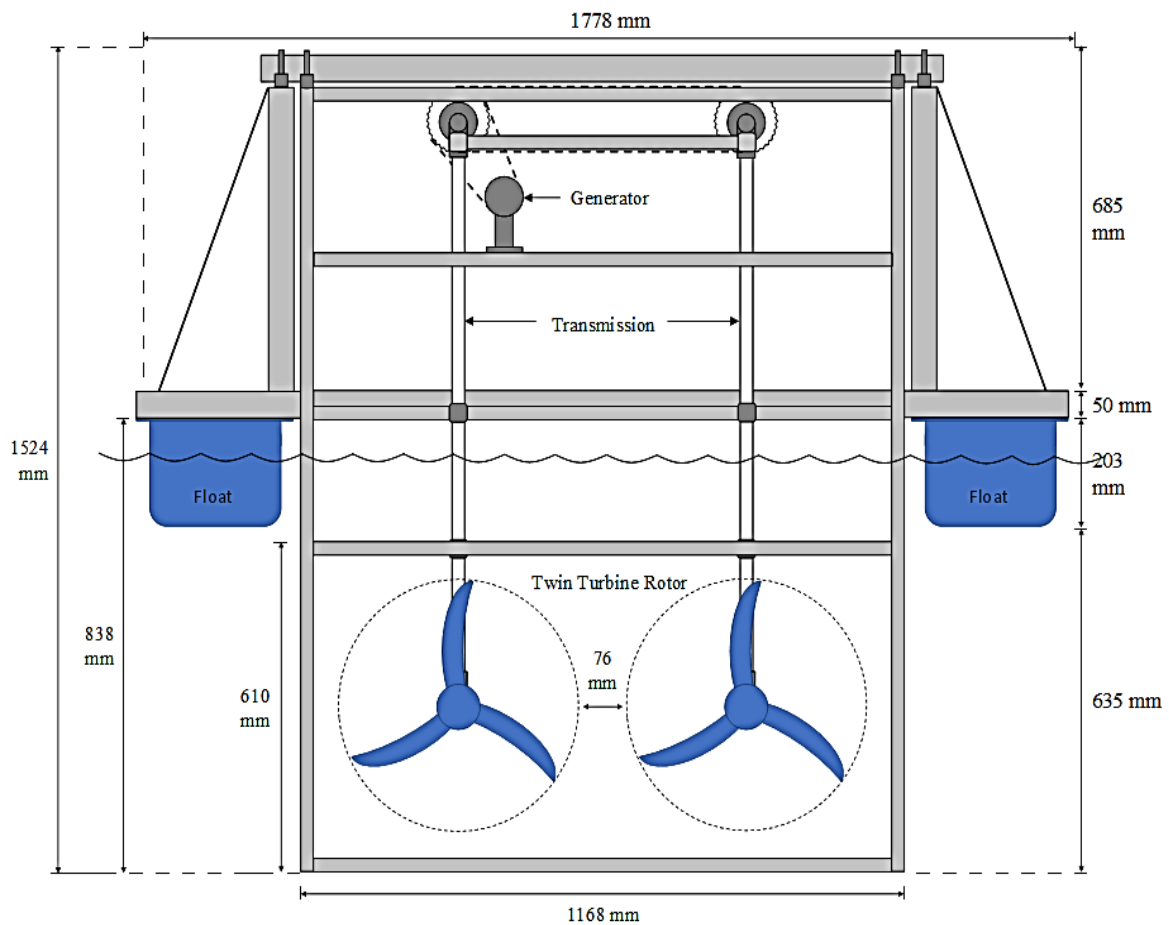


Figure 3.18: Front view of the prototype.

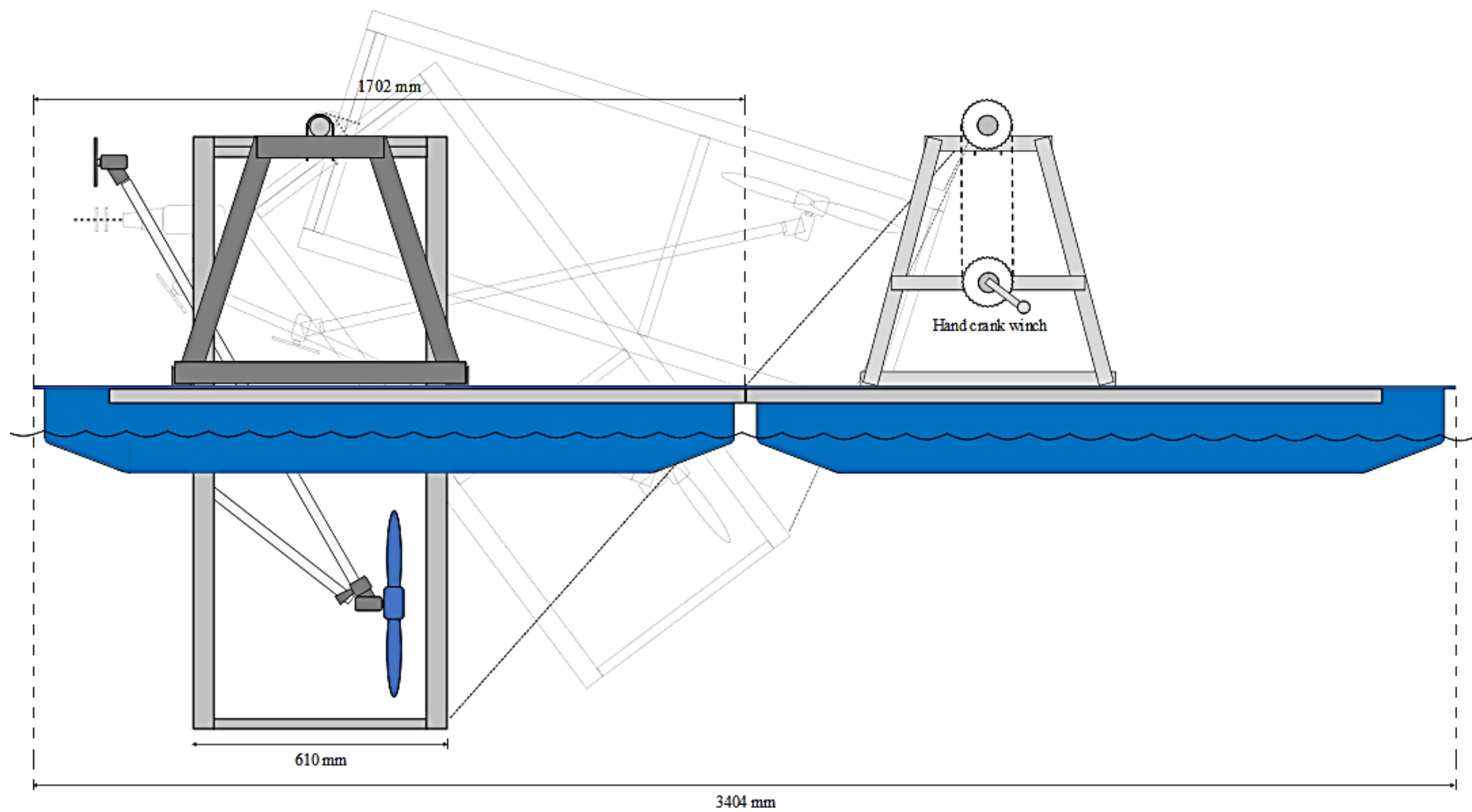


Figure 3.19: Side view of the prototype.

3.5.2 Construction

The construction started with the swingable section of the turbine. The study has decided to use a twin-turbine rotor design to increase the output power as the turbine rotor selected was small. The transmission fabrication started with some modifications to the inner driveshaft (where the flexible driveshaft from the backpack is attached) to fit an additional gearcase. Therefore, the long brush cutter shaft now would have a gearcase on both ends. Next, the fan rotor hub needed some trimming before attaching to the gearcase with a metal plate, bolts, and nuts, as shown in Figure 3.20. A metal plate inserted between them would add strength to the rotor assembly. Finally, the two long-brush cutter shafts and the turbine rotors are equally spaced and attached to the swingable section. The rotors are 76 mm apart.

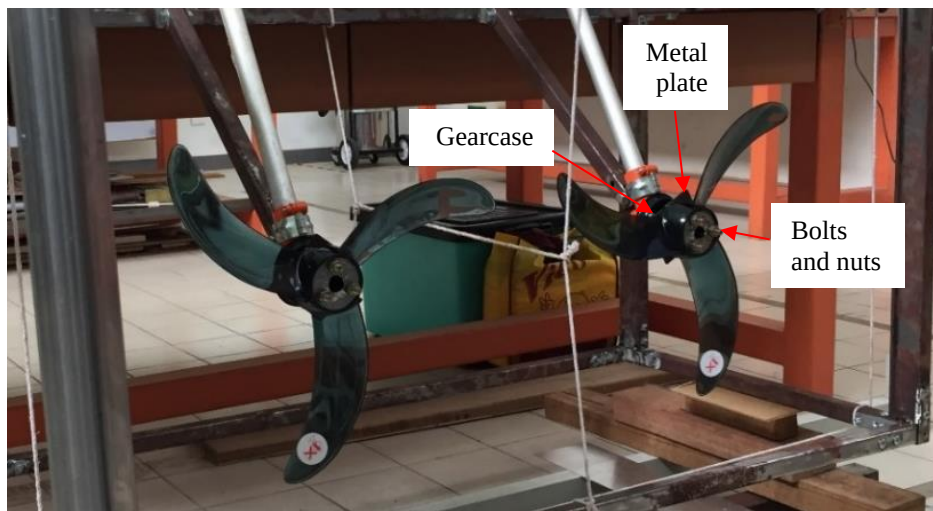


Figure 3.20: Twin-turbine rotors attached to the gearcases.

The generator is retained in its original housing to minimize the fabrication needed. Strong hardwood panels fabricated for the generator would hold it in place, as shown in Figure 3.21. A modified bicycle hub and sprocket are then attached to the generator's chuck and held in position by two pillow block bearings. The bicycle sprockets are then attached to the other gearcase for both brush cutter shafts. One gearcase would have double sprockets

(attached back-to-back with bolts and nuts), one sprocket for driving the generator (with a 2:1 gear ratio), and one more for running in synchronous with the sprocket from the other gearcase, as shown in Figure 3.22.

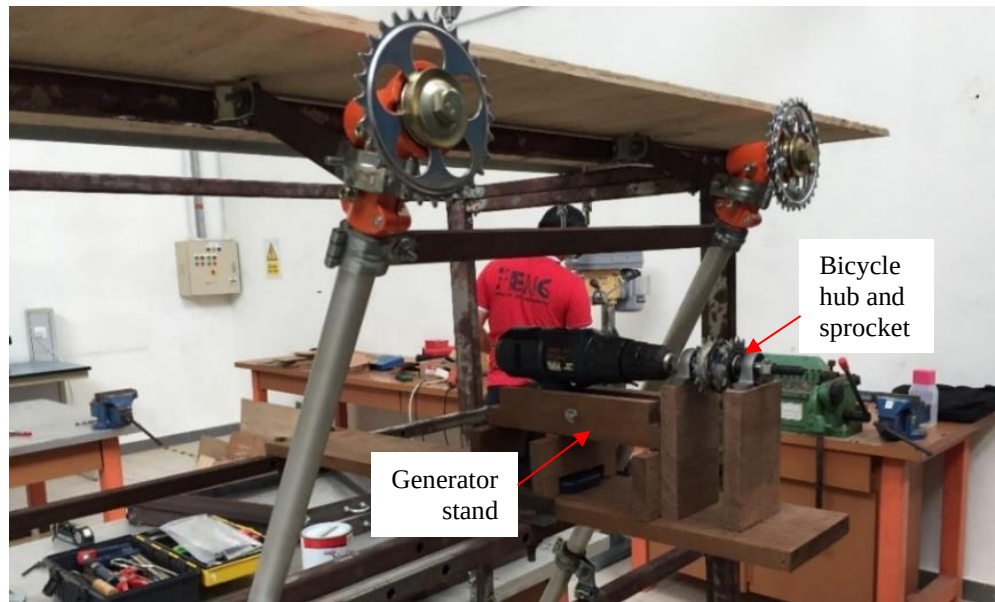


Figure 3.21: Fabricated generator stand.

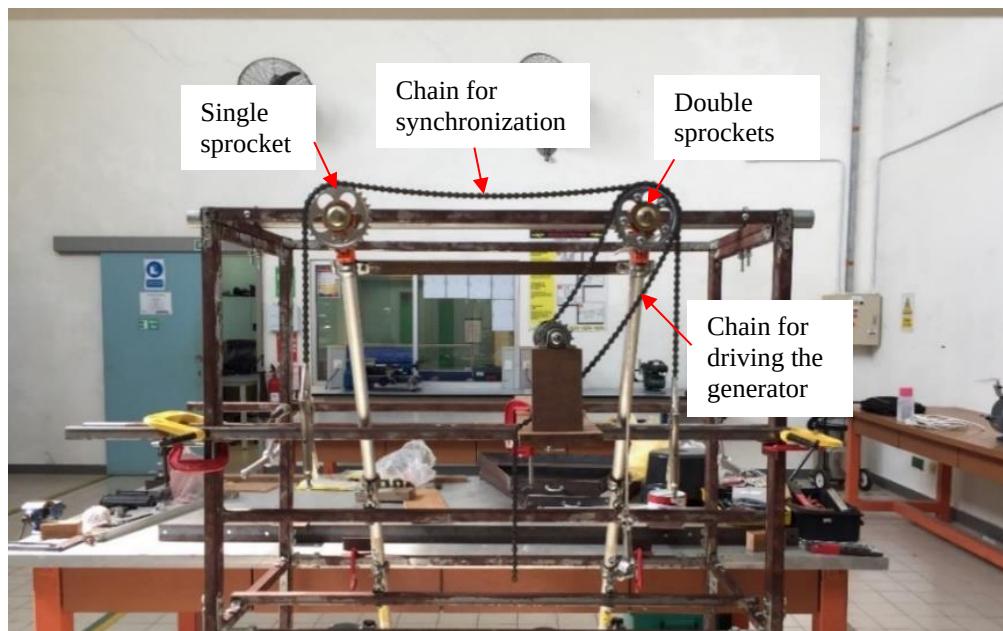


Figure 3.22: Fabrication of the generator transmission.

After assembling the two-stage transmission, a functionality test is done with a cordless drill, as shown in Figure 3.23. The fan rotor hub has a flat top (that can cause drag), as shown in Figure 3.14. Consequently, a small wooden nose cone is fabricated for the turbine rotor (and later will be coated with acrylic paint), as shown in Figure 3.24.



Figure 3.23: Testing the transmission with a cordless drill.

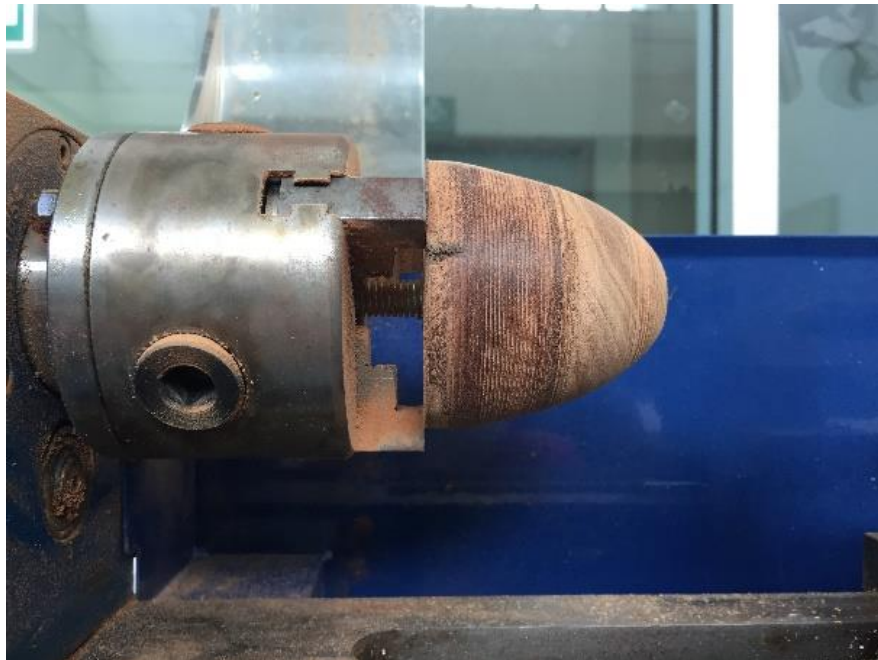


Figure 3.24: Fabricated nose cone.

With the swingable section completed, the fabrication advanced to the front pulley frame and mounting for the floats, as shown in Figure 3.25. A stand is fabricated for the hand crank winch, while a steel cable and two pulleys are attached to the frame, as shown in Figure 3.26.



Figure 3.25: Constructed frame for winching.



Figure 3.26: Hand crank winch and pulleys fixed to the frame.

The steel cable from the winch is then attached to the bottom part of the retractable section, as shown in Figure 3.27. For protection against the weather, a cover is fabricated with plastic cardboard and 25 mm hollow aluminium bars for the swingable section, as shown in Figure 3.28. The opening would allow measurement of the RPM or maintenance whenever needed.



Figure 3.27: Fixing the steel cable to the bottom of the swingable section.



Figure 3.28: Fabricated cover for the swingable section.

The completed prototype is shown in Figure 3.29, while Figure 3.30 shows the swingable section fully retracted.



Figure 3.29: The completed prototype.



Figure 3.30: The swingable section is fully retracted.

Before the field test, it was decided to run a simple pre-test for the prototype in the workshop with two DC 12 V 12 W LED light bulbs as the load and a cordless hand drill as a direct drive to the generator. When the lights are off, the cordless hand drill has no difficulty driving the generator at a higher speed and the transmission runs smoothly. However, when lights are connected, the output is insufficient to light up the lights to their full brightness, as shown in Figure 3.31. The study then repeated the test with smaller rating (12 V 10 W) LED lights, as shown in Figure 3.32. The simple test shows smaller ratings LED light tubes are better load for the prototype.



Figure 3.31: Repeated test with motorcycle filament light bulbs.



Figure 3.32: Repeated test with new LED light tubes.

3.5.3 Field Test

After about seven months of design and construction, the prototype was finally ready for field testing. The date agreed upon with the team and the head of Danu village was July 14th and 15th, 2018. To reduce the hassle of disassembling and reassembling the bulky and heavy prototype at the field test site, it had to be transported in one piece using a rented lorry, as shown in Figure 3.33 and Figure 3.34.



Figure 3.33: Putting the prototype onto the lorry.



Figure 3.34: En route to the field test site.

After arriving at the field test site, it is customary to pay a visit to the head of Danu village to acknowledge our presence and receive consent to conduct a two-day field test at the river. The approval was necessary as that particular section of the river is for river fish conservation known by locals as the *Tagang* System. The river section is a protected area and is strictly off-limit to any fishing activities. The prototype is then carried by four people and lowered to the river using a ramp near the cable-suspended pedestrian bridge, as shown in Figure 3.35 and Figure 3.36.



Figure 3.35: Lowering the prototype to the river using a ramp nearby.



Figure 3.36: The prototype had to be carried out by four people.

Upon reaching the river, the prototype is put in the river for the first time to check its buoyancy. As seen in Figure 3.37, it has sufficient buoyancy as predicted. Hence it can be easily guided to the spot for field testing, as shown in Figure 3.38.



Figure 3.37: Testing the prototype buoyancy.



Figure 3.38: The prototype is being guided to its field-testing spot.

When the prototype reached the testing spot, the river was shallow (around two feet deep), as shown in Figure 3.39. Therefore, the swingable section of the prototype was sitting on an uneven, rocky riverbed. As a result, the rear side of the turbine became tilted, as shown in Figure 3.40.



Figure 3.39: The prototype is secured to the testing position.



Figure 3.40: The turbine tilted as the river was shallow.

Figure 3.41 shows the simple field-testing setup. The study has decided to do a no-load test first. Next, a test with a single LED light as the load. Afterwards, with two LED lights as load. The output voltage is measured and recorded every minute. At the same time, a video camera captured the sprocket's turning for the RPM measurement, as displayed in Figure 3.42. While the flow velocity is quantified using the float method over a distance of 9 m. Figure 3.43 shows a simple float with a half-filled 500 ml plastic mineral water bottle for the test.



Figure 3.41: The prototype testing setup.



Figure 3.42: The prototype RPM measurement.



Figure 3.43: River flow velocity measurement with float method.

The river flow velocity is measured using the float method with a correction coefficient of 0.85 (Haan et al., 1994; Hauer & Lamberti, 2006). The field test results are analysed and discussed in Chapter 4, Section 4.2.1. Apart from the results, the study would also observe the performance of the turbine rotor, transmission, generator, and overall structural design. The performance evaluation will be discussed in Chapter 4, Section 4.2.2.

3.6 Improved Prototype

After completing the prototype field test, the study took time to examine the results and weaknesses to overcome. This information is crucial for the design of the improved prototype. In maintaining only off-the-shelf materials for the upgraded improved prototype construction, the study would follow through with similar steps in the construction process as the previous prototype, as shown in Figure 3.44. For the improved prototype, the objective would be to come out with a working prototype. Therefore, choosing the right and suitable materials is critical to overcoming the previous weaknesses.

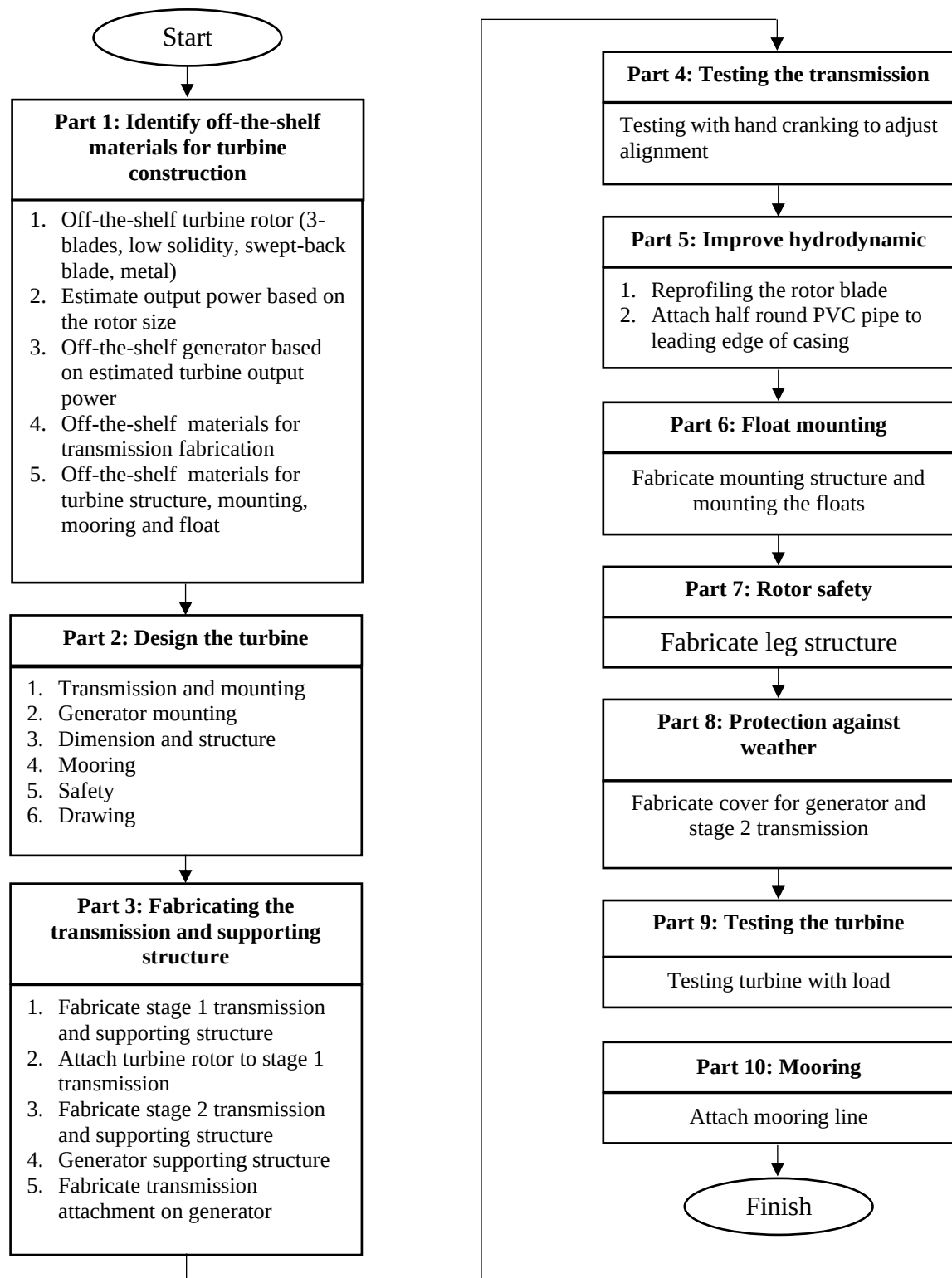


Figure 3.44: Flow chart for the improved prototype design and construction.

3.6.1 Design

For the improved prototype, the horizontal axis turbine configuration was again selected, for its self-starting capability, higher rotor speed, lack of torque fluctuation, and higher efficiency (Anyi & Kirke, 2010; Khan et al., 2009; Tian et al., 2018; Vermaak et al., 2014). While the non-submerged generator type of design is chosen for cost-effectiveness as it reduces manufacturing and maintenance costs (Instream Energy Systems, 2020; Khan et al., 2009; D. Kumar & Sarkar, 2015; Sørnes, 2010). It also reduces the difficulty of finding suitable waterproof components off-the-shelf such as a waterproof generator.

In the previous prototype field test, the two rotors with swept-back blades had shown their worthiness for working in a debris-laden river during the field test. Therefore, a larger fan rotor would be appropriate for the improved prototype. However, there is no bigger-size fan rotor available with that kind of design. Hence, it was decided to switch to the 0.585 m aluminium fan rotor with just two swept-back blades. The 0.585 m fan rotor would produce $(0.585/0.45)^2 = 1.69$, roughly 69 % more shaft power than the previous 0.45 m fan rotor.

The fan rotor in Figure 3.45(a) is the original aluminium fan rotor for an industrial stand fan (model KHIND SF2401). The thin and highly cambered section is similar to the NACA 6406 profile except that it has a blunt trailing edge, so this was ground and sanded to a sharp trailing edge to reduce drag without significantly affecting its strength for the rotor in Figure 3.45(b).

Meanwhile, Figure 3.46 depicts the differences between the original and reprofiled fan rotor. Other than that, the drawing in Figure 3.47 shows the measured chord length and twist angle of the fan rotor. With the 0.585 m fan rotor as the turbine rotor and the assumption of 0.20 overall efficiency, the improved prototype can generate between 26.9 to 90.7 W (68

% higher output than the previous prototype) from 1.0 to 1.5 m/s flow velocity shown in Figure 3.48. Due to the higher output power predicted compared to the previous prototype, the improved prototype would require a generator with higher ratings.



Figure 3.45: The fan rotor with two swept-back blades.

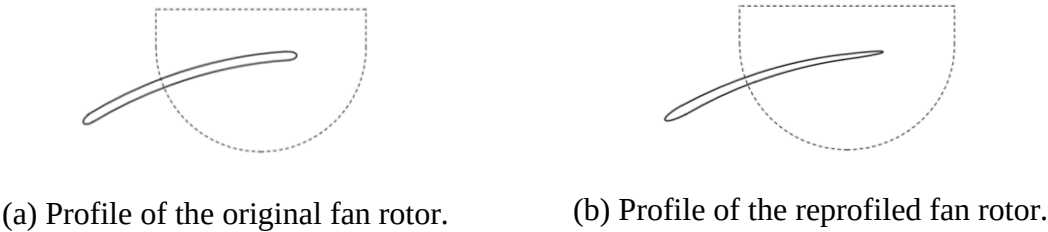


Figure 3.46: Difference between the original and reprofiled fan rotor.

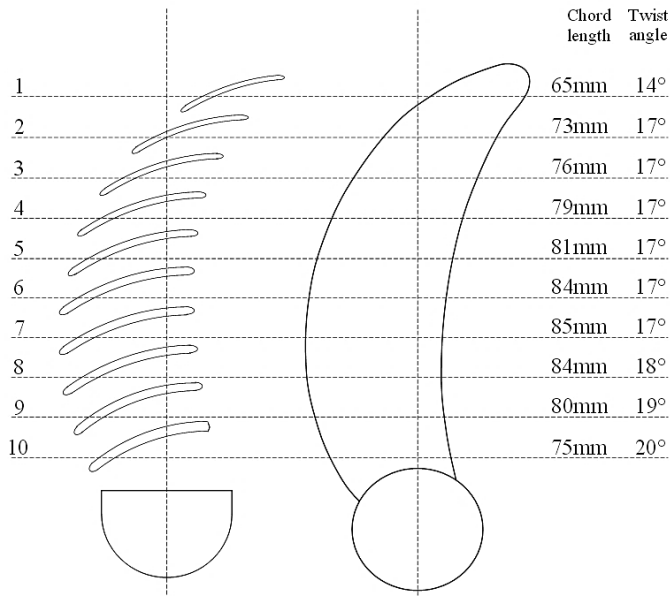


Figure 3.47: Chords lengths and twist angles of the fan rotor.

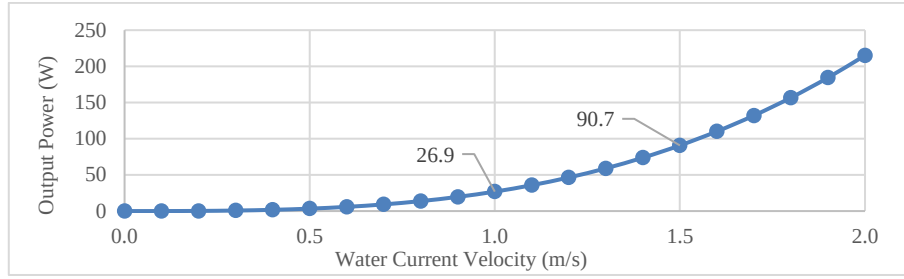


Figure 3.48: The predicted output power for the improved prototype.

When it comes to generator selection for the improved prototype, there are countless choices available, from high-speed to low-speed, from AC to DC, and beyond. In the end, the study has decided to choose a suitable generator based on two criteria: (i) Gearing requirement and (ii) AC or DC power. The RPM recorded from the previous prototype field test was 208. Therefore, the generator preferred for the improved prototype would be from the low-speed type to avoid the massive gearing ratio needed. Consequently, this could lead to a less expensive gearing system, and suitable off-the-shelf gearing components would be easier to acquire.

Due to the relatively small output power, the study has decided to use a DC generator to avoid further losses due to power electronics converter circuits. Although the usage of DC generators in small-scale HKT is not encouraged due to their low transmission efficiency (Güney & Kaygusuz, 2010; Vermaak et al., 2014), it can if the electricity production is for limited usage (Güney & Kaygusuz, 2010). The Permanent Magnet DC Generator (PMDCG) is also commonly used in small wind turbines (Bastankhah & Porté-Agel, 2017). Besides, DG using DC sources, i.e., solar power systems, is conventional in micro- or nano-grid to supply electricity to the off-grid rural communities. DC micro- or nano-grid powered by a DC source and low voltage DC (LVDC) distribution are more efficient as they have fewer power conversions (Burmester et al., 2017; Manandhar et al., 2016). Therefore, a small-scale

HKT with DC generators would be easier to integrate with a solar power system commonly used in rural electrification projects.

Eventually, the generator selection boils down to either a brushed DC or a brushless DC (BLDC) machine. Even though a BLDC machine is significantly more efficient (Dirjish, 2012), it produces AC power when run as a generator (Kafader, 2018). Consequently, the only choice left is a brush DC machine. The generator chosen is a low-speed Permanent Magnet DC Motor (PMDCM), model MY1018, commonly used for electric bicycles or scooters, as shown in Figure 3.49. Table 3.1 has its specification listed. With a rated speed of 2750 RPM and a 7.18:1 internal gear, the output RPM is $2750/7.18 = 383$ RPM.



Figure 3.49: Permanent magnet DC motor with an internal gearing system.

Table 3.1: Specification of the DC motor.

Model	MY1018
Rated Power	250 W
Rated Voltage	24V DC
Rated speed	2750 RPM
Unload speed	3150 RPM
Rated current	≤ 13.40 A
Unload current	$\leq 2.2/2.0$ A
Rated torque	0.87 Nm
Motor Efficiency	≥ 78 %
Gear Ratio	7.18:1

For the improved prototype transmission construction, there are many options available. Apart from the bicycle chain transmission and brush cutter shaft used in the previous prototype, one can use a belt and pulley system or a bevel gearbox for superior

efficiency. Both timing belt and bevel gearbox systems boast a 98 % efficiency (Grainger, 2019; ROYMECH, 2021) compared to 81 to 98 % for bicycle chain transmission (John Hopkins University, 1999). However, a belt and pulley system and bevel gearbox are typically far more expensive than the bicycle chain transmission. Consequently, bicycle chain transmission is still being used to reduce the cost of transmission construction. However, it is only limited to a short bicycle chain to the generator's sprocket in the second stage of the transmission system. Contrastingly, the first stage utilized a belt and pulley system. The motivation behind the two-stage transmission was to enable the creation of a small-speed multiplier system. To further reduce the cost, the transmission construction utilized a combination of new components and repurposed materials.

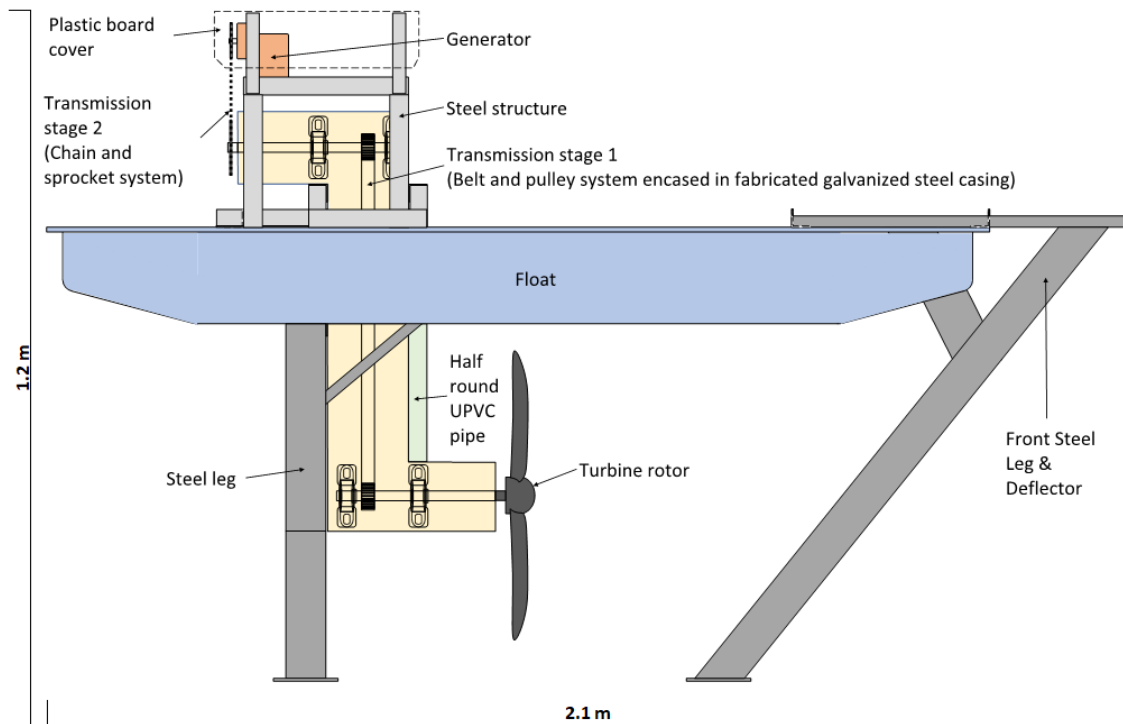
Meanwhile, the improved prototype design would not include any screen/grid, as that would cause a drop in water flow velocity (Anyi & Kirke, 2010; D. Kumar & Sarkar, 2015). The idea of adding a diffuser for augmentation, i.e., to increase the performance of the improved prototype, was also discarded as it is considered unsuitable due to the presence of submerged debris (Anyi & Kirke, 2010; Gaden & Bibeau, 2010). Also, the turbine mounting on float would maintain too. Furthermore, since designing an efficient and robust transmission for a twin-turbine rotor configuration is challenging, the study has decided to use a single-turbine rotor instead. Steel angle bars are used instead of hollow steel bars to increase the structure's sturdiness. The steel legs and floats can be taken apart and reassembled, i.e., without affecting the structural integrity, to assist transportation using a small pickup truck.

A set of leg structures was constructed for the improved prototype to protect the turbine rotor against hitting the riverbed (if the water level dropped below 0.8 m). This 0.8

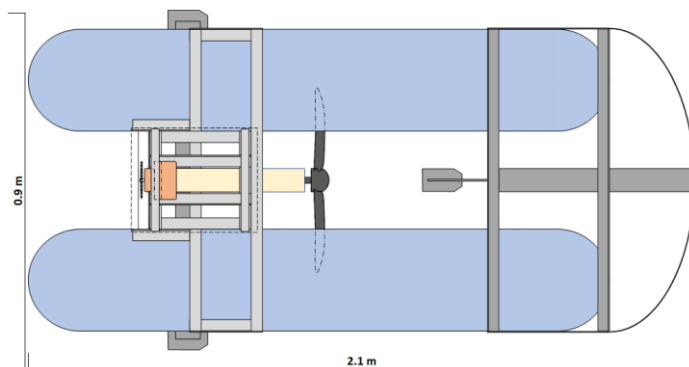
m also serves as the minimum water level needed for the turbine to stay afloat. The front steel leg and deflector would protect the improved prototype from the possible impact of large floating debris, as mentioned in section 3.3. The leg structure fabrication utilized a combination of 25 mm and 75 mm flat steel bars. Since the small-scale HKT design was to suit the application in a remote area, practicality in transportation, deployment, and recovery needs to be improved compared to the previous prototype. The improved prototype design is smaller and lighter with a dimension of just 2.1 m (l) $\times$ 0.9 m (w) $\times$ 1.2 m (h) and weighs around 60 Kg. Figure 3.50 shows the schematic drawings of the improved prototype design.

3.6.2 Construction

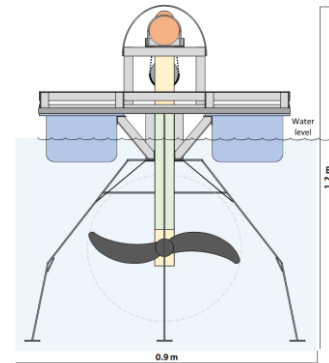
With the turbine rotor and generator acquired, the improved prototype design was completed, and the study then moved on to transmission fabrication. The new transmission and structure design would minimize submerged debris caught on the turbine structure as happened to the structure of the previous prototype. Considering the transmission does not come as a single off-the-shelf component, its fabrication would go hand-in-hand with the structure construction. The first stage utilized a timing belt and car pulleys to connect the turbine rotor shaft to the second transmission shaft. The timing belt has the advantages of requiring minimal maintenance and re-tensioning, the ability to operate in a wet and oily environment and running slip-free (Advanced Manufacturing Office, 2012). The two shafts are held in place by four pillow block bearings and encased in a fabricated “Z-shape” casing from galvanized lip channel steel. Galvanized steel would prevent corrosion, while a fabricated rubber gasket and oil ring would prevent leakage. A half-round Unplasticized Polyvinyl Chloride (UPVC) pipe is later attached to the leading edge of the casing to reduce drag.



(a) Side view



(b) Top view.



(c) Front view

Figure 3.50: Schematic drawing of the improved prototype.

The first stage of the transmission fabrication started with a suitable set of recycled car pulleys, a timing belt, and pillow block bearings. The pulley was first attached and welded to a fabricated 20 mm shaft shown in Figure 3.51. The assembly of all these components on slotted angle bars would help determine their size before cutting the lip channel steel, as shown in Figure 3.52. Next, the two sets (1 set as the casing cover) of

galvanized lip channel steel pieces are trimmed and welded to form the casing, as shown in Figure 3.53.



Figure 3.51: Pulley attached and welded to the shaft.



(a) The belt and pulleys layout.



(b) Galvanised lip channel steel cut to size.

Figure 3.52: Fabrication of the transmission casing.



Figure 3.53: Galvanised lip channel steel trimmed and welded.

Up until now, the fabrication work on the transmission was somewhat straightforward. The hardest part is getting the belting system installed and aligned. Fortunately, the pillow block bearings attachment allowed some adjustment. A belt guard fabricated inside the casing would ensure the belt stays on its course. The fabrication then proceeds to the end of the transmission, where the turbine rotor would be attached, as shown in Figure 3.54. The completed transmission casing was clean and coated with anti-leaking sealant, as shown in Figure 3.55.



Figure 3.54: Oil seal attachment on the transmission casing.



Figure 3.55: Casing coated with the anti-leaking sealant.

The transmission casing was later spray painted, and the belting system was installed and aligned, as shown in Figure 3.56. Meanwhile, the construction of the rubber gasket utilized a commercial-grade rubber sheet to prevent leakage. As an extra precaution, it was decided to add silicone glue.

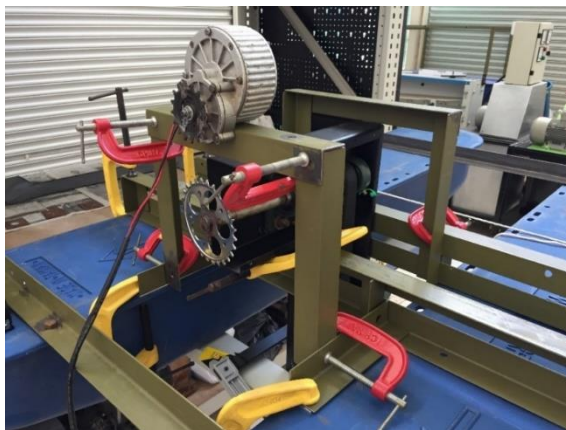


Figure 3.56: The completed first stage of the transmission.

Subsequently, the sprocket and turbine rotor were attached, and the assembly was placed in between two floats, as shown in Figure 3.57, for the erection of the turbine-supporting structure. The supporting structure fabrication utilizes 40 mm steel angle bars. The turbine rotor has three inches of clearance from the bottom of the floats. Afterwards, the erection of the generator supporting structure and a generator mounting plate was fabricated using a 2 mm steel plate, as shown in Figure 3.58.



Figure 3.57: Fabrication of the transmission supporting structure.



(a) Fabrication of the generator supporting structure.



(b) Fabricated generator mounting plate.

Figure 3.58: Supporting structure for the generator.

The second stage utilized a short bicycle chain transmission to connect the secondary shaft to the generator shaft. The exposed bicycle chain transmission would allow easy measurement of the turbine rotor's RPM at the bigger sprocket. Since the belting system (in the first stage) has a ratio of 1:1 and the bicycle chain transmission have 1:1.75, this has resulted in a 1:1.75 speed multiplier system. Hence, the combination of the DC motor

internal gearing and transmission ratio would be 1:12.565, which should be enough to drive the generator close to its the rated speed from the low turbine rotor RPM (i.e., around 219).

With the short bicycle chain added, it was decided to perform a simple test by turning the turbine rotor by hand to ensure the transmission was in working condition. A multimeter hooked up to the generator displayed 7 to 8 V produced and confirmed that the system was in good operating condition, as shown in Figure 3.59. The transmission test also provided the opportunity for adjusting the tension and alignment of the bicycle chain.

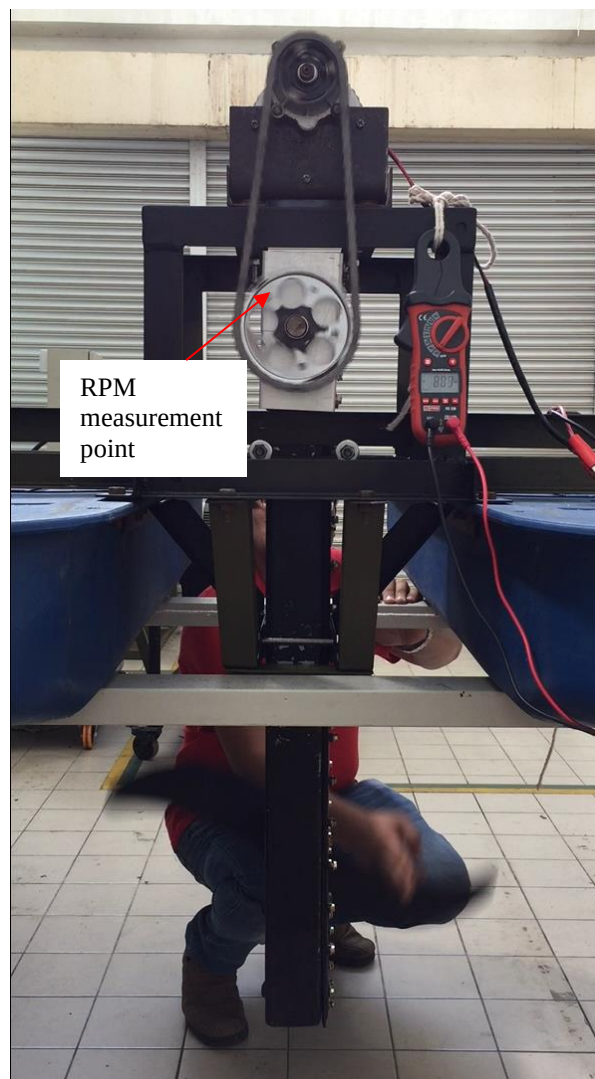


Figure 3.59: Testing the transmission.

In the next step, an additional set of supporting structures created at the side and rear of the transmission would ensure the submerged portion can withstand the force from the fast-flowing river flow. The supporting structure fabrication utilized smaller 25 mm steel angle bars and was attached using stainless steel bolts and nuts (for the submerged part) as depicted in Figure 3.60 and Figure 3.61.



Figure 3.60: Side supporting structure for the transmission.



Figure 3.61: Rear supporting structure for the transmission.

After completing the transmission support structure, it was time to fabricate the front and rear leg structure. While the front leg structure also serves as a larger debris deflector, its construction is 45° angles instead of vertical. The leg structure fabrication utilized a combination of 25 mm and 75 mm flat steel bars. The steel bars are bent and welded, as shown in Figure 3.62 and Figure 3.63.



Figure 3.62: Front deflector cum leg fabrication.



Figure 3.63: Rear leg structure fabrication.

With the leg structure completed and attached, the improved prototype is almost ready for its field test. For the finishing touches, to protect the generator from the rain, a plastic cover is used. A half-round UPVC pipe is later attached to the leading edge of the casing to reduce drag. Figure 3.64 shows the completed improved prototype with its leg structure attached, while Figure 3.65 shows the leg structure removed.



Figure 3.64: Completed improved prototype.



Figure 3.65: Completed improved prototype with leg structure removed.

Before the field test, the study conducted a pre-test to ensure the improved prototype was in good working condition. Based on the output power predicted of 26.9 W at 1.0 m/s river flow velocity for the improved prototype and the measured 0.86 m/s river flow velocity from the previous field test, it's decided to use only five DC 12 V 9 W LED lights (45 W in total) as the load. Figure 3.66 shows the pre-test conducted with the turbine rotor turned by hand. It also indicated simple hand-turned rotor produced $4.7 \text{ A} \times 10.3 \text{ V} = 48.41 \text{ W}$ of power.



Figure 3.66: The improved prototype test with a load.

3.6.3 Field Test

After about six months of construction, the improved prototype was finally ready for field testing. The date agreed upon with the team and the head of Danu village was Jan 26th, 2019. The steel legs and floats can be taken apart and reassembled at the field test site, i.e., without affecting the structural integrity, to assist transportation using a small pickup truck, as shown in Figure 3.67. After meeting with the head of Danu village, the improved

prototype was reassembled and put into position for its field test. The smaller improved prototype was less hassle and required less workforce to deploy compared to the previous prototype. Since the river flow velocity was higher than the previous field test, multiple ropes are needed to secure the improved prototype to a suitable testing position, as shown in Figure 3.68.



Figure 3.67: The improved prototype was transported using a small pickup truck.

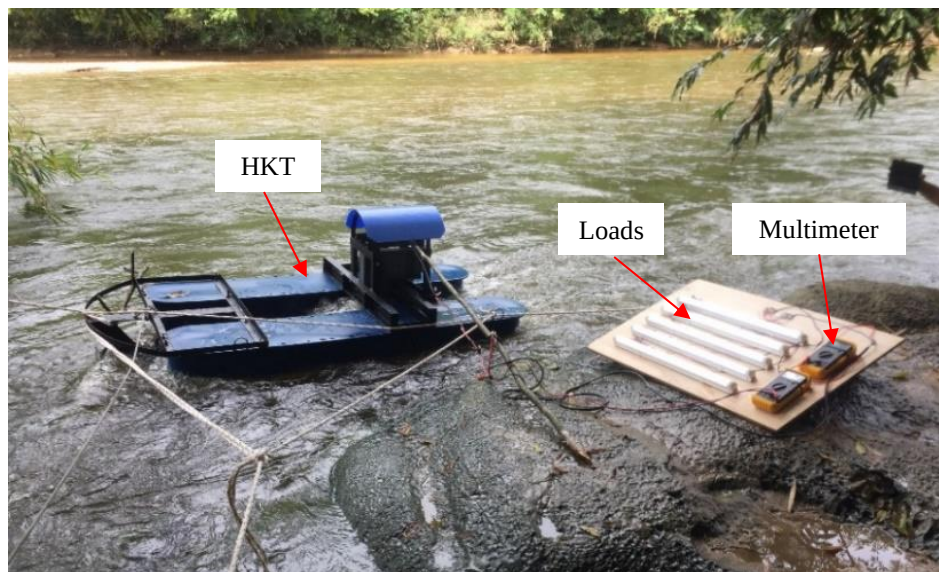


Figure 3.68: The improved prototype field test setup.

The northeast monsoon season (from December until March) brings heavy rains to the coast of Sarawak. This wet monsoon season has caused a rise in the water level at the field test site. The study has anticipated a higher water level and slightly stronger flow than the previous field test, but not up to the extent seen at the field test site. The water level has risen to over a meter while the river flow has significantly increased. Nevertheless, the study has decided to proceed with the field test with some extra precautions.

The first turbine rotor to be tested was the original fan rotor, as shown in Figure 3.45(a), followed by the reprofiled turbine rotor in Figure 3.45(b). For each rotor, a no-load test was performed first, then a load test. Next is the turbine's RPM measurement using a handheld infrared tachometer. The load utilized consists of five DC 12 V 9 W LED lights, while the output voltage and current are measured from the generator by two digital multimeters (APPA 93N). As the meter reading fluctuated rapidly, a video camera would record sample data for each test. Playback of the videos was done at a later stage to retrieve the data. The river flow velocity is measured using the same float method with a correction coefficient of 0.85 (Haan et al., 1994; Hauer & Lamberti, 2006). The field test results will be analysed and discussed in Chapter 4, Section 4.3.1. Apart from the results, the study would also analyse the performance of the turbine rotor, transmission, generator, and overall structural design. The performance evaluation will be discussed in Chapter 4, Section 4.3.2.

3.7 Generator Case Studies

In Section 4.3.2, the study has estimated the efficiency of the PMDCG to be 80 % which is acceptable. However, the one weakness encountered during the field test of the improved prototype was the PMDCG noise (from the internal gearing) during operation.

Although the generator's noise can only be heard up to a short distance away and is not a big deal, it is a form of pollution and a disturbance to the tranquillity of rural life.

To overcome the PMDCG noise issue, the study will conduct two case studies. In keeping the theme of simple small-scale HKT design and construction using only materials from off-the-shelf, the two case studies would focus on determining types of off-the-shelf/recycled motor/generator that can be directly used or modified in constructing a small-scale RES.

3.7.1 Case Study 1: Off-The-Shelf/Recycled Motor/Generator Used for Small-Scale RES Construction

The objective of the first case study is to determine the type of off-the-shelf/recycled motor/generator that can be used to construct a small-scale RES. To achieve this, the study would look at publication in journals and websites that contains such information. Findings from this case study will be considered useful inputs in designing and constructing a simple small-scale HKT with the choice of a tested off-the-shelf/recycled motor/generator. The results will be analysed and discussed in Chapter 4, section 4.4.1.

3.7.2 Case Study 2: Off-The-Shelf/Recycled PMSM as Generator for Small-Scale Turbine Construction

From the first case study, it is found that the Smart Drive motor is both an attractive and versatile candidate to be used as a generator for small-scale RES design and construction. Therefore, the study has decided to further evaluate this Smart Drive motor. The second case study would be divided into four parts as follow:

- i. Smart Drive motor output testing.

- ii. Smart Drive motor cogging test.
- iii. Smart Drive generator testing under different stator configurations.
- iv. Smart Drive generator for small-scale HKT design.

3.7.2.1 Smart Drive Motor Output Testing

In the first part, the case study will look into the details of the Smart Drive motor, particularly with the 42-pole 60s model that is available at hand, as shown in Figure 3.69. It is an External Rotor Permanent Magnet Synchronous Motor (ER-PMSM). It is a sinusoidally excited motor. Due to its three-phase sinewave back-EMF, it is also known as a brushless AC motor. The ratings for the Smart Drive motor are 240V, 50Hz, and 165W. The stator has 42 salient poles, and the rotor has 56 poles (4 poles in 14 blocks), as shown in Figure 3.70.



Figure 3.69: The 42-pole 60s Smart Drive motor.

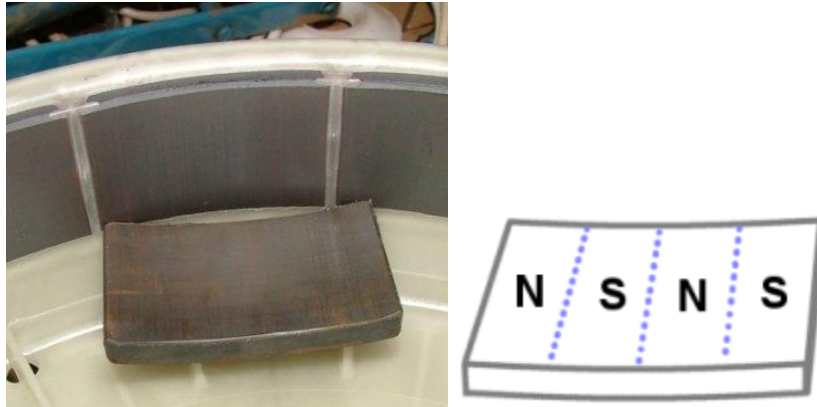


Figure 3.70: Permanent magnet block that contains 4 poles.

The permanent magnet is ferrite, and the slot-per-pole ratio is 0.75 (i.e., 42/56). The number of turns per coil is 170, and 2380 per phase (i.e., 14 coils connected in series), as shown in Figure 3.71. The wire material is copper with a size of 0.6 mm. The 14 coils in each phase are connected in series, while the three phases are star-connected, as shown in Figure 3.71.

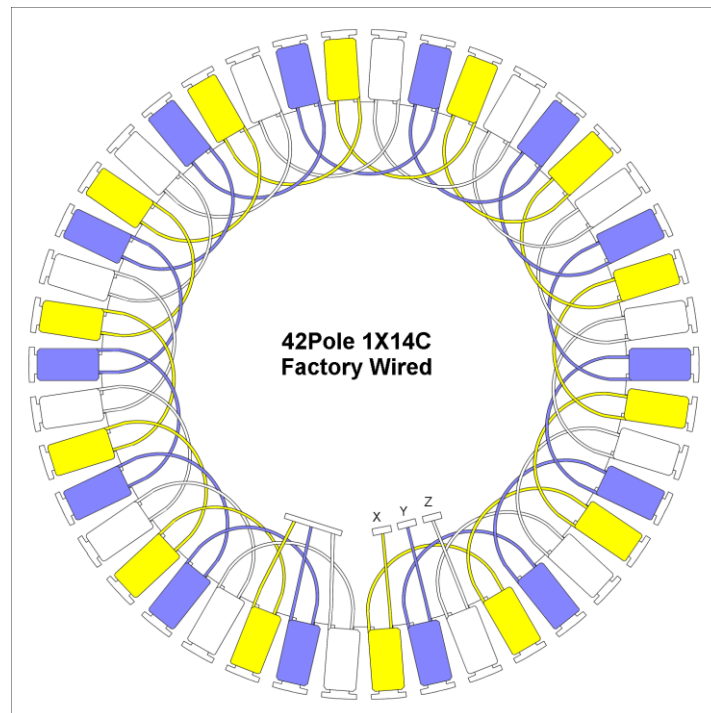


Figure 3.71: Series connection for the 14 coils.

The first experimental setup would verify the 60s Smart Drive motor is an ER-PMSM with sinewave Counter-Electromotive Force (back-EMF), as shown in Figure 3.72. The Smart Drive motor is hooked up to a small lathe machine in the laboratory as the prime mover. The Smart Drive motor is attached to a metal stand. One bicycle sprocket is attached to the lathe machine, and another sprocket is attached to the Smart Drive motor, as shown in Figure 3.72. A digital multimeter and an oscilloscope are connected to one of the motor's phases and neutral terminal. The lathe machine is switched on and slowly increases its speed until the Smart Drive motor starts running at 20 RPM. The rotation speed is maintained, and readings for the output voltage and waveform are recorded with the camera.

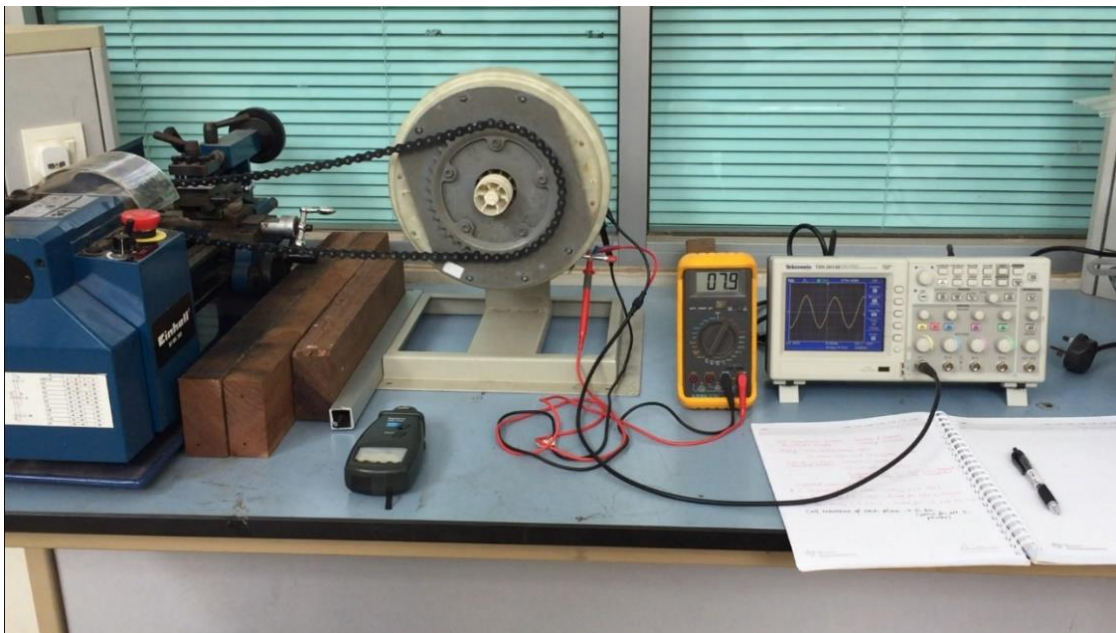


Figure 3.72: Experimental setup to verify sinewave back-EMF.

The second experimental setup is for testing the motor when running as a generator without load, as shown in Figure 3.73. Again, the rotation speed and output voltage are recorded in 10 RPM incremental steps. The objective is to establish the kind of output the Smart Drive motor can generate when running as a generator. The results for both experiments are analysed and discussed in Chapter 4, Section 4.4.2.1.



Figure 3.73: Testing the Smart Drive motor as a generator without load.

3.7.2.2 Smart Drive Motor Cogging Test

The second part of the case study will test the cogging torque (torque required to rotate the shaft from a standstill) of the 42-pole 60s Smart Drive motor. Cogging torque is a product of the magnetic interaction between the poles of the rotor's permanent magnets and the steel laminations of the stator's teeth (Collins, 2018). As cogging torque occurs in permanent magnet motors, including synchronous AC motors, brushed and brushless DC motors, the study would also test the brushed PMDCM used in the improved prototype construction for comparison.

According to Bhupendra (2015), the cogging torque of an electric motor can be found by simple rope and pulley-type dynamometer arrangement, by balancing (increasing) the weight of one end of the rope wound on the pulley. When the rotor starts to rotate, the required torque to rotate the shaft would be $\text{Torque} = (W_1 - W_2)R$, where R is the radius of the pulley. The unit for torque can be converted from "kgm" into "Nm" by multiplying the torque with the force of gravity (i.e., 9.81 m/s) (Haridas, 2014).

Figure 3.74 show the experimental setup for the cogging torque measurement of the 42-pole 60s Smart Drive motor. A container is used for collecting items (roll of electrical wire, drill chucks, pliers and multiple sizes of nuts and bolts that served as weight) as weight is added on W_1 , while an adjustable spanner is used as the counterweight W_2 . In the beginning, some items are added to the container to balance the weight of the adjustable spanner (i.e., $W_1 = W_2$). Next, a cotton string is used to reduce slip while being wound onto the motor, as shown in Figure 3.74. Later on, more and more weights are added to the container, starting from the biggest to smaller items, until the motor starts to rotate. The additional items added are then measured with a digital luggage scale. The same procedures are then repeated three times before switching to the PMDCM. The results are analysed and discussed in Chapter 4, Section 4.4.2.2.

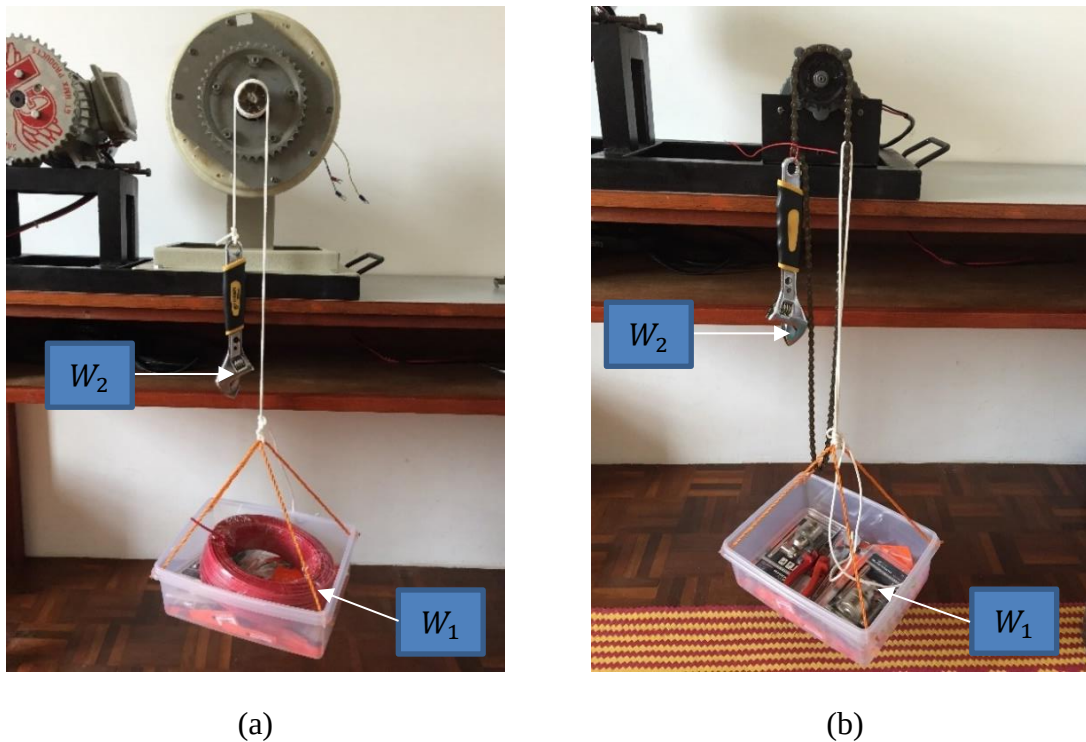


Figure 3.74: (a) Cogging torque measurement setup for the Smart Drive motor.
(b) Cogging torque measurement setup for the PMDCM.

3.7.2.3 Smart Drive Generator Testing Under Different Stator Configurations

The third part of the case study is to test the 42-pole 60s Smart Drive motor as a generator under different configurations. According to EcoInnovation (2016), the type 2 model stator of the 42-pole 60s Smart Drive motor can be rewired into eight different configurations (four in delta and four in star connections), as shown in Figure 3.75.

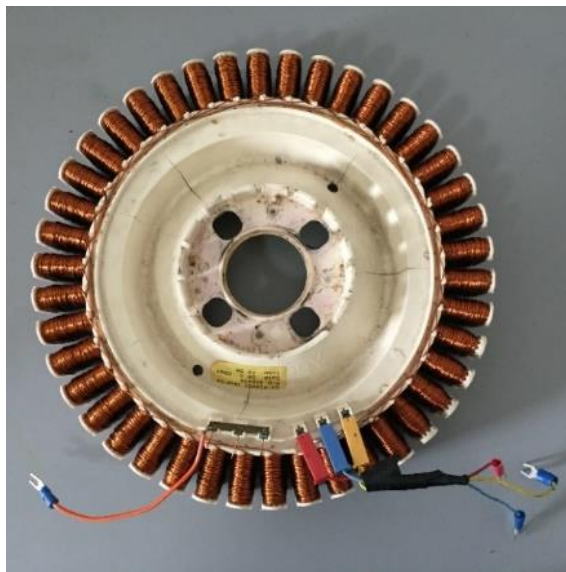
Wire Code	S	P	V/rpm Delta	V/rpm Star
100	14	1	0.152	0.266
100	7	2	0.076	0.133
100	2	7	0.022	0.038
100	1	14	0.011	0.019
80	14	1	0.398	0.699
80	7	2	0.199	0.350
80	2	7	0.057	0.100
80	1	14	0.028	0.050
60	14	1	0.580	1.018
60	7	2	0.290	0.509
60	2	7	0.083	0.145
60	1	14	0.041	0.073

Figure 3.75: Different stator wiring of the 42-pole Smart Drive motor (EcoInnovation, 2016).

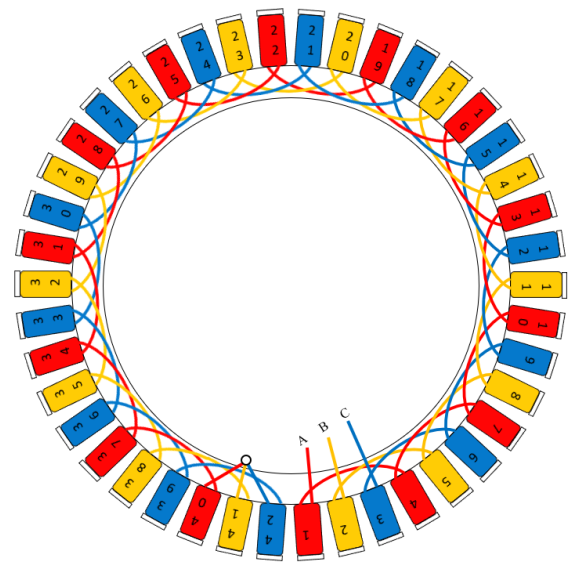
The “Wire Code” represents the three sizes of stator coil wire: 1 mm, 0.8 mm and 0.6 mm available for the Smart Drive motor series. Column S represents the number of coils connected in series (per phase), and column P represents the coils connected in parallel (per phase). In the meantime, the three phases can either be delta- or star-connected, with the star connection producing higher V/RPM. According to TheBackShed (2011), the delta connection generates more power at higher RPM, but the star connection starts making power at lower rpm and is the preferred option. Therefore, the study would rewire the stator in star and test all four configurations available for the 60 series. Before carrying out any

experiment, the study must first source a motor that can serve as the prime mover for the Smart Drive 60s generator. The study has decided to use what is available at hand, which is the Y90s-6 0.75 kW 910 rpm three-phase motor (refer to Appendix B). The prime mover's driver is the 0.75 kW 220V VDF-L AC Drive Inverter. In the meantime, a simple metal stand is designed and constructed for testing the Smart Drive 60s motor. The study also acquired a bicycle chain, sprocket and bridge rectifier (KBPC3510) for testing.

The first experiment will evaluate the Smart Drive 60s generator's (with the original factory-wired stator) output with and without load. In this experiment, a factory-wired stator is untouched, as shown in Figure 3.76. Each phase has 14 coils that are in series, and the three phases are star-connected. The factory-wired stator will be referred to as the 60-14s-1p-S connection.



(a) Factory-wired stator.



(b) Three-phase star connected.

Figure 3.76: The Smart Drive 60s generator factory-wired stator (60-14s-1p-S).

Figure 3.77 and Figure 3.78 shows the experimental setup and circuit diagram for the no-load test of the Smart Drive generator (with a factory-wired stator). Once switched on, the motor controller setting is increased until the Smart Drive generator starts to turn. Then the output voltage and RPM (taken with a digital tachometer as shown in Figure 3.79) will be recorded. The process is then repeated with every 10 RPM increment.

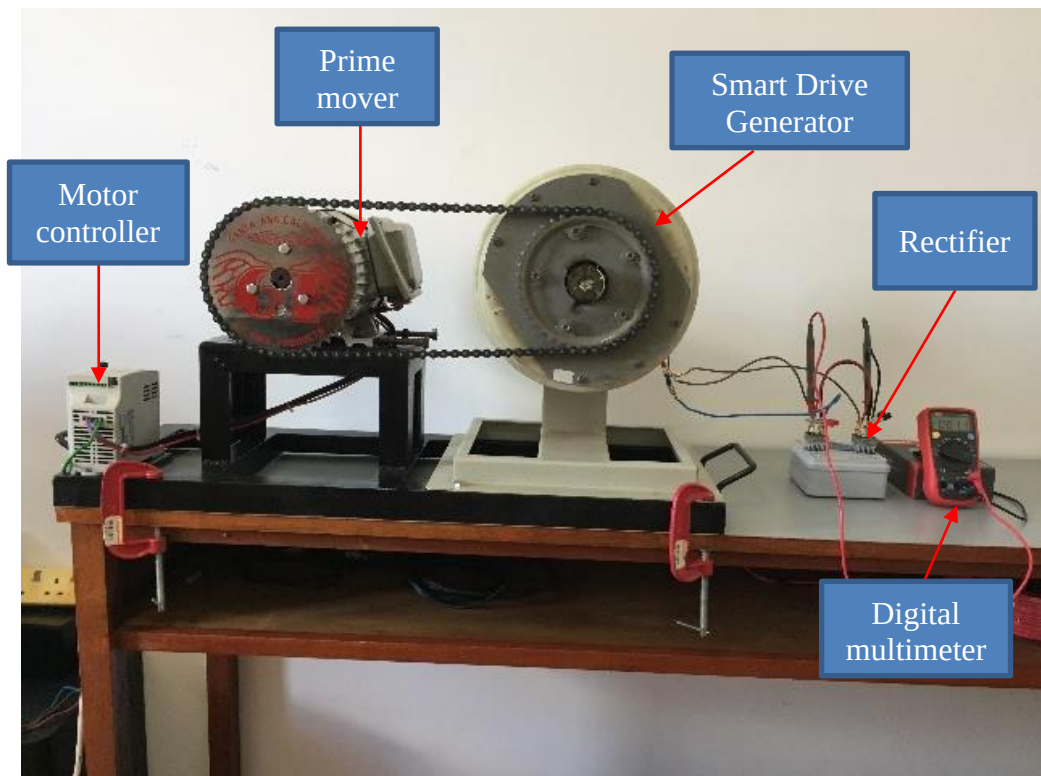


Figure 3.77: Experiment set up for the no load test.

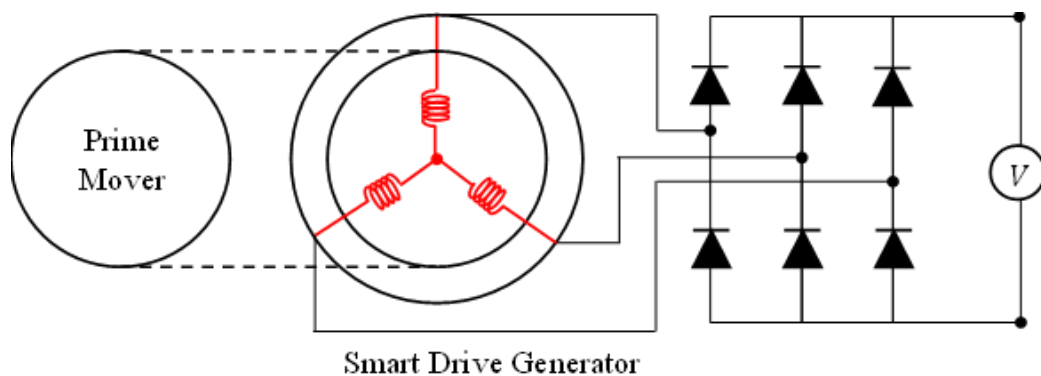


Figure 3.78: Circuit diagram for the no load test.

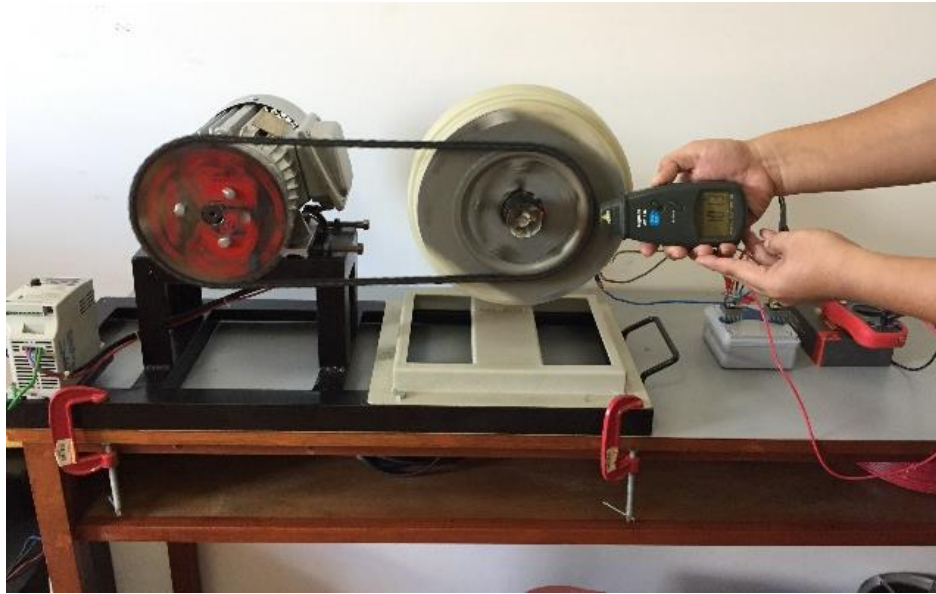


Figure 3.79: Smart Drive generator's RPM taken with a digital tachometer.

Next, the experiment will test the Smart Drive 60s generator (with factory-wired stator) with a load. Five LED light tubes are used as the load in this test. The test will begin with just one LED light as the load and subsequently increase at one LED light at a time. Figure 3.80 and Figure 3.81 shows the experimental setup and circuit diagram.

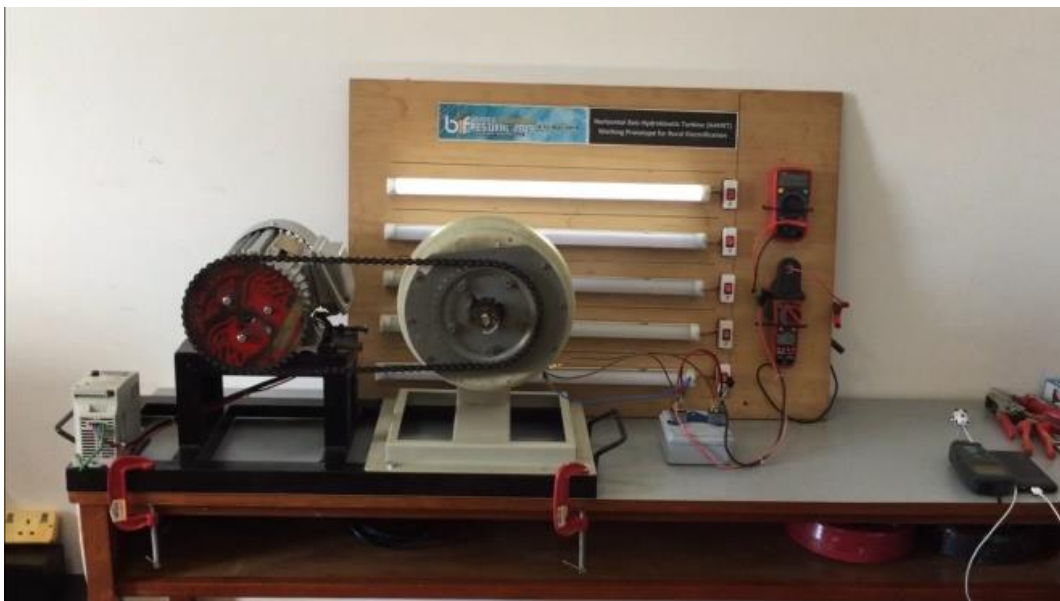


Figure 3.80: Experiment set up for the test with a load.

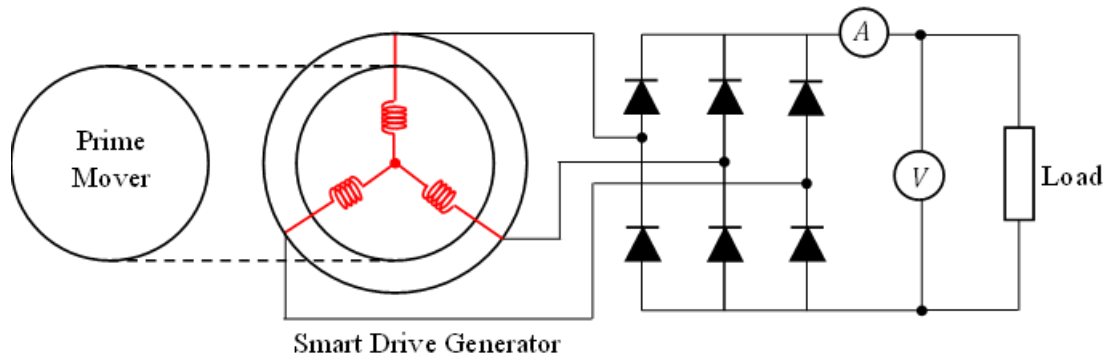
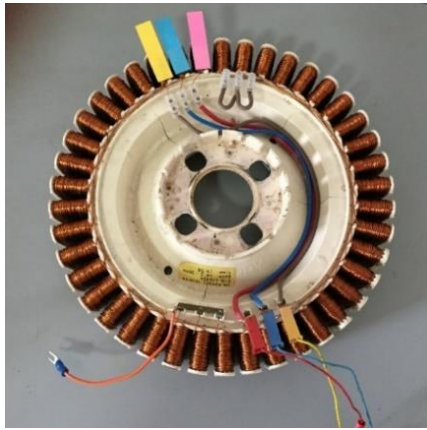


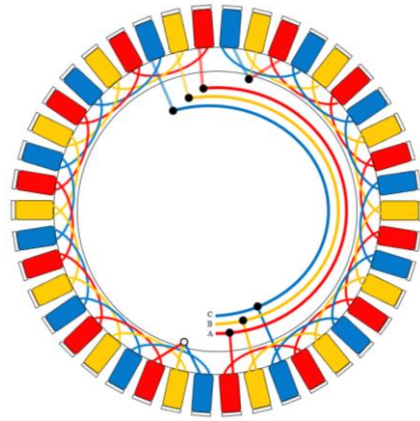
Figure 3.81: Circuit diagram for the test with a load.

A preliminary test shows the prime mover failed to drive the Smart Drive generator when loaded with just one LED light. Therefore, an alteration is made by driving the generator to a certain speed before the load is turned on. Then the output voltage and RPM are recorded. Subsequently, the motor controller would be adjusted to increase the Smart Drive generator's RPM, and the process is repeated. The test results of both experiments are analysed and discussed in Section 4.4.2.

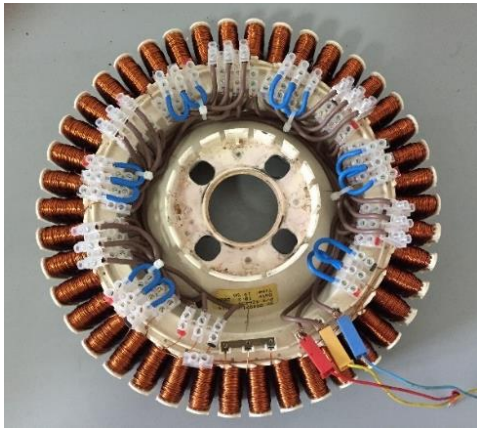
In the subsequent three experiments, the objectives are to evaluate the Smart Drive 60s generator's output when the stator is rewired into the 60-7s-2p-S, 60-2s-7p-S, and 60-1s-14p-S connection. The rewired stator is shown in Figure 3.82. In the case of the 60-7s-2p-S connection, the 14 coils in each phase are divided into two groups, with 7 coils in series for each group and the two groups are parallel connected. Meanwhile, for the 60-2s-7p-S connection, the 14 coils in each phase are divided into 7 groups, with 2 coils in series for each group and the 7 groups are parallel connected. And finally, for the 60-1s-14p-S connection, all 14 coils in each phase are connected in parallel. The circuit diagrams for the rewired connection are shown in Figure 3.83.



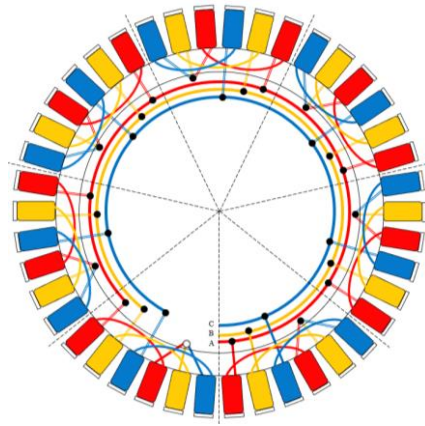
(a) Rewired 60-7s-2p-S stator.



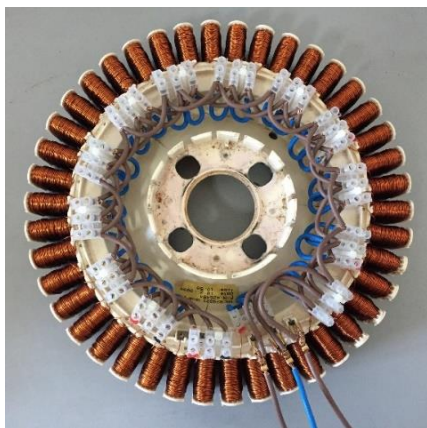
(b) Three-phase star connected 60-7s-2p-S stator.



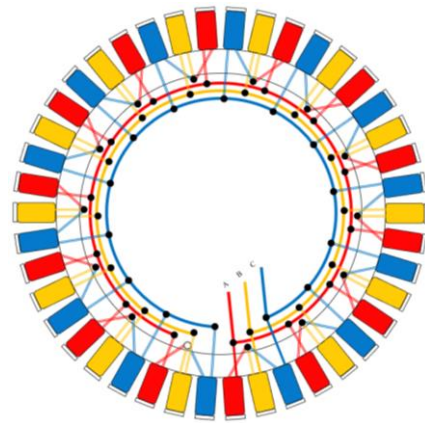
(b) Rewired 60-2s-7p-S stator.



(d) Three-phase star connected 60-2s-7p-S stator.



(e) Rewired 60-1s-14p-S stator.



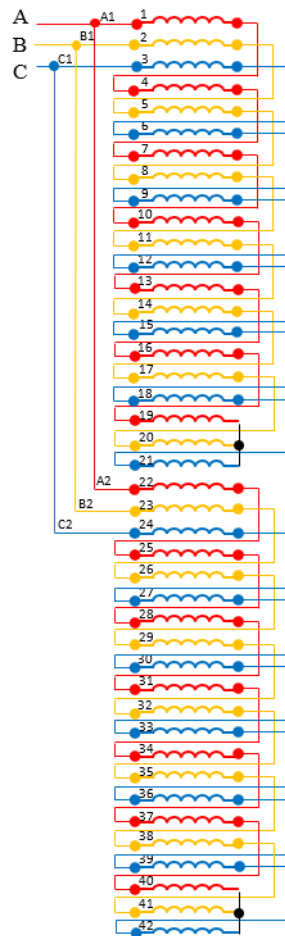
(f) Three-phase star connected 60-1s-14p-S stator.

Figure 3.82: The Smart Drive 60s rewired stators.

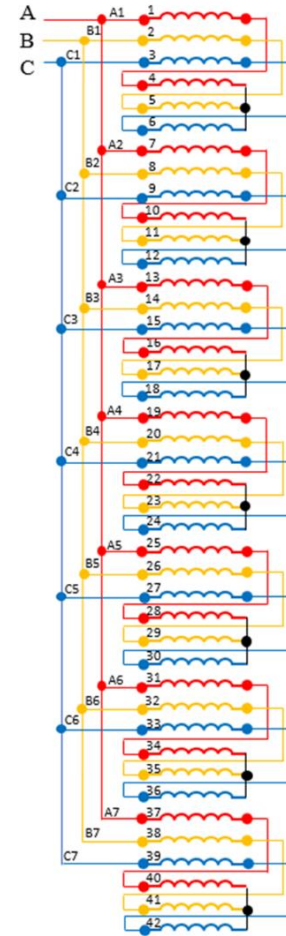
Original Stator (60-14s-1p-S)



Rewired Stator (60-7s-2p-S)



Rewired Stator (60-2s-7p-S)



Rewired Stator (60-1s-14p-S)

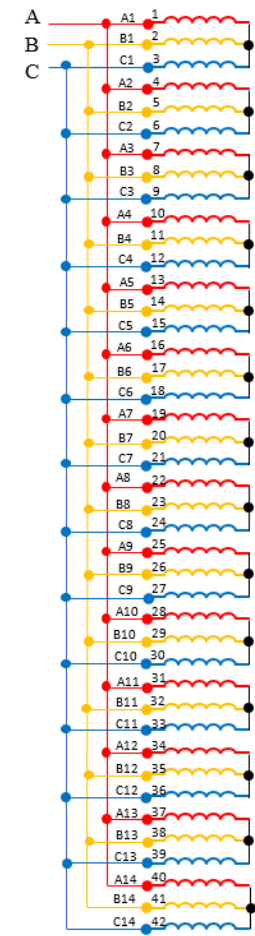


Figure 3.83: Circuit diagrams for the rewired stator.

The experimental setup, circuit diagram, and testing procedures for the three subsequent experiments are similar to the previous experiment on the factory-wired/original stator. The results of these tests are analysed and discussed in Chapter 4, Section 4.4.2.3.

3.7.2.4 Smart Drive Generator for Small-Scale HKT Design

Finally, the fourth part of the case study involved designing a small-scale HKT using the 42-pole 60s Smart Drive motor as a generator. In the third part of the case study, the results show that the rewired stator with 60-2s-7p-S and the 60-1s-14p-S connections are more suitable for small-scale wind or HKT design. This is due to less torque required to drive the generator, and the output voltage is not too high. However, this information alone is insufficient. Therefore, the study would search for more information regarding the performance of the Smart Drive generator used in small-scale RES construction. EcoInnovation (2004) shared a graph of many series of rewired Smart Drive generators in the 24 V system with star connection tested, as shown in Figure 3.84.

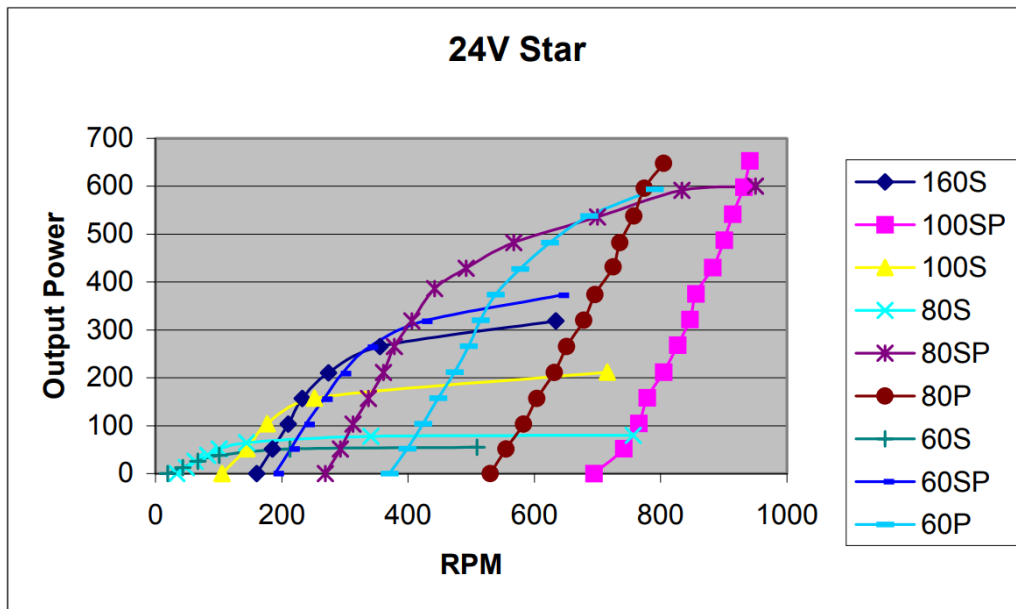


Figure 3.84: Different rewired Smart Drive generator output (EcoInnovation, 2004).

From Figure 3.84, the 60S refers to the Smart Drive's stator with the 60-14s-1p-S connection (i.e., the original factory-wired stator). While the 60 SP refers to the 60-2s-7p-S and the 60P refers to the 60-1s-14p-S stator connection. Figure 3.84 also reviews that the 60S produces the least output power (i.e., less than 100 W) and that power saturates from 200 to 750 RPM. This indicated that the Smart Drive generator with the factory-wired stator is unsuitable for small-scale power generation. Meanwhile, the output power of 60SP and 60P looks very promising.

The study has estimated the output power of the 60SP and 60P based on the graph in Figure 3.84, as shown in Table 3.2 and Table 3.3.

Table 3.2: RPM and Output power of the 60SP.

RPM	Output Power (W)	W/RPM
200	0	0.00
225	50	0.22
250	100	0.40
275	150	0.55
300	210	0.70
325	250	0.77
350	270	0.77
375	290	0.77
400	300	0.75
425	310	0.73
450	320	0.71
475	330	0.69

Table 3.2 continued

500	340	0.68
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Table 3.3: RPM and Output power of the 60P.

RPM	Output Power (W)	W/RPM
375	0	0.00
400	50	0.13
425	100	0.24
450	160	0.36
475	215	0.45
500	270	0.54
525	340	0.65
550	400	0.73
575	430	0.75
600	460	0.77
625	480	0.77
650	510	0.78
675	530	0.79
700	540	0.77
725	560	0.77
750	580	0.77
775	590	0.76
800	600	0.75

According to EcoInnovation (2016), the Smart Drive generator with the type 2 rotor (i.e., the same as the unit at hand) can produce up to 0.75 W/RPM. Therefore, from Table 3.2, the best operating RPM to generate 0.75 W/RPM for the 60SP is from 325 to 400 RPM. In the meantime, the 60P is from 575 to 800 RPM (from Table 3.3). Therefore, the study will use this as the baseline RPM for the Smart Drive generator in designing the small-scale HKT for the 24 V systems. While for the 12 V system, the design would assume that only half of the RPM is needed.

Other information required in the design process included assuming a small-scale HKT efficiency to work with (i.e., in this case, the study would assume a 0.3), and calculating the operating voltage, expected waterpower and river flow velocity required to drive the generator to the baseline RPM. According to EcoInnovation (2016), the optimum operating voltage for any Smart Drive generator is around 0.57 of the no-load voltage. Furthermore, the optimum power output from the Smart Drive is achieved at around 40 % loading, and the system must be used with a Maximum Power Point Tracking (MPPT) device. The results of the design are discussed in Chapter 4 section 4.4.2.4.

3.8 Chapter Summary

This chapter has explained in detail the materials and methods used in this study. First, a research framework and a flow chart are used to describe the phases and flow of the entire research work. This is followed by a section describing the selection of a reference – the Long Busang village – for the small-scale HKT design and a suitable site in the Padawan district near Danu village for the field test. The following section describes the step-by-step design and construction process of the two full-scale prototypes – the prototype for proof of concept and an improved prototype that would overcome the weaknesses encountered – and

procedures for their field tests. Finally, the two case studies involved off-the-shelf/recycled motors/generators. Detailed explanations are given on the procedures for finding the information needed and testing the 42-pole 60S Smart Drive motor as a generator.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

In this chapter, the results from the study will be presented and discussed in three sections. The first section will discuss the results obtained from the prototype field test. Next is the discussion on the results obtained from the field test of the improved prototype. Finally, the results obtained from the two case studies of off-the-shelf/recycled motors as the generator.

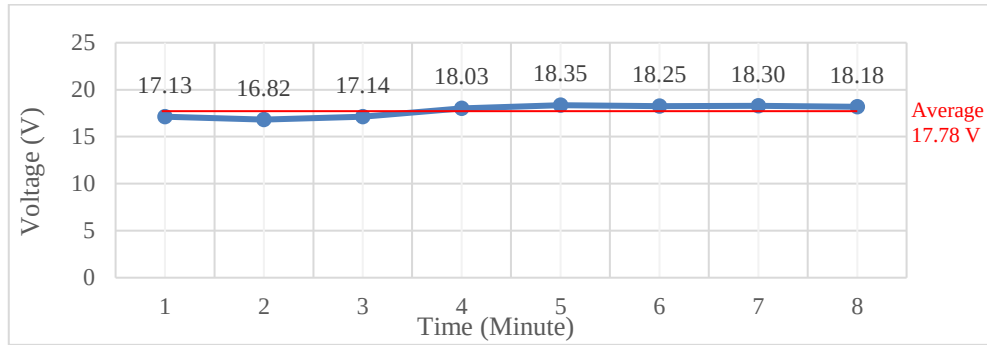
4.2 Prototype Field Test

The prototype field testing happened on July 14th and 15th, 2018. As it has not rained for many days, the river at the test site was shallow (at around two feet deep) compared to about a meter when surveyed. Consequently, the turbine's rear section was slightly tilted as it sat on the uneven, rocky riverbed, as shown in Figure 3.40. Regardless, the study decided to carry on with the test as the twin rotors were fully submerged.

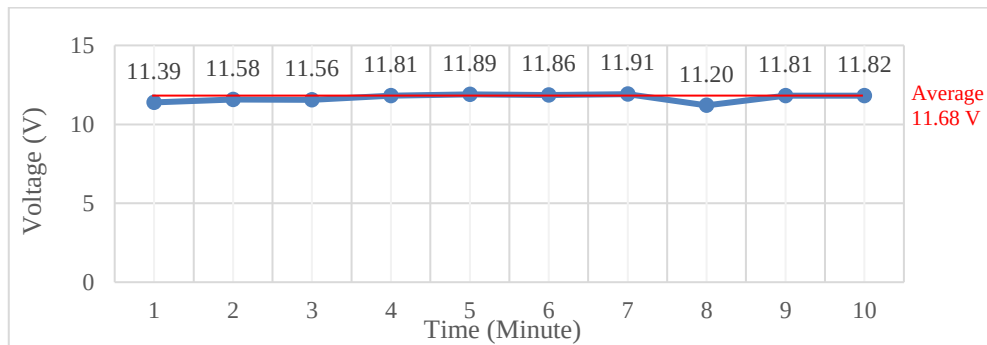
4.2.1 Results and Discussion

Figure 4.1 shows the results obtained on the first day of the field test. The graph in Figure 4.1(a) shows the prototype produced an average of 17.78 V for the no-load test. The turbine rotor RPM measured is 246. With over 17 V average voltage, the study was confident the prototype would generate enough power to supply two 12 V LED lights. However, the average output voltage dropped to 11.68 V, and the turbine rotor RPM dropped to 208 with just one LED light. At this juncture, the study has expected a further drop in the output voltage and RPM if there were two LEDs as the load. Unfortunately, the test could not be

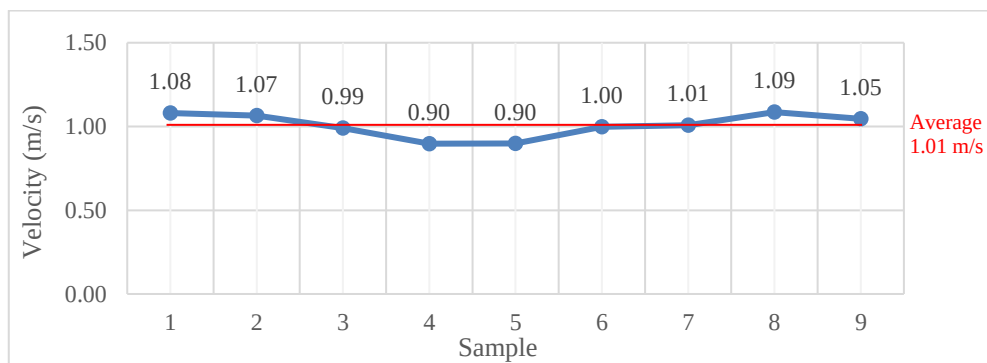
carried out due to a problem with the transmission. In closing, the river surface flow velocity measured, $V_m = 1.01 \text{ m/s}$, was corrected to, $V_c = V_m \times 0.85 = 0.86 \text{ m/s}$ to obtain the mean flow velocity of the river.



(a) Output voltage (no-load).



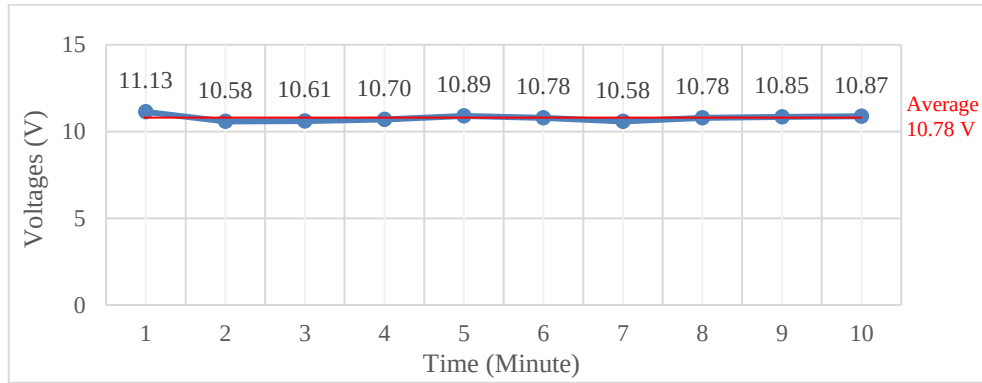
(b) Output voltage.



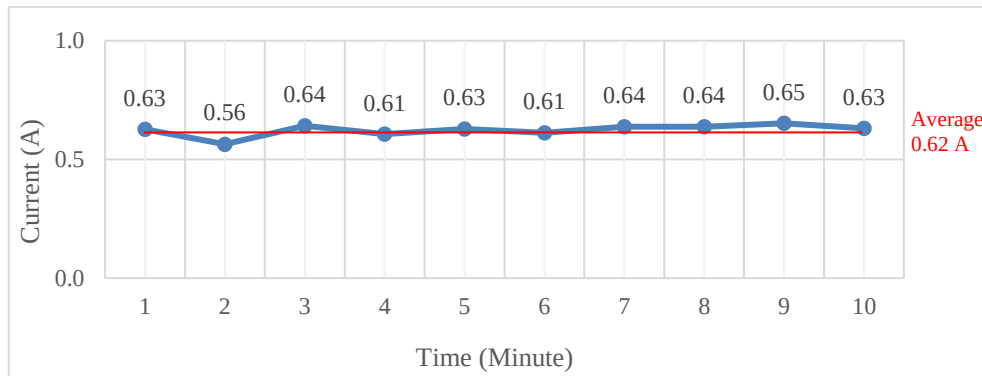
(c) River flow velocity.

Figure 4.1: First-day field test results.

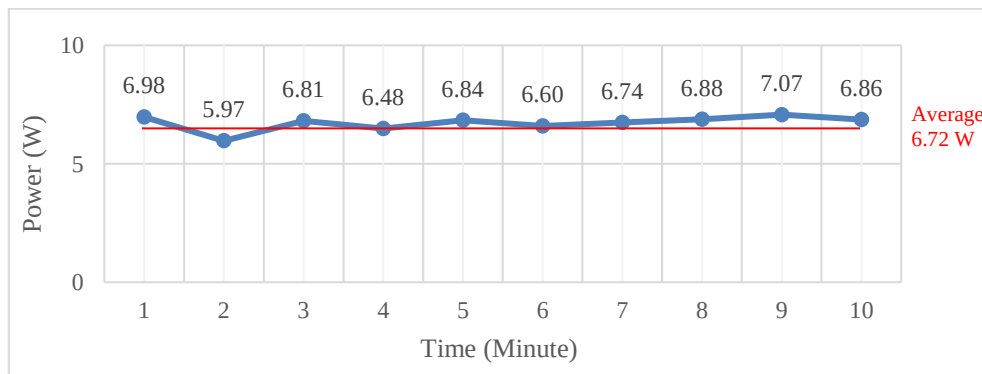
Regrettably, the transmission problem persisted on the second day. In consequence, the field test proceeded with only one turbine rotor driving the generator. The second-day field test results are orderly shown in Figure 4.2 and Figure 4.3.



(a) Output voltage.

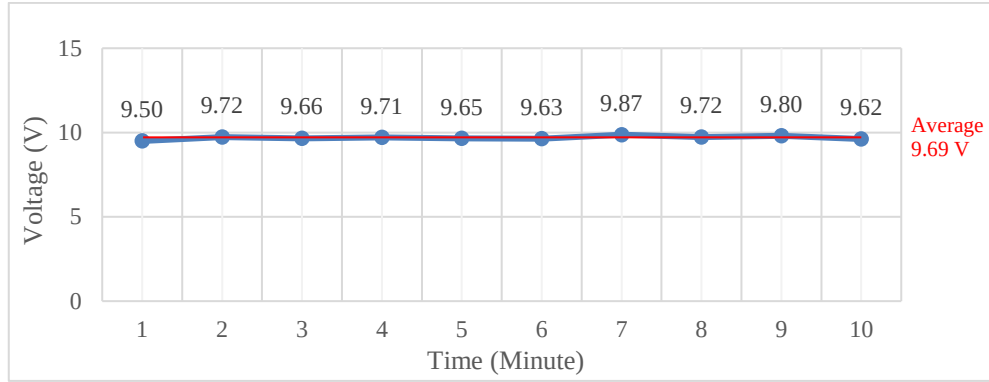


(b) Output current.

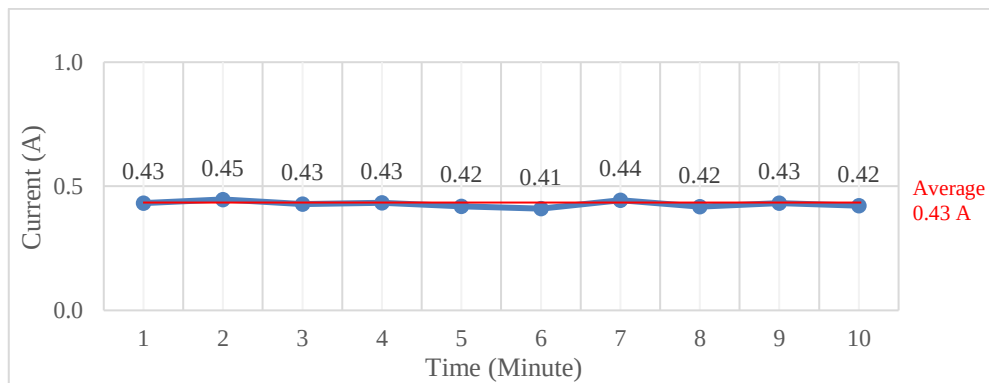


(c) Output Power.

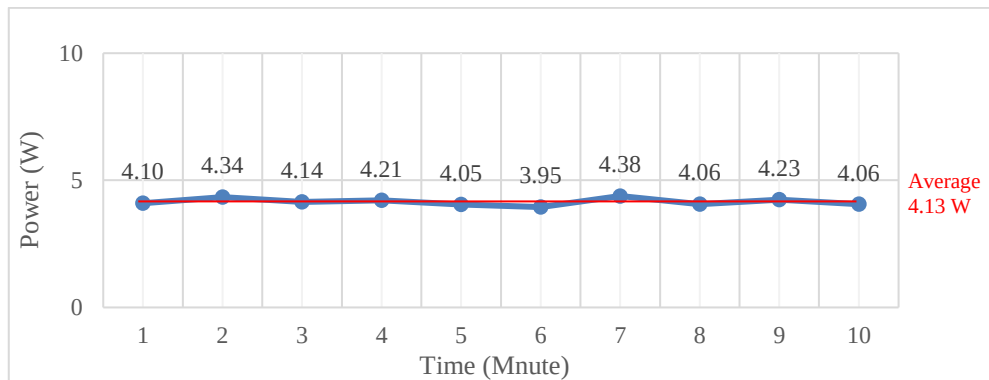
Figure 4.2: Second-day field test results with a single LED light as the load.



(a) Output voltage.



(b) Output current



(c) Output power.

Figure 4.3: Second-day field test results with two LED lights as the load.

With only one turbine rotor driving the generator and a single LED light as the load, the average output voltage produced was 10.78 V. Compared to the previous day's test with both rotors driving the generator, it is 0.9 V less. This 0.9 V meant an additional turbine rotor

only provided an extra 8.3 % to the output voltage. Meanwhile, the average output power, P_o produced is 6.72 W. If the same flow velocity of 0.86 m/s is assumed, the prototype has an overall efficiency, $C_p \eta = P_o/P_w = 0.13$. In contrast, with two LED lights as the load, the average output voltage fell to only 9.69 V. The P_o dropped to only 4.15 W and the overall efficiency to just 0.08. These test results show overall efficiency of the prototype varied with the load applied.

4.2.2 Performance Evaluation

In the prototype field test, other than testing the functionality, the study is also interested in the turbine rotor's ability to work in a river with the presence of submerged debris. Figure 4.4 shows submerged debris stuck to the turbine structure on the first day. While Figure 4.5 shows considerably more submerged debris caught by the turbine structure on the second day. Interestingly, both figures show no sign of submerged debris getting entangled in the turbine rotors. Besides, despite the presence of submerged debris, the turbine never ceases to operate.

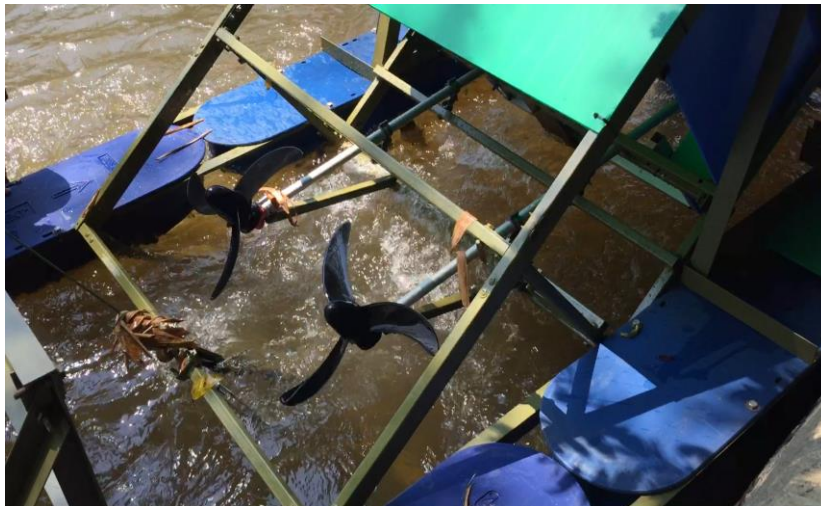


Figure 4.4: Submerged debris stuck on the turbine structure on day one.



Figure 4.5: Submerged debris stuck on the turbine structure on day two.

Through the two days field test, there were many lessons learned. The first lesson involved the long driveshafts. Its long aluminium body was not sturdy enough to handle the force, causing it to vibrate. Secondly is the position of the sprockets, as it is challenging to get the correct alignment. As a result, the chain broke off many times during the test. The third is the bicycle hub and sprocket assembly. Its fabrication was not strong enough to handle the force causing it to break loose at the initial testing stage. The fourth is the 2:1 ratio gearing, which is insufficient (to drive the generator to a higher speed from the turbine rotor's low RPM).

Next is the prototype structural design. Its design does not regard the ease of transportation, deployment, and recovery from the field test site. Aside from being bulky and heavy, it has to be transported as a whole to preserve its structural integrity. Also, disassembling and reassembling the turbine at the test site would be daunting. The swingable section of the turbine (made with hollow steel bars) is not sturdy enough and tends to wobble. Furthermore, that section also tends to catch submerged debris, which could be a big problem

for the turbine because that would introduce more drag and possibly interfere with the turbine operation.

4.2.3 Conclusion

The prototype built for the proof of concept can barely generate enough power for a 12 V 10 W LED light from a 0.86 m/s river flow velocity. The overall efficiency estimated is 0.13. When the load increased, the turbine efficiency dropped. Nevertheless, the twin-turbine rotor design increases the output voltages by 8.3 % compared to a single-turbine rotor. The fan rotor with swept-back blades also demonstrated its worthiness when used as the turbine rotor in a debris-laden tropical rainforest river. Ultimately, although the prototype constructed has a problematical transmission and is not very efficient, it was sufficient to prove that the adopted concept works.

4.3 Improved Prototype Field Test

The improved prototype field testing happened on January 26th, 2019. The smaller improved prototype was less hassle to transport and deploy than the previous prototype. However, the rise in water level and stronger river flow has warranted extra precautions in handling the field test. Although the high-water level would enable the improved prototype to float, it's decided to install the leg structures to avoid hitting the rocky riverbank (as there is no way to stop the rotor from spinning). Therefore, multiple ropes and tree branches are needed to secure the improved prototype's testing position. Furthermore, during the original turbine rotor no-load test, the output voltage registered was around 20 to 26 V. Therefore, the study has decided to treat all five 12 V LED lights as a single load to prevent possible overvoltage damage.

4.3.1 Results and Discussion

Figure 4.6 and Figure 4.7 display the results obtained from the field test.

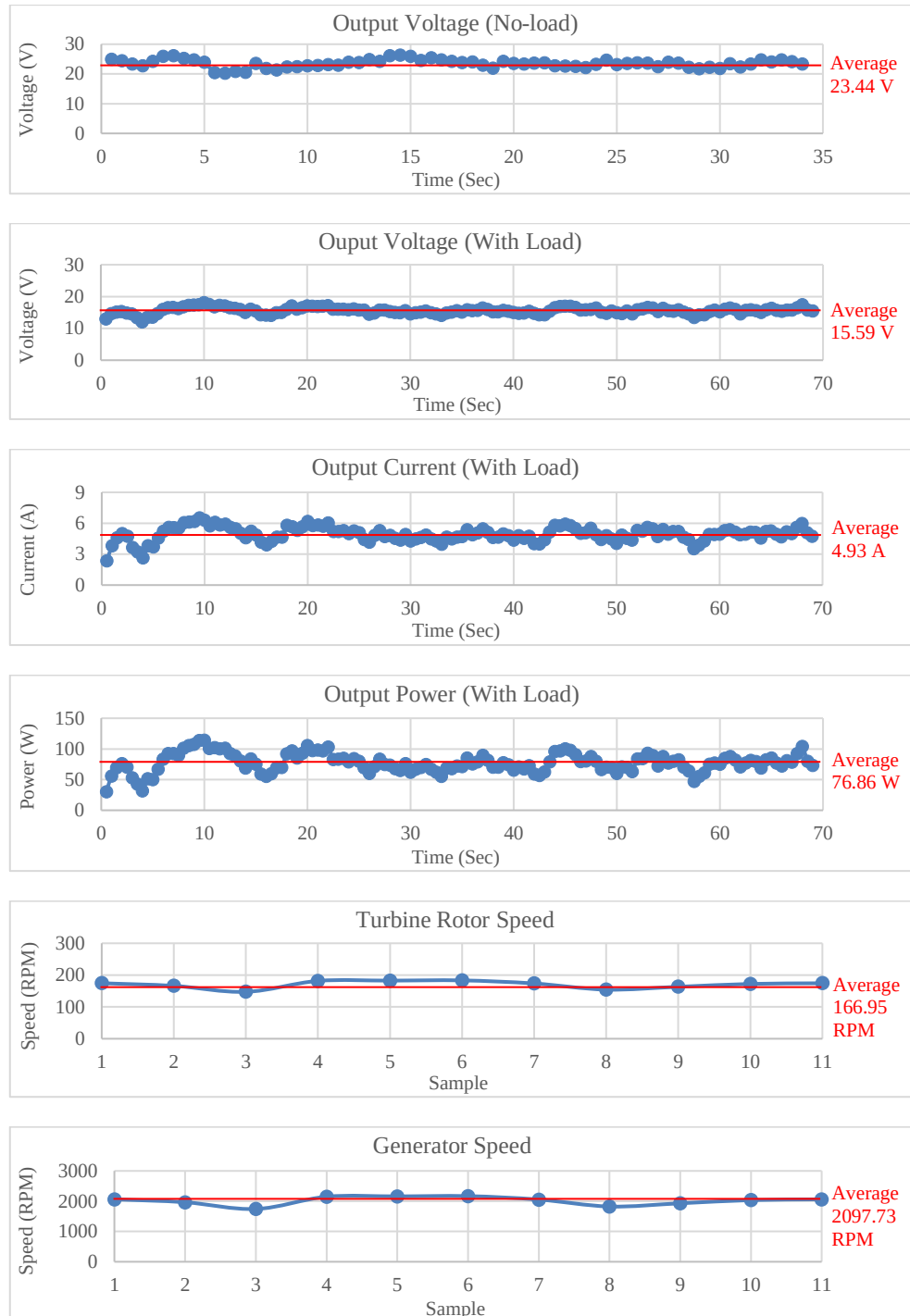


Figure 4.6: Field test results with the original fan rotor as the turbine rotor.

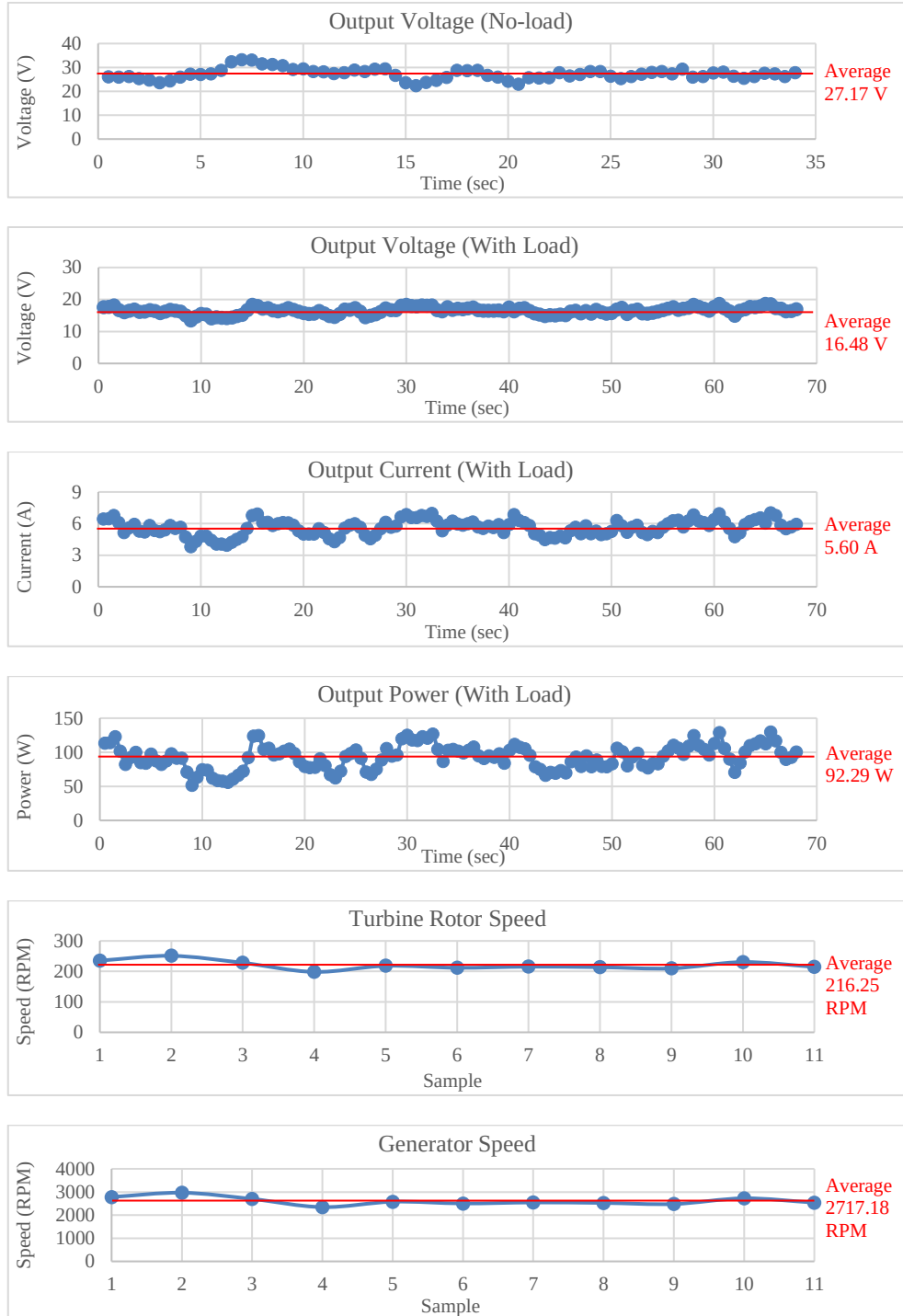


Figure 4.7: Field test results with reprofiled fan rotor as the turbine rotor.

Besides, the average river flow velocity measured (with the same float method) is 1.48 m/s, as shown in Figure 4.8, and after correction with the coefficient of 0.85, it became 1.26 m/s. The 1.26 m/s flow velocity during the improved prototype field test was

significantly higher compared to the flow velocity of 0.86 m/s for the prototype. Therefore, the higher flow velocity justified greater fluctuation occurred on the turbine's output due to greater turbulences in the water. Table 4.1 summarizes the two sets of results from Figure 4.6 and Figure 4.7 and their related analysis for easier comparison.

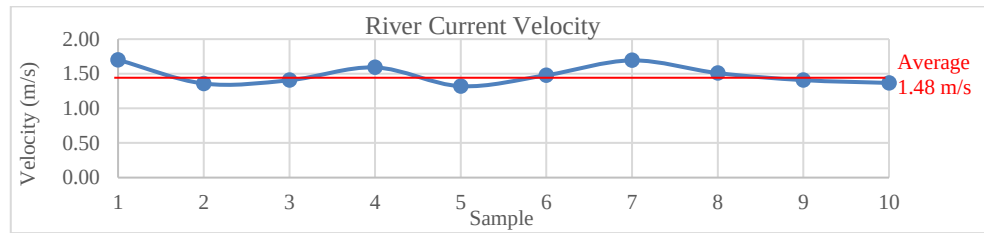


Figure 4.8: River flow velocity measured.

Table 4.1: Field test results comparison (turbine with load).

Variable	Original fan rotor	Reprofiled fan rotor	Improvement (%)
Flow velocity, m/s	1.26	1.26	
Available waterpower, W	270	270	
No-load output voltage, V	23.44	27.17	15.91
Output voltage, V	15.59	16.48	5.71
Output current, A	4.93	5.60	13.59
Output power, W	76.86	92.29	20.07
Energy, kWh/day	1.84	2.21	20.11
Rotor speed, RPM	166.95	216.25	29.53
Generator speed, RPM	2097.73	2717.18	29.53
Overall efficiency, $C_p \eta$	0.28	0.34	6.00

Table 4.1 shows the improved prototype fitted with the original fan rotor worked well and managed to produce an average no-load output voltage of 23.44 V. With load, the average output voltage and the current were 15.59 V and 4.93 A, equivalent to 76.86 W of power. The average turbine rotor speed was 166.95 RPM.

Table 4.1 also shows the performance of the improved prototype has significantly increased due to the reprofiled fan rotor. The average reprofiled fan rotor speed achieved had risen to 216.25 RPM (29.53 % higher). As a result, the generator ran at a higher RPM close to its rated speed as a motor. Therefore, it produced an average no-load output voltage of 27.17 V (15.91 % higher), 16.48 V (5.71% higher) average output voltage, 5.60 A (13.59 % higher) average output current, and 92.29 W (20.11 % higher) output power.

With the measured and corrected river flow velocity of 1.26 m/s and the 0.585 m turbine rotor, the available waterpower calculated is 270 W. The overall efficiency, $C_p\eta$ of the improved prototype calculated is 0.28 and 0.34, respectively, for the original fan rotor and reprofiled fan rotor. In short, the better performance reprofiled fan rotor has improved the overall efficiency of the improved prototype by 6 %. If a constant river flow velocity is assumed, the improved prototype with the original fan rotor can produce 1.84 kWh/day while the reprofiled fan rotor can produce 2.21 kWh/day or 20.11 % more energy per day.

4.3.2 Performance Evaluation

Based on the data available in Table 4.1, the study has already known the overall performance of the improved prototype. Hence, the study would evaluate the performance of each section of the improved prototype, as depicted by the block diagram in Figure 4.9. The results would provide a better understanding of the performance of each section of the

turbine. The estimation of power generated, and efficiency (in each turbine section) would start from the generator, followed by the transmission, and lastly, the turbine rotor.

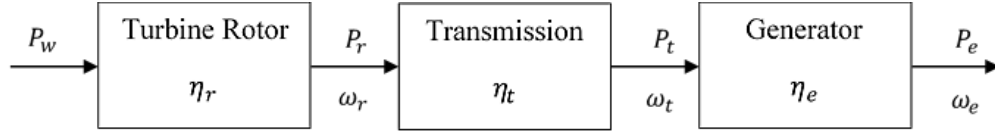


Figure 4.9: Block diagram of an HKT.

The generator efficiency was estimated using an equivalent electrical circuit of a permanent magnet DC machine in the generator mode, as shown in Figure 4.10, and the calculated generator losses.

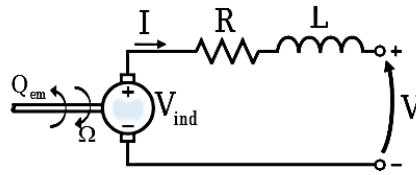


Figure 4.10: Equivalent electrical circuit of a permanent magnet DC generator (Bastankhah & Porté-Agel, 2017).

When a Permanent Magnet DC Generator (PMDCG) operates in steady-state conditions, the inductance L term in Figure 4.10 can be omitted (Hughes & Drury, 2013; Sharma, 2007). Hence, $V_{ind} = V + IR$, where V_{ind} is the induced voltage, and R is the total resistance in the circuit (the armature resistance R_a and the cable resistance R_c). In the meantime, the armature resistance has to be obtained through a simple experiment since direct measurement with an ohmmeter will not provide an accurate value (Edmund, 2012). Therefore, with the method suggested by Edmund (2012) (refer to Appendix C for the method), the average armature circuit resistance obtained is 0.4 ohm, as shown in Figure 4.11 and Table 4.2.



Position 1



Position 2



Position 3



Position 4

Figure 4.11: Experiment on PMDCM armature circuit resistance measurement.

Table 4.2: PMDCM armature circuit resistance measured.

Armature Angular Position	Position 1	Position 2	Position 3	Position 4
Voltage, (V)	1.0	1.0	1.0	1.0
Current, (A)	2.26	2.51	2.71	2.63
Armature Resistance, R_a (Ω)	0.44	0.40	0.37	0.38
Average Armature Resistance, $R_{a(ave)}$ (Ω)	0.4			

Besides the Permanent Magnet DC Motor (PMDCM) armature resistance, the study also measured the resistance in the cable, R_c used to connect the generator to the load utilizing a digital ohmmeter. The resistance measured is 0.4Ω . Therefore, the total resistance for the PMDCM equivalent circuit, $R = R_a + R_c = 0.8 \Omega$. From this total resistance, the study would calculate total voltage losses. Consequently, the electrical efficiency of the PMDCG is determined by $\eta_e = P_e / P_g$, where P_e is the generator's electrical output power, and P_g is the electrical power generated (power output and total losses) (Electrical Deck, 2020). Table 4.3 shows the calculated generator efficiencies.

Table 4.3: Estimation of the PMDCG efficiency.

Variable	Original fan rotor	Reprofiled fan rotor
Output voltage, V_o (V)	15.59	16.48
Output Current, I_o (A)	4.93	5.60
Output Power, P_e (W)	76.86	92.29
Resistance, R (Ω)	0.8	0.8
Induced Voltage, V_{ind} (V)	19.53	20.96
Power generated, P_g (W)	96.28	117.38
Generator Efficiency, η_e	0.80	0.79

Unlike the turbine generator, the study can only estimate the efficiency of the transmission based on studies conducted by other researchers. Since a timing belt and pulley system boast a 0.98 efficiency (Grainger, 2019; ROYMECH, 2021) compared to between 0.81 to 0.98 for a bicycle chain transmission (John Hopkins University, 1999), the study has estimated the efficiency of 0.98 and 0.96 for the first and second stage of the improved

prototype transmission. Consequently, the two-stage transmission system has a combined efficiency of $\eta_t = 0.94$.

As for the turbine rotor, the RPM measurement (during the field test) happened at the bigger sprocket, as shown in Figure 3.59. Therefore, the rotor RPM measured would not reflect the actual value (because it has not included the transmission losses). With the above estimation, the recalculated rotor and generator RPM are shown in Table 4.4. From Table 4.4, one can see that the corrected generator input speed (for the improved prototype with the reprofiled fan rotor) is very close to the targeted RPM of 383 for the PMDCG, as discussed during the design in section 3.6.1.

Table 4.4: Corrected rotor and generator speed.

Variable	Original fan rotor	Reprofiled fan rotor
Measured Rotor speed, (RPM)	166.95	216.25
Corrected Rotor speed, (RPM)	170.36	220.66
Calculated Generator input speed, (RPM)	292.16	378.44
Corrected Generator input speed, (RPM)	298.13	386.16
Calculated Generator speed, (RPM)	2097.73	2717.18
Corrected Generator speed, (RPM)	2013.82	2608.49

From the corrected rotor RPM in Table 4.4, the operational Tip Speed Ratio (TSR) of the original fan rotor calculated is $\lambda_o = \omega R/V = (17.84 \times 0.2925)/1.26 = 4.14$. While for the reprofiled fan rotor, $\lambda_o = \omega R/V = (23.11 \times 0.2925)/1.26 = 5.36$. The act of reprofiling the fan rotor to resemble the thin and highly cambered NACA 6406 profile has improved the TSR

by 29.47 %. The operational TSR of the reprofiled fan rotor is closer to the theoretical optimal TSR of 6.28, as demonstrated by Ragheb & Raghed (2011) and M. Ragheb (2014).

From the estimated efficiency of the generator η_e and transmission η_t , the study can factor out the power coefficient of the turbine rotor from the overall efficiency ($C_p\eta_t\eta_e$) of the turbine as $P_e = P_w C_p \eta_t \eta_e$, where P_e is the electrical output power, P_w is the available waterpower. The rotor power coefficient calculated is 0.38 for the original fan rotor and 0.46 for the reprofiled fan rotor, as shown in Table 4.5.

Table 4.5: Estimated power at each section of the turbine.

Variable	Original fan rotor	Reprofiled fan rotor	Difference
Available waterpower, P_w (W)	270	270	
Generator Output Power, P_e (W)	76.86	92.29	15.43
Generator power coefficient, η_e	0.80	0.79	0.01
Transmission Output Power, P_t (W)	96.08	116.82	20.74
Transmission power coefficient, η_t	0.94	0.94	
Rotor Output Power, P_r (W)	102.21	124.28	22.07
Rotor power coefficient, C_p	0.38	0.46	0.08

The estimated rotor power coefficient of 0.46 and operational TSR of 5.36 matched the optimum performance level of a typical 2-bladed HKT rotor, as shown in Figure 4.12.

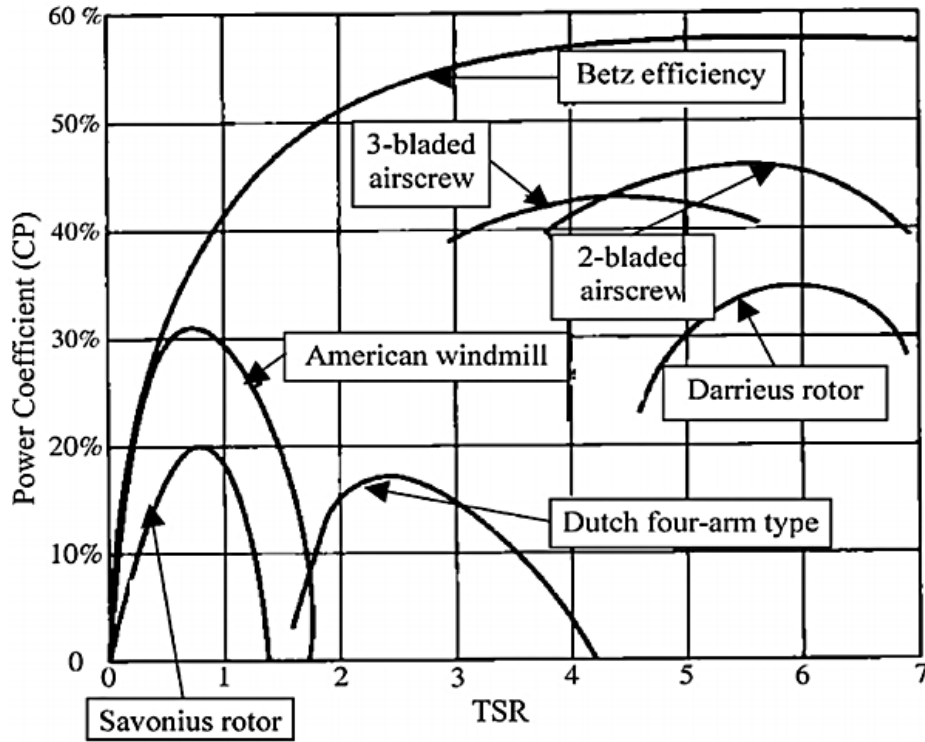


Figure 4.12: Typical performances of hydrokinetic rotors (Saini & Saini, 2019).

If the same turbine efficiencies are assumed, the projected output power of the improved prototype in Figure 4.13 shows its capability of generating between 38.42 to 129.68 W with the original fan rotor between 1.0 to 1.5 m/s flow velocity. At the same time, it is between 46.14 to 155.71 W for the reprofiled fan rotor. Compared to the predicted output power, these output powers are more than 40 % (for the improved prototype with the original fan rotor) and more than 70 % higher (for the reprofiled fan rotor). Similarly, Figure 4.14 projects the higher energy output the improved prototype can produce, from 0.92 to 3.11 kWh (for the original fan rotor) and 1.11 to 3.74 kWh (for the reprofiled fan rotor) within the same range of flow velocity. These results indicate that the improved prototype constructed has superior efficiency than the 0.20 estimated during design.

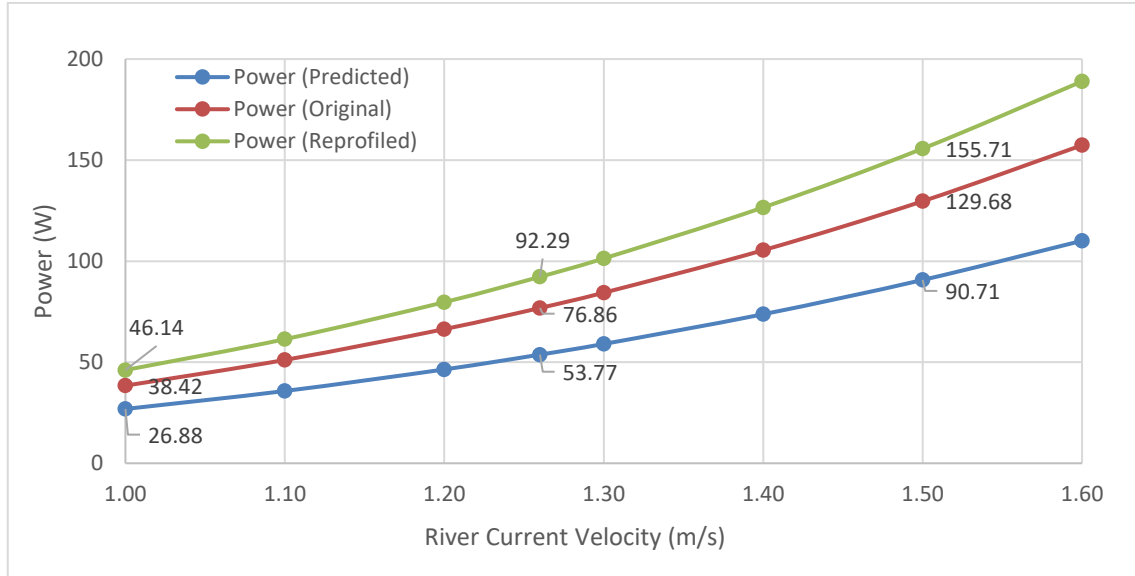


Figure 4.13: Projected output power of the improved prototype.

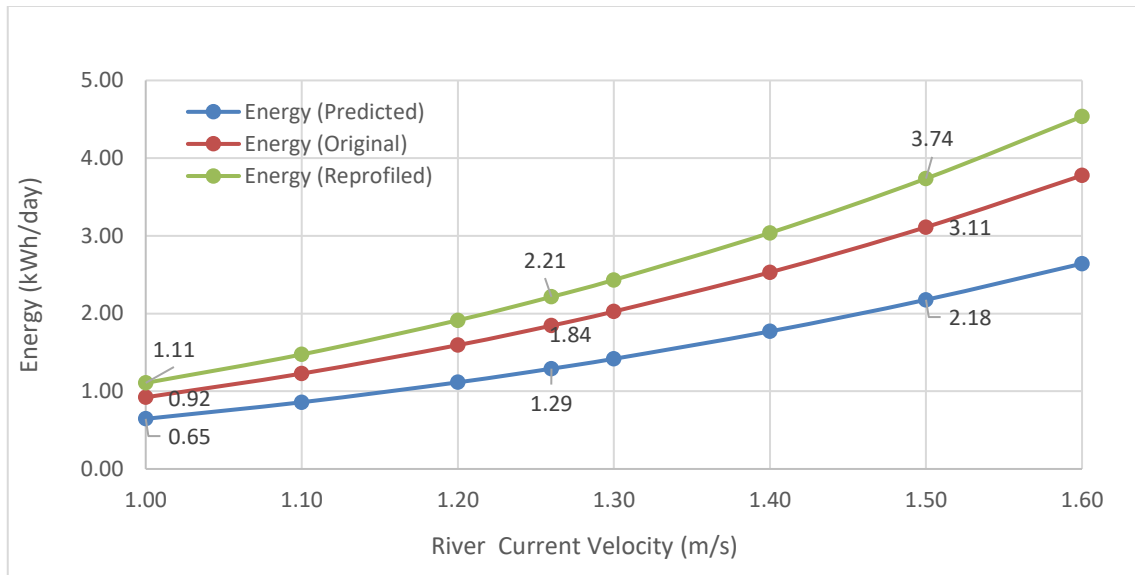


Figure 4.14: Projected output energy of the improved prototype.

On the other hand, despite the accomplishment, there are some issues with the improved prototype design. Firstly, some water leaked into the transmission casing, which is undesirable as it may lead to rust and corrosion of the bearings. Next is the PMDCG which produces a significant amount of noise during operation, which is also undesirable as it contributes to noise pollution.

4.3.3 Conclusion

The improved prototype has overcome the weaknesses of the previous prototype in many aspects as shown in Table 4.6.

Table 4.6: Comparison between prototype and improved prototype.

	Prototype	Improved Prototype (Original rotor)	Improved Prototype (Reprofiled rotor)
Dimension, m	1.5 m (<i>h</i>) × 1.8 m (<i>w</i>) × 3.4 m (<i>l</i>)	1.2 m (<i>h</i>) × 0.9 m (<i>w</i>) × 2.1 m (<i>l</i>)	
Transport	Lorry	Small pickup truck	
Weight, kg	100	60	
Motor Type	PMDC (Cordless drill)	PMDC (Electric bicycle)	
Rotor Size and Type	0.45 m 3-bladed Swept-back propeller	0.58 m 2-bladed Swept-back propeller	
Transmission	Brush cutter shaft and Bicycle chain system	Belt and pulley system and Bicycle chain system	
Structure	Hollow steel bar and steel angle bar	Flat steel bar and steel angle bar	
Output Power, W	6.7 (Flow 0.86 m/s)	76.8 (Flow 1.26 m/s)	92.3 (Flow 1.26 m/s)
Overall efficiency, $C_p\eta$	0.13	0.28	0.34
Cost, USD	500 (Materials)	300 (Materials) 450 (Labour)	

Firstly, it was easier to transport and deploy due to its smaller size and weight. Secondly, the transmission is significantly more efficient and runs smoothly throughout the four hours of the field test. Thirdly, there is no more issue of submerged debris caught on the turbine structure. Lastly, the turbine is more efficient and significantly produces more power. Since the power output is proportional to the flow velocity cubed, the improved prototype is estimated to generate 24 W with the original fan rotor and 29 W with the reprofiled fan rotor compared to just 7 W for the previous prototype (at the flow velocity of 0.86 m/s).

For the improved prototype with the original fan rotor, the rotor power coefficient achieved is 0.38. The turbine achieved an overall efficiency of 0.28 while producing 76.86 W at the river flow velocity of 1.26 m/s. If a constant river flow velocity is assumed, the turbine can produce 1.84 kWh of energy per day. On the other hand, when fitted with the reprofiled fan rotor, both the rotor power coefficient and overall efficiency significantly increased to 0.46 and 0.34. As a result, the turbine power output increased to 92.29 W, a 20 % increment. Subsequently, the turbine can produce 2.21 kWh of energy per day. Both cases have surpassed the usual 0.25 efficiency achieved by small-scale river turbines described by Vermaak et al. (2014).

4.3.4 Comparison With Commercial Small-Scale HKT

Table 4.7 shows the comparison of the improved prototype in terms of power output, required depth, and prices with three commercially available small-scale Hydrokinetic Turbines (HKT) for shallow inland rivers (less than 1 m deep) utilized for rural electrification projects.

Table 4.7: Small-scale HKT power output, required depth, and prices.

Micro-HKT	EcoCinetic Hydrobox	Idénergie River Turbine	Ibasei Cappa	Improved Prototype (with reprofiled fan rotor)
Cost (USD)	4,900	9,300	12,000	750
Output power (W) at 1.26 m/s	148	37	62	92
Min. depth (m)	0.90	0.66	0.50	0.80
Weight (Kg)	120	131	57	60
Axis	Cross-flow (Vertical)	Cross-flow (In-plane)	Axial-flow (Horizontal)	Axial-flow (Horizontal)
Rotor type	Savonius	Double Darrieus	Propeller	Propeller
Rotor size	0.73 m (D) 0.58 m ² (A)	0.66 m (D) 1.32 m (W)	N/A	0.585 m (D)
Mooring	With rope to a nearby structure	Anchored to riverbed	Fixed to the canal wall	With rope to a nearby structure

Note:

1. Prices are based on limited data gleaned from websites (European Commission, 2018; Idénergie, 2015; Kee, 2012).
2. Power output at 1.26 m/s for the commercial turbine has been estimated on the assumption that power is proportional to flow velocity cubed.

From Table 4.7, although the prototype produced less power compared to the EcoCinetic Hydrobox, it can produce more power compared to the Idénergie River Turbine, and Ibasei Cappa. But in terms of cost, it is very much less than the EcoCinetic Hydrobox, Idénergie River Turbine, and Ibasei Cappa.

4.4 Generator Case Studies

Two case studies were carried out that focus on determining types of off-the-shelf/recycled motors/generators that can be directly used or modified in constructing a small-scale Renewable Energy System (RES). The first case study searched for information on off-the-shelf/recycled motors/generators used for small-scale RES construction. The second case study involved extensive testing of an off-the-shelf/recycled Permanent Magnet Synchronous Motor (PMSM) as a generator for small-scale turbine construction.

4.4.1 Case Study 1 Results and Discussion

In this case study, the information obtained is from journal and website publications, as listed in Table 4.8. Table 4.8 shows various off-the-shelf/recycled motors used in small-scale RES design and construction in the past two decades, including the fan, washing machine, treadmill, centrifuge, and induction motor. The car alternator remains the only generator that is studied and used. For most cases, the specific efficiency of the generator/motor when used as a generator is not mentioned as their study's objectives were more to ascertain its practicality.

Table 4.8: List of RES using off-the-shelf/recycled motor/generator.

Author/Year	Type of motor/ generator	Motor/ generator Efficiency (%)	Output power (W)	Application
Gálvez et al., 2003	Modified ceiling fan motor	N/A	60	Wind turbine
Fernández et al., 2004	Modified car alternator	N/A	(12V DC)	Wind turbine
Menet, 2004	Modified car alternator	N/A	81	Wind turbine
EcoInnovation, 2004	Modified washing machine motor	80	600	Wind or micro-hydro
Irasari, 2011	Modified car alternator	53	73	Wind turbine
Krueasuk et al., 2011	Modified induction motor	62	56	Wind or micro-hydro
Pwint Phy & Htun Aung, 2014	Modified car alternator	N/A	200	Wind turbine simulation
EcoInnovation, 2016	Modified Smart Drive motor	80	1000	Wind or micro-hydro
Rodrigues et al., 2016	Modified car alternator, washing machine motor, Treadmill motor, centrifuge motor	N/A	186 (washing machine motor)	Wind turbine

Table 4.8 continued

Saad et al., 2017	Modified car alternator	N/A	107	Wind turbine
Kasagepongsar n & Suklueng, 2018	Modified waste motor	N/A	4000	Wind turbine
Dellva et al., 2019	Modified car alternator	N/A	75	Wind turbine
Leyland, n.d.	Modified washing machine motor	N/A	60	Micro-hydro

According to Fernández et al. (2004), the car alternator offers the following advantages when used the wind turbine generator:

- i. They are commonly used in widespread applications such as cars, trucks, buses, tractors and other farm and industrial vehicles.
- ii. Great mechanical strength.
- iii. Spare parts such as windings, rectifier bridges, voltage regulators, and bearings, can easily be found in auto parts dealer shops in almost all towns worldwide. Also, car maintenance workshops, with mechanics able to perform basic maintenance work on this equipment can be found even in otherwise very isolated and backward locations.
- iv. Wide operating speed range, from 400 RPM to 8000 RPM, and good current generating capability, reaching 320 A in modern units.
- v. Available in several standard output voltages: 12, 24, 32 or 48 V.

- vi. A range of matching heavy-duty batteries are also widely available, designed to be directly charged from the car alternator.
- vii. A range of matching (and rugged) integrated output voltage regulators are available in the market.
- viii. Some special models offer three-phase AC outputs.
- ix. Low unit and spare parts cost.
- x. Easy maintenance.
- xi. Tolerance to wide operating temperature changes without significant performance degradation.

These advantages have made the car alternator an attractive option although the theoretical efficiency of a conventional car alternator is rather low at 40 – 60 % (Irasari, 2011). Therefore, if the efficiency of a RES is not a major concern, then a car alternator can be used in constructing a simple small-scale RES for a rural household.

Table 4.8 also reviews a very promising candidate as a generator for small-scale RES that can produce significantly more power, that is the washing machine motor or the Smart Drive motor. It appears that the Smart Drive motor is a direct drive motor commonly used in washing machine brands such as Fisher & Paykel, Whirlpool, Maytag, and Haier. EcoInnovation (2016) said the Smart Drive generator could deliver 1.4 kW in the region of 1600 – 1800 rpm from the 80SP unit tested. Furthermore, EcoInnovation (2016) has claimed a typical 80 % efficiency for the Smart Drive motor when used as a generator for wind turbines and micro-hydro. The Smart Drive generator also offers versatility by offering up

to 96 choices of configurations for its three types of stators: the 42-pole, 36-pole de-cogged and 36-pole rewound de-cogged (EcoInnovation, 2016).

4.4.2 Case Study 2 Results and Discussion

4.4.2.1 Smart Drive Motor Output Testing

The first part of the case study was to look into the details of the 42-pole 60s Smart Drive motor. Therefore, the first experiment was conducted to verify that the motor was an External Rotor Permanent Magnet Synchronous Motor (ER-PMSM) that has a sinewave back-EMF. When the motor was running at 20 RPM, the digital multimeter showed a 7.9 V AC output and the oscilloscope's display confirmed that the Smart Drive motor was indeed an ER-PMSM with a sinewave back-EMF as shown in Figure 4.15.

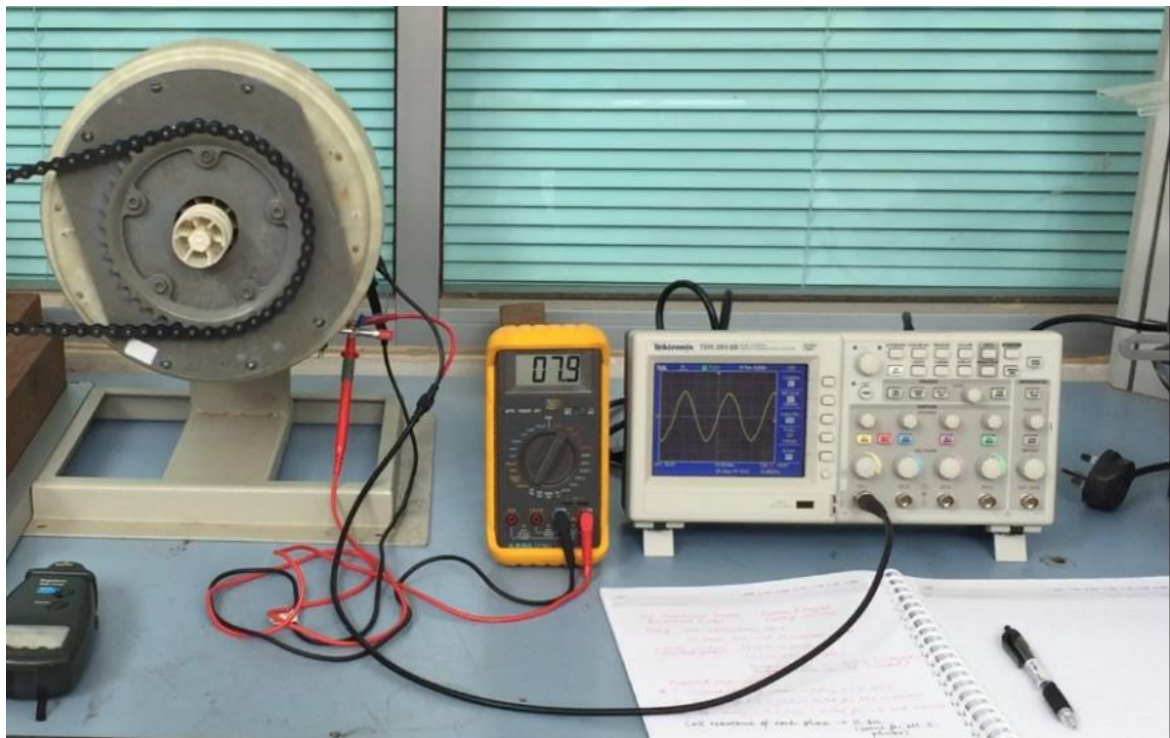


Figure 4.15: Output voltage and back-EMF waveform of the Smart Drive motor.

While the second experiment is to test the motor when running as a generator without load. The data recorded from a single-phase output are shown in Table 4.9 and the graph is shown in Figure 4.16. The graph shows a linearly increasing AC output voltage. The test must be stopped at 260 RPM because the lathe machine could not generate more torque to turn the motor to a higher RPM and would break down.

Table 4.9: Output voltage of the Smart Drive motor as a generator without load.

RPM	Output Voltage (V)	RPM	Output Voltage (V)	RPM	Output Voltage (V)
0	0.0	110	43.1	210	82.2
20	7.5	120	47.0	220	86.2
30	11.2	130	50.7	230	89.9
40	15.3	140	54.7	240	94.0
50	19.2	150	58.6	250	98.1
60	23.1	160	62.7	260	102.2
70	27.1	170	66.6		
80	31.0	180	70.4		
90	35.2	190	74.3		
100	39.0	200	78.2		

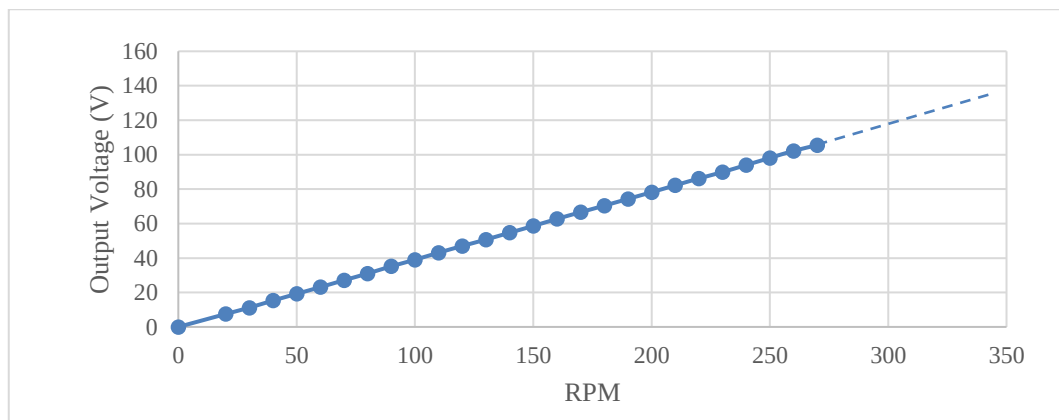


Figure 4.16: Output voltage of the Smart Drive motor as a generator without load.

4.4.2.2 Smart Drive Motor Cogging Test

The second part of the case study is to test the cogging torque of the 42-pole 60s Smart Drive motor. The Smart Drive motor cogging torque measurement results are shown in Figure 4.17 and Table 4.10. At the same time, the PMDCM cogging torque measurement results are shown in Figure 4.18 and Table 4.11. From the result in Table 4.9, it can be concluded that the average cogging torque measured for the Smart Drive motor is 1.29 Nm. While for the PMDCM, the cogging torque measured is 1.41 Nm. Based on these experiment results, technically the brushed PMDCM (though smaller in size) has a greater cogging torque (i.e., by 9.3 % more) compared to the Smart Drive motor. Therefore, at this juncture, it can be deduced that the Smart Drive 60s motor is the better option for small-scale RES construction, especially the wind turbine, due to its lower cogging torque.



Figure 4.17: Measuring the weight of W_1 for the Smart Drive motor.

Table 4.10: Cogging torque measured for the Smart Drive motor.

W_1 (Kg)	W_2 (Kg)	$W_1 - W_2$ (Kg)	R (m)	Cogging Torque (Nm)
6.80	0.45	6.35	0.02	1.25
7.20	0.45	6.75	0.02	1.32
6.85	0.45	6.40	0.02	1.26
7.25	0.45	6.80	0.02	1.33



Figure 4.18: Measuring the weight of W_1 for the PMDCM.

Table 4.11: Cogging torque measured for the PMDCM.

W_1 (Kg)	W_2 (Kg)	$W_1 - W_2$ (Kg)	R (m)	N-m
2.40	0.45	1.95	0.07	1.34
2.40	0.45	1.95	0.07	1.34
2.60	0.45	2.15	0.07	1.48
2.60	0.45	2.15	0.07	1.48

4.4.2.3 Smart Drive Generator Testing Under Different Stator Configurations

The third part of the case study tested the 42-pole 60s Smart Drive generator under four different stator configurations. The no-load test results are shown in Table 4.12, and the graphs are shown in Figure 4.19. From the no-load test, it was observed that the prime mover could not drive the Smart Drive generator with a factory-wired stator (60-14s-1p-S) at a speed slower than 50 RPM. Therefore, for comparison, the RPM range set for the testing is between 50 to 200 RPM for the remaining three configurations (i.e., (60-7s-2p-S), (60-2s-7p-S) and (60-1s-14p-S)). Although the prime mover can drive the Smart Drive generator to a higher speed, the test was stopped at around 200 RPM as the generator stand was wobbling excessively.

Table 4.12: The Smart Drive generator no-load tests.

Generator Speed (RPM)	60-14s-1p-S Output voltage (V)	60-7s-2p-S Output voltage (V)	60-2s-7p-S Output voltage (V)	60-1s-14p-S Output voltage (V)
50	47.6	23.7	6.2	3.0
60	56.5	28.5	7.5	3.6
70	65.4	33.1	8.7	4.2
80	75.3	37.2	10.1	4.8
90	84.2	42.1	11.3	5.4
100	93.5	45.6	12.7	6.0
110	102	50.3	14	6.6
120	111.3	55	15.3	7.2
130	119.1	58.8	16.3	7.8
140	127.7	63.5	17.7	8.4
150	137.1	67.8	18.9	9.0
160	146.1	72.5	20.2	9.6
170	155.3	77.3	21.5	10.2
180	164.7	82	22.8	10.8
190	174.2	86.5	24.1	11.4
200	183.1	90.8	25.4	12.0

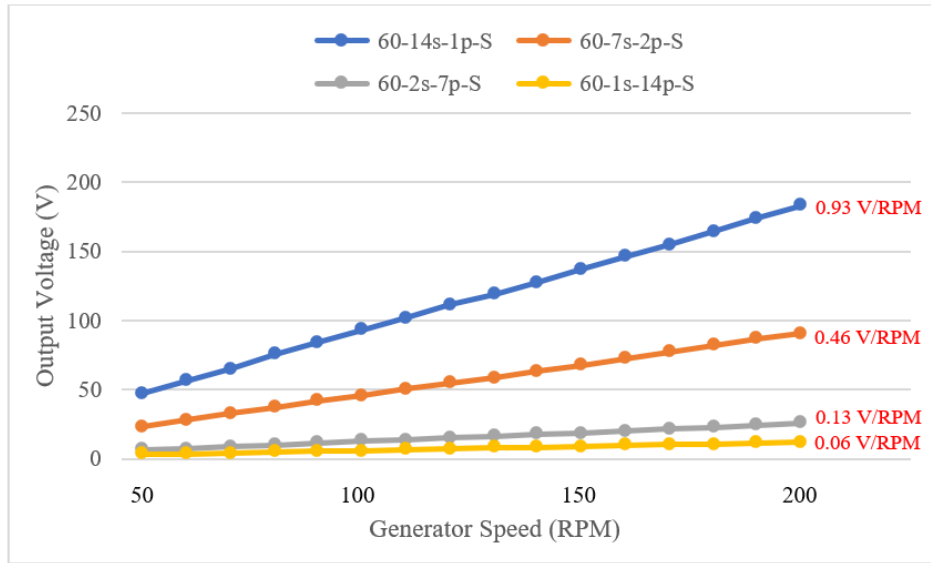


Figure 4.19: The Smart Drive generator no-load tests.

Figure 4.19 shows the no-load output voltage increased linearly with generator speed for all four stator configurations. The rate of output voltages with generator speed is summarised in Table 4.13. It is observed that as more and more coils are paralleled, the output V/RPM has significantly dropped, and the generator required less torque to be driven. All the tested V/RPM in Table 4.13 show lower values (from 9.6 to 17.8 % lower) than the output claimed by EcoInnovation in Figure 3.75. This could be due to the deteriorated strength of the permanent magnet as this Smart Drive motor is more than ten years old.

Table 4.13: Summary of V/RPM for the no-load tests of the rewired stators.

Rewired Stator Connection	Tested V/RPM	V/RPM by EcoInnovation	Difference (%)
60-14s-1p-S	0.93	1.108	16.1
60-7s-2p-S	0.46	0.509	9.6
60-2s-7p-S	0.13	0.145	10.3
60-1s-14p-S	0.06	0.073	17.8

For the Smart Drive generator test with load, the Smart Drive generator with the factory-wired stator is initially driven to a no-load speed of 189 RPM. Then the light switch is turned on for just one LED light. The test results for the Smart Drive generator with load are shown in Table 4.14. From the test results, it can be seen that when the light switch is turned on, the generator speed immediately plunges to 13.7 RPM. An attempt to increase the generator RPM only reached 17.1 RPM at maximum. Meanwhile, the maximum output generated was only 1.82 W. The results also revealed that the prime mover used was unable to generate more torque to drive the generator to a much higher RPM.

Table 4.14: Load test results for the 60-14s-1p-S connection.

Generator Speed (RPM)	Output Voltage (V)	Output Current (A)	Output Power (W)
13.7	8.6	0.1	0.86
17.1	9.1	0.2	1.82

For the test results of the 60-7s-2p-S connection (as shown in Table 4.15), the study faced the same issue as the factory-wired stator where the prime mover failed to drive the Smart Drive generator when it was loaded with just one LED light. Therefore, the generator is driven to a no-load speed of 188.5 RPM and then the switch to one LED light is switched on. At this moment, the generator's RPM immediately plunged to 26 RPM. The output power produced is 1.84 W. The study was able to increase the generator's speed slightly to a maximum of 31.8 RPM and the output power generated was 3.06 W.

For the test results of the 60-2s-7p-S connection (as shown in Table 4.16), the study was able to experiment without having to go through the steps of initially driving the Smart Drive generator to a certain speed. With the switch to one LED light switched on, the prime

mover could start driving the generator at 48.1 RPM, but the output was still zero. The study was able to derive five different speeds from the generator (at 25 RPM increment) and the maximum output produced was 17.38 W at 151 RPM.

Table 4.15: Load test results for the 60-7s-2p-S connection.

Generator Speed (RPM)	Output Voltage (V)	Output Current (A)	Output Power (W)
26.0	9.18	0.2	1.84
29.7	9.75	0.2	1.95
31.8	10.20	0.3	3.06

Table 4.16: Load test results for the 60-2s-7p-S connection.

Generator Speed (RPM)	Output Voltage (V)	Output Current (A)	Output Power (W)
48.1	6.2	0.0	0.00
75.5	8.5	0.1	0.85
100.3	11.0	0.3	3.30
124.1	13.1	0.7	9.17
151.0	15.8	1.1	17.38

For the test results of the 60-1s-14p-S connection (as shown in Table 4.17), the study was again able to experiment without having to go through the steps of initially driving the Smart Drive generator to a certain speed. With the switch to one LED light switched on, the prime mover was able to start driving the generator at 125 RPM, but the output power was still zero. As the generator required the least torque to turn compared to the previous three

stator connections, the study was able to derive ten different speeds from the generator (at 15 RPM increment) and the maximum output produced was 14.80 W at 260.5 RPM.

Table 4.17: Load test results for the 60-1s-14p-S connection.

Generator Speed (RPM)	Output Voltage (V)	Output Current (A)	Output Power (W)
125.0	7.3	0.0	0.00
140.4	7.9	0.0	0.00
155.1	8.7	0.1	0.87
170.6	9.6	0.2	1.92
185.1	10.5	0.3	3.15
200.5	11.3	0.4	4.52
215.6	12.2	0.6	7.32
230.3	13.1	0.7	9.17
245.8	14.0	0.9	12.60
260.5	14.8	1.0	14.80

Since the latter two connections required less torque to drive, the study has decided to continue with experiments with more load. For the 60-2s-7p-S connection, the results for the test with one LED (i.e., 9 W) and two LEDs (i.e., 18 W) as the load are shown in Table 4.18 and Figure 4.20. The study is unable to continue with more LEDs as load due to more torque being required. Figure 4.20 shows that when two LEDs are used as the load, the generator produces significantly more power after 100 RPM. At around 125 RPM, the generator with two LEDs as the load produced 13.64 W, which is 48 % more power than the generator with one LED as the load.

Table 4.18: The 60-2s-7p-S output power with two different loads.

Generator Speed (RPM)	Output Power (W)	
	with 9 W load	with 18 W load
50	0.00	0.00
75	0.85	0.82
100	3.30	5.10
125	9.17	13.64
150	17.38	N/A

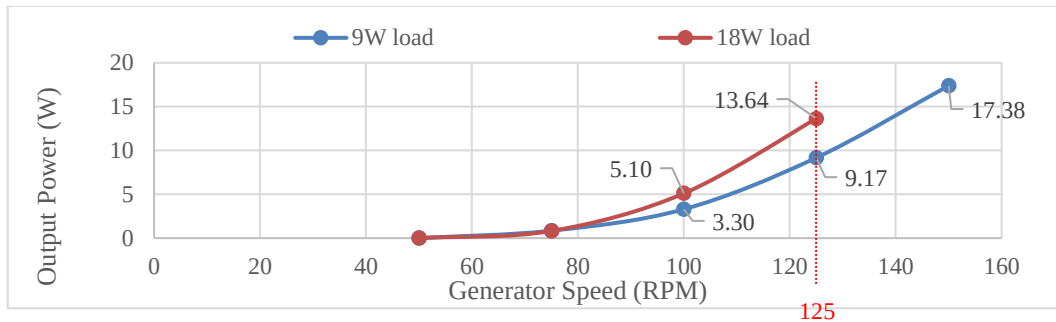


Figure 4.20: The 60-2s-7p-S connection test with two different loads.

Meanwhile, for the 60-1s-14p-S connection, the test results with one to five LEDs are shown in Table 4.19 and Figure 4.21. From Figure 4.21, it can be seen that when more LEDs are used as the load, the generator produces significantly more power after 150 RPM. At around 230 RPM, the generator with one LED produced 9.17 W, with two LEDs produced 16.25 W (77 % more power), three LEDs produced 19.20 W (109 % more power), four LEDs produced 22.23 W (142 % more power), and lastly, with five LEDs produced 25.08 W (173 % more power). However, the study was not able to test the generator at higher RPM (and possibly with even more load) due to the wobbly generator stand and limited torque from the prime mover.

Table 4.19: The 60-1s-14p-S output power with five different loads.

Generator Speed (RPM)	Output Power (W) with 9 W load	Output Power (W) with 18 W load	Output Power (W) with 27 W load	Output Power (W) with 36 W load	Output Power (W) with 45 W load
125	0	0	0	0	0
140	0	0.79	0	0	0
155	0.87	1.74	0.85	2.55	1.68
170	1.92	3.80	2.73	4.60	5.52
185	3.15	6.18	6.86	8.91	9.80
200	4.52	8.88	9.54	12.60	14.42
215	7.32	12.98	14.82	17.60	19.62
230	9.17	16.25	19.20	22.23	25.08
245	12.60	19.95	24.13	N/A	N/A
260	14.80	25.20	N/A	N/A	N/A

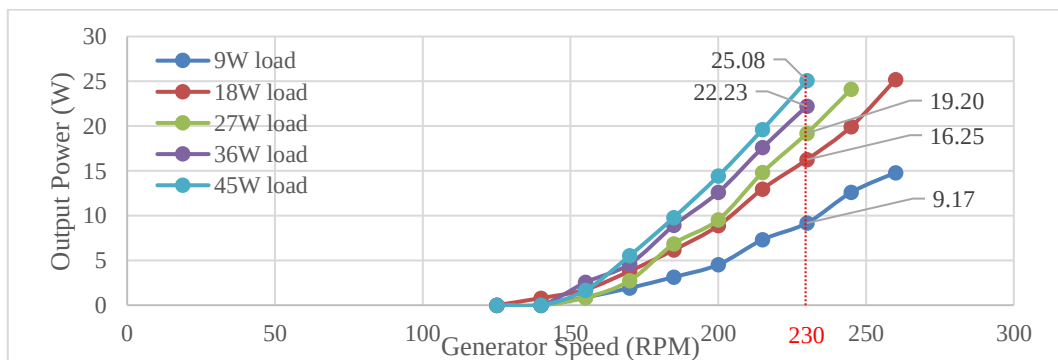


Figure 4.21: The 60-1s-14p-S connection test with five different loads.

As a conclusion for the third part of the case study which is to evaluate the Smart Drive motor as a generator under four different configurations, the 60-14s-1p-S (originally wired stator) and the 60-7s-2p-S (rewired stator) produces very high output voltages at lower RPM (i.e., 100 to 200 V in less than 200 RPM) with the no-load test and needs a higher torque to turn when loaded with just one LED light. On the other hand, the 60-2s-7p-S (rewired stator) and the 60-1s-14p-S (rewired stator) produce significantly lower output voltages of 12 to 25 V at around 200 RPM when tested without load. The latter two configurations also required less torque to turn when tested with loads. From this point of view, the 60-2s-7p-S and the 60-1s-14p-S connections are more suitable for small-scale wind or hydrokinetic turbine design and construction.

4.4.2.4 Smart Drive Generator for Small-Scale HKT Design

Finally, the fourth part of the case study involved designing a small-scale HKT using the 42-pole 60s Smart Drive motor as a generator. The rewired stator with the 60-2s-7p-S (60SP) and the 60-1s-14p-S (60P) star-connected stator are considered in the design. The design results are shown in Table 4.20. For the 60SP 12 V system, it can generate up to 150 W and is suitable for river flow velocity from 1.44 to 1.55 m/s. In contrast, the 24 V system can generate up to 300 W for river flow velocity from 1.82 to 1.95 m/s. In the meantime, the 60P 12 V system can generate up to 300 W and is suitable for river flow velocity from 1.75 to 1.95 m/s. Meanwhile, the 24 V system can generate up to 600 W for river flow velocity from 2.20 to 2.46 m/s. At this juncture, it can be concluded that the output power generated by the 60P is double the 60SP but it has to operate double the RPM. This can serve as the guide for small-scale HKT design and construction using the rewired Smart Drive motor as a generator.

Table 4.20: Small-scale HKT design with 60SP and 60P for a 12 and 24 V system.

Parameter	60SP		60P	
	24 V	12 V	24 V	12 V
V/RPM	0.145	0.145	0.073	0.073
W/RPM	0.75	0.75	0.75	0.75
Operating RPM	325 to 400	162 to 200	575 to 800	288 to 400
No-load Output (V)	47 to 58	23 to 29	42 to 58	21 to 29
Operating voltage (V)	27 to 33	13 to 16	24 to 33	12 to 16
Output Power (W)	244 to 300	121 to 150	431 to 600	216 to 300
Turbine Efficiency ($C_p\eta$)	0.3	0.3	0.3	0.3
Water Power (W)	813 to 1000	403 to 500	1437 to 2000	720 to 1000
Flow velocity (m/s)	1.82 to 1.95	1.44 to 1.55	2.20 to 2.46	1.75 to 1.95

4.5 Chapter Summary

In this chapter, the results from the study are presented, evaluated and discussed in three sections. The first section evaluated and discussed the results obtained from the prototype field test. The prototype built from off-the-shelf fan materials produced about 10 W of power and the turbine efficiency is estimated at 0.13. The bulky prototype was heavy and difficult to deploy/retrieve from the test site. Although the prototype constructed has a problematical transmission and is not very efficient, it was sufficient to prove that the adopted concept works.

Next, the field test results obtained for the improved prototype are evaluated and discussed. The improved prototype has managed to overcome the weaknesses of the previous prototype in so many aspects. It was smaller, and the transmission ran smoothly throughout

the field test. The turbine generated 76.86 W (1.84 kW/day) with the original fan rotor and 92.29 W (2.21 kW/day) with the reprofiled fan rotor from a river flow velocity of 1.26 m/s. With the original fan rotor, the turbine efficiency is estimated at 0.28. While with the reprofiled fan rotor, the turbine efficiency is estimated at 0.34. When compared to the cost of commercial small-scale HKT for the shallow river (less than 1 m), the improved prototype is constructed at a fraction of the cost.

Finally, the results obtained from the two case studies of off-the-shelf/recycled motors as the generator. The first case study found out the off-the-shelf/recycled car alternator is a practical candidate for simple small-scale RES construction if efficiency is not a big issue. While the Smart Drive motor in the second case study, which is an off-the-shelf/recycled PMSM from washing machines, is tested for its cogging torque and with four different rewired stator configurations. The Smart Drive motor has lower cogging torque and two of those configurations – the 60-2s-7p-S and the 60-1s-14p-S – are proven to be more suitable for small-scale RES construction. In the small-scale HKT design based on secondary data, a basic guide is produced for the HKT design with the 60-2s-7p-S (60SP) and the 60-1s-14p-S (60P).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

At the beginning of this research, the study investigated Sarawak's need for off-grid rural electrification. With nearly half of its population living in scattered rural communities and uneconomical grid connections, 5 % of Sarawak's population remains without access to 24-hour electricity in 2019. To address this issue, small-scale Micro-Hydropower (MHP) and Solar Energy Systems (SES) are widely implemented. However, small-scale MHP cannot be implemented where the topography does not favour it, while the SES has issues when implemented in tropical climates. The investigation is published in the Q4 Journal of Telecommunication, Electronic and Computer Engineering (JTEC) in 2017, as listed in Appendix D. Meanwhile, through the literature review on small-scale HKT for the shallow river, the study found that the cost of commercially available HKT is just too costly and might not be entirely suitable for tropical rivers.

In the second part of the research, the study has built a low-cost small-scale HKT prototype for shallow tropical rivers. The prototype is constructed using only readily available off-the-shelf materials for proof of concept. The 0.45 m fan rotor with swept-back blades used as the turbine rotor works well. It produced about 10 W of power from a river flow velocity of 0.86 m/s, and the efficiency is estimated at 0.13. However, the downside of the prototype is its design is too bulky and heavy, and its transmission issue during the field test. Despite that, the prototype has proven the concept works.

The third part of the research involved the construction of an improved prototype to overcome the issues mentioned with the previous prototype. The improved prototype is smaller in size but produces bigger output power. With the reprofiled 0.585 m fan rotor with swept-back blades as the turbine rotor, it produced 92.29 W of power from a river flow velocity of 1.26 m/s, and its efficiency is estimated at 0.34. It can produce more than 2 kWh per day, which is deemed sufficient for a typical rural household. Besides, the improved prototype only costs USD 750 and is a fraction of the cost of commercial HKT for shallow rivers. The only downside of this prototype is the generator's noise during operation. The details of this study are published in the 8th International Conference on Smart Grid and Clean Energy Technologies (ICSGCE 2020) and the Q1 Journal of Energy for Sustainable Development in 2021, as listed in Appendix D. The improved prototype also garnered First Place and Gold awards in the Borneo Innovation Festival 2019, as shown by the certificates in Appendix E. The citation for both journal papers as per the date of thesis submission is listed in Appendix F.

In the last part of the study, two case studies are carried out involving off-the-shelf/recycled motors as a generator. Results from the first case study show a car alternator is the preferred and practical choice as a generator for wind turbines but has low efficiency. Besides, the results also reveal the Smart Drive motor is both an attractive and versatile candidate to be used as a generator. In the second case study, the Smart Drive motor from a washing machine is tested with four different stator wiring configurations. The results indicated the Smart Drive has lower cogging torque and the 60SP and 60P configurations are more suitable as a generator for small-scale HKT. This case study also disclosed a basic guide for small-scale HKT design with a Smart Drive motor as a generator with the 60SP and the 60P configurations.

5.2 Contribution of The Study

HKT technology has been around for more than four decades. Even so, the technology application in off-grid rural electrification is still very limited in tropical regions (i.e., countries in central Africa and Southeast Asia), where the resource is abundant. In addition, the excessively high cost of devices built by the rich countries and the lack of research on practical HKT design for tropical rivers have hindered their advancement in tropical regions.

This study found that Sarawak's off-grid electrification approach is limited to the utilisation of the conventional MHP and SES, while the HKT approach has not been explored. The study has proven building a small-scale axial-flow HKT for shallow tropical rivers using only readily available off-the-shelf materials is both practical and feasible. Besides, the construction cost is greatly reduced. Nevertheless, the study also revealed the Smart Drive motor as a promising and versatile candidate to be used as a generator and how to modify its configuration to suit small-scale HKT construction.

The study has presented the idea to the Local Electrical Authority (LEA), and, through a series of talks, shows their eagerness to embark on developing this technology as an alternative to rural electrification in Sarawak.

5.3 Recommendations

The improved prototype has its belt transmission encased in a rectangular metal casing which is less hydrodynamic in its design. Besides, the brushed Permanent Magnet DC Motor (PMDCM) produces a significant level of noise during operation. To improve on this issue, the study has recommended the following:

1. Design the casing using an oval or ecliptical metal tube to reduce drag, just like the shape of a lower unit of an outboard engine.
2. Replace the belt transmission using the submersible pump hose. The flexible hose will reduce the size of the casing needed.
3. Change the brushed PMDCM to a low-speed Permanent Magnet Generator/low-speed Coreless Permanent Magnet Generator.

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APPENDICES

Appendix A: URLs Giving Prices for Small-Scale Solar and Wind Turbine

390W solar \$425.

https://www.eco-worthy.com/products/195w-390w-600w-780w-12v-off-grid-solar-panel-system-with-195-mono-solar-panel-for-cabin-home-rv?variant=35471837069477¤cy=USD&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic

300W solar USD 170.

https://www.wish.com/product/5d8c5274cb20463cfb5cc871?from_ad=goog_shopping&_display_country_code=MY&_force_currency_code=MYR&pid=googleadwords_int&c=%7BcampaignId%7D&ad_cid=5d8c5274cb20463cfb5cc871&ad_cc=MY&ad_curr=MYR&ad_price=611.00&campaign_id=9527731431&exclude_install=true&gclid=CjwKCAiA9bmABhBbEiwASb35V-GQ2cXutQzdWZJZK81Qi81OzdecQ_WRkKtYwju3oagaSEaUV46a4BoCoS4QAvD_BwE&hide_login_modal=true&share=web

800W solar PV USD355

<https://shopee.com.my/New-4x-200W-800W-Mono-Solar-Panel-Kit-Flexible-Waterproof-for-Camping---RV---Boat---Home-Solar-Accessories-Optional-i.58580142.7908459375>

300W wind turbine USD 96.

https://sea.banggood.com/300W-12V-or-24V-Wind-Generator-3-Blades-Kits-Motor-Kit-Electromagnetic-For-Home-Streetlight-Use-p-1631492.html?utm_source=googleshopping&utm_medium=cpc_organic&gmcCountry=MY&utm_content=minha&utm_campaign=minha-my-sea-en-pc¤cy=MYR&cur_warehouse=CN&createTmp=1&ID=49554&utm_source=googleshopping&utm_medium=cpc_bgcs&utm_content=sxxx&utm_campaign=sxxx-ssc-my-sea-all-1101-2quad-11sale&ad_id=476217431695&gclid=CjwKCAiA9bmABhBbEiwASb35V6yZas2MsUD2W8WaGIf21PAa4o4yfTzj0zbg9W_S5OePMtdSQM1ByxoCweUQAvD_BwE

300W wind turbine USD127

https://shopee.com.my/300W-Wind-Generator-24V-12V-Turbine-Energy-6-Blades-Power-Supply-Household-i.92578257.4074974496?gclid=CjwKCAiA9bmABhBbEiwASb35V_eby7mEtjZCi-tRd8xds8X_kbOKoq2oId27HJ14qExmypu7JCfVuxoCidAQAvD_BwE

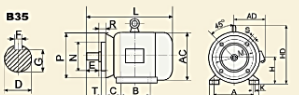
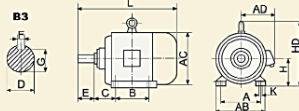
300W wind turbine USD143

https://shopee.com.my/Canca-300w-Wind-Generator-Kit--Diy-Wind-Power-Generator-i.301817101.3164405323?gclid=CjwKCAiA9bmABhBbEiwASb35V5uThtYRgblvTS4RL89f8SObu8CN4tnWJTkkRwprsoc2Yutv9ZgBBoCiygQAvD_BwE

Appendix B: Y Series Three-Phase Induction Motor Specifications



Y SERIES THREE-PHASE INDUCTION MOTOR



MOTOR FEATURES

- Utilize IP55 enclosures, others request
- Multiple feet locations
- Aluminum frame and shields and base
- High strength cable gland
- Shaft key and protector supplied
- Superior paint finish
- Motors made to heavy duty service factors
- Can be made with stainless steel shaft
- Motors made with stainless S1 duty
- Utilize Vacuum impregnated Class B or class F insulation
- High performance and efficiency

CUSTOMER BENEFITS

- Water dust and vermin resistant
- Quiet operation
- Electricity saving
- Easy installation (bolt on feet) or brackets as required
- Corrosion required
- Corrosion resistant
- Dependable
- Superior life
- Reliable in country, city or factory environments

INSTALLATION SIZE AND OVERALL DIMENSION																						
Frame No	Installation Size												Overall Dimension									
	A	B	C	D	E	F	G	H	K	M	N	P	R	S	T	AB	AC	AD	AE	AF	AG	
Y90	125	100	50	19	40	8	15.5	80	10	165	130	200	0	12	3.5	165	175	150	175	290		
Y90S	140	100	56	24	80	8	20	90	10	165	130	200		12	3.5	180	195	160	195	315		
Y90L	140	125	56	24	80	8	20	90	10	165	130	200		12	3.5	180	195	160	195	340		
Y100L	160	140	70	28	80	8	24	100	12	215	180	250		15	4.0	205	215	180	245	380		
Y112M	160	140	70	28	80	8	24	112	12	215	180	250		15	4.0	245	240	190	265	400		
Y132S	216	140	89	38	80	10	33	132	12	265	230	300		15	4.0	280	275	210	315	475		
Y132M	216	178	89	38	80	10	33	132	12	265	230	300		15	4.0	280	275	210	315	515		
Y160M	245	210	108	42	110	12	37	160	15	300	250	350		19	5.0	325	325	255	365	600		
Y160L	245	254	108	42	110	12	37	160	15	300	250	350		19	5.0	325	325	255	385	645		
Y180M	279	241	121	48	110	14	42.5	180	15	300	250	350		19	5.0	355	360	285	430	870		
Y180L	279	279	121	48	110	14	42.5	180	15	300	250	350		19	5.0	355	360	285	430	910		
Y200L	318	305	133	55	110	16	49	200	19	350	300	400		19	5.0	395	400	310	475	775		
Y225S	356	286	149	60	110	18	53	225	19	400	350	450		19	5.0	435	470	345	520	820		
Y225M-2	356	311	149	65	110	16	49	225	19	400	350	450		19	5.0	435	470	345	520	815		
Y250M	356	311	149	60	140	18	53	225	19	400	350	450		19	5.0	435	470	345	520	845		
Y250M-2	406	349	168	60	140	18	53	250	24	500	450	550		19	5.0	490	515	385	575	930		
Y250M	406	349	168	65	140	18	58	250	24	500	450	550		19	5.0	490	515	385	575	930		
Y280S-2	457	368	190	65	140	18	58	280	24	500	450	550		19	5.0	550	585	410	640	1000		
Y280	457	368	190	75	140	20	67.5	280	24	500	450	550		19	5.0	550	585	410	640	1000		
Y280M-2	457	419	190	65	140	18	58	280	24	500	450	550		19	5.0	550	585	410	640	1050		
Y280M	457	419	190	75	140	20	67.5	280	24	500	450	550		19	5.0	550	585	410	640	1050		
Y315S-2	508	406	216	65	140	18	58	315	28	600	550	660		24	6.0	744	645	576	865	1240		
Y315S	508	406	216	80	170	22	71	315	28	600	550	660		24	6.0	744	645	576	865	1270		
Y315M-2	508	457	216	65	140	18	58	315	28	600	550	660		24	6.0	744	645	576	865	1310		
Y315	508	457	216	80	170	22	71	315	28	600	550	660		24	6.0	744	645	576	865	1340		
Y315L-2	508	508	216	65	140	18	58	315	28	600	550	660		24	6.0	744	645	576	865	1310		
Y315L	508	508	216	80	170	22	71	315	28	600	550	660		24	6.0	744	645	576	865	1340		

--01-- [Http://www.eagle-power.com](http://www.eagle-power.com)



Y SERIES THREE-PHASE INDUCTION MOTOR

Model	Rated Output		Full Load					Ist/In Locked	Ist/In Locked	IN/IN max	Net Weight (kg)
	KW	HP	Speed(r/min)	Current(A)	Eff.(%)	Power factor(cos φ)	Rated Current	Rated Current	Rated Current		
380V 50Hz Synchronous Speed 3000r/min (2 poles)											
Y801-2	0.75	1	2830	1.81	75	0.84	6.5	2.2	2.3	17	
Y802-2	1.1	1.5	2830	2.52	77	0.86	7.0	2.2	2.3	18	
Y90S-2	1.5	2	2840	3.44	78	0.85	7.0	2.2	2.3	22	
Y90L-2	2.2	3	2840	4.83	80.5	0.88	7.0	2.2	2.3	26	
Y100L-2	3.0	4	2870	6.39	82	0.87	7.0	2.2	2.3	35	
Y112M-2	4.0	5.5	2890	8.17	85.5	0.88	7.0	2.2	2.3	45	
Y132S1-2	5.5	7.5	2900	11.1	85.5	0.88	7.0	2.0	2.3	47	
Y132S2-2	7.5	10	2900	15.0	86.2	0.88	7.0	2.0	2.3	71	
Y160M1-2	11	15	2920	21.8	87.2	0.88	7.0	2.0	2.3	116	
Y160M2-2	15	20	2920	29.4	88.2	0.88	7.0	2.0	2.3	130	
Y160L-2	18.5	25	2920	35.5	89	0.89	7.0	2.0	2.2	150	
Y180M-2	22	30	2940	42.2	89	0.89	7.0	2.0	2.2	175	
Y200L1-2	30	40	2950	58.9	90	0.89	7.0	2.0	2.2	227	
Y200L2-2	37	50	2950	69.8	90.5	0.89	7.0	2.0	2.2	255	
Y225M-2	45	60	2970	83.9	91.5	0.89	7.0	2.0	2.2	300	
Y250M-2	55	75	2970	103	91.5	0.89	7.0	2.0	2.2	369	
Y280S-2	75	100	2970	139	92	0.89	7.0	2.0	2.2	520	
Y280M-2	90	125	2970	164	92.5	0.89	7.0	2.0	2.2	577	
Y315S-2	110	150	2980	203	92.5	0.89	6.8	1.8	2.2	960	
Y315M-2	132	180	2980	242	93	0.89	6.8	1.8	2.2	1080	
Y315L1-2	160	220	2980	292	93	0.89	6.8	1.8	2.2	1150	
Y315L2-2	200	270	2980	365	93.5	0.89	6.8	1.8	2.2	1210	
Y355M-2	250	340	2980	444	94.5	0.90	7.0	1.2	2.2	1780	
Y355L-2	315	430	2980	555	95	0.90	7.1	1.2	2.2	1900	
380V 50Hz Synchronous Speed 1500r/min (4 poles)											
Y801-4	0.55	0.75	1390	1.51	73	0.78	6.0	2.4	2.3	17	
Y802-4	0.75	1	1390	2.18	74.5	0.78	6.5	2.3	2.3	18	
Y90S-4	1.1	1.5	1400	2.75	76	0.79	6.5	2.3	2.3	23	
Y90L-4	1.5	2	1400	3.65	79	0.79	6.5	2.3	2.3	27	
Y100L1-4	2.2	3	1420	5.03	81	0.80	7.0	2.2	2.3	35	
Y100L2-4	3.0	4	1420	6.82	82.5	0.81	7.0	2.2	2.3	38	
Y112M-4	4.0	5.5	1440	8.77	84.5	0.82	7.0	2.2	2.3	49	
Y132S1-4	5.5	7.5	1440	11.6	85.5	0.84	7.0	2.2	2.3	67	
Y132S2-4	7.5	10	1440	15.4	87	0.85	7.0	2.2	2.3	80	
Y160M-4	11	15	1460	22.0	88	0.84	7.0	2.2	2.3	124	
Y160L-4	15	20	1460	30.2	88.5	0.85	7.0	2.2	2.3	147	
Y180M-4	18.5	25	1470	35.9	91	0.86	7.0	2.0	2.2	169	
Y180L-4	22	30	1470	42.5	91.5	0.86	7.0	2.0	2.2	184	
Y200L-4	30	40	1470	58.0	92.2	0.87	7.0	2.0	2.2	241	
Y225S-4	37	50	1480	70.4	91.6	0.87	7.0	1.9	2.2	300	
Y225M-4	45	60	1480	84.2	92.3	0.88	7.0	1.9	2.2	330	
Y250M-4	55	75	1480	103	92.7	0.88	7.0	1.9	2.2	400	
Y280S-4	75	100	1480	140	92.7	0.88	7.0	1.8	2.2	546	
Y280M-4	90	125	1480	164	93.5	0.89	7.0	1.9	2.2	620	
Y315S1-4	110	150	1480	201	93.5	0.89	6.8	1.7	2.2	1030	
Y315M-4	132	180	1480	240	94	0.89	6.8	1.8	2.2	1100	
Y315L1-4	160	220	1490	289	94.5	0.89	6.8	1.8	2.2	1140	
Y315L2-4	200	270	1490	361	94.5	0.89	6.8	1.8	2.2	1190	
Y355M-4	250	340	1485	458	94.7	0.87	6.8	1.4	2.2	1900	
Y355L-4	315	430	1485	576	95.2	0.87	6.9	1.4	2.2	1940	
380V 50Hz Synchronous Speed 1000r/min (6 poles)											
Y90S-6	0.75	1	910	2.25	72.5	0.76	5.5	2.0	2.2	23	
Y90L-6	1.1	1.5	910	3.16	73.5	0.72	5.5	2.0	2.2	25	
Y100L-6	1.5	2	940	3.97	77.5	0.74	6.0	2.0	2.2	29	
Y112M-6	2.2	3	940	5.61	80.5	0.76	6.0	2.0	2.2	45	
Y132S1-6	3.0	4	960	7.23	83	0.78	6.5	2.0	2.2	63	
Y132S2-6	4.0	5.5	960	9.40	84	0.77	6.5	2.0	2.2	73	
Y160M1-6	5.5	7.5	960	12.9	85.3	0.78	6.5	2.0	2.2	84	
Y160M2-6	7.5	10	970	17.0	86	0.78	6.5	2.0	2.0	119	
Y180M1-6	11	15	970	24.6	87	0.78	6.5	2.0	2.0	147	
Y180L-6	15	20	970	31.8	89.5	0.8	6.5	1.8	2.0	181	
Y200L1-6	18.5	25	970	37.7	89.8	0.83	6.5	1.8	2.0	215	
Y200L2-6	22	30	970	44.6	90.2	0.83	6.5	1.8	2.0	235	
Y225M-6	30	40	980	58.9	92	0.85	6.5	1.7	2.0	294	
Y250M-6	37	50	980	72	90.5	0.85	6.5	1.7	2.0	300	
Y280S-6	45	60	980	85.4	92	0.87	6.5	1.8	2.0	506	
Y280M-6	55	75	980	104	92	0.87	6.5	1.8	2.0	552	
Y315S1-6	75	100	980	141	92.8	0.87	6.5	1.7	2.0	960	
Y315M-6	90	125	990	169	93.2	0.87	6.5	1.6	2.0	1090	
Y315L1-6	110	150	990	206	93.5	0.87	6.5	1.6	2.0	1150	
Y315L2-6	132	180	990	245	93.8	0.87	6.5	1.6	2.0	1210	
Y355M1-6	160	220	990	300	94.1	0.88	6.7	1.3	2.0	1620	
Y355M2-6	200	270	990	374	94.2	0.88	6.7	1.3	2.0	1750	
Y355L1-6	250	340	990	465	94.6	0.89	6.7	1.3	2.0	1980	

Appendix C: PMDC armature circuit resistance measurement

Test Procedure:

1. Hold the Gearmotor in place with the armature locked.
2. Make sure that the voltage is still high enough to drive a current of at least 10% of the motor's nameplate rating or 0.25 Amp, whichever is higher.
3. Starting with a "cool" motor (meaning the winding temperature is the same as the ambient, which should be at a normal room temperature of +25° C [+77°F]), measure the applied voltage and the current draw several times, with the armature in a different angular position each time.
4. Do each test quickly to keep the motor from heating up, because winding resistance changes with temperature and these changes would affect the accuracy of the tests.
5. The armature circuit resistance can then be calculated by:

$$R = V/I$$

Appendix D: Journal and Conference Proceeding Publications

1. **Khengwee, T.**, Hoole, P., Pirapaharan, K., Julai, N., Hj Othman, A.-K., Anyi, M., Haidar, A. M. A., & Hoole, S. (2017). A Review of Sarawak Off-Grid Renewable Energy Potential and Challenges. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, 9(3-10), 29–33. (Q4 in 2017)
2. **Tan, K. W.**, Kirke, B., & Anyi, M. (2021). Small-scale hydrokinetic turbines for remote community electrification. *Energy for Sustainable Development*, 63, 41–50. (Q1 in 2021)
3. **T. K. Wee**, M. Anyi and N. S. Song, 2020. Small-Scale Horizontal Axis Hydrokinetic Turbine as Alternative for Remote Community Electrification in Sarawak. *2020 8th International Conference on Smart Grid and Clean Energy Technologies (ICSGCE 2020)*, pp. 131-136, Kuching, Malaysia, 4 – 7 October 2020. IEEE.

Appendix E: Certificates from Borneo Innovation Festival



bif BORNEO INNOVATION
FESTIVAL 2019
PERINGKAT KEBANGSAAN

Certificate Of Award

This is to certify that

TAN KHENG WEE
DR. MARTIN ANYI
DR. NGU SZE SONG

731002135777
680528135029
800716135011

have been awarded the

GOLD

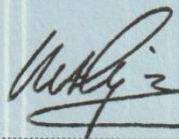
for the innovation/invention project of

HORIZONTAL AXIS HYDROKINETIC TURBINE SYSTEM

in

BORNEO INNOVATION FESTIVAL 2019
DEWAN SERBAGUNA, POLITEKNIK MUKAH

9-10 MARCH 2019



(PROF. DATO' Ts. DR. MOHD ISMAIL BIN ABD AZIZ)

Ketua Pengarah
Jabatan Pengajian Politeknik dan
Kolej Komuniti

Appendix F: Number of Citation

