

# Design and Development of a Small-Scale Mechanical Energy Conversion Device

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## Original Article

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# Abstract

This study aims to design and construct a small-scale mechanical energy conversion device. It is designed to produce electrical power by harnessing the available mechanical energy from renewable resources. This study started off with literature review for the predominant principles and laws on how the machine shall be fabricated in order to function. The process is followed by the material selection and analysis before proceeding to the final design and construction. The constructed machine is then being tested through series of experiments. It was found that the small scale device was able to produce 6V of maximum voltage with rotor rotation speed up to 3000 RPM. The outcome from the experimentation shows that the small scale device is useful for power generation from renewable sources, such as stream energy with a micro hydro turbine. For future study, the machine shall consider a few improvements, such as rebuilding it using laminated iron as rotor core and increase the number of poles to enhance the performance of the machine in term of energy conversion and extraction. The design and built of this machine would definitely contribute to the environmental sustainability and development of rural area.

## Introduction And Background Of Study

Electrical power is essential for the sustenance and the development for socioeconomic activities of a nation. The power consumption of a nation can even be described as the indicator for the measure of the economic progress(Hirsh & Koomey, 2015). Thus, elevation of electrical power consumption of a country signifies the growth of economic and industrial activities for that country. The electrical energy is generated through electromechanical generator in a power plant, which is normally powered by heat engines or other means of kinetic energy. In Malaysia, the power generation plants rely heavily on fossil fuels such as natural gas and coal. The main sources for power plants in Malaysia are coal (48.4%), natural gas (37.5%) and hydropower which only take up 12.7% (Malaysia Energy Information Hub, 2016). However, the heavy reliance on fossil fuels is one of the contributors for greenhouse gases emission as well as climate change. According to recent report, the energy consumption rate is expected to increase annually from 5–7.9%, which indicates that the energy security of nation should be taken into serious consideration as fossil fuels will be used up in coming future (H.C.Ong, 2011). Therefore, Malaysia is working on other alternative source of energy such as hydroelectric power plant to solve this problem.

The main issue that come to the case of power generation and distribution system is lack of electrical power supply in some of the rural or inland areas of Malaysia. Previous study has disclosed that only 92.93% of the rural areas are electrified (Nasrudin Abd Rahim, 2010). The case in East Malaysia is even critical, which Sabah only has 77% of electrified area and Sarawak on receive 67% of electrification over the whole state (Nasrudin Abd Rahim, 2010). The evidence that this publication shown suggest that alternative power generation methods should be implemented in these areas to eradicate the problem of power supply in rural areas.

The electrification of the rural areas in Sarawak is major motivation for this project. Besides, the outcome of this work will contribute to the renewable energy as well as the electrification of the rural areas in

Malaysia. The build and design of the mechanical energy extractor can benefit the those who are working on renewable energy generation through mechanical energy, typically on wind energy, hydro energy and wave energy. In addition, the promotion of renewable energy can significantly reduce the greenhouse gases emission thus contribute to environment preservation and conservation. In this aspect, the focuses of this research are:

1. What is the suitable design for a small mechanical energy extractor?
2. Can the design be implemented and build?
3. Is the output of the mechanical extractor reach the sufficient level?

This study attempted to answer the research questions by design and develop a small-scale mechanical energy extractor utilizing renewable energy to produce electricity.

## Literature Review

Most of the generators used in power plants over the world are synchronous generator. A synchronous generator is also known as an alternator, is an electrical machine, which can convert mechanical energy, usually rotation force from input into alternating current electrical power at certain voltage and frequency through Faraday's Law of electromagnetic induction (Theraja et al., 2005). Faraday's Law of Induction is one of the most crucial theory in the field of electromagnetism and power generation. Faraday's Law is divided into two part, which is the First Law and Second Law. The first law of Faraday's Law of Induction states that the change of the magnetic field around a conductor or interference caused by the conductor to the constant magnetic flux will induced current and voltage in that conductor. Whenever a conductor is rotate in the magnetic field, it will generate electromotive force (emf). This law serves as a foundation for the later development of various electrical motor and power generator(Klempner & Kerszenbaum, 2004).Meanwhile, the second law of Faraday's Law of Induction states that the electromotive force generated is proportional to the rate of change of magnetic flux around the closed loop. This can be simplified by the following equation,

$$e \propto \frac{\Delta \phi}{\Delta t}$$

Where e is induced electromotive force,  $\phi$  is the magnetic flux.

Lenz's Law is formed on the Faraday's Laws of Induction, which states that the properties of the electromotive force generated from the change of magnetic flux tends to have its current flow in such a way that its magnetic field is opposed to the direction of the change. This law fulfil Newton's third law of motion, which can be explained as the induced current on the conductor creates a magnetic field, which has its amount correspond and opposite to the direction of that magnetic field, which formed it. Apart from that, it also obeys the law of conservation of energy. If the magnetic field produced by the induced current has the same direction of the one which produce it, they will sum up both magnetic fields thus

creating higher current and continue to produce more and more magnetic field, which is violating the law of conservation of energy (Manning, 2014). The equation to sum up the Lenz's law is stated as below

$$e = - \frac{\Delta \phi}{\Delta t}$$

Where  $e$  is induced electromotive force,  $\phi$  is the magnetic flux.

Rotor is the rotating part of a synchronous machine. It can be classified into two types: salient pole rotor and non-salient pole rotor (Wildi, 2006). Salient type rotor is widely appeared in majorities of a synchronous generator in modern days (Fig. 1a). This type of rotor is consisted of six or more projecting magnetic poles attached to the core of the rotor. The characteristics of this kind of construction are normally distinguished by its larger rotor diameter and shorter axial length compare to the non-salient type. Besides, this kind of generators are used widely in low to medium speed synchronous generator due to their higher number of poles(Zorbas, 2015). There are several critical parts for the build of this kind of rotor, which are pole core and shoe, excitation field winding and damper winding. As for non-salient rotor, this type of rotor is also known as cylindrical rotor due to its physical shape. According to Theraja et al. (2005), this type of rotors is commonly used in high speed application, which usually has the working rotational speed exceeding 3600 rpm. The most obvious feature of cylindrical rotor is its shape, which is a smooth cylinder and the projection of magnetic poles is unseen. Comparing to salient type rotor, it has smaller rotor diameter and longer axial length to prevent itself to rotate too fast. The number poles on this type of rotor is usually two and four. The excitation winding of this kind of rotor is placed in the slots machined on the rotor, around the poles. Synchronous generator with cylindrical rotor have few advantages compare to the salient rotor type, which are observable like lower noise production due to its consistent air gap of the winding slot and having a better balancing of the machine(Theraja et al., 2005). The typical build of contemporary non-salient type rotor for synchronous generator is shown in Fig. 1b.

The generator is usually made up of a magnetic field and an armature winding. There are two common type of synchronous generator, which are rotating-armature type and rotating-field type. The rotating-armature type is defined as generator, which has its armature build as a rotor and the magnetic field is produce on the stator. However, this kind of generator is known to face difficulties such as insulation and high current transmission, thus limiting the power output. It tends to have limited application such as small generator for source of magnetic field excitation in larger alternators. For the case of rotating-field type generator, its rotor is acting as a magnetic field system whereas its armature winding is on the stator. On the other hand, this type of generator is widely used, as it can produce high energy output in contrast of the former type (T.F.Chan, 2009). Alternator or synchronous generator is agreed to be most important component in a power generation system. It acts as a mechanical energy extractor to extract mechanical energy from input source and convert it into electrical energy as output. For any conversion of mechanical energy to electrical energy, the employment of an alternator is inevitable. Besides, a well function alternator should have reasonable budget to be built with and produce adequate power depending on the source of energy input. From the extensive review of multiple literatures in the field of

energy generation, apparently there are some gap found, some of them worth mentioning such as many researchers aim design and develop generator with newer concept instead of optimising the existing one. However, there is limited study focus on the optimisation of the existed machine to increase devices' efficiency and effectiveness. On the other hand, most research efforts are being placed on building the larger scale of generator due to economic of scale for the production of energy. However, some research efforts should be placed on improving the existing small-scale device for certain reasons, such as portability and easy to install. These would contribute to rural development in Malaysia eventually. Hence, this study is designed to fill these gaps.

## Research Methodology

This study started off with literature review on the relevant concepts related to small and large scale mechanical energy extractor and technologies. A small-scale model is then developed based on suitable concept. The prototype was then being tested in laboratory. Finally, the data collected are analysed and validated statistically.

## Conceptual and Prototype Design

Review from literature indicates that synchronous generator concept is the most important component in a power generation system. It extracts mechanical energy from heat or renewable source and then convert it into electrical energy as output. For any conversion of mechanical energy to electrical energy, the employment of such concept seems inevitable. Therefore, this study employ similar concept but perform some modification on the concept. The conceptual design is shown in Fig. 3.

Some modifications made on the design are using six poles instead of normal one, which are four poles. On the other hand, the rotor is machined with aluminium blocks for its lightness and ease of machining. The magnet used in the system is neodymium magnet, which is known to the strongest type of permanent magnet that is commercially available. The finalized prototype is shown in Fig. 4.

## Results And Discussions

The prototype was tested in laboratory to measure the rotational speed (RPM) and voltage generated. To facilitate the process of data gathering and analysis, the three phase alternating current produced by the generator is rectify to direct current with installation of a three phase rectifier. Electric drill motor was used as prime mover to rotate the prototype with several different speed. The voltage output of the machine against the rotational speed is shown in Fig. 5.

Results from Fig. 5 indicate that high RPM is required to produce up to 6V of voltage. The max output voltage gain from the machine is rated at 6.04 V at rotor rotation speed at 3000 RPM. In power generation, magnetic permeability plays a critically important role. Magnetic permeability of a material is

correspondence between magnetic induction and magnetic field intensity of the material (Azuma, 2018). The material with higher magnetic permeability will have better conductivity for magnetic lines of force as shown in Table 1. To improve the existing prototype, material with higher magnetic permeability such as iron could be used to replace aluminium as material for rotor core. From Table 1, the magnetic permeability of the aluminium is far lower than the permeability of iron, which might affect the strength of magnetic field produced by the neodymium magnet poles notably.

Table 1  
Magnetic Permeability of Material (Zhang et al., 2017)

Medium	Permeability - $\mu$ - (H/m)	Relative permeability - $\mu / \mu_0$ -
Air	$1.25663753 \times 10^{-6}$	1.00000037
Aluminium	$1.256665 \times 10^{-6}$	1.000022
Austenitic stainless steel <sup>1)</sup>	$1.260 \times 10^{-6} - 8.8 \times 10^{-6}$	1.003-7
Bismuth	$1.25643 \times 10^{-6}$	0.999834
Carbon Steel	$1.26 \times 10^{-4}$	100
Cobalt-Iron (high permeability strip material)	$2.3 \times 10^{-2}$	18000
Copper	$1.256629 \times 10^{-6}$	0.999994
Ferrite (nickel zinc)	$2.0 \times 10^{-5} - 8.0 \times 10^{-4}$	16-640
Ferritic stainless steel (annealed)	$1.26 \times 10^{-3} - 2.26 \times 10^{-3}$	1000-1800
Hydrogen	$1.2566371 \times 10^{-6}$	1
Iron (99.8% pure)	$6.3 \times 10^{-3}$	5000
Iron (99.95% pure Fe annealed in H)	$2.5 \times 10^{-1}$	200000
Martensitic stainless steel (annealed)	$9.42 \times 10^{-4} - 1.19 \times 10^{-3}$	750-950
Martensitic stainless steel (hardened)	$5.0 \times 10^{-5} - 1.2 \times 10^{-4}$	40-95
Nanoperm	$1.0 \times 10^{-1}$	80000
Neodymium magnet	$1.32 \times 10^{-6}$	1.05
Nickel	$1.26 \times 10^{-4} - 7.54 \times 10^{-4}$	100-600
Permalloy	$1.0 \times 10^{-2}$	8000
Platinum	$1.256970 \times 10^{-6}$	1.000265
Sapphire	$1.2566368 \times 10^{-6}$	0.99999976
Superconductors	0	0
	$7 \times 10^{-6}$	1

Medium	Permeability $-\mu-$ (H/m)	Relative permeability $-\mu/\mu_0-$
Vacuum ( $\mu_0$ )	$4\pi 10^{-7}$	1
Water	$1.256627 10^{-6}$	0.999992

On the other hand, the present prototype uses 6 poles. It was known that increasing number of poles on the rotor can decrease the required rotational speed to achieve the desired voltage compare to a rotor with fewer poles (M.M.Ashraf, 2013). Taking two generators with the same stator windings as an example, one with 8 poles rotor while the other with 4 poles rotor, the one with 4 poles need to acquire the input RPM from the prime mover twice as the former one to produce the same out voltage. Thus, the increment of poles in the rotor can increase the output voltage of the machine.

The voltage output gained from the experiment implies that the generator is only suitable for low voltage applications such as powering street lightings for rural area development. However, more actual data is required to support this application. With such idea in mind, the prototype could be paired with devices that extract kinetic energy from renewable source such as micro hydro turbines. The potential setup for testing renewable generation is shown in Fig. 6. The pump system can be used to maintain water flows to simulate actual river flow; the pully system is useful for transferring mechanical energy generated from turbine to the prototype. This type of system is easy to fabricate and very useful for small scale energy generation related study especially for micro hydro turbine related studies.

## Conclusions

This study focuses on the designation and build of a small-scale mechanical energy extractor. The mini radial flux permanent magnet AC generator is successfully designed, constructed and tested. These actions have fulfilled the three objectives of this project. The working concepts and mechanisms are functionable and accurate. From the experiment conducted, the max output voltage gain from the machine is rated at 6.04 V at rotor rotation speed at 3000 RPM. The machine built is functioning without any major flaws. However, the performance of this machine is anticipated to be stepped up if some amendment for the machine design and construction is done. The suggested modifications of design are changing rotor materials with higher magnetic permeability, such as iron, and increase the number of poles. In conclusion, the outcome of this study can aid in the extension of present comprehension regarding micro energy extraction in the industry. Concurrently, this will also boost the development of rural area, which could contribute to the nation in the aspect of economy, social and industry.

## Declarations

Not applicable

## Competing interest:

The authors do not have any competing interest to declare.

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## Authors' contributions:

1. Man Djun Lee – Main author that contributes the main idea for this project.
2. Pui San Lee – Co-author that collects data under supervision of main author.

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## References

1. Azuma, D. (2018). *Magnetic materials. Wide Bandgap Power Semiconductor Packaging: Materials, Components, and Reliability* (Vol. 7). Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-102094-4.00005-0>
2. H.C.Ong, T. M. (2011). A review on energy scenario and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews, Volume 15*(Issue 1), 639–647.
3. Hirsh, R. F., & Koomey, J. G. (2015). Electricity Consumption and Economic Growth: A New Relationship with Significant Consequences? *Electricity Journal, 28*(9), 72–84. <https://doi.org/10.1016/j.tej.2015.10.002>
4. doi:10.1002/0471683388.ch2  
Klempner, G., & Kerszenbaum, I. (2004, July 28). Generator Design and Construction. *Operation and Maintenance of Large Turbo-Generators*. John Wiley & Sons, INC. <https://doi.org/doi:10.1002/0471683388.ch2>
5. M.M.Ashraf, T. S. (2013). Design and fabrication of radial flux permanent magnet generator for wind turbine applications. *The Nucleus, 2*(50), 173–181.

6. Malaysia Energy Information Hub. (2016). *National Energy Balance 2016*. Putrajaya: Suruhanjaya Tenaga (Energy Commission). Retrieved 29 October, 2018, from <https://meih.st.gov.my/documents/10620/9a9314a1-cf11-4640-a9de-3b31f336a416>
7. Manning, K. V. (2014). *AccessScience*. doi:<https://doi.org/10.1036/1097-8542.377200>
8. Nasrudin Abd Rahim, M. R. (2010). Rural Electrification in Malaysia. *Innovations for Renewable Energy*. Kuala Lumpur: University of Malaysia.
9. T.F.Chan. (2009). Synchronous Machines. In W. K. Po (Ed.), *Electrical Engineering* (Vol. Volume III, pp. 84–97). EOLSS Publications.
10. Theraja, B. L., Theraja, A. K., & Tarnekar, S. G. (2005). *A textbook of electrical technology: Volume 2: AC & DC machines in S.I. system of units* ([23rd rev.]). New Delhi: S. Chand & Company Ltd.
11. Wildi, T. (2006). *Electrical Machines, Drives, and Power Systems* (6th ed.). Pearson Prentice Hall.
12. Zhang, J., Liu, Y., He, T., & Liu, J. (2017). The magnetic driver in rotating wave energy converters. *Ocean Engineering*. <https://doi.org/10.1016/j.oceaneng.2017.06.060>
13. Zorbas, D. (2015). *Electric Machines: Principles, Applications, and Control Schematics*. *Journal of Physics A: Mathematical and Theoretical* (2nd ed.). Cengage Learning.

## Figures

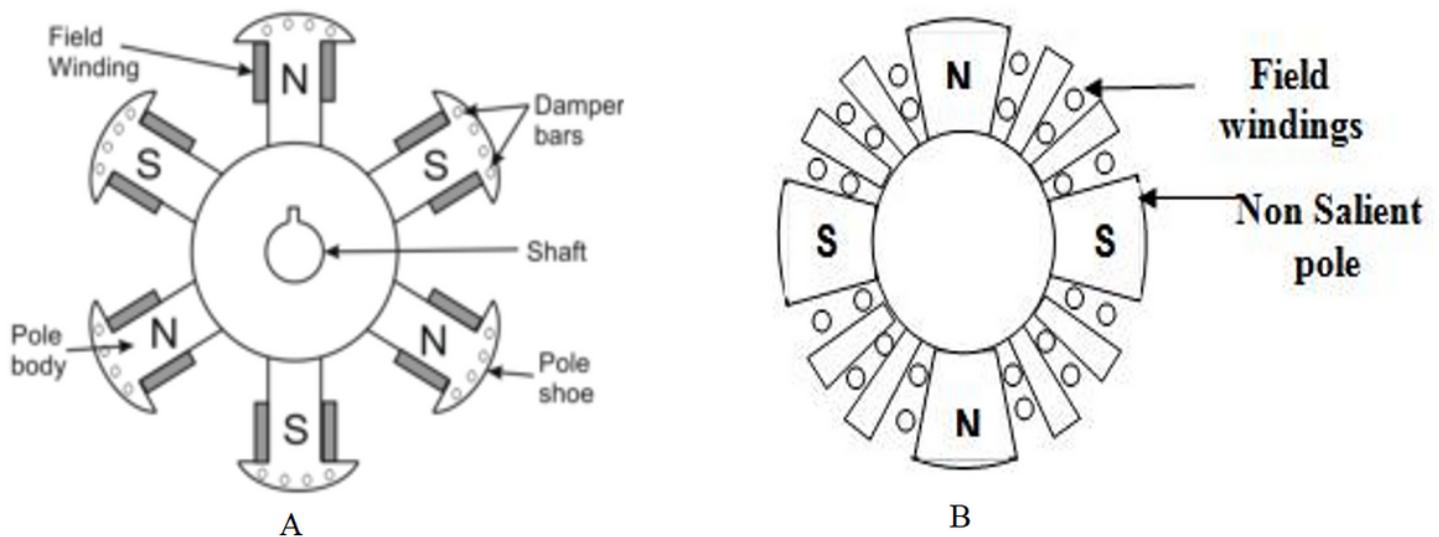


Figure 1

a: Salient Type Rotor b: Non-Salient Type Rotor

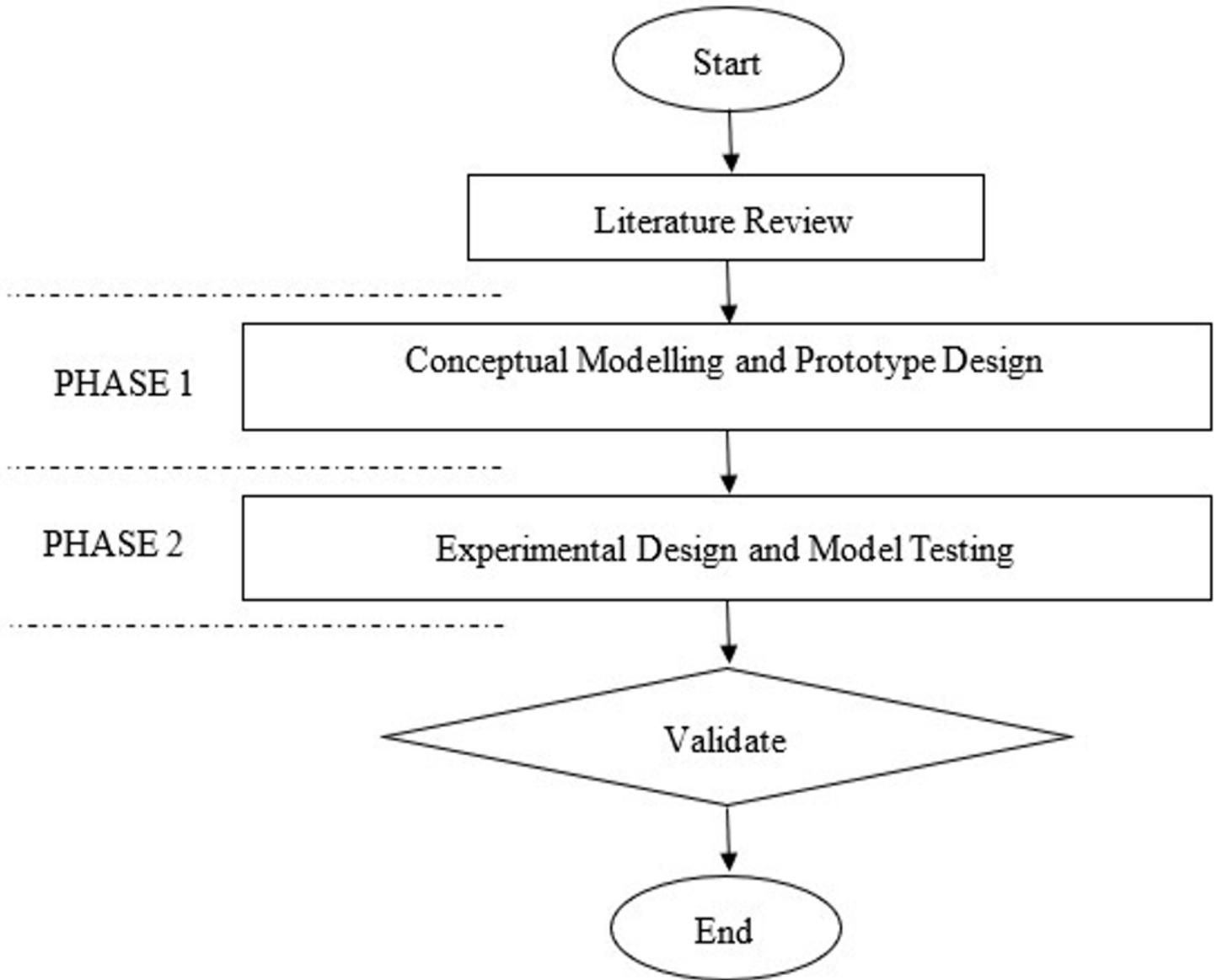


Figure 2

Research Methodology

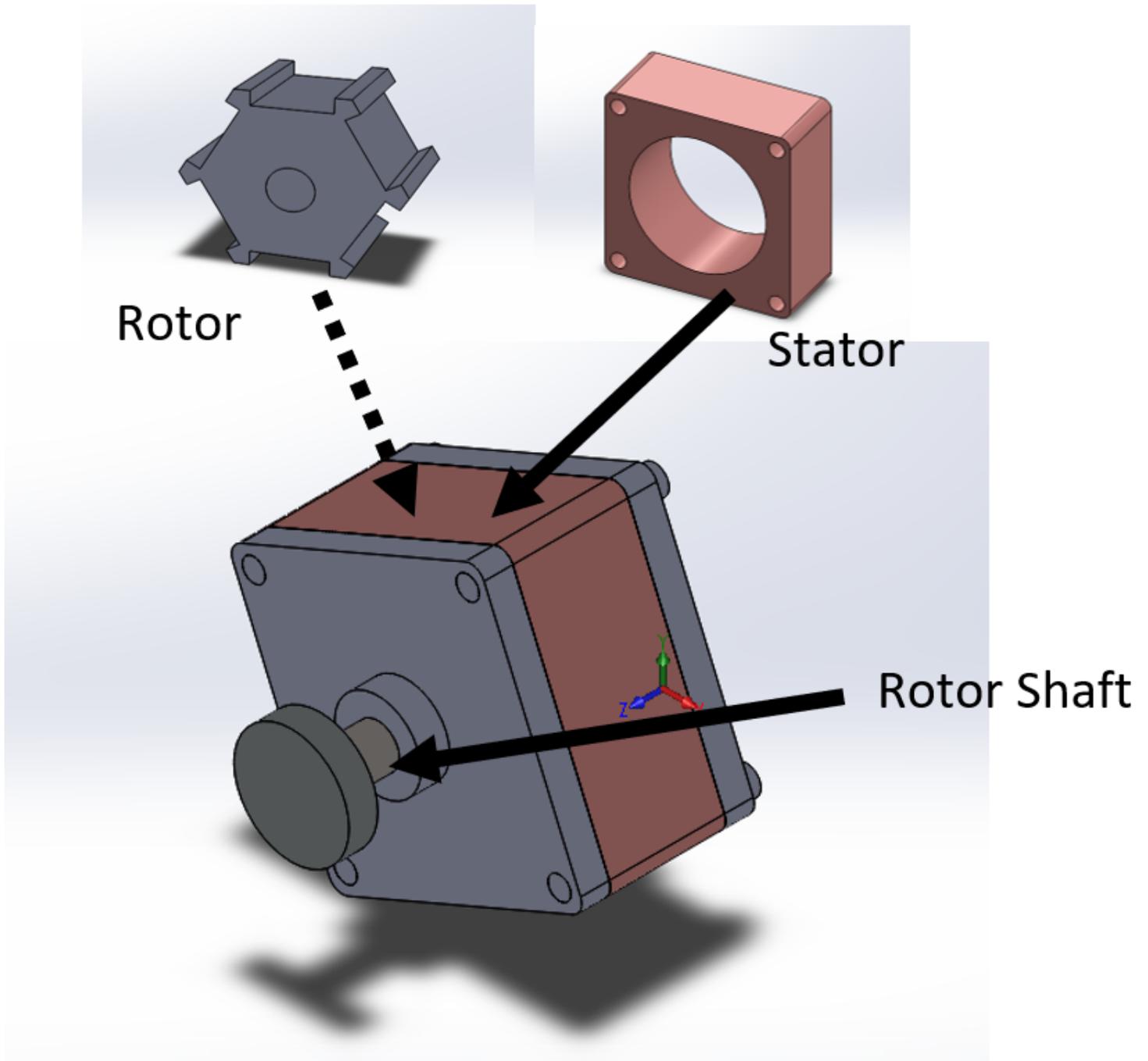


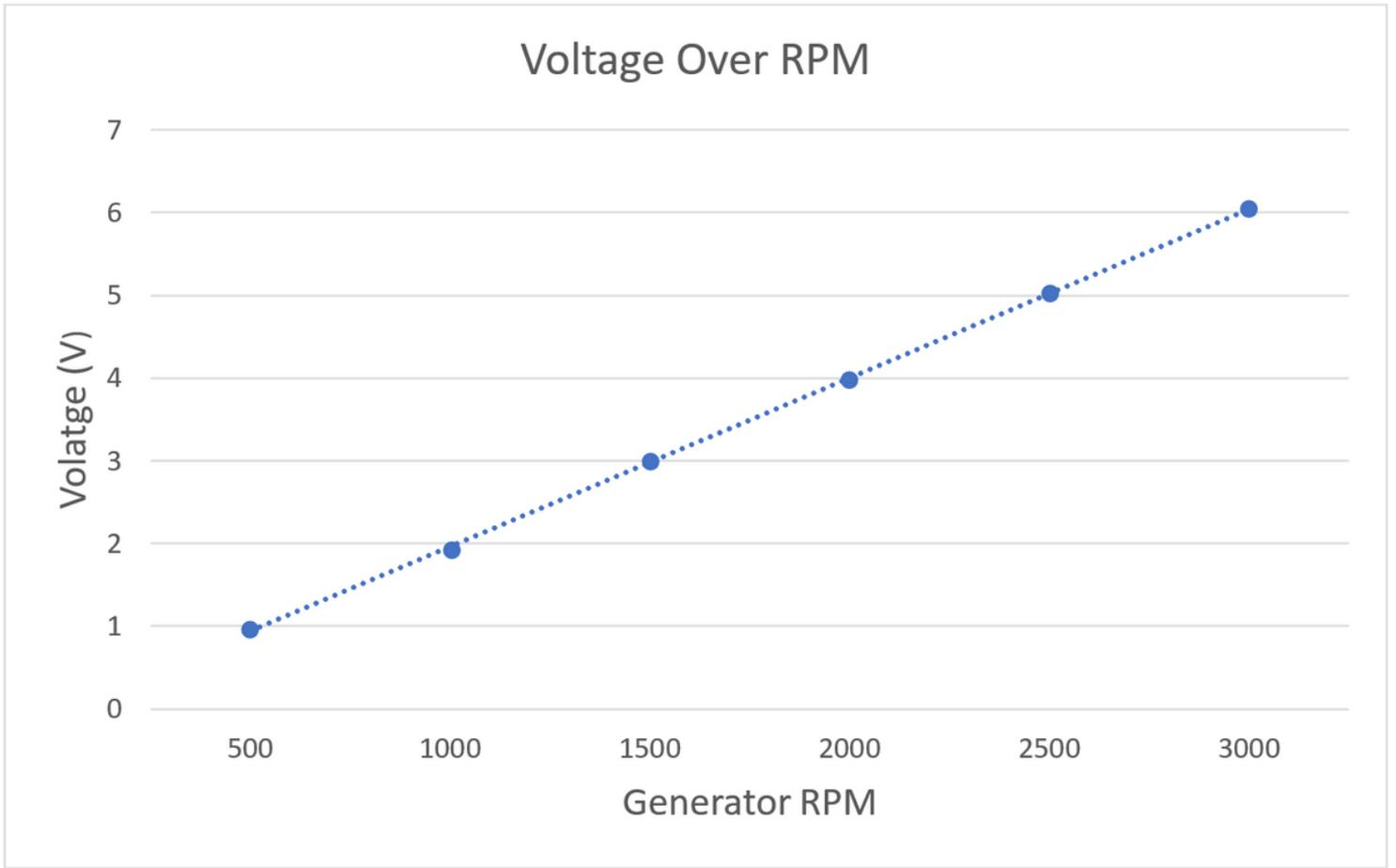
Figure 3

Conceptual Model



Figure 4

Prototype



**Figure 5**

Output Voltage Against Rotational Speed

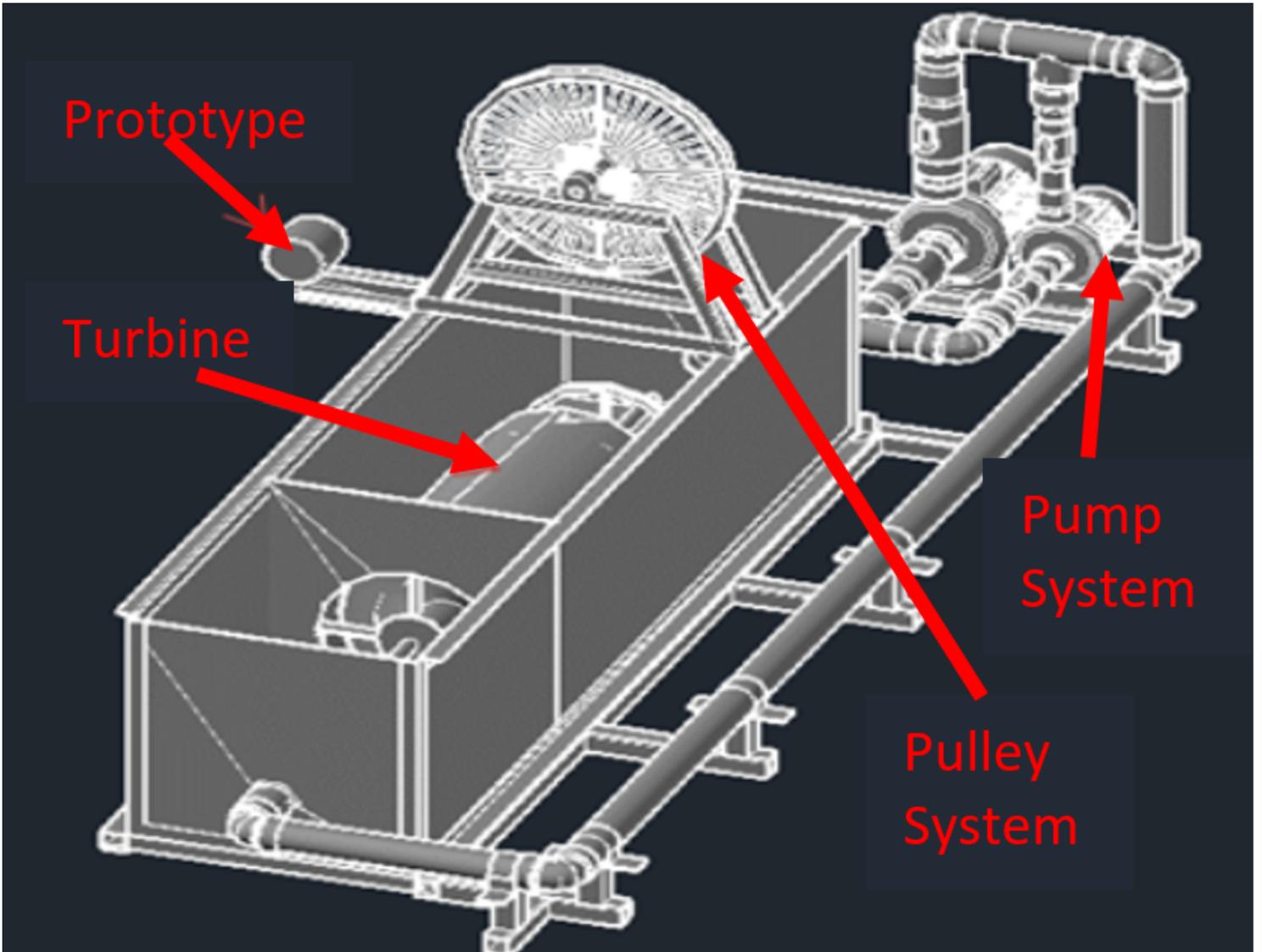


Figure 6

Potential Experimental Setup to Test Micro Hydro Turbine