Design of a Three-phase Generator Power Supply System Driven by a Micro Hydraulic Turbine

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Abstract. With the growing need for energy conservation and sustainability, water flow is seen as an extremely important means of energy production. However, people often overlook the flow of water around them, such as taps, which can also produce a useful amount of electricity or operate as an independent power supply system. Therefore, this paper introduces a device that captures and stores the kinetic energy from everyday faucet water flow for later release. Through the coordination of a blade turbine and a three-phase generator with an electric motor and other structures, the project managed to escape the electronic control system and store a certain amount of energy. Overall, the project is fully designed, and it proves that the idea is feasible. In this paper's design, this energy stored in the form of potential energy can be converted into point energy when needed and then kinetic energy to drive a launcher. The transmitter is just a way for the team to demonstrate to the outside world, and light and heat energy are places where they can be applied.

Keywords: Three-phase generator, Energy transfer, Energy storage.

1. Introduction

The use of electricity has been commonplace for nearly half a century. The reason is the electricity provided by the generator. Nowadays, the most used is the three-phase generator derived from multiple power systems which was invented by Galileo Ferraris, Mikhail Dolivo-Dobrovolsky, Jonas Wenström, John Hopkinson, William Stanley Jr., and Nikola Tesla in the late 1880s [1]. It is also the main part of our equipment. The three-phase generator is an electrical device that converts mechanical energy into electrical energy in three separate phases, each phase carrying an equal magnitude of current and voltage but reaching their peak at different times. There are several advantages of the three-phase generator, including high efficiency, controllable power factor, and constant frequency. The three-phase generator is usually more efficient when compared to other generators, for example, the single-phase generator, because of the high percentage of input kinetic energy into electrical energy. Besides, unlike the other generators, the three-phase generator can control 8its power by moderating its field excitation, as a result, it can be adjusted to a constant frequency which is important for use. However, there are also a few disadvantages that exist with the three-phase generator. The three-phase generator is often more expensive to purchase, which reduces its usage, it also contains the fees to maintain and repair which are more excessive than others. In addition, the three-phase generator produces more sound and noise which has a negative effect on residents.

In residents' daily lives, there are always many people who waste water by not closing the faucet valve. Even if they use water, the water energy is also wasted. So an energy collection plan was created by our group. The final goal is to make better use of water energy to make it have more uses. Our group wants to produce a generator that can let the light bulb shine/launch a ball to hit some goal to prove the great potential of the kinetic energy of falling water from a tap. This experiment focuses on discovering a way to make better use of water energy. We can add a turbine to the tap, and there is an axle shaft, that connects the turbine and a device that can transport water [2]. It is the reason that the device can start up, which can transfer another system of water from the bottom to the top. The device which can transport water can make sure the water is circulated. Hence, the water is brought higher, and its potential energy will be higher than before. Because there is a valve to prevent the water from dropping down, gravitational potential energy could be highly utilized by control the water dropping. When the water drops down, a waterwheel catches the water, thus making the waterwheel rotate. The generator is on the same axis shaft as the waterwheel. Then, the generator is connected to an engine. At the beginning of the equipment, when the valve is turned on, the water drops down, and the waterwheel rotates, so the water energy is changed to mechanical energy. Then, gears are used to change the rotational speed of the waterwheel, making the rotor rotate rapidly. After using a three-phase generator, this mechanical energy is converted to electrical energy. We'll introduce how this conversion is to electrical energy.

2. Method

2.1. Theories and Principles

The project is based on the following theories and principles, which will be explained in this paragraph.

2.1.1 Turbine Output Power

$$P = \eta \cdot W = \eta \cdot \frac{1}{2} \cdot mv^2 \tag{1}$$

$$V = A \cdot v \tag{2}$$

$$m = \rho \cdot V = \rho \cdot A \cdot v \tag{3}$$

$$P = \frac{1}{2} \cdot \eta \cdot \rho \cdot A \cdot v^3 \tag{4}$$

where P is power, η is the efficiency of the turbine, ρ is the density of the fluid, V is the volume of the fluid, A is the cross-sectional area of the flowing fluid, and v is the velocity of the fluid [3].

2.1.2 Gear ratio

$$\frac{z_2}{z_1} = \frac{n_1}{n_2} \tag{5}$$

where z_2 and z_1 are the number of teeth of the driven gear and driving gear respectively, n_1 and n_2 are the rotation speed of the driving gear and driven gear respectively.

2.1.3 Faraday's law of electromagnetic induction

$$\varepsilon = -N\frac{d\phi}{dt} \tag{6}$$

This law states that an e.m.f exists while a conductor is in a changing magnetic flux [4]. Where ε is the induced e.m.f, N is the turns of the coil, and $\frac{d\phi}{dt}$ is the changing rate of magnetic flux.

2.1.4 Lenz's law

Lenz's law: The magnetic field produced by induced current due to Faraday's law of electromagnetic induction is always against the change of magnetic flux, which shows as the negative sign in the formula:

$$\varepsilon = -N\frac{d\phi}{dt} \tag{7}$$

2.1.4 Coulomb law

Coulomb law: A circular magnetic field will be produced when a current passes through a liner conductor.

2.2. Previous Researches

The three-phase generator, due to its high efficiency and low-loss long-distance transmission, dominates approximately 70% of global industrial electric power [5]. According to Shadhu Khan and Chatterjee, the three-phase induction generator is commonly used in micro energy-producing systems nowadays [6]. As stated by Yadav and Chauhan, humans are facing severe energy problems, the increase in demand for energy is not able to be balanced by the energy supply. Thus, a micro hydro system that uses household water as power is designed by Yadav and Chauhan, and the Alternating Current (AC) generated by this system can operate some low-energy electric appliances such as televisions and refrigerators [7]. Bao and Priadi used a spinning wheel to launch the dog ball, we were inspired to use a high-speed spinning wheel to launch a table tennis ball [8]. This device will use the power generated by the three-phase generator and used in a shooting game.

3. Design and Implementation

This study attempted to build a device that would recapture the kinetic energy of running water from a faucet, store it, and then convert it into electrical energy. In a later idea, we decided to convert the electrical energy into kinetic energy by means of an electric motor to drive a small wheel to launch a small ball. These are the two parts of our device, and they will be explained separately.

Fig. 1 is a schematic of the first half. From left to right are the turbine, the reservoir, the waterwheel, the gearbox and the generator. As the water flows from the faucet, the turbine is driven to rotate, which is converted to horizontal rotation by a cardan shaft. The force of this rotation drives a simple sump pump in an attempt to pump water from the cistern below to the cistern above, which is a separate system for water. Specifically, this research attempts to create a pumping chamber and impeller that is as precise as possible. The impeller is housed in the chamber and is driven by a coupling connected to the power shaft. The rotation of the impeller creates a centrifugal force that draws water in through the inlet, removes it from the outlet, and flows it into the sink above.

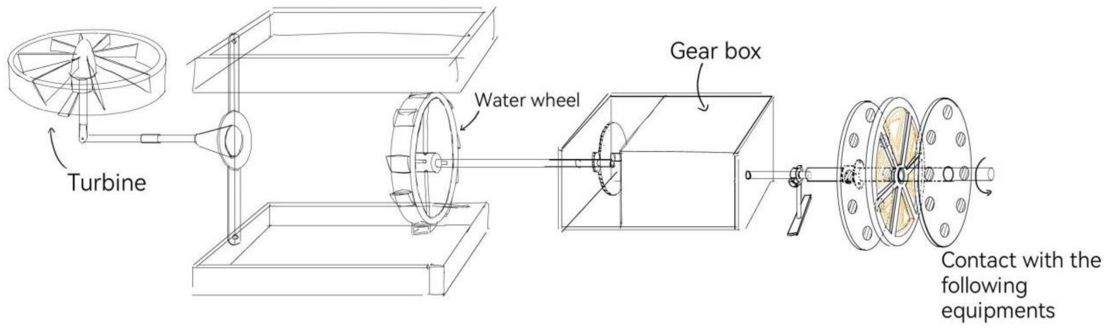

Fig. 1 Water three-phase generator power supply system driven by a micro hydraulic turbine. (Photo/Picture credit: Original)

For an example of a practical tap from school, it has a rate of flow of 0.000125 cubic metres per second, the diameter of the cross-section is 1.3cm, and the efficiency of the turbine is about 50%, so the output power of the turbine can be calculated:

$$\mathrm{A} = \pi \mathrm{r}^2 = \pi \cdot \left(\frac{1.3\times10^{-2}}{2}\right)^2 \approx 0.941\mathrm{m}^2 \tag{8}$$

$$\mathrm{v} = \frac{\mathrm{Q}}{\mathrm{A}} = \frac{0.000125}{0.00013273} \approx 0.941\mathrm{m/s} \tag{9}$$

$$\mathrm{P} = \eta \cdot \frac{1}{2}\rho \mathrm{A} \mathrm{v}^3 = 0.5 \cdot \frac{1}{2} \cdot 1000 \cdot 0.000133 \cdot 0.941^3 \approx 0.02765\mathrm{W} \tag{10}$$

From a practical point of view, the use of taps is discontinuous and short-lived, which is why the study accumulated water into a cistern and opened the cistern valve when it was almost full to uniformly release the water from the cistern above, where the bearings are expected to rotate at a speed of 20rpm. The outflow of water will impact the waterwheel and then fall back into the initial lower cistern. Under the flow of water, the waterwheel moves using the kinetic energy of the water flow and the gravity force it is subjected to. This rotation is transmitted to the gear unit, which uses small wheels to drive the large wheels with more teeth so that the rotational speed increases exponentially. The gear set consists of three groups each with a gear ratio of 3:1.

$$n_2 = \frac{n_1 z_1}{z_2} = \frac{20 \cdot 3}{1} = 60 \tag{11}$$

$$n_3 = \frac{n_2 z_2}{z_3} = \frac{60 \cdot 3}{1} = 180 \tag{12}$$

$$n_4 = \frac{n_3 z_3}{z_4} = \frac{180 \cdot 3}{1} = 540 \tag{13}$$

Accelerated by the gear set, the rotor of the three-phase generator is rotated on the bearings extending from the gearbox.

As shown in Fig. 2, in the design, the stator encompasses six coils, each of which is a 120-turn coil, using 0.5 mm diameter copper wire. Two coils are connected, facing each other to produce a waveform, and the three waveforms have a phase difference of 120° from each other.

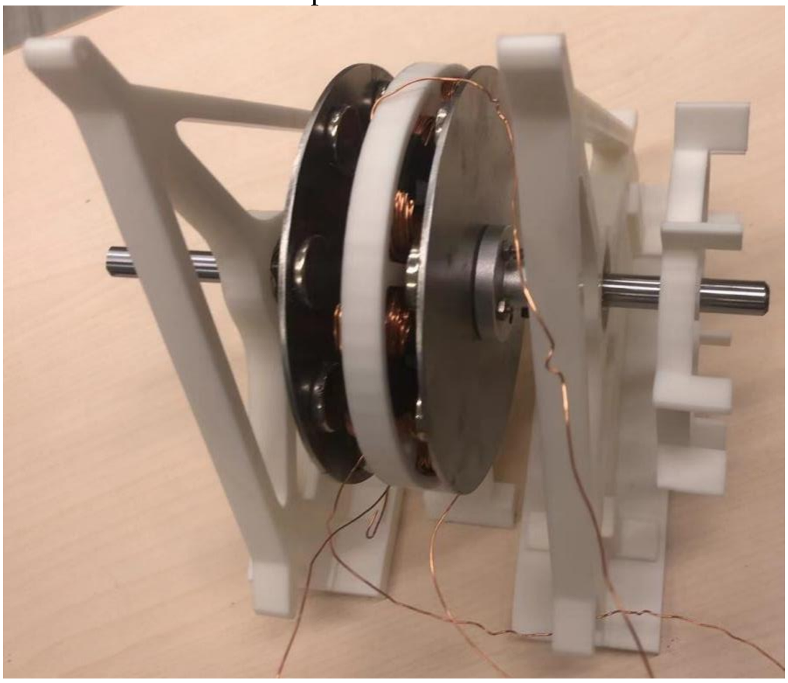

Fig. 2 Three-phase generator. (Photo/Picture credit: Original)

It is expected to produce a waveform graph like Fig. 3. Finally, the wires are clustered together to form a complete loop for use in subsequent connections.

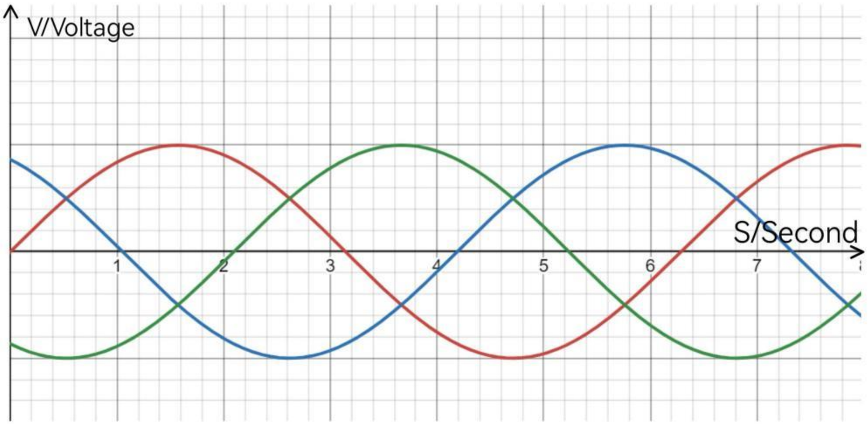

Fig. 3 Expected three-phase waveform graph. (Photo/Picture credit: Original)

The strength of the magnetic field of each magnet is 0.16T, the area of the coil is 5.30425×10−4 m2, there are 120 turns for each winding and each phase consists of two wingdings, and the rotation speed is 540rpm. The theoretic e.m.f is 2.93V and the calculation is based on Faraday's electromagnetic induction theorem

$$\varepsilon = -N\frac{d\Phi}{dt} = -120 \times \frac{540 \times 5.304 \times 10^{-4} \times 2 \times 0.16}{60} \times 2 \approx 2.93V \tag{14}$$

But this is only the ideal case, other factors such as inertia, friction, and air resistance can still greatly affect the real data.

The second part consists of the motor and transmitter. In the design, this research designed the motor to be smaller, hoping to obtain a lightweight device. Represented in Fig. 4 is the electric motor. Its six posts will be wound with copper wires as an important part of the electromagnetic induction, with each set of coils 100. noteworthy are the circular holes in each post, in which we inserted metal rods to enhance the effect of electromagnetic induction. This is because the high permeability of iron concentrates the surrounding magnetic field to reduce waste caused by magnetic field diffusion. Theoretically, the rotor of an electric motor can be driven to rotate. The driven shaft is used as a synchronizing wheel, acting on the rotation of a wheelset. When a small ball is placed in the wheelset, it is squeezed and accelerated. It is expected that the torque of the wheelset to reach 0.6 N·m. The ball weighs 1.2 g. The initial velocity of the ball is calculated to be 4.4 ms-1.

Fig. 4 Three-phase electric motor [9].

$$v = \frac{I}{m} = \frac{F \cdot \Delta t}{m} = \frac{1.2 \cdot 0.1}{0.012} \approx 10ms^{-1} \tag{15}$$

When the initial velocity is 10 meters per second, the best elevation that can launch the ball to the furthest distance is 40 degrees [10].

For the initial velocity of the ball, this paper calculates that it can be catapulted to a distance of 1.97 m.

$$R = \frac{{v_0}^2 \sin(2\theta)}{g} = \frac{10^2 \times \sin(80°)}{9.81} \approx 10.0m \tag{16}$$

However, due to the air resistance, the actual value will be smaller.

4. Testing

4.1. Magnet

The first of the three-phase generators of this study has 16 magnets and 2 iron plates (Fig.5). There are 8 magnets on each metal plate. They are stuck on the edges of the iron plate evenly. At first, using

14 magnets on each iron plate (Fig. 6) was decided. In the beginning, the opinion of the magnets on the generator is magnetic field it produces must be higher than the magnetic field that fewer magnets produce. When the 14 magnets were put on an iron plate, the magnet on the opposite side had opposite poles. According to Fleming's Right Hand Rule, the electrical current in coils on the opposite side is all pointing in the same direction, so the coils need to be put on the opposite side, and connected so that electrical current can go through from one coil to another. However, before connecting the coils, if the quantity of the magnets is the best was not calculated, and whether the iron plate can afford 14 magnets can stick to it is also a big problem. Unfortunately, because the iron plate is too small, so many magnets cannot stick to it. Hence, trying to put fewer magnets to stick on the iron plate is the only way to solve this problem. However, what we did not accept was that the winding factor of one iron plate with 8 magnets is higher than the winding factor of one iron plate with 14 magnets (Table 1). Thus, we decided to change the magnets from 14 to 8 on one iron plate (Fig. 7), even though the coils have to be connected again, for the polarities of the opposite magnets are different. The magnets which opposite to each other are the same pole. So, according to Fleming's Right Hand Rule, the electrical current points to different directions.

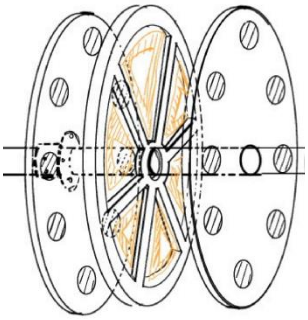

Fig. 5 Design of the generator. (Photo/Picture credit: Original)

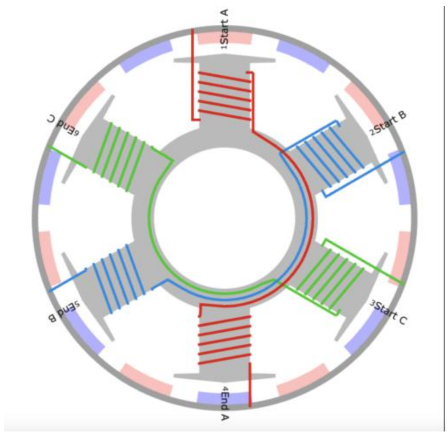

Fig. 6 The first assumption. (Photo/Picture credit: Original)

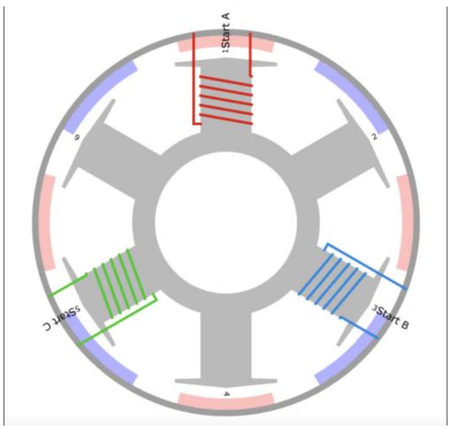

Fig. 7 The final plan. (Photo/Picture credit: Original)

Table 1 Data of different magnets

6 Coil	Winding factor	Coil connection
14 magnets	0.5	The direction of them
8 magnets	0.866	is opposite

4.2. Transportation system of the water

At the beginning of the equipment, a centrifugal water pump is used to let the water up, because this device can work without electricity. Hence, it can be connected to a turbine, then with the help of the axis, as the turbine rotates, the centrifugal water pump. However, there is a big problem that although it is a very ideal plan, the water cannot be sucked up. There are two reasons: first, the sealing of the pipes is not perfect, the pressure between inside and outside is too small, so the water cannot go up smoothly. Second, the speed that the turbine gives is slow, so the centrifugal water pump is not too fast, so the centrifugal force is not big enough. Thus, it cannot let the water up to the top. Because of these problems, the assumption cannot be achieved.

4.3. Assembling of component

There were many problems when the components were stuck, like as the bearings and iron plates needed to be together, they were stuck by the hot melt glue in the first plan. First, stick an axis and normal corn, and use the hot melt glue to stick it. After that, shake and rotate it to test if the glue can stick it tightly. However, the result is not very well, all these two kinds of tests have all failed. Thus, this experiment illustrates that hot melt glue cannot stick metals. So the plan which stick bearing and iron with hot melt glue has to be given up, for it may fall off. The end plan is to use 502 glue to stick them, then use it to stick magnets and iron plates. Hot melt glue does not have any functions. Because its volume is larger than other kinds of glues, the decision to use it fills up, some spaces like between bearings and a carriage made by Ploylactic Acid (PLA).

4.4. Phase-difference of three-phase generator

To ensure the phase position is correct, The oscilloscope is used to watch the phase difference.   However, when the coils and the oscilloscope are connected, the result illustrates that the phase difference was not the same as our expectation. Fig. 8 is the result of our first experiment. The phase difference is not balanced, after examining the coils' connection is found to be correct. So, why it is wrong is not known. Then, we try to change the port of the oscilloscope to connect with the coils, next, start the oscilloscope, then watch the screen, it presents a graph shown in Fig. 9. The graph in Fig. 9 is correct and meets our expectations. The reason that the first graph is incorrect is the coils are connected wrong to the oscilloscope, switching the ends of the coil to connect with the oscilloscope, it will succeed, for the ends of the coils are reserved, so the direction of the electrical current is inverse. Because of that, its difference of potential must be inverse. So the voltage on the graph must be inverse to the x-axis. Put it in another way, that function about the voltage horizontal moved for 180 degrees. The function that I mentioned above is the blue one in Fig. 8.

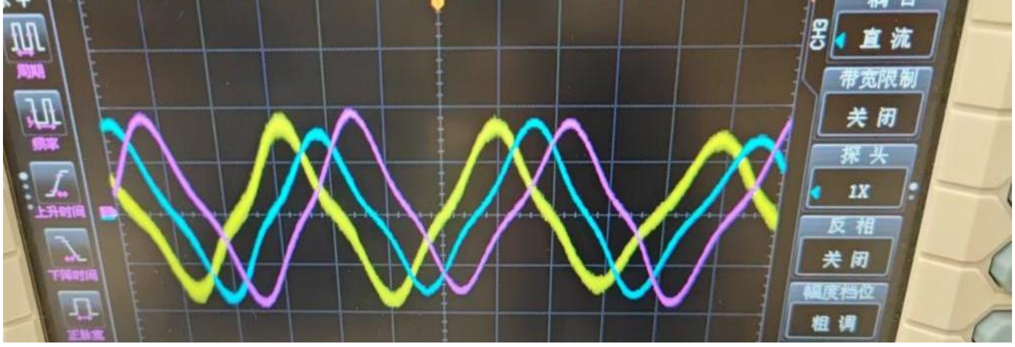

Fig. 8 The voltage which we first experiment observed. (Photo/Picture credit: Original)

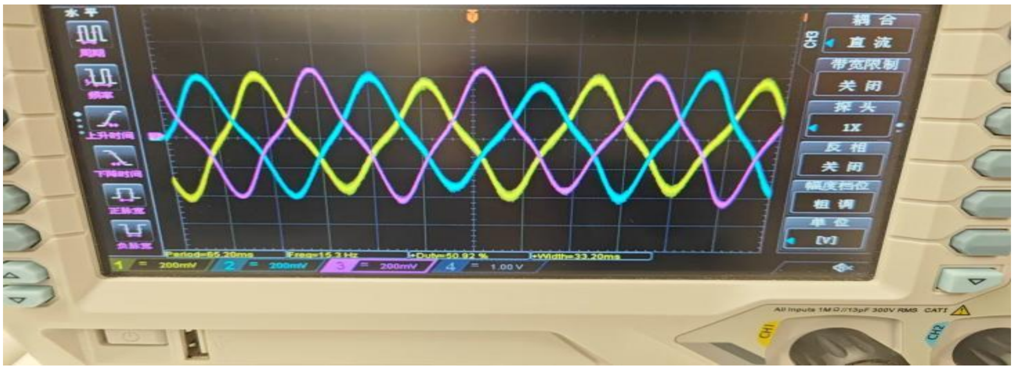

Fig. 9 The voltage that we second experiment observed. (Photo/Picture credit: Original)

5. Discussion

5.1. Result Analysis

Although the three-phase generator successfully produces a constant alternating voltage with a peak voltage of 0.5 V, slightly lower than the calculated value which is 2.93V. This means the efficiency of the generator is around 17%, this low efficiency is generally ascribed to work done in the external environment, such as heat lost in air and energy used to overcome friction force between the shaft and the wafer consisting of coils. Furthermore, the electric motor isn’t rotated while it is connected to the three-phase generator. It is mainly caused by the large inertia of the rotor and the serious friction between the rotor and winding. Another reason is that induced e.m.f is too low which makes low current and weak magnetic field. As the electric motor is unable to rotate, the ball is no longer to be launched.

5.2. Advantages

5.2.1 Environmental Friendly

In essence, the project reveals how electrical energy transfers to mechanical energy in an environmentally friendly which is the key point for distinguishing conventional energy and new energy. Additionally, the idea that using water from the tap to accumulate energy is an innovation that suggests a more common and feasible way for households to save energy, emphasizing the concept of self-consumption of energy. The project only turned electrical energy into mechanical energy, while it is also possible to convert electrical energy to other kinds, like heat energy so the project illustrates the thought of the diverse combination of renewable energies without damaging the environment. As greenhouse gases and other destructive disturbances have caused a lot of environmental problems like global warming, this thought is necessarily important to be widely applied to people’s daily lives.

5.2.2 Perfect Winding

The graph of the induced e.m.f is perfect, which means the winding and structure of the generator are great. The turns of the coil for each winding are absolutely the same and the electric angle is appropriate to form the phase difference of 120° . Furthermore, because the three generators are regular and consistent in shape because of the winding number of coils, the magnetic field of the magnet is stable, and a stable voltage and current can be generated, so that the initial launch speed of the ping pong ball is stable each time.

5.2.3 Lightweight and Portable

The most important part of our finished product, is, the three-phase generator, with the advantages of small size. The three-phase generator has a length of 0.16m, a width of 0.155m, and a height of 0.13m, which is the smallest of the three generators that are mostly available on the market. Therefore, it has a lightweight nature, making it easy to carry, and smooth use without difficulty.

5.2.4 Stable Structure

In addition, thanks to the excellent structural design of the generator, the structure of our generator is relatively stable, so it can well resist the vibration caused by rotating the rotor and improve the overall carrying capacity. More detailed, this research uses a skeleton structure, in other words, most of the parts are not filled, and the saved materials can save some money.

5.2.5 Long-distance Transmission

In addition, the generator phase of this paper is the same as the grid, so there is no impulse current generated, so there is no impact on the power system. From the overall point of view, the finished product we designed can achieve long-distance transmission, that is, it can realize the face-to-face operation to launch the ball, ensuring human safety and convenience.

5.3. Disadvantages

5.3.1 Low Induced e.m.f

However, everything has two sides, and our finished products also have some flaws and shortcomings. First, there is a large energy loss in the finished product, such as the friction between the gears is converted into heat energy, which reduces the efficiency. This made the current and voltage generated by the three generators far less than we expected, so the ball could not be ejected quickly.

5.3.2 Low strength Material

Due to the limited materials, we could not build some parts with high strength properties and self-creation at the same time, so we resorted to using 3D printers to create PVE materials because this material belongs to plastic and has the property of heating and melting, low strength so that even though generators and motors have exquisite structures, It's still not capable of carrying heavier objects. Because of the above shortcomings and deficiencies, we have taken the following measures to avoid and reduce these problems.

5.4. Solutions to Minimize Disadvantages

First, for the problem that the current and voltage are too small, we choose to use a gear set to increase the initial speed and increase the peak mass of water storage, which can effectively increase output although input is also increased at the same time. After that, we discussed the argument of material strength. The final decision was made to adjust the printing parameters, increase the housing thickness, and improve the overall part-filling rate from 8 percent to 15 percent or even 25 percent.

6. Discussion

In conclusion, aiming at the feasibility of storing electrical energy, this passage adopts an experimental inquiry method that uses a micro hydraulic turbine to generate a three-phase generator power supply system that is the main design of this passage, utilizing the law of Faraday, the law of Lenz and the law of Coulomb. This passage successfully made a three-phase generator which presents three perfectly shaped voltage curves against time on the oscilloscope and the output of 0.5V. Besides, this research also used a 3D printer to complete all the needed gear sets, the mechanical arm used to launch the ball with the water wheel. Unfortunately, the generator did not produce the value expected on voltage and current, as a result, the three-phase motor did not rotate at all. Besides, the passage used the material, which is PLA, which makes the project of research show low in strength, hence the three-phase generator power supply system driven by a micro hydraulic turbine needs to be repaired frequently. The main contributions of this project are this passage theoretically analyzed and studied the conversion of the various energies of water into electricity and discussed the practicality of this device to households and government. This project also reflects the meaning of electric energy being needed by people, in other words, it demonstrates the transmission of electric energy can achieve long distances and small losses. The future research and improvement directions can include the following aspects, the first one is to improve the selected material strength, by choosing stronger materials, or even letting a kind of 3D printer print metals, to improve the overall strength. Secondly, this passage will use magnets that have denser and stronger magnetic fields and twine the winding denser and have a greater number, additionally to let the gear spin faster to increase the current and voltage of the three-phase generator made. To summarize, the following project explores the use of three-phase generators to convert water energy into electricity. Although this research encountered voltage and current challenges, our work justifies the project and the ease of energy transfer. Going forward, consider increasing the material strength and optimizing the magnetic field for improved performance.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Klapoviq A. W. D. T. and Riyadi S., Performance Analysis of Three-Phase Induction Machine in Generator Mode," 2022 6th International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE), Yogyakarta, Indonesia, 2022, 1-6.

[2] Supply, N. W. G. P. M. a. E. Hydraulic turbine and turbine control models for system dynamic studies. IEEE Transactions on Power Systems, 1992, 7(1), 167–179.

[3] Editor Engineeringtoolbox. Wind power. Last accessed 2024/9/8, https://www.engineeringtoolbox.com/wind-power-d_1214.html

[4] Sears, F. W. Faraday’s law and Ampere’s law. American Journal of Physics, 1963, 31(6), 439–443. https://doi.org/10.1119/1.1969576

[5] de Souza, D. F., Salotti, F. A. M., Sauer, I. L., Tatizawa, H., de Almeida, A. T., & Kanashiro, A. G. A performance evaluation of three-phase induction electric motors between 1945 and 2020. Energies, 2022, 15(6), 2002.

[6] K. Shadhu Khan, JK Chatterjee, P. Three-phase induction generators: a discussion on performance. Electric Machines &Power Systems, 1999, 27(8), 813-832.

[7] Yadav, G., & Chauhan, A. K. Design and development of pico micro hydro system by using house hold water supply. International Journal of Research in Engineering and Technology, 2014, 3(10), 114-119.

[8] Bao, R., Priadi, E. Portable dog ball launcher (FetchIT), 2011, http://dx.doi.org/10.14288/1.0074447

[9] Duan, Y., & Harley, R. G. A novel method for multiobjective design and optimization of three phase induction machines. IEEE Transactions on Industry Applications, 2011, 47(4), 1707–1715. https://doi.org/10.1109/tia.2011.2156372

[10] Dai, J. Historical Relation between Mechanisms and Screw Theory and the Development of Finite Displacement Screws. Journal of Mechanical Engineering, 2015, 51(13), 13. https://doi.org/10.3901/jme.2015.13.013