Design and Manufacturing of a Three-phase Generator for Simple Physics Experiments

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Abstract. The three-phase generator is widely used in industrial, commercial, and civilian areas. It can be used as a power source for many mechanical equipment in the industrial field. In business, it can provide a steady power supply to the hotel or market. It can also be used as a backup power source for the home. Traditional single-phase generators are limited by their poor transmission capacity of power and need a lot of cables to produce them. These drawbacks will cause a lot of loss of resources. This study aims to design and manufacture a reliable low-cost three-phase generator. The experiment built a three-phase generator based on a generator power test and minimized the number of materials used to solve the problems existing in single-phase phase generators. The experiment can give people who work in the production field a deeper understanding of the internal structure and working principle of the three-phase generator.

Keywords: Three-phase generator; Alternating current; Changing magnetic field; Magnetic induction line.

1. Introduction

New energy, that is, unconventional or renewable energy, covers many forms of solar, geothermal, wind, and other forms, aiming to develop sustainable and environmentally friendly energy solutions to replace fossil fuels and combat climate change. The discipline of new energy is widely involved in many fields such as physics, chemistry, and material science. Renewable energy sources, such as solar and wind, are being employed more and more frequently these days to generate electricity [1]. The Danish physicist Hans Christian Ørsted discovered in 1820 that an electric current flowing through a conductor produces a magnetic field, which is where the generator got its start in the early 1900s [2]. Michael Faraday's hypothesis of electromagnetic induction, which he later proposed in 1831, was based on this discovery [3]. The idea underlying the contemporary electric generator is derived from Faraday's experiments, which demonstrated that an electric current may be produced when a magnetic field passes through a conductor [4]. The alternator was created in the 1880s by George Westinghouse and Nikola Tesla [5]. In addition, Tesla created a highly efficient alternator and the polyphase alternating current system [6]. The industry norm for large-scale power transmission is now alternating current. The increased use of generators was prompted by the rise in popularity of internal combustion engines and steam turbines. Another advancement in power generation technology came with the introduction of nuclear power generators in the middle of the 20th century [7]. Superconductors and nanotechnology are two examples of more sophisticated materials and technologies used in modern generators to increase their efficiency and dependability.

Although single-phase generators are a common type of modern generator used in production processes, they do have certain drawbacks. Single-phase motor drawbacks include low power consumption and low power output, low operating efficiency, tiny beginning torque, high starting power, and unsuitability for heavy load applications. As a result, the researchers are searching for a new generator that can replace single-phase generators and address their issues. Here, a phase generator came into being [8].

By creating and putting together a three-phase generator, this project aims to apply and illustrate the concepts of electromagnetic induction, which include Lenz's Law and Faraday's Law [9]. The following material examines the fundamentals of the three-phase generator and demonstrates how one can make one [10]. Next, the generator's fundamental framework is created. Using modeling technologies, the structure is built. The experimental result is compared with the theory when the practical procedure is completed. In conclusion, this paper analyzes what we do in society and offers some useful recommendations.

In contrast to previous experiments, the main focus of this one is on understanding the basic construction and operation of a three-phase generator through the process of building a small generator. This provides researchers with a generic method for producing dependable and reasonably priced three-phase generators.

2. Method

2.1. The Three-phase Alternating Current

Power transmission and distribution usually use a three-phase alternating current, consisting of a 120-degree phase difference each current differs from the other two. The current's shape can be expressed as a sine wave. Their mathematical expressions are as follows:

$$V_A(t) = V_m sin(\omega t) \quad (1)$$

$$V_c(t) = V_m sin(\omega t + 120) \quad (2)$$

$$V_B(t) = V_m sin(\omega t - 120) \quad (3)$$

where V_m means the peak voltage, ω means the angular frequency, and t means the time.

There are two connecting ways to connect each phase. One is called the Y connection, or it can be called the star connection. The three-phase windings' ends connect and make the same point, which is the zero point (neutral point). Among these, phase voltages and line voltages are symmetrical respectively, and the mains voltage is 30° out of phase with the first of the two corresponding phase voltages. The output voltage of this connection is lower, but the current is greater. The other way is a triangular connection or Y connection, that is, through connecting two sides of the three-phase windings to build up a closed circuit. The magnitude of the two kinds of voltages is equal, which is suitable for high-powered equipment.

2.2. Induction of Magnetic Field

The fundamental law in electronics is the principle of electromagnetic induction, and since there is a changing magnetic field, induct voltage can be produced. When a conductor moves in a magnetic field, the movement that reduces the magnetic inductance will create an electric potential in the conductor. The current will be produced when the conductor closes the loop. The strength of the magnetic which passes the conductor will also change as time goes on even when the conductor remains stationary. According to Faraday's law, which is a basic theory, the change rate of the electric potential increases as the size of the conductor increases, and their ratio of increases maintains a constant value. The symbol pi of Weber means the amount of the magnetic field. It is calculated using the formula:

$$\Phi = B \cdot Acos\ (\theta) \quad (4)$$

where Φ means the magnetic flux, B means the magnetic field density, $Acos\ \theta$ means the area in the direction perpendicular to the magnetic susceptibility.

Faraday's law of Electromagnetic induction was supplemented by Lenz's law by pointing out that the direction of the electric potential is consistent, which means the change of magnetic flux will be resisted by the induced current. Therefore, the induced current will remain in the direction of the original magnetic flux.

$$n\,\varepsilon = -N\frac{d\phi}{dt} \tag{5}$$

where ε is the magnitude of the induced electromotive force, N is the number of turns of wire, ϕ is the magnetic flux variation in this circuit, and dt is the change in period.

This formula has multiple physical meanings. Firstly, the induced electromotive force's direction is always in the direction of resistance to the changing magnetic field, and it is dependent upon the changing magnetic field. Furthermore, Lenz's Law ensures energy conservation because currents and electric potential create a magnetic field that resists change in the magnetic field. Furthermore, as the magnetic flux rises, the induced current's magnetic field will oppose this growth. Similarly, the magnetic field of the induced current will oppose the drop in magnetic flux.

2.3. Advantages of Three-Phase Generators

Firstly, the three-phase generator is highly effective. When converting mechanical energy into electricity, the efficiency is usually higher than 90 percent. In contrast, one-phase generator only has an efficiency between about 60% and 70%. High efficiency allows it to use energy more effectively, lowering the cost of production of electricity. Secondly, the stableness of the three-phase generator is high. Since it has three phases, when one of them breaks, two other phases can still work, reducing unnecessary downtimes. Thirdly, a three-phase generator is stable too. Since it has three phases, the volatility of voltage and frequency is small. The process of generating is smooth, causing less dilapidation to the equipment itself, reducing the probability of malfunctions, and increasing the life span of the generator, therefore lowering the cost of running. Lastly, it can fulfill most electrical demands. A three-phase generator can produce electricity with voltage from a few volts to several hundred volts, providing electricity for households, commercials, and industries. Meanwhile, it can also be combined with different accessories, such as transformers, to fulfill all kinds of electrical demands.

3. Design and Implementation

3.1. System Architecture

Usually, a three-phase generator consists of layers of magnets and coils. Magnets are permanent magnets, which produce a continuous magnetic field with constant direction. These kinds of magnets are made of metal that can’t be easily magnetized or demagnetized, such as steel. Strong direct current is passed through the metal to magnetize them, and therefore no current needs to be passed when using in a generator. The coil consists of copper wire that twists around a modeling tool when producing. Then, the wire is finalized into a fixed position and combined onto the coil layer. The number of coils must be multiple of 3 to produce three phases. Each coil stands for each phase and different phases are next to each other in a repeatable pattern. To explain, the coil of group 1 is located beside the coil of group 2 and the coil of number three. Coils of each group are connected to form a single complete circuit path, that allows current, or electrons, to pass through. One end of the wire relates to that of other phases, and there are two ways of connection, Y and D are shown in Fig. 1, depending on the different voltages needed, their differences will be later discussed. The other end is the output end, where the electricity is produced and is ready for future use, so it can be connected to either electrical appliances, such as motors, or power grids to transport electricity to further places. For the Y connection, as the picture below shows, three ends are connected into one single point, and then a neutral line is drawn out. Therefore, there are four lines for output. When connected between two lines, or phases, the voltage is around 380V, but when the connection happens between the neutral line and a single phase, the voltage is 220V. On the other hand, the delta connection has three ends of phases each connected, without connecting in a single point. In this way of connection, only three wires act as output cables, and only one voltage can be gained: 380V, which is the voltage between two phases since there is no neutral line. For magnets, the number of magnets must be multiple of two, with half of them south facing up, and the other half north facing up. Meanwhile, the positions of magnets are also crucial. When placing the magnets, the operator must calculate beforehand, making sure that only one kind of magnetic field passes one coil, so no magnetic field cancels each other out and therefore reaches the maximum efficiency of producing power.

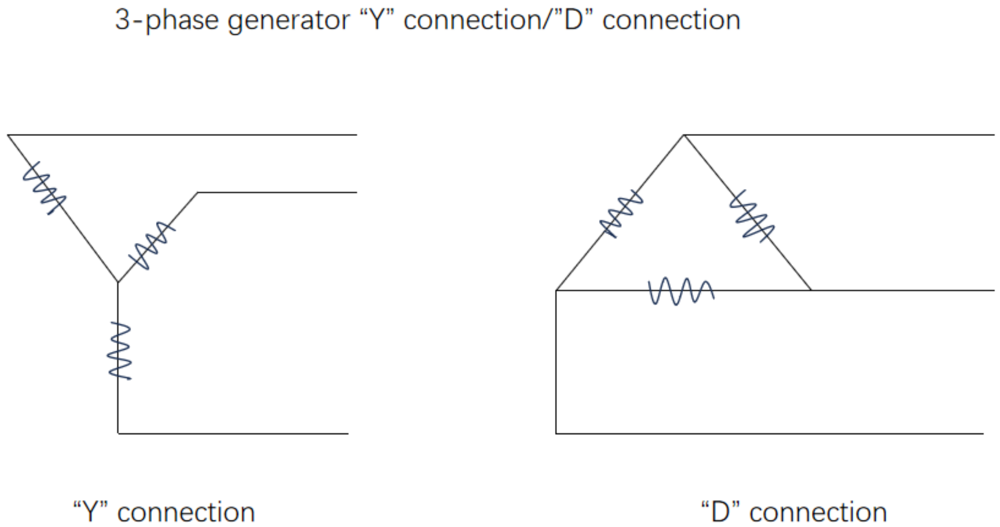

Fig. 1 Y-D connection. (Photo/Picture credit: Original)

3.2. Design

This three-phase consists of two coil layers and one magnet layer, as shown in Fig. 2. All parts of the colors white and red are modeled using a computer application, and then 3-D printed with a 3-D printing machine. The coil layer has 6 slots for placing copper coils, and each coil consists of 100 rounds of copper wire. There is a notch behind the bowl, the red one, which is used to put the connected wires. In this case, the wires could be placed more regularly, and the wires won’t mess up with the others to cause mistakes in the result. Between the slots for the coil and the notch, two-cylinder channels are designed while drawing the model, which is used to pass the wire through from inside to outside, and therefore can give out the electricity induced.

There are three holes on the outmost layer of the red bowl, which are used to pass through screws. In this way, two red bowls can be connected. They would not move just like stators in real generators which are shown in Fig. 3, when the inside disk spins and the operator can hold on to them to produce more spinning motion. Between two red bowls, an air space is kept, which is around 10 millimeters wide. This air space is used to allow the middle plastic disc to spin in, making sure that it would not hit any of the bowls, reducing resistance, and therefore increasing the efficiency of the generator. In the middle of each of the red bowls, one bearing exists, which has an inner diameter of 10 millimeters and an outer diameter of 20 millimeters. The bearing connects with the iron axle on the inside and with the bowl on the outside. The inner disk spins during the process of generating electricity, which is connected to the axle with a flange of inner diameter of 10mm (the flange is not shown in the picture), so when the axle is spun by external forces, the inner disk will spin as well. There are 16 permanent magnets on the disk, distributed evenly, and their centers--they are circular magnets--form a smaller circle as the bigger circle, the disk. The magnets have a pattern of north, north, south, and south, which is alternatively distributed. In this way, every coil will have a one-direction magnetic field, without two magnets with different poles canceling each other out.

Each oil has one input side and one output side. For the starting coil, its input end relates to the input end of the starting coil of other phases. For the middle coils, their input end relates to the output end of another coil in the same phase, and their output end is connected with the input end of another coil in the same phase. The end of the ending coil is drawn out of the red bowl, acting as one of the output wires of the whole generator, which, in our design, are three. Lots of black insulation tapes are used in the process to fix the copper coil in place, so they would not hit the spinning plate while operating.

Fig. 2 Coil and magnet layers. (Photo/Picture credit: Original)

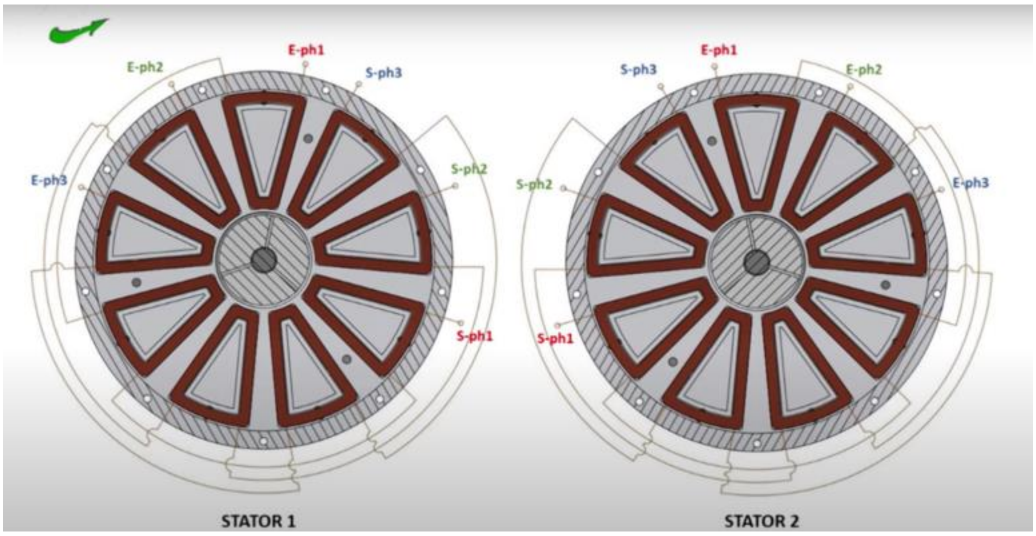

Fig. 3 Two Stators in Comparison. (Photo/Picture credit: Original)

3.3. Implementation Process

For the bowl and the coil part, the first step was to draw the model of the bowl on a computer application called Solid Works. Then it should be printed out through the 3-D printer to have a basic shape for later padding. The copper coil was finalized before sticking it onto the bowl by using a self-made winder to twist it 100 times and a drill to spin the winder to make the process faster. Later, they used insulation tape to shape the coil into triangles, making sure that it would fit into the triangle-shaped gap. Before connecting the two wires, they have to shave scratches off the paintwork on the wires using a craft knife, making it able to conduct electricity. However, the color of shaved bare wires and that of unshaved wires are almost the same in appearance. Therefore, it cannot be judged whether a piece of wire is shaved by eye inspection. As a result, the group figured out two ways to judge. Firstly, two sides of the wire can be connected on a multimeter, and if the multimeter makes a beep, both ends are well-shaved. Secondly, in an easier but less precise way, hands can be used to touch the wire, and if the wire feels rough, it is shaved, or else it is not. This procedure is very important since if the insulating coating of the wire is not well scratched, the emf of the phase generator cannot be detected. After putting all coils into the gap, insulation tape is needed again to fix them on the bowl. The bearing is the same size as the inner side of the bowl, so we stuff it in. Similarly, we first drew the model of the spinning disk and then printed it out using the 3-D printer. They utilize a marker to mark the magnetic pole of each permanent magnet later. Then they cram the round magnets into the hole with the same size in the correct order (south, south, north, and north). At last, they close and connect 2 pieces of yoke using screws that were designed beforehand for the whole structure using three screws.

4. System Testing

This experiment repeats three times.

In the beginning, the basic equipment and tools such as the multimeter, and oscilloscope were made sure that they could properly function. Rotating the rotor to check whether it had mechanical plugging or imbalance.

In the first test, the wires started to rotate when it had been linked to a three-phase generator. Meanwhile, by observing the shape of the voltage generated by the generator and continuously adjusting the oscilloscope until a relatively clear wave can be seen on the oscilloscope. However, there are several issues with the shape displayed on the oscilloscope, such as the different frequencies of the three voltage waves. The second test was conducted next.

Compared with the first test, there is added a sheet of iron between two layers which have several coils. Theoretically speaking, that will make the shape of waves become smoother and slinkier. The shape of waves in the second test does not have a significant change compared with the first one.

In the third test, connect the three different wires of bowl 2 to bowl 1. Then the waveform displayed on the oscilloscope showed a much smaller voltage than before. The conclusion drawn from this test is that when connecting incorrect wires, the voltages cancel each other out, leading to a tinier volumed voltage. For another aspect, when these wires are connected correctly, the total output voltage should be the sum of the two bowls.

5. Discussion

5.1. Results interpretation

After review of the wave graph, as shown in Fig. 4, there were no issues found during the experimental process. Therefore, it needs to find out why the waveform looks uneven. After discussion, several explanations were derived: the first explanation is that if the mass distribution of the rotor is uneven, it will cause the rotor to vibrate because it generates centrifugal force during rotation. These vibrations will cause unstable magnetic fields, thereby modifying the output voltage waveforms.

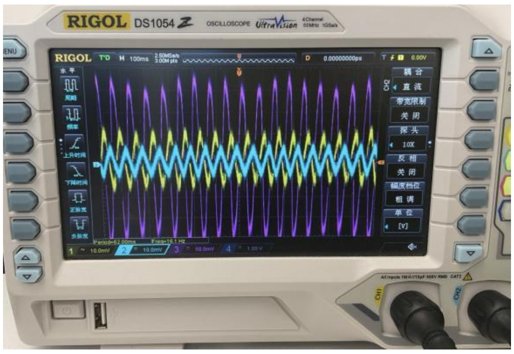

Fig. 4 Tested wave graph on the oscilloscope. (Photo/Picture credit: Original)

The second explanation is about installed bearings. If these bearings are worn or improperly, they will produce noise and vibrations when the rotor is turning. All these kinds of automated interruptions will transfer to stator windings and affect waveforms of the produced voltage.

It is considered that the most likely scenario is that the number of coils is different. That's because it is impossible to ensure every coil has the same number of windings. In that case, the output voltages will be unbalanced, so the shape of the waves is smooth.

In addition, assuming that lodestone or magnetizing coils on the surface of the rotor are unevenly allocated, some asymmetrical differences will be generated in the magnetism-based field. These changes may affect the output voltage firmness and the flatness of waveforms.

Moreover, the instability of the current results in fluctuations in the vigour of a magnetic field, and this will successively expand output voltage unpredictability and waveforms deformation.

Furthermore, the unsecured velocity of the main mechanical motor driving the generator exerts an influence on the output frequency and the shape of the wave graph. Additionally, the considerable amplitude between conflicting waves of a three-phase generator is another mess.

5.2. Improvement Suggestions

The rotor must be checked and balanced, to make sure that the weight is well-distributed. The status of the bear should be checked first and top up with petrol or even change the equipment if necessary. The turns should also be checked and changed into a suitable number, to make sure the symmetry of the three phases. The rotor magnets allotment and field coils must be checked to be uniform. To corroborate the sturdiness of the magnetic current, known as a symbol of I, the inspection of the excitation system is necessary. Investigations of machine-driven is another main factor to determine whether the speed is stable. The mechanical check is vital as well, for example, whether the balance of the rotor is no problem, whether the bear is in a nice situation, whether there are symmetrical stator windings, and whether the magnetic current is stable. The speed of the drive should be stable and the whole line connections should be fixed.

Precision balancing equipment is also recommended to correct the dynamic balance of the rotor, which aims to bring down the reverberation and sound of the rotor at a top speed. This should be achieved by improving the rotor steadiness to decrease mechanical deprivation and electrical vibrations. It is also advisable to find outstanding, lower-friction, and extreme-temperature bearings, also they should be regularly checked and lubricated. In addition, we can use better quality insulation makings and high-temperature unsusceptible windings to verify the constancy of the aggregate of windings and the arrangement. High-performance permanent magnet materials or electromagnetic steel plates can also be used to improve the material, increasing the rotor and stator's magnetic characteristics.

5.3. Applications of the Three-phase Generator

This three-phase generator can be used in physics and engineering courses, which makes students familiar with the operational theory and the design of the three-phase generator. The generator is easy to repackage, which is suitable for any kind of research and experiments. Furthermore, the research worker can use hand-made three-phase generators to test new materials、the ways for coil (in electric motor or transformer), and the control technical skills.

It also offers a lot of advantages, like the possibility of low costs and short manufacturing time、experimental verification, and iterative design. It can also be used for small-scale experiment research of power systems, renewable energy, and the containment of electrical machinery and such areas. The customized layout can do the test under different experimental conditions easily. Three-phase generators can be incorporated into single-phase generator systems at different locations. They can also be used in small families, where they are appropriate for low-power LED lighting, fans, and other small household equipment. A homemade three-phase generator can be utilized for practical experiments and creative endeavors in various DIY and online projects. This type of three-phase generator functions as a portable power source that meets minimal electricity needs in an emergency.

6. Conclusion

To sum up, during the experiment, the fundamental structure of a three-phase generator is designed, and the relevant components are printed out using a 3-D printer. When assembling the generator, using a warping head helped the group to fix the copper wire to maintain a fixed shape, therefore easier to fill it in the specific groove. Meanwhile, insulated rubber tape is used to make sure the coil would not be touching the spinning plate. During the fabrication process, the number of coil windings was repeatedly checked to ensure that the number of coil windings was the same for each phase. Three experimental tests were conducted to observe the voltage waveform of the generator by vibrating the rotor, connecting the wires, and using an oscilloscope.

New energy also needs to be improved in many aspects to meet the growing energy demand of human and sustainable development achievement. There are some important ways for improvement: (1) Improving new energy batteries, especially lithium-ion batteries, have made significant progress, but there is still room for improvement in energy density, cycle life, cost, and safety. (2) Improving the efficiency of photovoltaic and wind power generation, for example, photovoltaic and wind power generation is one of the most important parts of new energy, but its conversion efficiency still needs to be improved. (3) Improving charging facilities, for new energy vehicles such as electric vehicles, the degree of improvement of charging facilities directly affects its popularity.

While the science of new materials develops, more competent and insulated materials will be a very crucial area in the future. There is a concept that people should exploit a new kind of generator that has higher output and lower harmonic distortion in the light of definite requirements. The rotor is the part that is responsible for producing a rotating magnetic field in the generator, which greatly regulates the efficiency and stability of the generator. Future generators may innovate on the design of the rotor, like using new materials or making a better shape of the magnetic pole, to improve the output efficiency of the rotor and lower its loss. There is another problem that cannot be ignored, that is, the generator will make a huge amount of heat. Assuming that the heat cannot be consumed seasonably, it may influence the function and the age of the generator. But with a higher-efficiency cool-off system, the generator may work better in a high-temperature environment. Also, considering the worldwide challenge of energy-saving, the blueprint of the three-phase generator in the future will have a larger emphasis on the environment to a great extent. Using clean energy or environmental-protecting materials to reduce the production of emissions will be an important factor to consider in the future. Moreover, when artificial intelligence and the Internet are developing rapidly, the future three-phase generator may become more intelligent and automatic.

Authors Contribution

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

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