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Manufacturing a Wind Turbine Prototype Using Recycled Materials

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Abstract: This paper covers an effective method of manufacturing a wind turbine prototype after going over several ineffective ones. Firstly, the prerequisite mathematics and physics theory behind generators is reviewed, looking mainly at integration and Maxwell's equations. Secondly, the paper highlights the materials required, their sources of recycling and the reason for choosing them. After that, the manufacturing process is explained and since the generator produced induced quite a low voltage, improvements on the process are included at the end. Questions like why bar magnets are necessary instead of ring magnets and why a coil cannot be too thin are also answered. When making a prototype there are always ways of improving based on other materials or equipment that could be used, and these although not all used in the manufacturing process are addressed in the paper.

KEYWORDS: Electromagnetism, Generator, Induced Voltage, Maxwell's Equations, Recycled Materials, Wind Turbine

I. INTRODUCTION

Wind is not a new concept for humans. In fact, mankind has been using wind for thousands of years, initially utilized for agriculture irrigation and navigational purposes, but later to replace fossil fuels. (Zafar, 2018) Whilst coal and oil are still the world's largest energy producers, scientists are currently researching and developing new and existing methods to replace these sources with renewable ones; hence the wind. The industry of wind energy has seen rapid growth from 18GW (giggawatts) globally in 2000 to 590 GW in 2018, over 30 times that of 2000. (Dorrell & Lee, 2020). Despite this, most ongoing research regards major power stations and wind farms as opposed to minor prototypes, which is why these paper views the topic from a slightly different angle, looking at a smaller 'home sized' prototype. The materials used have all been recycled from different sources, and most can be easily recycled afterwards. Recycling wind turbine blades is currently a major issue globally, and so scientists are looking at reusing them in various ways. An example of this, is the 'Blade Bridge', being built in Ireland solely out of used turbine blades (*Winds of Change*, 2022). The prototype analyzed and developed in this paper, utilizes various materials in order to prevent these issues. The prototype draws on applications of Maxwell's equations in order to produce a small voltage. By containing a cylindrical mobile aluminum core with neodymium bar magnets attached onto it in a vertical orientation and copper coils wound around the outside acrylic structure, the spinning motion that occurs when a force is applied to the fan, causes a varying magnetic flux which in turn induces a voltage.

II. PREREQUISITE MATHEMATICS

To properly understand electromagnetic theory, we need a basic understanding Maxwell's equation. This requires an understanding of integral calculus. Roughly speaking, integration is the addition of many small parts to find the whole.

There are two main types of integration that we need to understand: definite integration and indefinite integration.

The first type is indefinite integrals, also known as antiderivatives, and serves as the inverse process of differentiation. This means integration can be used to find the velocity from the acceleration or the curve from the gradient etc. and hence uses the rate of change of an equation or function to find the original equation or function.

The second and more relevant type is definite integration, as it's utilized in all of Maxwell's equations. Definite integration is used to find a function of a given area or space, for example the induced voltage from the changing magnetic field over a certain area. Knowing that this is done over a certain area, we can use the graph in figure 1 as a basic model of this integration. Assuming we're trying to find the area under the curve in figure 1, a great starting point

for an approximation would be drawing multiple rectangles of equal width (dx) and calculating the total area. Although we'd have a decent estimate, we'd need to take this further in order to get closer to the real value of the area.

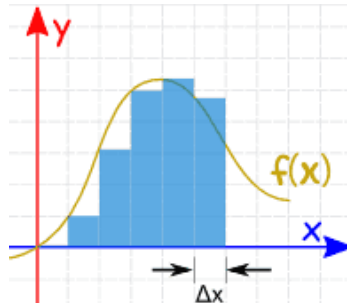


Figure 1 (Introduction to Integration, 2020)

The logical next step to make the estimate more accurate, would be to make the widths of the rectangles smaller. They would remain of equal width, but dx would become smaller as shown in figure 2. The new answer calculated would still be an estimate, but one that is much closer to the real value than that calculated in figure one.

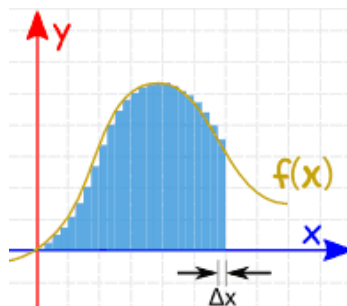


Figure 2 (Introduction to Integration, 2020)

Now in order to continue getting closer to the real value, we would keep making dx smaller and smaller and hence to get the actual value dx would need to be infinitesimally small, which is what integration allows us to do. By integrating we make dx sufficiently small and hence there are infinite parts being added, with no uncertainty, as shown in figure 3.

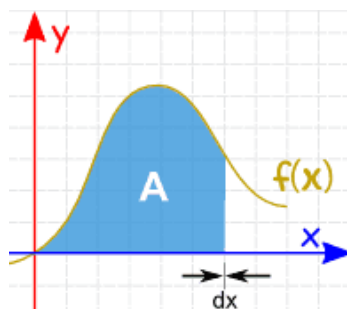


Figure 3 (Introduction to Integration, 2020)

The integral symbol is \int which is followed by the differential variable, in this case dx , so the function of the area under this curve would be $\int f(x) dx$.

Now applying this to other areas such as electromagnetism is not much different as it means we add infinitesimally small parts to get a whole, and with magnetic and electric fields being vector fields (regions with each point containing a vector), integration is used to get an accurate answer when undertaking calculations to do with either. In electromagnetism, a more complex form of integration called surface integration is used to find the area of the projection on a surface normal to the plane, also known as the flux.

III. GENERATOR ELECTROMAGNETISM THEORY

In order to evaluate the essentials of the generator in order to induce maximum voltage, a basic understanding of Electromagnetic theory is required. The theory describes the relationship between electric and magnetic fields and their interaction with matter all around. This concept is the basis of the development of many electrical devices as well as the transfer of information through radio waves and can be summarized and explained through Maxwell's equations. A generator consists of two main parts, magnets and coils. The magnets create a magnetic field, and the coils induce an electric current once a force is applied. Maxwell's equations explain how this is the case and how the variation of any one of these parts can affect another.

Gauss's law for electric fields

This equation connects the electric charge enclosed within a closed surface to the electric flux emanating from that surface. It can be expressed mathematically as:

$$\oint \mathbf{E} \cdot d\mathbf{A} = Q/\epsilon_0$$

where $\oint \mathbf{E} \cdot d\mathbf{A}$ represents the electric flux (electrical flow) through a closed surface, Q is the total electric charge enclosed within that surface, and ϵ_0 is the permittivity of the vacuum. The link between electric fields and the distribution of electric charges in space is described by this equation. According to this rule, the total charge contained within a closed surface is equal to that surface's electric flux divided by the electric constant (ϵ_0). Electric flux, which is defined as the dot product of the electric field and a small area element, is a quantity used to describe how much electric field flows through a specific area. This means that according to the equation, the total amount of electric field produced by an electric charge is proportional to the magnitude of the charge, and the amount of electric field produced by an electric charge decreases with increasing distance, according to the inverse-square law. Based on the equation, electric charges can also be positive or negative, and electric field lines that originate from positive charges terminate at negative charges (*Maxwell's Equations*, 2023). This is crucial to note when manufacturing this generator as it means that any overlapping coils could have a cancellation effect on each other, reducing the induced current.

Gauss's law for magnetic fields

This equation relates the magnetic flux through a closed surface to the absence of magnetic monopoles in nature. Mathematically, it can be written as:

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

where $\oint \mathbf{B} \cdot d\mathbf{A}$ represents the magnetic flux through a closed surface and \mathbf{B} is the magnetic field.

This equation states that the magnetic flux through any closed surface is always zero, which means that there are no magnetic monopoles in nature. Instead, magnetic fields are always created by magnetic dipoles, which consist of two equal and opposite poles separated by a small distance. The equation implies that magnetic field lines always form closed loops, and that they do not originate or terminate at a single point (*Maxwell's Equations*, 2023). This is significant when manufacturing this generator as a current is only induced with alternating magnetic poles passing the stationary copper coils. Understanding that there are no magnetic monopoles clarifies that the orientation of the magnet placement is key to achieve alternating poles.

Faraday's law of induction

This equation describes how a changing magnetic field can induce an electric field. Mathematically, it can be written as:

$$\oint \mathbf{E} \cdot d\mathbf{l} = -d\phi_B/dt$$

where $\oint \mathbf{E} \cdot d\mathbf{l}$ represents the electric field around a closed loop, ϕ_B is the magnetic flux through the loop, and dt is the time interval over which the magnetic field is changing.

This equation states that the EMF induced in a closed loop of wire is equal to the rate of change of the magnetic flux through that loop. The EMF induced is given by the integral of the electric field around the loop, which is equal to the negative of the time derivative of the magnetic flux through the loop. This means that a changing magnetic field can create an electric field, and that the strength of the induced electric field is proportional to the rate of change of the magnetic field (*Maxwell's Equations*, 2023). This is the most important of the equations for the manufacturing of the generator, and states that the strength of magnetic field and the speed at which the magnets spin, are directly proportional to the induced voltage. Hence having large wings on the wind turbine with maximum surface area as well as minimal weight is necessary to maximize force and acceleration as well as maximum velocity.

Fleming’s Left-Hand Rule

Fleming’s left-hand rule is a rule that shows us the directions for electric currents, magnetic fields, and thrust or force, all relative to each other. If one was to make their left thumb and first two fingers mutually perpendicular to each other, as shown in figure 4.

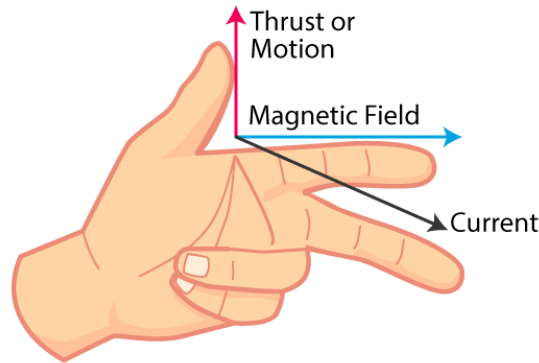


Figure 4 (Admin, 2019a)

The thumb would represent the force or thrust experienced by the wire, whilst the index finger would represent magnetic field and the middle finger would be the current in the wire.

This relates to the Lorentz force law with the following equation:

$$F = BIL\sin \theta,$$

Where F is the force experienced by the wire, B is the magnetic flux, I is the current in the wire, L is the length of the wire, and θ is the angle between the wire (conductor) and external flux lines. This equation shows that the force is proportional to the magnetic flux, current, length of wire, and $\sin \theta$. Based on this, at the point where the wire is perpendicular to the magnetic flux lines, the force is at its greatest. Also since the equation can be rearranged based on the application, the induced voltage would be at its highest. Furthermore, when all three factors are mutually perpendicular, the maximum induced voltage is reached (*Schoolphysics ::Welcome::*, 2020). This equation shows that having the maximum length of wire in coils, as well as the highest force possible, is essential to inducing a high voltage from the generator.

Theory of an Electrical Generator

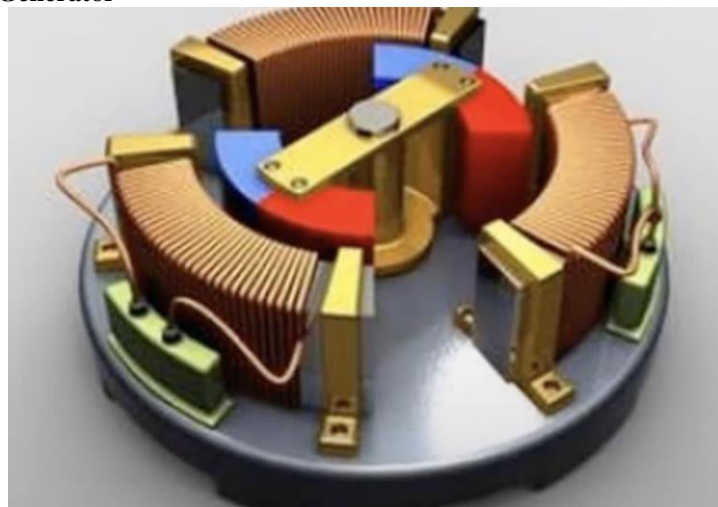


Figure 5 ((Feldman, 2017))

In figure 5, we can see two permanent magnets in a cylindrical structure of coiled copper wire, which is wrapped around an iron core. These magnets are what cause the first part of our equation, the magnetic field/magnetic flux density. We can use Faraday’s law to understand that the magnetic flux as well as the motion of the coil caused by an

external force, induce a potential difference. A large-scale application of this would be wind turbines, where the wind causes the turbines to rotate , and as with an AC generator, the motion of the wind induces a potential difference and converts the mechanical energy into electrical energy. The rotational movement of the central magnets which alternate positive and negative, causes a change in magnetic flux. In the wind turbine prototype that this paper covers, the magnetic core rotates due to the force of the wind on the turbines attached to the generator. This variation of magnetic flux induces a voltage which is why the generator can turn motion or force into electrical energy. Other types of generators could have the stationary and mobile phases the other way round with rotating coils and stationary permanent magnets, with the change in magnetic flux once again inducing a current.

IV. MANUFACTURING PROCESS

Materials

Exterior – Main Frame Structure

When choosing a material for the frame of the turbine, various factors must be considered, with the main two being accessibility and robustness. After much consideration, 10mm thick acrylic was chosen for the exterior frame structure, to ensure that it would be easy to make and would be tough enough to withstand tight coiling whilst carrying a relatively heavy metallic interior. The acrylic used in this project, was obtained from the remainders of previous student projects which involved laser cutting acrylic and left scraps. Although using a metal like aluminum or steel may have been more sturdy, with the facilities available to an average high school student, it would not have been possible to laser cut into sheets of such materials, which is why acrylic was favored.

Interior – Rotating Magnetic Cylinder

When it came to the interior, using the optimal metal was crucial, ensuring that it was light enough to spin with a minimal applied torque, yet strong enough not be easy shattered or dented. According to Civil’s guide (*126 Typical Densities of Metals and Alloys* |, 2021), the density of aluminum is approximately 2700kg/m³ whilst steel is around 7800kg/m³ which were the two available rods in a construction site waste area. Due to its much lower density aluminum was used for the interior rod (Tech, 2019). The aluminum for this project was obtained from a wasteland near a blacksmith.



Figure 6

Exterior – Turbine Blades

Although many materials would have been sufficient to make the turbine blades, a PVC tube was used as the material is light, relatively hard, easily manipulated and quite accessible in waste. This pipe was found in industrial waste, alongside many more but was cleaned and used for the project.



Figure 7



Glues

When gluing two metal parts together, Araldite epoxy adhesive was used as it was recommended by various experts in the field. This was also used when sticking a metal and a plastic component together. On the other hand, plastic weld or regular supermarket super glue were used when sticking two plastic components together. The plastic weld was better for precision in small gaps due to the syringe used for its application, but both glues worked perfectly fine.



Figure 8

Design 1

Exterior

When designing the wind turbine, various factors had to be accounted for, one of which was choosing the stationary and mobile phases. For a generator to induce a current, the magnetic flux must vary and one of the two components (magnet or coil), must rotate. For this project, the magnet was intended to be the mobile component, whilst the coils remained stationary. This is because if the coils were to be mobile, slip rings would be required which would complicate the process and make it more difficult. It is also very challenging to find slip rings in any wasteland or recycled material, defeating the purpose of the project. In order to design the exterior/frame the desktop application ‘CorelDraw’ was used, to create two-wheel shaped parts with 12 teeth, as well as 12 cuboids (Tech, 2020). A laser cutter was then utilized to cut the designs onto old 10mm acrylic sheets that had been left over from previous projects, as show in figure 9.

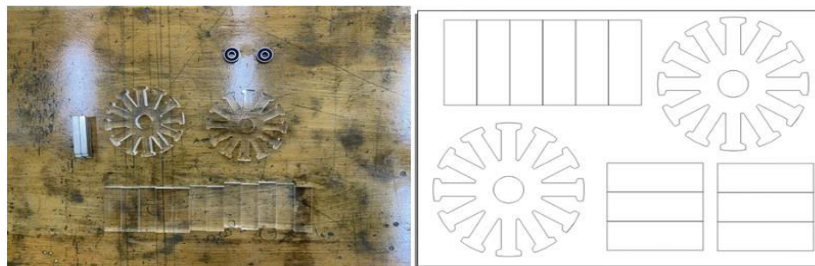


Figure 9

The wheel shaped parts had a diameter of 120mm, with a hole in the middle of 22mm, to be able to fit a ball bearing perfectly. The cuboids had dimensions 25x70x10mm. After being laser cut, the regular cuboids were aligned with the teeth of the wheel and applied plastic weld from a syringe to stick them onto the wheel. This created the exterior structure which would later hold the rotating components of the wind turbine, as shown in figure 10.



Figure 10



The long PVC tube was then cut into three 120mm long cylinders, where each was cut in half vertically using a ruler, a set square and a scroll saw, as shown in figure 11. These were to be used as the fans for the turbine, as they had quite a large surface area, meaning they would ‘catch’ a lot of wind and hence produce a high force, to induce a larger voltage.



Figure 11

Interior

For the interior, or magnetic mobile component, an aluminum rod was used, which was placed in a metal lathe, to cut down to a diameter of 50mm. An 8mm hole was then drilled into its center, to place another rod inside it. The second rod was stuck on using epoxy glue, and the same glue was used to stick two ball-bearing to opposite ends of the rod. The bearings were stuck on to allow a spinning rotational movement between the acrylic exterior structure and the internal aluminum structure. These bearing were taken from old radio-controlled cars, although many they can be found in old house appliances such as microwaves, dishwashers and even rolling stools. On the outside of the thicker rod, several neodymium bar magnets were stuck with plastic pieces in between them. These magnets were stuck in opposing North and South pole orientations. This was to ensure that as the magnets passed the coil of wire, the wire experienced regular changes in magnetic field, going north-south north-south etc. This variation would cause a time dependent magnetic flux, which would induce a voltage, as $F=BIL$, (explained in ‘Generator Electromagnetism Theory’).



Figure 12

After the interior and exterior components were glued together, three 400x10x10mm cylindrical aluminum rods were welded in an equally spaced-out circular arrangement, as shown in figure 13.

Initially the plan was to use steel rods, but after realizing that it was not possible to weld steel onto aluminum, the plan changes and aluminum rods were used instead.

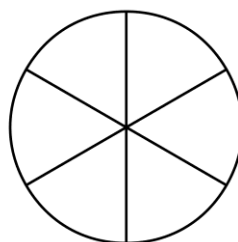


Figure 13 (Fraction Pie Divided into Sixths, 2020)

Despite the sophistication of the design, when connected to a multimeter with crocodile clips and wires, there was no induced voltage, no matter how fast the turbine was spinning.

Reviewed Errors

Magnets. After analysis of the design and the placement of other magnets near it, only for them not to experience a magnetic field, it was clear that the magnets being used were too weak and so the coils were not experiencing a magnetic field. This meant that the coils were not experiencing a varying magnetic flux and hence no voltage could be induced. For this reason, the small bar magnets were replaced with four large ceramic ferrite ring magnets, which were attached onto the interior rod with epoxy glue.

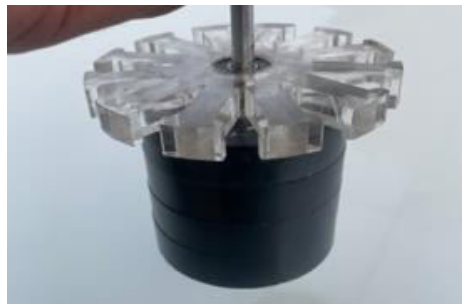


Figure 14

It was evident shortly afterwards that this would not work due to the four magnets having a cancelling effect on the net magnetic field. With the north pole being at the top and the south pole being at the bottom, it meant that as the magnets spun, there would be no change in magnetic field as the relative north and south poles would be maintained as they spun around. This meant that there was no magnetic flux and hence no induced voltage as the magnets acted as one large magnet.

Thin coil. In this initial design a 0.2mm diameter enameled copper coil was used which meant that when winding the coil it was difficult not to have overlaps. The overlaps meant that the voltage was going in opposite directions and cancelling itself out. Furthermore, the thinness of the wire meant that it had a very high resistance as $R = \rho l / A$. This equation shows that for the same material where resistivity is constant and at a constant length, resistance is inversely proportional to cross sectional area. As a wider diameter means a larger area, it also means that thicker wires have lower resistances. The high resistance meant that a very high voltage had to be induced in order for it to be detected, as lots of energy would be lost in the wire as heat.

Coil Orientation. After varying all of the suspected limitation above, and still having no induced voltage, it was clear that the coils and magnetic flux were not mutually perpendicular as they should have been and instead were parallel. This meant that the orientation of the coils had to be rotated by 90 degrees in the vertical axis. In order to achieve this, a completely new design had to be laser cut.

Design 2

Exterior

The second design used the same tools as the first and had similar dimensions, but was quite different in shape, to accommodate for the change in the orientation of the coils. The circle on the outside was also 120mm, but rather than having 12 teeth, it had 4 curved oval holes, which would carry the wires. In between these holes, identical cuboids from the first design would be attached vertically with super glue. This design would carry the same metal interior as the previous one, with several improvements.



Figure 15

Improvements

Strong magnet (bar). In the final design, stronger neodymium bar magnets were used and were more spaces out, with only 4 stuck around the cylinder. This was firstly to ensure that the coils would experience a magnetic flux, but at the same time, the same coil would not experience the same magnetic pole, causing the induced voltage to cancel out. To make the already strong magnets stronger, a stacking process took place, with various magnets that had been used in the process, being staked on top of the original bars. This created an even stronger magnetic field.



Figure 16

Thick insulated coil. As for the coil, a much thicker 0.6mm diameter insulated copper coil was used. The increased thickness meant that the new coil had a much lower resistance than the previous one. The wire being thicker also meant that it was easier to wind around the acrylic structure to make a coil. Finally, the insulation much like an enameled copper wire, was there to prevent a short circuit which would damage the prototype due to overheating.

Testing. Before all the components were glued on and the wire was coiled on, the prototype was tested using a small amount of coil around a leftover acrylic piece from the first design. This was placed near the magnets and was used to see if there would be an induced voltage with the new design, which there was.



Figure 17



Figure 18

Final Design. After testing, the structure was all glued in place, and had wires coiled around it. Small acrylic blocks were stuck to the bottom surface to elevate it in order to prevent and scraping with the surface it was placed on. The wires were then connected appropriately, to prevent any cancelation of the induced voltage and multiply it instead. Finally, the PVC half tubes were added on with super glue, and the design was complete. Figures 19 and 20 show a picture of the final prototype and a video of it working.



Figure 19



Figure 20

V. CONCLUSION

The aim of the project was to see if it was possible to make a prototype wind turbine out of recycled materials, taking into account the resources available to an average high school student. This proved to be a success as the prototype did induce a voltage, but despite its success in inducing a voltage, the voltage peaked at around 20mV, which is significantly smaller than that required to power an average bulb. This means that although it is theoretically possible, the generator can have no real applications or uses unless improvements are implemented so that it is able to produce a higher voltage.

Firstly, the use of enameled copper wires rather than thick insulated ones would allow for more coils, which would mean a higher induced voltage without the risk of a short circuit. This risk is real only if the coils are made of bare copper. The reason higher voltage would be induced is because as the length of wire increases, for the same voltage there is more magnetic flux (cuts of the magnetic field), and hence a higher induced voltage.

Secondly, a stronger magnet could be used to increase the strength of the magnetic field and hence the magnetic flux, inducing a larger voltage as explained by Faraday's law of Induction. This law suggests that the EMF (electromotive force) induced in a closed loop of wire is equal to the rate of change of the magnetic flux through that loop.

Finally, the use of three or six magnets and holes in the design rather than four, would allow for the transformation of the prototype to a three-phase generator, which if utilized could produce a higher voltage. As three phase generators provide power in sequence that ensures a continuous uninterrupted flow of power that never drops to zero. On the other hand, single phase generators deliver one constant wave of power which varies with current, meaning that it could reach zero. This makes three phase generators more powerful than single phase. (AURORA, 2019)

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