A simple generator to be used in the project-”Energy from Wind and Ocean”

What are the main requirements for a power generator?

Torque and mechanical angular speed

A generator is in general driven by a turbine or and engine. In wind power installation a large turbine is designed to rotate at a certain nominal speed, ω, and to deliver a specified nominal power, P. The turbine is controlled to deliver electric energy for both higher and lower speeds according to some design strategy. In this case we focus on the working point that is described by the nominal quantities.

When power and angular speed is specified the torque delivered by the turbine and generator in balance is now given by:

$P = \varpi \cdot T$ and $T = \dfrac{P}{\varpi}$

The torque tells us much about the size and cost of the generator. Many people focus on the power when they evaluate the cost but a high speed generator can be very small while the low speed wind generators are normally very large and costly. Henceforth, if the system is without a gear the generator speed is normally very low and the torque becomes big to achieve the needed power.

When the torque level is known the volume and cost of the machine can be estimated. Note that both volume and cost are proportional to the required torque. For a small generator the speed is often relatively high and a gear is not requested.

The torque can for many machines be evaluated by the simple formula.

$T = k \cdot D^2 \cdot L$

in which the L means the axial length of the machine and D is the diameter. This formula is used for cylindrical machines which is the most common generator type. In this project you are going to make an axial flux generator, with a more complex formula for the Torque. However, the formula above is easily converted to

$T = k' \cdot V$

Which gives a strong indication that volume and cost often increases proportionally with the volume, V, of the machine.

Other quantities to be chosen in the generator design

Voltage level

Depending on the power grid to or eventually the power electronics converter to be connected to, the generator the voltage level much be chosen. There is definitely a tendency to increase the voltage for larger power units. However, most wind generators are still made for the industrial voltage level 700 V. Note that this is a relatively low voltage which results in designs that have to handle very large currents given by the law:

$$P = U \cdot I$$

In which the U is the voltage and I is the current. For a low voltage and large current is needed to produce a certain power. From this we also see that the current to be used is consequence of the specified power, P, and current, I.

In our case we are going to make a generator which is relatively small we chose to use the voltage 20V. Such a voltage can easily be used to charge batteries and also easily measured in the lab tests.

In this project is important to measure the voltage that the generator produces and compare it with the expected design voltage.

Efficiency- linked to the resistance of the windings.

In general the efficiency of the generator is very important for the economy in a real project. Lower efficiency directly result in reduced power production and thereby a reduced income. In many cases the efficiency is high in electrical machines. For hydropower generators it is not rare to have an efficiency above 98%. However, this is for very large generators, and in wind power it is more common to have 95% efficiency. Note that it costs to make higher efficiency and for an optimized design this cost is compared to what is gained in income over the lifetime of the generator.

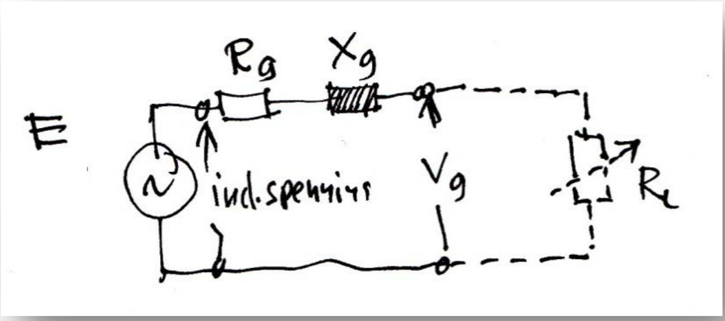
In this project we should be satisfied with an efficiency around 90%. This will be a driving number when generator losses and copper winding area is to be chosen. In short, higher efficiency requires lower losses, lower resistance in the winding and at the end more copper area in the generator.

Generator resistance and winding losses should be measured in the laboratory test in this project to verify the design calculations.

A practical and simple calculation model for the generator

Equivalent circuit

Most generators are described by the following circuit diagram.



Induced voltage

The voltage source at the left of the figure is the induced voltage in the generator, often called the EMF. This voltage is for a given magnetic design proportional to the rotational speed, meaning:

Parameters

Other parameters in the model are:

- R_g=generator resistance (winding resistance)
- X_g= the reactance in the generator. This is due to the fact the magnetic field around the current carrying winds, induces counter acting voltage.
- R_L=Load resistance in which the produced energy is consumed. This resistance is variable to account for variable load. The load can also be extended to become an inductive of capacitive load. Note: In most large wind power systems, the generator is linked to a grid or a converter. The Load resistance is the in the model replaced by a voltage which are either stiff or controllable (with power electronics).
- V_g= the terminal voltage of the generator. This implies that voltages over the internal source E, and over R_g and X_g are internal and normally not accessible. You measure the terminal voltage V_g.

Some comments to the use of the calculation model (equivalent circuit).

- The model is used to determine the voltage balance and drop through the machine.
- The voltage E is the driving force in the model and the current is flowing from E to the load resistance.
- E is normally larger than the terminal voltage. We expect a voltage drop from E to the load over the Rg and X g. However, remember that this circuit is an AC circuit and if the load becomes capacitive, the voltage can be higher at the terminal than at E.

- $E = k \cdot \varpi$ or $E = k^{*} \cdot \varpi \cdot \phi_{PM}$ or $E = k^{**} \cdot n$

  in which n is the rpm (rotations per minute) of the machine. The frequency of E is also proportional with the speed. The flux from the Permanent magnets are here to be assumed constant.

How is a simple wind power turbine operated – seen from the electric point of view.

This is illustrated by two cases.

Case one; The generator is coupled to a load.

In this case we assume that the turbine and generator is mounted together on a common shaft. The wind will then at a very low speed start to rotate the turbine and generator. Since the generator is not connected to any load no current is flowing and no torque is produced.

The voltage in the generator is induced and at a certain speed this voltage can become dangerously high and even destroy the insulation and the generator. Furthermore, if no measures are introduced, (such as pitching the blades), the speed will increase beyond all acceptable limits. The turbine will eventually explode and the same can happen to the generator.

This case shows that there is a fine balance between the turbine torque and the generator torque. If this balance is not ensured and if the turbine control is then out of operation, the whole system will break down.   If no electric power can be delivered to the grid or other loads, no torque is produced and the turbine speed will increase.

Case two: A load resistance is connected to the generator

A load resistance is connected so that the current will dissipate (burn) electric energy in the load. We assume now that the turbine torque at this point is bigger than the generator torque and that the speed is thereby increasing. However, as a result of the increased speed the induced voltage E will also increase. Subsequently the current will increase with a significant increase in power delivered to the load.

Note that the frequency is proportional with the speed, and the current is therefore calculated by using the formula (given by the circuit model):

$$I_g = \frac{E_g}{Z_{circuit}} = \frac{E_g}{\sqrt{(R_g + R_{last})^2 + X_g^2}} = \frac{E_g}{\sqrt{(R_g + R_{last})^2 + (2 \cdot \pi \cdot f_g \cdot L_g)^2}}$$

The power delivered to the load is simply given by:

$$P_{load} = I_g^2 \cdot R_{load}$$

But since there are significant losses in the generator, the turbine must deliver mot than the load power. This implies that $P_{load} \neq P_{turbine}$ and the losses are given by $P_{losses} = I_g^2 \cdot R_g$

The power delivered by the turbine (wind) is given by

$$P_{turbine} = I_g^2 \cdot (R_{load} + R_g) = \frac{E_g^2 \cdot (R_{load} + R_g)}{(R_g + R_{last})^2 + (2 \cdot \pi \cdot f_g \cdot L_g)^2}$$

The turbine designer does often want to now the relation between the torque and the turbine speed, which now can be written as

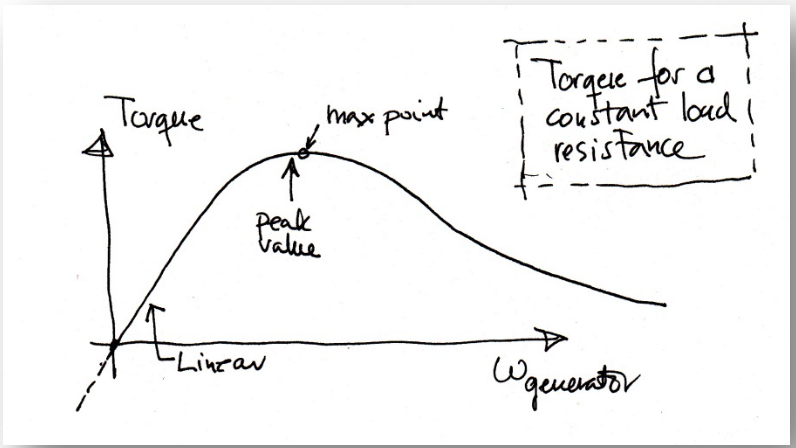
$$T = \frac{P_{load}}{\varpi} = \frac{I_g^2}{\varpi} \cdot (R_{load} + R_g)$$

$$T = \frac{\frac{E_g^2}{\varpi} \cdot (R_{load} + R_g)}{(R_g + R_{last})^2 + (2 \cdot \pi \cdot f_g \cdot L_g)^2} = \frac{\frac{(k \cdot \varpi)^2}{\varpi} \cdot (R_{load} + R_g)}{(R_g + R_{last})^2 + (\varpi \cdot p \cdot L_g)^2} = \frac{(k)^2 \cdot \varpi (R_{load} + R_g)}{(R_g + R_{last})^2 + (\varpi \cdot p \cdot L_g)^2}$$

In which p is the pole pair number (p=1) if number of poles are two.

This equation shows that for low speeds the torque is proportional with the generator angular speed. For higher speeds the torque reaches a maximum and goes down again if the speed increases more.

A sketch of this torque characteristic is shown the coming figure.



A first calculation on the generator performance parameters

Before the generator is designed in detail we must be able to calculate the performance parameters of the machine. It implies that the inductance and resistance must be determined from the specified data. Note that some of the data used here is based on experience from earlier projects.

Requirements

We chose:

- $U_{Terminals}$= 20[V]
- η = 90[%]
- P = 100[W] output from the generator
- n = 1700 (rpm)

Calculation of losses

P_{losses}= 10% of P_{in} and $\eta = \frac{P_{out}}{P_{in}} = 0.9$

$$P_{in} = \frac{100}{0.9} = 111 \text{ [W]}$$

Calculation of current

$P_{out} = U_{terminal} \cdot I_g$ (Resistive load) $100 = 20 \cdot I_g \Rightarrow I = \frac{100}{20} = 5$ [A]

Calculation of Rg

$$I^2 \cdot R_g = P_{losses} \Rightarrow R_g = \frac{11.11}{5^2} = 0.444[ohm]$$

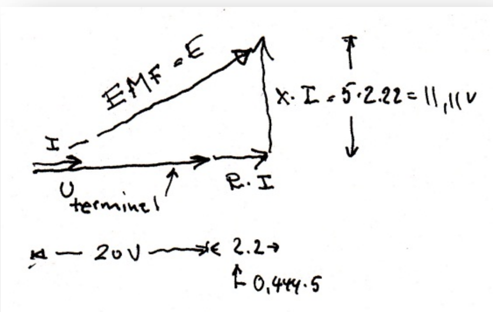
Reactance

The reactance is on this stage difficult to calculate. However, empirically for PM generators of this type a rough estimate is:

$X_g = 5 \cdot R_g = 5 \cdot 0,444 = 2,222$ at nominal frequency

Voltage balance – vector diagram

From the equivalent circuit for the generator the following vector diagram established:



$$E = \sqrt{(20 + 2.2)^2 + 11{,}11^2} = 24{,}64 \text{ [V]}$$

Verification of the generator performance data

The basic data that we have determined so fare are also the same to be measured in the laboratory after the design is made. The expectations for the generator are described by these parameters and the laboratory tests are performed to verify if we are able to make such a satisfying generator.

Design of a very simple generator

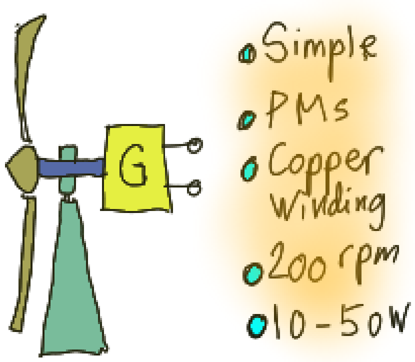
To make an electric generator that is driven by wind is not so difficult. You mount a few Permanent magnets to some moving parts in such a way that the magnetic field (flux lines) is passing some stationary windings. An induced voltage will occur, which can be used to make a current production from the generator.

How large this voltage gets and what voltage drop you will experience when the current starts to load the generator is a bit more complicated to predict. However, most of this can be understood and analyzed by using the basic electromagnetic theory learned in early physics courses. A thorough analysis requires more models and tools not expected to be used here!

In the course "Energy from Wind and Ocean" student groups are expected to make various turbines and make them propel a self made generator in a wind tunnel lab set up. The generators are expected to be tested separately, driven by an electric drill. The project is expected to motivate the students to improvise and find simple solutions.

Nevertheless, many have tried to make such very simple generators in order to demonstrate functionality and design approaches. There are many references to such projects to be found in the internet and a few will be presented here. The main goal is to get the student to become a bit practical and to make him/her believe that such design practice is both fun and possible. The following sketch gives the main requirements.

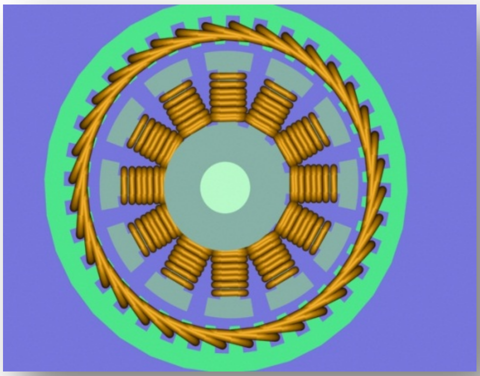
- Simple generator – without a rigged mechanical structure. Without iron cores and perhaps build by using wood, plastic etc.
- Use of permanent magnets
- Use of copper windings
- Rotational speed 1700 rpm
- Expected output power – 100 Watts.



The bearings and shaft are established as a standard set up and premade by the workshop at NTNU, (as shown in later examples) and the number of components should be limited. Of course if students want to make something more advanced that is also OK. The University will try to help with needed resources as far as possible. When testing the generator separately before going to the wind tunnel, a simple drive like an electric drill should be used.

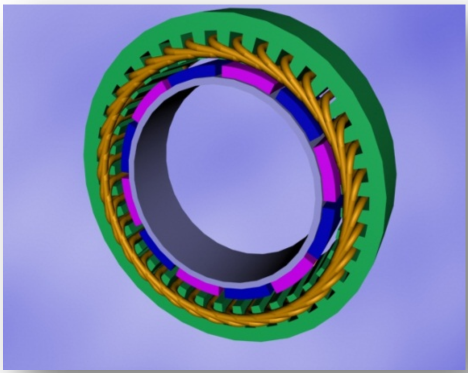
Axial flux generator

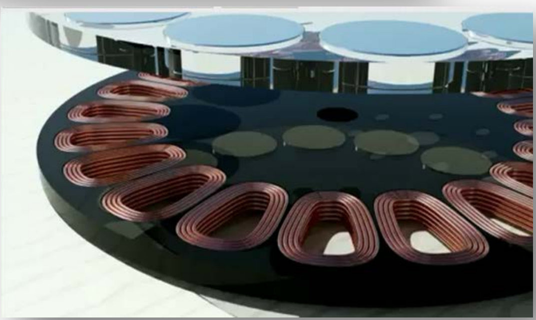
There are several types of design concepts to choose from. The most common concepts are radial flux machines and axial flux machines



Radial flux machines with field winding.

Radial flux machine with permanent magnets

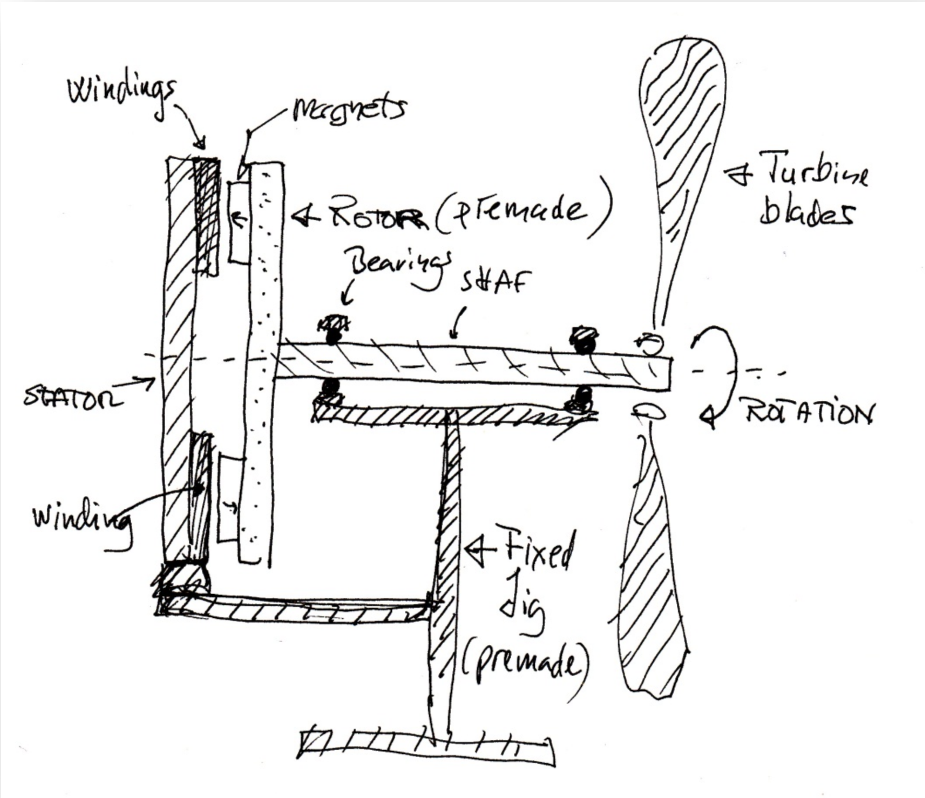




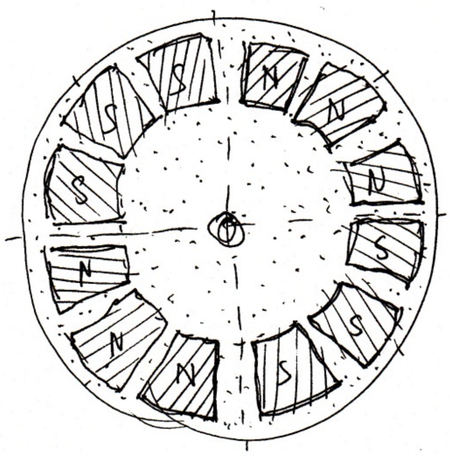
Axial flux machines (exploded view)

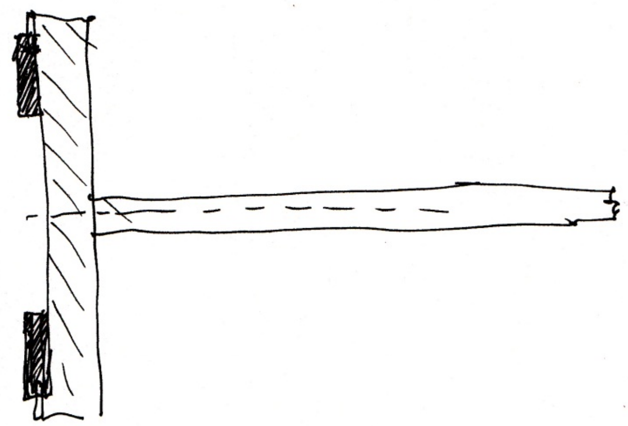
Axial flux machines with magnets close to the windings

In this project a simple one sided axial flux machine with an ironless stator is to be made by the students. A readymade rotor (with magnets) and a test jig are available for the students. The students are thereby expected to design a stator and test this in the test jig. A sketch of the setup is shown as follows:

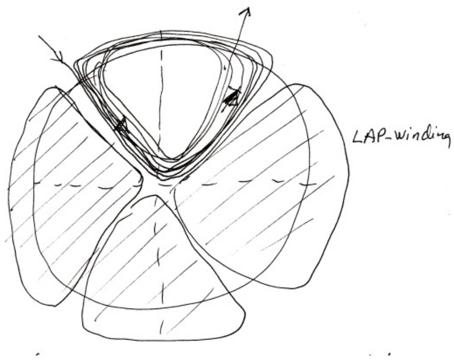


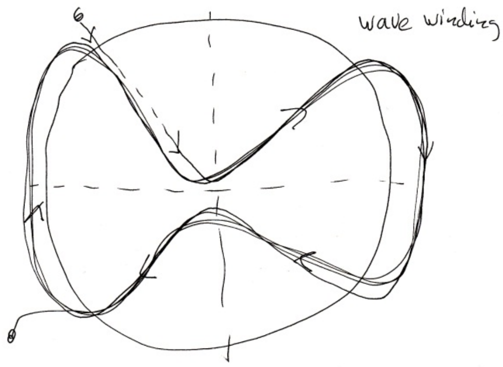
From this description the following basic parts will become available for the students:





- Readymade rotor consisting of two poles, each with several magnets6 – 8 permanent magnets, FerroBorNeudym, Br= 1.2 T





- Copper wire, dimension 2 mm^2- can use several in parallel to get the same cross sectional area.
- Building materials – such as three or Plexi glas. Discuss this with the supervisor.

In the coming pages a simple analysis of such a generator is presented. It is in this case assumed that the magnets are glued to a disc rotor made of a preferable a magnetic material. The magnetic material can be of solid iron or of a steel lamination.

The generator is axially magnetized – meaning that the magnetic field point axially outwards or inwards depending on the magnetic pole to be investigated..

The flux from a Permanent Magnet

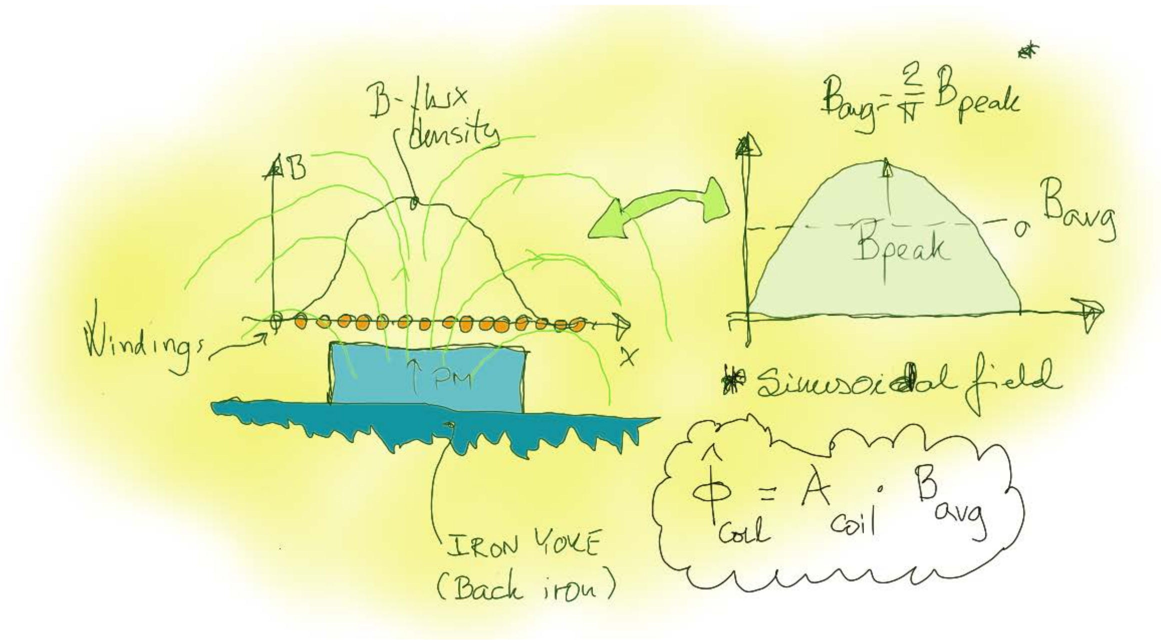
It is difficult to accurately determine the flux from a permanent magnet located alone in air. Without a ferromagnetic (iron) structure around the permanent magnet the flux will flow very freely into the surrounding air and the flux density will be much lower than if such an iron core was used. However, in our case we do it simple. One of the advantages of doing it so simple is that we avoid the strong forces between the magnets and the iron. The disadvantage is obviously that we get a lower flux density in the generator.

It is thereby also difficult to determine what forces that will act upon the current carrying windings in the generator. Even more is it difficult to determine the flux that penetrates the winding area to induce the voltage in the coil. We must simplify in this case!!

We assume that the coil covers the same area as the magnet (or bigger), and that the coil is located approximately 1 mm away from the magnets (air gap length is 1 mm).

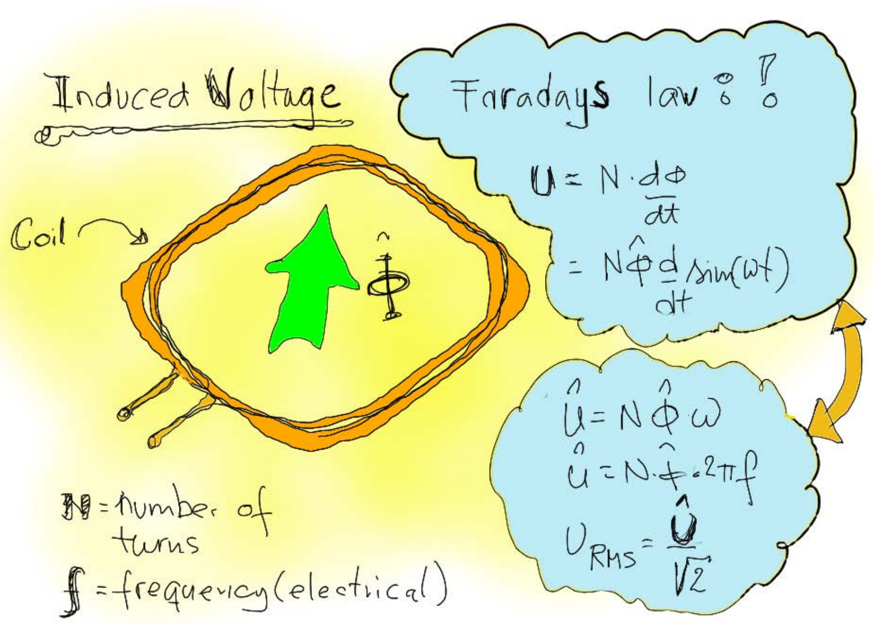
Flux density around the magnets

The flux density at this distance from the magnet surface is assumed to be B_{peak} (to be calculated later in this paper).The relationship between peak flux density and peak flux in the coil is presented in the following figure. The flux density must be calculated with a numerical tool (FEM) based on a 3D mode .



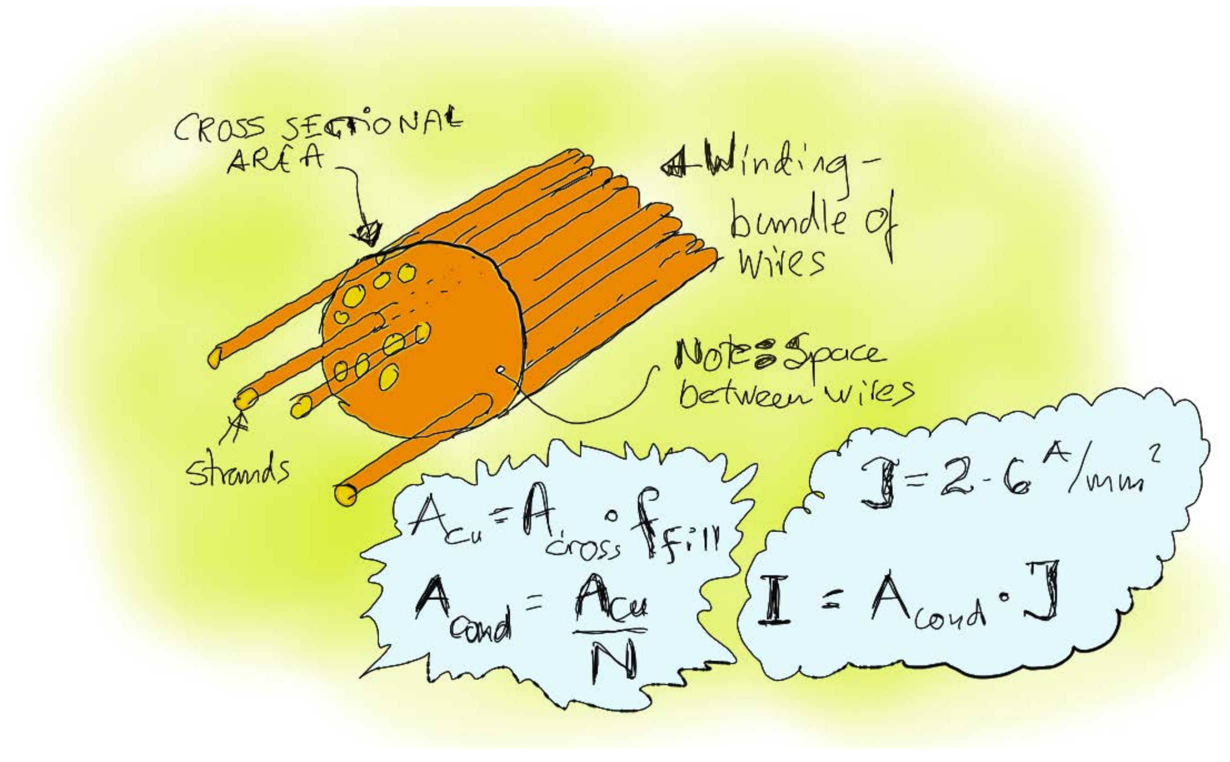
Induced voltage

Assume that the number of turns I the following design to be 100 in each coil. The calculation of induced voltage is then based on the classical Faradays law when the peak flux through the coil is given as follows:



Copper fill factor (there is space between the wires)

After the voltage is determined the current loading of the generator must be evaluated. The problem in most machines is that if the current density (current per copper are), the design becomes too hot (depending on the cooling capability). Very often it is forgotten how much space there is between each turn in the coils, and the parameter copper fill factor is therefore introduced. Note: It is difficult to get an efficient fill factor larger than 0.5. In the following the fill factor equal to 0,45 is used. In the following figure the relationship between total are, copper are and the use of fill factor is illustrated.



The radius of the cross sectional area of the coil is assumed to be 1 cm. The coil span is assumed (as stated before) to be the same as the magnet area.

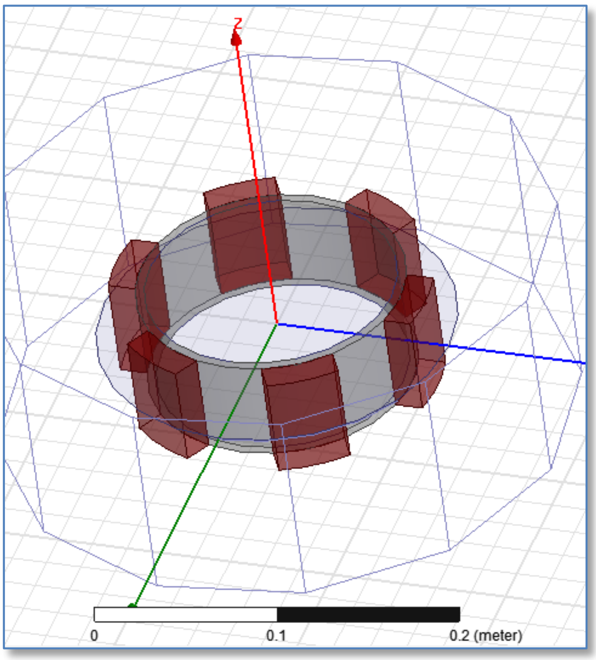
Furthermore is the current density assumed to be from 2 to 6 a/mm2 – without getting to hot.

Based on these assumption, a generator should be able to produce around 30 W (even more). A lot can be done by the students in changing this design. Creative solutions involving axial flux designs can be introduced and this memo is made only to give a introduction to the design process.

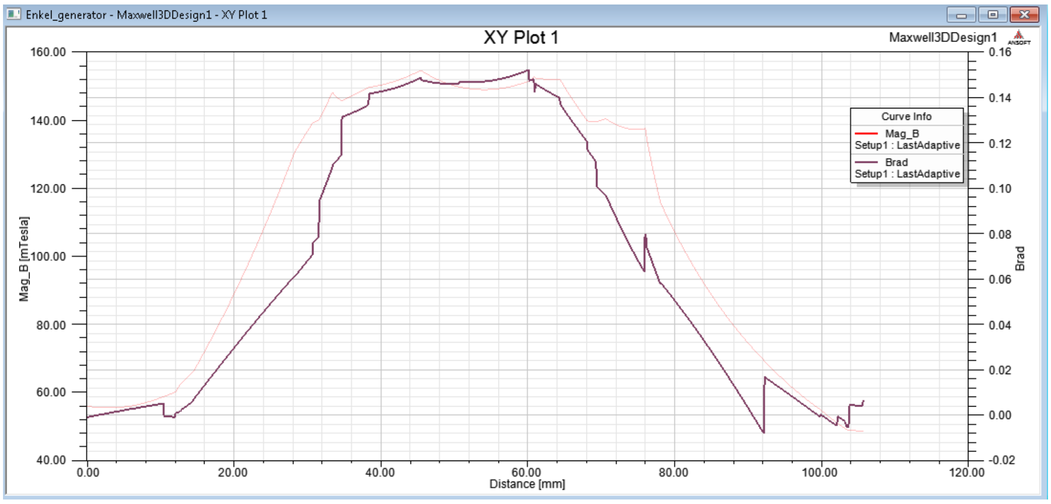
The students must do their experiments and get their experience.

Some more calculations

Enclosed are some calculations made by Astrid Røkke and Zaoqiang Zhang. The figure below show a Finite Element Model (3D) that was used to calculate the magnetic field around the magnets.



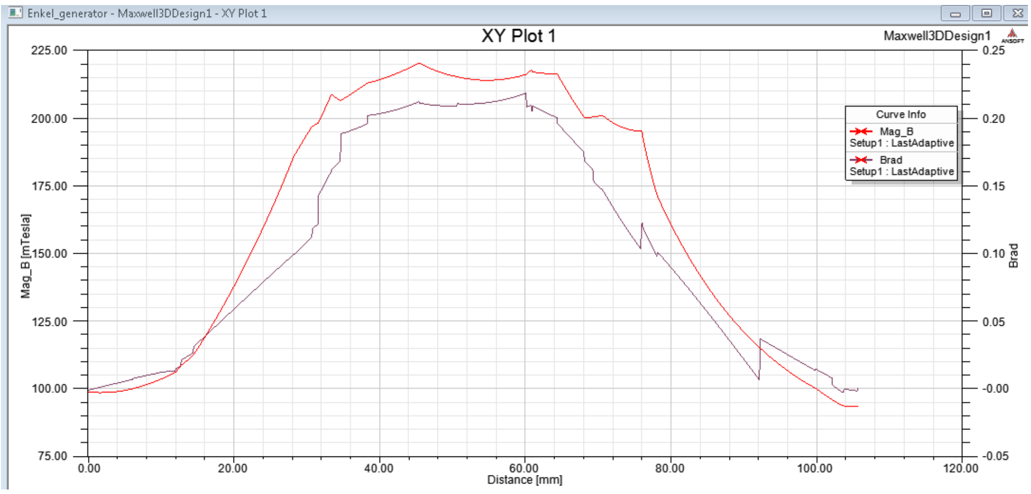
A 3D-analysis showed that 1,5 cm magnets was need to get a sufficiently large magnetic field. The radius of the rotor was set to 7,5cm – tio utilize the relatively small magnets. The dimensions of the the deisgn is listed in a following print out of an XL file. A test was done for a complete ironless machine and proved to give very litle power, and a flux density as low as **0.14 T** at a distance of 11 mm from the magnets. The closer you get to the surface of the magnets the stronger the field gets. With air only in the generator the following fluxensity was determined.



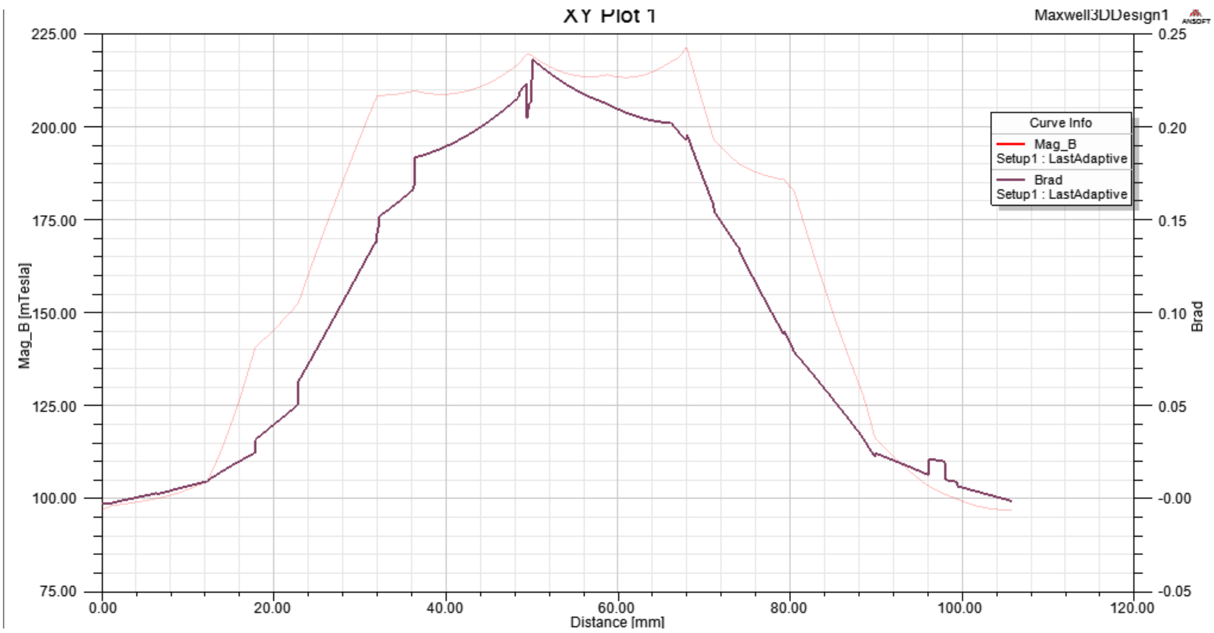
Not: It is the scaleon the right hand axis that is to be used. (Brad)

If iron in the rotor is introduced, a significantly large flucx demnsity is achieved:

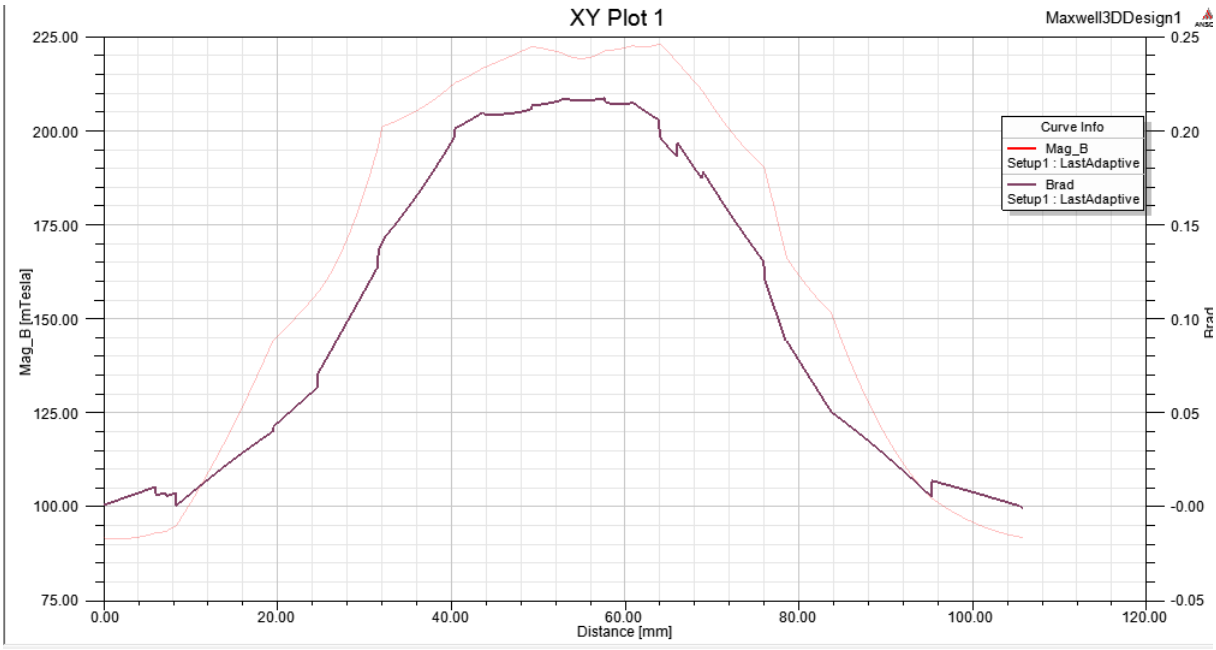
Solid steel in the rotor yoke.



With 1cm yoke thickness:



With 5mm yoke thickness



Ironless axial flux machine – principle design

Homemade Axial Flux Generator - Part 1 - The Mechanics....

This is copied from an internet page, see ref

http://eaglesfeartoperch.blogspot.no/2013/01/homemade-axial-flux-generator-part-1.html

Late last year, I'd thought I'd have a go at building an experimental generator which could be used with a wind turbine, either a new-build Savonius vertical-axis type or else utilising my spare set of home-made blades for our existing horizontal-axis machine.

I'm starting small, at only around 150 mm (6") overall rotor diameter but I've a couple of worn front brake discs lying around in the workshop from my old MGF (long gone now....) which could possibly be used for a larger version in the future.

After first looking around at what others have done on YouTube etc, I came up with a slightly different design to most of the others and then set to work. At this stage it's intended to be a 3-phase alternator and so with 12 magnet poles we'll need 9 coils cutting the flux during rotation. This will give the required 120 degrees of phase separation during operation - there's several animations available on the web which show moving graphs of the voltages induced in a 3-phase alternator.

The generator coils will be static, i.e. will form the 'stator', and the magnets are fixed to steel plates and rotate, i.e. the 'rotor'. The assembled rotor comprises two parts, the outer and inner. The rotor shaft rotates in ball-bearings in the housing, to which the stator will be fixed in position.

I bought a couple of profiled steel plates from eBay, for the rotor discs. I already had several pieces of aluminium round and square bar in the workshop from which to machine the bearing housings and shafts etc.

bearing housing, temporary central bolt,
rear bearing, rear stub shaft and bearing spacer

There are two bearings fitted in the front of the housing, so the generator shaft can rotate independently, and a third at the rear which will support the direct connection of a turbine blade set via a stub shaft. The entire blade hub / generator assembly could then be retained by a single M10 central bolt - I've just used a length of studding for the moment, turned down to 8 mm diameter at the rear end so I can fit into the cordless drill chuck for testing.

The cylindrical bearing spacer fits over the shafts and provides contact between the inner races of the front and rear bearing sets. The spacer is slightly longer than the distance between the bearing bore faces in the housing. This allows the central bolt to be fully tightened without overloading the bearings and causing them to lock-up, as would be the tendency if the load path was taken across the ball elements by tightening over both the inner and outer raceways. An alternative would be to use a length of studding as a central shaft and adjust the axial load on the bearings during assembly so they're free to rotate without excessive end-float, and then fit locknuts to retain the shaft in the set position.

The four tapped holes shown on the face of the housing are to fix the stator assembly. I drilled sets of tapped holes on all the other housing faces to give a variety of mounting options for the assembled generator without having to take it apart and re-machine it in future.

The lower profiled block currently shown attached under the bearing housing can be bored out at its base to fit directly onto a turbine mast pole if it's to be used for a horizontal-axis machine - for the moment, it simply allows me to hold the generator in the vice for assembly and testing.

Again from eBay, I bought 50 neodymium disc magnets at 20 mm diameter and 5 mm thickness. At £39, these were from N35 material, the lowest grade available but 50 x N35s were around the same price as 25 x N40s and I needed 48 of them in the design.

On the CNC machine, I first machined pockets in the steel plates for the first column of magnets, and also drilled the mounting and fixing holes. Once this machining was completed, I match-marked and assembled the rotor plates together with the shaft and trued-up the outside diameters on the lathe, so they were both concentric with the shaft - this should help ensure the rotor assembly is already close to being balanced, although I may still need to add a few balancing weights during testing to eliminate any vibration.

Twelve magnets were then fitted into the pockets of each rotor plate with epoxy, and then the next column of twelve magnets was placed on top.

outer rotor plate, with the first sets of magnets fixed
and showing shaft mounting bore & holes

and the inner rotor plate at the same stage....

*One word of caution, is that neodymium magnets are **very** strong and they must be handled with respect at all times. If you allow steel tools etc to become too close to the magnet surfaces, then they'll come together very sharply and there's a risk of damaging the magnets.*

The magnet poles are arranged alternately North-South around the discs, and the fixing holes in each rotor plate are drilled and match-marked to ensure that the North pole of magnets on the outer rotor plate is opposed on the inner plate by a South pole, and vice versa. This arrangement retains the flux within the rotor plates and across the gap between - it's very effective, touching the back faces of the plates with a screwdriver shows that there's very little magnetic force there at all, but the front faces are very strongly magnetic.

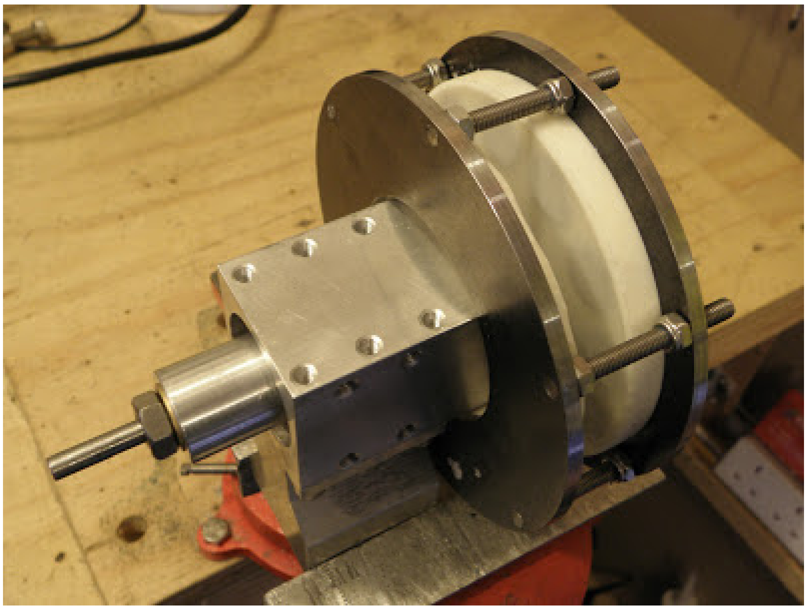
Then, to retain the outer set of magnets, I made a mould around the centre of each disc, mixed up some polyurethane casting resin and then poured it in to encapsulate the magnets.

second column of magnets and shaft fitted (the outer screws are temporary for moulding purposes only)

mould for the outer rotor.....

after pouring, solidification and demoulding....
the magnets are just below the surface of the resin

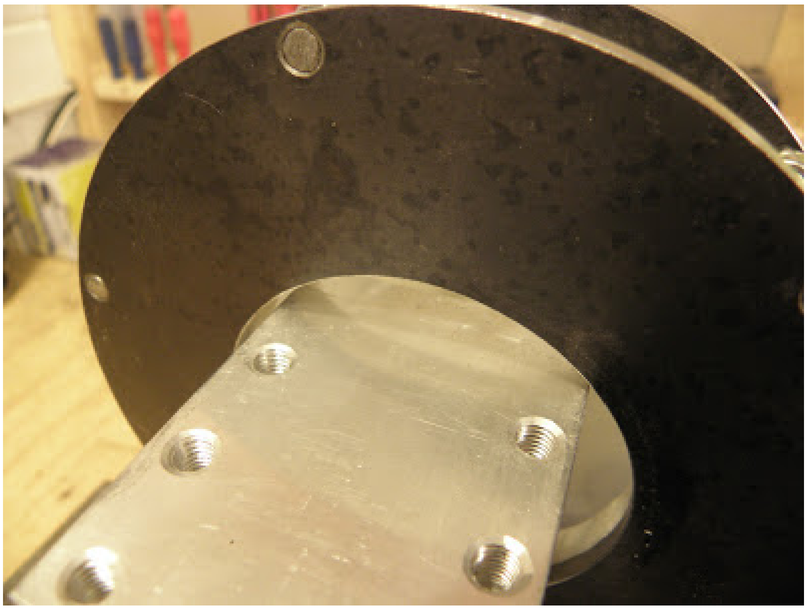
The two-part polyurethane casting resin was bought on eBay, quite expensive at £21 delivered for just one litre, but it's a fast-cast system with a potlife of just a few minutes and ready to demould in less than half an hour. There's more than enough for the two rotors and also to fully encapsulate the stator coils.



trial assembly of the mechanical components

The above photo is of a trial assembly of the generator - at this stage, all the mechanical components are basically complete, except for a spray coat of Hammerite or similar on the rotors to guard against corrosion of the steel parts. The studs and nuts I've used are all from stainless steel. The magnet surfaces are already covered with polyurethane - it's important that they're not exposed to the elements, since even though they're supposed to be nickel plated during manufacture, my previous experience with similar magnets is that they can very soon show signs of corrosion.

You can see I've used lengths of studding to separate the two halves of the rotor. This allows the gap between, and hence the clearance between the magnets and the stator coils, to be adjusted to a minimum on final assembly. The closer the magnets are to the coils, the better the generator performance.



clearance between the inner rotor plate and bearing housing...

From the above photo, you can see the clearance between the inner rotor and the square bearing housing. This allows the rotor to turn freely without fouling the housing and also provides a cable route to pass the wires from the stator through the inner rotor bore.

So, now that it's mechanically complete, I'll move onto the tricky part of winding the coils etc. I've already bought the winding wire and 3-phase bridge rectifier, and started on making coil formers etc - I'll show the construction of the stator and initial testing of the finished generator in a future post....

Homemade Axial Flux Generator - Part 2 - The Coils

Following on from our earlier post, quite a while back now, I managed to get around to constructing a stator coil a month or so ago. This particular project has had a very low priority due to work commitments and the many other projects I'm also on with, especially in the garden.

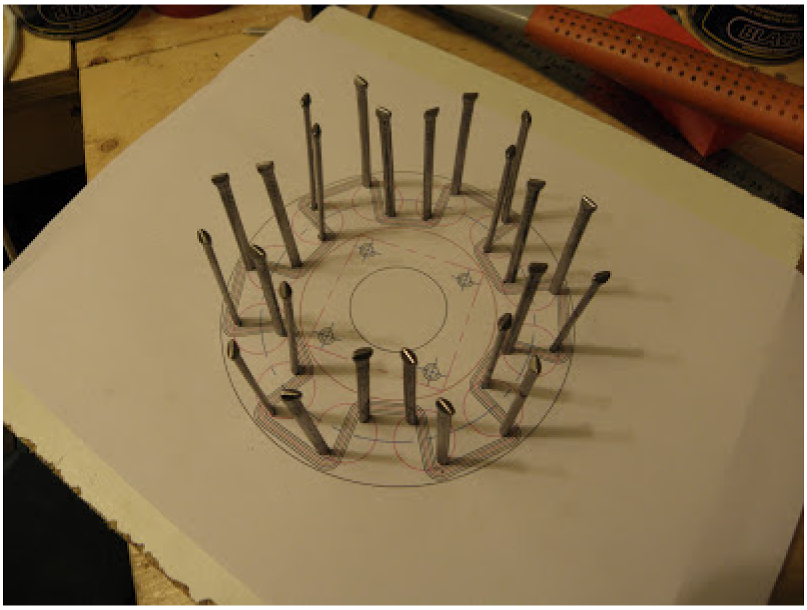
Firstly, I made a mould to cast the coils from an old piece of timber, using the CNC machine to generate the internal disc profile. Using the CNC wasn't strictly necessary, a simpler but equally effective mould could have made up from plastic strips or similar.

on the CNC machine....

Pins were added to form the four stator mounting holes, and then the mould was coated with a few coats of liquid latex to make it easier to get the coil out after casting.

latex coated....

In the end I decided to make serpentine coils which would be much easier to wind than individual coils, so I printed-off a template of the magnet and coil leg locations and pasted it onto a piece of board. Using wire oval nails, a simple winding former was constructed. Twelve magnet pairs on the rotors, and hence twelve coil legs at the same radial spacing.



the coil former....

So then it was a case of winding the coils. I made three, one for each phase. After winding, the coils were tie-wrapped and then flattened between two pieces of wood in the vice.

the three coils.....

At this stage I replaced the tie-wraps with insulating tape, to make the coils thinner overall. The coils were checked with a meter for continuity and resistance, and each wire lead marked to its coil location and also indicating the direction of the wind. It's important that the three coils are all laid and connected with the winding in the same direction.

now taped and marked.....

The coils were then stacked, with each slightly offset circumferentially from the one below.

the coil stack...

Then the assembly was placed in the mould, ready for encapsulation with polyurethane resin. The mould was first sprayed with a dry PTFE lubricant, to aid demoulding. The M6 capscrews and nuts as seen in the photo below were also placed in the mould to assist with removal.

in the mould....

after pouring - a couple of air bubbles, but no problem....

Getting the solidified stator coil out of the mould was much more difficult than anticipated, and eventually required splitting of the timber mould using a chisel along the grain.

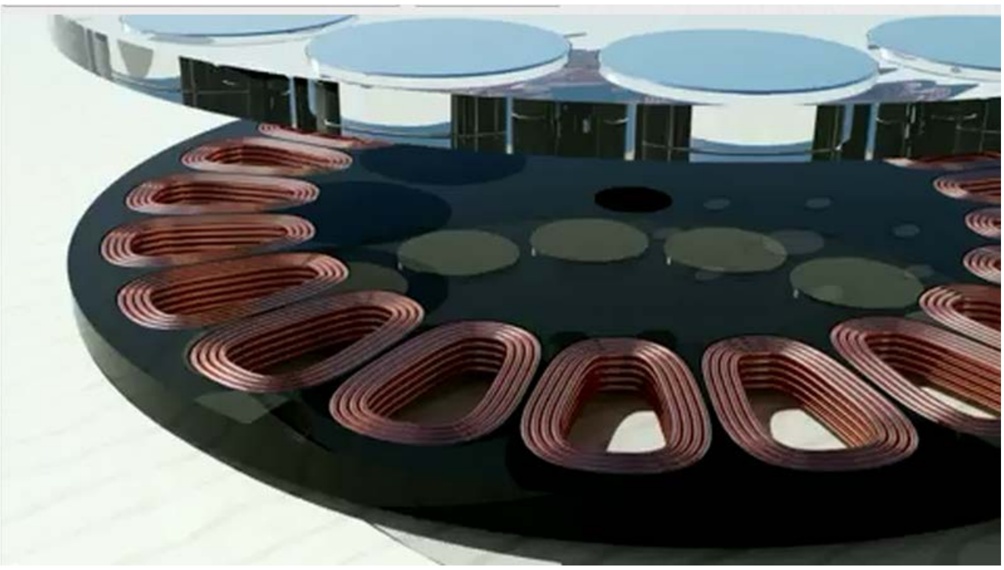
However, I was quite pleased with the overall appearance of the finished stator. Some of the wire enamel is slightly exposed in places around the periphery, but this is not a problem - in any event, it's intended to paint both the stator and rotors.

After a day to allow the polyurethane to fully cure, I dressed the casting with a file and countersunk the fixing holes.

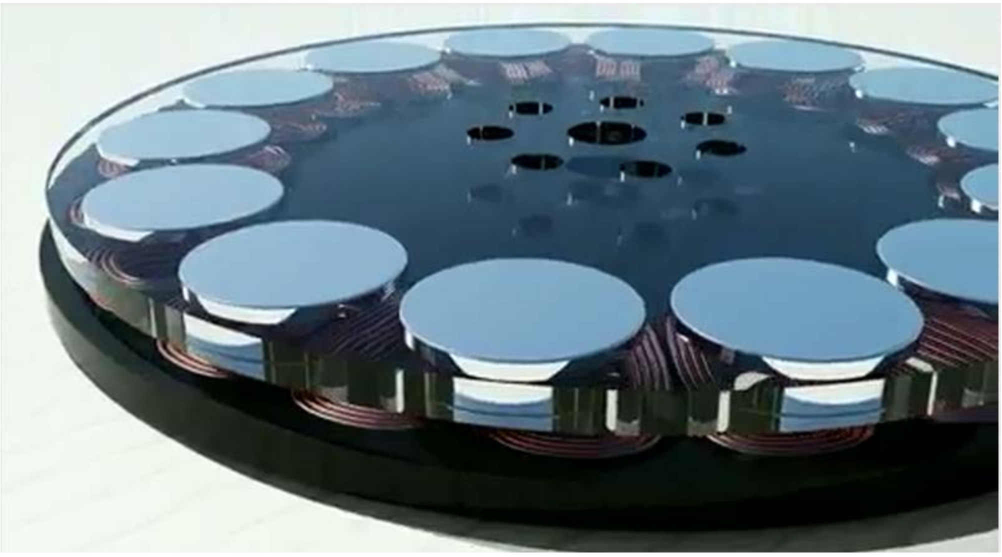
Note that I cast the stator with all 6 coil leads available for external connection. This allows experimentation with either star or delta connections in the case of a three-phase arrangement, or even to connect all the coils in series to make a single-phase generator. If you know in advance exactly how you want to configure the windings, then some of these connections could be made earlier and encapsulated within the resin, resulting in fewer external wiring leads.

finished stator coil trial-fitted to bearing housing.....

http://www.youtube.com/watch?feature=endscreen&NR=1&v=ue1qPgUCm5k



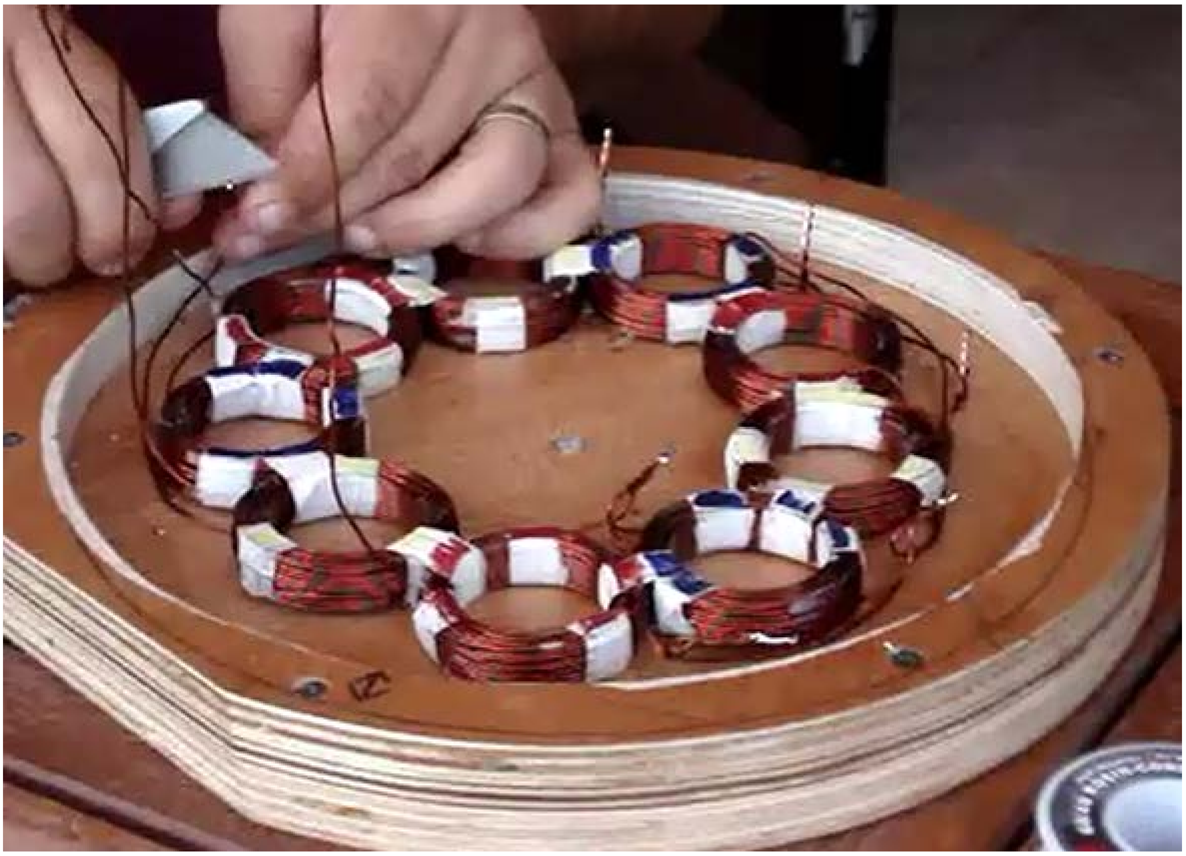
Made by gluing magnets and winding to disks (of plexi glas or steel).



Building of an axial flux generator

Good film

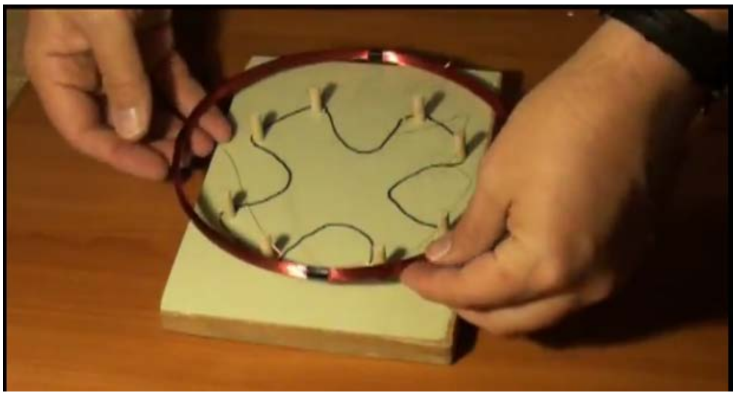
http://www.youtube.com/watch?v=NKDYeyu0R30&feature=related

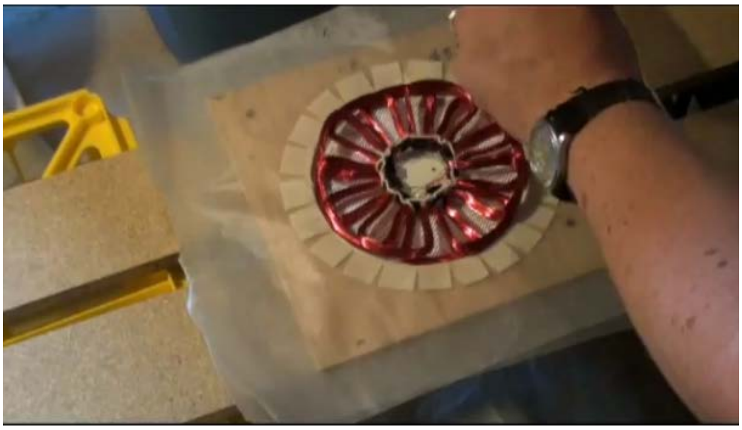


How to make a wave winding in an axial flux generator

Often coils are made as lap windings. However the coil can go over many poles, and is then often called a wave winding. This can be very efficient and as easy to build. .

http://www.youtube.com/watch?v=udDBHyk8Ne4&feature=related



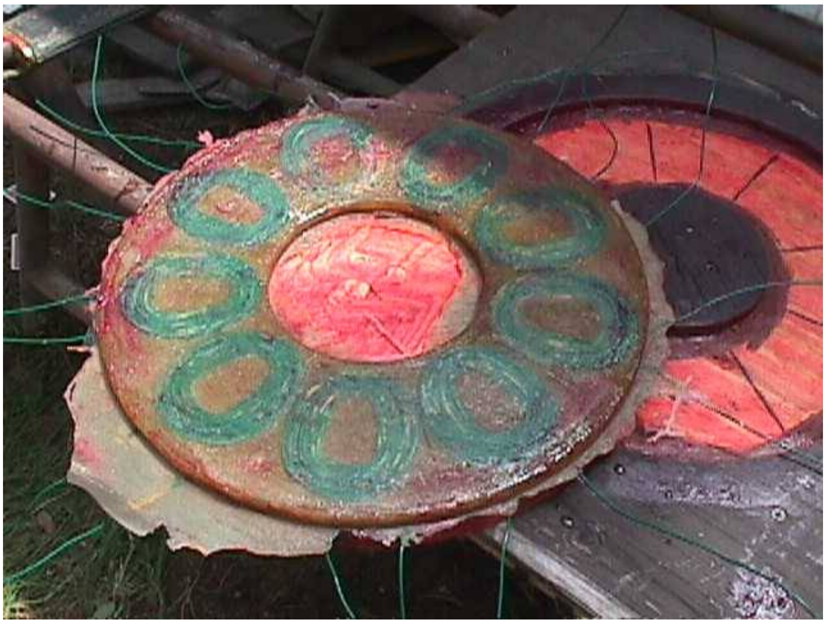


To build a generator with lego brick

http://www.youtube.com/watch?v=TUn1ippsKIY

Generators based on car parts

http://www.otherpower.com/trips1.html



Windings for an axial flux machine

http://www.youtube.com/watch?v=2anTW_QQQfk&feature=fvwrel

How to make a polyester cast

Another casted axial flux generator

http://www.youtube.com/watch?v=eG-ZXYH4OzU&feature=related