

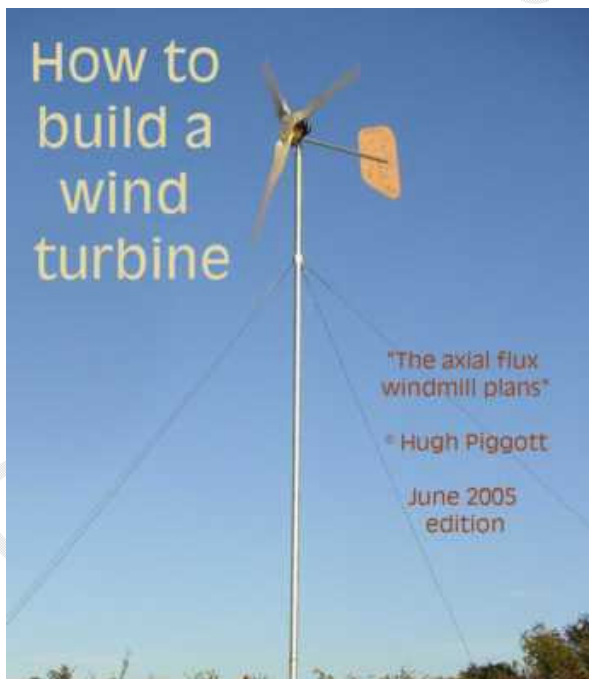


Basic Principles Of The Homebrew Axial Flux Alternator

If you are new to the topic of building Permanent Magnet Alternators, then this is for you! My purpose is to help people learn about the DIY wind turbines that are gaining in popularity. Basic concepts are introduced here, but it's still up to you to read on; this hobby is very multidisciplinary! For every topic, you can find a wealth of additional information – I hope I can help start you off in the right direction. Those with corrections or suggestions are welcome to contribute.



A Successful 17' Wind Turbine Design by Dan Bartmann (www.otherpower.com)



**Hugh Piggott's Popular Design Manual
(www.scoraigwind.com)**

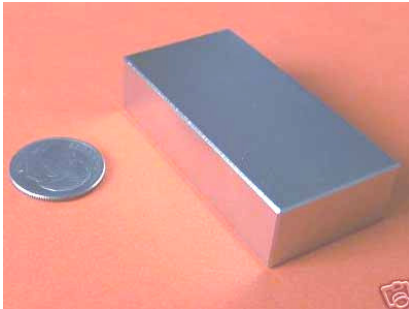


**My own turbine project
www.sparweb.ca**



Magnets

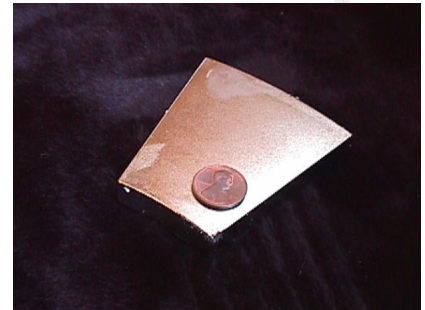
The Neodymium magnet has been a key technological development that allows practical and efficient alternators to be built. The high strength of Neodymium is part of what makes computer hard drives so compact. Now the material is available commercially for all sorts of purposes. Many sizes are perfect for DIY alternators. Below are some common sizes used:



2" x 1" x 0.5"



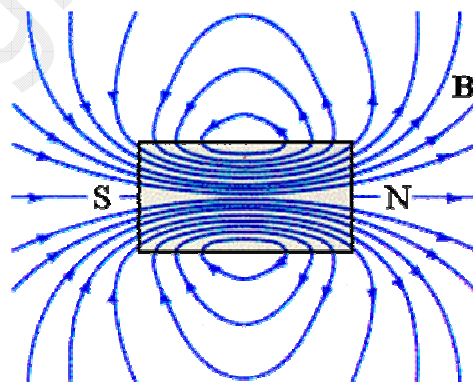
1" Diameter x 0.5"



Circular Arc

"Magnetic field" is the technical term for the lines of force that are often drawn around magnets to symbolize it. The magnetic field intensity is measured in either Teslas (after the inventor Nikola Tesla), or Gauss (after the mathematician). The symbol "B" is used for the field intensity (like "F" for force, "W" for weight). The intensity, B, gets stronger as you get closer to the magnet, since the lines get closer together.

There is always a North Pole and a South Pole. The magnets we prefer to use have poles on the faces with the most surface area. The example magnets shown above are more flat in one direction: the poles are on the broadest faces. Some types of magnets are longer on the polarized axis, but an axial flux alternator is efficient and lighter when the magnets are just big enough for the job, and no bigger.



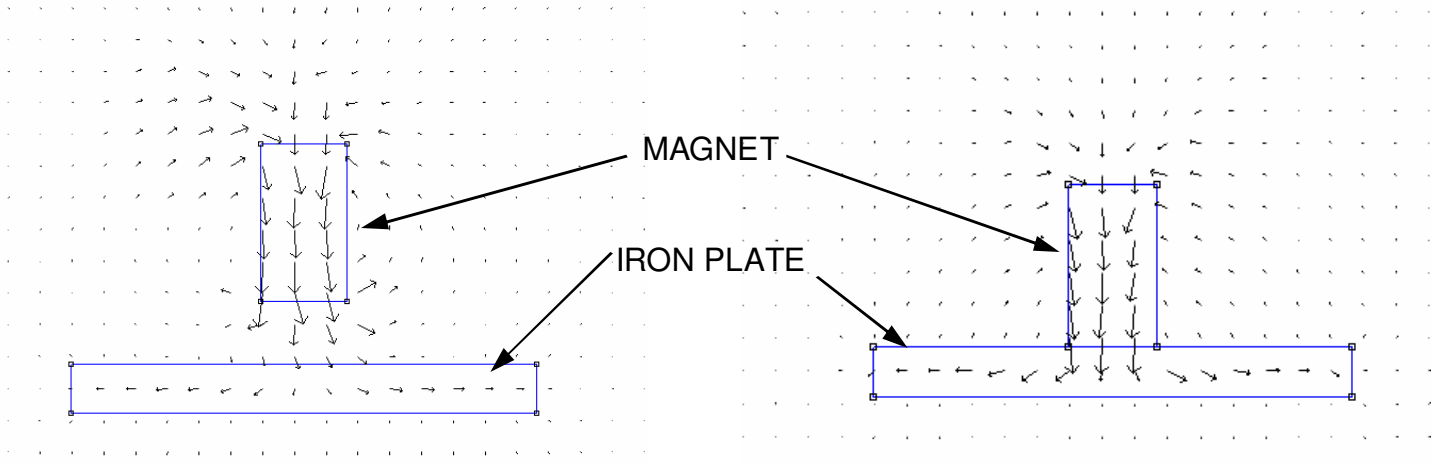
Magnetic Field Lines Around a Magnet

When magnets are made, the magnetic poles are "frozen in" with an external electromagnet as the metal cools. If a magnet gets too hot, its strength will weaken.



Magnetic Fields

A few illustrations will improve the understanding of how magnetic fields are manipulated. When magnets are attracted to metallic objects, the attraction can be witnessed by a distortion of the field lines that we saw above. The lines are drawn to that object, in much the same way that the object itself is drawn to the magnet. As the magnet gets closer to the plate, field lines pass through the plate and get stronger. The increasing size of the arrows in the diagrams below illustrates this.



Field Lines Through an Object Attracted to a Magnet

Field Lines Through an Object in Contact With a Magnet

When the plate is in contact with the magnet, the field lines can become very concentrated in the plate. They concentrate themselves in the plate, and if the plate is thick enough, very few lines emerge out the other side. Through the neodymium magnet itself, the magnetic strength doesn't change much.

In a sense, holding a magnet beside the plate of iron is like holding a ball above the ground. The ball falls due to gravity, and it comes to rest at a lower *potential energy*. Same with the piece of iron; once it is in contact with the magnet, the potential energy is lower.

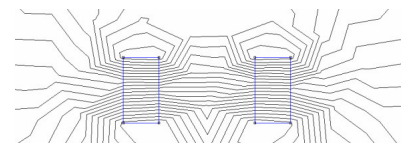
The magnetic field of the magnets is manipulated in this way. The next illustrations show two magnets that are close together. If similar poles are close together, then the lines diverge, and the effect is felt as repulsion. If their opposite poles are close together, then the lines converge (attraction). As they get closer, more lines get closer together, making the field more intense.



Magnetic Repulsion



Magnetic Attraction



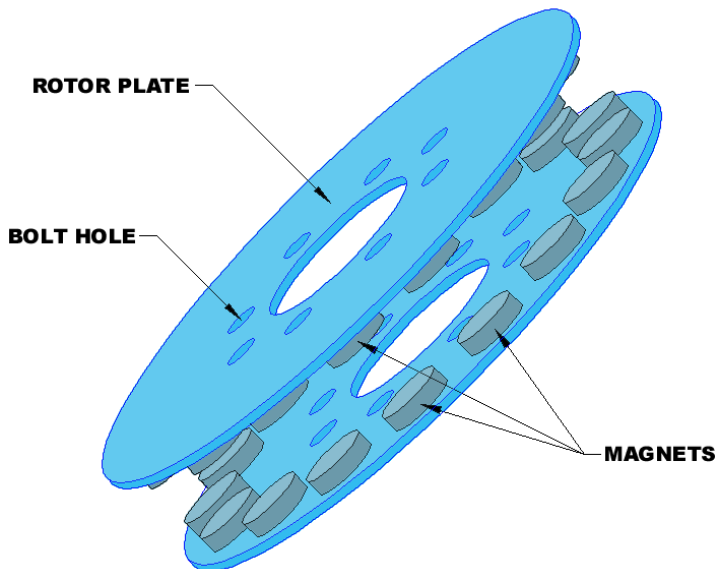
Magnets in Proximity (dense field lines)



Concentrating Magnetic Energy

The magnetic field is manipulated to our advantage, when making a Permanent Magnet Alternator (PMA). By concentrating the magnetic field between two opposite magnet poles, and capturing the flux in iron plates that would otherwise be wasted, we direct as much energy as we can through the gap between the faces. This design is called an "Axial Flux Alternator".

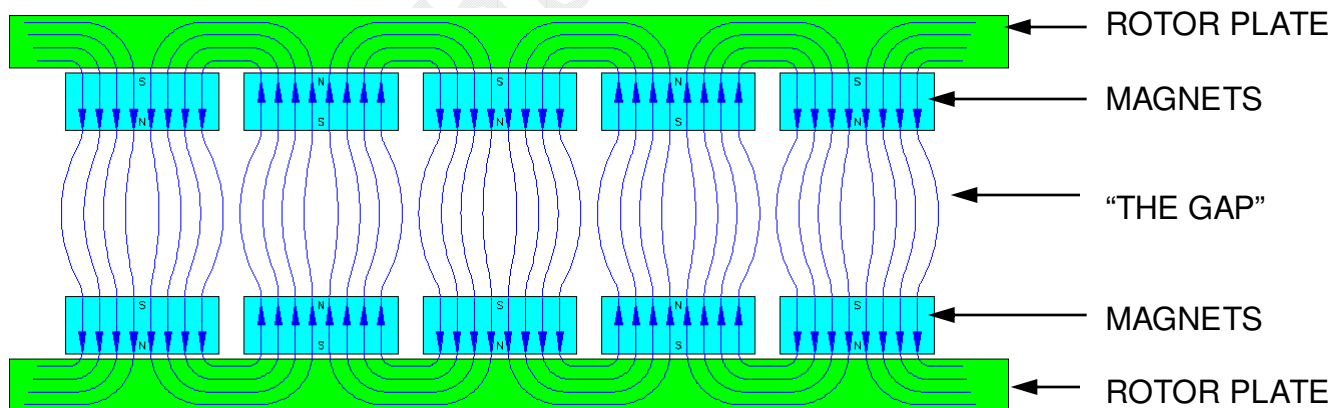
They usually look like this:



This set of rotors features round magnets. This is common on smaller axial-flux alternators, but as they get larger, it is often more practical to use rectangular magnets, which are available in larger sizes, and even wedge-shaped ones. It is important that the rotors be made of steel or iron, so that they conduct the magnetic flux.

The magnets are arranged in a N-S-N-S pattern around the circumference of the rotors. Opposite poles face each other. If you trace the field lines, they travel from one magnet face, straight to the magnet face opposite, then travel through the steel rotor plate to the next magnet, and back across the gap. Coils of wire in the gap capture the magnetic energy in those field lines.

Rotors of a Small Permanent-Magnet Alternator



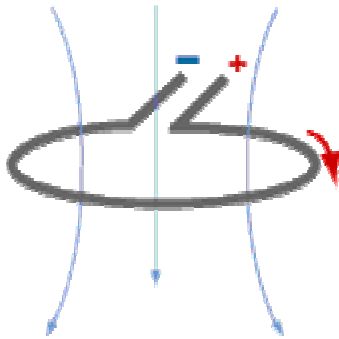
Field Lines Traced Through a Dual-Rotor Permanent-Magnet Alternator

The path of magnetic flux should be more clear with the diagram above. The field has been concentrated by confining it between the plates. The field also alternates between North and South. A compass inside this gap as the rotors turn would flip back and forth frantically. A compass outside the plates is weakly affected, because the fields have been confined.



Harnessing the Magnetic Energy

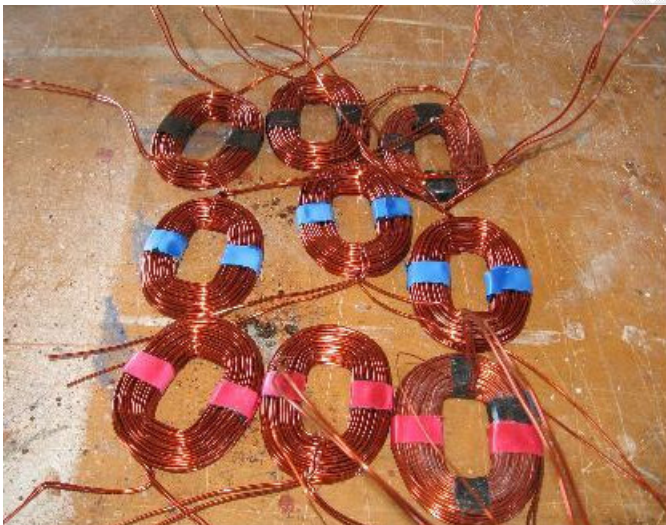
Now we come to the humble coil of wire. It doesn't do much on its own, but in the presence of magnetic fields, interesting things happen. A single loop of wire encloses a certain amount of area. The field passing through this area is a "magnetic flux". It is measured in Webers.



Not much happens when the surrounding magnetic field is sitting still, but when you put the system in motion, a voltage potential is produced. The more rapidly the magnetic field changes (either greater or lesser), the more voltage is created.

It doesn't actually matter how the field is changed for the phenomenon to occur. You may have magnets that get closer together, that oscillate back and forth, flip over and over, or perhaps you don't move the magnets at all, and instead flip the coil back and forth.

In our machine, coils of wire are held steady, while the magnets spin past on the rotors. Because the magnets were arranged N-S-N-S, the direction of the field flips each time a magnet goes by. Each coil sees a flipped magnetic field, and pulse of electricity is produced. When the field flips back, a pulse of opposite voltage is created. This coil is now producing alternating voltage.



Here is a set of 9 coils that were wound for a Permanent Magnet Alternator. They are all the same size, and have the same number of turns each.

Wire comes in a variety of sizes. The diameter (or "gauge") of the wire determines the maximum amount of current it can carry. Heavier wire can carry more current than thinner wire. The builder selects a wire size that allows the current required for his design, but no bigger.

If a single loop of wire captures a certain amount of voltage in a changing magnetic field, then more of those loops will capture more voltage. The builder wants many turns of wire to capture as much as possible. This objective conflicts with the objective of allowing more current, because heavier wire takes more space. Less turns of heavy wire, or more turns of thin wire? A balance is sought by the builder to meet his needs. Experienced builders learn how to strike the right balance. It is more of a mystery to the new recruit. Hopefully the diagrams at the end of this document will help.



Coils of Wire in the Stator

If regular jacketed wire was used to wind coils, a lot of space would be wasted in plastic jackets. A solution was found a long time ago, and wire can be bought that is coated in a thin non-conductive enamel. When coils of enameled wire are wound, each loop is isolated from the other, and the maximum compactness occurs.

Connecting the coils of wire introduces an important question in the design of the Permanent Magnet Alternator: Will there be 3 separate phases or just 1?

Single phase alternators are simple to hook up – all coils are wired in series with each other, and they all work together to make one large pulse at the same time. While this is simple, the windmill experiences quite an abrupt “bump” for each pulse. It can hinder windmill performance and cause annoying vibration. Builders still use single phase when it’s convenient, and adapt the design to resist the vibration. It is also more complicated to overcome the inefficiency when rectifying that voltage to put DC into a battery, but it can be done.

A more elegant solution is to wire up the coils for 3-phase operation. At any given point, only one third of the alternator is at peak power, the other two are either dropping or rising to their next peak. Vibration is reduced not only by having peak currents $1/3$ as intense, but also by having them 3 times more often. When rectifying the 3-phase power so that a DC battery can be charged, the current is also much smoother. The cost of extra rectifiers should not be an obstacle. They will last a long time if properly selected.

When the coils of wire are cast together into one plate, they are supported as a unit called a “stator” (it remains “static” while the rotor rotates). Builders usually arrange the coils in a star-shaped pattern in a flat mould. Into the mould they pour a polyester or epoxy resin. Then they close the mould, and when it has cured, the stator comes out as one big disk with the coils encapsulated inside. All of the internal electrical connections were made in advance. Either they selected one particular 3-phase connection arrangement, or they have enough wires coming out to allow some external connection changes. (See Appendix C for a variety of choices in wire connections).





Magnet and Coil Matching

In an alternator producing 3-phase power, then one group of coils is at peak current while the others are not. To do this, some of the magnets align with only one phase at a time. Instead of figuring out how this is done from scratch, here's the trick:

For every coil of wire in the 3-phase stator, there are 1.33 magnets.

Coils	Magnets	# Coils Per Phase
6	8	2
9	12	3
12	16	4
15	20	5
18	24	6

No, don't go slicing a magnet in half. The absolute minimum number of coils in a 3-phase alternator is 3 coils. One for each phase. You would therefore need 4 magnets. Actually, that would be fairly clunky. Here are some typical combinations:

Anything with more than 24 magnets is getting complicated, and the first-time builder should beware. Similarly, varying the proportion of magnets and coils begs trouble, unless you know how to avoid the pitfalls of making single-phase alternators (but you wouldn't be a newbie).

Matching the Alternator and Prop

The decision on how many coils/magnets to put into the Alternator is somewhat arbitrary, somewhat mystical. Basically, the more coils you have, the more voltage you produce (if all other parameters stay the same). But, the stator will produce less current, so the net power may not increase. That may be offset by a windmill speed range that captures more energy in the long run.

So far, we haven't mentioned the wind mill blades that will ultimately be attached to the alternator. When at the point of deciding how to configure the stator, the size and design of the windmill must also be considered. Does the windmill run fast or slow? Are there often strong winds that, if harnessed, would be of benefit? Are winds usually light, requiring a windmill that gets the most out of a gentle breeze?

Usually, the purpose of the DIY wind turbine is to charge batteries. If you hook the PMA to the rectifiers, and the rectifiers to the batteries, then you effectively clamp the voltage to a specific value, either 12V, 24, or sometimes 48V, depending on your system. The PMA design should produce the right voltage for the bank of batteries.

The batteries are a load on the Alternator. The charging voltage will rise to a peak level (about 10% above the battery's standard voltage), and then the rectifiers open to allow current to flow. Now the alternator produces constant voltage and current increases as it turns faster. In the windmill situation, higher winds turn the blades faster, and provide more power to overcome the heavier PMA load. If the blades are too small, however, there won't be enough power to start the alternator in low wind. If the blades are too big, the alternator won't load the prop efficiently and they will spin too fast.



Mounting The Rotor and Stator Together

The stator is fixed while the rotor turns. How do people usually put this together? The best way to start is to see how others have done it. There are several ways, but most resemble the hub of an automobile; in fact, automobile hubs are usually used!



You can see 12 coils in these stators:
There are 16 magnets on the rotors below:

Below you can see the process of assembly of the rotors and stator. This is done cautiously because Neodymium magnets are very powerful. If the two rotors in this PMA were allowed to snap together, the impact would likely shatter the magnets, and any hands that happened to be in between!



One magnet rotor mounted to the hub.
Jacking screws extend up, to mount
and adjust the opposite rotor.



Rotor and hub mounted on tower head.
Stator is in position in front of the rotor.



Second (Opposite) Rotor Being
Lowered Into Position



Second Rotor in Position

Technical Data

What performance should the Permanent Magnet Alternator have? Dan Bartmann tests his alternators and has collected a lot of data over the years.

The Rotors weigh 23 pounds each (13 Pounds of magnets + steel plate X 2)
The Stator weighs nearly 20 pounds (16 pounds of copper)

At 80 RPM, this alternator will produce 50 Volts, unloaded. When connected to a 48V Battery system, Dan has recorded 600 Watts at 100 RPM. (Roughly 12 Amps). This is actually a fairly large PMA, suitable for a windmill size of about 17 feet diameter. At higher wind speeds, the prop turns much faster and he can capture upwards of 3 kiloWatts.

A more modest size of alternator, with a 6-8 foot prop, could also produce up to 500 Watts, but at a significantly higher RPM. Smaller props naturally turn faster, so a good match can be made by the beginner who works carefully to select prop and alternator operating ranges that coincide.



Where to Start With Your Wind Turbine

There are a lot of questions to be asked at the beginning. One of the best ways to start is to pick something that works, that is well documented, and to follow the instructions carefully. Hugh Piggott, Dan Bartmann, and Ed Lenz all have well-designed wind turbine projects that offer the beginner an excellent start. And they're not the only ones.

1 What will I do with the power?

Often, Renewable Energy systems are designed to charge a bank of batteries. An inverter turns the battery voltage into AC that household appliances and lights can use. It doesn't have to be this way. You may want to put the energy to heating coils in your house's heating system. Maybe you want to heat water. The electricity may be useful in your house, or instead in a remote building with no power at all. Maybe you're ambitious and can feed it back into the grid. (Or maybe you're looking for the perfect lawn ornament to impress your neighbour).

2 How much power do I need?

That jumbo windmill could light every light in your house, but how can you commit to that scale of project on your first time out? You don't seriously think you can run your air conditioning system all summer on a puny wind turbine, do you? If you're building it just for the fun of it, then the right size is the size you can handle. If you have a purpose in mind, then figure out what you need, apart from what you want, and how you can conserve to make the job easier.

3 Where will the wind come from?

Something we often take for granted. "Just build it – then put it in the wind..." but most of us live near trees, buildings, neighbours, etc. The location and wind that you have should figure into the design early. If you have light wind most of the time, then you probably want a large windmill that's producing power even when turning slowly – though it won't be able to take full advantage of strong winds. Or... you often get strong winds and want to capture all that energy – but it may produce nothing in lighter breezes. There are compromises to be made.

4 How long will this take?

This project could take a while. You're going to draw a lot of drawings, cut a lot of wood, drill a lot of holes in steel, weld a lot of tubing, mix lots of epoxy, wind a lot of wire, and stand around scratching your head in puzzlement quite a lot, too. My dumb mistake? I built two simultaneously. It took twice as long to get anything finished!

5 Do I have to do it myself?

There are a lot of companies that build these things for you. You get the whole thing, too; tower, inverter, batteries, etc. Go the DIY route if you're sure you're going to enjoy the experience and finish the job. But you don't seriously think that DIY is a lot cheaper, do you?



To Learn More

Below is a brief bibliography of places to go to learn more about building windmills. You can start here, and then venture out into the enormous volume of information that rest of the Internet holds.

DIY Projects

Hugh Piggott (Scotland)	www.scoraigwind.com
Dan Bartmann (USA)	www.otherpower.com
Ed Lenz (USA)	www.windstuffnow.com
The Backshed (Australia)	www.thebackshed.com/Windmill
Antonio Cecere (Italy)	www.webalice.it/acecere48/index.htm
Steven Fahey (Canada)	www.sparweb.ca

Scientific Research

Sandia National Labs	www.sandia.gov/wind/
NREL	www.nrel.gov/wind/

Electrical Theory

All About Circuits	www.allaboutcircuits.com
FEMM (Magnet Models)	www.femm.foster-miller.net/index.html
Magnets	
K&J Magnetics	http://www.kjmagnetics.com
Magnetsource	http://www.magnetsource.com

Commercial Wind Turbine Manufacturers

Bergey Windpower	www.bergey.com
Southwest WindPower	www.windenergy.com
Jacobs	www.windturbine.net
African Windpower	www.africanwindpower.com
Xzeres	www.xzeres.com

Wind Energy Associations and Watchdogs

AWEA (USA)	www.awea.org
CANWEA (Canada)	www.canwea.ca
Danish Wind Insustry Assoc.	www.windpower.org
Wind-Works by Paul Gipe	www.wind-works.org/



Appendix A - Wire Gauge Table

There are two columns of allowable current in this table. This is deliberately included to help the reader in two different places.

- 1) When winding the stator, use the “chassis wiring” column,
- 2) When connecting your mill to the battery bank, use the “power transmission” column, because the mill is usually very far away from the building where the batteries are.

I would consider the column for “chassis wiring” a hard limit – you could burn up your stator if you overload it. On the other hand, delivering your power from the mill to the battery depends a lot of if the distance is long or not, or if you find that a little extra resistance in the line helps keep the windmill’s speed in the right range, or many other factors, that can come into play.

AWG gauge	Diameter Inches	Diameter mm	Ohms per 1000 ft	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission
0000	0.46	11.684	0.049	0.16072	380	302
000	0.4096	10.40384	0.0618	0.202704	328	239
00	0.3648	9.26592	0.0779	0.255512	283	190
0	0.3249	8.25246	0.0983	0.322424	245	150
1	0.2893	7.34822	0.1239	0.406392	211	119
2	0.2576	6.54304	0.1563	0.512664	181	94
3	0.2294	5.82676	0.197	0.64616	158	75
4	0.2043	5.18922	0.2485	0.81508	135	60
5	0.1819	4.62026	0.3133	1.027624	118	47
6	0.162	4.1148	0.3951	1.295928	101	37
7	0.1443	3.66522	0.4982	1.634096	89	30
8	0.1285	3.2639	0.6282	2.060496	73	24
9	0.1144	2.90576	0.7921	2.598088	64	19
10	0.1019	2.58826	0.9989	3.276392	55	15
11	0.0907	2.30378	1.26	4.1328	47	12
12	0.0808	2.05232	1.588	5.20864	41	9.3
13	0.072	1.8288	2.003	6.56984	35	7.4
14	0.0641	1.62814	2.525	8.282	32	5.9
15	0.0571	1.45034	3.184	10.44352	28	4.7
16	0.0508	1.29032	4.016	13.17248	22	3.7
17	0.0453	1.15062	5.064	16.60992	19	2.9
18	0.0403	1.02362	6.385	20.9428	16	2.3



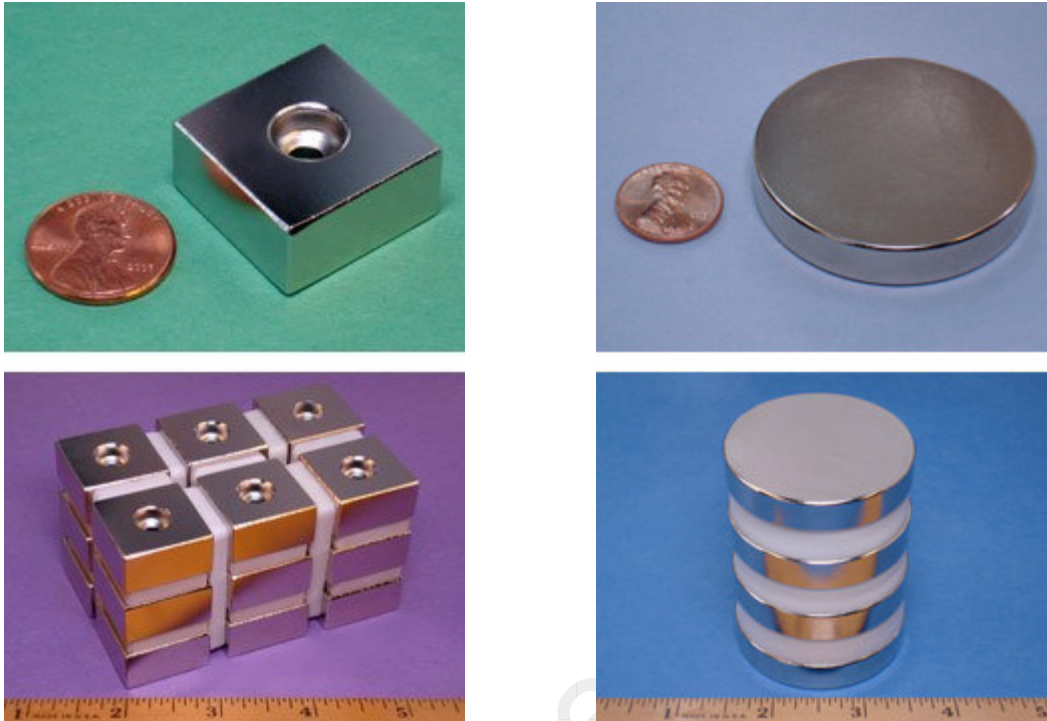
Basic Principles Of The Homebrew Axial Flux Alternator

19	0.0359	0.91186	8.051	26.40728	14	1.8
20	0.032	0.8128	10.15	33.292	11	1.5
21	0.0285	0.7239	12.8	41.984	9	1.2
22	0.0254	0.64516	16.14	52.9392	7	0.92
23	0.0226	0.57404	20.36	66.7808	4.7	0.729
24	0.0201	0.51054	25.67	84.1976	3.5	0.577
25	0.0179	0.45466	32.37	106.1736	2.7	0.457
26	0.0159	0.40386	40.81	133.8568	2.2	0.361
27	0.0142	0.36068	51.47	168.8216	1.7	0.288
28	0.0126	0.32004	64.9	212.872	1.4	0.226
29	0.0113	0.28702	81.83	268.4024	1.2	0.182
30	0.01	0.254	103.2	338.496	0.86	0.142
31	0.0089	0.22606	130.1	426.728	0.7	0.113
32	0.008	0.2032	164.1	538.248	0.53	0.091
Metric 2.0	0.00787	0.200	169.39	555.61	0.51	0.088
33	0.0071	0.18034	206.9	678.632	0.43	0.072
Metric 1.8	0.00709	0.180	207.5	680.55	0.43	0.072
34	0.0063	0.16002	260.9	855.752	0.33	0.056
Metric 1.6	0.0063	0.16002	260.9	855.752	0.33	0.056
35	0.0056	0.14224	329	1079.12	0.27	0.044
Metric 1.4	.00551	.140	339	1114	0.26	0.043
36	0.005	0.127	414.8	1360	0.21	0.035
Metric 1.25	.00492	0.125	428.2	1404	0.20	0.034
37	0.0045	0.1143	523.1	1715	0.17	0.0289
Metric 1.12	.00441	0.112	533.8	1750	0.163	0.0277
38	0.004	0.1016	659.6	2163	0.13	0.0228
Metric 1	.00394	0.1000	670.2	2198	0.126	0.0225
39	0.0035	0.0889	831.8	2728	0.11	0.0175
40	0.0031	0.07874	1049	3440	0.09	0.0137

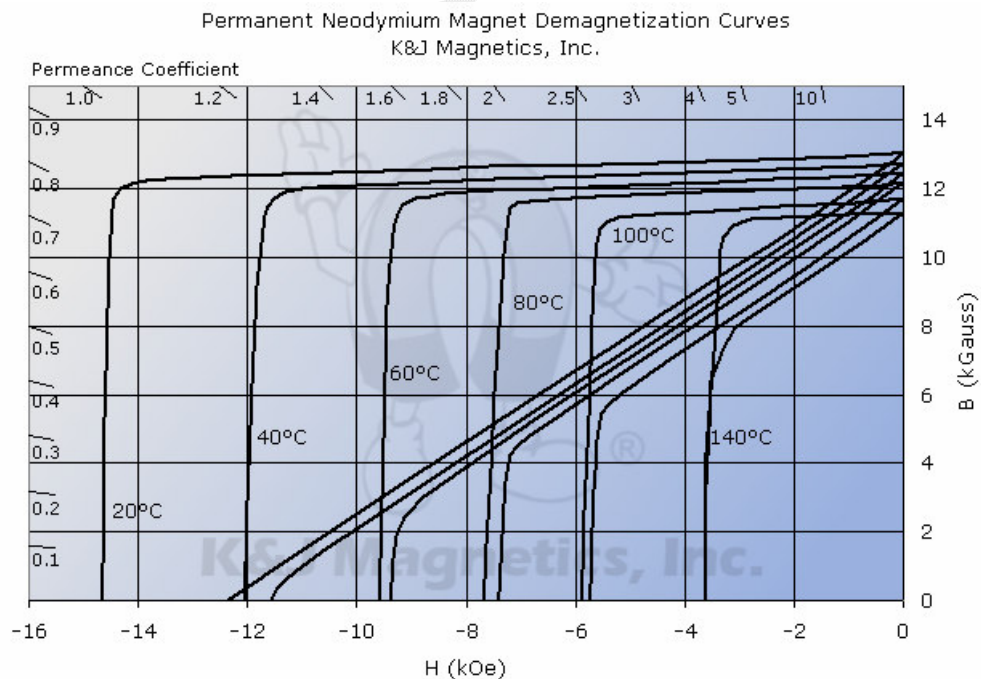
(www.powerstream.net)



Appendix B - Neo Magnet Data



Samples from a popular internet supplier of Neo Magnets
(There are literally hundreds of suppliers to choose from)



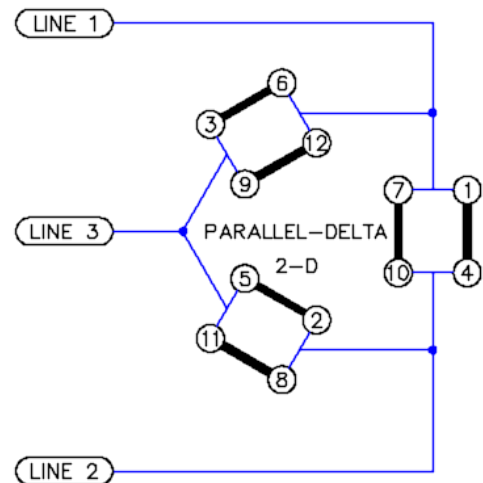
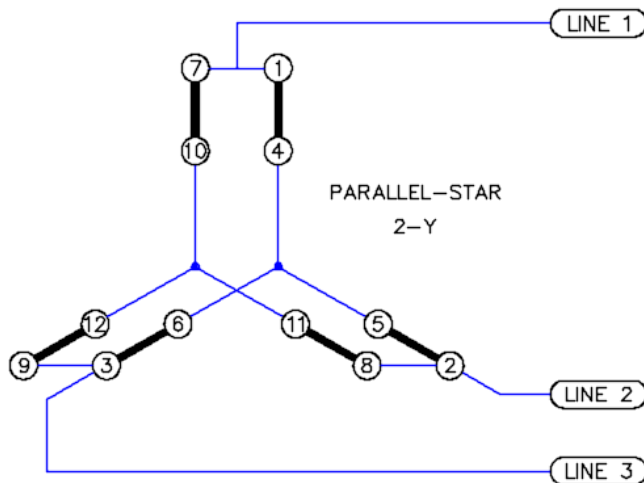
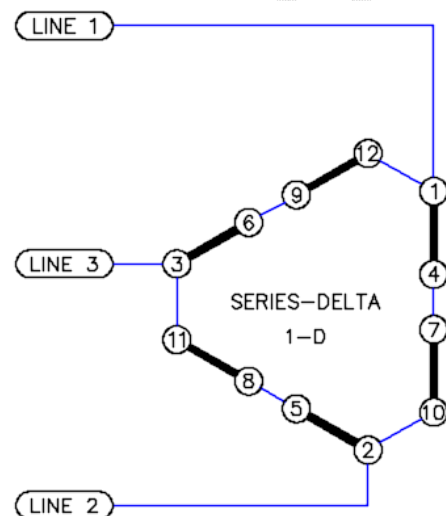
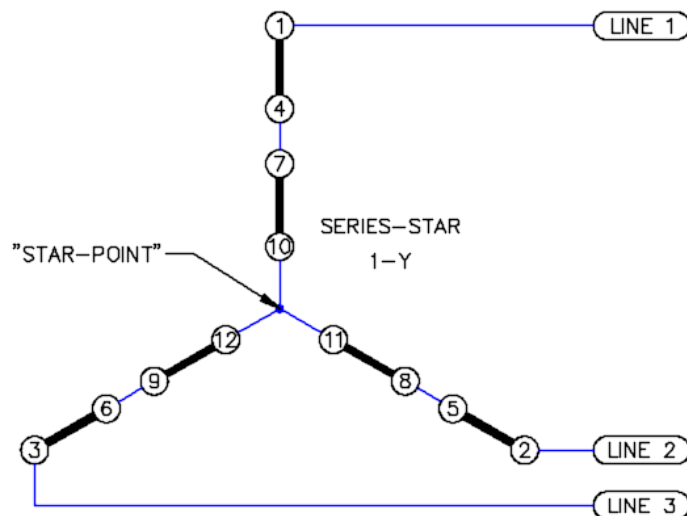
(www.kjmagnetics.com)



Appendix C - 3-Phase Wire Connections

The simplest way to connect the coils of a 3-phase alternator is in “Star”. Join the ending wires together, and the three start wires come out. Each phase comes out of the start wires. Alternatively, a “Delta” connection can be made by joining the starts and ends of each successive phase together.

The diagrams below apply to an alternator that has 2 coils in each phase. The stator would have 6 coils in total. The wires 1 & 4, for example, are the start and end of one coil in that phase. This can be adapted for, say, a 9 coil stator, when each phase would have 3 coils.



More complex “Parallel” connections can also be made, if you have enough connections available. You do this to reduce the voltage (if the alternator cuts in too soon, for example), and the reward is that you can have twice as much current.



Appendix D – How to Size Your Windmill and PMA (sort-of)

Say you want a Wind Turbine that generates 500 kWhrs of electricity per month. With this target, your next choices don't have much to do with the turbine itself.

How much wind do I have?

What battery bank size do I need?

Look at the wind speed and frequency data that has been collected for your area. Assume that the average wind speed is 6 mph (or 10 kph, or 3.6 m/s or 8.8 ft/s, however the data is presented). That average wind will have 1/2 kWhr per month per square foot of kinetic energy in it. One half. Think about that for a while...

If the goal is to collect 500 kWhr per month, then 1000 square feet of windmill area are needed, at an absolute minimum. That translates into a 40 foot diameter windmill. Wow.

Most wind energy comes from STRONG winds. If we consider days with 20 mph winds, then every square foot of windmill area now has 18 kWhr per month. This is a much more significant amount of energy. If the average wind was 20 mph, then only a 7 foot diameter windmill is needed.

Now you can appreciate the advantage of having strong wind. When evaluating your site, you really need to know more than just the average wind speed, you should find out how often the wind blows at different speeds. If those 20 mph winds come along 5% of the time, and the 6 mph winds 25% of the time, any windmill will produce more energy during the month from the 20 mph winds than it can from the 6 mph winds, even if they are less common.

500 kWhrs translates into a continuous demand of 700 watts. Pretty typical for a single-family house in North America. In the summer, it's less, in the winter, more. If your battery bank is going to deliver an average 700 watts to the house, then it had better not go flat when the wind dies down! Having two days' worth of energy stored in the batteries is necessary for peace of mind. That also depends on where you live – some places always have wind, others can go without for many days.

More math: 700 watts at 12 Volts is a DC current of 60 Amps. As soon as you turn on the microwave oven that will shoot up to over 200 Amps. To carry that, BIG wires are necessary. You would be better to set up the batteries for 48 Volts in a system of this size, and that would bring the draw down to 15 Amps, normally, and 50 Amps for the bigger load. Two days constant demand on this 48V battery bank would require 720 Amp hours.

Lead-Acid batteries can't be drawn down too far or they sustain damage. To prevent a discharge below 66% after 2 days, the bank requires a capacity of 2160 Amp-Hours. If it was composed of 12V, 200 Ah cells, that would equal about 44 cells. It is a fact of life that batteries are expensive, and much harder to make yourself than a windmill. This is where the big cash outlay happens when you are determined to have an independent or off-grid installation.

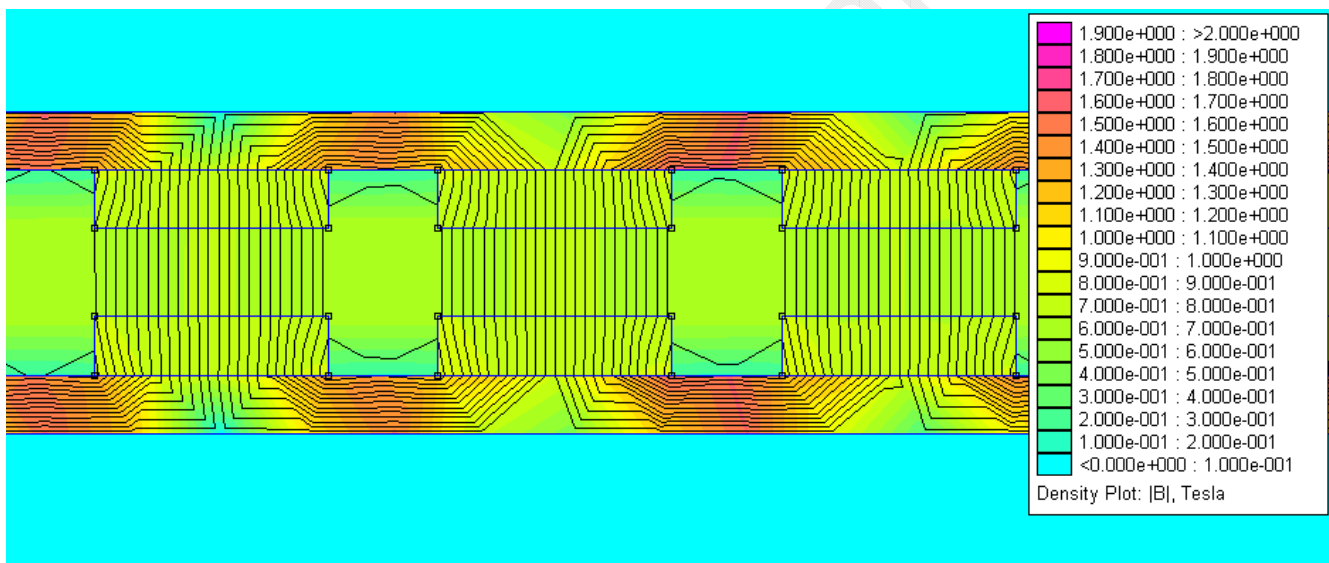


Appendix E – Finite Element Analysis of a PMA

There are ways to simulate electro-magnetic machines like the Axial Flux Alternator. The mathematics can be found in university physics textbooks that govern the way they work. Often, seeing is believing, and the computer-savvy may enjoy using simulation software packages to learn more.

I have enjoyed using FEMM to simulate the generators that I build. FEMM stands for “finite element magnetic modeling”, and it is a software package that is freely available from www.femm.foster-miller.net/index.html.

To start, you must draw the parts accurately and assign realistic types of materials to the spaces. The drawings should be of “cross-sections”, where what you see is a slice through the machine. The software must be given realistic information, but also parts that are simple to analyze. The FEMM tutorials will give you a good start if you follow a few through to the end. Here is an example.



Trying different variations on a design sheds a lot of light on the effects of changing one thing or another. In this case, I'm showing you a simulation of the axial-flux alternator. Two rotors face each other, and field lines are drawn crossing from magnet to magnet. Also notice how the lines travel in a continuous loop through the backing disk, into the next magnet, and on across the gap to the next one.

Some lines don't cross the gap. A few of these are visible in the simulation. This is called "leakage", and it wastes the magnet's potential energy.