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BRING A TOUCH OF WISDOM TO YOUR WORLD…

HOW-TO BUILD A WINDMILL.©

The plans that follow are a step-by-step procedure in constructing an efficient generator. The generator is the heart of any windmill and is for this reason the main focus of this booklet.

Factors to consider when evaluating small wind generators.

The power available in the wind is a function of the density of the air and the speed of the wind. The calculations follow:

Power density is the power (in watts) contained in air at sea level, at 60 degrees F. at a given speed:

Power density = .05472 x speed^3 (cubed) in mph = watts/meter^2 (squared)

Inserting the appropriate numbers for a few common wind speeds we get:

10mph	15mph	20mph	25mph	30mph	35mph	40mph
54 watts/m^2	184 watts/m^2	437 watts/m^2	855 watts/m^2	1477 watts/m^2	2146 watts/m^2	3502 watts/m^2

Table 1 Power density (watts/sq. meter) at different wind speeds

This is the raw energy of the wind. Unfortunately, it isn't what we can extract from the wind. There are two limitations we need to consider. ***The Betz limit*** and the inefficiencies of any machine we build. There are others as well, but we won't deal with those right now.

The Betz limit of Energy from the wind

Given the nature of the wind, there is a finite amount of energy that we can get from it. This has been derived and is known as the Betz Limit. This works out to 59%.

Applying the Betz limit of 59% - The most power physically able to be extracted from the wind, assuming a device efficiency of 100%.

10mph	15mph	20mph	25mph	30mph	35mph	40mph
31 watts/m^2	108 watts/m^2	257 watts/m^2	504 watts/m^2	871 watts/m^2	1233 watts/m^2	2066 watts/m^2

Table 2 Betz limit of 59% of the power per sq. meter at various wind speeds

Of course, wind turbines are not 100% efficient, neither are generators or electric transmission techniques. The challenge is to come as close to the Betz limit as possible by optimizing the rotor design and reducing loss due to friction and generation. The following are the Betz numbers for various size rotors. First we'll determine the swept area for the rotor sizes. For horizontal axis wind generators, this is equal to the area of a circle with the rotor length being the diameter.

Area of a circle = (p) radius2

Area for a 1 meter diameter (3.3 foot) rotor = (3.14) $.5^2$ = 3.15 * .25 = .785 sq meters
Area for a 2 meter diameter (6.6 foot) rotor = (3.14) 1^2 = 3.14 * 1 = 3.14 sq meters
Area for a 3 meter diameter (9.9 foot) rotor = (3.14) 1.5^2 =3.14 * 2.25 = 7.065 sq meters

Applying Betz -- **(.59) Power Density * area** for various rotor sizes

Rotor diameter	**10 mph**	**15 mph**	**20 mph**	**25 mph**	**30 mph**	**35 mph**	**40 mph**
1 meter	24 watts/m^2	84 watts/m^2	201 watts/m^2	395 watts/m^2	683 watts/m^2	967 watts/m^2	1621 watts/m^2
2 meters	97 watts/m^2	339 watts/m^2	807 watts/m^2	1582 watts/m^2	2735 watts/m^2	3871 watts/m^2	6487 watts/m^2
3 meters	228 watts/m^2	770 watts/m^2	1825 watts/m^2	3564 watts/m^2	6158 watts/m^2	9779 watts/m^2	14.6 kw/m^2

Some wind turbine manufacturers use 27 or 28 mph as a standard wind speed

for rating the performance of their turbines. If we apply the same wind speed to the Betz limit for the diameters shown above, we get the following:

1 meter diameter	2 meter diameter	3 meter diameter
498 watts	1993.9 watts	4.486 kilowatts

Table 4 Power density of the raw wind @ 27mph = 1077 watts/sq meter. The Betz limit (59%) applied to this ---> 635 watts/sq meter

The numbers shown above should serve as a sanity check since there is no machine made that is 100% efficient (see below). If you think you've beaten these numbers, check your figures.

Mechanical Inefficiencies

In addition to the limitations imposed by the Betz limit and air density, there is the fact that all mechanical devices suffer from energy loss due to friction. Electrical devices, like generators and alternators, suffer from energy loss due to inefficiencies of electrical conductivity in copper wire. In addition to this, there are speed ranges in which generators/alternators are not efficient and the fact that at high speeds wind turbines tend to self-destruct, requiring that they furl away from the wind or be manually shut down during high wind events.

These all combine to result in wind generators that are extracting 12 to 30% of the power contained in the wind as usable electrical energy. There are some wind generators that are purported to extract as much as 40% that are verifiable. If we calculate 30% of the total power in the wind for the turbine sizes and wind speeds shown above, we get the table below, units are watts.

Rotor diameter	**10 mph**	**15 mph**	**20 mph**	**25 mph**	**30 mph**	**35 mph**	**40 mph**
1 meter	12.89	43.49	103.09	201.35	347.94	552.51	824.74
2 meters	51.55	173.97	412.37	805.41	1391.75	2210.05	3298.96
3 meters	115.98	391.43	927.83	1812.17	3131.43	4972.6	7422.66

It's not that wind turbines of this size can't extract more energy from the wind than this, some do. What is shown in the table above is the ballpark figure for what wind turbines of this size are likely to extract at these wind speeds. Those who advertise figures drastically higher than these, and especially higher than the Betz numbers (above), should be questioned.

Step 1. Building my own blades.

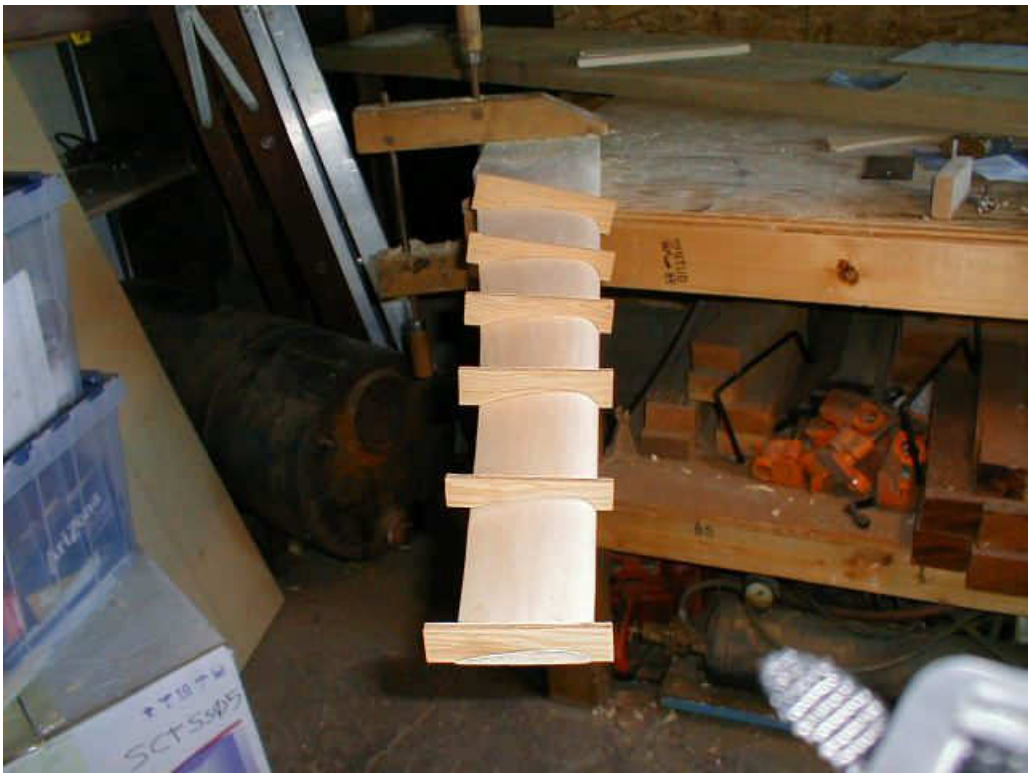
Part of the allure of building a windmill is to carve the blades. The craftsman in me drools over the prospect. I love carving wood. But I didn't know where to start, so I found a web site with some books on the subject and ordered a few books. Two in particular were quite valuable. These were both by Hugh Pigott; Wind power Workshop and Brake drum Windmill Plans. The web site I bought these from was picoturbine.com. They are also available from otherpower.com. Hugh Piggot has a very helpful web site at Scoraigh Wind Electric, which includes alternator information also.

Blade materials

I used basswood (linden) for the blades. I don't believe it is the best wood to use, which would be quartersawn sitka spruce. Sitka spruce is hard to come by here in Texas and I'm not up to any trips to the coast for a while. I'm certainly not going to buy expensive wood sight unseen. Basswood has numerous good qualities however. It is soft (easy to carve), has little difference between flatsawn and quartersawn sections, and is more available than sitka spruce. It takes finishes well and is very light in weight. It is not brittle like redwood or western red cedar and so shouldn't shatter quite as easily. I purchased three 8' planks of rough 2x6 basswood lumber with the intent of making at least 10' diameter blades. I discovered that I could stagger the blades such that I could build a smaller 7' diameter set first, just like the ones in Hugh's Brake drum windmill book. So I chose the less desirable ends of the three planks and cut the outlines of the blades.

Templates for the Blades

I've created a .pdf file which should print out to full size templates for the blades I made using Hugh's book (refer to the “airfoil3.pdf” attachment). There is some chatty info I've included as well. Below is a photo of the templates in use on a blade in the carving process.



Carving the Blades

I carved the blades by hand after cutting the shape roughly on a band saw. I made a template for the overall outline, shown to the right of the photo below. The blades were first cut to this outline and then the shape and angle of the twist was drawn on each one.



Two sides of the blades shown in different stages of cutting. Note the airfoil profile on the near ends.



Three stages of carving shown from the leading edge (back side) of the blade. Note the burn marks from band sawing the basswood. The blade needs to be sharp and with few hook teeth per inch.



The same three stages from the trailing edge of the blade, again with the backside up.

Attaching the blades together

Most of the screws were applied from the backside of the hub. The weights were applied from the front side (see balancing the blades, below).

Finishing the blades

I decided to use 3 coats of oil-based primer followed by 4 or more coats of oil based epoxy resin high gloss enamel. I wanted the superior adhesion of the oil based paint (over latex) and I wanted the extra hardness of the enamel. I brushed each coat heavily taking care not to get many runs. I sanded with 220 grit open coat silicon carbide sandpaper between coats. There were still brush marks on the final coats, so I may spray the last few coats to achieve the desired smoothness and mirror finish.

Balancing the Blades

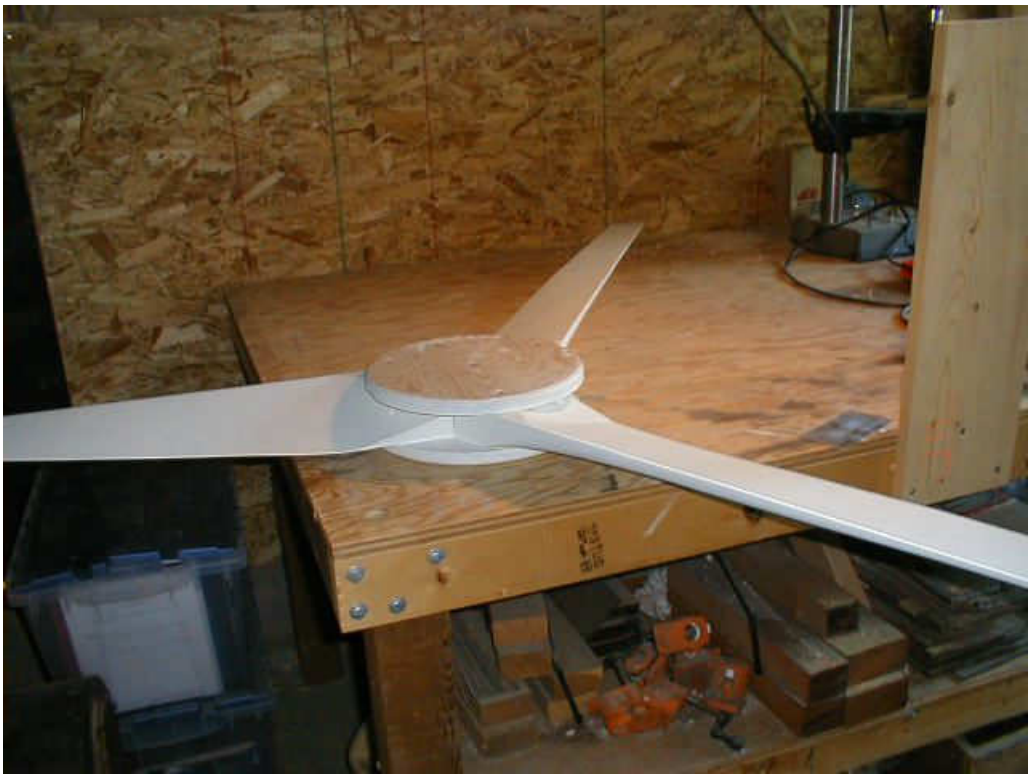
WARNING: While all aspects of building a windmill are important, this one is crucial. Without proper balancing, a wind machine will exhibit signs of instability, affecting performance and safety. An unbalanced blade can wear out bearings quickly, run noisily, stall out prematurely and even shatter.

There are several aspects to balancing wind generator blades. I prefer to have the rotating axis of the blades in the exact center of the circle described by the blades. This is relatively easily done by making each blade the same exact length and aligning them on the hub so that the tips of the blades are all the same distance from the center of the hub. It is necessary to measure the distance of the tips from each other, to make sure they are equidistant from the other blades as well. For a hub, I sandwiched the blades between two (exterior grade) plywood circles, ~11" in diameter.

NOTE: Balancing means adding weights somewhere. Initial testing showed that one of the blades was considerably heavier than the other two. This appeared to be the actual density of the wood, so I was stuck. I had to add a lot of weight to the other side(s). I decided that I didn't want to put holes in the blades themselves and so I purchased about 2 lbs of ¼" round lead fishing weight. This is like a ¼" string of lead spaghetti. I drilled ¼" holes in the plywood circles and epoxied lead spaghetti into the holes. In the photo below, the heavy blade is on the right. Note the numerous dots (the holes filled with lead) on the opposite side of the plywood circle. I used the setup shown below to finish the balancing. By spinning the blade and noting where it stopped, I was able to discover the heavy areas and compensate with lead on the other side.



Blades mounted in the makeshift-bearing shaft (really long nail) for dynamic balancing. Note the longer basswood planks against the wall for the next set of blades. (10' diameter planned)



View of the front of the blades up, showing the flat front side, curved backside and twist.

Step 2. Rewinding a fan motor to get a slow speed DC Generator

The electric power plant.

There are two types of generators that we can employ for our wind generator. In the automotive world, we know these as generators and alternators. Generators are properly known as dynamos. The main difference between them is that dynamos utilize a commutator to transfer power from the coils on the armature to the outside world. A commutator is a multi-part cylinder made of copper, which

allows the brushes to pull energy from the coils only when they are in one position relative to the magnetic poles. In essence, this allows you to "skim the top" of the electric cycles to produce DC. Usually, there is a commutator section for each slot in the armature, although there may be an additional slot. An alternator differs from this in that it has two slip rings instead of a commutator. The alternator produces AC current, which is then usually run through a set of diodes to produce DC.

From the searching you've already done, you are probably aware of how difficult it is to find a generator or alternator that generates an appreciable amount of power at ~300 rpm. How many rpms you need will depends on how many blades are on your turbine and how well they are designed and constructed, but 300 seems to be a good ballpark figure. So how is the search going? Find any 300rpm motors out there? I've heard that there are such motors out there being used for computer tape drives (big tape drives, small wind turbines) and battery powered floor washers (I've never seen a battery powered one myself). My own experience is that these things are rare. Most plentiful are auto and truck generators, alternators and fans.

The first thing to do is to wander around some junkyards and see what's available. Check out the nameplates for voltage, current and rpm information. You can check the state of bearings, but I would advise replacing these even if they appear to be OK. They are used and you're proposing to put several million more revolutions on them. If you find a generator, motor or alternator large enough, you may decide to go with it, even though it's rated at relatively high rpms. Now you have a problem you must solve before you can use it. For wind turbine use, you have to get the thing to generate a decent amount of power at a usable voltage at a relatively slow speed. It would be preferable that this be somewhere around 300 rpm or lower.

Lowering the rpms.

The motor/generator you have is rated at a certain voltage, amperage and speed. These are all tied in together and changing one of them changes the others. A generator rated at 12 volts at 1750rpm, will generate power above and below this speed, but will only supply 12 volts at or above 1750rpm. With a load that draws 12 volts, it will supply power to the load at 1750rpm and above, but not below. This is called the "cut in" speed for that voltage.

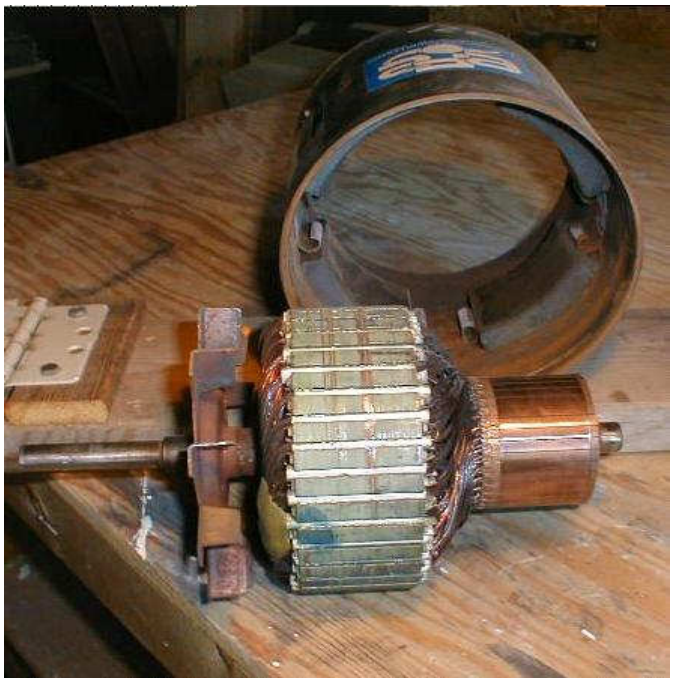
To change the cut in speed for a generator or alternator you can

1. Increase the field strength,
    1. Replace the magnets with stronger ones in PM generators
    2. Supply more power to the field coils in shunt generators and alternators. This may require replacing the field coils.
2. Increase the number of field poles,

    1. Replace the magnets with more magnets (in pairs) with the same flux. This may require resizing the armature coils.
    2. Add more field coils in shunt generators and alternators.
3. Increase the number of windings in the armature coils,
    1. More windings should give you more volts at a given rpm, all else being equal. You will probably loose power capacity if you have to reduce the size of the wire. Current is determined by wire size and since power (watts) = voltage x current (amps)... you loose if the current is reduced.
4. A combination of the above.

PM generator/alternators are preferred by wind enthusiasts. I've rebuilt one for slower speed and was able to do by replacing the magnets and rewinding the armature coils. Let's use that experience to examine this subject.

The motor I found was a model 7600 from Electric Fan Engineering. It was rated at 12 Volts, 50 amps and was a four-pole permanent magnet fan motor produced for heavy trucks. It had two rather noisy bearings, but ran very fast when connected to a 12 volt battery, or fairly slow connected to a 12 volt, 3amp battery charger - which was very hot after about 15 seconds of running this fan. I was able to get a reading of around 15 volts when running it off a 1725 rpm motor at roughly a 1-1 gearing. Calling EFE only gained me the information that it was rated somewhere around 2000 rpm. Below is a picture of the insides of this motor. The shell casing is ~8" in diameter (OD), although it isn't exactly round. Note the four large pole magnets inside the casing.



The photo doesn't show the brush assembly or the shell ends and bearings. The four magnets are ¾" thick and measure 2 ½ " deep by 3 ½ " long. The magnets are held in by double sided sticky tape and metal spacers. The entire motor weighed in at 45 lbs. The wire on the armature appears to be 15 or 16 gauge copper. It appears to have a rather complicated winding scheme which disassembling did little to demystify. I suspect that it utilized a frog leg-winding scheme, which is a combination of lap and wave coils. There were four wires coming from each commutator segment, completing two turns around 9 slots, giving a total of 8 turns (4 coils of 2 turns each). It was more complicated than this, but let's go with this simplified version to run through some calculations.

I did some quick calculations (see “Mick Sagrillo's paper.pdf” attachment), which gave the following for just rewinding and not adding magnets.

Volts	Amps	Watts	RPM	Wire Gauge	Turns per coil
12	50	600	1750	15	8
12	25	300	825	18	16
12	12.5	150	412.5	21	32
12	6.25	75	206	24	64

Since I had been really happy about finding a 600-watt motor, I was less than thrilled about putting all sorts of work into it and getting a 100-watt generator out of it. Now of course at higher speeds more power is produced, so this isn't 100 watts max. However, current is dependent on wire size and 24 gauge wire will handle a lot less of it than 15 gauge. It will have larger heat losses, especially at only 12 volts. So while this may generate 12 volts of power at +/- 200 rpm, it isn't able to supply the power the original motor/generator could, speed not withstanding.

Magnets 'r us

The other way of lowering the cut in speed is to increase the field strength and/or the number of magnetic poles. With shunt field type generators and some alternators, it is possible to increase the power to the shunt coils, resulting in an increase in the magnetic field and a corresponding increase in output from the armature coils. There is a limit to how much these coils can take without rewinding. So there may not be a practical solution here. PM motors/generators could use a change of magnet type, from ceramic to rare earth for an increase in field strength (flux). Sizing becomes an issue here, as most rare earth magnets

are quite thin (¼"), while ceramic magnets are fairly thick (½ " and up). It becomes necessary to build platforms for the new magnets to get them close enough to the armature to maintain a decent air gap between the magnet and the armature. It may be worth it but I'm not sure it will get a decent cut in speed if you leave the number of poles the same.

The other method is to increase the number of magnetic poles. A doubling of poles (of the same flux) should result in a corresponding doubling of voltage at the same speed or the same voltage at ½ the revolutions per minute. The following table assumes the same armature used for all the options and the same amount of flux for each pole. It also assumes that there won't be a problem with using an armature wound for 4 poles (**there is though! So keep reading**).

Volts	Amps	Watts	Revs/minute	Poles
12	50	600	1750	4
12	50	600	825	8
12	50	600	412	16
12	50	600	206	32
12	**50**	**600**	**354**	**20**

I won't get into motors with shunt fields. With PM motors/generators, to add poles it is necessary to remove the old magnets and replace them with the correct number of thinner (width only) magnets. If the magnets are less thick, then extensions of ferrous metal (Iron or steel) need to be used to keep the air gap close. In my situation, I chose to replace the four large poles with 20 smaller magnets. Looking on the web I found some 6" x ½" x 1" ceramic magnets at wondermagnet.com. Six inches was way too long, so I bought 10 of them and cut them in half with a radial arm saw and a ceramic blade. I set the blade to only cut into the magnets 1/16th of an inch and cut very slowly backwards. Most of the magnets broke cleanly in half while I was still cutting them. The few that broke at odd angles didn't bother me since I only needed 2 ½ " of length to match the 2 ½ " of armature surface. The difference wouldn't be a problem.

Lining up the magnets inside the motor housing, I measured and found a large air gap. The original magnets were ¾ " thick and were curved to fit the inner surface of the housing. These new magnets were ½" thick and were flat. I had hoped the lack of curvature would offset the difference in thickness, but I was wrong. There was only about a 1/32 " gain over the ½" thickness. This was remedied by cutting matching pieces of 3/16" x ¾" x 3" weldable steel bar and epoxying them to one face of each magnet.



I used slow setting (30 minute) epoxy to glue the steel bars to the magnets, after roughing the surface with emery cloth. It was then time to place the magnets and check the air gap.



Paper was used to space the magnets evenly before gluing. As can be seen in the photo above, there is no way to fit another pair of magnets into this housing. From a physical standpoint, 20 was a good choice. The original 4 poles were

placed so that the poles alternated every 90°. The brushes and armature windings were set up accordingly. So in order to have a chance of this working without rewinding the armature, there had to be a similar arrangement with the new magnets. This requires a number of magnets divisible by 4. I originally was thinking of using 18 poles since there were 37 armature slots and commutator segments. This would have probably lead to a bit more power for a given rpm, but would also have a stronger "cogging" effect resulting in poor startup. For better or worse, I glued in 20 magnets, making sure to alternate the poles. From a physical standpoint, 20 was a good choice. The original 4 poles were placed so that the poles alternated every 90°, with north bei ng 180° from the other north. The brushes and armature windings were set up accordingly. So in order to have a chance of this working without rewinding the armature, there had to be a similar arrangement with the new magnets. This requires a number of magnets divisible by 4. I originally was thinking of using 18 poles, but the 90° angle wasn't there. As it turned out, many of my thoughts on this subject and about not rewinding the armature were wrong.

Now just to confuse the issue, books on generator design refer to magnetic degrees. 360 magnetic degrees is from north to north or south to south. 180 magnetic degrees is from north to the nearest south or south to it's nearest north. The coils in a generator should span 180 magnetic degrees. In other words, from the center of one pole to the center of it's nearest opposite pole. See “mag-degrees” diagram attachment for clarification. When there were four poles, each coil spanned 90 physical degrees in order to span 180 magnetic degrees. With 20 poles, each coil would span 18 physical degrees. In the new configuration, the original four pole windings actually end up spanning 900 magnetic degrees, or 5 changes of pole type. When I put the 20-pole casing together with the four-pole armature, I was only able to get .5 volts by hand spinning the shaft and speed didn't change the reading. Trying to run it as a motor from a 12-volt battery resulted in no movement at all and a loud hum. This was not a good sign. It is apparent that merely increasing the number of poles is not sufficient and that the armature needs to be rewound to match the new pole configuration.

Step 3. Rewinding the Armature

As it turns out, my reasoning was flawed concerning the windings and number of poles. And I only state it here for the reader to NOT make the same mistake. According to the textbooks I was able to find, the coils should span 180 magnetic degrees, or from the north pole to the adjacent South Pole. By adding magnets, but not rewinding the coils, I was using coils meant for 4 magnets, and thus spanning 9 armature slots (37/4 = 9 and omit the remainder). This meant that each coil is now spanning 5 changes of polarity or 900 magnetic degrees. Turning the 20-pole generator without rewinding the armature yielded poor

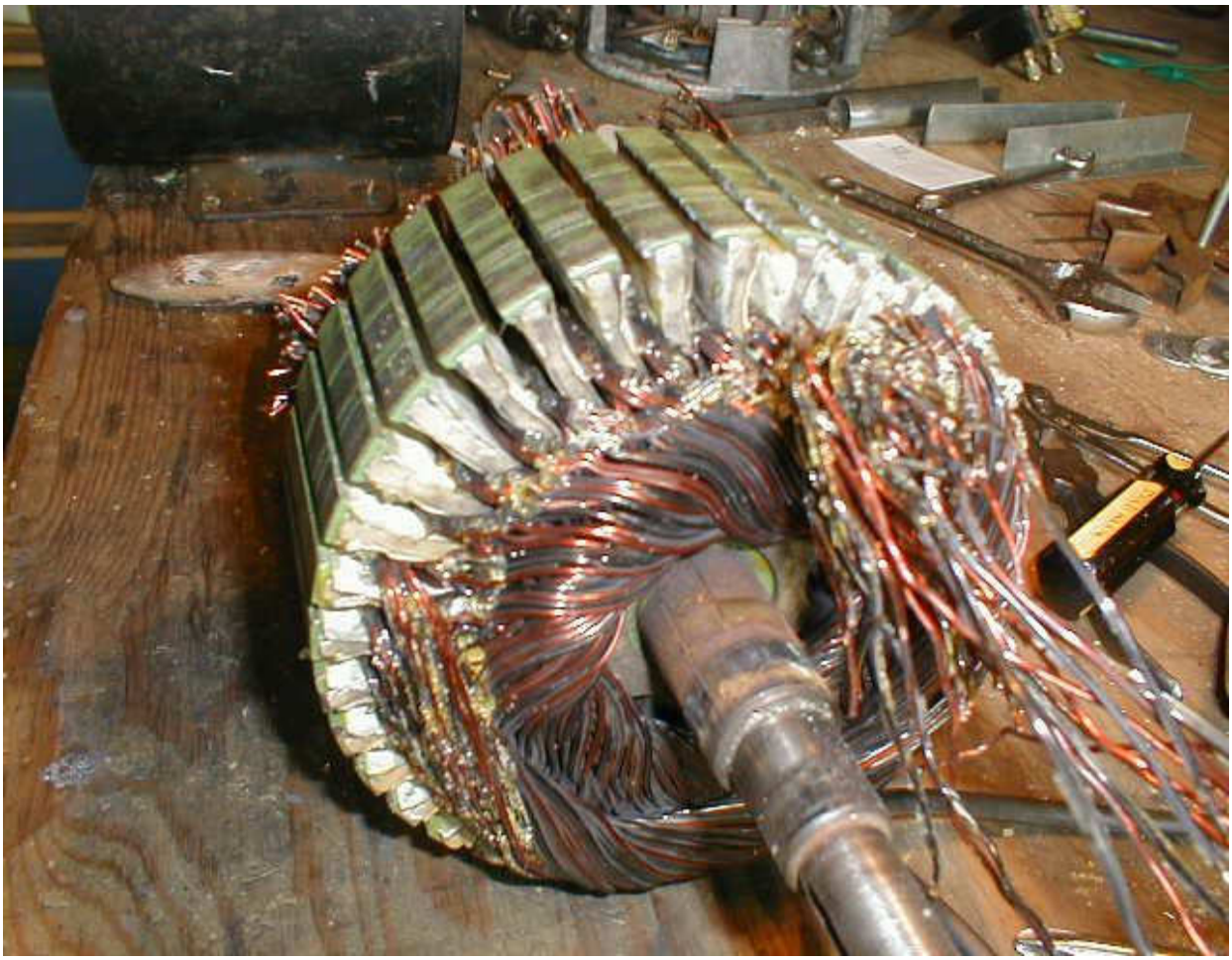
results. I thought it over, read a lot and decided I'd have to rewind the armature anyway.

A word about the steel spacers. I originally was going to put them facing the housing. However, in testing I discovered that the magnetic pull from the steel was considerable more than that from the ceramic magnet that it was glued to. I wanted that strength facing the armature. I also figured that if the air gap got too close, it would be easier to grind the steel down than the ceramic. As it turned out, the air gap is small, but when the casing is snugged up, the armature doesn't rub on the pole pieces.

Adventures in rewinding

Before attempting to rewind the armature, I went to the local university library and took out a few books. The best of these IMHO was *Electrical Machines, Direct and Alternating Currnet* by Charles S. Siskind (McGraw-Hill, 2nd Edition 1959). Reading this helped me visualize what I had to do.

To begin with, I had to strip the old wire from the armature. This is easier said than done. I had hoped to trace the path of the old wiring, but this proved difficult. The wires were heavy and were varnished in place, making for a physically challenging task. It took the better part of a day to pull all the wires from the armature and my right arm was stiff for days afterwards.



When it was finally stripped of all wire, it looked like this:



The stripped armature showing the large copper commutator and the armature slots ready for new coils.

Volts	Amps	Watts	RPM	Poles	Wire gauge	Turns/coil
Original - 12	50	600	1750	4	15	8
Assuming - 12	50	600	354	20	15	8
Maybe - 60 to 90	12.5	612.5 - 900	354	20	21	60

I left the plastic inserts in each slot to protect my own coils. I used the jig shown below to wind the new coils. I had no idea how many turns I'd be able to use and did a little trial and error before settling on 60 turns using 21 gauge wire. (I was

hoping 21 gauge copper wire would carry 10 amps or so at 60 to 90 volts retaining the 600-watt rating of the original motor at a much slower speed.) Revisiting the tables from above, I made some rash assumptions and postulated the following, which turns out to be rashly optimistic, especially the part about gaining, not loosing, wattage.

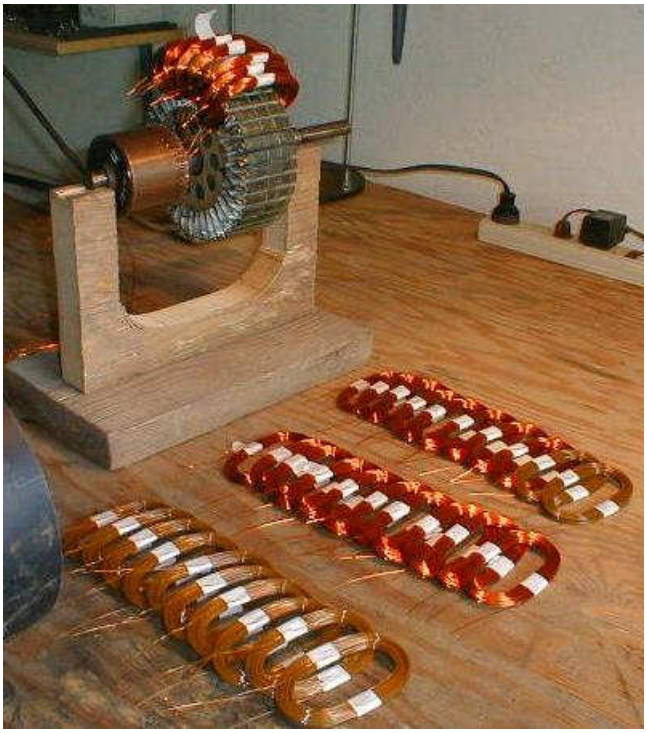
Only testing would tell if I was totally out to lunch. It turns out that I was way off.) See the “test results” in Step 5. to see how far off this expectation really was.)

In order to make 37 coils, I made the jig shown in the next two pictures. It is made from 1/8" masonite board, scrap 2x4 lumber, a few screws, a ¼" dowel and a bolt. Epoxy was used on the end piece only, since it had to be disassembled 37 times to extract the coils.





The motor serves only to hold the spool of wire. It isn't plugged in and does not run.



Here are two other photos of the winding jig. View 1 and view 2.

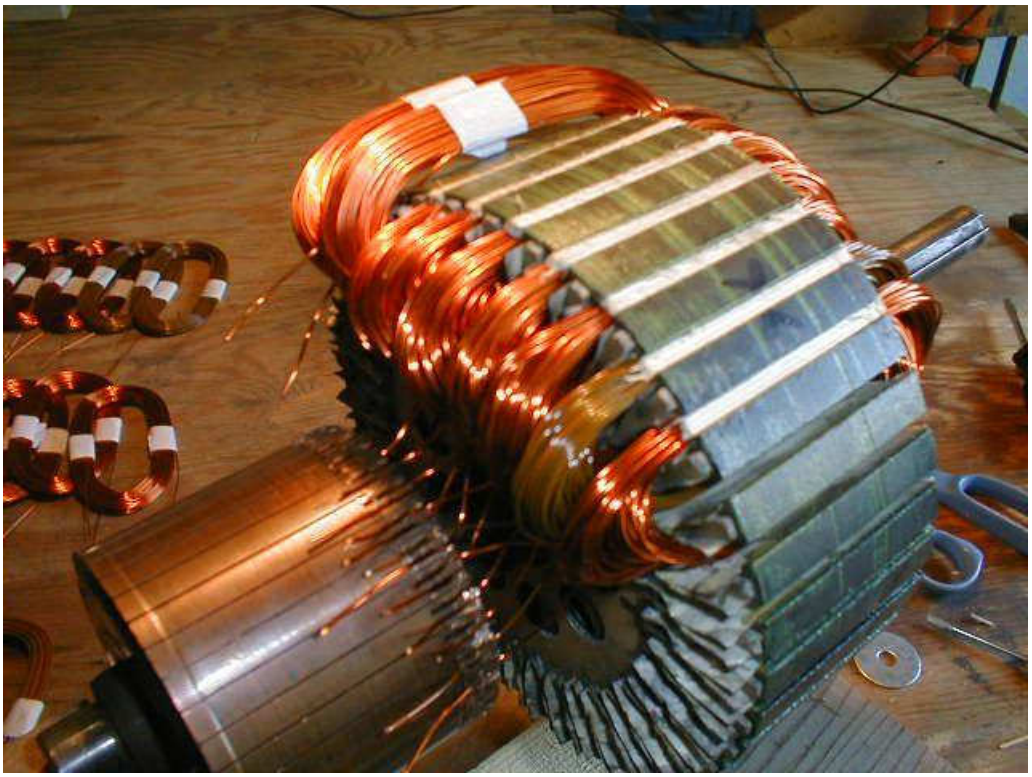




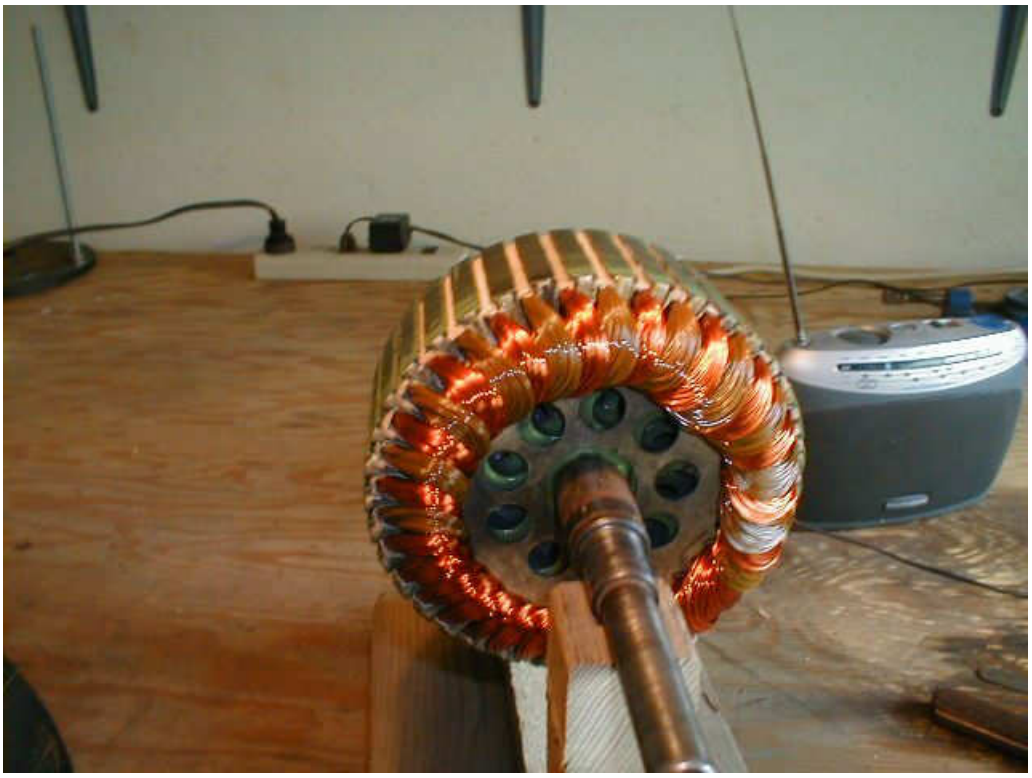
37 coils ready to be installed. Note the tape for holding the shape before installing. Each coil is 1/8" thick to fit into the armature slots. The tape is removed on installing so the wires can be moved around inside the slot. The coils are longer than the armature slots so they can go around each other.



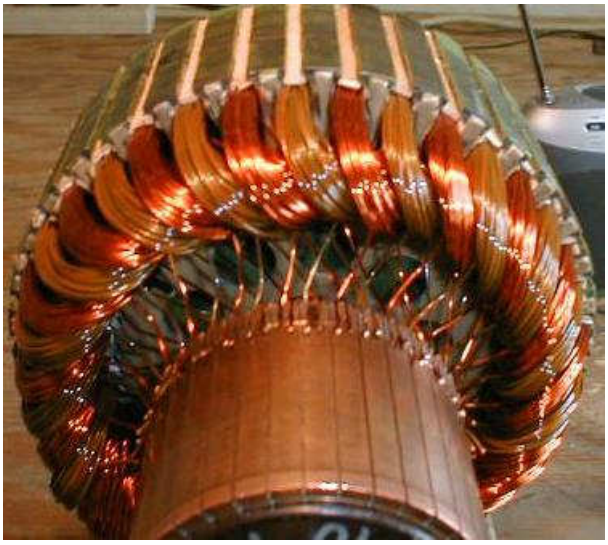
The first six coils, lower ends installed. Tape secures the coils until they are installed in the slots.



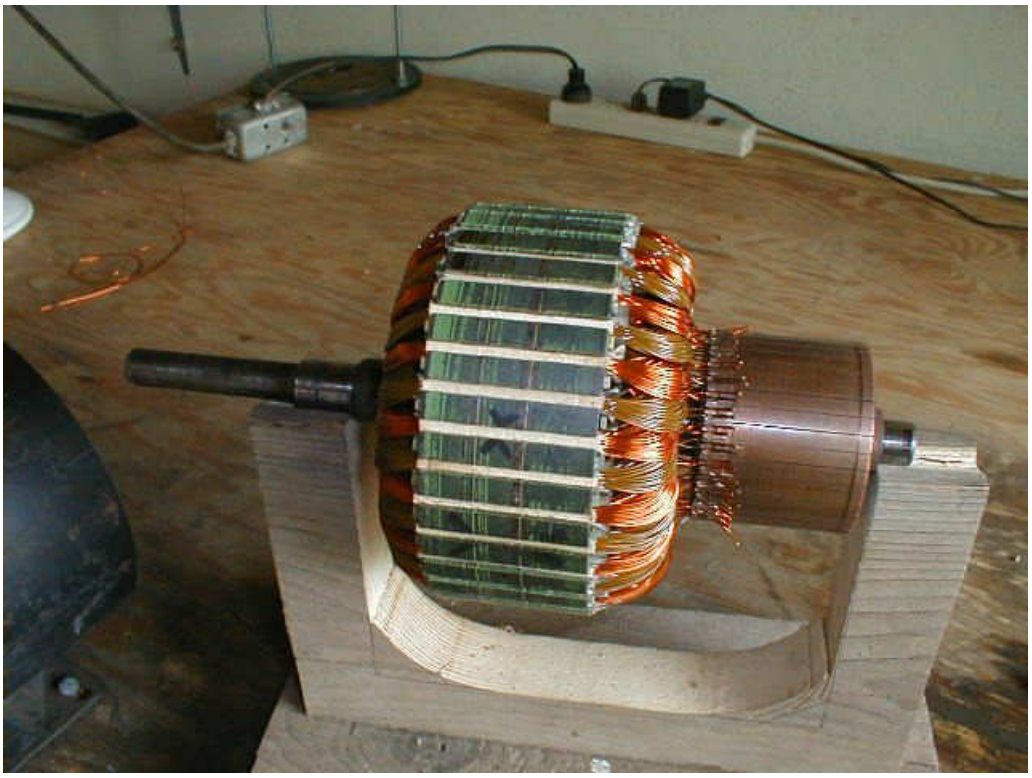
View showing that each coil skips a slot. Wood strips secure each slot. Each slot contains the front of one coil and the rear of another. Room must exist for the coils belonging to the slot in the middle to cross between the two coils.



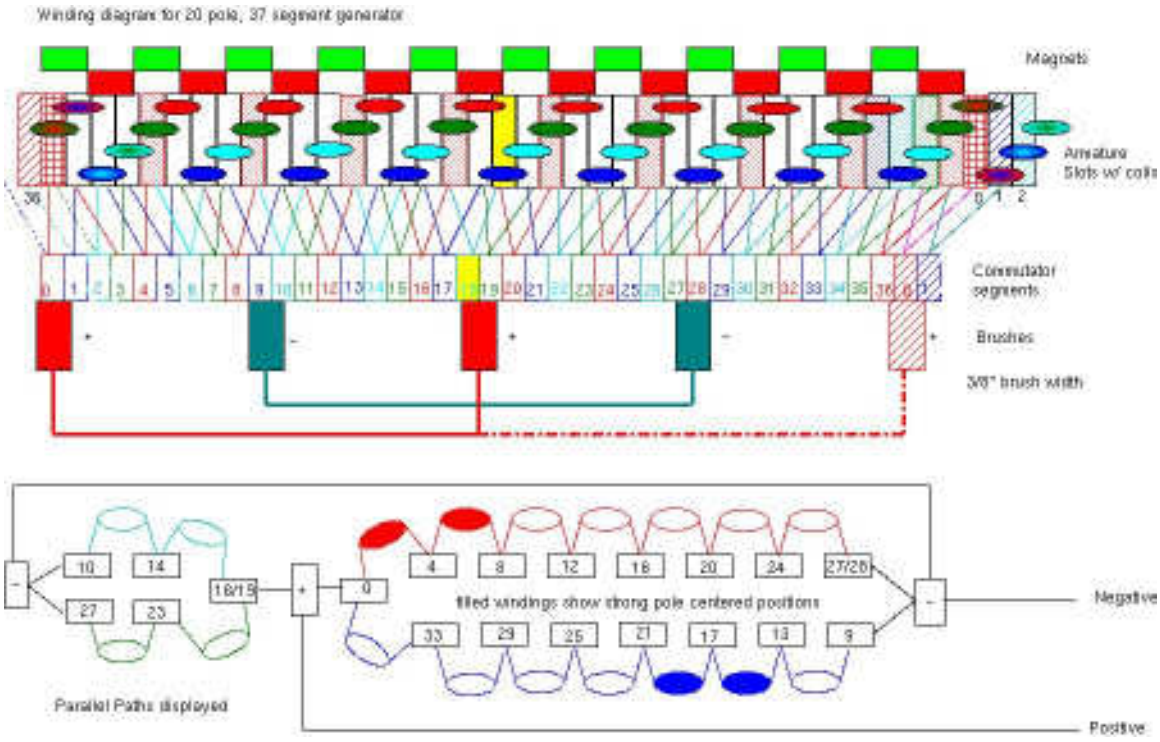
The semi finished backside of the armature. Note how the coils are bent over on each other to conserve space.



Commutator side of the armature, showing the connections to the commutator segments. There are two wires attached to each commutator section. When the last segment is connected, every segment is connected to every other electrically.



I used this wiring diagram to determine the pitch (spacing) of the wire ends.



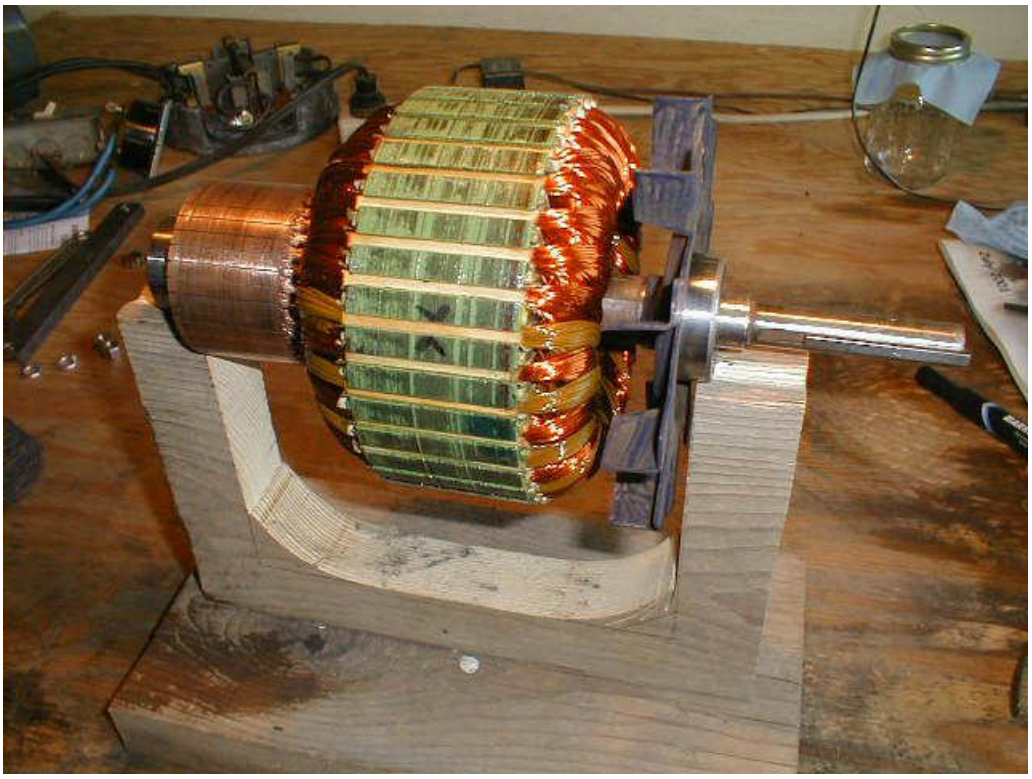
Side view before securing connections. The connections were secured by

pounding on the slots holding the wires with a nail punch. I tried soldering, but my heat source wasn't strong enough. Since the slots in the commutator sections originally held much larger wire (15 vs. 21 gauge) I wrapped the two wires together, pulled them through one of the two slots, and pounded a lot of brass to get a solid connection.

Step 4. Final touches for the generator.

Balancing the armature

The bearings and fan blade are installed onto the newly varnished armature. The coil ends have been secured to the commutator segments and it is ready for testing, however, the armature is slightly out of round and not particularly well balanced at this point.

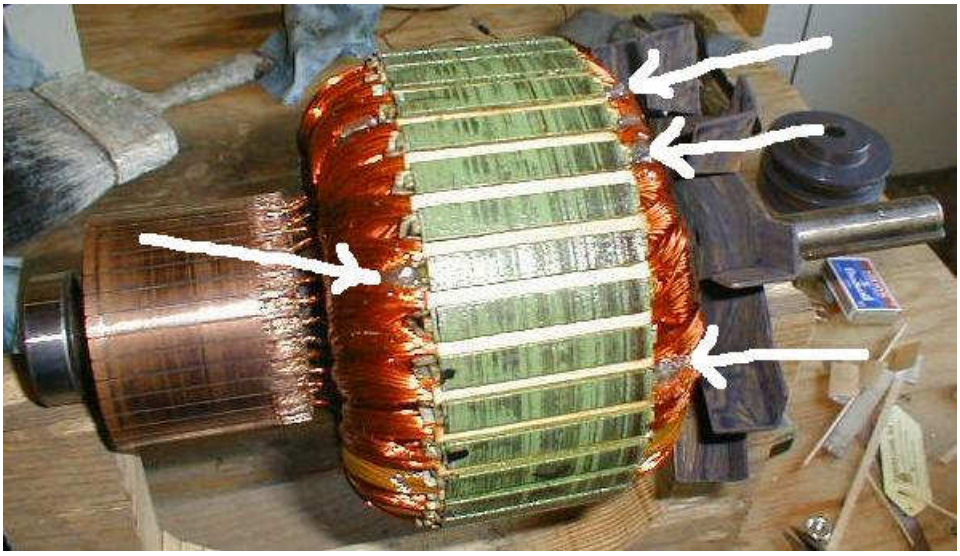


Testing

I installed the bearings on the armature and mounted it on my quickly assembled stand. Spinning it numerous times revealed that one side of the armature was heavier than the rest. It would consistently stop with this area on the bottom. At times it would stop in another position and then slowly roll backwards to its

favorite position, the heavy side down. Furthermore, tapping on the stand would cause a motionless armature to rotate towards the heavier side.

To counteract this imbalance, I cut and reshaped pieces of lead so I could wedge them into the gaps between the coils. I then placed them on the light side of the armature and spun it numerous times, refining my placement of the weights until I was unable to determine a heavy side. I then epoxied the weights into their proper positions.



The arrows point to places where lead has been inserted and epoxied into place for balance. With any luck, the balance is good enough to keep vibrations to a minimum and allow longer life for the bearings.

Grinding those magnets

In installing the armature, I discovered a slight bit of rubbing between the armature and the iron magnet extenders. I knew that it was a very small air gap and so was not particularly surprised. I looked around my workshop and found an old 7" abrasive disk that had worn down to a 6 $^{1}/_{8}$" diameter. Mounting it on a ½" mandrel gave me a means of reaming out the inside of the casing and shaping the magnets to a circular inner face. With the armature outside diameter being 6", the 6 $^{1}/_{8}$" disk would give me an air gap of $^{1}/_{16}$", which is still close but shouldn't rub.

I mounted the disk on the drill press, secured the shell securely and spent the next 3 hours slowly reaming out the magnets. I set the drill press to 700 rpms and proceeded very slowly to avoid heating the magnets beyond "warm to the touch". This was to keep the epoxy solid and to keep the magnets strong. In retrospect, it was wise to put the iron spacers on the inside rather than between

the magnets and the shell. I would not have wanted to be grinding directly on the magnets.



View of the grinding process. Note that the case is not entirely round, nor are the thicknesses of glue, magnets and iron bar all uniform. This results in uneven results when grinding. Some bars are shaped across their entire face, others are untouched. It should result in a more uniform air gap however.



A view of the finished product of grinding. Note that the left and right (of the photo) bars have been fully ground across their faces. The upper bars are only partially ground. Before assembly the iron filings, which fill the gaps, were removed from between the magnets.



The generator shown assembled for testing. The threaded bar holding the ends together is not original. The original motor had two long bolts that connected the ends inside the case, passing between the pole pieces. With the new magnet arrangement, there is no longer any space between the poles. Luckily, the faceplate is oversized and has tapped holes I was able to use for the new exterior straps. Note the small 12-volt battery in the background. The original motor turned very fast when connected to this battery, in fact it jumped when first connected (bolt that thing down first!). When rewound, connecting to this battery resulted in 160 rpm clockwise and ~240 rpm counter clockwise. Results are shown in a table below.

Method	**Rpms**	**Voltage**	**Stage of completion**
12 volt battery	~1700	12	Original state as from junkyard
Hand spinning of shaft	0 to 160	< 1	Original state as from junkyard
12 volt battery	Would not turn	12	20 magnets, original armature
Hand spinning of shaft	0 to 160?	0.5	20 magnets, original armature
12 volt battery	160 clockwise	12 (2 amps)	20 magnets, rewound armature

Method	Rpms	Voltage	Stage of completion
12 volt battery reversed polarity	~240 counter clockwise	12 (6 amps)	20 magnets, rewound armature
Hand spinning of shaft	0 to 160?	Up to 14	20 magnets, rewound armature

Tuning the brushes

Because this is a generator with a commutator, the positioning of the brushes in relation to the poles is critical. This isn't the case with alternators, but this is what I have and it needs to be adjusted properly. The following is the process I used to determine the best placement for the brushes.

Below is the very simple setup I used for hand turning the shaft. I used a 9" pulley to give me enough leverage to give it a good spin. At each setting (shown in next photo) I gave the pulley a strong clockwise spin and observed the bounce of the voltmeter needle. I rather arbitrarily labeled one of the leads from the generator + and the other - for testing purposes. I connected the "+" lead to the "+" lead of the voltmeter and likewise with the "-" lead.



Once the generator was assembled, it was necessary to adjust the placement of the brushes in relation to the magnets. This was done by turning the rear plate (which the brushes are attached to) in relation to the shell casing (which houses the magnets). This yielded some very interesting results. The back plate of the generator is shown below with markings on the tape relating to the voltage I was able to generate by hand turning the shaft. I tested turning both clockwise and counter clockwise. The voltages for clockwise are shown on the top of the tape. The counter clockwise readings are shown on the bottom of the tape. The polarity of the leads was kept the same for this test.



It should be noted that when in the 14-volt position, it was relatively easy to turn the shaft clockwise and difficult to turn it counter clockwise. As the adjustment was moved further to the right it became more difficult to go clockwise, but became easier to turn the shaft counter clockwise. The results are shown in table form below.

Position from left	**Clockwise voltage**	**Counter Clockwise voltage**	**Clockwise torque required**
1	9	- ?	Some resistance
2	14	- ?	Easiest

Position from left	Clockwise voltage	Counter Clockwise voltage	Clockwise torque required
3	9	2	Some resistance
4	5	5	More resistance
5	- ?	7	Hard
6	- ?	9	Very difficult
7	- ?	7	Hard

From the standpoint of being spun by a relatively small force, like the one my 7' three blade rotor will produce in my light wind area, it would appear that the 14 volt setting would be the most likely to give decent results. Still, I needed more information.

Motoring

I hooked up an ammeter, switch and battery to the generator in series to find out more. I loosened the straps holding the rear plate (and the brushes) so I could turn the brushes while motoring the generator. I read the ammeter (which had a scale of 1 to 10amps) while motoring and turning the rear plate. The voltage is coming from the battery, which we will assume is 12 volts, although the voltmeter says 13.5VDC when I test just the battery. I discovered that there is a range of position (shown around the 14V mark on the tape) where the speed when motoring appears fairly constant near 160 rpm. Within this range, the current draw and noise does change but only slightly. It appears to draw the least amperage (2 amps) and run quietest at the left side of the range.

At the right side of the range it draws 3 to 3 ½ amps and sounds coarse. It gets louder, slower and draws more current as the plate is moved to the right out of the range. Moving the plate further left results in a rapid increase in speed and current draw up to about 240 rpm (6 amps). Turning even further than this pegs the 10-amp ammeter and causes the speed to slow, stop and then reverse.

There is a slight ¼ to ½ amp bump that occurred throughout the test, which was smallest when the draw was 2 amps.

Testing with a fan and the final placement of the brushes

OK, so there've been all sorts of tests, but what really can be used to determine the best placement of the brushes. That would be the place where the most power is generated with the least amount of power input. The only way to determine that is to put a measurable load on it and spin it. Since I was limited to hand spinning at low speed (under 100 rpm) I had to find a really light load that I

could measure visually. I found it in a spare wafer fan. Wafer or muffin fans are the small flat fans used in computer cases. They usually are rated for 12 volts. The one I had showed a rating of 12 volts .2 amps. I don't know what speed that was rated for and I really don't care.

I hooked up the fan and spun the generator. The fan didn't spin so I reversed the leads and spun the generator again. This time the fan spun quickly, even with just a partial turn. I had found my final test. I knew where the most efficient motoring position was, and I knew the easiest spinning position. They were the same place, which was where it was set now. I moved the brushes each direction to where more amperage was required and spun again and again, watching the movement of the fan each time. Each time it took more force to move the fan less than it had at the original position. This confirmed that the most efficient motoring position was also the most efficient generating position. It was also the quietest operating position in both modes. So now I know that this is the most efficient placement for the brushes. I have it adjusted optimally for generating.

Step 5. Test results on rebuilt generator

In order to go from complete guessing to actual planning, I had to run the generator at some known speeds and discover what the output was, at least in voltage at various speeds. The following picture shows how I did this. I secured the generator facing up and used 2" and 2 ½" pulleys on my drill press. Knowing what speed the drill press was running at allowed me to calculate the speed of the generator shaft using 2 ½", 9" and 10" pulleys on the generator. The setups, speeds and results are shown in a table and graph below.

Predictably, after 25 years of great service, the spindle of the drill press chose this day to seize up. A few minutes disassembly time and some oil fixed the problem. Results are shown below.



The test setup for finding voltage at various rpms.

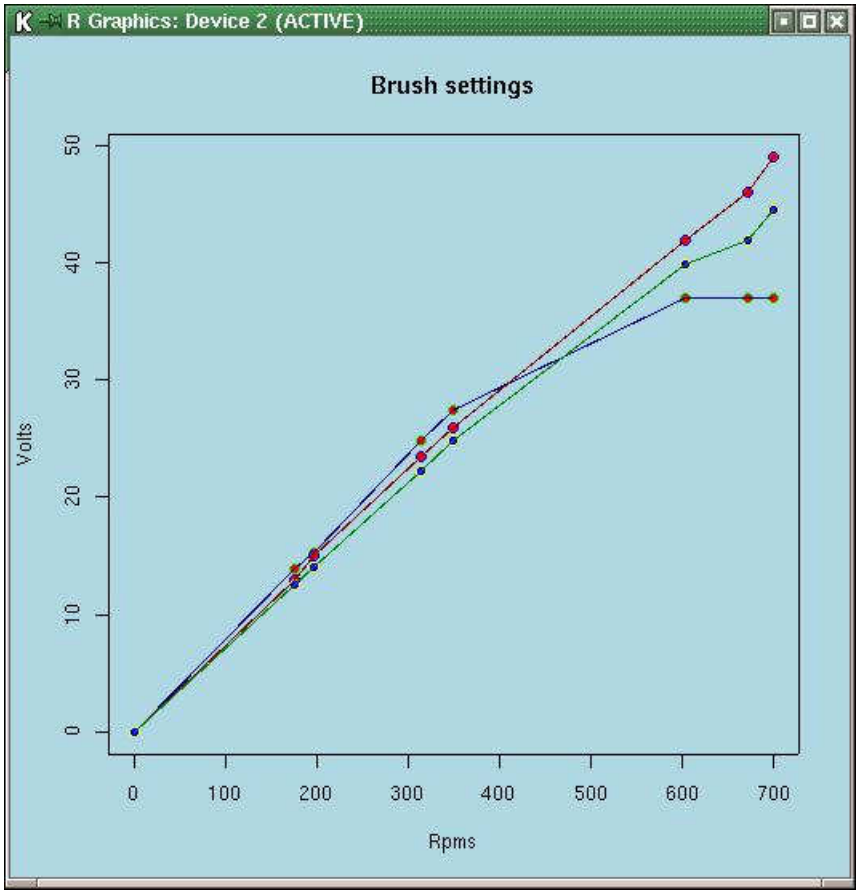
The following table shows the results of this testing. The three positions (pos 1,2 & 3) are slightly different positions of the brushes in relation to the magnets. Although the positions are not all that different from each other, there are marked differences in performance.

RPM @ generator	Voltage pos. 1	Rpm/volt pos.1	Voltage pos. 2	Rpm/volt pos. 2	Voltage pos. 3	Rpm/volt pos.3
132	9	14.7				
146	10	14.6				
176	12.5	14.1	13.9	12.7	13	13.5
196	14	14	15.3	12.8	15	13.1
236	16	14.75				
260	17.9	14.5				
314	22.2	14.1	24.8	12.7	23.5	13.4
350	24.9	14	27.5	12.7	26	13.4
452	29.5	15.3				

RPM @ generator	Voltage pos. 1	Rpm/volt pos.1	Voltage pos. 2	Rpm/volt pos. 2	Voltage pos. 3	Rpm/volt pos.3
500	32.9	15.1				
603	39.9	15.1	37	16.29	42	14.3
672	42	16	37	18.2	46	14.6
700	44	15.9			49	14.3

The rpm/volt ratio suggests that this generator is most efficient below 450 rpm no matter where the brushes are placed, but is better in the latter two test positions. I could get more volts for lower rpms in the second position, but the generator sparked dramatically and had a loud whining sound I didn't like. In addition, the sparking became so violent it appeared to hamper voltage flow into the brushes above 600 rpm. I backed it off slightly and settled for the values shown in red above (#3).

The graph below shows extrapolations based on the speeds tested during testing. The colors of the lines match the colors in the table above



The green line indicates test position 1. The blue line indicates test position 2. The red line indicates test position #3, (which is the position I chose to go with. It is the closest to the straight-line theoretical output, and sounds the best.)

NOTE: It should be noted that had I converted this to an alternator by installing slip rings and removing the commutator, I would not have had to do any adjusting of the brushes, although I would have had to change them to match the slip rings. Dynamos are fascinating devices, but are quite complex compared to alternators.

It would appear that as far as speed goes this rebuild was a success. The cut in speed went from 1700 +/- rpm down to 162 rpm for 12 volts. It would appear that it will now generate some usable voltage at wind turbine friendly speeds without gearing.

Matching this generator to the 7' rotor and low wind conditions

The rotor I built was per Hugh Piggott's specifications. His math is better than mine, so I'll refer you to his "Wind power Workshop" book pages 148 and 149. The math is all there. Assuming a 3-blade 2-meter (6.5 feet) diameter rotor with a

tip speed ratio of 6, in a 10m/s (22 mph) wind we can get 573 rpm from our rotor with 283 watts of available power. But a 3 m/s (6.7 mph) breeze it will only get us to 172 rpm with only 7.6 watts of available power. Looking at the tests for the generator, it is possible for it to generate some power at 3m/s using these blades. Not much, but it's something.

Now the site I'm looking at is in the western plains of Texas (see below). In the fall and spring and when storms are moving around, there can be some pretty hefty winds, however during most summer days it is semi calm with occasional slight breezes. During the evenings there is usually a small breeze. Over all it is a better site for photovoltaics than wind turbines. Checking the graph above, I see that I could get power from this generator for a 12-volt load above 168 rpm. If I use more than a 12-volt load I won't get much power out of this generator during a good part of the summer. Small though the power generated may be, trickle charging beats not not charging at all. Plus there's all those solar panels I'll be installing, right?



Counting the cost

One reason many people want to build a wind generator is to save money. While that may have originally been one of my concerns, it isn't any more. Not that I'm

rich, but I've become convinced that unless your time is worth absolutely nothing, you will not save much money building your own wind generator.

However, to be fair, I've decided to put into print what I've spent on this little gem. I won't include most tools since they can be and are used for other things. I also won't include parts that I've had laying around that get used. If you don't have these things at hand, it'll cost you something, even if it's just scrounging time. If you have a history of "doing it yourself" then you have at least some of what you need on hand.

Item description	**Cost in $US**
Books by Hugh Piggott (required reading)	$40.00
Baswood for 3 - 3.5' Windmill blades	$50.00
¼" Lead wire for balancing blades	$3.00
Heavy duty truck fan, used	$20.00
Magnets - 10 ½" x 1" x 6"	$40.00
Bearings (2)	$6.50
Wire - 5 lbs of 21 awe copper - used about 4 lbs	$25.00
Digital tachometer (for testing)	$30.00
Total Cost	**$214.50**

Step 6. How to regulate speed in excessive winds?

Furling and Shutdown Systems

- **Furling Systems--**We use the term "furling system" to describe a mechanism that turns the wind generator rotor at an angle out of the wind, either horizontally or vertically, to protect the machine from damage during high winds. Ideally it will keep power output levels near the maximum even when fully furled. Our early wind turbine designs didn't use furling systems, and I feel fortunate that some of them are still flying. A wind turbine that furls is also much more gentle on your tower and guy wires--

the force on an over speeding wind turbine increases as the wind gets stringer.

There are a variety of furling system designs:

- **Variable Pitch--** An ideal but extremely complicated solution is to use blades which change pitch depending on the wind speed....these also have the advantage of keeping power output at the most efficient point for the current wind speed. During low winds, the blades are pitched for best startup. In higher winds, they rotate and adjust shaft speed to the ideal RPMs for the generator. In extreme winds, they turn the blades even further to protect the unit from damage. The problem is the complexity of making a system work reliably...but it can be done! Large commercial wind generators use this system exclusively, as do antique and modern Jacobs turbines, and some old WinChargers.
- **Tilt-Back--**In these designs, the generator body is hinged just behind the nacelle. When wind speed gets too high, the entire nacelle, hub and blade assembly tilts back out of the wind to nearly vertical. As the wind slows down, it returns to normal horizontal operating position by either springs, wind action on a tilted tail, or a counterweight. Commercial wind generators that use this method are the old Whisper models (from before the buyout), the Windstream, and many homemade designs.
- **Furling Tail--**The generator is mounted off-center horizontally from the yaw bearing. The tail is also angled in this axis. The tail is also angled in the vertical axis, and hinged. When the wind force back on the rotor is strong enough to overcome the off-axis generator making it want to yaw and the angled tail trying to keep it from yawing, the tail folds up and turns the alternator away from the wind direction, forcing the wind turbine to yaw out of the wind. When wind speeds drops, the tail is returned to normal operating position by gravity, or springs. Many commercial and homemade designs (including mine) use this system, and it has proven to be very reliable.
- **Folding Vane--**Similar to the furling tail, but the tail boom is fixed, with a hinged vane underneath. Used on some older Winchargers and homemade designs, the disadvantage is that tail and vane are more highly stressed from wind force during furling, as they still are sticking out there in the gale.
- **Flexible Blades--**The theory is that the blades flex both back toward the tower and around their main axis, and therefore protect themselves from over speeding. It does work if the materials and details are correct...for example, the blades must not flex back far enough to hit the pole, and they must withstand flexing during cold

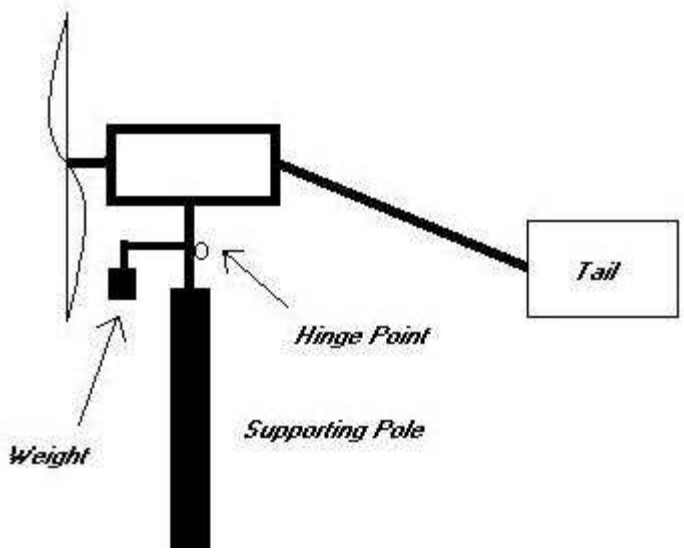
weather too. The popular Air 403 and new Air X from SouthWest Wind power use this system for furling. One problem is that it is noisy....in fact the Air 403 is noisy even in gentle 15 mph winds, BEFORE it starts producing power. The Air X has some fancy electronic circuitry to reduce noise.

    - **Air Brakes--**Noisy and full of vibration, but they do work. Older WinChargers used this system. Metal cups extend from the hub from centripetal force during high winds, and noisily slow the machine down; they retract back into the hub when the wind slows.

- **Shutdown Systems--**This is a manual control that completely shuts the wind generator down. It is not allowed to spin at all, and should be able to survive extremely violent winds in this condition. It can be electrical or mechanical.
    - **Electrical Shutdown--**With permanent magnet alternator machines, simply shorting the main AC power output leads together should effectively shut down the wind turbine. The problem is that when the machine is spinning at high RPMs during a windstorm, the shutdown may be either impossible electrically (the turbine is performing too inefficiently for shorting the output to have any effect), or too damaging to the alternator (the heat produced in the stator coils by shutdown at high speeds turns the coils into molten slag.) The normal method is to simply wait for a space between high wind gusts to short the mill with a switch. This method has successfully shut down turbines while putting 30 amps into 12vdc...numerous shutdowns at 10-20 amps of output have caused no vibration or problems. You can use a manual switch, or simply a shorting plug to do this.
    - **Mechanical Shutdown--**These systems physically brake the wind generator, or force it out of the wind by turning the tail parallel to the blades. Even the mighty Bergey Excel 10kW wind turbine has a mechanical crank for emergency shutdown. Generally, a cable is attached to a hinged tail, with a small hand winch located at the bottom of the tower for the operator.

Furling

The best way I found was the "furling tail" arrangement, consisting of mounting the prop a bit to the side of the vertical axis of the mounting pole, say a few inches. This produces a bit of a turning force on the whole unit, but of course the tail is mounted in the normal manner, aimed just a bit to the other side if necessary, producing the same amount of force the other way.



The key is to make the tail boom "break away" when enough of a turning force is present on the unit because of high winds. The prop then turns to the side of the vertical mounting pole, which it pivots on and no longer faces the wind straight on. The tail also turns and the effect is to fold the prop and the tail together.

Some sort of hinge and spring arrangement would probably suffice. You can also mount the hinges at an angle off of vertical, say 30 degrees, so that whenever the tail moves to the side it also moves up at that angle. That makes the weight of the tail itself provide the "springing" action. Of course the angle has to be adjusted depending on the weight of the tail, offset of the prop axis, etc., but this is doable and reliable.

Regulation

- With battery-charging wind generators, regulation of the incoming voltage is accomplished by the battery bank itself, *until* it is fully charged. Though a PM alternator or DC generator's open-circuit voltage might be 100 volts, the battery bank keeps the wind generator circuit voltage at its own level. Once the battery bank fills, system voltage will rise rapidly and something must be done with the unneeded incoming power. Simply disconnecting the windmill is *not* an option--a windmill allowed to 'freewheel' will quickly blow itself up from over speed. The power must be diverted into some sort of load.
- **Turn on Some Lights! --**This is the oldest, simplest and most reliable method of regulation. Problem is, you have to be there to do it. But by turning on house lights, heaters, etc. that more or less equal the extra

power coming in, you prevent the batteries from overcharging, keep a load on the windmill and keep your system voltage in the normal range.

- **Shunt Regulation--**These systems simply sense the battery voltage and divert all or part of the incoming wind power into heating elements (known as a 'dump load'), thus keeping a load on the windmill while ceasing to charge the batteries. The very simplest solution is a manually thrown switch that disconnects the incoming power from the batteries and connects it to some heating elements...just keep in mind the voltage requirements of the heaters must be a good match to the alternator for braking to occur. Simple systems that divert all the incoming power at once can be built using Trace C-series charge controllers or relays and voltage sensors. More complicated systems use power transistors or pulse width modulation to divert only part of the incoming power, or the entire amount, as charging needs require. Both Home Power Magazine and Hugh Piggott's Website have plans and schematics for building shunt regulators. Some commercial solar charge controllers can be set to function as dump load controllers, like the Trace C40. A controller intended only for solar power will NOT function with a wind turbine, nor will an automotive voltage regulator.
- **Diodes--**A permanent magnet DC generator (such as a surplus tape drive motor) does need a diode in the line--otherwise, the battery bank will simply spin it as a motor. The diode should be rated for higher amperage than the maximum output of the motor, and must be well heat-sinked.
- **Bridge Rectifiers--**Since alternators make AC power and batteries need to charge with DC power, conversion is needed. This is accomplished with bridge rectifiers, which are simply an array of diodes. For single-phase alternators, standard bridges with 4 diodes are used. The biggest bridge that's commonly available at a reasonable cost is 35 amps--for larger wind generators multiple 35-amp bridges can be hooked in parallel to give greater power handling capacity. The bridges must be well heat-sinked to a large piece of finned aluminum or steel. Three-phase alternators need rectifiers that use 6 diodes in an array...these can be scavenged from old car alternators, or built using 6 large barrel diodes.

Building a solar electric system

My entry into solar energy came as a direct result of my interest in wind energy. I started building a wind generator and purchased batteries so there would be something for it to charge. Then I ended up getting some solar panels because the wind generator wasn't finished. Learning more about how not to ruin batteries led me to purchase a charge controller. Then I had to get an inverter to be able to use all this energy. In the mean while I had to get a tower for the wind machine, install it, get the right kind of charge controller for it, get a diversion load for it, and so it seems to go on forever. It's a fun, if rather involved, hobby.



The 24-volt battery bank. Weighing in at over 3000 lbs. These are lead cadmium telco UPS batteries. They are not meant to cycle more than 15% from full charge.



The PV combiner box and solar boost 3048 charge controller. These carry 48volts from the PV panels.



The Main disconnect box - 175 amps at 24 volts DC, and the 2.5Kw 24vdc/120vac inverter. This begins the 120-volt AC side of the system.



Here is the overall view of the system. The PV panels are outside the building on the left side. The wiring enters the combiner box and is fused with a 10-amp fuse per panel pair. A single pair (plus ground) leaves the combiner box and goes to the charge controller. 48 volts from the PV panels is converted to 24 volts and sent to the batteries via a 35 amp dual disconnect switch. The charge controller makes use of a temperature sensor connected to a battery terminal. Note that all wiring except for the shielded 2/0 gauge wiring to the large Disconnect box and the system ground is in conduit.

This concludes the Windmill construction. It's still necessary however to build a tower to support your turbine. Because there are many different types and styles of towers for many different locations I will not cover this here. See my booklet "How to build a Home Wind generator for the average hobbyist", to get an idea. In the end however the tower size and design will be decided by you and your location.

I hope you enjoy these plans, and we wish you all the luck and fun in your construction.

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