A WIND TURBINE RECIPE BOOK

THE AXIAL FLUX WINDMILL PLANS

WITH THANKS TO ALAN BUSH, DAN BARTMANN, LES VINCENT (aka Flux), AND COUNTLESS OTHERS WHO HAVE INSPIRED ME.

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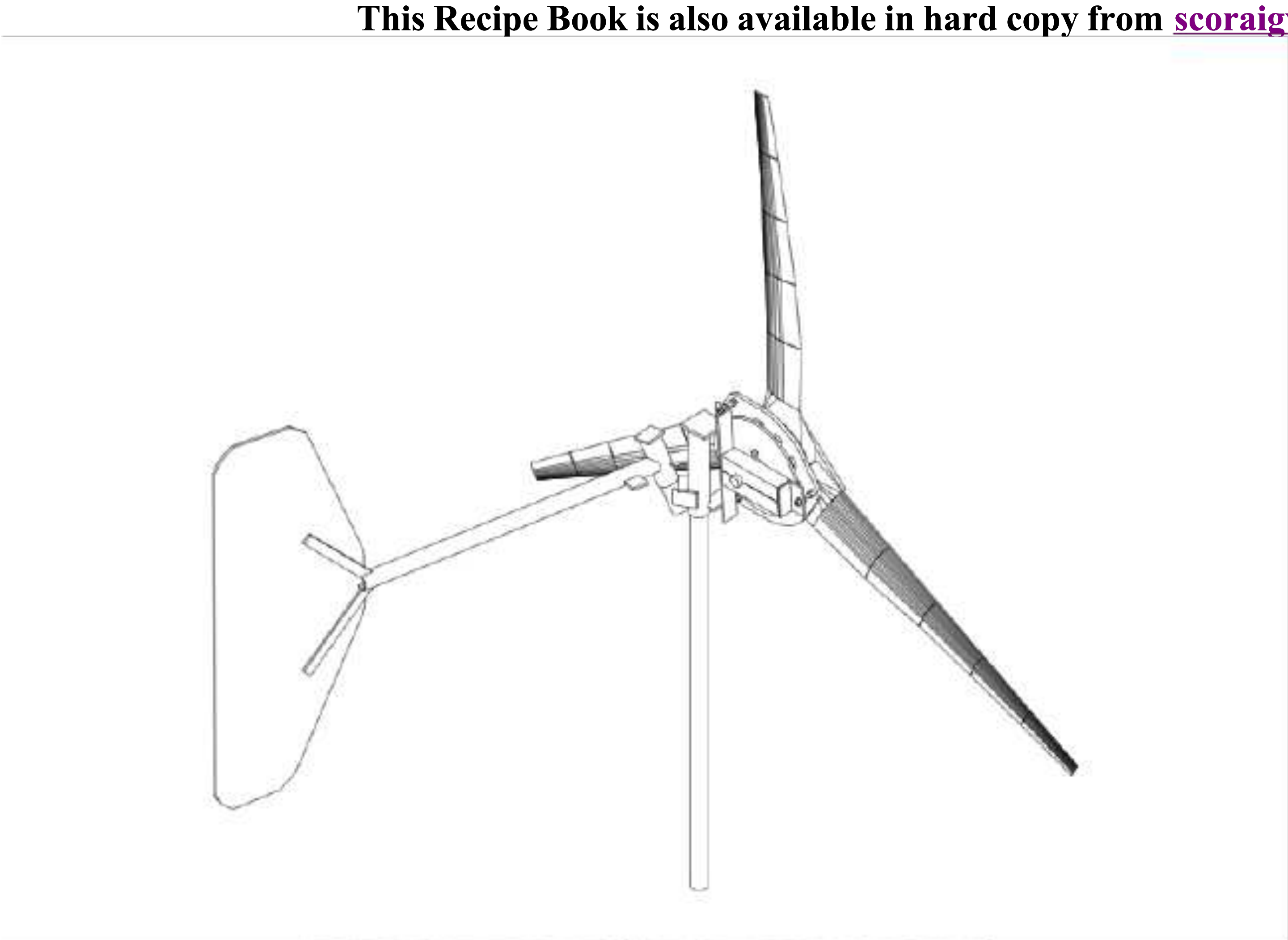

METRIC EDITION

THIS BOOK

This is the 2014 edition of my 'Axial Flux Windmill plans'. I describe how to build 6 different sizes of wind turbine.

There are several sections of general interest, but most of the book is very specific to the stages of construction, and has dimensions for each size of turbine tabulated alongside diagrams and text. At the back you will find a set of basic drawings of the four main types of head for the turbines.

I recommend looking at my web sites http://www.scoraigwind.com (especially the diaries of the courses) http://www.scoraigwind.co.uk and also my YouTube videos for more ideas and visualisation of the designs.

This book is all metric (dimensions in mm) but I have also produced a separate 'English' version with dimensions in inches, AWG wires sizes, and using the 2" x 1" x ½" magnet blocks that are common in North America. I strongly recommend you use the right book for your magnets.

Have fun! Hugh

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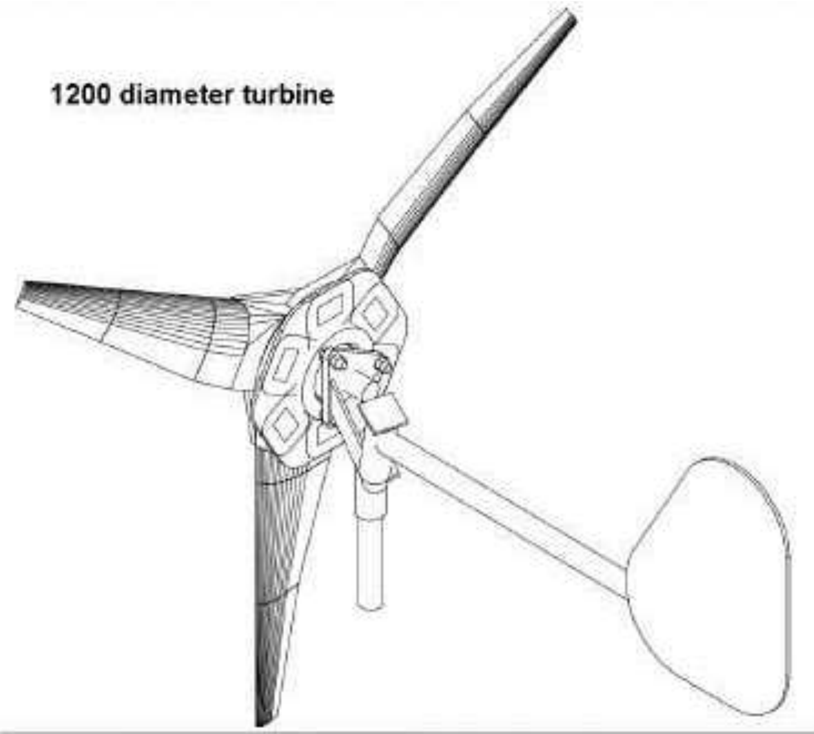


The title page shows the general arrangement of the 1800 – 3000 metre diameter turbines.

Choosing what to do

Be safe!

There is plenty of scope for hurting yourself or others when building and operating small wind turbines. You follow these guidelines at your own risk! I am not going to fill this manual with all the safety notices and disclaimers that make many manuals unreadable. But I will point out the main hazards up front.

In my experience, most people hurt their fingers when handling magnets. In some cases I hear that they lose fingers. Treat the magnets with respect and never leave magnets or magnet rotors lying around loose.

Wear protective clothing where it helps safety – for example when grinding metal you should always use eye protection. All workshop activities have a degree of danger if conducted carelessly or with ignorance. Take care to learn how to use your tools.

Batteries are particularly hazardous items. They can deliver a lot of energy in the event of a short-circuit, causing burns or fires. They contain explosive gasses that can spatter acid in your eyes if ignited by a spark. They contain lead that is a persistent toxin and a backbreaking weight to lift.

Erecting towers can be deceptively tricky and many people have dropped wind turbines from a height in the attempt. Needing a new set of blades would be a setback, but nothing compared to crushing a child. Keep everyone out of the fall zone, and pay attention all the time. Do not erect a wind turbine tower in a public area where people congregate beneath it.

Battery-charging wind turbines do not generally create any risk of electric shock, but bear in mind that when they are running fast and not connected to a battery the voltage they produce is much higher than nominal battery voltage. Dangerous voltages can arise in exceptional conditions (especially with 48-volt systems), so it is best to keep junction boxes closed.

How big?

The amount of energy that you will get from the turbine depends mostly on two things: the diameter of the blade rotor, and the exposure to good winds. The power rating of the alternator in watts actually has very little influence for most of the time, because full rated power is only available in stronger winds. The rest of the time the power output is limited by the wind and by the size of the rotor.

I have included a very rough estimate of the cost of materials in the table as well. Much will depend on how you buy things, what the shipping cost is, whether you can re-use some discarded materials such as steel pipes or timber. There is a list of useful suppliers at the back of this book. Also a glossary of terms.

Cost is less significant than the time it takes to complete a project like this. You are likely to be at it for weeks rather than days. I recommend building a small one first so as to get experience and also so as to get a final result before you run out of enthusiasm. It is hard to describe the feeling you will get when it starts to produce power.

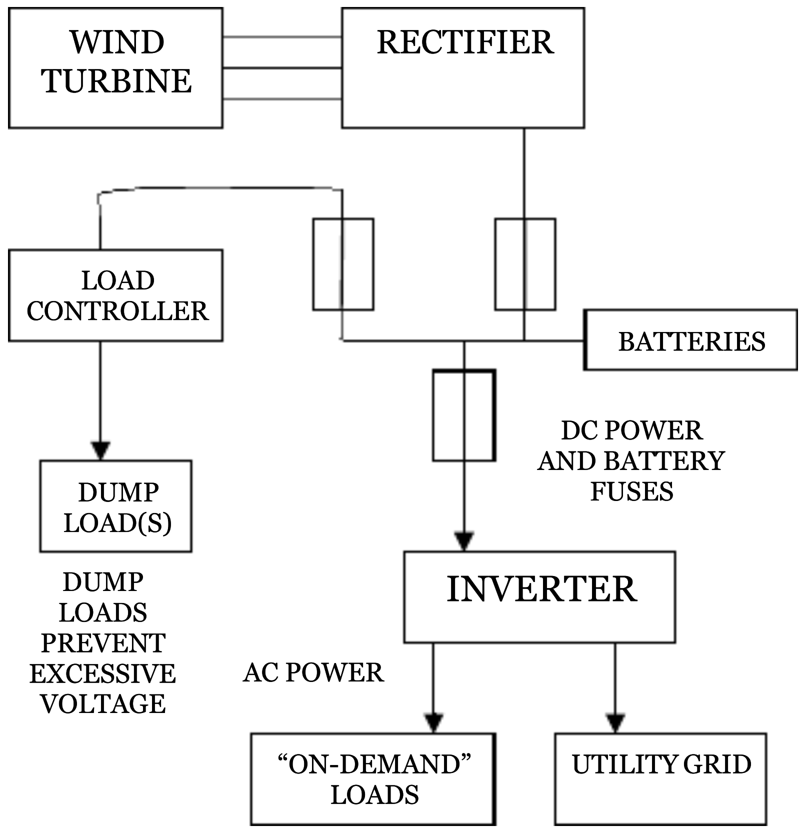


Diagram of a small wind system

3-phase AC power from the wind turbine is converted to DC power by a rectifier. (Only one DC wire is shown to simplify this diagram but you need two.) In most cases the DC is then made into single phase AC power (normal household electricity).

Estimated monthly energy production at different mean windspeeds						
Turbine diameter mm	1200	1800	2400	3000	3600	4200
Power rating	200 W	350 W	700 W	800 W	1000 W	1000 W
Mean 3 m/s	5 kWh	12 kWh	22 kWh	34 kWh	49 kWh	67 kWh
Mean 4 m/s	14 kWh	30 kWh	54 kWh	85 kWh	122 kWh	166 kWh
Mean 5 m/s	23 kWh	53 kWh	93 kWh	146 kWh	210 kWh	286 kWh
Mean 6 m/s	33 kWh	74 kWh	131 kWh	205 kWh	296 kWh	402 kWh
Mean 7 m/s	41 kWh	92 kWh	164 kWh	256 kWh	369 kWh	502 kWh
Estimate cost of materials	£250	£350	£500	£600	£800	£1000

What can the wind turbine do?

Small wind turbines are a good way to produce electricity in a windy place. Wind energy is highly dependent on the wind speed, so it is a good idea to erect a tall tower to reach the best winds. The turbine needs to be well above surrounding trees and buildings - not just at rooftop level. If the location is not windier than average, then small wind is probably a waste of effort but there is no reason not to do it if you just want to do it. There is no reason to drive around town in a big four-wheel drive vehicle, but people do that. If you need to build or buy a small wind turbine, then that is fine too (even better!). But you need to understand that it will not save you any significant money (unless the site is really windy). It will be less environmentally damaging than a four wheel drive, but it will not immediately 'save the planet'

AN INVERTER IS JUST A BIG BOX OF ELECTRONICS

The wind turbines in this book are primarily designed for charging batteries. They can provide electricity where there is none.

It is good to connect solar photovoltaic (PV) panels that charge the battery when the wind is low, and it's also easy to convert battery power into AC power for conventional household wiring and appliances. But the batteries and other items of equipment to do this are not cheap.

If you already have utility grid power on site then there is not so much point in storing energy in batteries. The most effective use of wind energy is to feed it straight to the grid using a special 'grid connect' inverter. You will also need a protection box to limit the voltage.

Home made wind turbines will not however be eligible for the new 'Feed in Tariffs' that are making small wind profitable here in the UK.

Some prefer to use the wind for heating only. This saves the hassle of dealing with the utility, and avoids the issues of energy storage in batteries – it is much cheaper to store heat – but in the end the value of heat energy is often much lower than that of electricity.

Load controllers

It is not a great idea to simply connect a heater directly to the turbine because that will prevent it from starting up. The heater has to be turned on when the voltage is high enough. You need a 'load controller' that automatically turns on the heater(s).

A LOAD CONTROLLER IS A SMALLER BOX OF ELECTRONICS

The wind turbine is rather like an engine whose throttle you cannot control. If there is no wind then it will not turn at all, but if the wind is strong then you have to give it something to do or it will overspeed and run wild. If the wires are disconnected from the turbine then the voltage will shoot up until it can damage lights and electronic equipment.

Whether you want heat or not, you should use some sort of electronic load control that connects heaters to the turbine when the voltage rises above the desired level. Such controllers are easily available for battery charging systems and are becoming more widely available for grid connection applications as well. Be aware that load controllers that are designed to work with batteries cannot usually function without batteries, although in some cases you can use capacitors in place of batteries to stabilise the voltage if the operating frequency of the pulses is high enough.

If you are keen on electronics then you can make your own load controller. Some of them work by switching multiple small loads on and off on a slow timescale while others work by very rapidly switching a single load. The amount of energy you dump depends on how long the load is pulsed on compared to the period between pulses. I also sell load controllers of various types, so just ask me if you need one.

The energy that is diverted to heat can be used in a water heater and then diverted to lower priority uses once the water is hot. The system can become very complex if you wish to make the best use of your wind energy. This may be justifiable if you are dumping a lot of energy into heating.

A dedicated solar PV charge controller will not work for a wind turbine unless it has the option to be used in a load control mode. Most solar electric charge controllers regulate charge by disconnecting the solar panel, and this is not a good idea with a wind turbine. Xantrex C-40 and Morningstar TS45 controllers (see left) are both optionally suitable for 'diversion loads' but the latter has a quicker response to gusts. The LDR controllers made by Solar Converters are cheaper and more suitable for direct heating without batteries.

Choosing battery voltage

12-volt batteries are only suitable for very small systems because the wires you need are very thick, expensive and clumsy. Unless you have a special reason to need 12 volts, then choose 24 volts or better still 48 volts. You can easily build a 48-volt battery using four 12-volt batteries. 48-volt power can be converted to mains voltage AC power with an inverter.

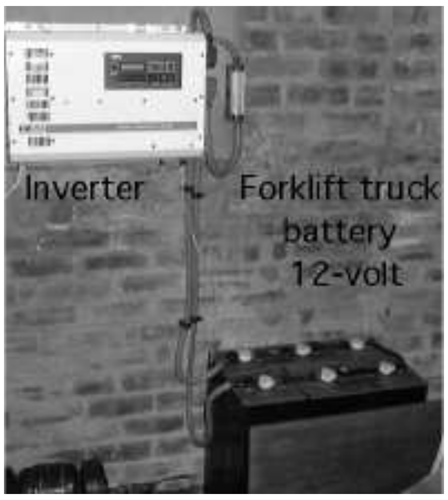
Cheaper inverters are available for 12 or 24-volt battery systems, so if you cannot afford a high grade inverter then 24 volts may be the best choice.

If you are feeding the mains grid without batteries then a good choice of inverter is the 'Windy Boy' 1700 watt inverter from SMA. This grid connect inverter works over a range of voltages from about 140 to 350 volts. There are many other such inverters to choose.

If you plan to use the turbine for heating then the voltage will depend on what sort of heaters and critically what sort of heating controller you wish to use. But a higher voltage will enable the transmission wires to carry the energy with a smaller current which wastes less power as heat in the wires.

Battery types

There are many types of batteries, even among the generic 'lead acid' family that is used for small wind systems. Car batteries are not suitable for storing significant amounts of energy – just for delivering a brief high surge of power to start an engine. Most other battery types can be expected to last about five years but life expectancy depends heavily on how they are used. They can last two or ten years.



Forklift truck batteries are good for very heavy, deep cycles of charge and discharge but do not hold their charge well over periods of weeks. They generally work best where a small battery capacity is used for regular daily charge and discharge. The one shown has six individual 2-volt cells making up 12 volts.

Semi-traction or 'leisure' batteries look more like huge (60-kg) car batteries. Used in boats etc, they often come in 12-volt units. Widely available, cheap and good at holding their charge, they are a popular choice.

Sealed batteries of the gel and AGM types are used for low-maintenance and remote sites or for situations where spillage is a major concern. They are twice the price of 'flooded' batteries and are easily damaged by incorrect charging voltages.

Secondhand batteries are an attractive way to reduce both cost and environmental impact of your renewable energy system. But in many cases a used battery is not worth the trouble. The best type is the old 'standby' battery built from single cells in transparent cases. Some of these can last for 25 or 30 years.

Why some popular ideas are not good ideas

Car alternators

A car alternator appears attractive for home-brew power generation, because it is made for the job of charging batteries and is widely available at low cost. But it is a bad choice for a wind generator. The efficiency in normal use is never more than about 60%. In practice it usually wastes over half of the power that drives it. The bearings are too small to reliably support large blades (over about 1500 mm diameter). There are three main problems:

1. It is designed to be lightweight and robust and to withstand running at very high rpm. At low speed (below 1000 rpm) it produces no usable output. If you mount wind turbine blades on the shaft then they will turn it relatively slowly. This speed mismatch can be addressed in one of several unsatisfactory ways:

- Use shorter blades. The tips have less far to go per revolution, so they can spin at higher rpm. This solution can produce power in high winds when the speed and power are sufficient to energise the field coil. But you will find that most of the time the wind is insufficient and the turbine produces nothing. Small blades cannot catch much energy nor run vary fast in low windspeeds.

- Use gearing to increase the rpm. This involves extra cost, extra power losses, extra unreliability and overall ugly and clumsy engineering. Wasted effort for a disappointing output.

- Rewind the coils to work at lower speed. Use more turns of thinner wire in each coil. This reduces the cut-in rpm but also increases the losses in the coils themselves, limiting the power output and further reducing the already low efficiency.

2. The alternator field coil needs to be supplied with power to excite the magnetic flux. To get output at low speed, you need the flux to be maximised. This current in the field coil represents a constant power loss of 30-40 watts during operation. The loss clobbers the output in low winds. 40 watts continuous nearly adds up to one full kWh of energy per day.

Solutions? You can fit it with permanent magnets. This is very laborious and what you are left with is still rather small and light, so the efficiency is still very poor unless the machine is very small (50 -100 watts say).

3. The internal regulator in the alternator is not suitable for charging a remote battery. If the battery is not close by then the voltage at the alternator will be higher than battery voltage and so the regulator will start to limit the output before the battery is charging properly. Also the way it reduces output is to reduce the magnetic field. This unloads the blades, which will run faster and cause noise, vibration and wear to all components (bearings, blade tips, etc).

You will have to remove and bypass the internal regulator.

While it is cheap and attractive at first look, the car alternator is more trouble than it is worth. It is simpler and better to build a purpose-built alternator for a wind turbine.

Steel cores in the stator coils

Most conventional alternators have cores made of laminated steel that enhance the magnetic circuit through the coils of copper wire and thus increase the output voltage you can get from a given amount of magnet material.

The axial flux alternators described here do not use cores in the coils and so they need much more magnet volume to achieve the same performance. You could fit cores into the coils, but it would not be advisable. The magnets would seek to align themselves with the coil cores and this would make the alternator very hard to start and very rough in operation. The uneven torque is known as 'cogging'.

Alternators with steel cores are harder to start generally and they do experience quite a noticeable magnetic drag, which impacts on the efficiency in low winds. The axial flux alternators in this book are very free turning and much easier to build. The only disadvantage is the higher cost of magnets.

Multiple rotors and stators

Very many people ask me if you can increase the power of the axial alternator by adding more rotors and more stators. The answer is yes, but it is not the best way to use the materials.

You want low operating speed and high efficiency at minimum cost of magnets and wire. If you build an alternator with two stators and four sets of magnets then you will get twice the power at the same speed.

If you instead put all the magnets onto rotors of double diameter, and all the coils into one big stator, then each coil will also produce twice the voltage. So you have double the coils but each coil can produce twice the power with the same losses. The coils can each actually produce four times as much power with the same energy conversion efficiency but the losses would then be proportionately very high.

If you put all your magnets and coils into one alternator with twice the diameter, you handle between 4-8 times as much power instead of just 2 times.

Any time you adapt the design you will need to take care that the alternator matches the blades you are using. Alternator speed depends on magnets, coil details, battery voltage etc. If the speed is too low then the blades may stall whereas if it is too high then the blades will not be able to run fast enough to drive the alternator. See the section on alternator design at the end of the book.

Vertical axis wind turbines (VAWTs)

'Vertical axis' turbines have a vertical shaft that is driven by blades that move horizontally like a roundabout. 'Horizontal axis' describes the more conventional windmill which has to face itself into the wind and whose blades revolve in a vertical plane. The vertical axis wind turbine idea is popular even though it is thousands of years old and has long ago been superseded technically by the horizontal axis blade rotor.

Attractive features of the VAWT include the ability to take wind from any direction, and the ability to drive a generator at ground level. But in spite of a huge amount of research, vertical axis wind turbines have failed to become widely successful. They can be hard to start, hard to stop, and they have inherently lower efficiency than horizontal axis turbines. (They convert less of the energy that is in the wind). Putting them on lower towers means that they have also got access to less wind. It is often hard to mount a VAWT on a tall enough tower where it can get a good wind.

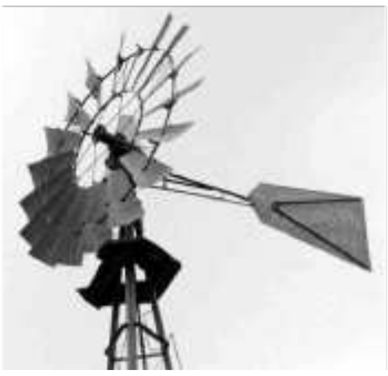
Low speed vertical axis wind turbines of the 'Savonius' type are useful for really basic simple rugged machines with low efficiency, and low rpm. But the same amount of effort put into a horizontal axis machine will yield much greater returns. Low speed alternators are very heavy and expensive.

High speed Darrieus 'egg-beater' or alternatively H-rotor type vertical axis (VAWT) wind turbines are popular in university engineering departments but have never been successful in the marketplace, except for a few years in the 1980s in California. In brief, the main problem with high speed vertical axis wind turbines is the fact that the blades suffer from reverse buffeting by the wind every single revolution. This causes severe fatigue loading which

shortens the life expectancy of blades. This is usually the main reason why they fail to become commercially viable.

There are numerous small VAWTs appearing in the marketplace these days but none of them seem to have any sort of track record. In fact none of them seem to be able to offer any real world measured data for energy production. Beware of computer-generated predictions of output!

Multi blade rotors



The old water-pumping windmills were built with multi-bladed rotors so as to produce high torque in low winds. They work very well for this purpose. More blades obviously push harder and lift the water from deep under the ground.

For electricity production you need speed rather than torque, because the amount of magnets and wire you need to buy is much less at high rpm. At high speeds you can catch all the power (not torque but power) that there is in the wind using only two or three blades. Three blades run more smoothly than two, so that is the number I suggest you use.

Rooftop mounting

Another idea that has caught the public imagination lately is to mount a small wind turbine on the roof of the house. This has long been known to be a bad idea, but public interest in urban wind energy has encouraged sales people to offer rooftop mounted wind turbines nevertheless.

Windspeed at rooftop level is very poor due to the fact that obstructions such as buildings and trees have a dramatic effect on the flow of air, breaking it into diverse vortices and gusts that contain very little energy but do cause wear and tear of the turbine. Access for installation and maintenance is often difficult or expensive. In urban areas the turbine should really be placed at least 10 metres above the rooftop level, which is not very practicable with a roof mounted tower.

Wind turbines are machines that produce some vibration during operation. In windy locations this can cause problems with noise in the building, and even damage to the structure of the building. On most sites this will not be a problem because the wind will be insufficient for the turbine to do much, but the whole exercise is likely to be a waste of effort. On very exposed sites the building will be seriously impacted, and the occupiers will find the noise distracting. In either case there would be much better results form putting the wind turbine on an independent tower, well above the building and a distance away from it.

While I sympathise with urban dwellers who wish to make use of wind energy, I have to discourage the idea because I know it is not a good one. Solar water heating and PV are much better choices for rooftop renewable energy.

Saving money off the electricity bill

When people contact me with an enthusiastic desire to save money by using a small wind turbine to cut their electricity bills, I always feel uncomfortable. I am enthusiastic about small wind energy but I also have a realistic knowledge of what it can do, having used it for thirty years. As you can see from the table at the start of this section, even a well sited wind turbine can only produce a few kWh units of electrical energy per month. Achieving this output will cost a lot of money and time compared to the effort required to save money by reducing electricity consumption in most cases. If your electricity bill is high then energy conservation is going to pay quicker dividends than a small wind turbine.

Wind energy itself is free but converting it to usable electricity is no free lunch. You will reduce your electricity bill by using a small wind turbine, but if saving money is your motivation then there are cheaper and easier ways to achieve this end. Investing in home insulation, heating controls, energy saving lights and modern fridges and freezers will be the first things to consider. Burn wood to heat your house. Switch off your TV and computer systems when not in use. You can easily save a lot of money with energy conservation measures and reduce your environmental footprint. Once your electricity consumption has been minimised then you can think about meeting your needs with wind and solar power. But you are not likely to save money in the end when you consider everything you have bought and done. The pleasure of using small wind energy comes at a price.

If you have a suitable site for a small hydro turbine then there is a much better chance of saving money with renewable energy that way. A good hydro power site can be a real money-earner.

Mounting a wind turbine on a car to charge the battery

Obviously a wind turbine mounted on a vehicle will experience good winds and be able to produce healthy output. But the drag caused by the turbine will put an extra load on the engine of the vehicle.

There is no free energy to be had in this way except on rare occasions when you are coasting down a hill. While driving on the level the engine will have to produce more power to charge the battery in this way than it would by charging it via a conventional alternator with all its shortcomings.

It can be fun and also interesting to mount a wind turbine on a vehicle for test purposes. But this is not an efficient way to produce power. Nor is it a particularly accurate way to measure the performance of the turbine. Its main virtue is that you can control the windspeed at will.

Using a centrifugal clutch or brake to limit speed

This would just wear itself out in a few days on a windy site. The thing with wind turbines is that they work a lot more hours than most of the machines we use. A brake has to come on completely and stop the turbine or it will wear itself away and become useless.

Building a duct that forces the air through a smaller diameter rotor at high speed.

It simply isn't worth all the extra material involved in building a duct like that. The wind tends to divert around it so you don't gain as much as you would think. It is actually more effective to build a conventional blade rotor with larger diameter, than to make a duct. Some big companies have spent a lot of their investors' money finding this out.

What goes wrong with homebuilt wind turbines?

Those who have worked with them agree that small wind turbines are surprisingly troublesome pieces of equipment, whether bought new or home built. Catching the wind is fun but can be frustrating because of all the little things (and some big ones) that go wrong.

Here are some typical examples of things that might happen:

- Poor welding skills and poor blade balance lead to the tail falling off. When the machine is shaking, the tail tends to be the worst affected part.
- Diodes in the rectifier fail due to poor connections and/or poor cooling. Or due to nearby lightning or similar surges. It pays to have a nice big heatsink. Earthing the tower helps to prevent lightning-induced surges.
- In some cases the bearings can give trouble. When bearings fail they can allow the rotors to rub the stator with consequent damage that reduces the life of these parts.
- In very turbulent and wild conditions the gyroscopic forces on the blades have been known to push them back into contact with the tower so that they break. This is a very rare but persistent problem. In the 2008 book I changed the direction of furling of the turbines so that now the gyro forces push the blade tips out from the tower as the machine moves into furl. This is the yaw movement where the blades tend to be racing fastest. This change has successfully prevented contact. But it does add to the moment that tends to bend the tower top pipe. In the case of the 3000 turbine a thick wall pipe is 48 mm needed.

- Longer term the biggest issues tend to be with corrosion of the magnet rotor plates, or the magnets themselves that can lead to a major failure in under 5 years. The magnet rotors must be painted very well or the disk/plate should be galvanised if the turbine is used in a damp climate. Take great care not to scrape or damage the magnet coatings. In the photo you can see damage to the coating of the magnets, caused by metal swarf (sharp strips and fragments of cut steel from drilling and tapping holes) in the air gap. Once the protective plating on the magnet is punctured, the magnet corrodes and swells gradually. This magnet was cut out of the casting and replaced. I will soon publish a new book about how to build a turbine using the older ferrite magnets that do not corrode.

Small wind turbines can last twenty years, but repairs are called for now and then. It's hard to say how often, because all builders are different, as are all sites. I would expect a couple of problems in the first year, and maybe one per year thereafter. Can be just a blown diode, or can be a new set of blades need to be carved. It's a good idea to collect a stock of spares for the turbine so as to be able to get it back into action fast in the event of problems.

Useful web pages for more information:

http://www.scoraigwind.co.uk/buildyo
http://www.windpowerwiki.dk
http://www.fieldlines.com
http://www.thebackshed.com/forum/
http://www.navitron.org.uk/forum
http://www.windempowerment.org
http://www.wind-turbine-supplies.co.uk/
http://www.buildyourownwindturbine.com/
http://www.tripalium.org
http://www.otherpower.com
http://www.v3power.co.uk
http://www.briery.com/wind_turbine/
http://www.windstuffnow.com
http://www.homepower.com
http://www.mdpub.com/Wind_Turbine/

Tools

In most cases there are various options depending on cost and what skills you may have.

Safety etc.

Safety glasses, gloves and ear protectors. Plasters for fingers. Hand cleaner. Paper towels.

All-purpose tools

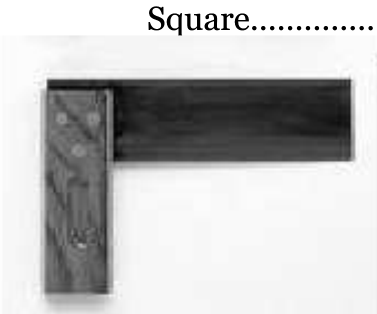
Cordless drill with screwdriver bits, screwdrivers, pliers, vice grips, clamps, vice, files, hammer, centre punch.

For marking and measuring

Tape measure, steel rule, pencil, felt pen, level, scissors,

Compasses .... protractor .... callipers

Square..............................Bevel



Weighing scales .... level

Electrical

Wire cutters, wire strippers, knife

Multimeter .... soldering iron .... Crimping tool

Resin preparation

Catalyst dispenser or syringe for measuring small volumes. Buckets and pots, spoons and sticks for mixing resin.

Steelwork

Electric Arc Welder.
At least 130 amps output for 3.2-mm rod electrodes.
(A Mig welder is also fine.)
Mask,
Chipping hammer

Chop saw for steel
(and/or bandsaw)
speeds things up
Hacksaw,
Metal shears
(for cutting lead flashing),

Oxy acetylene torch can be useful but not essential

Drill press
for accurately drilling holes
Drill bits,
hole saws

Spanners (wrenches),
Files
Taps for threading holes

Angle grinder

Woodworking tools

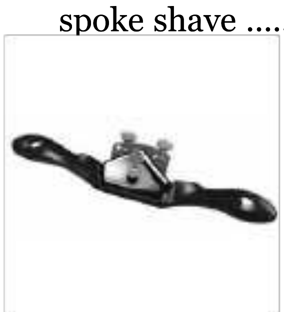
A bandsaw
and/or a circular saw can be useful but not essential.

Hand saw, chisels,
sharpening stone
Drill bits for wood.

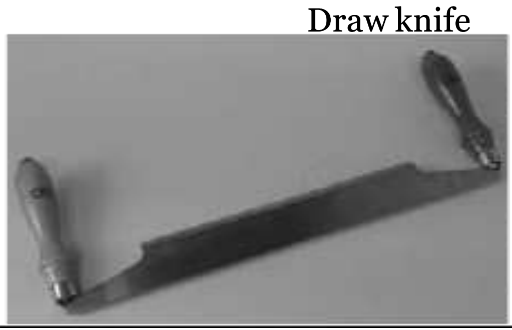
Chainsaw for big ones?

Jigsaw

spoke shave .... plane .... block plane



Draw knife



Using the tools

You may need to hire or borrow some tools that you have little or no experience of using. Take the time to watch others demonstrate the right way to hold them and guide them safely and comfortably. Try them out on some waste material before doing anything critical.

Cordless drill

Most cordless drill batteries have a memory (especially Nicad ones) and will give best results if you discharge them as completely as possible before re-charging.

You can often drive screws into wood directly without a pilot hole, but be aware that it may take a couple of revolutions of the screw before it bites properly into an underlying piece. So if you are screwing one piece of plywood to another (for example) then make a hole in the first one so as to prevent the screw from jacking it away from the piece beneath while the tip is getting started into that second piece. Otherwise you will create a space between the pieces of plywood.

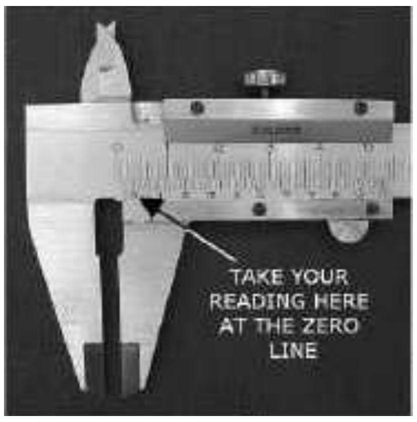
Screwdriver bits

Be aware of the different types of 'cross-headed' screws that are incompatible with each other. The main ones are the well known 'Philips' type and the more recently popular 'pozidrive' (PZ or prodrive) type. Pozidrive screws and bits both have noticeable marks at the 45 degree positions between the arms of the cross. If you use the wrong type or size of bit on a screw then you will damage both the screw head and the bit, ending up frustrated.

Measurements

Remember the old saying "measure twice, cut once" and take your time about measurements. Literally measure them again and you may be surprised to find out the errors you have made. The dimensions in these plans are rarely very critical but it's still necessary to take a bit of care. Be especially careful about the outer parts of the blades near the tips. Try to work within 1 mm tolerance there.

Vernier callipers



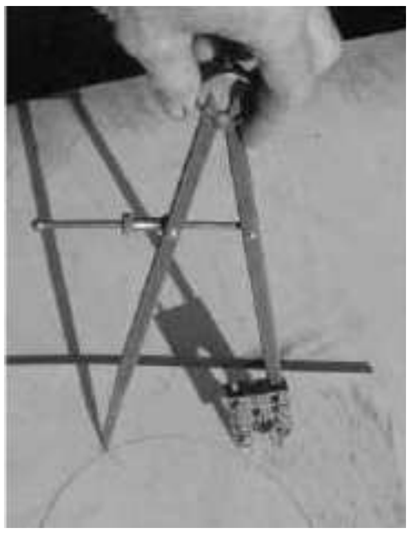
can be a great way to take accurate measurements provided you know how to use them. Close the jaws and check that the reading is zero. Most people misunderstand the vernier scale and fail to notice that the correct hairline to take readings from is labelled '0'. You can measure overall size with the parts of the large jaws that meet each other. Internal sizes (hole bore etc.) are measured with the other jaws, and depth can be measured with the rod at the end. This depth gauge is a good way to check the magnet rotor separation if you pass it through the jacking-screw holes.

Levels

A 'spirit level' is never perfect. Note that the bubble will sit a little to one side of centre. If in doubt try the level both ways around so as to verify the bubble and average the answers out for a more accurate result.

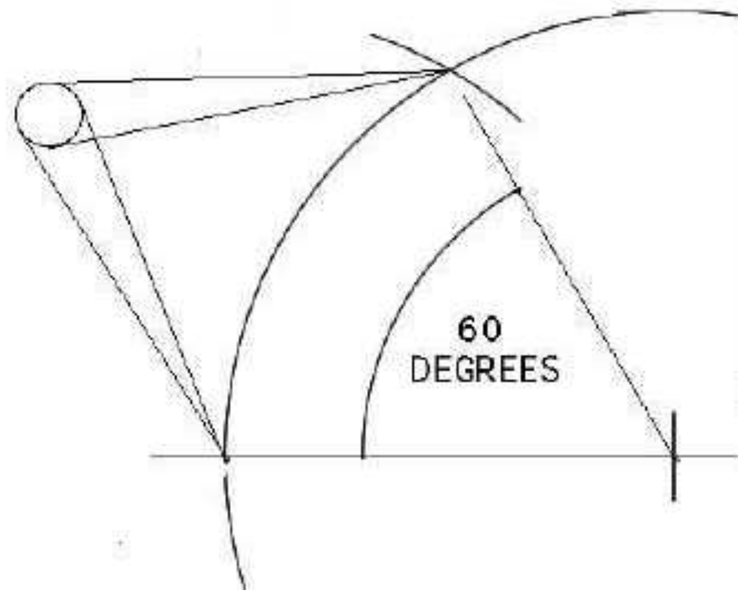
Compasses

There are a number of circles to draw on pieces of plywood, so a nice big set of compasses will be useful. If you don't have compasses then you can draw around things like bowls and cans, or make your own compasses out of a strip of plywood. Just drill a hole near to one end for the pencil, and then use a screw through the ply near the other end as a pivot. Move the position of the screw to adjust the radius. But this kind of thing is clumsy.



I have a big pair of dividers (spikes on both arms) and I fix a pencil to one arm with a heavy electrical wiring terminal. PVC tape also works.

Once you have drawn a circle, you can use the compasses on the same setting to make a hexagon, and divide the circle into six, 60 degree angles. This trick can be handy for laying out magnets, coils, stator mounts, etc. in cases where the number is divisible by three.



You can walk the compasses or dividers around a circle, marking one arc at 60 degrees, and then marking another arc from that point, and so forth until you return to the start. It's an interesting test of accuracy to see how close to the starting point you can get after the six steps. To divide angles in half, just use trial and error and find where the two circles meet; see page 42. To find 40 degrees (1/9th of a circle) you first find 120 degrees (1/3rd) and then divide this in three using trial and error to get the right setting for your compasses.

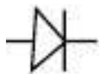
Multimeters

The multimeter is your 'eyes and ears' for electrical work. Take a measurement between two points in a circuit by pressing the tips of the probes firmly against clean, bare metal.

The first thing is to choose a measurement range. To check a battery for example, choose a DCV (direct current volts) range. For example choose 20 VDC (volts DC) for a 12-volt battery - a little higher than the expected battery voltage. Check that the negative lead is connected to 'COM' (common) and the red one to a socket that mentions 'V' (volts) among other things. Press the red probe tip into the positive terminal and the black into the negative. You will get a minus sign with the reading if you get this back-to-front. You should find that the battery voltage is about 12.5 volts. If it is below 12 then it is in need of charging. Connect a load to the battery and measure voltage again so as to check how well it holds up.

To measure alternator output use an ACV (alternating current) range. If the voltage is too high for the range then you will see a symbol 1 on the left of the display.

Check rectifier diodes using the diode check function of the meter (symbol shown on right).



Before connecting the probes you will see the 'open circuit' display of '1' on the left hand side. Disconnect the battery and the alternator from the diodes. You should get two different results depending on which way around you connect the probes across a diode. One way is open circuit. The other way you will get a number around 500, but I would not worry too much about the exact number so long as you do not get zero. Zero indicates a shorted diode. Open circuit in both directions is the other way they fail.

The Ω (ohms/resistance) range can be used to check continuity and resistance of the windings. Again zero is a short circuit and 1 on the left hand side is open circuit.

Soldering technique

You will need a soldering 'iron' (actually made of copper) and resin-cored solder wire. The important points are to make the wire clean enough and hot enough. Then the solder will run onto the wire and fill the joint. If the wires are thicker than 1 mm you will find a large soldering iron helps. You can even use a scrap piece of copper pipe on the end of a six inch nail, heated on a gas burner.

First scrape off the enamel from the ends of the wires to a length of about 20 mm. You can use a sharp knife or sandpaper but be very thorough. Plug in the soldering iron so that it heats up while you are cleaning the ends. Do not leave the scraped tails to oxidise. Use them while they are still bright.

Make sure the copper tip of the soldering iron is clean too. Wipe it, and if necessary file off any corrosion. 'Tin' the copper wire by touching the solder wire to it. The solder will run onto the iron if it is hot enough. Next 'tin' the wire with solder. Do this by placing the flat spot at the tip of the iron against the bright copper surface and touching the solder wire into the crack between them. When solder melts into the crack wait a few seconds while the wire gets up to temperature and then you can proceed to touch the solder wire directly onto the copper wire. The solder should melt directly onto the copper. Do not attempt to apply solder from the iron onto the copper as the flux will be gone, and it will not flow.

When the tips of the wires have been tinned, you can form the joint by twisting them together. Again place the soldering iron against the joint and heat it until the solder melts. Add some solder if necessary until the wires are nicely soldered together. Slip some sleeving over the joint or tape it to prevent accidental contact with other bare wires.

The best way to bring the power out of the stator is to use flexible wires with tough, heat resisting insulation. Solder them to the winding wires within the stator casting so that there is no chance of the rigid winding wires being bent or broken.

Crimping connections

Crimping (crushing wires in a small tube) is a good way to connect wires. You can use pliers or mole grips with care, but the correct crimping tool is best. Special PIDG insulated crimp receptacles are ideal for connecting the rectifier.

Bare copper crimp lugs are good for terminating wires onto batteries and bolts. Small bore copper tube can be used to make crimp connections of heavy wires.

Electric Arc welding

This is probably the most difficult skill required, but it is very satisfying. As with soldering, the key factors are to get the job clean and hot. You need good contact for the earth clamp and a clean surface to strike an arc.

Grind off the rust and slag. A sanding disk on the angle grinder is a good way to do this.

Take care never to look directly at the arc or you will damage your eyes and this can be painful later. Warn others too. It is very hard to see where you are striking the arc because the glass in the mask is so dark. Gently tap or rub the tip of the electrode on the job until the arc starts up, and then pull it back up very slightly to prevent it 'freezing' onto the work. If it sticks on then break it off and try again. You may need to take a new rod. If it freezes every time then check that you have a good earth connection and turn up the current on the welder. Once the rod is warmed up it's easier to start.

When the arc starts up, take care not to move too fast. Keep the rod pretty steady and allow the work to warm up. Then gradually move along the work, melting the steel underneath and building up a bead of metal. A layer of slag forms on the top. Try to prevent the slag getting under the weld. I like to set up the job on a gentles slope, and work uphill from left to right with the rod at an angle so that the slag cannot easily run in front of the weld pool. When you have completed a run, and the slag has cooled you can chip it off and lay another run beside and overlapping the first.

The advice I always have to give is to move more slowly. The process happens quite slowly and if you move too fast then you will get an uneven result because the weld is not hot enough to penetrate. If you move too slowly it might melt a hole right through the steel, but this is very unlikely except at thin edges and corners. Beginners welds are often scattered blobs on the surface of the steel. The reason is that they are moving too fast. Creep along the surface as slowly and steadily as you can.

When welding two pieces together, the main point is to keep good penetration into both pieces. Weave gently between them taking the time to ensure good contact and penetration of each in turn. Otherwise you may get to the end and find that the weld is all on one side of the gap, with a band of slag along the other side. You can actually bridge across a gap up to about 3 mm if the parts do not fit well. But timing is important or you will make the gap bigger by melting the edges.

As the weld cools it will shrink and this causes parts to move. Try to make the first welds in places where shrinkage cannot cause movement. Tack the parts in several corners so as to lock them in place before doing any heavy welding.

Take care not to weld on galvanised metal or other steel platings because it is not only difficult but the fumes are highly toxic. Grind them clean first.

Cutting steel

A good quality hacksaw is probably the cheapest and most efficient way to cut steel and provided you use a good quality blade and use the saw correctly it is also quite fast. Press down gently on the forward stroke and use the full length of the blade in a steady rhythm. It is no harder than sawing wood. A little oil can help.

Most people prefer to use a chop saw or a grinder. With any cutting machine there is danger, especially if the steel moves, so clamp it well. Wear eye protection and direct the sparks downward and away from other people and from sensitive areas where they may cause a fire, or damage paint or bearings. When cutting with an angle grinder, use a thin cutting disk. Do not use thin disks for grinding.

Drilling

It is surprisingly difficult to drill a hole in the correct place. The best way to be accurate is to drill through something else (usually the other part that is to be bolted on). For example drill through a wheel-hub flange and into the steel magnets rotor (or vice versa). This will mean drilling at full diameter straight away, whereas it is easier to drill using a pilot hole of smaller diameter. Drilling a 10 or 12 mm hole directly is slower but quite feasible provided the drill is sharp and you apply good pressure. A drill press makes this easy but if you cannot get the work under it you can still do it with a hand held drill, taking care to keep the drill bit perpendicular, and resting your weight on it. This is much easier if the work is at floor level.

If the drill makes a squealing noise then stop. It is blunt. Get another drill bit or sharpen the old one, and apply more pressure. Use a lubricant.

Take care when a drill is about to break through the back of the workpiece. In the case of steel it is likely to jam and break or spin the work around. Reduce your pressure as you finish the hole. In the case of wood it may splinter the back of the piece, so rest on another waste piece and drill on into that to get a clean hole.

Tapping a thread

Tap Thread	Hole mm
M8	7
M10	8.5
M12	10.25
M14	12
M16	14

Taps usually come in sets of three, but you may only need to use the first one which is the most tapered. The hole needs to be slightly smaller than the final size (see diameters on right). Most are common sizes but the 10.25 can be achieved by wallowing a 10 mm drill around to ream it out (make it larger).

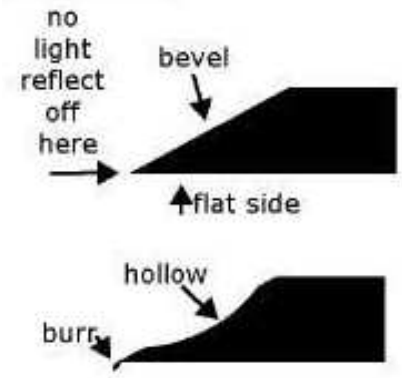
The 'tap holder' is a cross-bar handle. Use it to press the tap firmly down into the hole and turn it so as to ream the hole and begin the thread. Use lubrication, hold it straight and press very hard as you turn it clockwise to get started. One the thread has bitten it will guide itself but do check that it is going in true. Correct the line if necessary by sideways pressure while screwing in and out. Once you have a good thread going you can progress quite fast, but it is helpful to back off a half turn after every turn so as to break the chips.

Wood saws

Power saws present obvious dangers to the fingers. High velocity dust in the eyes is also painful. If using a bandsaw, do not pull the wood toward you or the band may become derailed. Stop the saw if you have to withdraw the wood from it.

When turning a corner, do not apply side pressure to the saw. Press forward but steer the wood or the saw to change direction. For example to steer a jigsaw you must swing the *back* end of the saw around while keeping the blade still. Otherwise the blade will deflect and the cut face will be angled.

It is a good idea to practice cutting. See how accurately you can do it using a dummy line and then cut as close as you confidently can to the real line. You can plane off any surplus wood later to reach the line accurately. If you cut the piece of wood too small then it may become unusable.



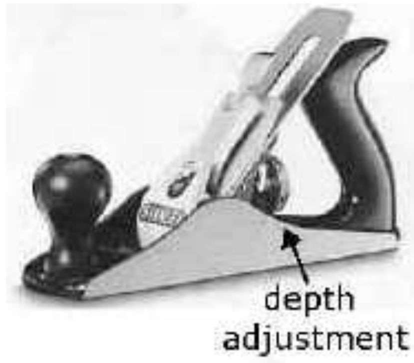
Other wood cutting tools

All tools work best when sharp. Take the time to get a good edge on the blades. If you can see light reflected off the edge then it is blunt.

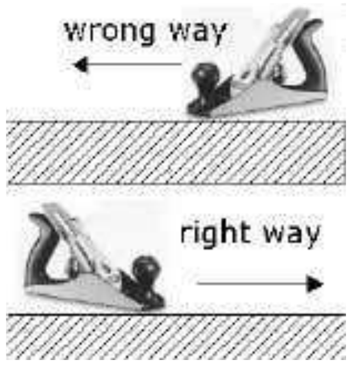
Hone the bevelled side with a flat stone or diamond card as desired with oil or water as required. Learn to find the best angle by rocking the tool until it sits on the bevel. Rub it hard until a small burr appears on the flat side. Then rub the flat side briefly without any angle (completely flat) to push the burr over. You may have to go to and fro between sides a couple more times until the burr is gone. If the angle becomes too obtuse then you can attack the bevel with a grindstone. A hollow face makes subsequent sharpening easier. Take care not to overheat the edge when grinding as this spoils the temper of the steel.

My favourite wood tool is the draw-knife, and you can almost carve a blade using that alone. Try it one way up and then the other because they each work best in different situations – flat faces or hollows. Be aware that it's a long blade that can all be used by sliding it across the work as you cut. A sawing motion saves effort and improves control.

The spokeshave is better for really fine cuts, and for smoothing out hollows. You have to press down hard with the spokeshave as it tends to judder along and make a mess. But the best tool for straight faces is the plane. A large one for coarse work and a small 'block plane' for delicate work. Adjust the depth of cut to suit conditions as you go.



With all hand tools you will have better results working with the grain of the wood. The fibres in the wood cannot be seen but they emerges from most cut faces at an angle. If the tool works against the grain then it picks up these fibres and tears the wood. Work with the fibres so that they are flattened, giving a smooth finish.



The easiest way to find out the direction of the grain is by trial and error, but one does have to be aware of it. The grain is different in different places, and can change suddenly around knots.

Sandpaper

Most people want to use sandpaper a lot while shaping the blades. Hand sanding is not very productive though. Sandpaper removes wood extremely slowly and tends to produce a relatively rough finish compared to a sharp cutting tool. The growth rings in the tree are composed of hard and soft wood that the sandpaper removes unevenly, leaving the hard rings proud in a series of ridges. A plane will cut them equally and leave a flat surface.

Power tools

Power tools can definitely speed up the process of carving large blades, but hand tools are quieter and create less dust. A sharp tool can usually keep up with a belt sander.

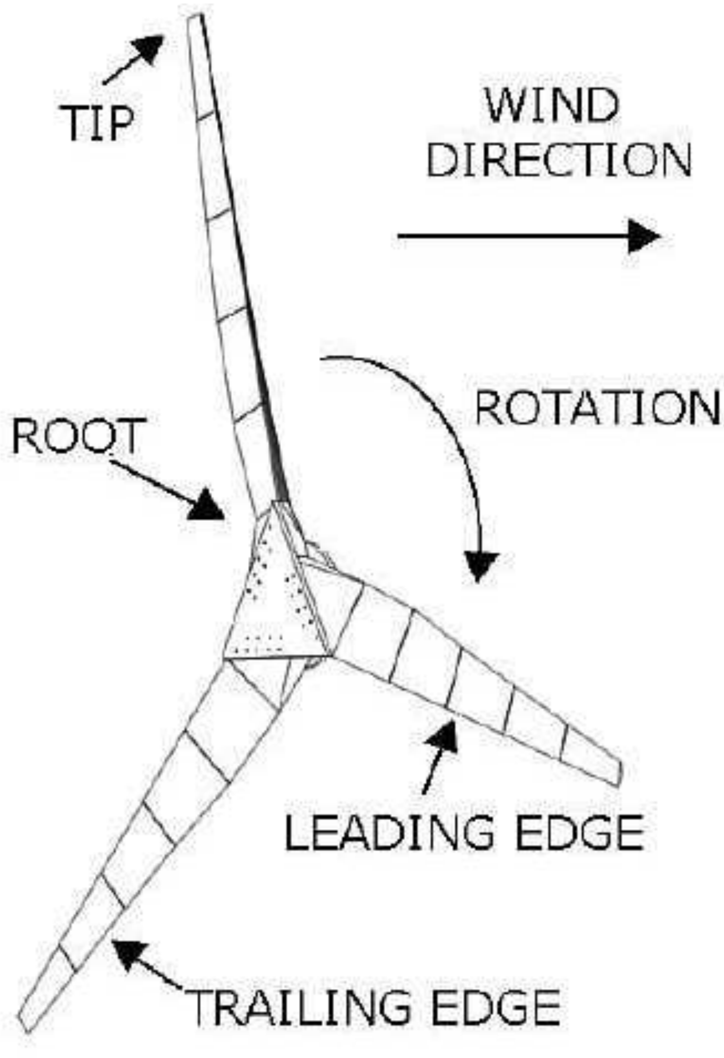
A chainsaw can save a lot of time when carving really big blades. Multiple cross cuts work well.

Blades

This is a description of how to carve wooden blades for your turbine. Wood is a very suitable material, being light, strong and resistant to fatigue. For one-off blade production it is hard to beat. On the downside, being a natural material it is hard to find consistent quality stocks of wood.

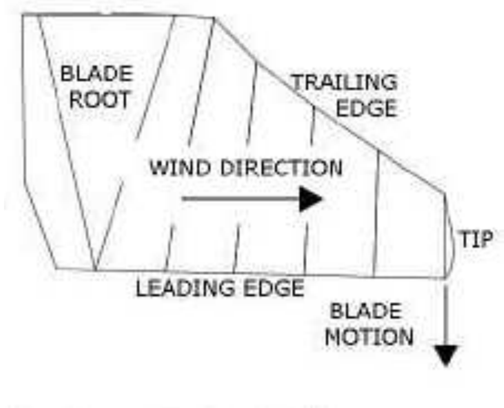
Plastics and metals can also be used to make blades. Glass-fibre reinforced polyester composite (GRP) is a common choice of plastic composite. But making good blades with GRP is much harder than making wooden ones, especially at first. GRP is ideal for larger batches of blades, which are easy to produce after the structural design has been worked out and the moulds have been created. Sheet polypropylene is also quite a good choice of plastic for crude hollow blades. Some people like to cut their blades out of PVC pipes and you will find a few recipes for this on the web.

Metal is not so good for blades because it is very apt to fatigue, especially at the fastenings (around rivet holes etc.).



Parts of the blade

There are 3 blades, rotating clockwise. The outer end is called the tip. The inner part at the hub is called the root. The blade edge that strikes things first is called the leading edge. The streamlined part that leaves the air behind is called the trailing edge.



The blade tip is narrower than the root. A very narrow blade is all you need to catch the power of the wind when the blades are turning fast.

Closer to the root the blades move more slowly and so they should be wider and more steeply angled to the wind. But the outer part is the most important. The root part does not sweep much wind compared to the part near the tip.

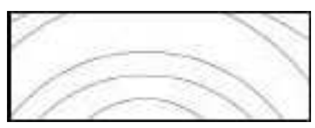
The windward side of the blades is flat, but the back is curved like the top of a wing. The back generates a lift force, pushing the blades back and slowing the wind.

Selecting the wood

Look for pieces of wood without knots, with very small knots, or with knots that you can work around and discard. The name of the tree is not so important, but cedar and larch are good. Pine and spruce are often used. Avoid dense timber (hardwood) because it will produce large gyroscopic forces as it spins.

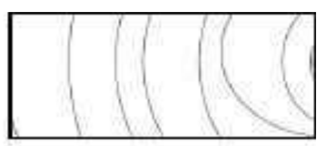
It is possible to build a blade up out of strips of wood laminated together with glue. Laminated blades are less prone to weaknesses due to knots etc., but they are more difficult to carve with hand tools.

The way the piece is cut out of the tree can make a difference, although it is not critically important. Here are some examples of what the end of the piece might look like. But always check for knots!



The first example of grain section is the least ideal. It will tend to warp. But knots are less likely to run right across and weaken it.

The next one is better, but it would be better still if the grain rings ran vertically.



The third example is the best of the three. This is sometimes known as 'vertical grain' or 'quarter sawn' wood.

MINIMUM SIZES FOR BLADE WOOD (3 PIECES) mm. Larger is better.						
Turbine diameter	**1200**	**1800**	**2400**	**3000**	**3600**	**4200**
wood width (min.)	95	95	125	145	195	225
thickness (min.)	35	35	40	45	60	75
length each blade	600	900	1,200	1,500	1,800	2,100

The blank shapes

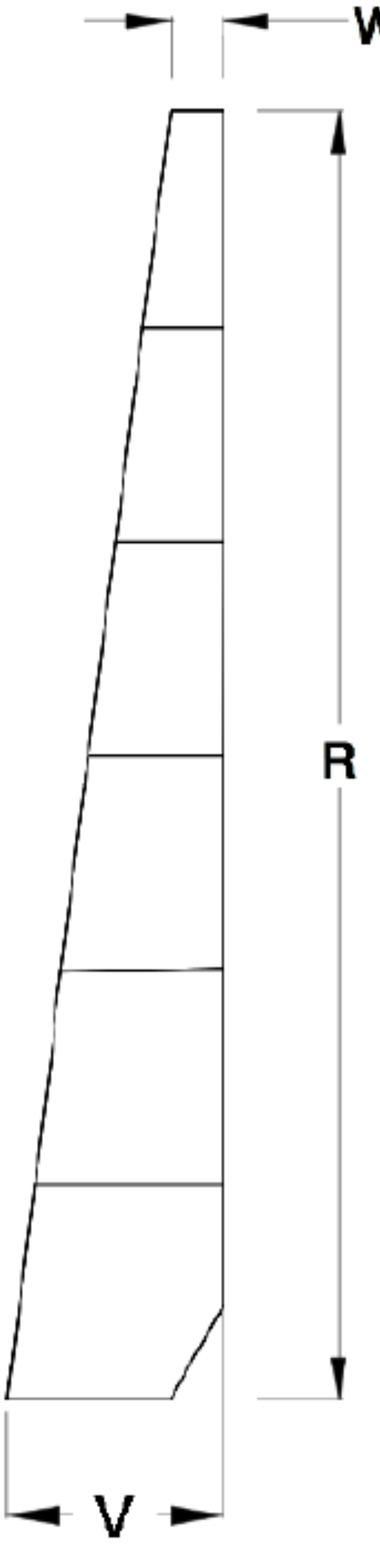
Start by marking out the blade blanks, the pieces of wood from which the blades are carved. Minimum sizes for the blanks are listed above, but larger sizes are also great. If the wood is wider or thicker than the minimum then you can make the blade root larger, which is always good. The important outer part of the blades is always the same.

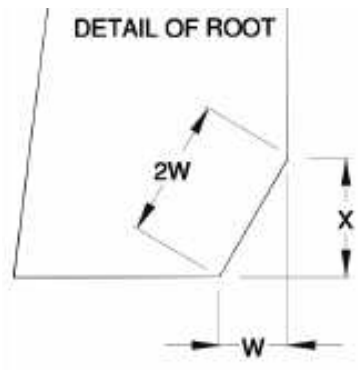
It is easier to choose good blade blanks if you have long pieces of wood to work with. This makes it easier to avoid knots.

Make a plywood template of the blank shape of one blade. The length R will be half of the diameter of the turbine. See table below. Lay the template on a long piece of wood in various positions to determine the best parts from which to cut out each blade.

Mark six stations on the template at equal intervals so you can mark their locations on the wood. (The 1200 mm diameter blades have fewer stations.)

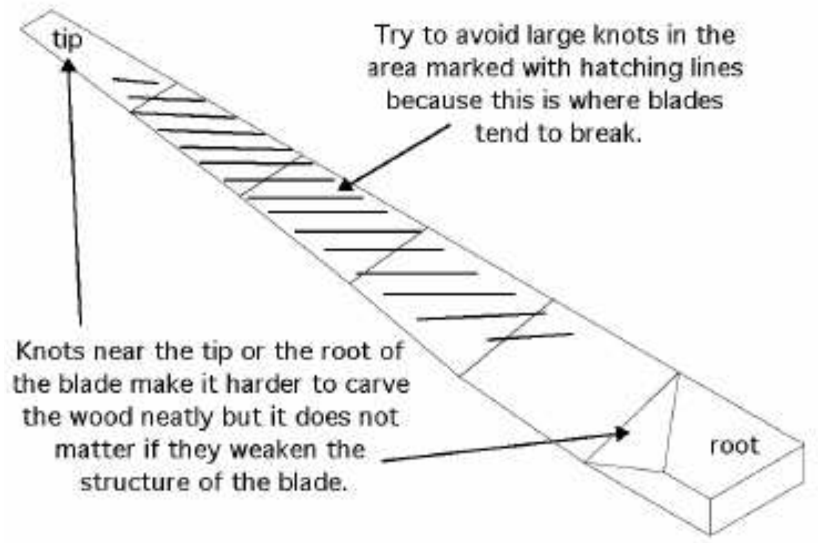
The template end 'V' is usually wider than the wood. That's OK! Use whatever width of nice wood you can find.



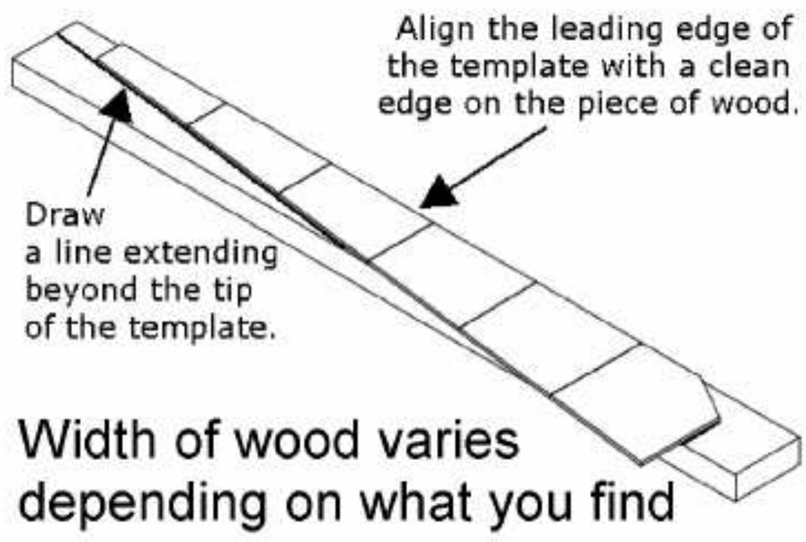


Find the clearest face of the wood and choose a clean straight edge of that face for the leading edge. Most of the finished blade will be close to this face of the blank.

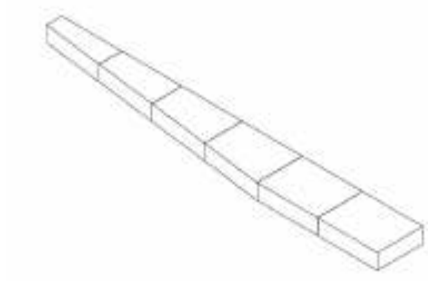
When laying the template on the wood, try to avoid including knots, especially in the zone marked by hatching lines in the sketch below.



A blade with very small knots is fine, but large knots can disturb the grain of the wood so much that there is very little strength left.



The diagram shows how to lay the template onto a piece of wood and mark the shape of the blade. Lay it this way up.



Try to cut the blanks slightly longer at the tip than the final blade size. (Then you can trim the surplus at the end of the carving process to get a neater tip.)

DIMENSIONS OF THE BLADE BLANK TEMPLATE in mm

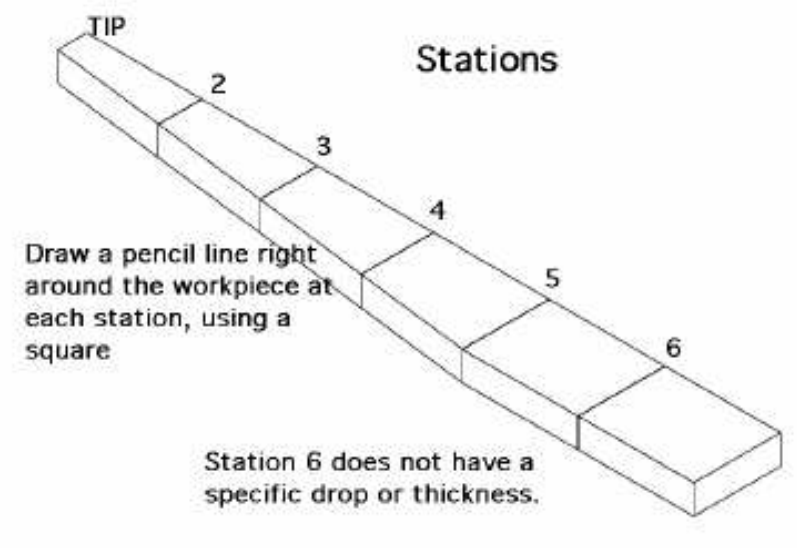
Turbine diameter	1200	1800	2400	3000	3600	4200
R	600	900	1200	1500	1800	2100
V	150	140	200	250	300	350
W	38	50	50	63	75	88
X	66	87	87	109	130	152
Stations at	200	150	200	250	300	350

Finally cut around the shape that you have drawn, and create the blank shape of the blade.

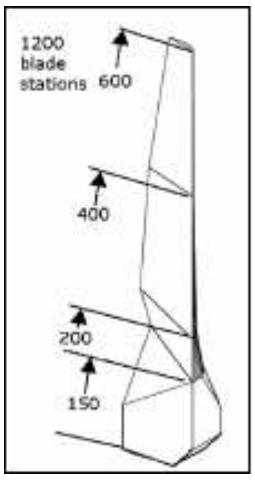
The root of the blade needs to be cut to a 120 degrees point, so that the 3 blades will fit together inside the hub, but there is no rush to do this if you wish to leave it until the blades are being assembled together.

The trailing edge line

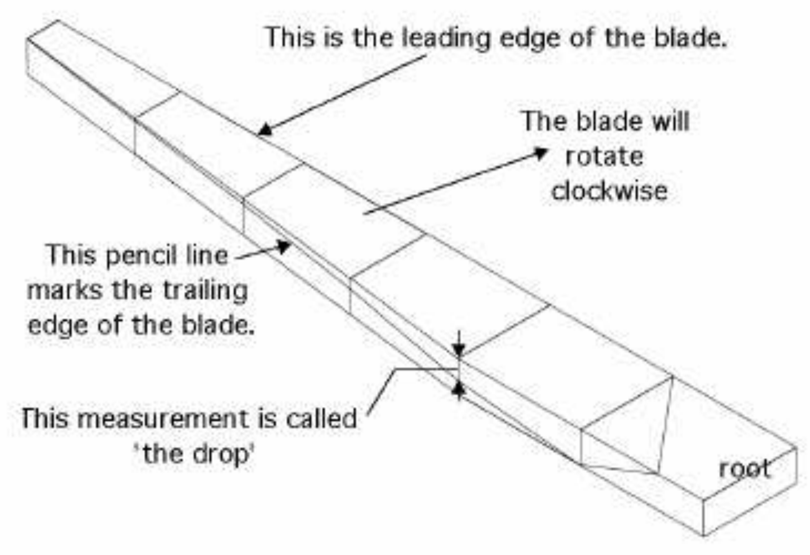
At this stage draw a line around the piece at each station using a square. Measure and mark stations at six equal intervals. No need to be very precise about the stations.



(The 1200 mm diameter machine has fewer stations as shown on the right. The last station, where the ramp starts, is 150 from the root. The others are evenly spaced at 200 and 400 from the root.)

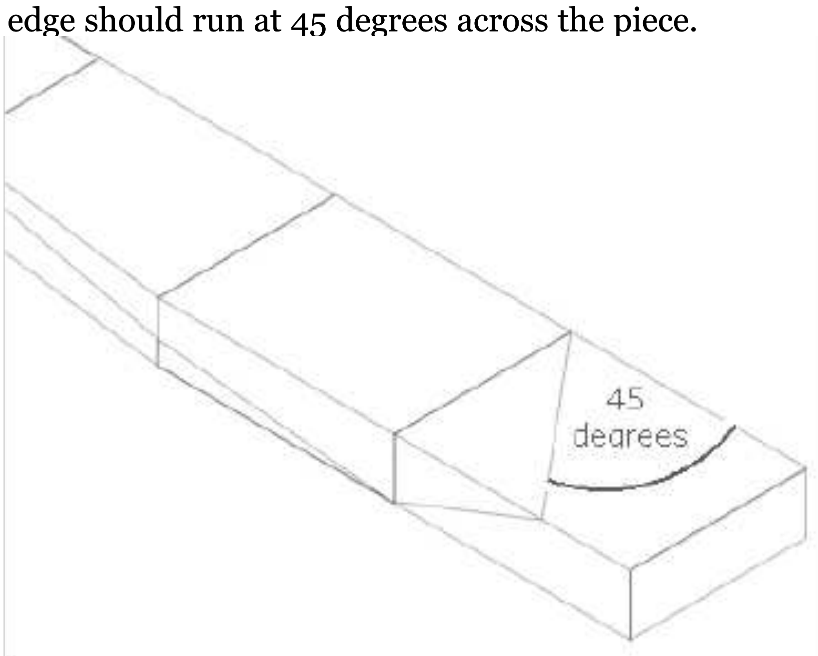


When the work piece is lying on a bench as shown above, the windward 'front' face is uppermost. The 'leading edge' is the top edge of the face furthest away. The 'trailing edge' will be marked as a pencil line on the nearer face of the piece as shown below:



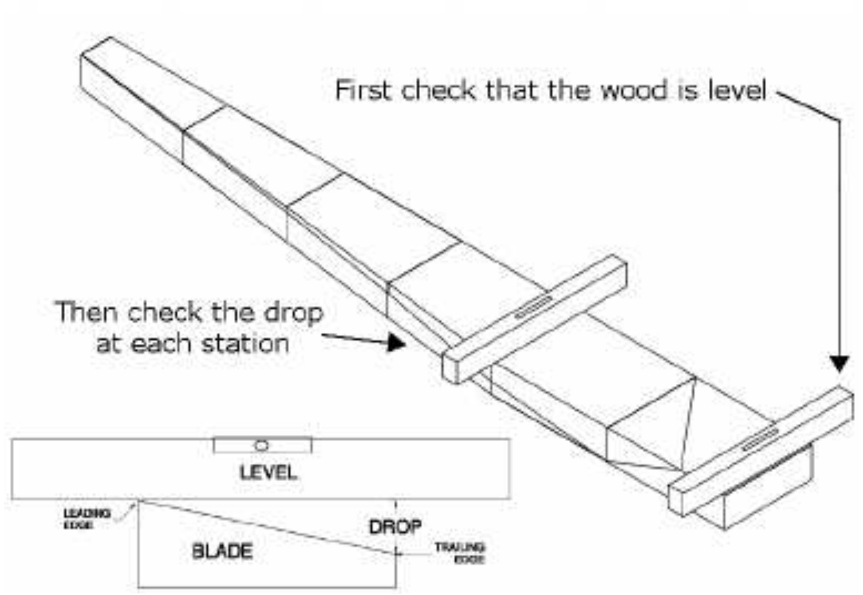
The position of the trailing edge is defined by a measurement called the 'drop' at each station. If the wood is not already warped/twisted (see right) then the drop can be measured down from the front face of the wood. Mark the drop at each station, and then draw a line to join the marks. At the last station, nearest to the root, maximise the drop to the full thickness of the available wood. Draw the trailing edge line right down to the bottom edge.

From there the cross section of the blade tapers rapidly back to the full size of the blank piece in a triangular ramp, bordered by two lines. One line starts at the leading edge and the other at the trailing edge and they meet at a point as shown. The line from the leading edge should run at 45 degrees across the piece.



Drop in mm at each station. Station 6 drop is full thickness.						
Turbine diameter	1200	1800	2400	3000	3600	4200
TIP	1	2	1	1	1	2
2		4	3	4	5	6
3	5	8	7	9	11	13
4		14	15	19	22	26
5	28	28	32	40	48	56

The drop controls the angle of the blade, which is a critical parameter. Try to be accurate in measuring and marking the trailing edge, especially in the outer part of the blade. If the face of the wood is warped then the drop will still not be accurate, even if measured as described above.



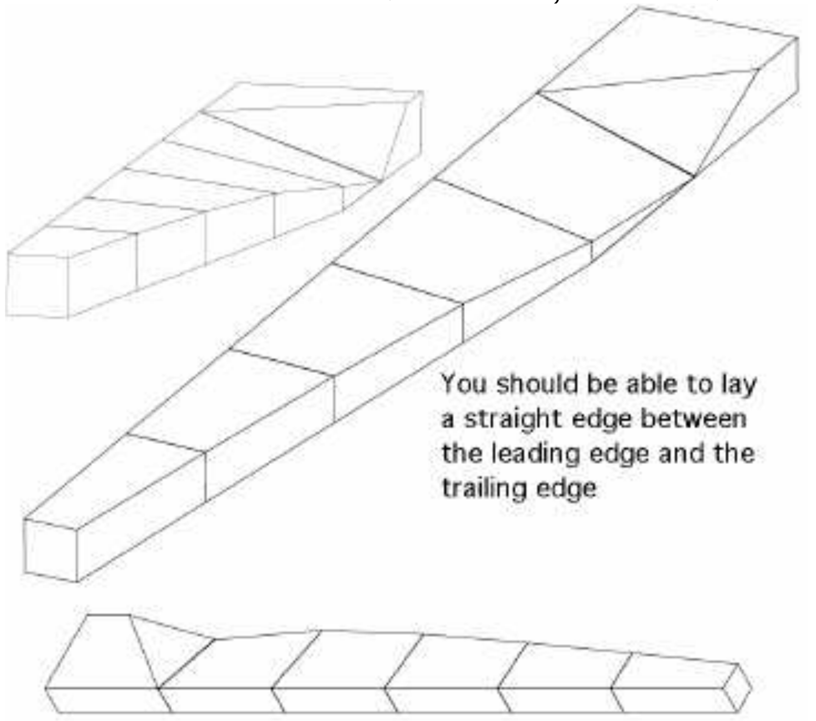
If you suspect that the wood is warped, then use a spirit level to check the drop as shown above.

First set the work-piece up such that the root area is level and then check the drop at each station along the length. Push the spirit level up with the end of a rule until it sits level when making the measurement.

This check can also be done while the carving is in progress. You can correct the drop by shaving more wood off the trailing edge, or even off the leading edge if necessary. But if possible you should try to keep the leading edge straight.

Carve away wood above the trailing edge line to create a new face

The face you are cutting extends right up to the leading edge, but take care not to cut into the leading edge itself. The face is flattish but twisted, as shown below:



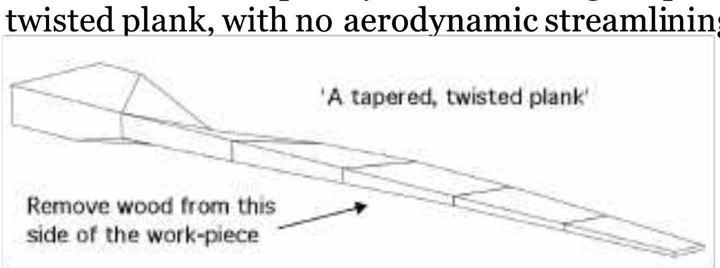
When you think you have finished, lay a ruler across the blade between the leading and trailing edges. If it cannot touch them both then you have to remove the hump in the middle of the face until it is flat.

A plane is the best tool to use in the outer part of the blade because it gives a smooth, straight finish. (Some people like to use an electric planer for the coarse cutting work.) But planes will not work in the hollow part near the root. I use a draw knife in the hollow part, but others prefer to make numerous cuts into it with a saw, and then break out the wood with a chisel (known as 'kerfing'). Use a spoke-shave to smooth it off. Some prefer the belt sander. A sharp draw knife is quickest. Try not to cut a sharp notch – make a smoothly rounded hollow that does not reach the bottom corner of the line.

As a general rule the outer part of the blade toward the tip is the part that needs careful attention to detail and you should spend time on this part. The inner, wider part of the blade is less important and can be more coarsely formed, so you do not have to take so much care here. Just try to keep all the blades looking the same, but do not worry so much about precision.

Blade thickness

Having completed the above task creating the windward or 'front' face of the blade, it is time to shave the 'back' of it down until the blade has the correct thickness. At this point you are creating a tapered, twisted plank, with no aerodynamic streamlining.



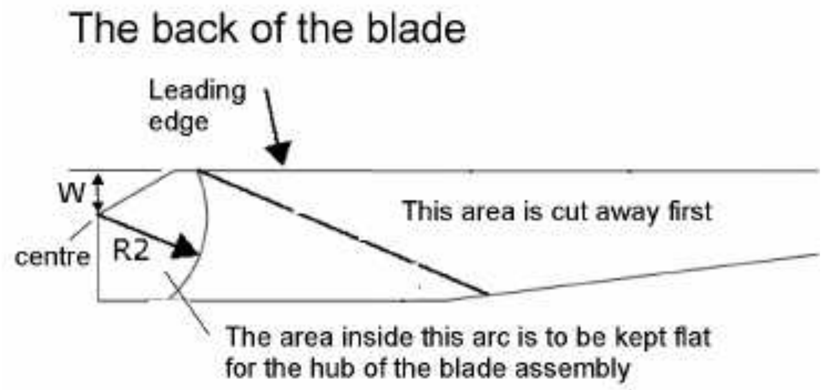
Later you will make the back of the blade curved and streamlined.

Again you must measure and mark the thickness of the blades at each station.

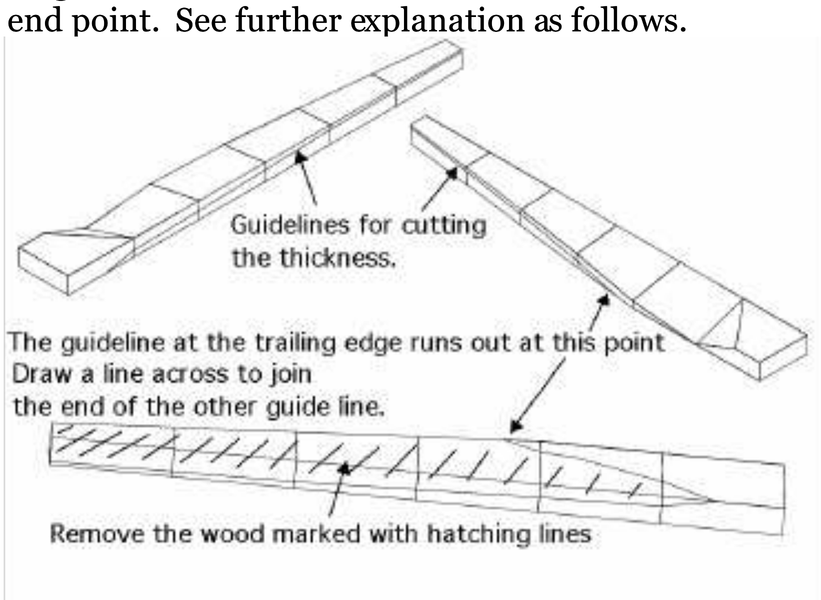
Thickness in mm at each station. THIS IS NOT THE DROP!						
Turbine diameter	1200	1800	2400	3000	3600	4200
TIP	5	6	6	7	8	10
2		8	9	11	14	16
3	10	11	14	17	20	24
4		14	19	23	28	33
5	17	20	27	34	41	47
R2	*100*	*100*	*125*	*150*	*188*	*225*

Start by drawing guidelines along the edges of the work-piece at the correct distance from the leading and trailing edges at each station. You will not be cutting the leading or trailing edges that you were working with in the previous stage. You measure the thickness from those edges, draw guidelines, and then cut away all the surplus wood beyond these lines from the back (down-wind side). This means removing most of the thickness of the work-piece at the tip.

The root of the blade will be left untouched. The centre of the blade assembly is the distance W from the leading edge at the root. (This is the same W as the width of the tip.) R2 in the above table is the radius from the centre of a circular flat area on the back that is never to be cut at all.

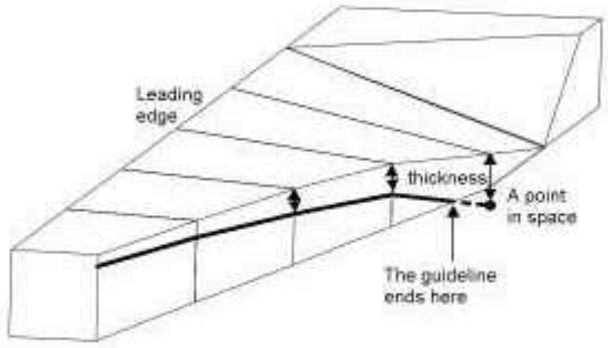


The guideline that you measure from the leading edge has to terminate where it reaches the above flat zone. The guideline along the trailing edge connects to a diagonal line across the back and thence to the same end point. See further explanation as follows.

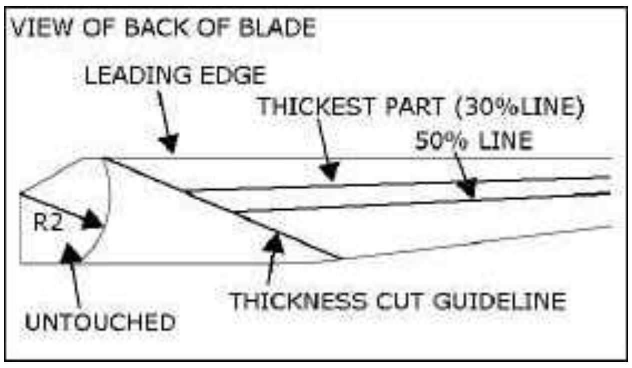


The lower drawing with the hatched lines shows the back of the wood where you must remove the surplus.

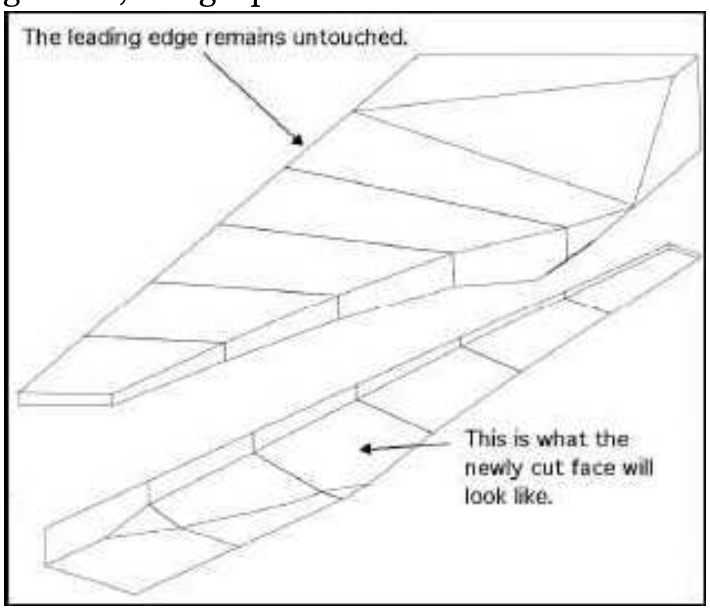
When marking the guideline beside the trailing edge, you will find that the line runs off the wood at some stage as it approaches the root where the thickness is greatest (see below). Draw the line as far as you can, heading toward a point in space where the next station's thickness would have been marked.



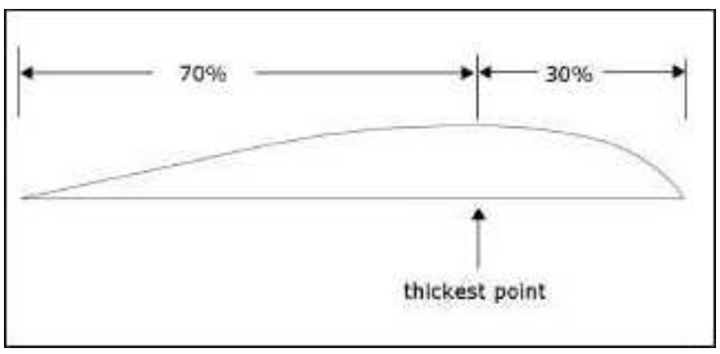
Then carry the line around the corner and diagonally across the back of the work-piece to join the end of the leading edge guideline.



When carving the blade down to the correct thickness, cut away wood beyond the guidelines to create a face between these lines. Start with rough cuts and then make it a nice straight face, using a plane where possible. As you approach closer to the lines themselves, you need to start to check the actual thickness with callipers. At this stage you can ignore the guidelines and focus on achieving the correct thickness at each station as measured with callipers directly.



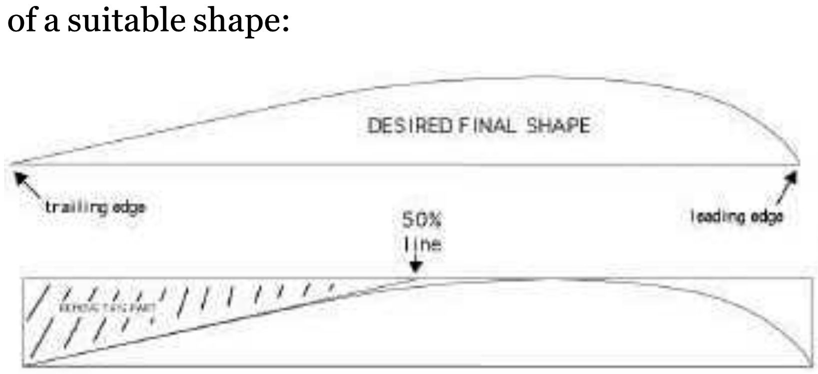
The blades do not even have to be the correct thickness all the way across their width. But try to be as accurate as you can in the area where they will finally be thickest. Check the thickness at each station at a point 30% of the way from the leading to the trailing edge as shown right. This is where you should use the callipers.



Make sure that the thickness is roughly constant across the work-piece so that the back face you are cutting is parallel to the front face you cut in the previous stage.

Airfoil shape

The blades need to have a streamlined airfoil shape to spin fast with the minimum of drag. Here is a picture of a suitable shape:



The first stage before carving it is to draw a centre line along the back of the blades (shown as 50% line in the diagrams above).

Then cut a new face that connects this line to the trailing edge, so that the trailing edge ends up sharp as shown. The width of the trailing edge should be under 1 mm. As you get close to the edge, clamp the blade sideways in a vice with the edge uppermost, so that you can see the light reflected off it and judge how much more you can safely plane off. Use a very small, sharp plane for this job.

When the trailing edge has been cut like this, you can then move on to curving off the back of the blade, aiming for a shape like that shown above.

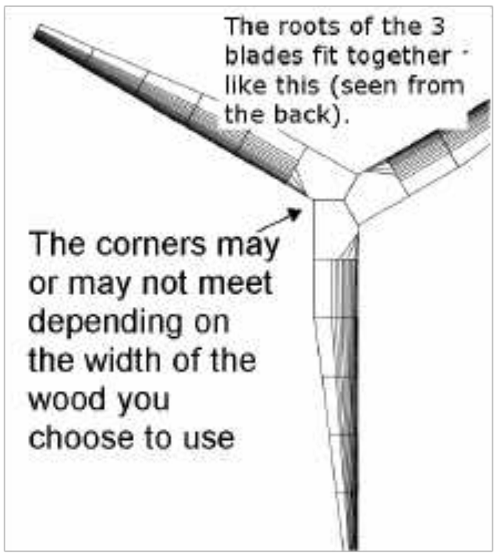
Do not cut the leading or trailing edges themselves although you will work right up to them, from the back side this time. Take care not to make the leading edge a sharp angle like the trailing edge – it should be a coarse, blunt angle. It can be a little more rounded than shown according to taste. This may help to delay stall.

Shave wood off the unwanted corner on the back, creating more corners, shave them off in turn until a smooth curve is created. Take care that the thickest point is not left as a flat spot nor cut to a sharp summit. The thickest part should have a very smooth and gentle curve. Avoid carving off any wood in the 'flat zone' described by a circle of radius R2 from the root.

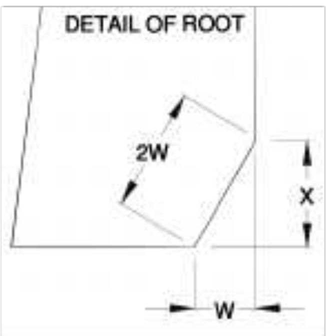
When the blades are completed and you are happy that they are a nice shape, then cut off any surplus length that you may have included beyond the tip station. Use a very fine saw blade to cut it off, working inward toward the middle of the piece from both edges, so as not to splinter the wood.

Hub assembly

Cutting the 120 degree angles at the roots



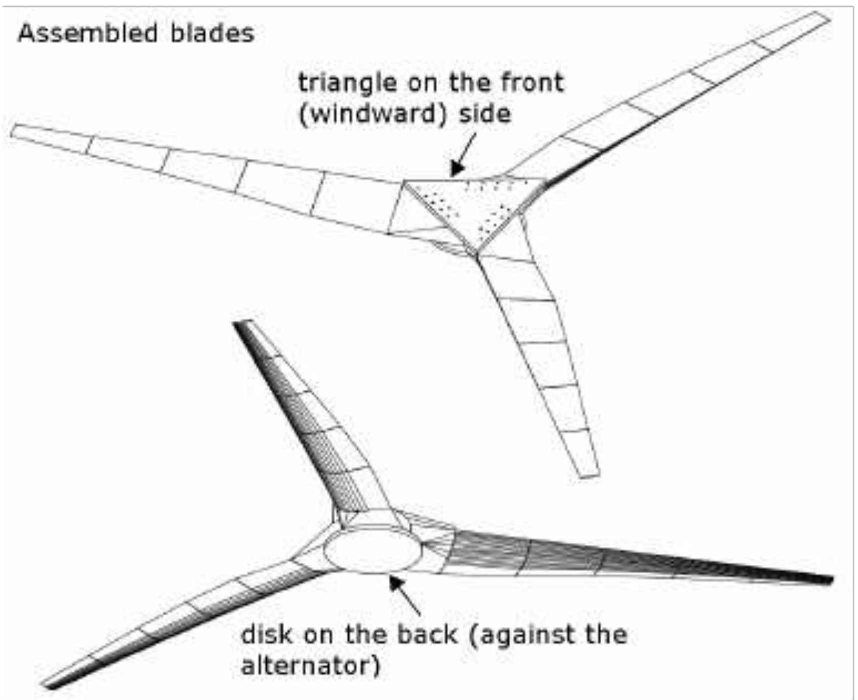
Now if you have not already done so you must cut the triangle out of the root of the blade so that there is a 120 degree point on the end of each blade so that they all three fit together.



The dimensions W and X are given in the table of dimensions of the template at the beginning of this section (page 16).

The diagonal line labelled "2W" is twice the length of the tip width W.

Note that the side corners do not usually meet exactly. If the wood is wide it may not look exactly like the drawings.



The plywood pieces that sandwich the blades.

The blade assembly is held together by two plywood plates that are screwed onto the front and the back of the assembly. The front piece is triangular and the rear is a disk. I like to use birch plywood. Find something tough and durable. Make sure it is protected from the local weather conditions so it does not suffer in heat, ultraviolet or changing humidity. Metal can also be used.

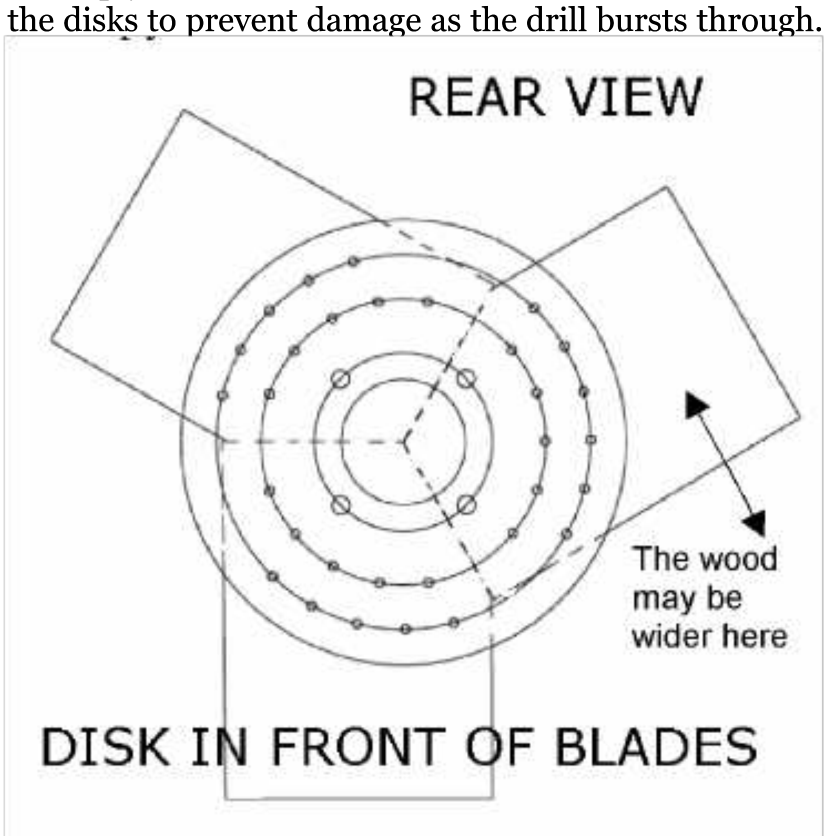
Dimensions of plywood pieces

Turbine diam.	1200	1800	2400	3000	3600	4200
thickness	9	9	12	12	18	18
Disk diameter	200	200	250	300	375	450
Triangle side	268	274	357	446	536	625
Stainless steel screws	30 @ 25mm	40 @ 30mm	50 @ 30	60 @ 30	60 @ 50mm	75 @ 50

Marking out the holes in the plywood

The plywood pieces must be pre-drilled with patterns of holes for the mounting studs and the 5-mm screws that hold the blades together.

Start with the holes for the long mounting studs, which pass through the blades and the magnet rotors in the alternator. Draw a circle on the centre of the disk, using the same diameter as the large hole in the magnet rotor. Now place a magnet rotor on top of the disk, centring it on the circle you have just drawn. Clamp them together, and drill through the magnet rotor holes so as to create an identical pattern of holes in the plywood disk. Place some wooden waste behind the disks to prevent damage as the drill bursts through.



Next draw more circles between the mounting holes and the outside of the disk, so as to lay out the screw holes evenly.

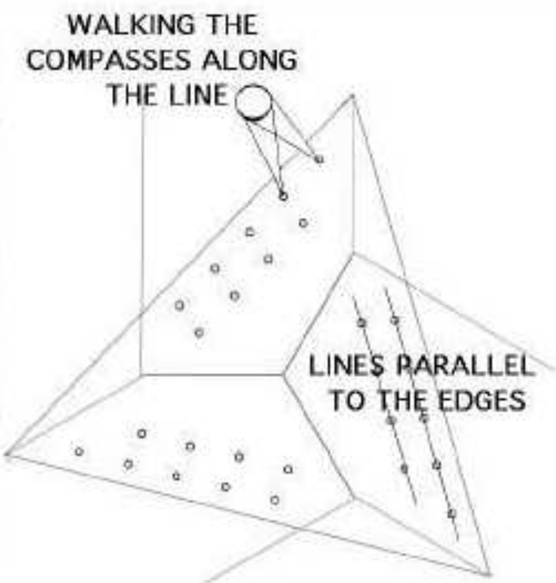
On one of these circles, you will take your compasses and walk them around the circle to mark six equally spaced points. Use three of these six points to mark out the three lines where the blades will meet each other. Avoid getting mounting holes or screws on the join between blades. If there are four holes then the best

way to lay them out is to start exactly midway between two of the mounting holes.
Lay a blade on the plywood in position, and draw the shape of its outline. Do this three times so you can see the area where the blades touch the plywood.

Now set the compasses to the desired spacing of the screws (say 25 mm), and walk around the arcs that you have drawn, to mark a pattern of hole positions. Avoid making screw holes very near to the edges of the blades.

Drill clearance holes for the screws (holes large enough that the screws pass through without catching the plywood) and countersink them so the screw heads are flush with the plywood. Drill these holes with a drill-press (pillar drill) if possible so to as keep them perpendicular to the surface.

Do not drill the larger mounting holes in the **triangle** at this stage, but do consider the circles where these holes will be, so as to avoid putting screws there. Again avoid making screw holes too near to the edges of the blades. Draw some parallel lines and lay out a neat pattern of screw holes on the triangle.



<u>*Assembling the blades*</u>

Find a level floor area large enough to lay the blades out on face down, with their 120 degree roots meeting at the centre. Or place the blade roots on a level table and support each tip so that the leading edges are level.

Centre the plywood disk on the arcs you drew to define the flat area (radius = R2). Drill a small (8 mm) hole at the centre of the plywood disk so you can check that it is centred where the blades meet. Make sure that the blade tips are equally spaced apart.

When you are happy that the layout is symmetrical and the plywood disk is perfectly centred, fix the disk down with a few screws (say 3 per blade), bearing in mind that it will be removed later.

Turn the assembly over and fit the plywood triangle to the front permanently, with all its screws. Support the blade tips so that all three blades are level while doing this.

Now turn the assembly back over and mark the positions of the mounting holes as follows. Placing the tip of a drill in each hole in the plywood disk, drill just a small dimple in the blade roots at each hole position. Remove the disk so that you can drill 'clearance' holes centred on the dimples. The clearance holes should be at least 25% larger diameter than the mounting studs, and go right through the blades and out through the triangle. The studs will be a tight fit in the plywood disk, but there is no virtue in making them a tight fit in the whole assembly. Drill the clearance holes perpendicular to the plywood surface while resting the plywood on some scrap material so that the drill does not burst out and damage the surface.

Get a couple of friends to check that your drill is vertical by holding squares in front of them as shown in the photo. Finally put the disk back onto the rear of the assembly and screw it down using all the screws.

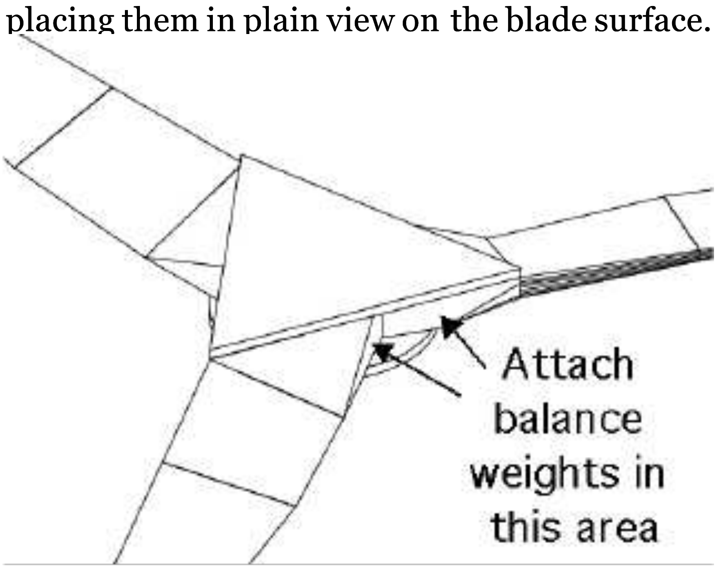
Push a piece of threaded rod into each hole and verify that it is square to the plywood. If necessary the holes can be enlarged from the front until the studs pass through squarely.

You can dismantle the assembly for painting or transport. If you wish to glue it together then you can do so, but there is no need for this. The screwed-together assembly is very strong. In some climates, plywood has as short life, and it may be necessary to use metal or plastic plates instead. But well painted plywood lasts well in most places. Some people like to fit a nose-cone or 'spinner'. This can improve the looks of the turbine and protect the plywood.

Balancing

The centre of gravity of the blade assembly must be at the centre of rotation, or the wind turbine will shake and parts will fall off (usually the tail is the first casualty).

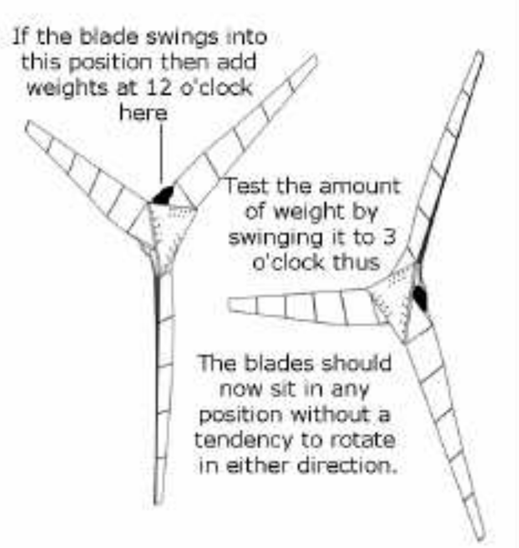
Even if it has been perfectly carved, the centre of gravity of the blade assembly will be off-centre because the density of the wood will not be uniform. It is not hard to move the centre of gravity by attaching small weights (pieces of lead flashing used for roofs, or fishing weights, or even off-cuts of steel). A good place to attach weights is between the blades and behind the plywood triangle. But the exact position depends on where they are needed. Sometimes it is hard to avoid placing them in plain view on the blade surface.



Balancing in position

The simplest way to balance the blades well is to fit the blades in position on the alternator rotors, and balance the entire rotating assembly. This has several advantages: it also balances out any eccentricity of the alternator itself, and it makes no assumptions about the centre of rotation of the blade assembly that could be false. However this can only be done accurately indoors, because the slightest wind will make it impossible to detect an imbalance.

Ideally there should be no bearing-seal and little or no grease in the bearings during this procedure. The first stage is to simply watch how the blades sit of their own accord. In most cases they will swing like a pendulum toward a preferred position (where the centre of gravity is lowest).

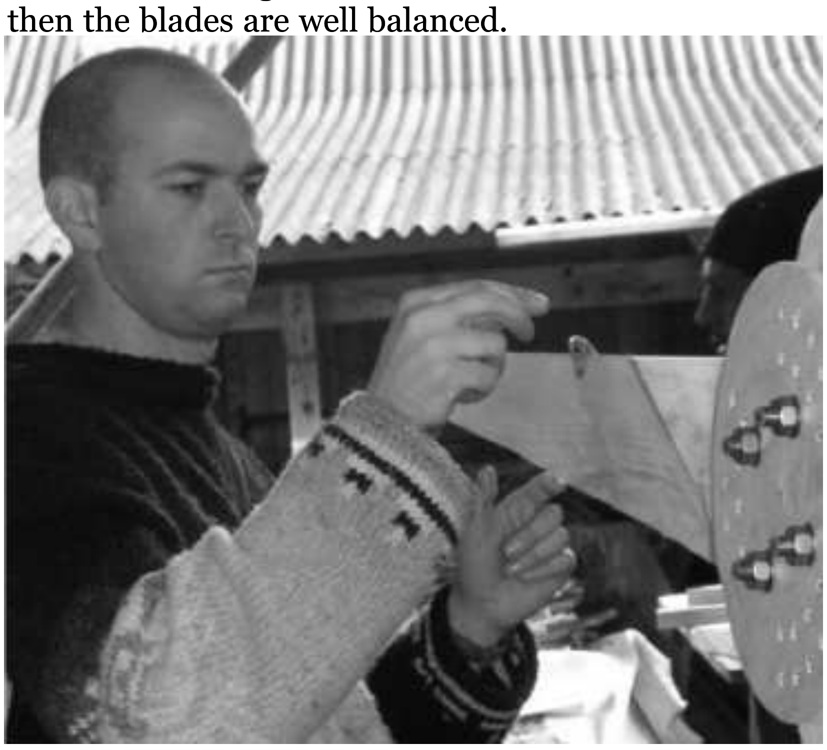


Add some weight above the centre (opposite to the centre of gravity). Check for success by looking for any remaining tendency for the blades to rotate spontaneously in any direction from any position.

At this stage the blades will probably be well enough balanced to run smoothly, but if the bearings are stiff then it may be hard to do a good enough job. Either way it is easy to do a further test as follows.

Fine balancing

Find a small weight that can sit on the edge of a blade, or attach the weight to a hook. Set one blade horizontal and rest the weight on it to see if it will start the turbine turning. If it fails to start, move the weight outward toward the tip of the blade until you find a position where it just has sufficient torque to start up against the friction. Make a mental note of the position and try this test on the other two blades. If the distance along the blade is the same in each case then the blades are well balanced.

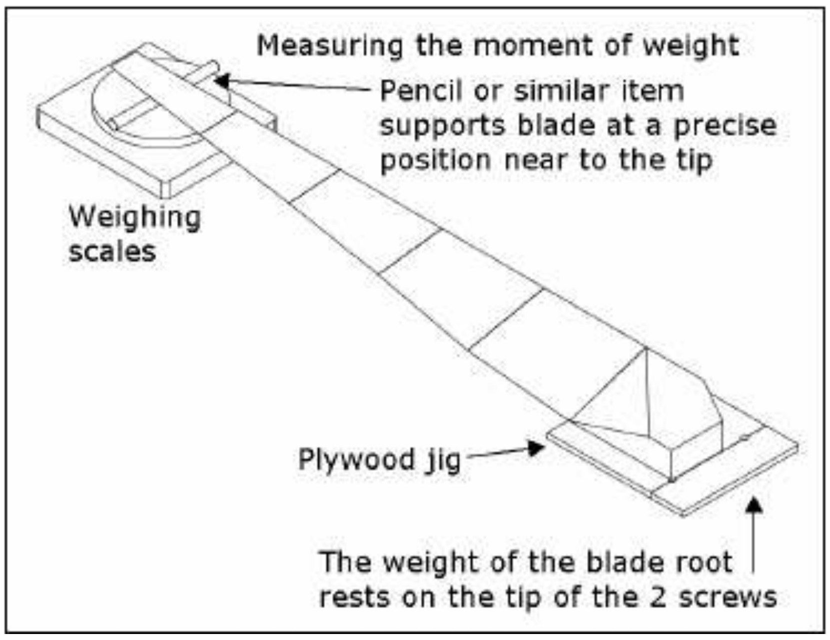


If there is one blade where the weight does not have to be moved out very far before the blade starts to descend readily, then this blade is a little too heavy. Add some weight in the recess behind the triangle on the opposite side of the blade assembly from this heavy blade so as to correct the position of the centre of gravity. Repeat the test and adjust the size of the weight accordingly until you have a situation where each blade can be started downward by applying the test weight in about the same position.

Alternative ways to balance the blades

If the blades are too big to assemble inside a sheltered space then you may have to balance them on their own. This will not work out unless the blades are very carefully centred on the alternator because any error in the positioning of the assembly as a whole will defeat the whole effort.

You can compare individual blades with each other to check that the assembly is going to be balanced. But it is not enough to simply weigh each blade. What you are looking for is the 'moment of weight' of each blade. The simplest way to compare the moments of weight is to set the blades up so that they rest on a pivot at the root. You then measure the weight of the tip of the blades and compare these readings. Take care to take each weight measurement at the same distance from the root, so that you compare the moments of weight based on the same radius of action.



In the diagram above, a plywood jig is used as a pivot for the root of the blade. There are two pivot screws through the plywood on a line that meets the root end of the blade. Screw this plywood to the underside of the blade so that this line just touches the root. Rest the weight of the root on the points of the first two screws. Weigh the tip using a pencil or similar item on the scale pan to control the exact point at which you take the weight measurement. Use the same setup for each blade. If there is any difference in the moments of weight, then add some weight to the lighter ones among the 3 blades so as to end up with equal readings.

Balancing on a spike

If it is possible to assemble the blades inside a sheltered space lying horizontally then you can balance the assembly by sitting it on a spike. Drill a small dimple hole in a piece of metal plate, and screw the plate to the back of the plywood disk. The dimple must be at the exact centre of the blades as they will be mounted (the centre of the circles of mounting holes).

Set up a spike (a centre punch or similar item, held in a vice maybe) and carefully rest the dimple onto the tip of the spike. Support the blades exactly level in both directions and observe which direction they tip over. Add weight to the opposite side and try the test again.

This is a sensitive test, but it depends critically on getting the correct centre in the first place.

When setting the blades up level, place a support under each of the three tips so that there is a very small amount of free movement. Then all you have to do is observe which blades are resting and which is lifted off its support. In the end it should be possible to rest the blades on any two of the three tips.

Dynamic balance

The blades have to rotate in the same plane, or there will be a dynamic imbalance. Check that the tips of the blades track each other through space by placing an object such as a hammer handle close to one blade tip. Then turn the blades until another tip comes close to the handle and judge whether they are following each other. A small error (under say 1% of blade length) is no cause for concern but a large error in blade tracking is worth correcting. It is hard to find a thin enough packing washer to adjust the mounting of the blades by a small enough amount. It is simpler to over-tighten the nuts on one side so as to force the blade into line.

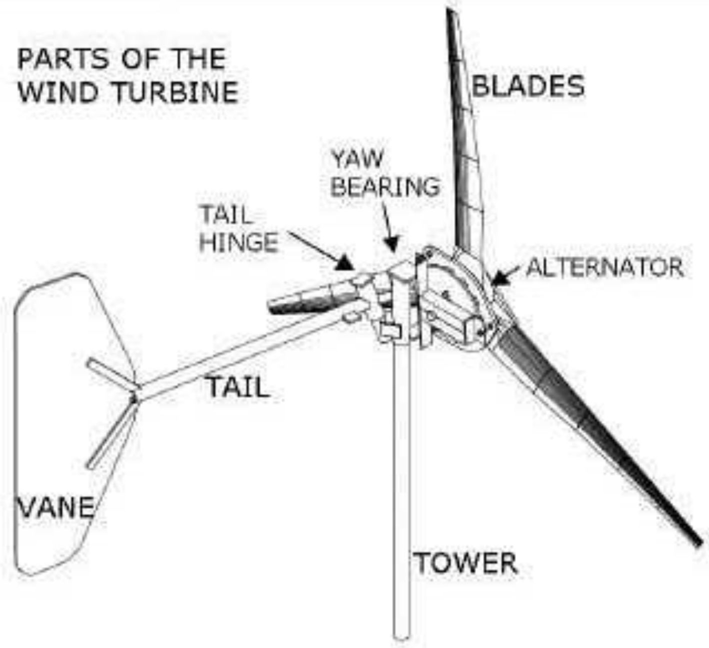
Painting and finishing

Good quality exterior wood paint is the best choice for the blades. Varnish will suffer from UV light and tends not to last long although it looks great. Make sure the wood is well primed, add several top coats, sand them down and apply a final coat of gloss paint.

Some people use linseed oil and nothing else to treat the blades and this works very well. It's necessary to put more oil on from time to time.

The leading edges of the blades may suffer some damage over time, especially if the turbine is allowed to run free without a connection to the battery to control its speed. You can buy special 'leading edge tape' for aircraft propellers (see list of suppliers on page 62), but this does not always stick well. Or rebuild the edge with epoxy and filler powder for a robust finish. Another idea being tried is 'G8 polyurethane sealer' as a coating on the leading edge.

Mechanics



There are drawings of all the types of turbine on page 3 and on pages 64 and 65 at the back of the book.

The yaw bearing

As the wind direction changes, the wind turbine has to swivel or 'yaw' on the tower top to face the wind and catch its power. The 'yaw bearing' is the interface between the turbine and the tower.

The yaw bearing consists of two pieces of steel pipe – one inside the other. The smaller, inner one is a short stub welded to the tower top. You need to weld a heavy piece of plate across the top of the larger outer pipe. The plate bears on the top of the tower stub and prevents the turbine from slipping down. You will need to keep this contact surface well greased. In wet places it is also worth keeping the rain out of the yaw bearing.

For heavy turbines it is a good idea to also cap the inner pipe with a circular steel washer to provide a larger bearing surface. Or simply to place one or two washers on top of this tower top stub. The outer pipe fits over this tower top stub and rotates freely.

Here are the recommended sizes of steel pipe expressed as 'nominal bore' sizes in inches with the overall diameter for each nominal size.

YAW BEARING PIPE SIZES			
Turbine diameter	1200	1800-3000	3600/4200
TOWER TOP STUB	1" NOMINAL 33.4 mm	1.5" NOM. 48.3 mm	2.5" NOM. 73 mm (76)
OUTER YAW PIPE	1.25" NOM. 42.3 mm	2" NOMINAL 60.3 mm	3" NOMINAL 88.9 mm

The inner pipe takes a critical load, especially on turbulent sites where a speeding rotor yaws sharply and creates high gyroscopic bending forces. Find pipes with thick walls for the tower top stub.

This style of yaw bearing is crude but effective. The sloppy fit is no problem. More sophisticated bearings tend to fail and seize up. And the friction damping of the crude bearing is beneficial in reducing idle yawing motion in light winds that can lead to problems with twisting up the wiring to the ground.

Wiring is again very simple and crude. Wires from the alternator are passed through a hole at the centre of the yaw bearing cap and allowed to hang the length of the tower. It is important to use sturdy but flexible wires and anchor them securely. Leave a nice loop of slack at the bottom end. On a good windpower site they will twist up only gradually over a period of years.

The photo shows a yaw bearing pipe with a steel plate on top. The C shaped arc of pipe provides a support for wires that pass down the hole at the centre of the yaw pipe. The wires will be secured to this support with cable ties that prevent them moving and chafing.

Some people prefer to make sliding contacts (brushes) instead of allowing the cables to twist like this. If the slip-rings and brushes are very well made and properly weather-sealed then this can be a good alternative. I would recommend a more precisely fitting bearing in such cases. But a crude yaw bearing with hanging wires will function very well for years without attention on a good site where the wind is not too turbulent. Simple solutions are often the best ones. On turbulent sites this system can still work provided there is a plug and socket to allow untwisting of the cable when necessary.

The alternator

The alternator consists of one or two magnet-rotors that turn with the blades, and a stator that is mounted on a stationary frame. The first item to select when building the mechanical parts of the alternator is a bearing hub to support the spinning magnet rotors and blades.

Choosing a hub

A wheel bearing hub from a car or van is a good choice for a wind turbine alternator. The smaller machines normally use a car or trailer hub with four holes (wheel studs) on a 4 inch or 100 mm circle. The Golf for example has a simple rear hub.

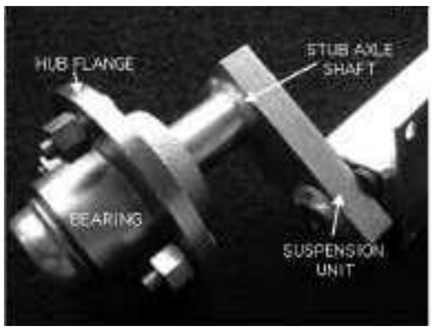
The larger three machines could use bearings from a van (Ducato, Boxer, Master etc.) with five holes in the flange. The bearings are a potential source of problems, especially on high wind sites, so it pays to get a good bearing hub.

The photo shows a van wheel hub (left) and its stub axle shaft with tapered roller bearings (right). Here are some sizes of hubs for larger turbines:

		DUCATO, PRIMASTAR, BOXER, TRAFIC, VIVARO
	SPRINTER, MASTER, MOVANO	
PCD	130 mm	118 mm
distance between bolts	76.4 mm	69.4 mm
number of bolts	5	5
bolt diameter	14 mm	14 mm
Suggested turbine diameter	3600	3000

Car and van hubs are available from scrap yards in all shapes and sizes. The main thing to look for is a simple mounting at the rear – ideally a flat flange at the base of the stub shaft, that can be bolted directly to the turbine alternator frame. The brakedrum needs to be removed. Often it is only held in place by a small screw, and you can knock it off with a hammer once this has been removed. In some cases it is an integral part of the hub, and has to be cut off with a grinder and a cutting disk, cutting just outside the circle of wheel-stud holes. Take care not to burn out the grinder.

Trailer hubs are a convenient choice because they are new items and can often be bought from the internet. Make sure that you get a stub shaft to go with the hub. The base of the stub shaft is often a simple 'spindle' or enlarged shaft, that has to be welded into a large hole cut in the alternator frame. It is easy to cut large holes in steel with a suitable high quality hole-saw.

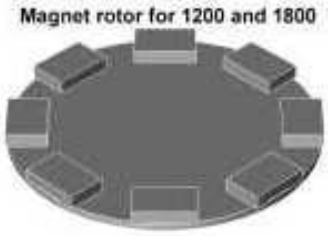


The photo shows a small trailer hub, whose axle/shaft is welded into a suspension unit. You should buy a 'loose stub axle' and weld it into the alternator frame in a similar fashion. You can knock out the wheel studs with a hammer, and mount the magnet rotors on it, in place of a wheel. The single magnet rotor of the 1200 turbine has to mount on a true surface on the back of the flange.
Bearing hubs are usually sealed, but this is a mixed blessing. The rubber seal keeps out dirt and moisture, but makes the bearing stiff to turn. Some people on low-wind sites prefer to remove the seal, because the turbine is more productive in low winds without one. However this is likely to shorten the life of the bearing.

Tapered roller bearings are easy to dismantle for cleaning. Remove the dust cap and the big nut. The hub and bearings will slide apart. After cleaning with petrol/gasoline, grease liberally but do not pack 100% with grease. Reassemble the hub and tighten the nut. Slacken the nut until it turns freely without excessive play. Lock the nut with a pin.

Mounting-stud sizes for the smaller three turbines should be 10-mm diameter (M10 thread), but the larger ones should be 12 or 14 mm. If the existing holes are too small, then drill them out to a larger size. If they are too large then you can use larger studs or find suitable pipe to act as bushes. Measure the hole spacing (pitch circle diameter or PCD) with great care, and make a drawing. Order the steel disk from someone with a profile cutting machine. Bear in mind that 100-mm and 4" PCD are both common sizes, and are not the same!

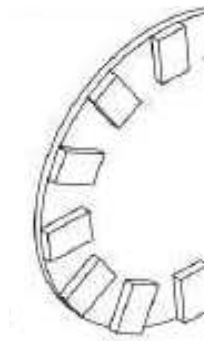
Magnet rotor for 1200 and 1800



Magnet rotor disks

The smallest turbine has just one disk. The 1800 has two steel disks, but only one has magnets fitted to it.

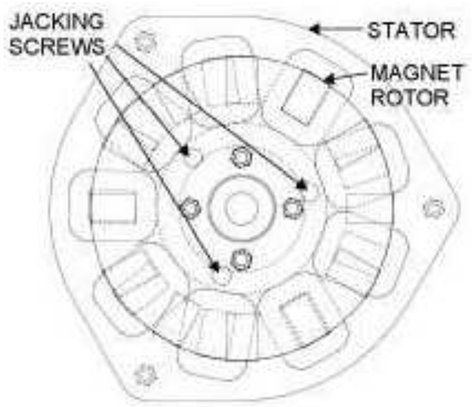
All the other turbines use two magnet disks They have magnets arranged radially as shown on the right.



STEEL DISK SIZES mm			
Turbine dia.	1200 (one)	1800	2400
DIAMETER	230	260	300
THICKNESS	6	6	8
Turbine dia.	3000	3600	4200
DIAMETER	350	400	450
THICKNESS	10	10	10

The disks have to be made of steel, not aluminium, plywood or stainless steel, as none of these have the right magnetic properties. They will need a good protection against rust if used in a coastal situation. Paint or powder coat the disks before they are cast in resin.

Disks can be flame-cut, or sheared in polygonal form with a guillotine, but these days, in the developed world, it is best to have them cut out by a specialist CNC profile cutting machine with a plasma arc, water jet or laser. This is very tidy, and should not be expensive. One advantage is that you can have the mounting holes cut very precisely. If this is impossible then by all means use oxy-acetylene, and then drill the plates out by placing them on the wheel hub and drilling through the hub's holes. Never attempt to drill the holes by measuring and marking the hole positions. This is never accurate. Drill through the existing holes in the hub, placing a bolt in each hole after you have drilled it.



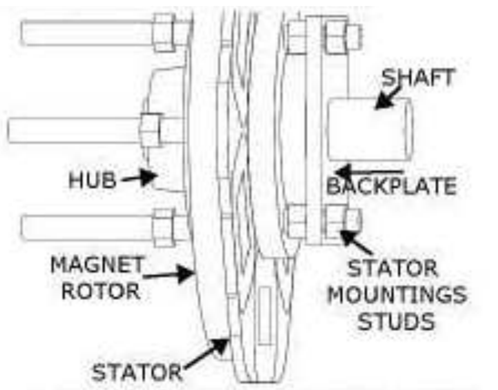
Take care to make the central hole large enough to clear the hub comfortably so that the disk sits flat on the hub flange. In some cases it is best to fit one disk to the back of the hub flange, but this is not easy unless the flange has been machined at the back. In some cases the hub itself can be reversed on its shaft, but this has implications for seals and dust covers.

Drill and tap one of the disks in three places so that you can use jacking screws. See pages 45 and 48 for more assembly details.

Alternator frame

The alternator frame supports the stub shaft that carries the hub. It also supports the stator. The frame in turn is supported by the yaw bearing. The centre of the alternator needs to be offset sideways from the centre of the yaw bearing so as to make the turbine yaw away from the wind (under the control of the furling tail described later).

The frame of the smallest turbine is simply a small backplate, because the stator mounts are at the centre.



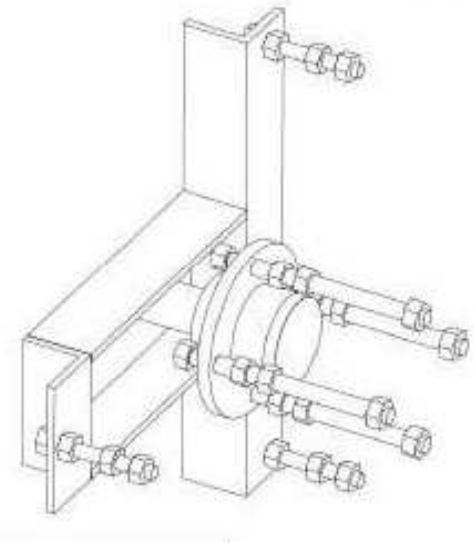
ALTERNATOR FOR SMALLEST TURBINE

Frames for all the other turbines are made from angle-section steel, in a T or an H shape, depending on the number of stator mounting points.

The stator mounts are the short studs with nuts in the drawing. The rotors and blades will mount on the longer studs in the hub. Two pieces of steel angle make a channel section with a flat surface in the middle.

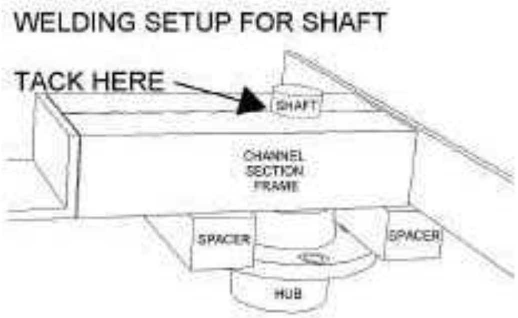
If the shaft has a flange, then you can bolt this flange onto the flat surface.
You should try to keep the magnet rotors close to the frame so as to keep the stator mounts short, and this can affect how far forward you mount the shaft Sometimes it's better to pass the shaft through the flat surface, and to bolt the flange on from behind.

If the shaft has a spindle rather than a flange then you can make a big hole into the same flat surface using a hole saw and weld in the spindle. Or if you have no saw, you can grind out two semicircular hollows in the two pieces of angle (B and C below) prior to welding them together.

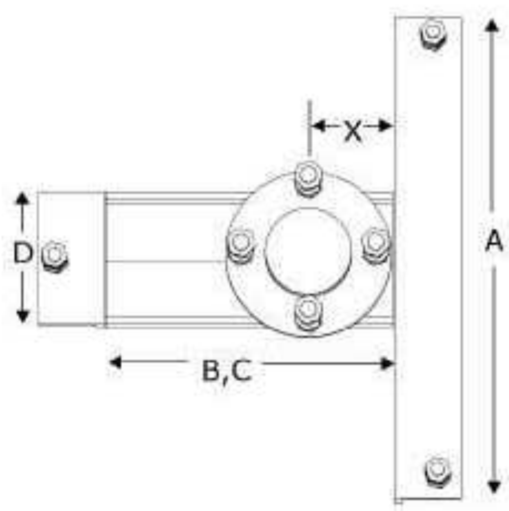


Make sure that the stub shaft is central in the alternator frame and mounted exactly square to it. Use spacers to keep the spindle square to the frame while tack welding. The spacers should be chosen to allow clearance for any magnet rotor and nuts behind the hub flange.

Start with three small tacks, bearing in mind that steel contracts as it cools. If it is not tacked on square, then grind off the tacks and try again.



The 1800 – 3000 turbines use a T shaped frame for 3 stator mounts. Their stators have 3 mounting points.



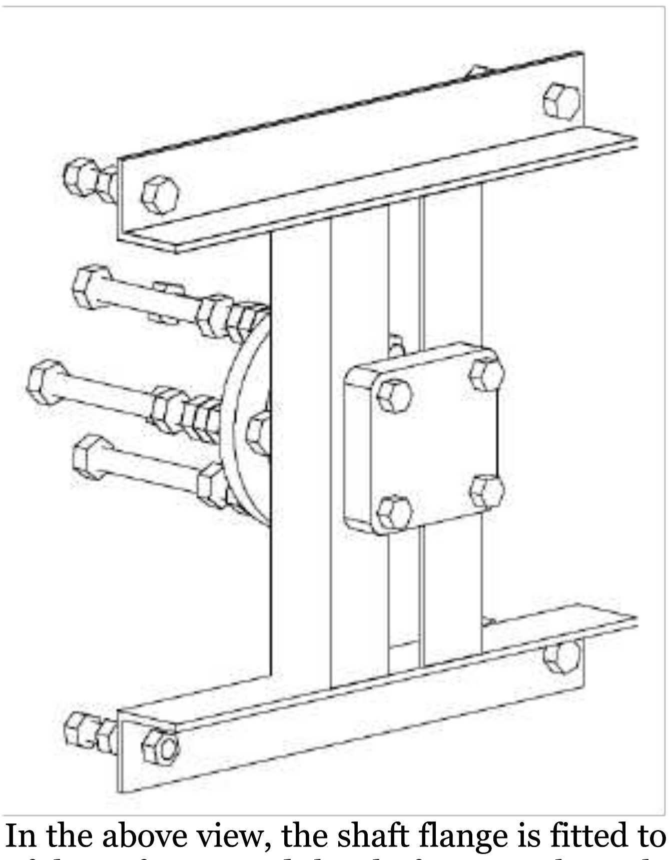
FRAME DIMENSIONS mm - 50 X 50 X 6 ANGLE			
Turbine diameter	1800	2400	3000
Length of upright A	344	353	411
Channel pieces B,C	203	216	267
End bracket D	100	10	100-130
Position of shaft X	57	65	82

Cut the 4 pieces A, B, C and D. Weld B and C together in a channel. A and D go on the ends. Take care to make the T square and symmetrical. The stator mounting faces must be in the same plane. Lay the frame face down on the bench while welding

In the case of the 3000 diameter turbine the hub might be larger, so you may have to spread B and C apart instead.

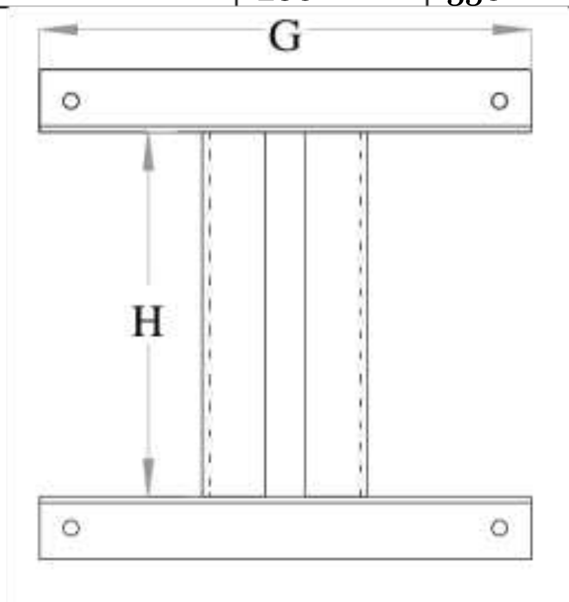
X is the distance of the shaft centre from the upright piece.

The larger turbines with 12 coils have 4 stator mounts and the frame is H shaped. The channel formed by the two pieces of angle has to be wide enough to encompass the hub, which often means that a gap appears between the two pieces of angle as in the drawing below.



In the above view, the shaft flange is fitted to the back of the H frame, and the shaft passes through the frame. This is a good way to keep the stator mounting studs short where the shaft is long. Another trick is to mount the rear magnet rotor on the back of the hub flange. You can adjust the position of the magnet rotors relative to the frame in various other ways. For example you can use nuts as spacers between the frame and the shaft flange or between the hub flange and the magnet rotor. I like to run the back magnet rotor close to the steel frame so as to keep the stator mounts as short as conveniently possible.

FRAME DIMENSIONS 50 x 50 x 6 mm ANGLE		
Turbine diameter	3600	4200
G	380	430
H	280	330



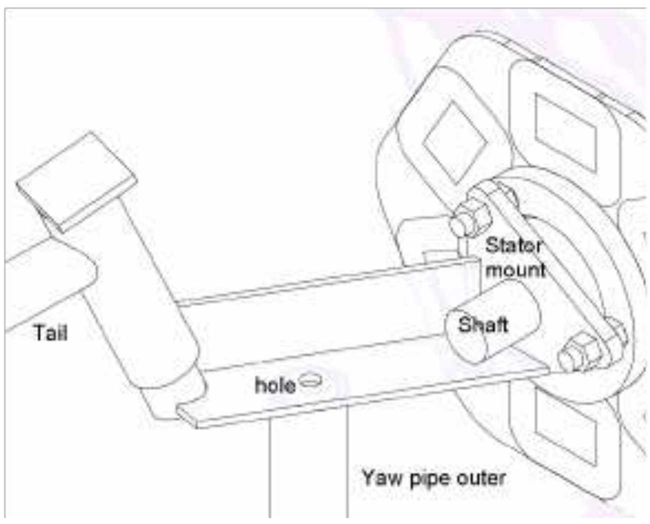
Mounting the alternator to the yaw bearing

The alternator frame must be strongly welded to the yaw bearing. The shaft centre must be offset to one side to suit the furling system.

OFFSET DISTANCE LATERALLY FROM ALTERNATOR CENTRE TO YAW CENTRE IN mm			
Turbine diameter	1200	1800	2400
OFFSET	60	100	125
Turbine diameter	3000	3600	4200
OFFSET	150	200	250

The alternator frame is either tilted slightly (4 degrees) or cantilevered forward (or both) so as to achieve ample clearance between the blade tips and the tower. On turbulent sites it is not uncommon for gyroscopic forces to push the blade tips back toward the tower during sudden yaw movements.

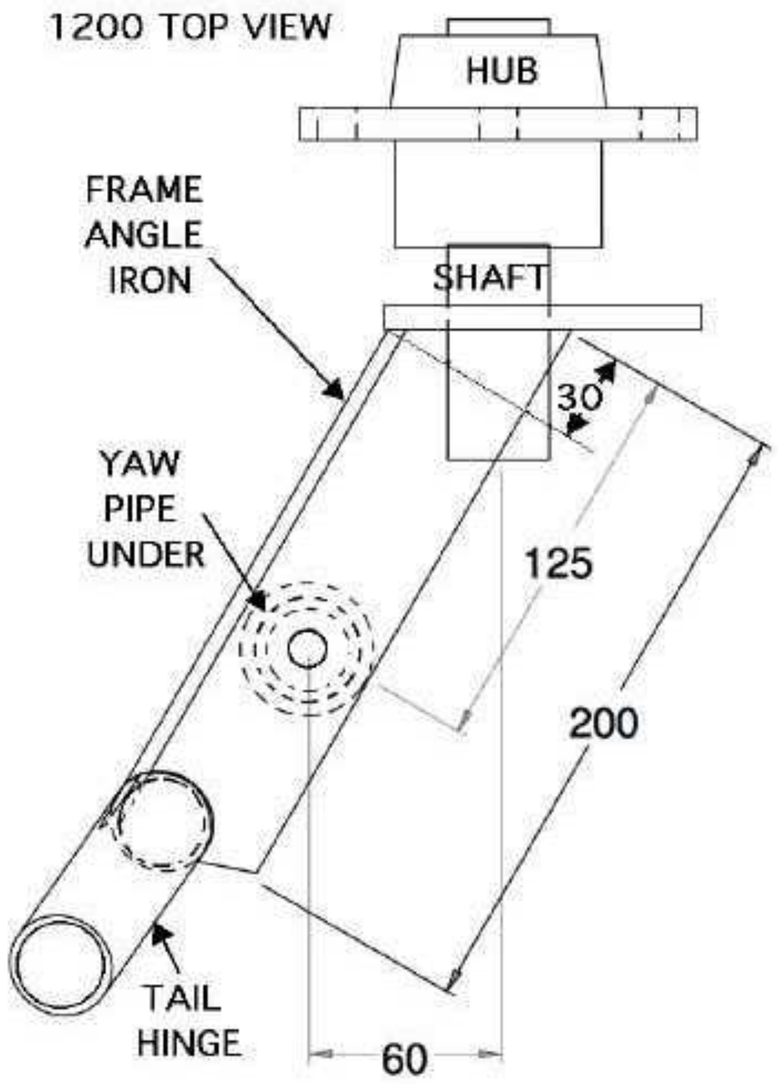
1200 machine



The frame of the smallest machine is very simply a length of steel angle (50 x 50 x 6 mm) that supports the alternator backplane at one end, and the tail hinge at the other.

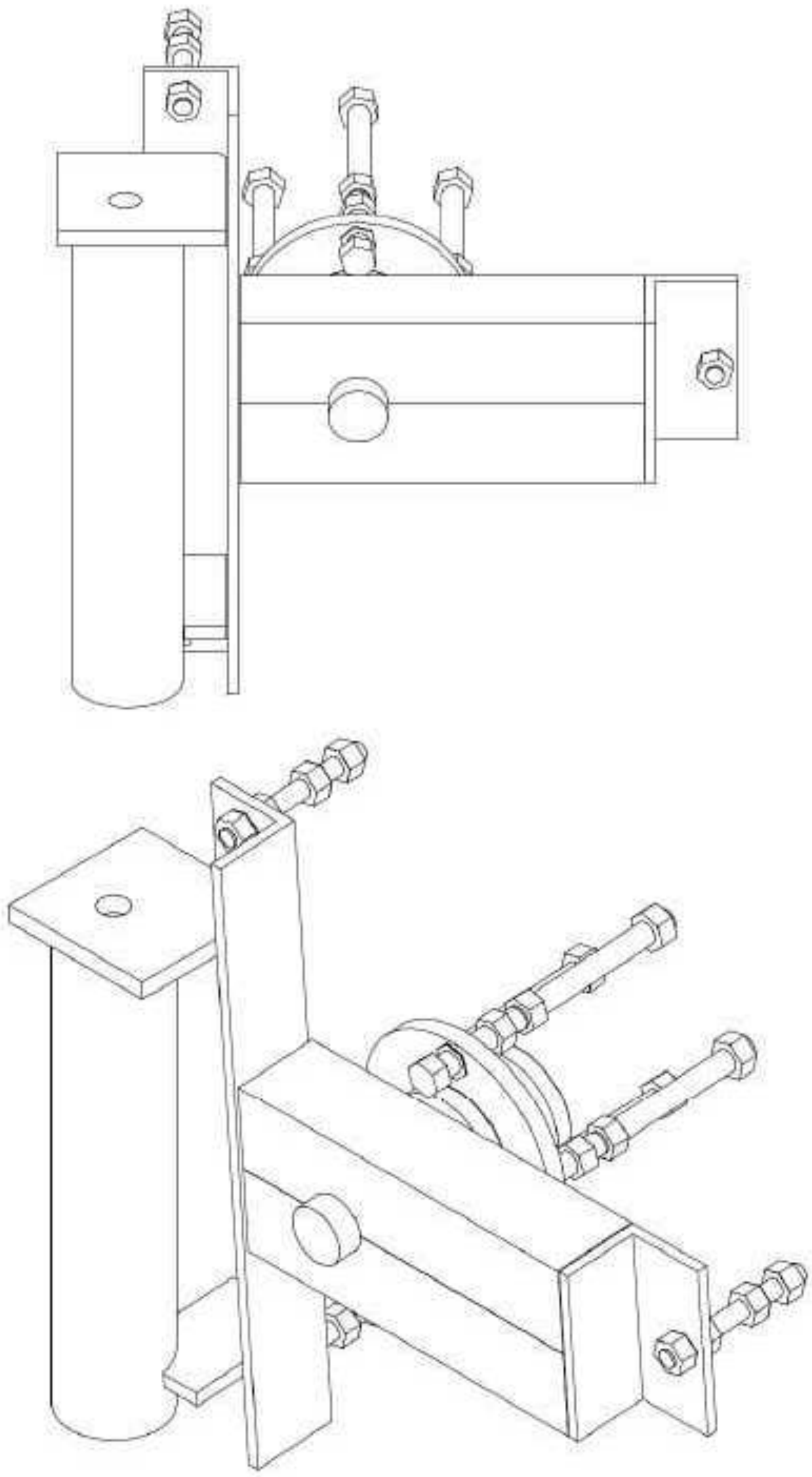
Overall length is 206mm. The alternator end is cut off at approx. 30 degree angle as shown on the next page (30 mm off square).

See pages 3 and 64 for more views of this turbine.



The top plate of the yaw bearing, needs a central hole for wiring. The plate extends beyond the yaw pipe sideways to create a gap 'I' between the pipe and the alternator frame, and forwards a distance 'K'. The lower bracket shown on the left of the sketch has the same 'I' dimension but also extends a larger distance 'J' from the pipe so as to kick the bottom of the alternator frame outward. This creates the 4 degree angle between the alternator and the vertical.

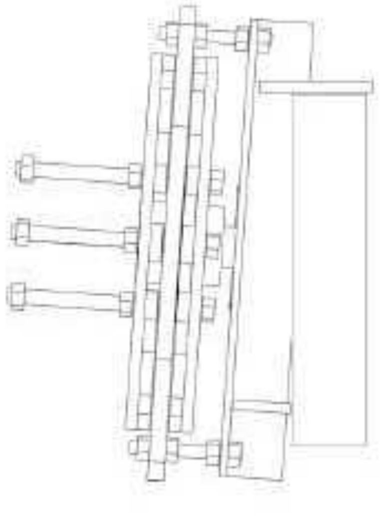
ALTERNATOR FRAME TO YAW TUBE SIZES mm			
Turbine diameter	1800	2400	3000
Length of 60 mm OD yaw tube	240	280	331
I	9	24	32
J	37	45	53
K	20	25	30



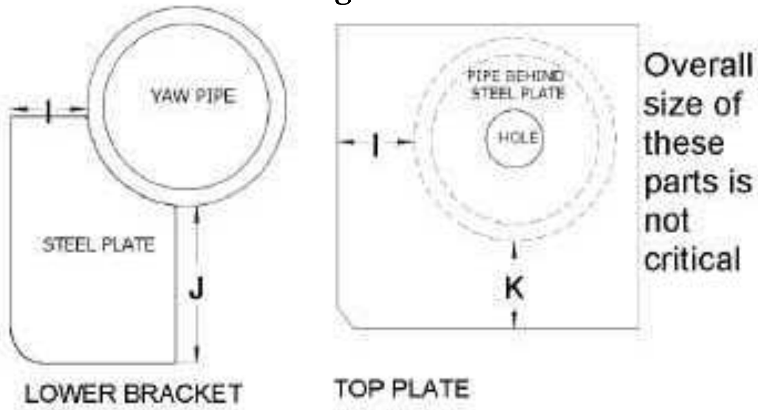
1800 – 3000 turbines

These all have T shaped frames. The upright leg of the T is connected to the yaw bearing outer tube as shown.

Weld a square top plate onto the 60 mm yaw tube (with a central hole). Rest this inside the steel angle. (You will need to take off any sharp corner first.)

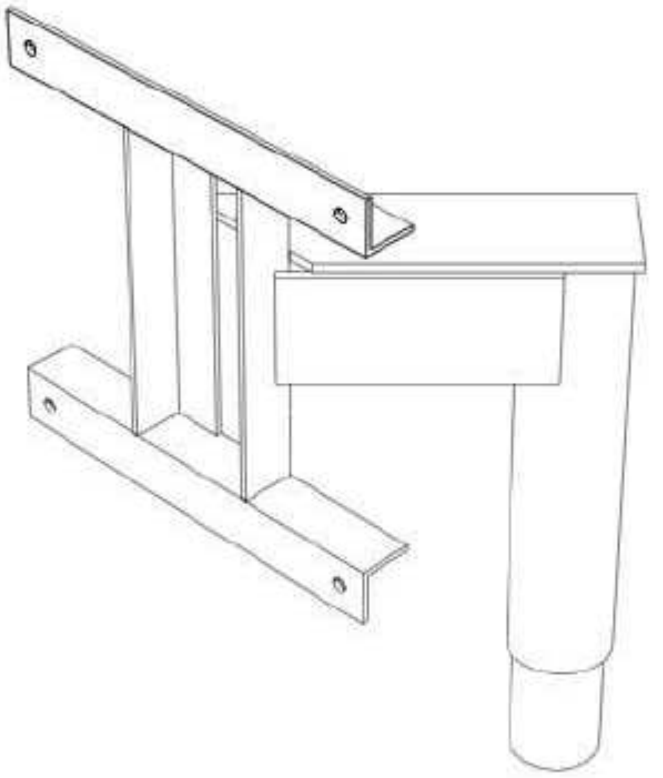


Below are two top-views of the yaw-bearing pipe. In both cases, the vertical piece A of the alternator's T-frame will rest against the rounded off corner at the lower left of the drawing.

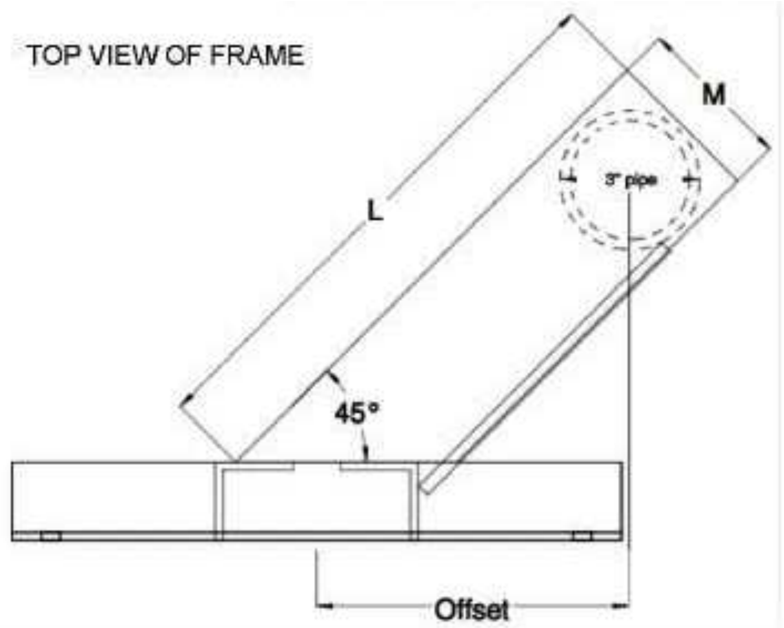


3600 and 4200 turbines

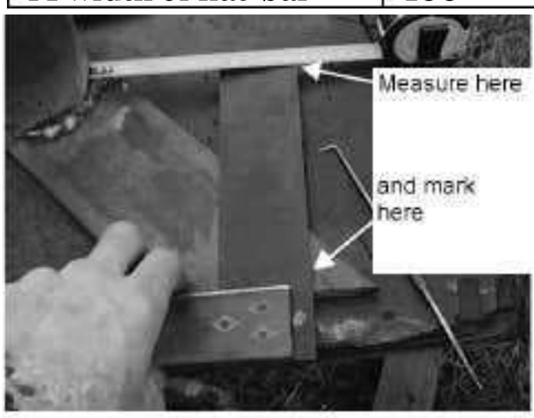
Use a piece of heavy flat steel bar (100 x 10 mm) to cover the top of the yaw bearing and extend out to support the H frame at a 45 degree angle like this:



Use a second piece of the same bar upright beneath it to stiffen it. Make sure you have the correct offset between the centre of the frame and the centre of the yaw pipe, as shown in this top view. The 89mm pipe is under the first piece of flatbar but its position is shown with dashed lines in this view.



FRAME DIMENSIONS 100 x 10 mm FLAT BAR		
Turbine diameter	3600	4200
Offset	200	250
L length of flat-bar	360	430
M width of flat-bar	100	100



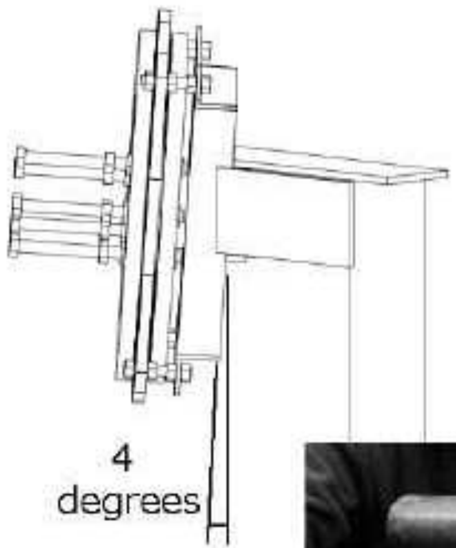
Mark the position of the centre of the alternator on the underside of the flat-bar.

Subtract half of the pipe diameter to get 156 or 206 mm offset.

The exact length of the 89mm yaw pipe is not critical, but I recommend about 400-500 mm length.

The photo shows how a junction box for wiring can fit neatly inside the angle formed by the two pieces of flat bar.

The overhanging position of the alternator frame helps to keep the blades clear of the tower and also helps with furling in high winds.



For a further factor of safety against the blades striking the tower you could also tilt the frame 4 degrees off vertical.

Incline the frame at 4 degrees to the bench and then hold the yaw bearing level while tacking it in position.

It's also necessary to check that the offset distance mark is central on the alternator frame, and that the frame is square to the big flatbar. Then tack it in place and weld it strongly, adding the second heavy flat-bar between the yaw pipe and the frame.

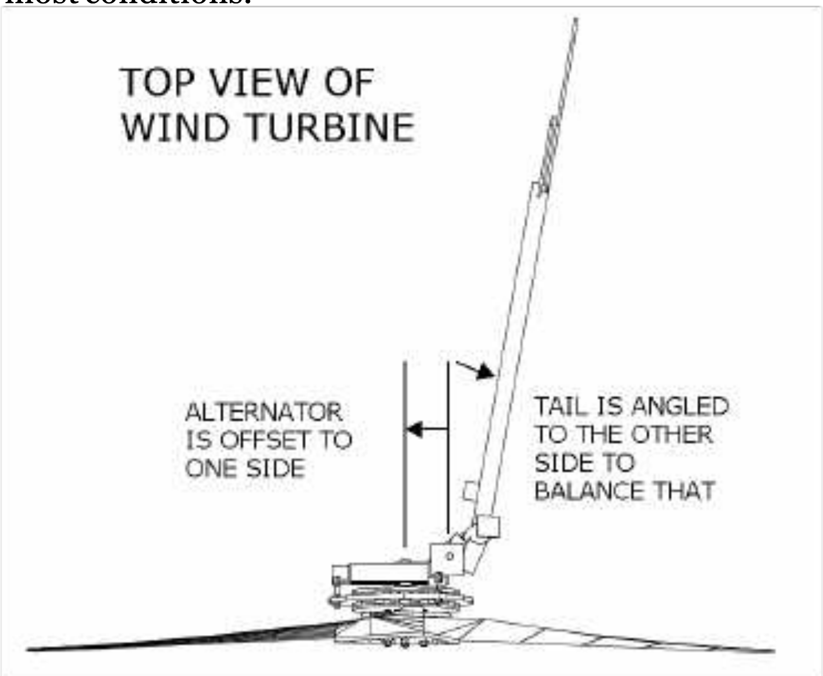
12 volt turbine rectifier boxes

This is a good time to think ahead to the mounting of a rectifier box on the top of the yaw bearing if you need to (for 12 volt battery systems). See page 48 for details.

The tail

The tail is a plywood vane bolted to steel flat bars on a steel pipe. Wind pressure on the tail pushes it backward and thereby makes the turbine face the wind, pivoting on its yaw bearing. However the tail does much more than simply push the turbine around to face the wind. The tail also allows the turbine to furl out of stronger winds and protect itself from overload.

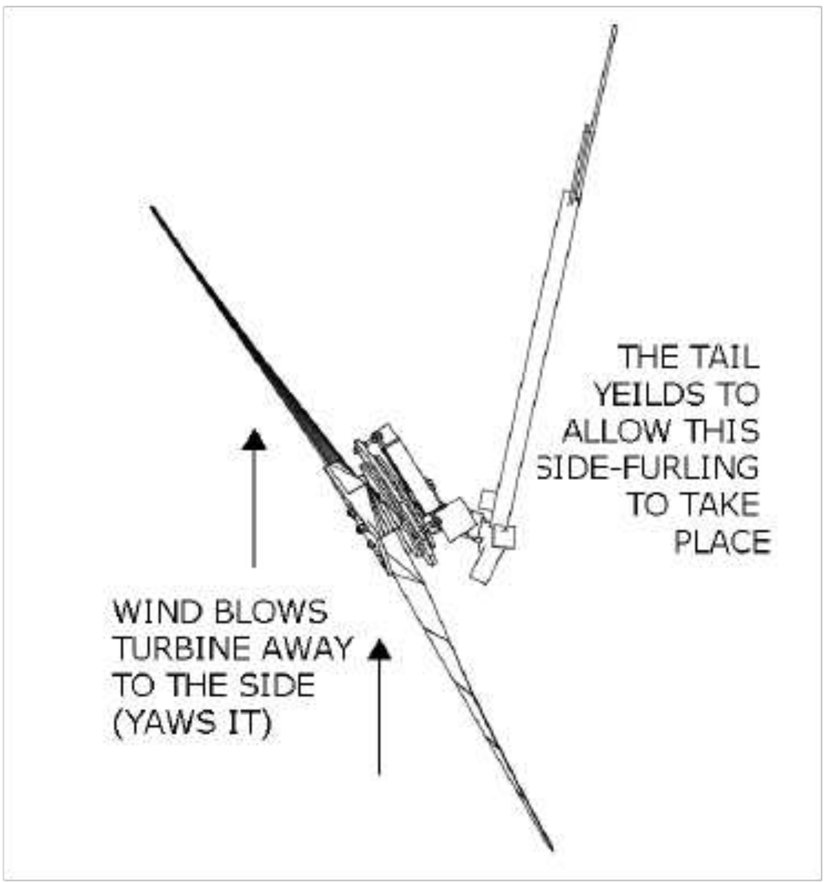
The alternator frame is mounted onto the yaw bearing off-centre, in order to create a 'yawing moment' that tends to swivel the turbine around sideways to the wind. The tail is deliberately angled a little to the opposite side in order to balance this tendency and to keep the turbine facing squarely into the wind under most conditions.



As the wind gets stronger, the thrust force on the blades increases but so does the force on the tail, so the wind turbine keeps facing the wind squarely.

The tail is mounted on a hinge that allows it to swing away from its normal position when the wind exceeds a certain thrust force. At the chosen level of wind thrust, the tail can no longer hold the turbine facing squarely into the wind. It swings sideways and slightly upward, allowing the turbine to face away from the wind. As the turbine swings to the side, the wind thrust is diminished, and so the furling motion of the tail stops, and an equilibrium is established that limits the thrust force of the wind on the machine.

The tail has to have a large enough area to control the blades and overcome their tendency to turn away or the turbine will never be able to face the wind. This is a separate consideration from the furling design. For correct furling, what matters is the weight of the tail and its length. By making the tail heavier you can delay the furling and drive the turbine harder in stronger winds. A turbine with a light tail will furl sooner and have an easier life, but produce less. Neither will make any difference in low winds however. Be ready to make small changes to the weight of your tail if the output is more or less than ideal when you test it out.

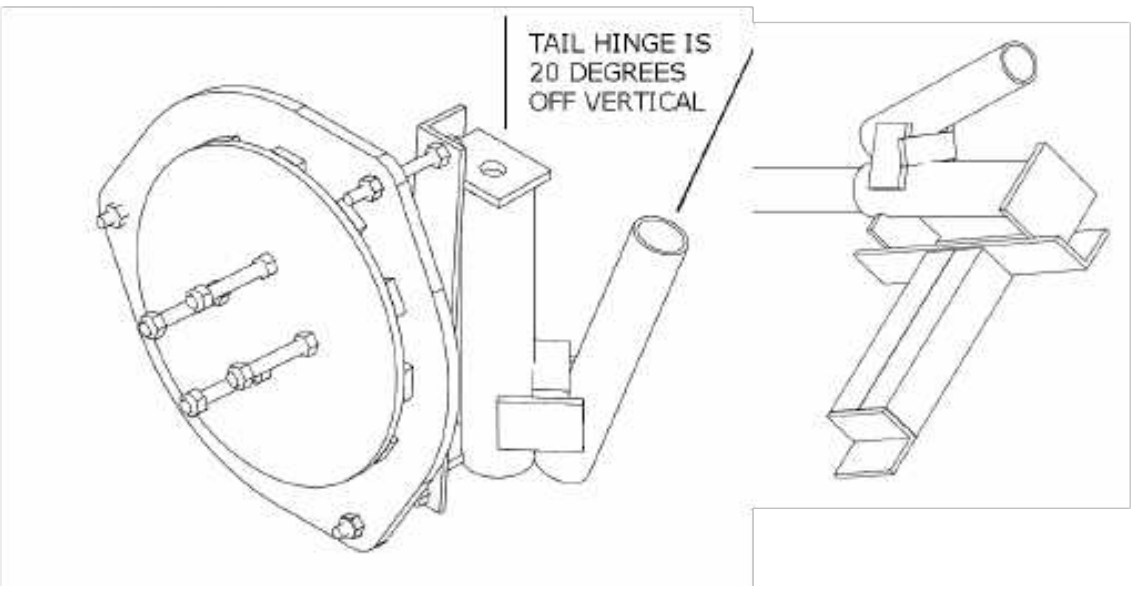


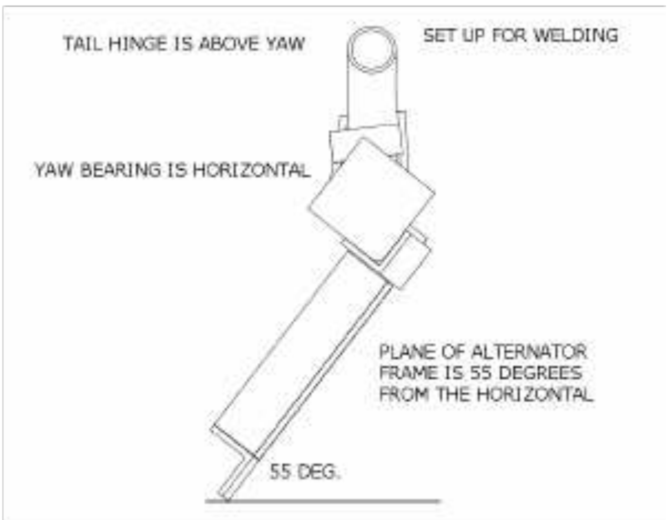
When the machine is furling, the blades continue to turn and produce power, but if rated power is exceeded the turbine will furl, that is to say it will yaw away from facing the wind directly, so as to prevent overload. Ultimately the tail can swing into a position that is almost parallel to the blades, allowing the blades to swing edge-on to the wind direction and escape from its violence.

Furling works well to limit the power and speed so long as the turbine is connected, but it will not prevent a disconnected turbine from over-speeding.

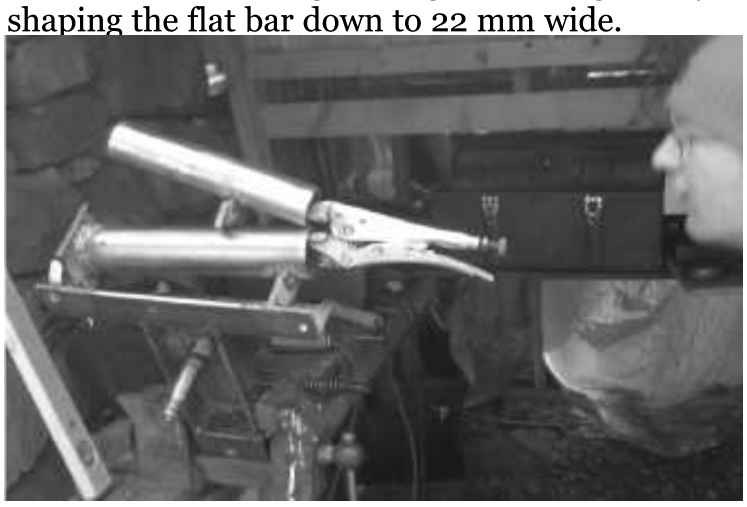
The inclined hinge

The tail is mounted on a very simple hinge, built from two pipes in much the same way as the yaw bearing. The inner pipe of the tail hinge is attached to the outer pipe of the yaw bearing at an angle of 20 degrees to the vertical. See pipe sizes in the table on the next page.





Weld the inner pipe of the hinge onto the yaw pipe securely because it has been a common weak point, especially with beginners' welding and when the blades are out of balance and the tail starts to bounce about. Start by welding a cross piece of 30-mm flat bar to the inner pipe of the hinge, positioned 85 mm from the end so as to give the desired 20 degree tilt. In the case of the 3600 and 4200 diameters, for battery charging I recommend reducing the angle to 15 degrees by shaping the flat bar down to 22 mm wide.



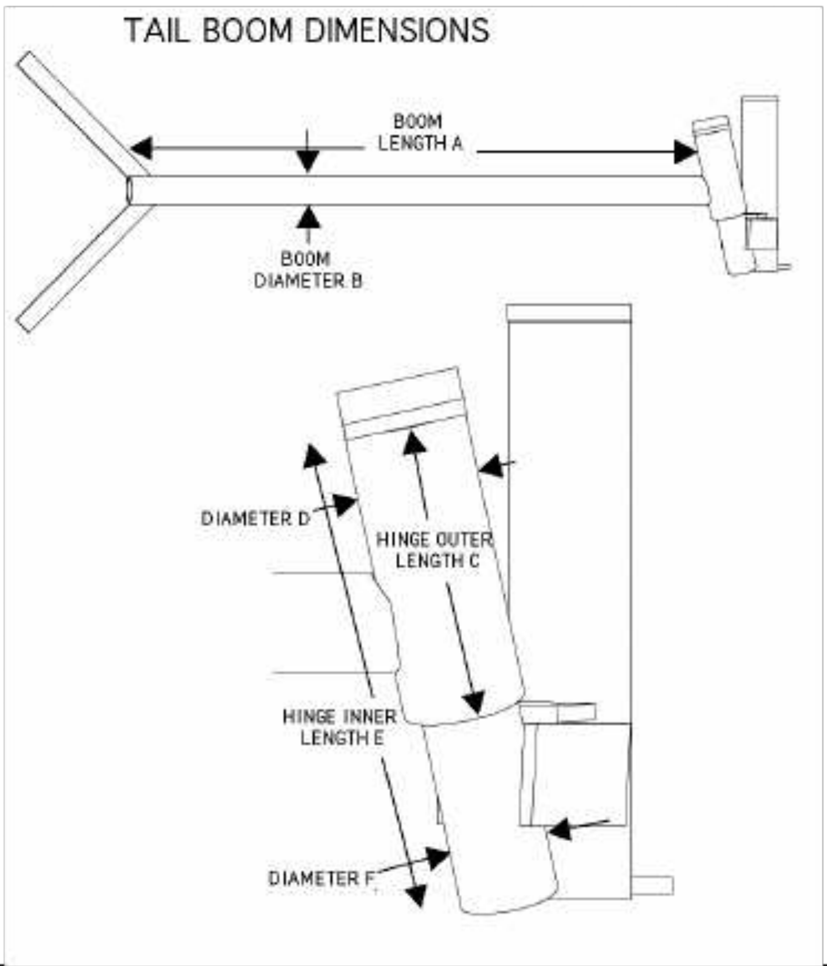
Then weld this inner pipe to the yaw bearing outer pipe, about 10 mm from its bottom, and finally add two cheek pieces.

The hinge is not fixed to the downwind (back) side of the yaw bearing, but about mid-way between the back and the side. (55 degrees off downwind.)

A good way to set it up for welding is to prop the frame of the machine up on the bench or the floor at 55 degrees to the horizontal. Then weld the tail hinge pipe on in a vertical plane above the yaw bearing pipe, judging this by eye if you like.

The axis of one pipe is directly above the axis of the other one.

Tail boom



STEEL PIPE DIMENSIONS FOR TAIL mm			
Turbine diameter	1200	1800	2400
BOOM LENGTH A	700	800	1000
Diameter B	33.4	48.3	48.3
HINGE OUTER C	130	100	150
Diameter D	42.2	60.3	60.3
HINGE INNER E	150	200	250
Diameter F	33.4	48.3	48.3

Turbine diameter	3000	3600	4200
BOOM LENGTH A	1200	1500	1800
Diameter B	48.3	48.3	48.3
HINGE OUTER C	200	200	250
Diameter D	60.3	88.9	88.9
HINGE INNER E	300	300	350
Diameter F	48.3	76	76

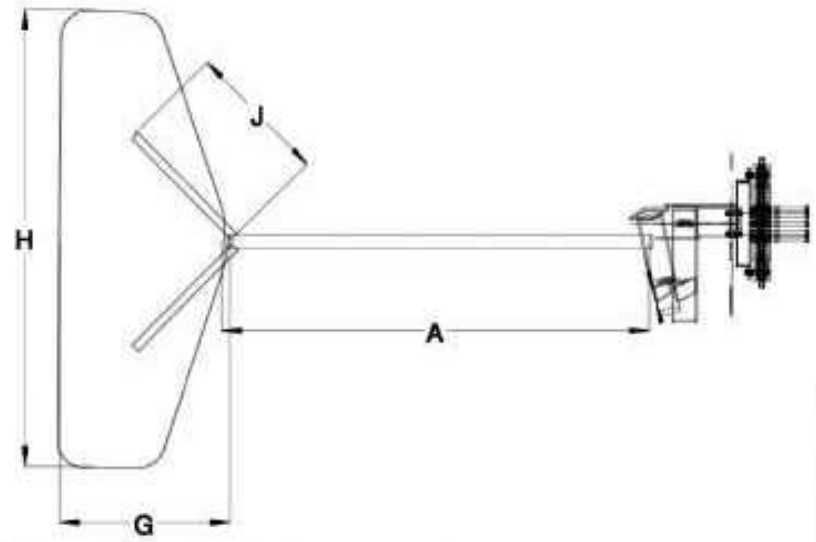
The outer pipe of the hinge (the moving part) needs a cap of steel plate on top that can rest on the top of the inner pipe, to take the weight and also to keep rain out of the bearing so the grease does not wash out. Weld a piece of plate on there taking care not to spread slag into the inside where it can foul up the smooth motion of the hinge. If you do not have a wide enough scrap of plate then weld two pieces of flat-bar side by side.

Weld the end of the boom to the hinge outer at about 70 degrees so that it sits horizontally when resting on the low end stop (see next page). A few extra gussets will bring peace of mind, as this is a highly stressed connection, especially for blade diameters above 3 metres. The end of the pipe is thin and very hard to weld. In the case of the 1800 turbine you can just flatten the end of the boom a bit and cut it at a 70 degree angle, but the larger turbines have long tails that put quite a strain on the 48 mm pipe. Shape the boom end to fit the hinge pipe neatly, and add some triangular bracing pieces to reinforce the join.

Tail vane and brackets

The tail brackets are pieces of flat-bar cut off at 45 degrees to meet the boom. The idea is that the vane is positioned beyond end of the boom. The vane looks better if it is vertical rather than parallel to the hinge.

You can make the tail vane any shape you like the look of, so long as it is roughly the overall size specified in the table below. If the area is too small then the vane will not be able to hold the blades to face the wind in low winds. The weight of the tail controls the way the turbine behaves in stronger winds too, so check the actual weight against the value in the table.

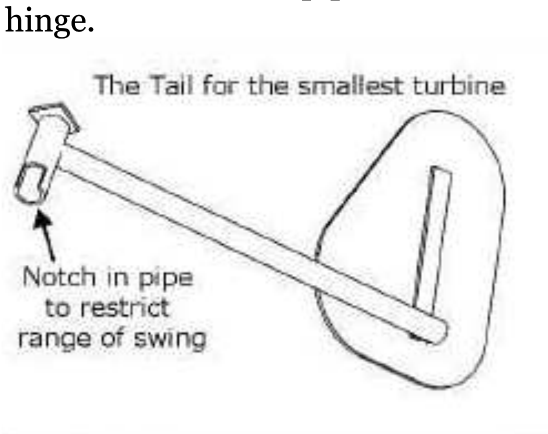


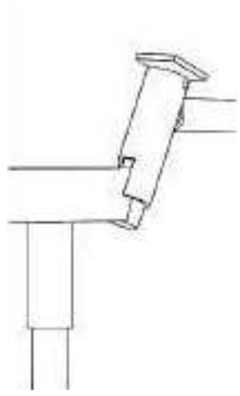
Some people like to make quite complex shapes, but you must bear in mind that the wind turbine is seen as a whole and the shape must work together with the blades to produce a coherent aesthetic design.

Tail stops

The tail should only move through about 100 degrees of swing. You will need to create stops that limit the range of movement.

The smallest turbine's tail can be dealt with by cutting a notch in the outer pipe of the tail hinge.

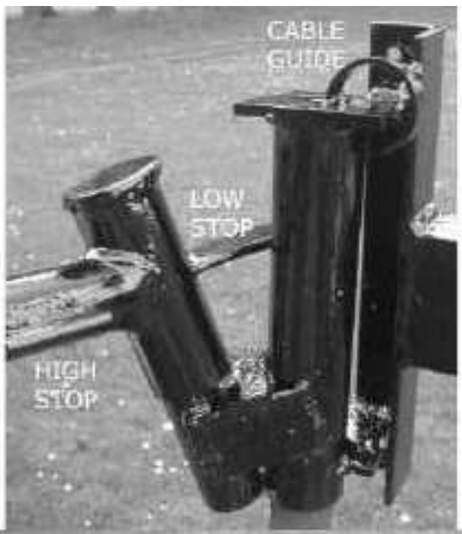




The notch drops over the edge of the steel angle that supports the hinge inner pipe.

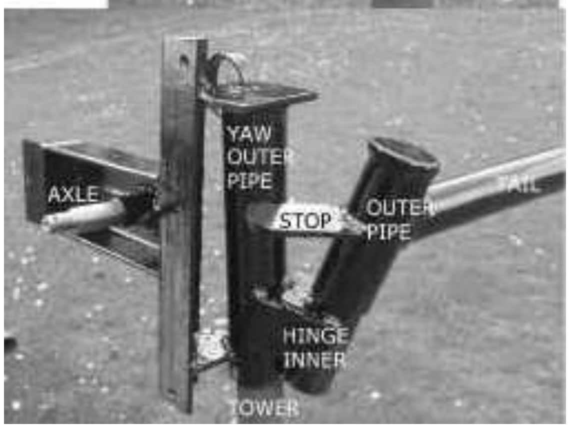
Turbine diameter	1200	1800	2400	3000	3600	4200
Tail hinge angle for battery charging	20 deg.	20 deg.	20 deg.	20 deg.	15 deg.	15 deg.
Tail vane area G X H	20x50 cm	40 x100cm	50 x120 cm	70 x130 cm	70 x 170cm	90 x 200cm
Thickness of plywd.	6 mm	6 mm	6 mm	9 mm	9 mm	9 mm
Weight of vane	400g	1.1kg	1.8kg	3.2kg	5kg	7.6kg
Flat bar section mm	8 x 30	8 x 30	8 x 30	8 x 30	6 x 50	6 x 50
Length of each flatbar lug 'J' above	One at 20 cm	Two at 30 cm	Two at 30 cm	Two at 40 cm	Two at 50 cm	Two at 60 cm

The larger turbines require stops to be welded on to the hinge outer that prevent the tail swinging too far down, and a stop between the boom and the yaw pipe to prevent it swinging too far up into the blade.

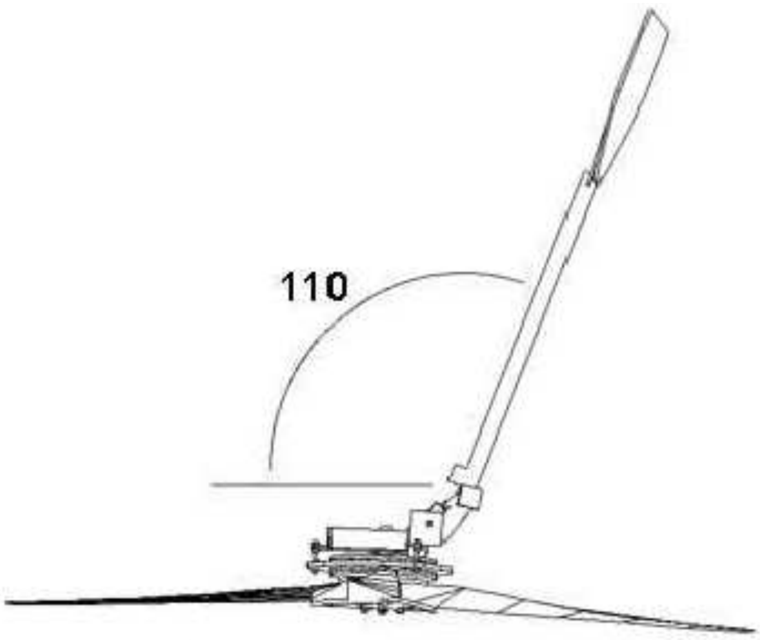


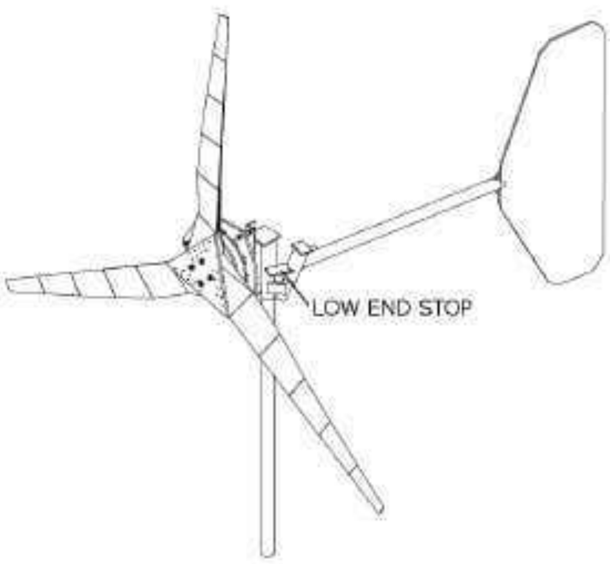
It is easiest to fit and adjust all of these stops by assembling the turbine with the tail at the correct angle.

The low end stop



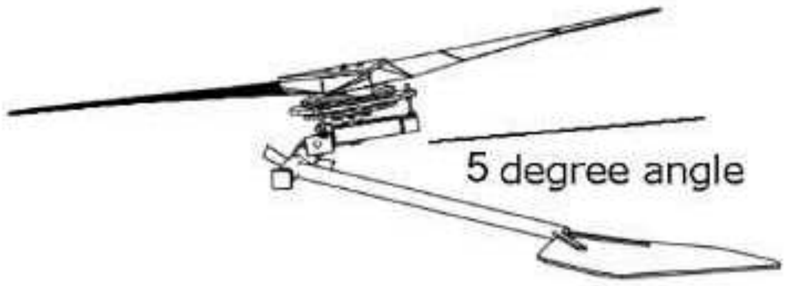
This determines where the tail will normally sit. Restrain the tail in a position where it makes an angle of 110 degrees approximately to the back of the alternator frame and tack weld a piece of flat bar onto the tail hinge outer pipe. The end of this flat bar must rest against the yaw bearing outer pipe in such a way that the tail cannot swing further down than this low end position. Remove the tail and weld the stop on securely.

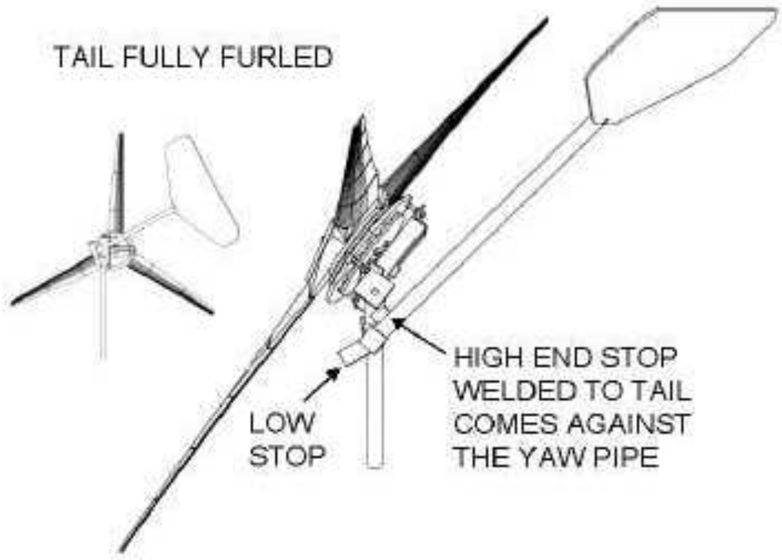




The high end stop

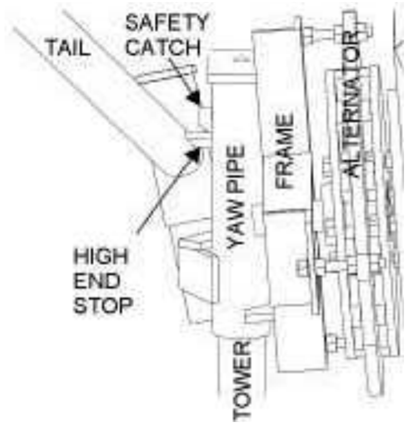
Weld a piece of flat steel bar to the side of the boom so as to prevent the tail from swinging too close to the blades.





The high end stop is a piece of flat steel bar welded to the side of the tail pipe. When the tail is fully furled, the bar contacts the yaw pipe, and prevents the tail from swinging too close to the blades.

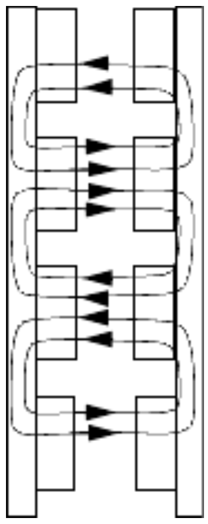
It's good to weld a little 'safety catch' to the yaw pipe above this point of contact so as to prevent that tail from slipping upward and off its hinge when in this fully furled position. This is especially handy when you are using the tail to support a large turbine while fitting the blades before erecting the tower.

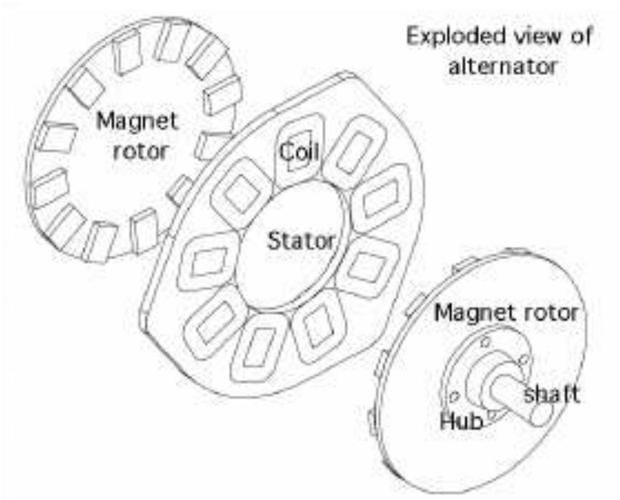


Electrics

Energy conversion

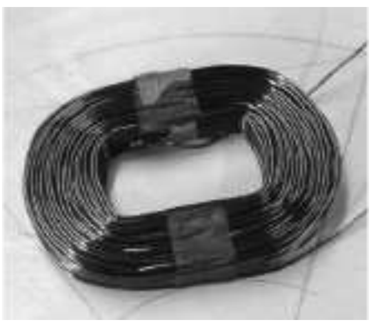
The alternator is very simple. The magnets are mounted on steel disks (magnet rotors) that turn with the blades on the same hub. In most cases there are two magnet rotors. The magnets are arranged facing each other. There is a strong magnetic flux in the space between them. The poles of the magnets are their largest faces. The steel disks behind them complete the magnetic 'circuit' between the back poles of the magnets.





The magnets are first glued to the painted surface of a steel disk and then cast in resin and glass fibre as well, so as to protect them from damage (they are fragile and corrode easily) and to hold them from flying off the rotor.

The stator is the name for the assembly of coils. Here is a photo of a coil. It is made by winding turns of enamelled copper wire. The coils are connected together and then placed in a mould and cast in polyester or vinyl ester resin.



The stator is then mounted between the magnet rotors, so that the magnetic flux from each magnet passes through the centre of each coil in turn.

Any change in the magnetic flux passing through a coil will induce a voltage in that coil. More rapid movement, or stronger flux induces a higher voltage in each turn of each coil. These three factors determine the voltage produced by the coil as a whole:

- revolutions per minute (rpm),
- amount of magnetic flux, and
- the number of coil-turns.

At low rpm, the coils will produce a low voltage. When the turbine reaches a certain 'cut-in' speed, the voltage becomes high enough to charge a battery. Only when the speed is above cut-in can the stator feed current into the battery. Below that speed the blades spin freely without any restraining torque. The same is true at all speeds if the battery becomes disconnected. Under these conditions the blades can become noisy due to running faster than they are designed to run.

Power is the rate at which energy is produced. The electrical output of the turbine will depend mainly on the strength of the wind and the size of the blades. The blades produce mechanical energy that is converted to electricity by the alternator. A powerful alternator will not help if there is not enough mechanical power.

Voltage alone is not the same as power. If there is no external circuit connected to the coils, or if the voltage is too low for battery charging, the magnet rotors spin freely, because no energy is being converted. But when a circuit is connected then current in the coils creates magnetic forces that interact with the magnets to oppose the motion of the blades.

Current manifests itself as torque (resistance to turning). Voltage is proportional to speed. Voltage combined with current amounts to electrical energy being produced. Speed combined with torque are the ingredients of the mechanical power you need to put in (using the blades) so as to get electrical power out. In both cases, power is measured in watts, and if sustained it will deliver energy in Watt-hours or kiloWatt-hours (AKA kWh units of energy).

Some energy is lost in the conversion process, due to the electrical resistance of the wires in the coils, and this lost energy also heats the coils. In low winds there is very little energy loss in the alternator. In higher winds the larger currents will ultimately burn the coils out unless the turbine furls and protects itself. The stator is very exposed to the wind and is cooled by it, enabling it to survive higher power conversion than it could if it were confined in an enclosure.

If you connect the output wires together in a 'short circuit' then there will be a high current, that produces a large torque, that slows the blades dramatically. Short circuiting the stator like this can be useful for 'braking' the turbine. The very high torque will usually stall the blades and kill their speed, bringing them down to a very slow and feeble mode of operation that is ideal when you are raising and lowering the tower or even for parking the turbine if the battery is full.

Choosing wire size and number of turns per coil

The number of turns per coil and the wire size have been carefully chosen so as to make the coils fit exactly into the stator. The number of turns controls the voltage produced at the desired cut in rpm. A 12-volt alternator needs only about half as many turns per coils as a 24-volt one working with the same blades (at the same rotational speed).

If the number of turns is too small for the chosen battery, then the blades will overspeed while trying to reach the cut in rpm. If the number of turns is too many then the alternator will start to charge the battery at a very low speed, and will exert too much torque, preventing the blades from reaching their best speed. This can lead to stalling of the blades and hence very little power. So it is important to have the correct number of turns to suit the chosen blade size and battery voltage (page 54). You can also adjust the magnetic flux to fine tune the speed. (page 48).

The wire sizes given here are the thickest wire that you can easily fit into the coil with the chosen number of turns. Thicker wire gets less hot when carrying current, and wastes less power. A 12-volt alternator will need to handle twice as much current as a 24-volt one (for the same power) but because the wires in the coils are shorter and thicker, the heating of the coils is just the same. (The wires from the turbine to the battery will also need to be much thicker to prevent excessive loss, and here you do need more copper for 12 than for 24-volt systems because they have to go just as far.)

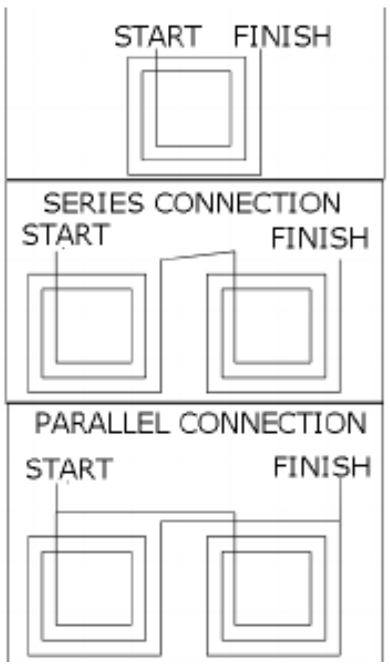
Very thick wires are clumsy to handle, so beyond a certain point it makes more sense to wind the coils with several wires 'in hand' instead of just one. If you are winding with two wires in hand then you will need to have the wire on two reels, and feed them both into the coil winder at once. Two thinner wires also make less of a lump in the finished stator as they cross over the coils coming out of the middle of each coil.

In most cases for 12 volts, the stator's coils will be connected in parallel rather than in series so as to reduce the wire size needed in the coils (see '12-volt stators' below).

Stator wiring connections

Each coil will produce a voltage, but the voltage of the whole stator depends on how the coils are connected together. There are various options for connecting things together

A coil has two ends: the start and the finish. Coils can be connected together in series or in parallel as shown below. In series, the finish of one coil connects to the start of the next. The voltages of the coils add together to produce a double voltage between start and finish of the pair.

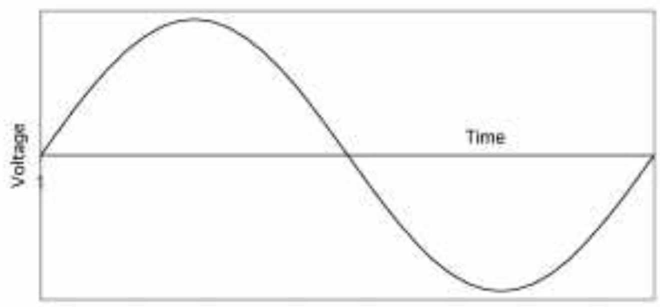


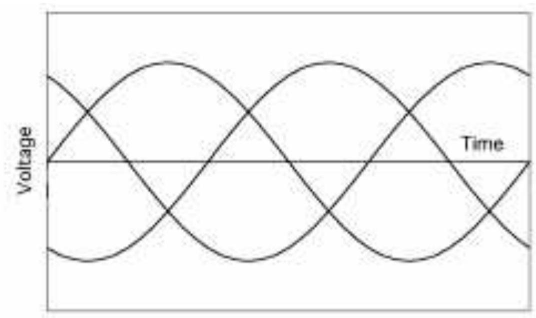
In parallel connection, both of the starts are connected together and so are both of the finishes. The resulting voltage is the same as one coil, but by sharing they can carry twice the current.

I prefer to connect coils in series. There is a problem with using parallel connections in a hand-made alternator. Inevitably the output voltage from each coil will be slightly different. These differences lead to parasitic currents between the coils that waste power. But series connections between coils for low battery voltages implies a very small number of turns of very thick wires in each coil that can become clumsy to handle. With parallel connection one can use thinner wire. And the problem of parasitic currents can be dealt with by a special rectifier on board the wind turbine (see '12-volt stators' below).

Three-phase stators

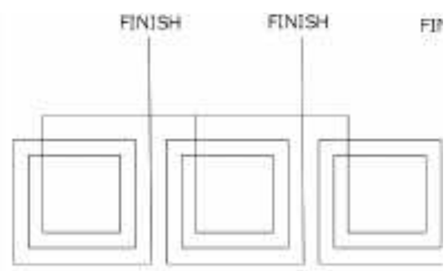
Each coil will produce an 'alternating' (AC) voltage as the alternating magnet poles pass over it (north, south, north, south, etc.). A graph of how this voltage varies over time looks like this (sine wave):





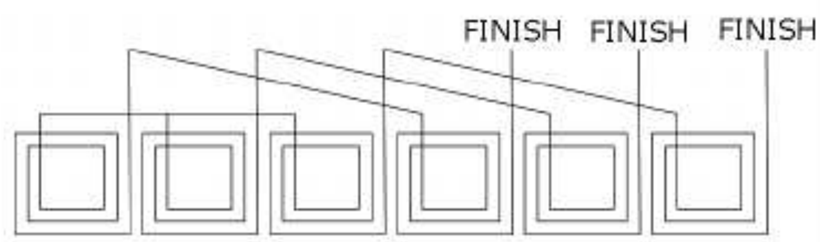
The alternators in this book are all 'three-phase'. The stators contain three groups of coils that produce the same voltage but at different times. Three-phase stators make better use of the space than single phase, and also deliver a smoother output.

The best scheme for connecting the three-phase coils together is called 'star' (also known as 'wye') connection.



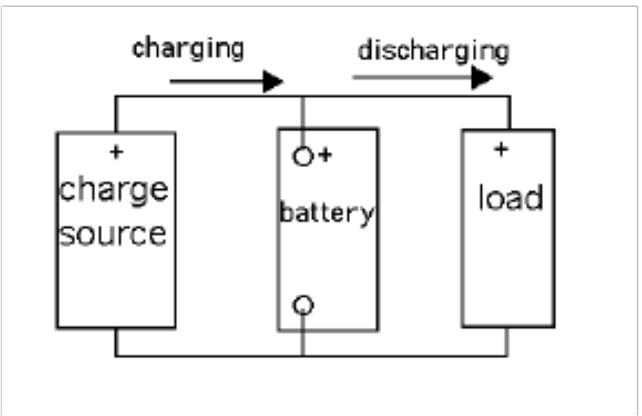
(There is another scheme called 'delta' but I prefer to avoid this because again it allows parasitic currents in the coils.)

In star connection, all three starts are connected together as shown above. The output wires are the three finishes. In most cases the best connection scheme is series/star. A series/star example with six coils is shown below:

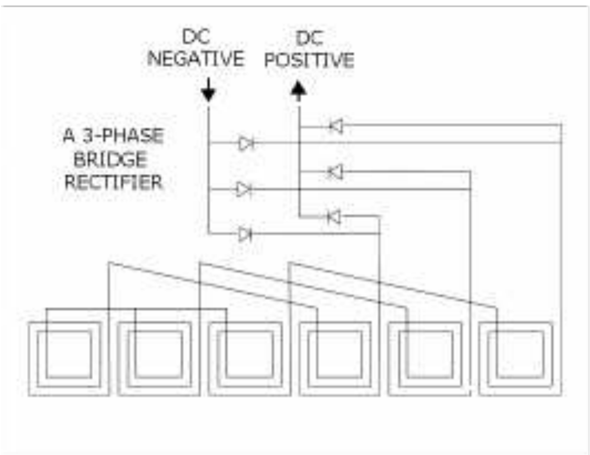


Coils 1 and 4 are in the same phase, so they are series connected. The other two phase groups are 2&5, 3&6. The smallest stators (in the 1200 and 1800 turbines) are connected like this. For larger alternators there are three or four coils in each phase, for a total of nine or twelve coils in the stator.

Battery charging with DC



Batteries are chemical devices that store energy. There is a voltage between the terminals but it is pretty steady, not alternating like the voltage between the ends of a coil. To charge a battery with energy you have to force a current of electric charge to pass into the positive terminal of the battery and out of the negative. As the battery discharges, this energy is used, forcing current out of the positive terminal and through any loads that you choose to connect across its terminals. In both cases these DC currents return to their source because there can be no current without a complete circuit. In some cases the wind turbine can feed current directly through the loads, and the battery will not even have to participate. But usually there will be a mismatch between the supply and the demand that is accommodated by the battery.



To produce a DC output (direct current which does not alternate) for charging a battery you have to connect the three AC phases to a 'bridge rectifier'.

The little arrow symbols in the diagram represent diodes – devices that only allow current in the direction of the arrow. The bridge network of diodes ensures that current can only go one way in the DC circuit. The bridge converts AC into DC and also prevents the battery from discharging into the stator.
The numbers of turns per coil in the table below are carefully chosen to work well with the respective battery voltage.

The coils

Use enamelled copper wire often called 'magnet wire' or 'winding wire'. Grade 2 (which is good for up to 200 degrees C) is ideal, but lower grade is probably adequate. The clear enamel coating on the wire insulates it from its neighbours in the coil.

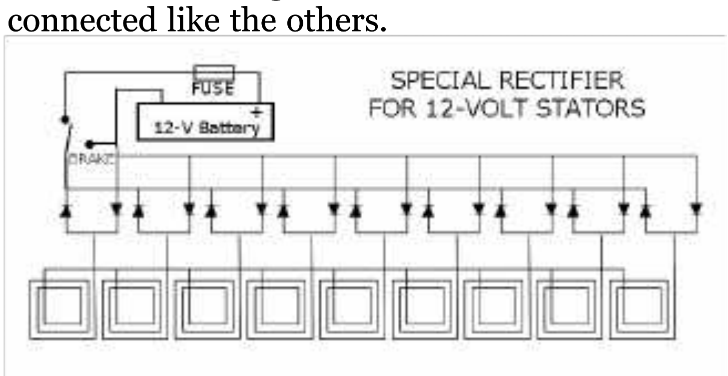
The price of copper is rather high at the time of writing, but the best deals can be got by buying about 20 kg in a reel. In Europe the wire is specified by its outer diameter of copper (unlike electrical wiring which is listed by cross-sectional area of copper in sq mm). In the USA and some other countries the wire is sized by American wire gauge (AWG). Adding 3 to any AWG size reduces the weight of the wire to one half. Multiplying a metric size by 0.71 reduces its weight by half. (See tables on page 56)

"Two in hand"

Where the table specifies "2@1.5" wire you will need to put the wire on two reels and feed two wires into the winder side by side. Connect these wires in parallel. You could use a thicker, single wire if you prefer but this will be hard to form and will make a larger lump where it crosses the end of the coil

*12-volt stators marked **

In most cases I have marked the 12 volt stators with an asterisk * denoting that these stators are not series connected like the others.



For 12-volts series-connected, the wires become very thick and so clumsy. I therefore propose a parallel connection for these stators.

Turbine diameter	**1200**	**1800**	**2400**	**3000**	**3600**	**4200**
Number of disks	**1**	**2**	**2**	**2**	**2**	**2**
Magnets/disk	**8 on one disk only**		**12**	**12**	**16**	**16**
Number of coils	**6**	**6**	**9**	**9**	**12**	**12**
Weight of wire	**1.5kg**	**2.6kg**	**3kg**	**5kg**	**5kg**	**7kg**
12-V diam(mm)	1.4	1.4	1.7	1.8	1.7	1.7
Turns per coil	76	130*	73*	90*	80*	100*
24-V diam(mm)	1.06	1.5	2@1.5	2@1.6	2@1.8	2@1.8
Turns per coil	140	110	45	55	37	45
48-V diam(mm)	0.75	1.06	1.5	1.6	1.8	1.8
Turns per coil	270	220	90	110	75	90
GRID TIED INVERTERS 150-500V INPUT (USE PROTECTION)			wire dia. (mm)	0.85	**0.9** 0.85	**1.06** 0.85
			Turns per coil	400	**300** 350	**260** 400

To avoid parasitic currents, I recommend that you use a separate pair of diodes for each coil. This means placing the rectifier on the wind turbine. There are too many wires to bring down.

See also page 48 for how to mount the rectifier on the turbine. There are many pros and cons to this arrangement, but overall it works best for 12-volt systems. 12-volt wiring needs to be very heavy to reduce the losses of power inherent in the high currents required. Using two DC wires is more efficient than three AC wires. It is not hard to cool a rectifier up there in the wind.

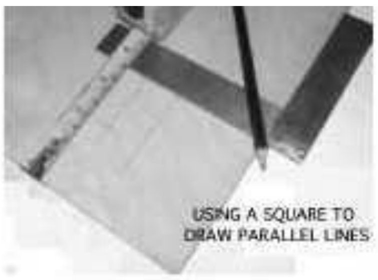
But the rectifier on the turbine is harder to inspect and repair if necessary. The short-circuit brake is also more complex, because you have to disconnect the battery before you connect the two wires to each other (see c/o switch in diagram on page 36).

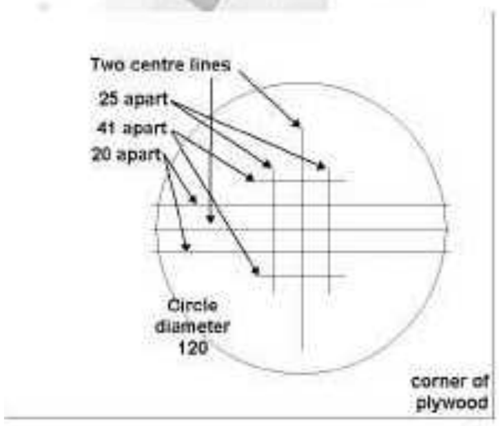
Making the coil winder

The coil winder is the same for any of the wind turbines. Only the spacer thickness varies.

The shaft is made of 10 mm threaded rod, bent into a crank shape, and fitted with a handle made of pipe. Use pairs of nuts tightened securely against each other to position the handle and also to retain the shaft in a hole through a piece of 48 mm pipe that supports it. Weld the pipe to a piece of steel angle that you can screw to the edge of the workbench. Feel free to modify the details of the design. If you think ahead then the same upright piece of pipe can also be used as a stand for assembling the turbine on later. Make sure the pipe is long enough that the blades do not hit the floor.

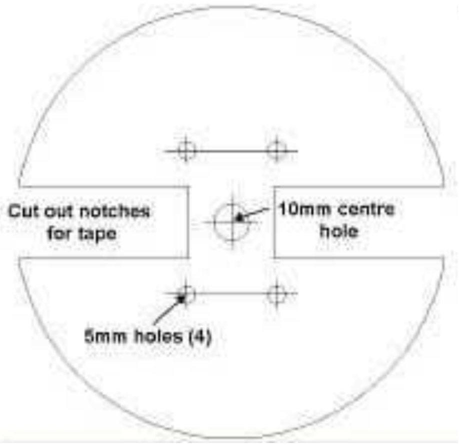
You need two 'cheek pieces' to contain the coil. They can be made from pieces of 12 mm plywood. Before cutting anything out, precisely mark out the hole patterns for the pins that the coil is actually wound on.





The simplest way to mark the hole pattern accurately is to work near the corner of a sheet of plywood. Use a square riding on the edges of the plywood to draw parallel lies. Keeping a distance of roughly 80 mm from each edge, draw two centre lines for the piece. Next draw two lines 25 mm apart (12.5mm each way) in one direction, and then two lines 41 mm apart (20.5 each way) at right angles. Your hole centres for the pins will be at the four corners where these lines meet. Draw a third pair of lines 20 mm apart (10mm each way) for the two notches that you will cut out for taping the coils.

Draw the overall circle (radius about 60 mm) on the centre point. Cut out this notched cheek piece with a jig saw. Curved corners are a good idea, to prevent the wires snagging. Mark the shape of the second by



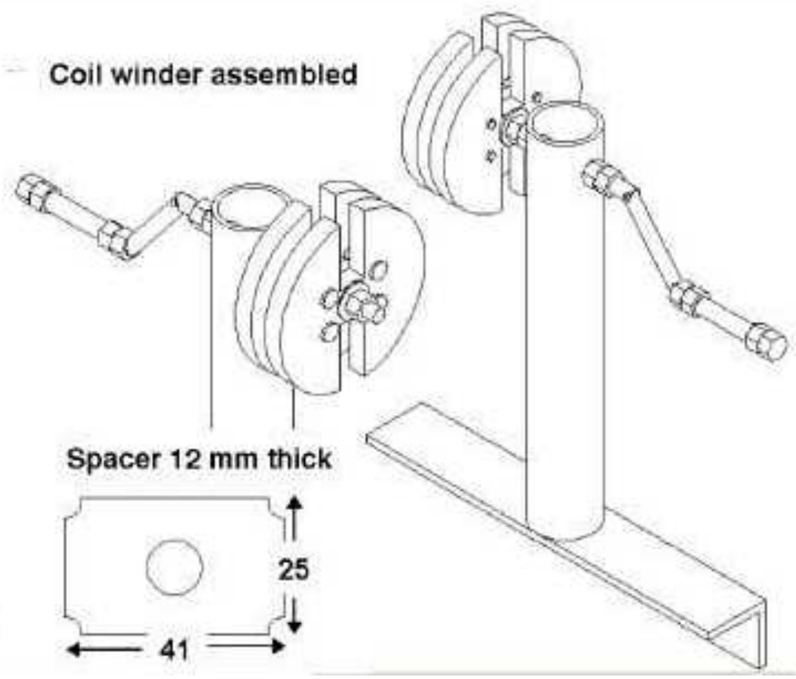
drawing around this first piece, and cut that one out too.

Carefully punch the centre point and each of the pin centres with a centre punch. Clamp the first piece on top of the second, and drill the holes through both pieces at once.

Using a drill-press, cut the five holes neat and square, through both disks. Make sure there is some waste wood underneath so that the drill does not burst out at the back. Start each hole by lifting the plywood so as to fit the tip of the drill into a punched hole, then bring the drill down so the disks lie flat on the support and drill through.

Mark the disks so that they can be reassembled in the same way in future. This will make it easier to fit the pins and to ensure that they are parallel.

You will also need to make a spacer that keeps the two cheek pieces the correct distance apart, 12 mm (10 mm for the 1200 turbine).



The best approach is to drill the hole pattern in a piece of plywood, using the first cheek piece as a guide (drilling through it), and then cut between the centres of the corner holes to create the spacer piece. You can adjust the thickness if the first coil attempt does not fit the stator. A thicker spacer makes a narrower coil.

Assemble the threaded crank shaft into its supporting stand and lock the nuts to each other so that there is about 50 mm of bare thread projecting. Place a big washer, one cheek piece and then the spacer onto the shaft. They will stay on during the winding job. You may wish to glue the spacer onto the rear cheek piece. Make sure that it does not bulge outside the space defined by the four pins.

Put on the front cheek piece and clamp the assembly together with a nut and washer. Make sure the cheeks are assembled in the original orientation, using your marks. Fit the four pins into their holes. Tighten the nut securely so that the plywood pieces cannot spin on the rod.

Winding the coils

Place the reel(s) of wire on the floor beneath the winder. If it is a large (20kg) reel then it is best to place the side of the reel flat on the floor, so that the wire pulls off the other side. If it is a small reel then it may be better to slide the reel onto an axle so that the reel unrolls as the wire is used.

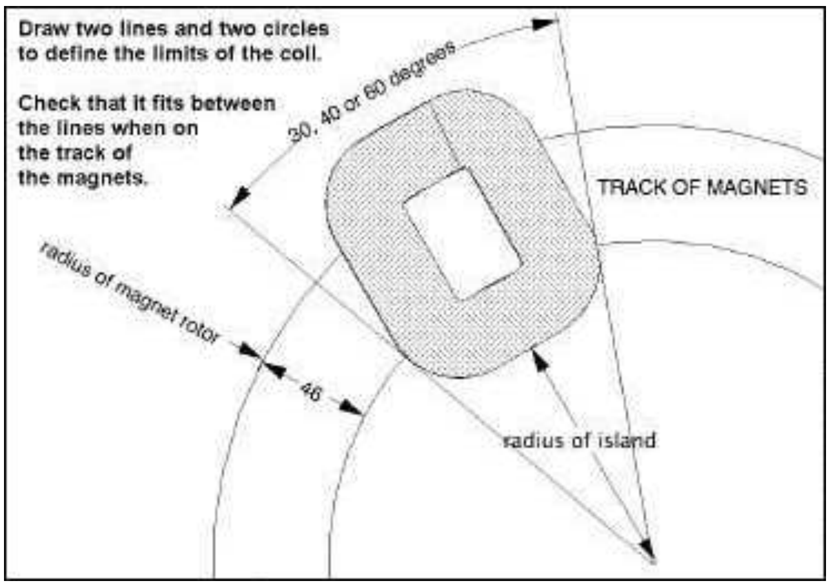
Do not manipulate the wire unnecessarily. Ideally it should be free of kinks and bends. But do make a sharp 90 degree bend about 200 mm from the end and fit this into a notch so that the tail comes out at right angles. Press the wire against the outer cheek and wrap the tail of wire loosely around the tail of the threaded rod.

From now on you need to keep hold of the wire(s) with one hand and the handle of the winder with the other hand. Keep a gentle tension in the wire(s). If you release the wire then the coil may lose its shape and be impossible to salvage.

Start winding the handle and keep count of the turns. Make sure that the turns build up in an even layer, one wire snugly next to the other, until you have reached the rear cheek piece. Then start a second layer working back toward the front again. Do not allow the wires to zigzag in a random fashion, as this wastes space. The coils must be tidy to fit into the stator.

The count of turns does not have to be perfect, but try to be accurate. When you have reached the correct number, do not release the tension in the wire, or you may lose the shape of the coil and it can be ruined. Tape the coil up neatly with a single layer of PVC tape passed under the coil at the base of each notch. (Fold the end of the tape in half against itself before you start each coil, to make it easy to feed the tape through. Cut this end off after.)

Snip the winding wire off leaving a 200 mm long tail at the 'finish'. Remove the four pins and the front cheek so that the coil is released from the winder. When the first coil has been wound you should check its size to make sure that it will fit into the stator.

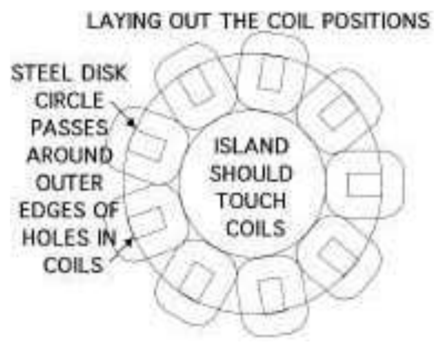


For example if there are 12 coils they must fit within a 30 degree segment (9 coils each fit within 40 degrees, 6 coils each fit 60 degrees). Draw out the shape on paper or plywood. Lay the coil in its place so that the outer edge of the hole matches the outer edge of the magnet disk. If it looks fine, then carry on and wind more coils. You can also find out the ideal size for the island at this stage (see page 40). In the smallest machines you also need to consider clearance from the rotating parts in the centre when making the island.

I like to weigh each coil so as to check that they are consistent (+/- 5% say). A heavier coil may indicate a mistake with counting turns or it may simply be more loosely wound, but if one coil is radically different from the others then I prefer to reject it.

If the coil is well formed but does not fit the stator, then you may have to try again using a thicker spacer or making the central hole smaller, but this is very unlikely to be necessary if the coils are wound with care. If the coil is too small, then try winding with less tension or use a thinner spacer so as to get the optimum overall size. If you can get all of the coils the same size and touching each other then it becomes easier to fit them into the stator mould in a properly balanced way. You will also achieve the thinnest stator this way, maximising both the clearance and the surface area for cooling.

Connecting the coils

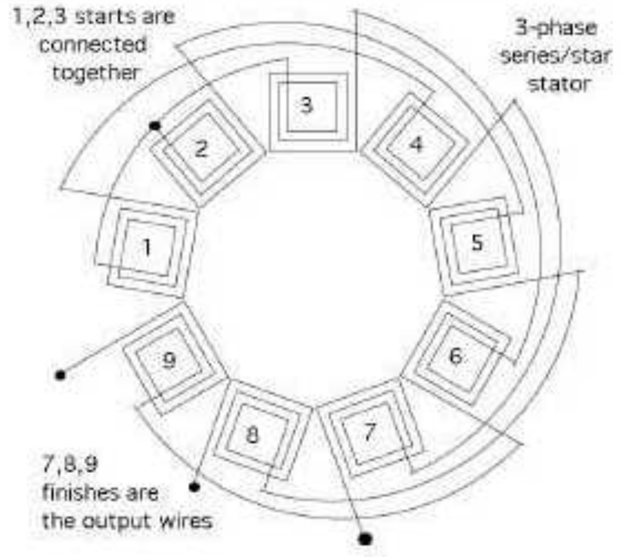


You should lay the coils out carefully in their correct positions and clamp them in place while making these connections. This makes it easier to position them in the mould later.

Draw around a magnet disk and align the outer edges of the holes in the coils with this circle.

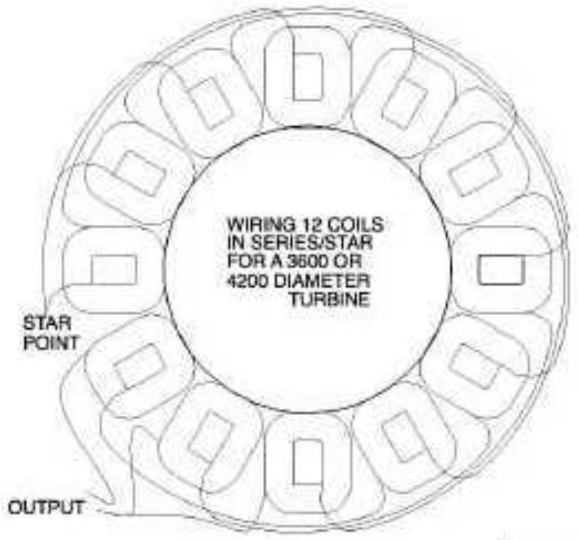
In most cases, the coils in the stator will be connected series/star. The first diagram shows 9 coils as in the 2400 or 3000 diameter machines.

Coils 1, 4 and 7 make up one phase group. If a north pole is passing coil 1 then another north pole will be passing coil 4 and another coil 7, so they are all experiencing the same induced voltage at the same instant. These three coils are connected in series.



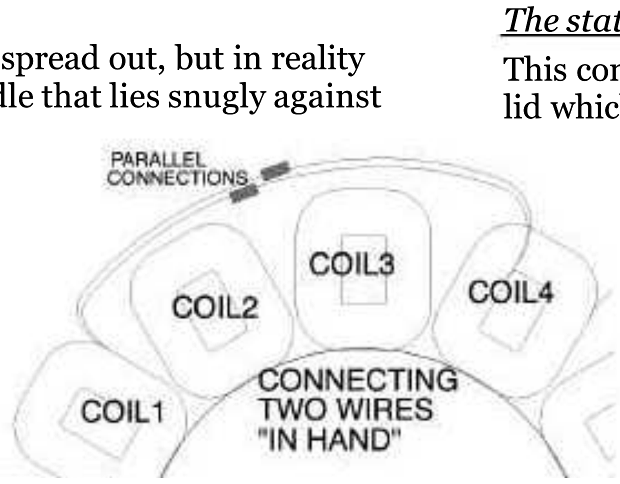
Finish of coil 1 connects to start of 4, finish of 4 to start of 7, and finish of 7 is one of the 3 output wires.

Connect the other two phase groups (2, 5 and 8) and (3, 6 and 9) in the same way. Starts of coils 1, 2 and 3 connect to each other (at the 'star point') and to nothing else. Coils 8 and 9 provide the other output wires.



With 12 coils then the phases are (1,4,7 and 10) etc. Connections between most of the coils are very simple: connect the finish to the start of the third coil on (skipping two). Bypass two coils and connect to the third one. Often a good position for the actual solder join is between the two coils you are bypassing. See the section on tools for advice about soldering.

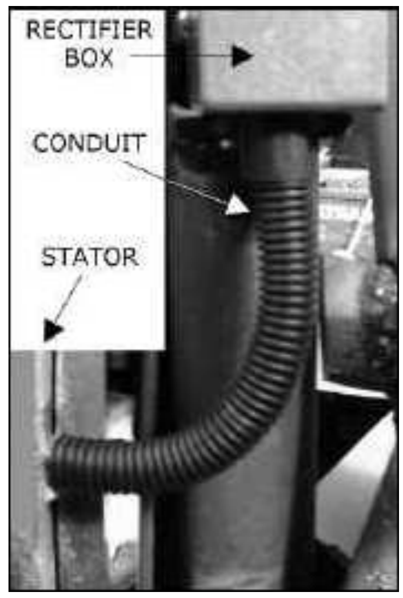
The diagrams show the wires spread out, but in reality they need to form a neat bundle that lies snugly against the outside of the coils.



Where there are two wires 'in hand' (e.g. 2@1.5mm) they are connected in two parallel connections as shown here. I prefer to keep the two connections apart to reduce parasitic current pathways.

Take care with thin wires that the coils do not flip over.

12-volt stators



The 12-volt windings marked with a * in the table have no series connections between coils. Instead the starts are all connected to a ring of 'neutral' wire that runs right around the stator and connects to nothing else but the starts. The finishes are each connected to a tail of flexible insulated wire that is brought out of the stator to a rectifier box mounted on the top of the yaw bearing. I like to cover these nine wires with a piece of flexible conduit.

Output wiring

Use tails of flexible insulated wire for the output of any stator. Solder them to the three finishes (or more in the case of 12-volt stators). They need to be more robust than the windings wires because they will be subject to bending, vibration and abrasion of various kinds. I like to use equipment 'hook-up' wire sometimes known as 'tri-rated' wire. The solder joints should remain within the resin casting.

Finally test the continuity of the stator using the multimeter set on Ω (Ohms). You should get the same low reading between any pair of wire tails.

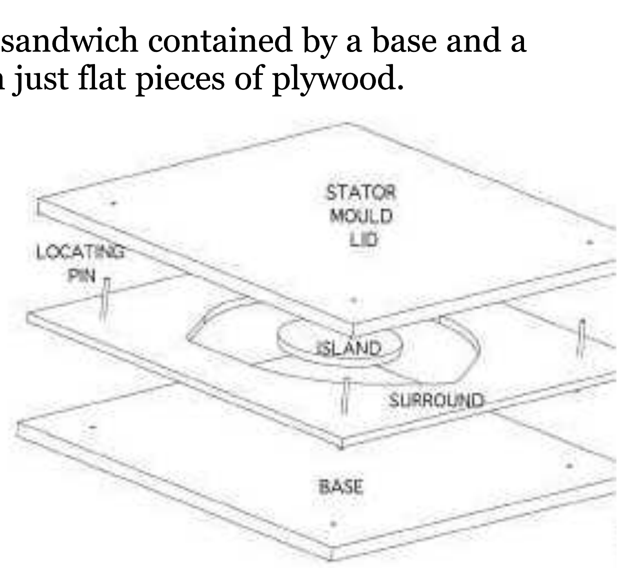
The moulds

The stator and the magnet rotors will be cast using polyester or vinyl ester resin that encapsulates the coils and magnets. Start by making moulds to contain this resin during the casting process.

Make the moulds from plywood, MDF or similar sheet material. Better quality plywood will give a neater finish. You will coat the moulds with some sort of polish or grease (petroleum jelly is good) before adding the resin, but leave this until you have done a 'dry run' to check that the coils or magnets fit correctly, together with the glass cloth that is used to give the casting strength.

The stator mould

This consists of a sandwich contained by a base and a lid which are both just flat pieces of plywood.



In the middle the coils are cast in resin. The edges of the resin casting are contained by a third, middle piece of plywood called the 'surround'. The hole in the middle of the stator is formed by a piece called the 'island'. See stator shapes on pages 64 and 65.

Cut out three square pieces of plywood, with side length A (nominal sizes - see table below). The middle piece can be the same thickness as a coil. It could be a little thinner, but never thicker because you need to be able to squeeze the stator thickness during the casting. You want the stator to be thin so there is ample clearance from the magnets and good cooling. The magnets need to be about 20 mm apart.

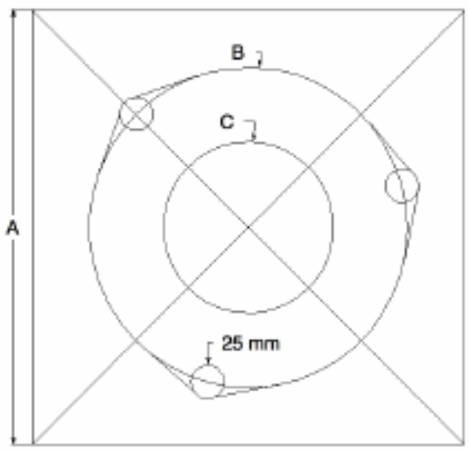
The lid and base need to be strong material with a smooth finish. Screws grip much better in plywood than in other boards when clamping the lid down.

I like to drill three holes through the stack so that I can always reassemble the pieces in the same way using pins made from nails or bolts. This is especially useful when placing the lid on during the casting process.

Mark out the shape of the stator on the central surround piece of plywood as follows:

Start by drawing diagonal lines across the corners to find the centre. With the 16 pole machines you could also use these lines to mark the four mounting points.

At the centre, draw outer and inner circles with radius B and C respectively.



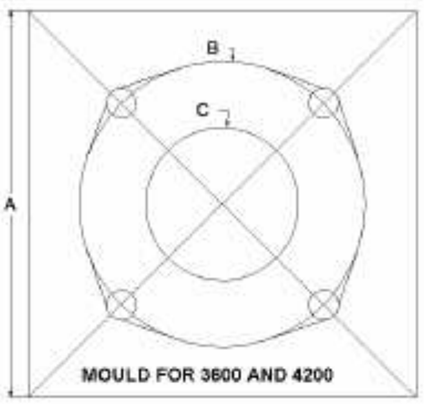
C is the radius of the island/hole in the middle of the stator. Check that the island fits the coils you have wound as you lay them out for soldering. Coils vary in shape.

Often with the 1200 and 1800 I make the outer shape of the stator hexagonal.

Diam.	Magnets	coils	Mounts	A	B	C ?
1200	8	6	3	450	152	45
1800	8	6	3	500	172	66
2400	12	9	3	600	186	83
3000	12	9	3	600	220	99
3600	16	12	4	650	240	129
4200	16	12	4	700	272	147

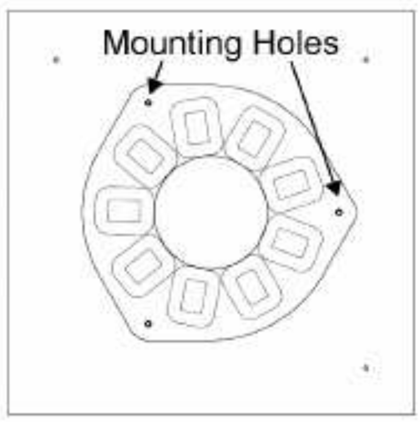
Now mark the positions of the mounting holes. They lie on the same circle (radius exactly B) that marks the outside of the stator. There will be 3 of these holes on the turbines 1800-3000 and 4 holes in the larger 3600 and 4200 stators. As usual the smallest turbine will be different, with mounting studs set into the central part of the stator. See next page for a diagram of the 1200.

The 3 mounts can be laid out using the compasses to walk around the larger circle and choosing every second mark. (See page 11 for more.)



In the case of the larger turbines the 4 mounting holes will be where the diagonal lines hit the circle. But in all cases do **check that they are equally spaced apart.**

At each mounting point, draw a circle with radius 25 mm. Place a ruler so that it just touches both the small circle and the big circle, and draw lines (called 'tangents') to outline the outer shape of the stator casting. Do not cut along this line just yet.



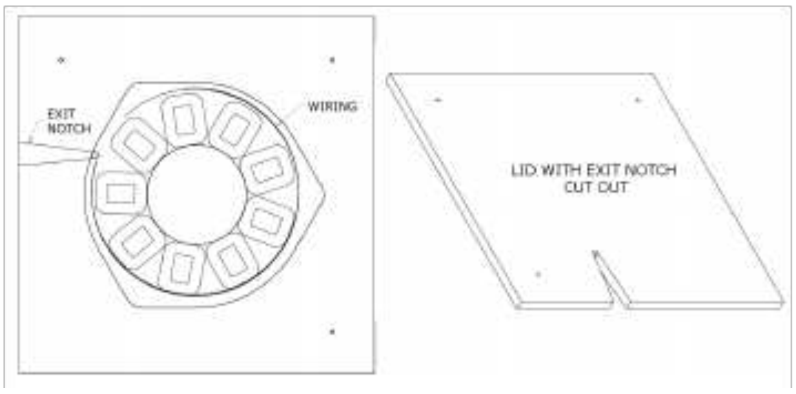
The sketch shows the coils in position in the mould, touching the island. When touching it their centres should be lying between the magnets' centres as they spin past. The extra space at the perimeter is for wires.

When arranging the wires, do keep them well away from the mounting points or they may get cut by a drill.

At this stage you should make a plan for clamping the mould together hard and evenly when the resin is setting. My preference is to drill clearance holes just through the surround and the lid so that I can clamp the lid down onto the base firmly with plenty of screws biting into the base. If the plywood is soft then use washers under the screw heads.

This is a good time to drill these holes before the island is cut out and loses its fixed position at the centre. The holes also allow air to escape, as the pressure comes onto the casting with the first few screws going in. Screws or bolts will get contaminated with resin and are not likely to be re-usable but the rest of the mould can be used many times over.

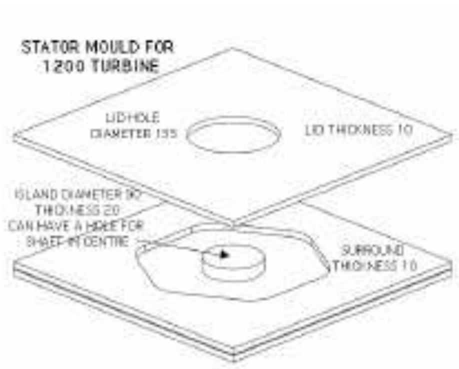
Now cut out the shape of the stator with a jigsaw to form the surround for the mould. Follow the outline with a single cut so that the stator-shaped off-cut is still usable. You can drill large holes in the off-cut for starting out with the saw blade. Use a sharp, fine-toothed blade and take care steering around the curves smoothly. Never apply side-pressure to the blade, but steer with the back end of the tool, swinging it sideways steadily as you press forward so as to direct the saw along the line. If in doubt, try a practice run first.

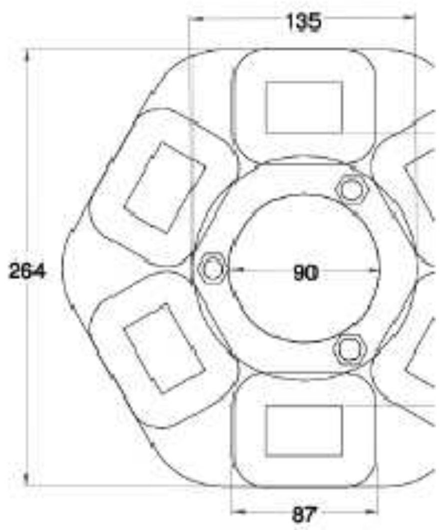


Now re-unite the surround with the lid of the mould so as to mark the exit point of the wiring onto the lid. The exit point should be close to the edge of the casting in a position where the wiring can be easily brought to the connection box. Keep it away from mounting points. Separate the lid from the surround and cut out the exit notch.

The 1200 stator mould

The outer part of the 1200 stator is only 10 mm thick. The stator has three mounting studs set into it at radius 55 mm from the centre in a raised portion of the casting 20 mm thick. A central hole with radius 45 allows for the shaft and hub passing through.





Fix the studs to the steel back-plate during the casting process.

The top of the island rises to the same level as the top of the lid so as to form the raised ring that the studs are embedded into.

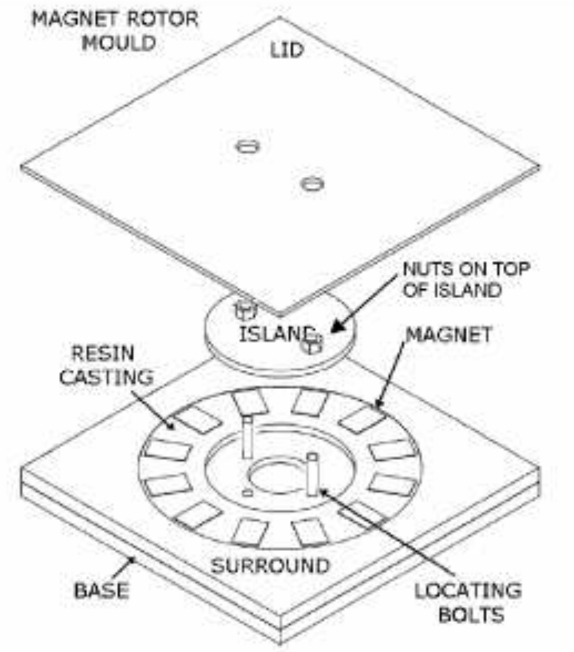
The tricky part is to support the studs in their correct positions during the casting. Fix them to their backplate. If the shaft has been welded on then you may have to make a hole in the island and the base to pass the shaft through. This can help you to centre the stator.

The wiring comes out of the hole in the lid alongside the studs.

The magnet rotor mould

MAGNETS: N40-42 grade 46 x 30 x 10 mm			
Turbine diameter	1200 /1800	2400 /3000	3600 / 4200
No. of magnets	8 on one disk	24 12 per disk	32 16 per disk

The magnet rotor is cast in resin for two reasons. One is to restrain the magnets from flying off the rotor in the event that the turbine overspeeds. I like to place a layer of thin fibreglass cloth on top of the magnets to improve the strength of the resin casting. The casting also protects the magnets from damage. NdFeB (neo) magnets are very vulnerable to degradation by corrosion, so it is important that the coating is not damaged. The resin and the fibreglass cloth help to prevent the coating from being scraped off.



You may wish to make two of these moulds so as be able to cast the two magnet rotors at once. (However the 1200 and 1800 turbines each only have one rotor with magnets on it. The 1800 also has a blank steel disk on the other side of the stator. Also please note that these smaller turbines have the magnets arranged end-to-end, and not radially like the others. Please study the drawings on page 64.)

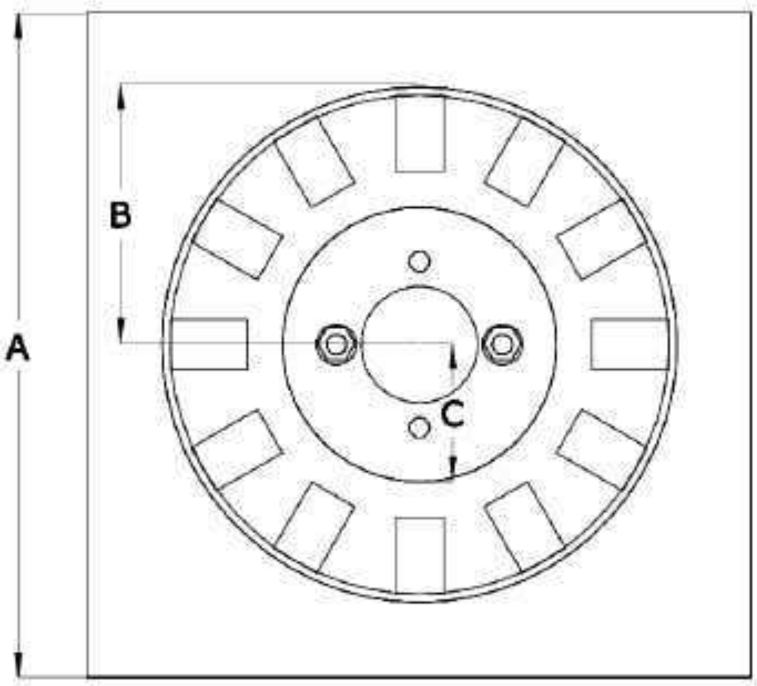
Again the mould is a sandwich with a heavy base, a surround and a lid. I often use thin plywood or MDF for the lid and then hold it down firmly using pieces of steel on top. The magnets pull the steel down very hard. But make sure there is a layer of resin and glass cloth over the magnets. The lid can be clamped down in other ways. Try to prevent the lid from sliding around once it is on. This drags the glass cloth.

The thickness of the surround must not be higher than the steel disk plus magnet plus one mm. If it is lower then you can use a bead of silicone around the edge so that the lid bears down firmly onto the magnet faces. A very thick layer of resin will reduce the running clearance between the alternator parts and/or force them too far apart so that the operating speed of the alternator will become too high.

STEEL DISK SIZES mm			
Turbine diameter	**1200**	**1800**	**2400**
DIAMETER	230	260	300
THICKNESS	6	6	8
Turbine diameter	**3000**	**3600**	**4200**
DIAMETER	350	400	450
THICKNESS	10	10	10

The hole in the surround is about 5 mm larger radius than the magnet rotor, so that the casting covers and protects the edges of the magnets. Make an island of 9 or 10 mm plywood bolted to the steel plate that prevents resin from flooding over the mounting holes at the centre of the steel disk. All the parts are kept in concentric position by two bolts that penetrate the base, the steel disk and the island. The nuts go on top of the island. The lid will need much larger holes to fit over the nuts.

Here are the sizes for the moulds. The nominal overall size of the pieces is A. The radius of the hole in the surround that forms the outside of the rotor is B. The island has radius C.



Turbine diameter	**1200**	**1800**	**2400**
Approx. mould side A	350	400	400
Rotor radius B	120	130	155
Island radius C	65	66	83
Turbine diameter	**3000**	**3600**	**4200**
Approx. mould side A	500	500	600
Rotor radius B	180	205	230
Island radius C	99	129	147

The magnet positioning jig

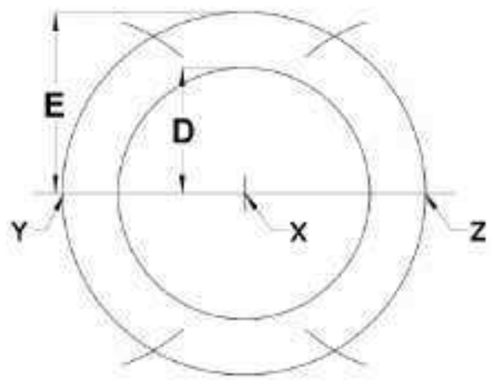
Before casting the magnet rotor you should glue the magnets to the steel disk. Use a jig (template) to place the magnets accurately on the disk. The jig is made of thin plywood with two holes that are used to bolt it to the steel disk concentrically.

Start by finding a centre point X that is more than E mm away from the edges of a piece of thin plywood.

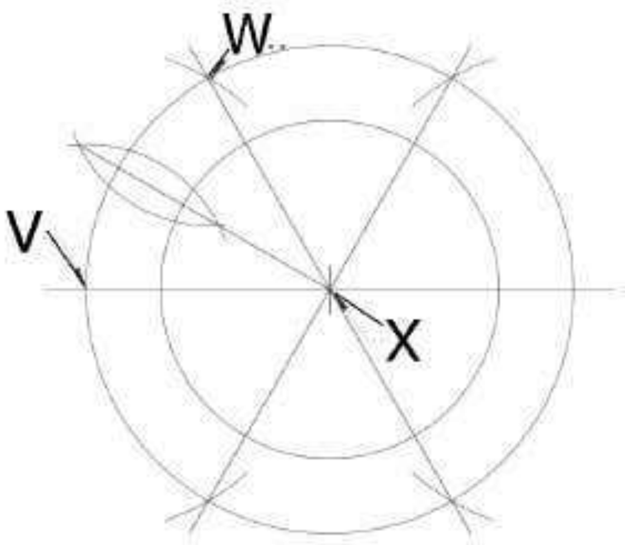
Draw a line through X. Draw two circles centred on X with radius D and radius E.

Turbine diameter	**1200**	**1800**	**2400**
Number of magnets	8	8	12
Smaller radius D	83	98	104
larger radius E	115	130	150
Turbine diameter	**3000**	**3600**	**4200**
Number of magnets	12	16	16
Smaller radius D	129	154	179
larger radius E	175	200	225

If there are 12 magnets then you will need to divide the circle into six parts as follows. Using the same radius E, but centring on Y and Z, draw arcs on the outer circle marking the 60 degree points.

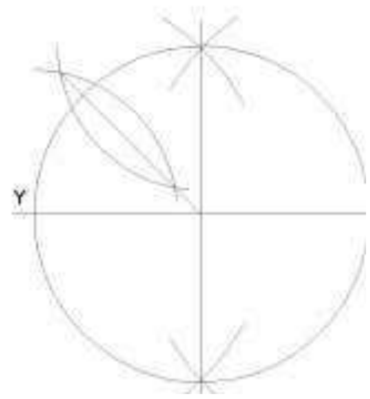


Draw lines through the centre X at 60 degrees.



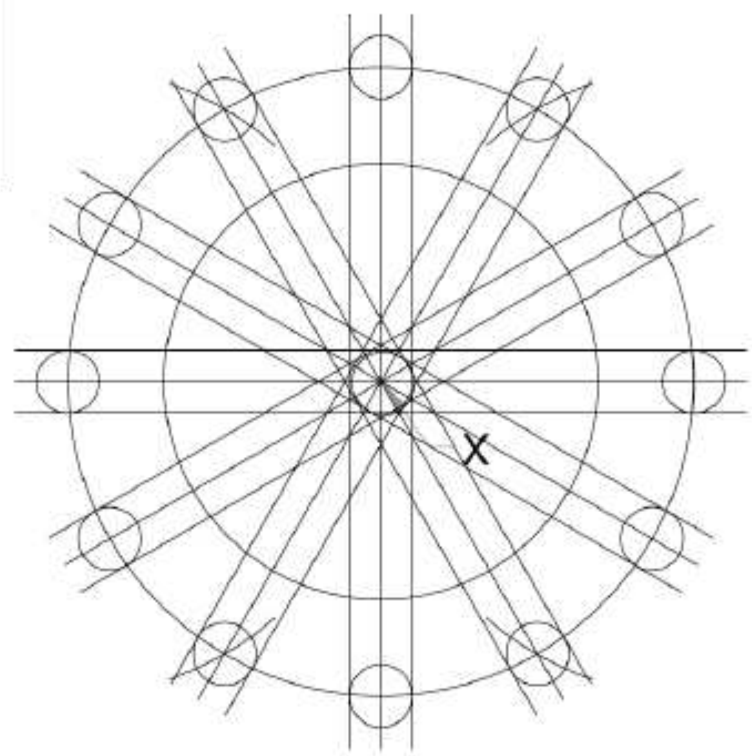
Divide the 60 degree angles in half as follows. Choose an arbitrary setting of the compasses to create overlapping arcs centred on V and W as shown. Draw lines through the intersections of these latest arcs and the circle's centre X to cut the angle in two.

Continue right around the circle carefully marking out 12 evenly spaced centres for the 12 magnets.



If you are working with 8 or 16 magnets then you can skip the 60 degree stage of the process, and just use this angle-halving technique to keep on dividing angles in two until you have the correct number of divisions. Start with Y and Z and find 90 degrees then go to 45 (for 8 magnets) and further halving them again for 16 magnets.

Now you should have divided the outer circles neatly up so as to mark the evenly spaced centres for the

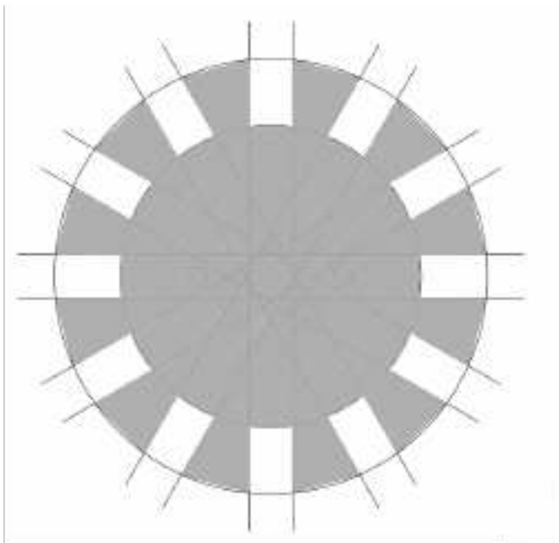


magnets.

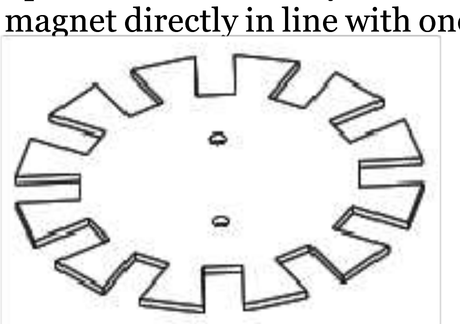
When you have marked all the points, then draw a small circle with diameter same as a magnet width on each point, and at the centre.

Turbine diameter	**1200**	**1800**	**2400**
Circle radius	23	23	15
Turbine diameter	**3000**	**3600**	**4200**
Circle radius	15	15	15

Draw many parallel lines that just touch these circles as shown and you have the outlines of the magnet jig. Cut out the shaded portion with a jigsaw to create the jig. Check as you go that the magnets fit neatly.



Measure the size of the big hole in a magnet rotor disk centre. Draw a similar circle on the centre of the jig. Place a magnet disk exactly on that centre. Line up at least one of the mounting hole centres with the magnet centres on a diameter line. Drill 2 or 3 holes through the mounting holes in the disk and the into the plywood jig. These will allow you to position the jig upon the disk centrally and with at least one magnet directly in line with one hole.



Resin casting

You can cast the stator and magnet rotors in ordinary polyester resin (as used for making fibreglass boats or for resin castings). NPG polyester resin is slightly better because it withstands higher temperatures. It is also possible to use epoxy resin. This is much more expensive but better for the magnets because it adheres better and is also waterproof. Corrosion of the magnets is more likely when the casting is polyester. Epoxy is not so good for the coils because it does not conduct heat so well. Vinyl Ester resin is very popular for resin casting both coils and magnets because it is easier to cast and withstands higher temperatures than polyester. It is also waterproof.

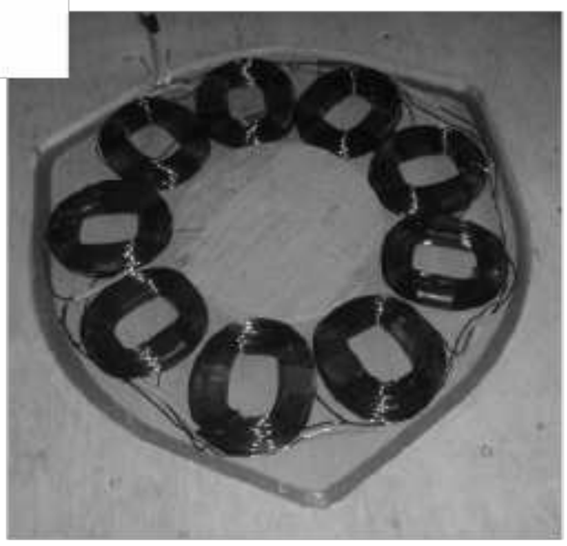
Ester resins contain an accelerator premixed with them and you add a catalyst to make them set. The catalyst (highly toxic peroxide) reacts with the cobalt accelerator producing heat that sets the resin. When you make castings you need a lot less catalyst than for laying up fibreglass boats. Castings tend to heat up and set prematurely because the heat is trapped inside. If you use too much catalyst or the room is warm, this can mean that the resin sets before you can place the lid on the mould and squeeze it to the right thickness. If the casting heats up then it will also get very stressed as it cools, and it may warp or crack.

Adding a filler such as talcum powder, or alumina trihydrate (ATH) powder to the resin mix will reduce the tendency of the casting to heat up. These powders conduct heat well, and this also helps the stator's coils to keep cool when working with currents. Filler powder is very cheap and pretty essential for making good resin castings. Other powders may also be suitable. You can also add powders to epoxy to reduce cost and improve heat dissipation.

Casting the stator

Start by preparing everything You will need:

- A mould with a lid that clamps down,
- An assembly of coils connected together,
- Two pieces of fibreglass cloth cut out to the shape of the stator,
- Some wax or grease to make sure the mould doesn't get stuck to the resin. (Don't get this on anything that you do want resin to stick to),



- Resin and disposable buckets to mix it in
- Scales to weigh out the resin.
- Catalyst, and a syringe or similar to measure it out.
- Talcum powder or aluminium trihydrate.
- Silicone or other caulk in a tube,
- Protective gear such as disposable gloves and safety glasses,

- Newspaper to cover the table top and to catch any spillage of surplus resin.

Do not embed any other electrically conductive substances (apart from the coils) in the stator casting or the magnets will induce electric currents in them, wasting power and heating the stator up.

Go through a 'dry run' where you check that it all fits together before waxing the mould. Place a piece of glass cloth into the bottom, then slide the coils in carefully with the wires at the chosen exit point. Check that the stator mounting holes will be well away from any coils and wiring. Fit a big nail or screw in the mould at the exit notch so you can tie the wires securely out of the way of the overflowing resin. Place another layer of cloth on top and put the lid on using the three pins to align it with the rest of the mould. Check that you have the means to clamp it down tightly with screws, bolts or whatever. Check that there are holes for air to escape and surplus resin to overflow (usually some of the central clamping-screw holes also serve this purpose).

When satisfied, disassemble everything and grease the mould including the interior, the edges of the surround, and the faces of the surround and lid. Be generous, especially on the edges of the plywood and in the wiring exit notch where the surplus resin will overflow out. Also cover any screw heads and bolt threads that could get covered in resin. Avoid greasing the coils or the glass cloth. Vaseline (petroleum jelly) is a good substance but any grease, wax or polish seems to work.

Allow sufficient time to do the casting job – usually about an hour is plenty. If the room is cold then you may need to use heat later to warm a polyester casting up and help it set. Leave heating it until the lid is on. You can warm it up the next day if necessary, if you are not in a hurry. Vinyl ester seems to set at just about any temperature.

If the temperature is above 20 degrees be aware that the resin may start to cure fast, so be sparing with the catalyst. You may be safer cutting the catalyst dose in half. A trial run will give you an idea of the time it takes to set.

If in doubt, mix the resin in small batches to avoid having a big pot of resin mix standing around at one time. Large bodies of resin tend to heat up and set prematurely. But if you are very confident you can put it together fast then you can mix the Vinyl Ester resin in one shot. I always mix polyester in batches.

The styrene monomer solvent has an unpleasant smell and can cause giddiness and nausea. This job is best done in an open area with good ventilation, or even outside where possible.

Mix 200 grams of resin with 3 cc of catalyst and stir thoroughly for a minute or two. You do not need to be very precise about ratios with catalysing resin. Spread this liquid mix around the bottom of the mould but do not wipe off any polish. Lay down a layer of cloth and saturate it with resin. Poke it so as to chase out bubbles of air.

Now place the coils in the mould. I like to arrange them on a piece of plywood above the mould, and then simply slide the ply out from under them so they drop into place quietly. You do not want to drag the cloth out of place by moving them too much in the mould. Pour any surplus resin over the coils so it soaks between the wires.

Meanwhile someone can start to mix 400g of resin with 6 cc of catalyst. Mix the catalyst well at first and then add powder. Add 200-300g gradually, stirring as you go, but avoid whisking in air. Add as much as you can so long as the mix will still pour. If the resin is very runny (casting resin) then you can add as much as equal weights of powder and resin. Pour this mix into the mould and mix another batch. Keep going until the mould starts to get full.

During this process place a small bead of silicone caulk around the surround, about 30 mm from the edge of the casting to limit any overflowing of the resin when the lid comes down on it. This helps to prevent unsightly voids. Also bang the mould with a hammer to encourage air bubbles to rise out of the casting.

When the mould is full, place the top sheet of glass cloth on top of the coils. Mix a final 200 with 3 cc of catalyst without powder to wet it out. Then bring the lid down, carefully aligning the locating pins, and screw it down hard.

Leave polyester castings overnight to set and cure. Vinyl ester sets in a couple of hours. When the resin that has escaped is set hard, remove the lid and invert the mould, supporting the casting. Knock the edges of the mould against the table until the casting drops out of the mould. Clean off any ragged edges before the resin reaches full hardness.

Don't forget the jacking screw holes

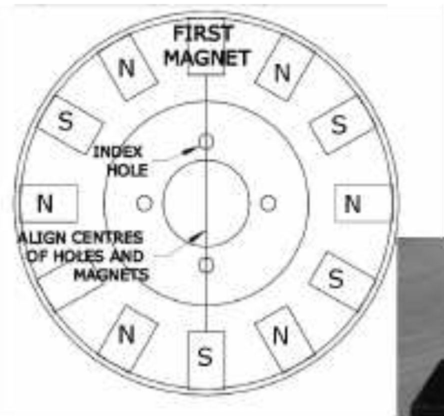
One of the rotor disks needs to be drilled and tapped for jacking screws that will be used to separate the rotors during disassembly (and to control the assembly). Drill and tap them before the magnets get involved. Drill 3 evenly spaced holes at a suitable distance from the resin casting and from the mounting studs. The holes need to be a little smaller than the threaded size. See page 13 for guidance. Keep the tap perpendicular to the plate while you make the thread.

The jacking screw holes are in addition to the mounting stud holes. You can see both hole patterns clearly on page 48. The disk shown on this page has no jacking screw holes. Only one disk needs jacking screws.

Casting the magnet rotor(s)

This process is similar to the stator casting. But first you have to glue the magnets to the steel disks. It's best to coat the magnet disks with something that protects them from corrosion and that keeps them out of contact with the magnets. Magnets scraping on bare steel often get damaged and there seems to be a rapid onset of corrosion in the magnets after that. Galvanize, powder coat or at least paint the disks first.

Choose one of the mounting holes in each disk to be an 'index hole'. Align it with the first magnet centre, so that these first magnets on the two rotors face each other when the alternator is assembled. (They also must attract each other.) Mark the index holes clearly with a centre punch or a grinder in an area where the resin will not obscure the marks. Fit the magnet jig in place with two or more bolts so that the index hole lines up exactly with one magnet.



There is a danger of the jig getting glued to the disk if it touches it. Place washers between them so as to create a gap. Cyanoacrylate ('super') glue is ideal because it sets fast. I like to put it under each magnet, but some like to add it after the magnets have all been placed.

Try placing some magnets without glue at first to gain experience with handling them. Handle them with great care, taking them one at a time. Take extra care when removing from a stack as they tend to flip back and snap onto another magnet. Hold on with two hands where possible. Put any loose magnets that are not in use on a steel surface, preferably on the wall, but try not to scratch the coating. Loose magnets on the workbench tend to fly off and hit things at great speed. When this happens they often shatter. Keep any delicate electronics, credit cards, phones, etc. away from magnets, to avoid the strong magnetic field.

It does not matter which way up the first magnet is placed onto the first disk. Snap it carefully into its notch and push it right home quickly before the glue sets. Try not to scratch the coating.

The magnets on the disk must alternate, north south, north. so that the flux alternates in the coils. Each time you fit another magnet it has to be the right way up. Hold it in your palm, close your fingers tightly, and try bringing the back of your hand down above the previous magnet. If it is repelled then it is the right way up to place on the disk beside the other. If it is attracted then turn the new magnet over first.

When you have a few magnets in place then try the polarity test on them all. Your test magnet will be attracted and repelled alternately as you move it around the circle.

When it comes to loading the second rotor with magnets, you must be aware of the index holes. The first magnet, aligned with the index hole on disk one must attract the first magnet on disk two. The back of the new magnet must be repelled by the first magnet of the first disk. Place it onto the second disk at the index mark without turning it over. The top faces of the two first magnets will now attract each other. Place the rest of the magnets, alternating them as before.

These magnet rotors are now hazardous items that can hurt people if they come together with each other unexpectedly. You can lose a finger. Store them carefully. Keep them away from work areas with metal swarf and dust that would stick to the magnets and be hard to remove.

When you have fitted the magnets, do a 'dry run' in the moulds. You need a disk of glass cloth the same shape as the area between the island and the surround.

First place the magnet rotor in the bottom of the mould and then bolt the island down onto it Your piece of glass cloth should fit on top at this stage. Finally place the lid on top and check that the magnets stand a little proud above the surround. The lid must clear the nuts and washers used to bolt the island down. It has to sit right down onto the island. Check you can sit the mould level, in spite of the bolt heads under it.

Take it apart and grease everything you do not wish to have resin stick to. Grease the mould all over and both sides of the island. Keep the glass cloth and magnet rotor free of grease and greasy fingers. Grease the lid, including the inside edges of the holes in it. Smooth off the grease inside the mould to get a neat finish around the edges. Drop the rotor into place carefully and bolt the island down gently. If you over-tighten the nuts you will warp the island. Hold the spanner in both hands or it will damage the magnets. Grease the nuts and the bolt threads liberally so you can undo them later.

Mix a runny resin mix and pour it carefully into the gap around the edge of the rotor disk, trying to chase out any bubbles that might spoil the appearance. Put a thin line of silicone on top of the surround to catch surplus resin. Mix resin and powder to fill the spaces between magnets. Hammer the mould to remove bubbles. Finish with a runny mix on top of the glass cloth so as to saturate it. Place the lid on top carefully so as not to drag the cloth out of place. Hold it down by placing many steel objects evenly on top of the magnet faces.

You can set the mould(s) level under a heat lamp for a while to speed up the polyester setting process. It is good to get the lids off before they have fully hardened though, because there will be some resin over the top of the island that has to be trimmed off neatly. Take great care working near the magnets with a knife. The magnets will grab it.

When you have taken the rotor out of the mould, clean away surplus resin, especially from the areas around the mounting holes. Store the rotor safely out of the way of fingers and magnetic debris.

You may wish to paint the magnet rotors with a special paint such as a bitumen epoxy coating. Corrosion of the steel disk can cause the magnets to come off. If the magnets' coating gets damaged then the magnets themselves corrode. An impermeable seal over the whole thing is a good investment.

Alternator assembly and testing

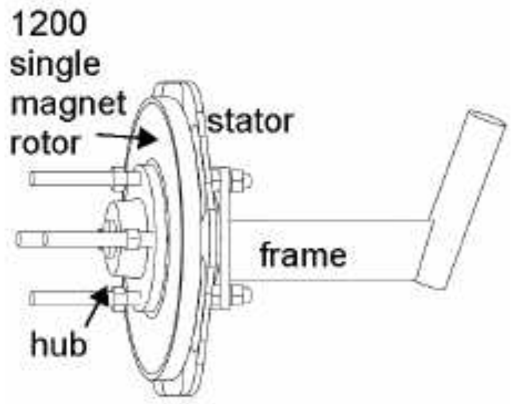
The alternator is held together by long studs made of threaded rods ('all-thread'). These are the same threaded rods that the blade hub is mounted on. I like to use stainless steel rods. The rods need to fit the holes in the hub

Recommended sizes for stainless steel studs (mm)						
machine	1200	1800	2400	3000	3600	4200
Stud dia.	10	10	10-12	12	12-14	14

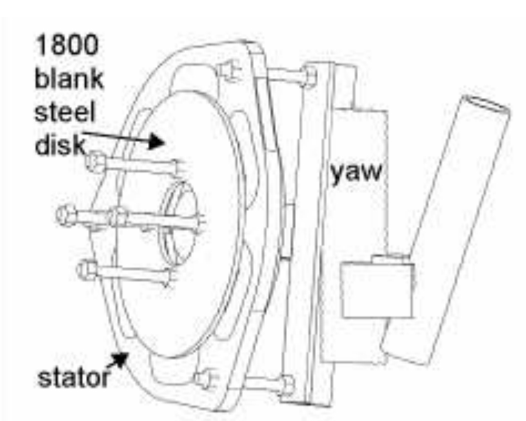
If necessary, enlarge the holes in the hub flange by boring them out, or you can make them smaller by inserting bushes, or even 'helicoils' that create a thread. If enlarging the hub holes it helps to place the steel rotor disk on the hub, and drill through the precisely cut pattern of holes in the disk. This helps to avoid eccentricity. Do all such drilling jobs before casting the magnets onto the disk.

Rotor mounting options

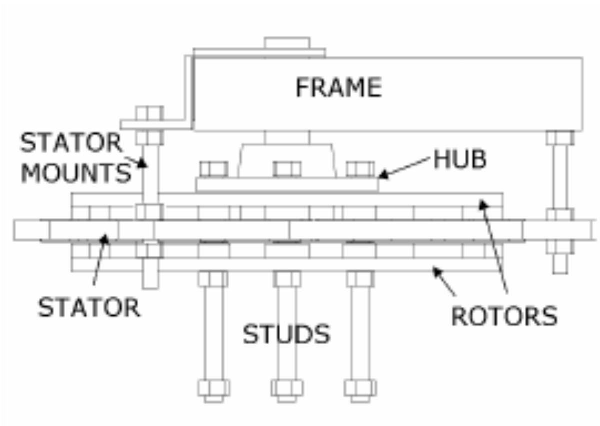
The single rotor for the 1200 turbine is mounted on the back of the hub, facing the stator.



The other turbines have two rotors although the 1800 has only got magnets on the back rotor. See also the drawings on page 64.

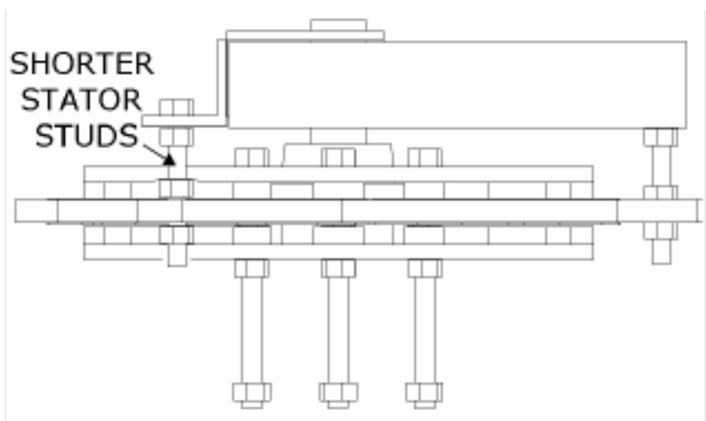


There are various options for mounting the two magnet rotors of larger turbines on the wheel hub. You can mount them in front or behind the wheel flange. In the top view shown below, the magnet rotors are both mounted on the front of the hub.



(In some of these sketches the magnets are visible, whereas in reality they would be embedded in resin.)

In some cases the hub flange is machined flat on the back, and so you can mount one disk behind and the other in front. This makes for a more compact alternator with shorter stator mounts.

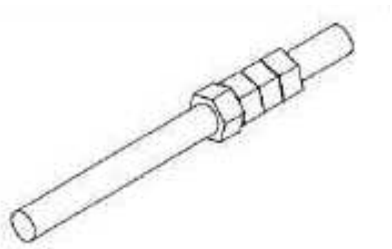


It is generally easier to build the alternator if the front magnet rotor is on the front of the hub flange and can therefore be mounted after the hub is on its bearings, but you can even put both disks on the back (see right). This works OK and can help to keep the stator mounts very short, but the alternator is awkward to assemble.

Shorter stator mounts are more robust, but provided they are securely tightened, a long stator mounting stud also seems to work. The nuts on the stator mounts must not be over-tightened or they will crack the stator, but they do need to be carefully locked, either with thread sealant or by adding extra (contra-rotating) nuts locked against the first ones very tightly. Do this after the assembly is completed and you are happy with the clearances.

Rotor mounting studs

The studs that are used for mounting the magnet rotors and the blade assembly must be long enough to go right from the back of the alternator to the front of the blades and accommodate nuts between the two magnet rotors, and at both ends. I like to make them a little longer still just for luck.

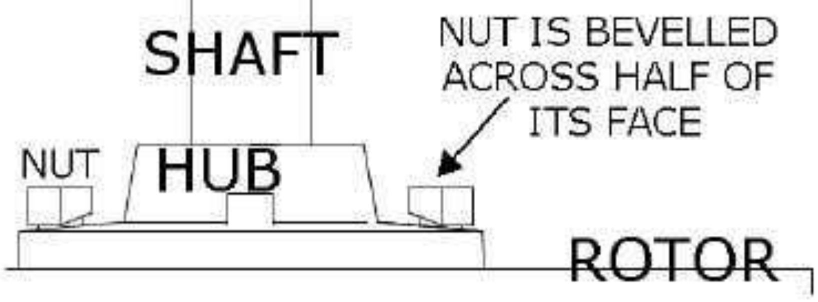


The magnet rotors need to be spaced apart by a precise distance so that they run true with the correct gap to fit the stator. Use a stack of nuts on each stud to build a spacer.

Add washers if required to fine-tune the gap. Washers my need to be checked with callipers and sorted for thickness. A total gap of 40 mm between steel disks is a good first assumption.

Build up the stack of nuts in the correct position before you assemble the alternator. Take care to tighten the nuts evenly against each other so that each stack is the same size. It is hard to do this when they are between magnet rotors because the magnets will grab the tools.

In cases where the back of the hub is not flat then it may be necessary to grind off the corners of the nuts so that they do not put a bending load on the studs.



In such cases you will need to tighten the stud onto the nut when you fit the first magnet rotor. The nut itself cannot be turned and tightened later. But if the back of the hub flange is flat, then you can leave the tightening of this nut until both rotors are fitted, making it much easier to assemble the alternator.

Assembly

Magnet rotor faces may need to be cleaned to remove any resin, magnetic dust or metal swarf. Swift strokes outward with a dry paint brush work well for dust.

You will need to drill holes in the stator and in the welded frame, at the positions of the stator mounts that you marked in the original layout or your stator. Use the off-cut piece of plywood from the mould, placed on the frame and centred carefully, as a guide to the drill. Start with a 5mm drill and follow with a full sized one that the stator mounting studs will fit. When the frame has been drilled you can place the stator casting on the frame and take great care to centre it so the coils will be under the magnets as they rotate. Clamp it gently in place and drill out the holes using a large drill that passes through the existing holes in the steel frame. I hope you don't drill through any wires!

In the case of the smallest, 1200 machine, you start by mounting the stator. For the other turbines, start by mounting the first magnet rotor and the hub. If the rotor is to go behind the hub then you will need to mount this before mounting the hub. Otherwise start by mounting the hub on its shaft and bearings.

Clean and grease the bearings. Use plenty of grease, but do not pack them totally solid with grease.

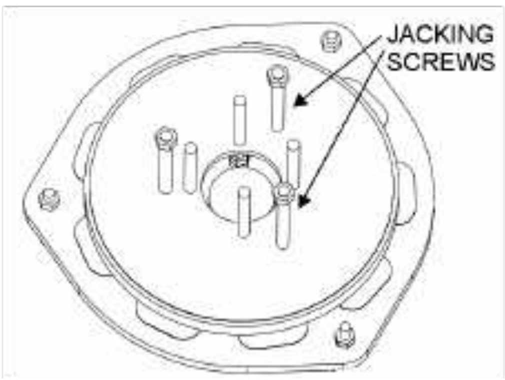
Adjust them up tight with the nut so that there is no play, but do not over-tighten them so they are stiff to turn. Lock with a split pin.

After the first rotor is on, place the stator onto its mounting studs, but do not attempt to adjust its position with the nuts at this stage.

Now mount the second magnet rotor. Check that the index holes of the two rotors are aligned. Take great care of your fingers because the two magnet rotors will attract very strongly.

The best solution is to use 'jacking screws' threaded through the second rotor (usually the front magnet rotor) and use these screws to gradually lower the rotors together.

You can assemble the alternator in its normal position or lying on its



back as shown. The jacking screws need to be clear of the other studs and the resin casting. You can make them up by cutting lengths of threaded rod and welding a nut on the end of each. Make them long enough to stand out beyond the ends of the mounting studs so you can easily get at these welded nuts. I use a socket spanner in a cordless drill to spin the screws in and out. Take care to keep the disk level when jacking it.

When the second magnet rotor is sitting down on its pile of nuts then you can judge how well the alternator fits together. Adjust the stator mounts so that the stator sits in the middle of the gap between the two rotors. There should be about 1.5 mm minimum clearance on each side as you spin the rotors around. If there is less, then take the second rotor off and add a washer to each stud to increase the spacing. Tighten the magnet rotor down onto the stack of nuts (and maybe washers) with nuts on the outside. Check the gap again while spinning the alternator around. Make sure that the rotors are running true and that they do not come close to the stator at any point. A piece of 1.5 mm thick board is ideal for checking clearance in the gap as you lock the stator mounts.

Note that the alternator will turn freely so long as no wires are touching but if you touch 2 output wires together there is a pulsating resistance to turning the rotors. If all 3 wires are touching then there will be a strong, smooth resistance due to the high current into the short circuit. Shorting them like this can be used to brake the wind turbine.

12-volt turbine rectifiers

A good way to install the rectifier for the 12 volt stators with multiple AC wires is to use a die-cast aluminium box mounted on top of the yaw tube. Any AC wire can connect to any AC terminal on a row of single-phase rectifier blocks. All of the DC positives are joined to the positive cable to the battery, and likewise all of the negatives.

The box is well cooled by the wind but needs to be well sealed against moisture entry. Allow the box to vent via the cable exit into the tower at the bottom.

The cables down the tower need to be well anchored or the connections may be damaged by their weight and twisting motion.

Testing the alternator

At this stage you can test the alternator by checking the output voltage at different speeds. Use a multimeter set for 'ACV' and place one probe on each of any two wires. You will find that the AC voltage between any two wires is the same but varies in proportion to speed. An easy speed to measure is 60 rpm, which is one turn per second. Here is a table of predicted AC voltages for each size turbine and each nominal battery voltage (DC). You can also test at 120 rpm and look for twice the voltage.

AC voltage at 60 rpm			
Turbine diameter	**1200**	**1800**	**2400**
12V	1.9	2.3	2.9
24V	3.4	4.2	5.3
48V	6.8	8.4	10.6
Turbine diameter	**3000**	**3600**	**4200**
12V	3.5	4.2	5.2
24V	6.5	7.7	9.4
48V	12.9	15.6	18.8
350V	47	63	52

The DC voltage is approximately 40% higher than this, but the rectifier takes about 1.4 volts from the total. DC voltage does not vary in exact proportion to speed.

Another test is to connect the rectifier and check the DC output voltage to find the 'cut-in' rpm. If the AC voltage is much higher than the table predicts, or the cut-in rpm is much lower, then you should increase the gap between magnet rotors to reduce voltage and prevent the turbine from stalling.

Predicted cut-in rpm			
Turbine diameter	**1200**	**1800**	**2400**
Cut-in rpm	300-310	240-260	200-210
Turbine diameter	**3000**	**3600**	**4200**
Cut-in rpm	160-170	140	110-120

12-volt turbines can usually cut in at the slightly lower rpm without fear of stalling because the wiring in 12-volt systems is more inclined to create a voltage drop that pushes up the rpm and prevents stalling later.

Installation

The electrical wiring needs to be thick enough to carry the current without becoming dangerously hot. All connections need to be nice and tight. If you use terminal blocks, make sure that the screws are tightened as hard as you can. A better solution in most cases is to crimp a lug onto the end of the wire and to bolt it down.

Here are some minimum recommended wire sizes in square mm allowing for occasional over-currents:

Diameter	1200	1800	2400	3000	3600 +
Nominal Power	200 W	350 W	700 W	800 W	1 kW
12-VDC	2.5	6	16	25	25
24-VDC	1.0	2.5	6	6	10
48-VDC	1.0	1.0	2.5	2.5	4
24-VAC	0.7	1.5	4	4	6
48-VAC	0.5	0.5	1.5	1.5	2.5

Choose fuses (or breakers) that will blow before your chosen wires can overheat. Check their current ratings based on size and insulation type and avoid bunching the wires. Take care choosing wires and fuses because a blown fuse or a tripped breaker will allow the turbine to run fast and produce excessive voltages.

Current in the transmission wiring will create a 'voltage-drop' between the higher voltage at the turbine and lower at the battery voltage. Heavier, shorter wiring will have a lower resistance and produce a lower drop in voltage. Long, thin wires result in a larger drop.

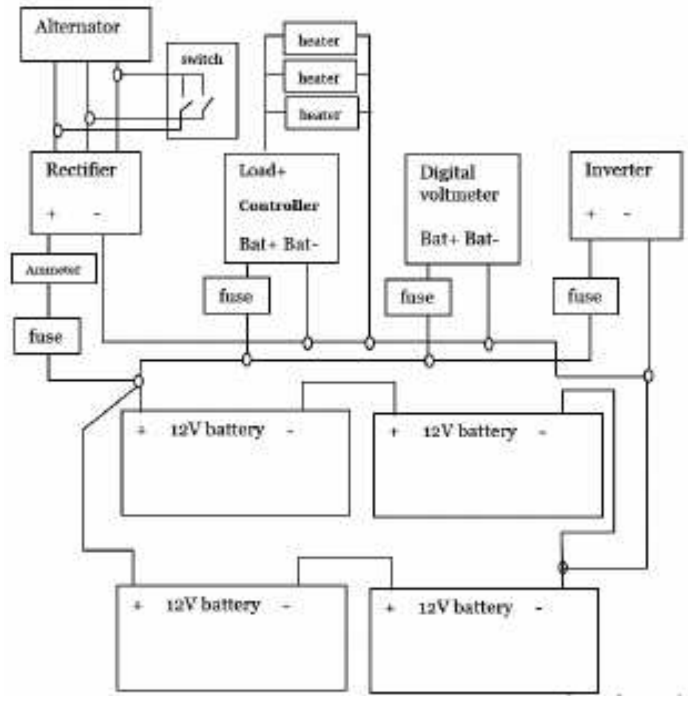
On the one hand a big volt drop wastes energy by requiring the turbine to produce more voltage (hence power) that is simply used up in warming the wires. On the other hand if you use wires that are short and thick then the turbine will stall due to low speed and the blade efficiency will be drastically reduced.

The table below shows the recommended lengths of cable (one way in metres) using the wire sizes above, to get the best performance out of the wind turbine. The length includes the tower height. If the length is much less, then the turbine may run too slowly and stall when battery voltage is low. If the length is more, then you can benefit from using thicker wires. For example double the minimum distance and you double the wire size in sqmm.

Turbine diameter	1200	1800	2400	3000	3600	4200
12-V	30	30	60	50	50	20
24-V	25	25	55	45	40	15
48-V	65	30	80	60	70	20

Wiring the batteries

Group your batteries in series strings that add up to the desired system voltage. In a 24-volt system for example you could use pairs of 12-volt batteries wired in series. Connect more pairs to each other in parallel to add capacity. The circuit diagram shows a typical layout. The positive and negative connections to the inverter, rectifier etc. are best connected to different ends of the parallel links so as to even out the wiring resistance between battery strings.



Never disconnect the battery from the wind turbine, because the voltage will rise sharply and damage the electronics. The charge controller is unlikely to be able to prevent this voltage rise without the presence of batteries. Brake the turbine before working on battery connections.

All the circuits from the battery must pass through fuses that are chosen to carry the maximum current in the circuit but will blow before the wiring gets overloaded. It is normal to put the fuses in the positive wire. Strictly speaking there should be a fuse in each negative wire too unless the negative is earthed.

The rectifier and brake

If the rectifier is at the battery there will be three wires arriving from the turbine. It's a good practice to bring these three wires first to a brake switch that can be used to park the turbine while you work on the rest of the wiring. Never disconnect the wind turbine without first applying a short circuit to the wires so as to prevent it from running away. A low-tech way to do this is just to 'T' off three wire tails that you connect together when you wish to brake the turbine. Another solution is to use a big 2-pole main switch from a household fuse panel.

The rectifier consists of diodes but they are often packaged into bridge rectifiers already. A 3-phase bridge rectifier will have five terminals on it.

You should fit lugs to the ends of the wires with a crimping tool and then screw them on to the rectifier.

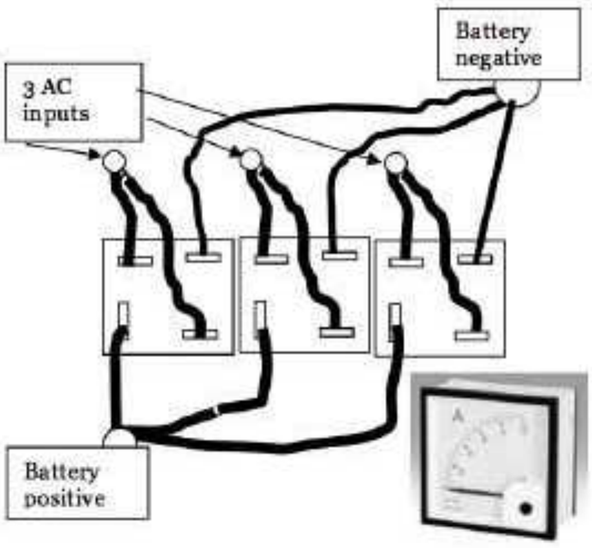
Another solution that is less costly is to use several 'single-phase' rectifier blocks that look like this:

The AC terminals are in opposite corners, and the positive DC terminal is at right angles to the others.

You can connect with high quality PIDG crimp 'receptacles' or solder.

Make good connections or they will heat up and the diodes will fail. Rectifiers need to be bolted to a heavy aluminium heatsink to keep them cool. Scrap aluminium will do, provided it is clean. Use 'heatsink compound' under the rectifier to improve the contact.

The single-phase bridge package contains four diodes and you can use it for two of your AC wires, placing the third wire on a separate block. But a better solution is to use three of these single-phase units and to combine the two AC terminals on each unit so as to reduce the current in each diode and prolong its life:



Meters

Connect an ammeter in the line from the rectifier to the battery so that you can see what the wind turbine is putting out. A moving coil meter with a needle on a scale is easiest to read, because current changes so rapidly over a wide range. For more data you may also wish to fit a more sophisticated meter such as the 'Dr Wattson' amp-hour meters that are now available at low cost.

It is important to have a good battery voltmeter (with its own small fuse for safety). A clear digital display is really helpful when reading battery voltage, because small changes are significant.

Controller

You will need a load controller to protect the battery from over-charge. The Morningstar 'Tristar' 45 or 60 amp controllers can be configured to work as 'diversion load' controllers and will dump some current into heaters if the wind turbine produces more than the batteries need. I use 300 watt resistors from Arcol (see suppliers list) as dump load heaters. A one ohm heater works well at 14 volts, and a 3 ohm heater is suitable for 28 volt operation. These are typical battery charging voltages for 12 and 24 volt (nominal) systems. These heaters will dump up to 14 and 9 amps respectively. Add more heaters in parallel until you have enough load to absorb all that the wind turbine can produce together with any extra solar PV charging current that is not already regulated.

More here **http://scoraigwind.co.uk/** under "charge controllers"

You can also build your own charge controller using circuits available on the web - for example on my own older web site at
http://www.scoraigwind.com/circuits/chargecontrol.htm

Inverter

There are many options for buying an inverter that will give you AC power from your batteries. Choose your inverter before deciding what voltage your wind turbine should be. Bear in mind that higher voltage systems use less copper in the wiring, so try to find a 48-volt or 24-volt inverter unless you have a good reason for wanting a 12-volt system.

Cheap inverters can work very well, but the more expensive sine-wave models are slightly better if you can afford to pay the difference. Buy a big enough inverter to meet your highest demand, bearing in mind that some items (such as fridges) need a hefty surge of power to start up even though they do not use much once running. Keep the inverter close to the battery and connect it with heavy wires but do not sit it on top of the battery in a small compartment or it will corrode. Better to separate the battery from the inverter by a bulkhead or partition wall.

If you are using a 'grid connect' inverter without batteries then take great care that the wind turbine voltage does not rise too high and destroy the inverter. The inverter will not load the turbine all the time. You will need a controller that brings heaters on in time to prevent the voltage from going wild.

Wire up the batteries and controller and most importantly the brake switch before you erect the wind turbine for the first time. You would not test drive a car without brakes. The wind turbine will overspeed if not connected to a load. This will not immediately damage it but it is a stressful mode of operation and can be alarming to watch. If you run the wind turbine without batteries connected then the high voltage will destroy any inverter or other electronics that are connected to it.

Commissioning the turbine

Complete the electrical system, and erect the tower (on its own) and adjust guys and lower it again. Make sure that all the nuts in the machine are locked so that they cannot vibrate loose, and the blades are properly balanced. Install the turbine on the tower and check that it spins freely. Then apply the brake switch and check it by trying to spin the rotor. Finally erect the tower with the turbine on it.
Take the brake off and enjoy the fruits of your labours.

Towers

Wiring the tower

The wiring inside the tower needs to be tough and flexible to withstand movement of the turbine on the tower top. I recommend using three single, 'tri rated', flexible equipment wires. A sheathed cable (with three cores) would withstand more abrasion, but is less able to take hundreds of twists, so overall I prefer using three single conductors. Leave plenty of slack wire. You can slip a large bore piece of plastic pipe or conduit over the wires where they emerge at the bottom if it looks as if they will rub on the steel. This also protects them against being chewed by livestock. But keep it loose and easy to see the extent of any twisting so that you can take action if necessary.

On turbulent sites, fit a plug and socket to the wires at the tower base and untwist them periodically. But on most good sites the twists will build up quite slowly and there will be no need to worry for a few years.

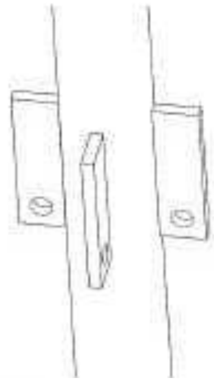
Use 'steel wire armoured' (swa) cable from the tower base to the rectifier at the battery shed. You may be able to find length of this in scrap yards. Connect thick wires together cheaply and effectively by pushing them inside 30 mm lengths of copper pipes (small bores such as 8 or 10 mm pipe) stripped and laid side by side, and crimping them thoroughly. You may wish to include three branch wires in the junction at the tower base, for short circuiting the turbine during tower erection.

Tower pipe sizes for towers with guys (guyed towers)

Here are some minimum recommended sizes of water pipe to use for the various turbines. Larger pipes would have a larger factor of safety. The assumption here that you will guy the pipes close below the blade tips with guys that are not too steep – I recommend 45 degrees or so for the guys. This will minimise the stresses on the pipe. If the tower is guyed more steeply and further down then larger pipes may be better.

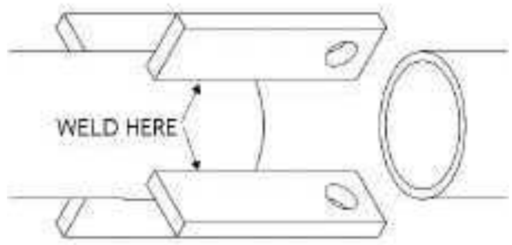
Turbine diameter	1200	1800	2400	3000	3600	4200
PipeO.D.	48	60	60	73	89	101
Steel guy rope mm	3	4	6	6	8	8

Pipes often come in 6 or 7 metre lengths. Use at least one set of guys per length of pipe, but the top guys will take the real strain. Lower ones can be thinner since they are simply there to keep the pipe straight so it will not buckle.



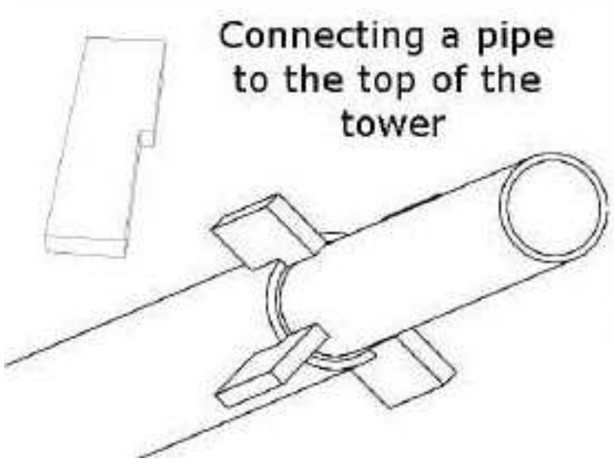
The best way to attach the guys is to shackle them on to lugs that are welded to the tower. Make the lugs out of flat steel bar 8-10 mm thick with holes drilled in them.

Also place such bars at the butt joins between two pipes. Start by welding some or all of the lugs half way on to one pipe, but projecting beyond the end.



Then push the other pipe into position between them and weld it to the same lugs. This helps to keep the pipes concentric, and also allows you to weld onto the pipe without the danger of a weld contracting and pulling the join out of line. Finish by welding the pipes to each other. The end result is very strong and you can also attach guys to it.

Where the yaw bearing calls for a smaller pipe size at the top you can join them with stepped pieces of flat bar that weld on in the same way. Or butt weld the pipes to a central, horizontal plate with a big hole drilled in it for the wires to pass through, but this is less strong.

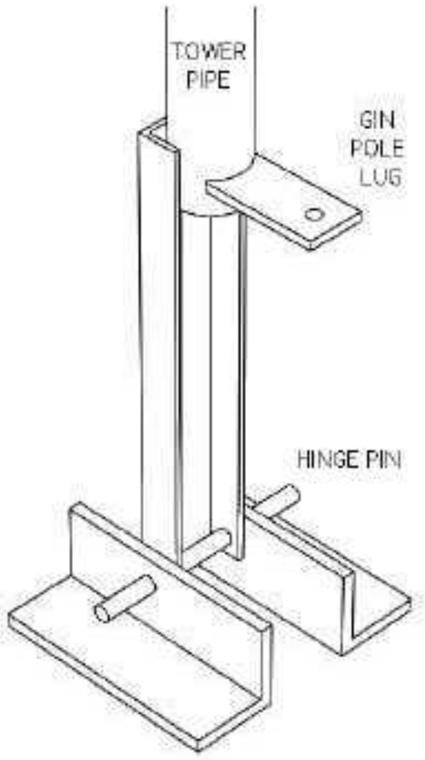


If the pipe sizes are close then you can sometimes push one inside the other and join them by drilling and tapping in screws (photo next page).

A cap washer welded on the top of the tower is advisable for heavy turbines.

At the tower base you will need a hinge. I recommend extending the tower beyond the bottom of the pipe so as to allow any twists in the wiring to emerge easily. A good solution is to make a channel out of two pieces of angle as shown below.

You can make a simple hinge at the bottom of the channel section using a big bolt through the channel section. Support that on two more large pieces of angle bolted to a rock, sleeper, concrete pad (as above) or simply onto a steel frame. Much depends on ground conditions but the tower base needs no very substantial foundation. The guy anchors are the important thing.



In fact, a simple T-piece (one metre of pipe or angle) welded at right angles to the bottom of the channel and resting on the ground against a boulder can work very well as both a base and a hinge.

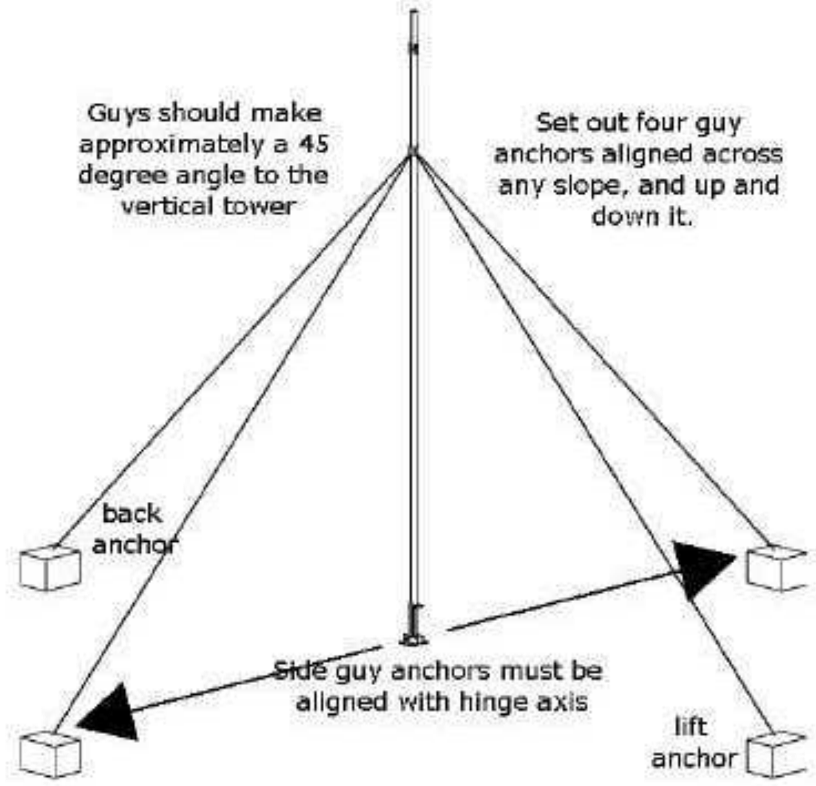
Note that in the sketch there is a lug welded to the tower for attachment of a pipe that will be at right angles – the 'gin pole' used for lifting the tower.

Guy anchors

In order to make the tower easy to raise and lower, you should use four guys. Anchor them at a distance about equal to the tower height away from the tower. Tie heavy chain around a cross bar of pipe or steel angle buried in the ground or set in concrete. In some cases you can shackle the chain to rock bolts instead. Or bolt a steel bracket to the rock, and shackle the chain or the guys onto that.

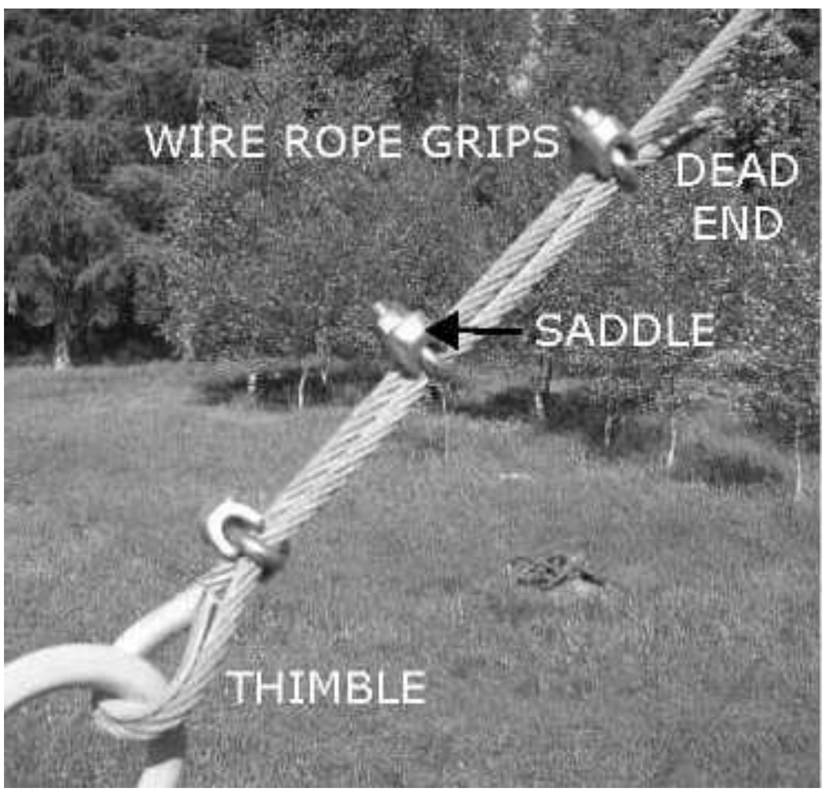
Two of the anchors should be on the same level as the tower base hinge. If there is a slope, then the back anchor (see diagram below) should be up the slope. The side anchors should be on a straight, horizontal line through the hinge so that their tension remains the same throughout the lift.

If in doubt, place the tower hinge a little above the line between the anchors and/or a little toward the lift anchor, so that the guys become tight when the tower is vertical and become slacker when lowering.



The most popular material for guys is steel wire rope. But you can also use high tensile fence wire, chain and other things where appropriate. When I use HT fence wire, I always fit two or more strands because it can fatigue unexpectedly. Otherwise it is very durable and strong.

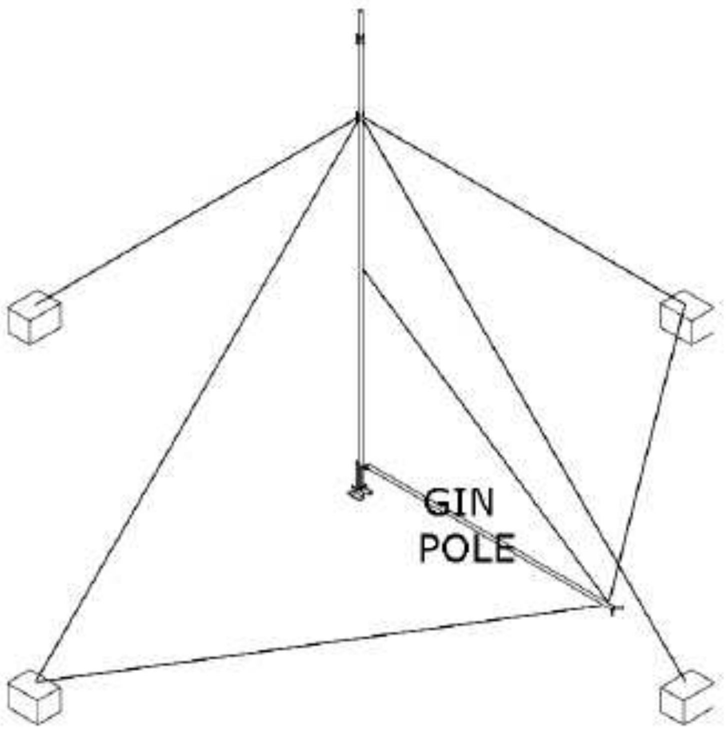
Steel wire rope can be cut with a grinder, and made into eyes by it doubling back around a hard eye or 'thimble' and tying to itself with three rope grips.



Fit the saddle of the rope grip to the live part of the rope and the ‘U’ bolt on the dead end. The U bolt tends to cut the rope, so it must not be on the live part.

Lifting the tower

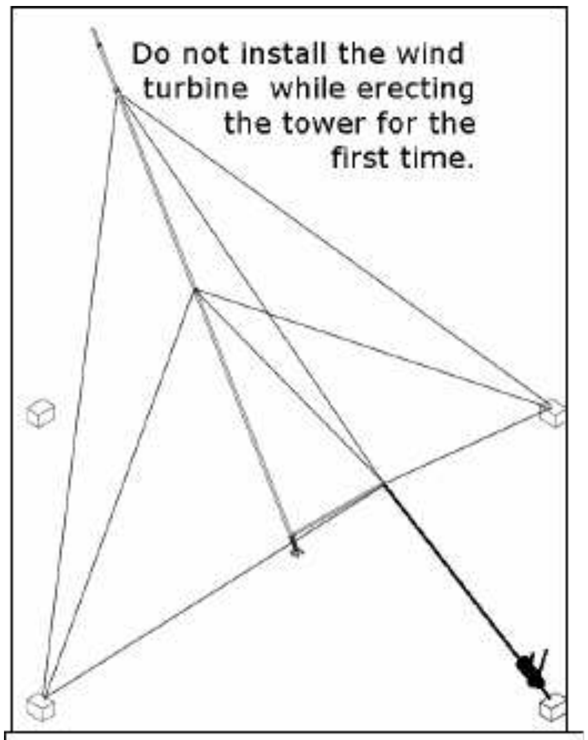
Use a gin pole fitted to the lug at the tower base for lifting and lowering the tower.



If the tower is short, then you can lift the tower using one of the guys passing over a saddle/fork at the top of the gin pole. The gin pole itself needs three guys: one to the tower and one to each side anchor. The gin pole lug is a hinge, and the guys hold it in place.

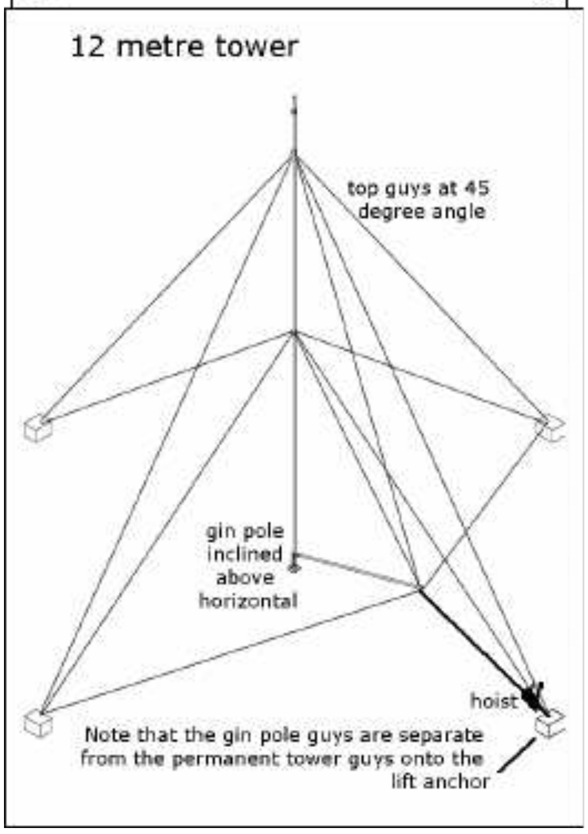
Avoid using a vehicle to pull up the tower as this is rather dangerous. Use a Tirfor or similar ‘rope hoist’ to raise it by hand easily and slowly.

Make provision for attaching the guy to the anchor before detaching the hoist. A long chain and plenty of shackles are useful for this. Take the chain around the side of the hoist and shackle it to the lifting guy.



Taller towers

If the tower is tall and there are several guy levels, then you also need to have several guys from tower to gin pole. Attach the lifting cable to the top end of the gin pole. The angle between tower and gin pole must then be less than 90 degrees, so that even when the tower is vertical the hoist still pulls it against any wind or random forces. Use completely separate guys for anchoring the tower.



Adjusting the guys

Do not try to adjust the guys until the tower has been erected for the first time. During the first erection you can tie them on loosely with just one grip, or use fibre ropes to hold the tower upright. Take care that the guys do not become over-tensioned and break during the lifting operation.

When the tower is up, adjust and tension the guys starting with the bottom set, while using a level placed against the tower. Be aware that before you tighten a guy on one side, the opposite guy may need to be slackened first. Sight carefully along the tower to check that it is straight as you adjust the upper levels. The tension is not critical but the tower must not sway, nor must the guys be so tight as to stress the structure unnecessarily.

Use a turnbuckle to tension the guy wire(s) easily.

When lowering the tower you can attach the winch, then unwind the turnbuckle completely, thus releasing the guys on the lift side. When making it fast again remember to lock it so that it cannot unwind inadvertently. All shackles and turnbuckles must be tightly locked against the effects of vibration.

Alternator design

I have tried to provide a wide enough range of recipes in this book so that you will not need to design your own alternator, but you may be interested to understand the way I have gone about designing them.

Matching the blades

The alternator must be designed so as to absorb the amount of power that the blades can deliver at any given rotational speed over its operating range. The blade tips will run best at a speed that is a certain multiple the wind speed. At each windspeed we can predict both: the blades' best speed of rotation, and also the power that they should crank out (based on what that wind offers for a blade rotor of that size).

Tip speed ratio (lambda λ)

Most of the blades in this book are designed to work at a tip speed ratio 7. This means that the blades tips should move at 7 times the windspeed. Windspeeds for turbines are usually expressed in metre per second. (2.2 mph = 1 m/s)

A 3 m/s windspeed is suitable for starting to produce power. In such conditions the blade tips should ideally run at 3 x 7 = 21 m/s

In a 10 m/s windspeed the turbine should reach close to full power and the blade tips should ideally run at 70 m/s. Speeds above 80 m/s tend to erode the blade leading edges.

Calculating the blade rotor rpm

Rpm = (blade tip speed x 60)/(diameter x 3.14)

Units are m/s and metres. Full power 10 m/s winds are over 3 times faster than the cut in at 3 m/s. The ideal blade rpm for full power is therefore more than three times faster than the cut-in rpm. This is a problem because the typical speed range of the alternator from cut-in to full power is less than double.

Blade power

The theoretical power contained in the wind is:

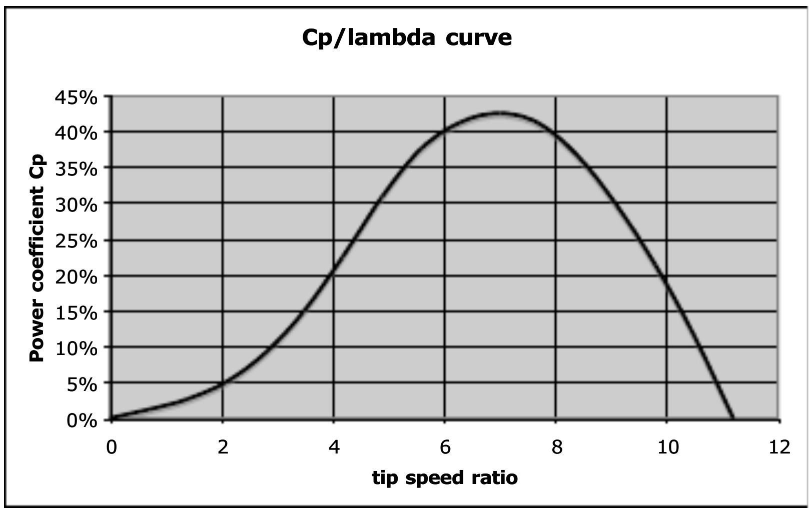
Power = (density of air)/2 x area x windspeed cubed

Density of air is 1.2 kg per cubic metre (or close).
Area is diameter (m) squared x 0.785 (0.785 = $\pi/4$)
Windspeed is in metres per second (m/s) again.

However it is not physically possible to catch all of this wind, and in reality the mechanical power that the blades can produce is a certain percentage of this, known as the coefficient of performance or Cp.

The highest possible Cp is 59.3% (known as the Betz limit). If you try to capture more wind energy than this, then the wind just diverts away and goes around the wind turbine instead. Catching wind energy slows the air down and blocks the flow.

The actual power coefficient of the blades depends on the operating tip speed ratio. Here is a chart showing how it might vary (theoretically) for a blade rotor designed for $\lambda = 7$.



Cp peaks at the design tip speed ratio but it is still useful at lower and higher ratios, from about 5 to 9.

Below tip speed ratio 5 the blades literally stall. The wind strikes the leading edge at a coarse angle and fails to follow the back curve but separates instead and creates a lot of turbulence and drag.

Above tip speed ratio 9 the blades generate a lot of drag due to excessive speed and the wind now hits the blades at a too fine angle of attack.

When using an alternator connected simply via a rectifier to a battery it is not possible to keep the blades at the ideal tip speed ratio over the full range of windspeeds. The battery will hold the speed relatively constant. The best option is to compromise and cut in at a higher rpm than the ideal, so that the tip speed ratio becomes optimal in a mid-range windspeed, and does not rises high enough in stronger winds when the blades would like to be running quite fast but the alternator speed is holding them back.

When designing an alternator to match blades that prefer to run at tip speed ratio 7, I actually try to set the alternator speed so that the blades are running at tip speed ratio 8.5 or more when they cut in at 3 m/s windspeed. At around this point the wind is just strong enough to overcome the friction in the bearings and so forth.

machine	1200	1800	2400	3000	3600	4200
design tsr	5	6	7	7	7	7
cut in tsr	6.25	7.5	8.75	8.75	8.75	8.75
cut in rpm	300	240	210	167	140	120

Calculating the output voltage vs. speed

The alternator cut in speed (rpm where it starts to produce power) should match the targets above. The way to find the alternator cut-in speed is to work out the voltage you will get from the alternator as a function of rpm. The cut in rpm is where DC output reaches battery voltage.

Voltage induced in a wire depends on the rate of change of magnetic flux through the coil. You can easily calculate the total flux that passes through the coils due to the magnets, using their flux density and total area. In each revolution this flux will cut the wires twice: once entering a coil and once leaving.

So the average voltage
= 2 x total flux x number of turns x revolutions per second

total flux = area A sq.m x flux density B (Tesla)
turns n = turns per coils x coils in series
revolutions per second = rpm/60

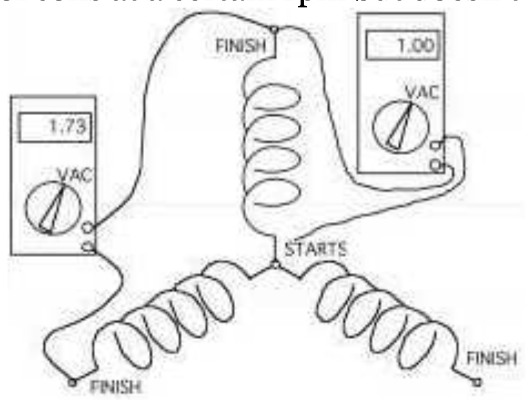
So average voltage = A x B x n x rpm/30

Area of one magnet is 46 x 30 mm = .00138 sq.m

machine	1200	1800	2400	3000	3600	4200
No. of magnets	8	8	12	12	16	16
A sq.m	.011	.011	.017	.017	.022	.022
B tesla	.3	.44	.62	.62	.62	.62

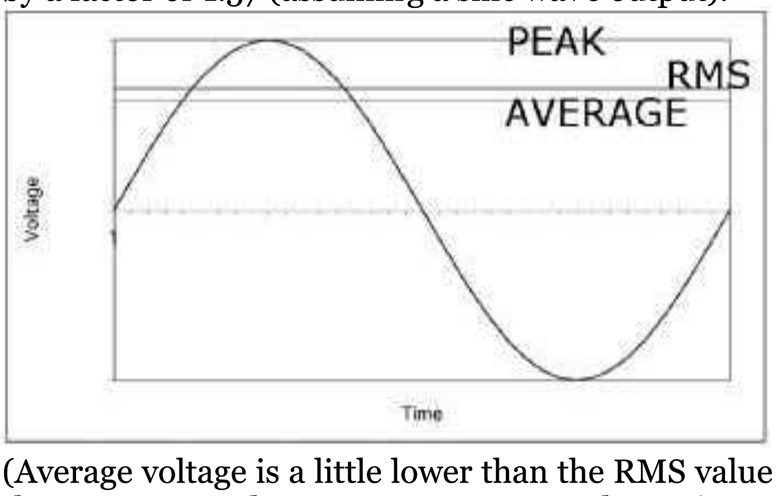
The flux density B depends on the way the magnets are used. If there are magnets on both disks and the air gap is approximately equal to the combined 'length' of magnet (20 mm in this case), then B will be about half of the 'remanent flux Br' of the magnets – in fact 0.62 Tesla (or 620 milliTesla). The 1200 has only one disk. The 1800 has two disks but only 8 magnets. These smaller turbines have lower flux density. Practical measurements bear out these assumptions.

The equation can tell us the average voltage of a group of coils at a certain rpm but doesn't give the DC output.



The voltages of the three phases combine to increase this average by a factor of root(3) or 1.73 at the output wires.

Furthermore the peak will be higher than the average, by a factor of 1.57 (assuming a sine wave output).



(Average voltage is a little lower than the RMS value that we commonly use to measure AC voltages.)
So the output voltage from the thee-phase winding will peak at 2.72 times higher than the average voltage for one phase. (2.72 = 1.73 x 1.57).

The DC output at the rectifier will be just below this peak value. It is reduced by the voltage lost in the rectifier itself, which is about 1.4 volts. This loss is a much more significant fraction of the total for 12-volt systems than it is for 24 or 48-volt ones.

The equation for DC voltage output therefore comes out as follows:

DCV = (A x B x n x rpm x 2.72/30) – 1.4

To find the number of coil turns required for a given rpm one needs to turn this equation around thus:

Total series turns n = (DCV + 1.4) x 11/ (A x B x rpm)

For example to get a 24-volt DC cut in for the 1200 machine then:
DCV = 24
A = .011
B = .3
rpm = 300
n = (24 + 1.4) x 11/(.011 x .3 x 300)
= 280 turns (total per phase)

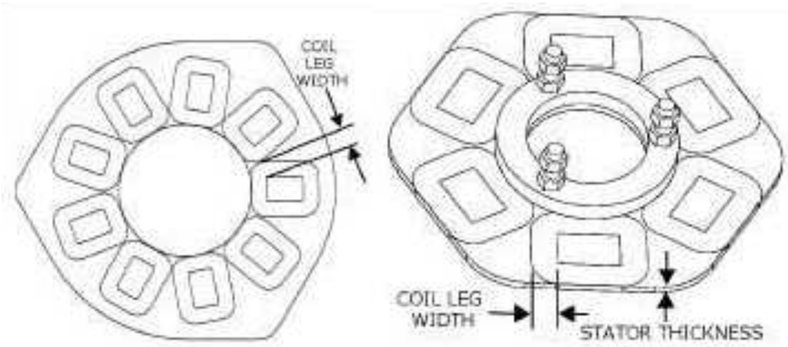
There are two coils in series per phase, each having 140 turns or so per coil.

That sums up my procedure to decide the number of turns per coil in the alternator.

Wire sizes and power losses

Size of wire to use

Choose the largest wire size that fits the available space to minimise that the loss of power and heating of the stator.



Available space for copper depends on the size and thickness of the stator. Thickness of the coil is a little less than the stator because of fibreglass cloth on the outsides. You need to work out the other dimensions of the coils from the overall diameter of the magnet rotor via a drawing of the stator itself. Three coils for every four magnets works nicely, but the coil leg width depends heavily on the spacing of the magnets.

The coil leg width is limited by the size of coils that fit next to each other. This will depend on how tightly they are wound, and you have to make an estimate of the percentage of the space that you can fill with copper. Space factors between 55% to 60% seem to be typical although with great care you can do even better.

Very thin wires waste some space with the relatively large percentage of enamel they use. Enamel adds about 0.06 mm to the diameter.

The cross-sectional area of copper that you can fit into the coil can be calculated as follows:

Sq.mm copper = coil leg width x thickness x 0.55

machine	1200	1800	2400	3000	3600	4200
no. magnets	8	8	12	12	16	16
rotor diameter	230	250	300	350	400	450
coil thickness	10	13	13	13	13	13
coil leg width	23	28	21	30	25	32
coil area sqmm	230	364	273	390	325	416

Standard wire diameters

Diam. mm	Area Sq.mm	American Wire Gauge AWG	D mm	Metric sqmm
0.71	0.40 mm^2			
0.75	0.44 mm^2	21	0.72	0.41 mm^2
0.8	0.50 mm^2	20	0.81	0.52 mm^2
0.85	0.57 mm^2	19	0.91	0.65 mm^2
0.9	0.64 mm^2	18	1.02	0.82 mm^2
0.95	0.71 mm^2	17	1.15	1.04 mm^2
1.00	0.79 mm^2	16	1.29	1.31 mm^2
1.06	0.88 mm^2	15	1.45	1.65 mm^2
1.12	0.99 mm^2	14	1.63	2.08 mm^2
1.18	1.09 mm^2	13	1.83	2.62 mm^2
1.25	1.23 mm^2	12	2.05	3.31 mm^2
1.32	1.37 mm^2	11	2.31	4.17 mm^2
1.40	1.54 mm^2	10	2.59	5.26 mm^2
1.50	1.77 mm^2			
1.60	2.01 mm^2			
1.70	2.27 mm^2			
1.80	2.54 mm^2			

In the example of the 1200 machine with 140 turns per coil we can say the available copper area will be

Sq mm copper = 230 x 0.55 / 140 = 0.9 sq mm

There are only certain sizes of wire available so it is a case of choosing the nearest one. 1.06 mm diameter wire works in this case.

There is a lot of flexibility really because you can use slightly thicker coils or thinner coils to nudge the coil dimensions toward the right size to fit the stator. This will have a small effect on the clearances, or on the 'air gap' that also affects the magnetic flux density.

Another trick to fit more copper into the stator is to use a smaller hole in the middle of the coil. For example a keystone shaped hole that is smaller than the magnets at one end can allow you to squeeze in more, thicker wires. The flux caught by the inner turns of wire is less than it should be, so there is a slight drop in output voltage.

Coil resistance

The resistance of the coil is important for working out the performance of the alternator when it is producing current. Longer, thinner wires have more resistance than shorter thicker ones. We already know the thickness of the wires but we need to calculate the length. Average length of a turn of wire:

= 2 x (magnet length + magnet width) + 3.14 x (coil leg width)

For example if the coil leg width is 23 mm then the length of one turn will be 224 mm.

Total length of wire = coil turns x coil turn length (example = 140 x 224 = 31,400 mm)

Weight of wire in a coil (g) =length x area x 0.009 (example = 250 grams)

Resistance (ohms) = (length / area) / 56000 (Example = 31400 / 0.88 / 56000 = .64 ohms)

This resistance depends on temperature though, so there is no single accurate answer. This is for 20° C. At 70° C it will be 25% higher.

Stator resistance

A simplified way to consider the current in the stator is to say that it only uses two of the three wires at any given time, and passes through two phases in series. In fact there will be some sharing of current at times between all three wires, but this is hard to allow for and secondary in magnitude. So we can estimate the stator resistance:

= 2 x coils per phase x resistance per coil (example = 2 x 2 x .64 = 2.6 ohms)

In the 12-volt stators where the coils are connected in parallel there is a different way to calculate stator resistance whereby you divide by the number of coils in parallel thus:

Stator ohms
= 2 x (coils in series / coils in parallel) x resistance of coil

Current and power loss

Current = power / voltage

For example if the output is 200 watts and the voltage is 24 volts, then current = 8.3 amps.

Power loss = resistance x current squared

(example = 2.6 x 8.3 x 8.3 = 180 watts loss)

In other words, at 200 watt output, our little 1200 mm diameter turbine will be losing 180 watts in its stator winding. The blades will have to produce at least 380 watts to cover this.

Rectifier loss

There will also be some loss of power in the rectifier due to the voltage dropped across the diodes. Each diode will drop about 0.7 volts, so

rectifier loss = 1.4 x current
(example = 1.4 x 8.3 = 12 watts)

Note that the rectifier loss is worst with lower system voltages and higher currents. The stator loss is the same regardless of system voltage, because the resistance is much lower in the shorter, thicker wires of the lower voltage windings.

Efficiency

Clearly this example is not very efficient because the alternator needs 392 watts input to give 200 watts out. Efficiency is therefore 200/392 = 51 %, or less when you consider other losses.

This is however the worst case. At lower power you will be able to show that the efficiency is much better. (For example at 48 watts, 2 amps, losses are 13 watts.)

There will also be friction in the bearings and seals to consider, but there are no core losses (because there is no steel in the stator), so this type of alternator is best in low winds when you need the efficiency most.

Windspeed

Knowing the power required to drive the alternator, you can find out the windspeed needed. Assume that the Cp is 35% which means multiplying by 0.35, so

Blade Power = 0.35 x (1.2/2) x area x windspeed cubed

Area is diameter (in metres) squared x 0.785

Windspeed cubed = Blade power / (0.165 x diameter^2)

For example = 392 / (0.165 x 1.2^2) = 1651

Cube root of 1651 is 11.8 metres per second windspeed. This is the rated windspeed for the 1200 turbine.
The larger turbines in this book reach rated power at 10 or 11 m/s.

Stator cooling

It is helpful to work out the heat dissipation per square centimetre of stator surface so as to avoid burning the stator out. The resin is a poor conductor. Look at the places where the coil is near the surface. Exposed surface of a coil on each side equals coil leg width x coil turn length, so

Surface = 2 x coil leg width x coil turn length

(example in cm = 2 x 22.4 x 2.3 = 103 sq.cm)

Each coil will only be working 2/3 of the time according to our approximate analysis of the current in the stator.

Loss in each coil = 2/3 x resistance x current squared

(example = 2/3 x .64 x 8.3 x 8.3 = 32 watts)

(Or you could divide the total stator loss by the number of coils instead. The answer is the same.)

Dissipation in watts/sq.cm = 32/103 = 0.3 W/sq.cm

This much heat will cause a rapid temperature rise in a bench test in the workshop, but on the top of a pole in a good wind it is sustainable. Significantly higher dissipation is not advisable.

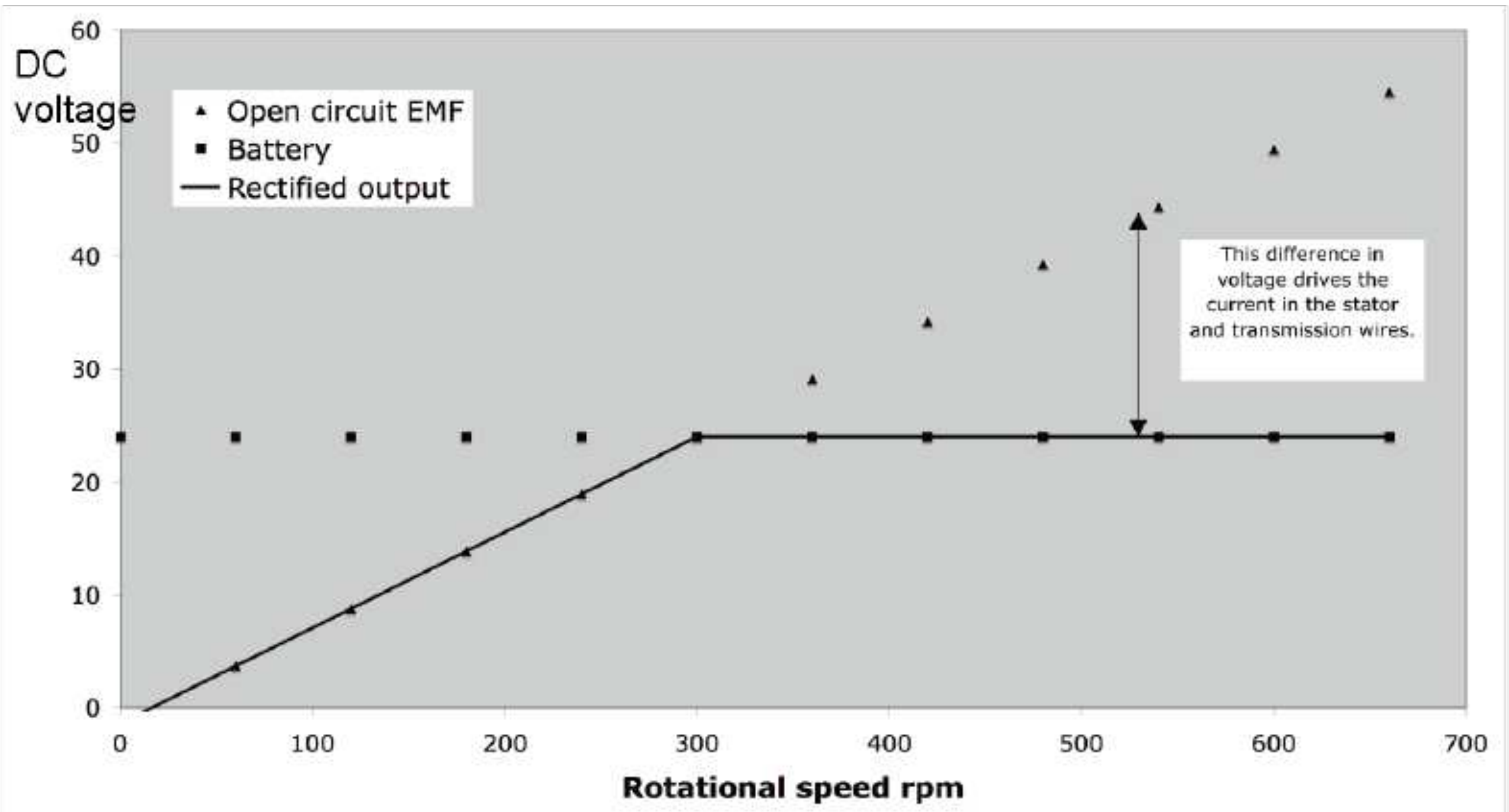
Estimating the rpm

You already know the estimated cut in speed, but it's useful to try to predict the speed at which the alternator will produce a certain power output. This helps with predicting the blade rotor tip speed ratio and stuff like that.

Open circuit voltage from the wind turbine (with nothing connected) is more or less proportional to the rpm. Call this 'electro-motive force' or EMF. Actually the DC EMF is not exactly proportional to rpm because the rectifier drops the voltage down by about 1.4 volts, but this is a minor adjustment.

If the alternator is connected to a battery, then its actual DC output voltage is 'clamped' to the battery voltage. The battery voltage is a lot more stable than the alternator EMF. When you connect the battery to the alternator, the battery wins. The alternator tries to push the voltage higher as it speeds up more but it can only push it up very slightly. What happens is that the higher EMF of the alternator pushes current into the battery, raising the battery voltage slightly (if the battery is off load at the time and no current is being used by heavy loads).

The significance of the EMF is that it drives the current into the battery. By Ohm's law, the difference between EMF and battery voltage, divided by the impedance of the circuit, determines the current. Impedance is not exactly the same as resistance but it is similar. You can read about the differences in electricity textbooks.

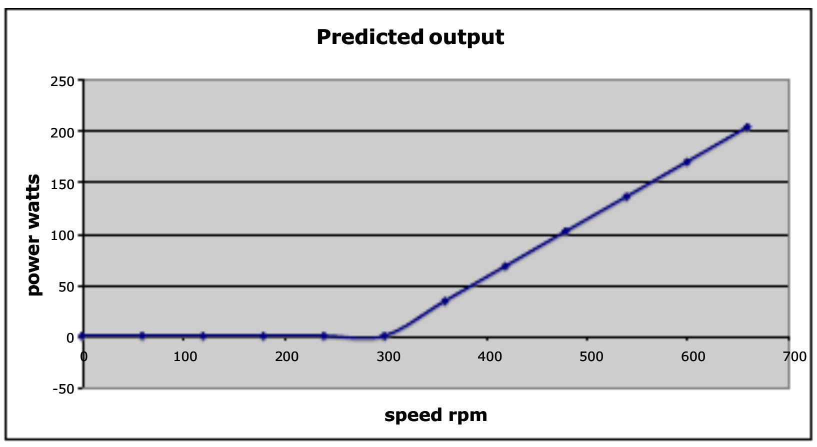


The impedance of the stator is not simply its resistance. There is some self-inductance that causes reactance too and the rectifier makes this very difficult to analyse concisely. A simple rule of thumb is to multiply the resistance by a factor of 1.3 to correct for this and get a rough idea of the impedance. Thus one can get an idea of the power/speed curve.

To find the rpm, you need to estimate the extra voltage required to drive the desired current, add this to the battery voltage and then finally find the rpm needed to produce this much EMF.

You want 8.3 amps out of the little 24 volt turbine used as an example up to now. Multiply the resistance by 1.3 to estimate impedance giving 3.3 ohms. Add a bit for a cable from the turbine to the battery, for example 50 metres of 6 sqmm cable would have resistance about 0.3 ohms so you can say the total impedance is 3.6 ohms. Required extra voltage will thus be 3.6 x 8.3 = 30 volts. Battery voltage is 24 volts. Total EMF will be 54 volts.

rpm = (DCV + 1.4) x 11/ (A x B x n)
= 55.4 x 11 /(.011 x.3 x 280) = 630 rpm



But bear in mind that this is a very approximate process, with several assumptions and simplifications. There are plenty of variables that can influence this outcome, including temperatures in the coils.

You can go through the same calculations but starting with a battery voltage at 28 volts and using a lower current to obtain 200 watts and it will give another answer. The speed will not be much different but the efficiency is better because of the lower current.

Blade speed at full power

You can calculate the windspeed required to give full power (see earlier example 11.8 m/s) and also a rotational speed for full power (630 rpm). From these it is possible to calculate a notional tip speed ratio at full power and to check whether the turbine will stall or not.

Revs per second = (630 / 60) = 10.5 per second
Circle travelled by tips each rev = 1.2 x 3.14 = 3.77 m
Tip Speed = 10.5 x 3.77 = 39.6 m/s

Tip speed ratio is therefore = 39.6 / 11.8 = 3.35

This ratio is low but acceptable, given that the design tip speed ratio for this little turbine is only 5.

Exploring some alternator design factors

Magnet spacing

To get the most power from a magnet rotor of given diameter, place many large magnets close together. To get the most power from a given set of magnets, use a large rotor and place them far apart, leaving more space for copper, and less leakage of flux between magnets. Keep a ratio of 3 coils to 4 magnets.

The effects of speed

If you double the speed of the alternator, then you can:

- Keep the stator the same and the voltage will double. If the current is the same then you get twice as much power that way.
- You can also double the current and get four times as much power, with four times as much loss, so the % efficiency is the same. But cooling may be an issue.
- Halve the number of magnets and handle the same power with the same efficiency.

The effects of battery voltage on efficiency

For a given alternator at a given speed, the output voltage will depend on the turns per coil, and the series parallel connections in the coils, as described earlier. Lets keep the connections the same and just vary the turns per coil.

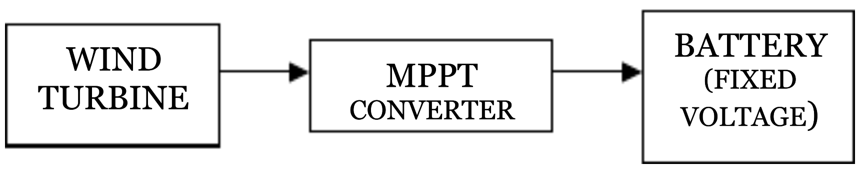
You can double the battery voltage by putting more turns of thinner wire into the coils to get the correct cut in speed. You would (roughly) double the number of turns in each coil. If you double the turns in a coil then you must use wire with half the cross sectional area of copper (sq mm). The effect on the resistance of the coil is to increase it fourfold (double length of wire and half the area).

The current at this higher voltage will be halved. Power loss in the stator depends on the resistance times the current squared. Current squared will drop to ¼ while resistance increases four times. So the power loss in the stator coils is exactly the same regardless of the chosen voltage.

Choice of battery voltage will not make any difference to the efficiency of the stator coils if the speed is unchanged. You would get about the same performance from a 12-volt, a 24-volt or a 48-volt alternator with the same cut in speed. (Actually the rectifier losses would make the 12-volt option slightly less attractive.)

Varying the voltage with the speed

So far the assumption has been that the voltage is clamped by a battery. You can also consider changing the operating voltage in response to changes in speed of a given alternator. This is sometimes called 'maximum power point tracking' (MPPT). It's quite an exciting avenue of wind turbine development.



In low winds, the alternator can only generate relatively low voltage, whereas in high winds it has the ability to produce much higher voltage. Connecting it directly to the battery handicaps its efficiency by tying it to the same voltage under all conditions. Using a converter to change the voltage, allowing it to rise in higher winds, has several benefits.

- The alternator losses depend on the square of the current, so an increase in voltage and corresponding reduction in current (for a given power output) cuts the losses in the coils, saving energy and avoiding overheating.
- The blades will work best at a constant tip speed ratio which implies that the rotational speed should change in direct proportion to windspeed. Working a constant voltage implies working at more like a constant speed, whereas using a converter allows you to vary the alternator speed more widely.

This book does not attempt to offer a design for such a converter, but they have been built for both commercial and homebrew turbines. The question you could ask is whether the extra complexity, cost and vulnerability to failures is justified by the extra power obtained in this way.

The basic direct battery-charging design without a converter has poor efficiency in stronger winds because of the high resistance in the stator (caused by the need to cut in at low rpm) and also the tendency to stall the blades (for the same reason). But it does have the advantage of simplicity and reliability. Reliability is the biggest problem with small wind turbines, outstripping any efficiency problems. The slowly turning rotor blades of the direct-connected turbine are also very quiet and suffer less wear and tear.

High voltage transmission

If the best site for the turbine is a long way from the battery, and the battery voltage is necessarily low due to the choice of inverter, then you can wind the stator for high voltage operation and step this down with three transformers at the battery. (Or use a high voltage MPPT controller or a grid tie inverter. You may be able to couple a grid-tied inverter to the AC side of your battery-based inverter in some cases.)

Make sure that the transformers are not saturated at low frequency. The frequency equals the number of poles on one rotor times rpm/120. If a transformer is designed for 240 volts at 50 Hz for example, and the actual frequency is only 25 Hz, then the maximum voltage should be 120 volts.

You may wish to use a relay to disconnect the transformers when the wind turbine is turning slowly because the current they use in low windspeeds can impede startup.

In theory you can also change the taps on the transformer so as to vary the operating voltage in different windspeeds achieving a crude MPPT effect. But it's not easy to design a circuit that can tell when to make the changes.

It goes without saying that high voltages can be dangerous. Make sure that all wires are safely insulated and all connections are safely in earthed boxes. I like to fit an over-voltage trip on such systems to short out the turbine if it becomes unloaded.

Glossary

AC - 'Alternating current' as produced by the alternator. 'AC voltage' is alternating voltage.

Airfoil (Aerofoil) – A cross-sectional shape for the blade that has good lift/drag ratio so that the blade can move fast through the air without wasting power.

Air gap – A gap in a magnetic circuit where there is no iron or steel. The gap can be full of copper or plastic or anything but is still considered to be air as far as the magnets are concerned.

Alternator – A machine for converting mechanical power into electrical power. Moving magnets induce alternating voltage (EMF) in stationary coils. This voltage is proportional to speed. If a circuit is connected to these coils then alternating current will flow. The alternator then becomes harder to turn and absorbs mechanical power, while electrical power is being generated.

Ammeter – A device for measuring the current (amps) passing through it.

ATH – Aluminium trihydrate, used in powdered form as an alternative to talcum powder for thickening the resin mix and moderating its reaction heat.

Brake switch - A switch used to short-circuit the wires from the alternator so that the turbine stops.

Catalyst - A chemical used to make resin set solid. Catalyst reacts with 'accelerator' already present in the resin solution to produce heat and set the resin.

Coil – Magnets passing a piece of wire will induce a voltage in it but to get a useful voltage you need many turns of wire wound into a coil. The turns are in series with each other, and so the voltage builds up.

Controller – An electronic box that switches surplus power automatically into heaters. Usually these operate at a certain voltage. The controller adjusts the amount of current diverted to heat so as to prevent the voltage rising above a set level. Drawing current (from the battery or alternator) pulls the voltage down.

Current – Flow of charge around a circuit of copper wire through a supply and a load so as to transfer energy.

Cut-in speed – the rpm at which the alternator starts to produce enough voltage to be usable.

DC – 'direct current' of positive charge - flows from positive to negative. Mainly found in battery circuits. The term DC is also used for voltages that do not alternate.

Diameter - The distance from one side of a circle to the other. The width of a disk right across the middle.

Drag - A force exerted by the wind on an object. Drag is parallel to the wind direction at the object. (see Lift)

Drop - Used here to describe a certain measurement of the shape of a windmill blade. The trailing edge 'drop' is marked at each station so that the blade angle is correct at that station.

Dump load – A heater that is used to control the voltage by taking excess current from the supply.

Efficiency – In this book the word is used to denote the percentage of power that is converted by a device. For example if an alternator absorbs 100 watts of mechanical power to produce 50 watts of electrical power then it is 50% efficient. The rest is wasted as heat.

EMF – Electromotive force. Another name for the open-circuit voltage of a supply when no current is drawn from it.

Enamelled copper wire – wire that has a clear insulating coating on it so that it can be wound into coils without any electrical contact between the turns in the coil.

Flux - The 'stuff' of magnetism. Similar to 'current' in electricity. It can be visualised as 'lines' coming out of one pole and returning to the other. Flux density in Tesla is the same as Webers of flux per square metre. A Weber of flux per second cutting a wire generates one volt.

Frequency – The number of times that an AC voltage actually alternates in each second. Measured in Hertz (Hz)

Furling – An automatic self-protective operation that reduces exposure to violent winds by facing the blades away from the wind. In this book that furling motion is produced by a lateral offset of the blade rotor from the centre of yaw. The tail and its hinge control the yawing motion so that it limits the power production.

Fuse – A device for protecting circuit wires against overload. If the current is too high the fuse melts and breaks the circuit, cutting of the current.

Grain – the fibres within a piece of wood that give it strength. They emerge from a cut surface at an angle

Grid – the mains electricity supply as provided by a power company or utility. Using a 'grid tied' inverter, you can feed power back into the grid supply, and you can earn money by doing this.

Inverter – A device that converts DC battery power to AC power, similar to grid power, on demand.

Jig - A template or device used to correctly place the magnets on the rotor.

Knot – a disturbance in the grain of the wood in a tree caused by a branch. You should try to avoid including large knots as they weaken the blade.

Leading edge - The edge of a blade that would strike an object placed in its path as the rotor spins.

Lift - A force exerted by the wind on an object. Lift is at right angles to the wind direction at the object. (see Drag)

Load – an electrical load is just something that draws current in a circuit. A heater, a lamp or any appliance.

Magnetic circuit – The pathway for flux from one pole of a magnet to the other. Similar to an electric circuit, in that the amount of flux depends on the amount of iron (equivalent to copper) that carries the flux.

Mould - A shaped container in which resin castings are formed. The mould can be discarded after the casting has set, or it can be use many times.

Multimeter - A versatile electrical test instrument, used to measure voltage, current and other parameters.

Neodymium or neo - The nickname given to a type of permanent magnet containing the elements neodymium, iron and boron (NdFeB). Very strong, and getting cheaper all the time. The strength is indicated by the grade. Grade 40 is cost-effective at this time.

Offset - An eccentric position, off centre.

Open circuit – A situation where a supply is present but there is no circuit for current.

Parallel – a connection between coils or batteries that shares current between them while the voltage is the same for all of them as for one alone.

Phase - The timing of the cyclical alternation of voltage in a circuit. Different phases will peak at different times. A group of coils with the same timing is known as 'a phase'. All of the alternators in this book have three phases that follow each other in an even succession so that the output is smooth.

Polyester - A type of resin used in fibreglass work. Also suitable for making castings. See also vinyl ester.

Power - the rate of delivery of energy. Can be electrical (voltage x current) or mechanical (speed x torque).

Rectifier - A network of semiconductor devices (diodes) that redirects AC currents to flow one way only in a DC circuit for charging the battery.

Resistance – The degree of obstruction to the passage of electric current in a circuit or a part of one, measured in ohms (Ω). Equal to the voltage across an object, divided by current through it (Ohm's Law).

Root - The widest part of the blade near to the hub at the centre of the rotor.

Rotor - A rotating part. Magnet rotors are the steel disks carrying the magnets past the stator. Rotor blades are the 'propeller' driven by the wind and driving the magnet rotors.

RPM – revolutions per minute. The measure of how fast something revolves, this is important for the behaviour of both blades and alternators.

Series – a connection of coils or batteries that increases the voltage between the ends of the string.

Short circuit – An electrical circuit contains a power supply that produces a voltage. When the supply is connected to a load then current passes around the circuit through the load and energises it. If instead the circuit is completed without a load (shorted) then the current is only limited by the resistance of the supply. This current is usually too high, and creates a hazard that must be guarded against by including fuses in the wiring of the supply. In the case of the wind turbine, the current is limited by the power of the blades. The short circuit overloads the blades and stalls them, bringing the wind turbine speed down to a crawl.

Soldering - A method for making electrical connections by heating the wires with an 'iron' and then coating everything with molten solder.

Station – A point on the blade's span where the shape is measured. There are several stations along the blade. The shape follows straight lines between them.

Stator - An assembly of coils embedded in a slab of resin to form part of the alternator. The magnets induce a voltage in the coils and we can use this voltage to generate electrical power.

Styrene monomer - The nasty smelling solvent used for the resin solution (polyester and vinyl ester resins).

Tail - A projecting vane mounted on a boom at the back of the windmill used to steer it into or out of the wind automatically.

Tap - a tool for making thread inside holes so you can screw things into the hole.

Thrust - The force of the wind pushing the machine backwards.

Torque – Turning force. Mechanical power consists of both speed and torque. (power = speed x torque)

Tower - The mast supporting the windmill.

Trailing edge - The blade edge furthest from the leading edge. The trailing edge is sharpened, so as to release the passing air without turbulence.

Vertical axis (VAWT) – a type of turbine with no yaw bearing because the blades rotate on a vertical shaft.

Vinyl ester – An ester resin that is harder to find and more expensive than polyester, but has superior properties. It is easier to work with, is waterproof, withstands higher temperatures, and is a better adhesive.

Voltage – The electrical pressure from an electrical supply which is usually fairly constant and has a nominal value. For example '12 volts DC' from a battery can vary between 11-15 volts depending on whether it is discharged or charging up rapidly.

Wild – when the wind turbine is running freely without any connection to anything then the voltage can be described as wild because it varies wildly. Wind turbine frequency also varies with speed of rotation, and so wind turbine output is often described as 'wild AC' unlike grid power that has constant frequency (say 50 Hertz) and near constant voltage.

Workpiece - The piece of wood or metal being shaped in the workshop.

Yaw bearing - the swivel at the top of the tower on which the wind turbine is mounted. The yaw bearing allows the turbine to face the wind.

LIST OF USEFUL SUPPLIERS

(MOSTLY IN THE UK, BUT MANY OPERATE WORLDWIDE)

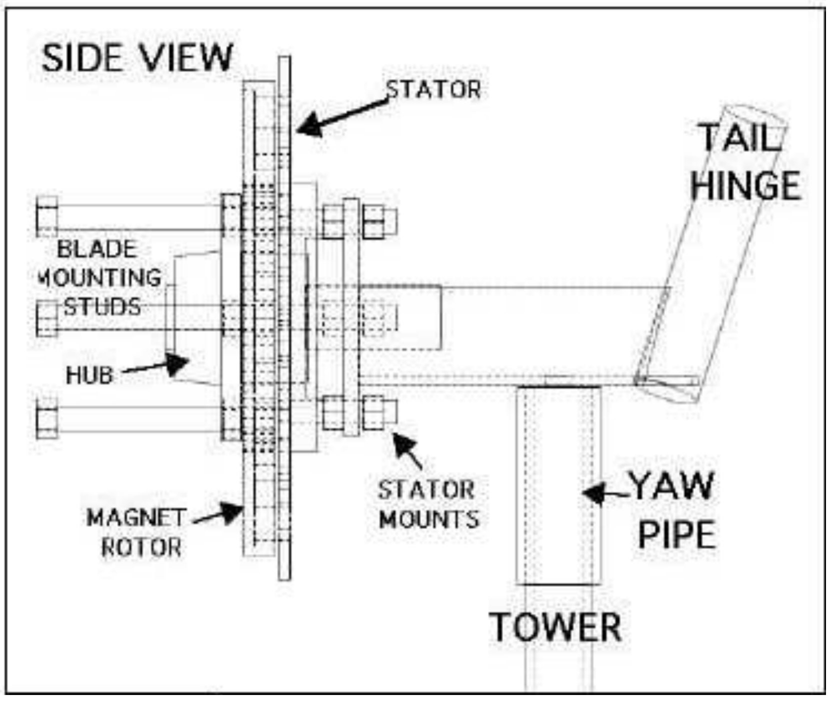
Goods supplied	Name and web address	Phone and street address
Magnets	Patrik Larsson (Sweden) http://www.solbergavind.se/	Phone 0046 (0)411-306 35 Mobile phone 0046-(0)708-30 63 50
	WEB ONLY .... http://powermagnetstore.com/ UK	
	sales@sanmumagnets.com in CHINA.	
	http://www.magna-tokyo.com/ in Japan.	http://www.magnes.hu/ in Hungary
	CERMAG (UK) http://www.wind-turbine-supplies.co.uk/	94 Holywell Rd, Sheffield, SA4 8AS (0114) 244 6136 07841 330663
Winding wire	EC WIRE LTD UK	(01924) 266 377
	EC wire Ireland	14 Ushers Island, Dublin 8 - tel 01 671 8754.
	http://www.wind-turbine-supplies.co.uk/	07841 330663
Polyester Resin etc	Glasplies Fibreglass Supplies http://www.glasplies.co.uk/	Tel 01704 540626 2 Crowland Street, Southport, PR9 7RZ
Vinyl Ester Resin	http://www.polyfibre.co.uk/	0121 327 2360
Steel disks	Emsea Ltd. http://www.emsea-laser.com/	Tel: +44 (0) 1684 299156 Unit 5, Green Lane.Tewkesbury, GlosGL20 8HD
Trailer hubs	http://www.wind-turbine-supplies.co.uk/	07841 330663
Guys, rope hoists, chain	A P Lifting Gear Company 01384 250552	Or http://www.liftinggeardirect.co.uk/
Birch plywood	James Latham http://www.lathamtimber.co.uk/	0191 469 4211 Nest Rd, Felling Ind. Estate, Gateshead
Voltage regulators	Scoraig Wind Electric (email below)	01854 633 286 (I ALSO SELL INVERTERS)
	2V microsystems http://www.powerpal.co.uk/ppelec.html	Tel: +44 (0) 1525 874 226 Fax: +44 (0) 1525 877 226
	Solar Converters Inc. http://www.solarconverters.com/	Canada 001 519 824 5272 Also imported by me (scoraig wind electric)
Water heaters (any voltage)	TP Fay (Kirkby) Ltd http://www.tpfay.co.uk/	Tel 0870 3 50 50 58
Workshop tools and supplies DC electric and mechanical	Beal (UK) Ltd http://www.beal.org.uk/	Tel: 0113 253 8888 Albion Mills, Church Street, Morley, Leeds,LS27 8LY
Fixings (stainless threaded rod, screws etc)	http://www.stainlesssteelcentre.co.uk http://www.screwfix.co.uk/	0500 41 41 41
Copper cable (steel wire armoured, tri-rated, etc)	Batt cables http://www.batt.co.uk/	Branches all over the UK and elsewhere
Rectifiers, connectors, wires, solder, PIDG receptacles, meters	Rapid Electronics http://www.rapidonline.com/ http://uk.farnell.com/	Rapid Orderline: +44 (0)1206 751166 PIDG receptacles code 33-3730 Cheap rectifiers code 47-3228 DIGITAL VOLTMETER –farnell CODE 1216318
Leading-edge tape for blades ('prop tape')	P and M Aviation http://www.pegasusaviation.co.uk	P&M Aviation, Unit B, Crawford Street, Rochdale, Lancashire OL16 5NU, UK

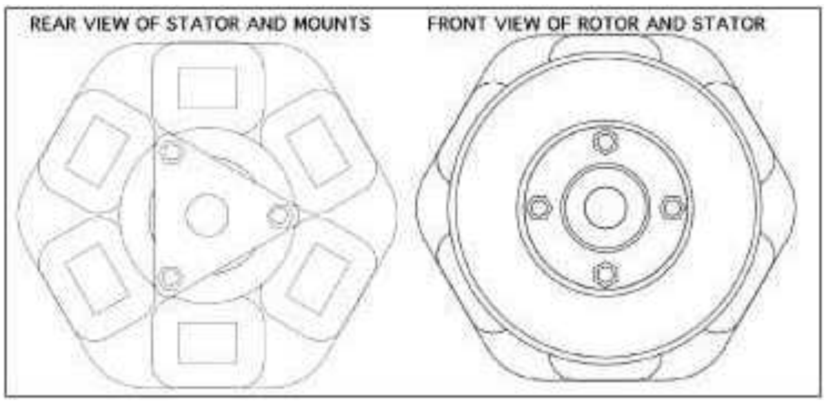
MATERIALS REQUIRED FOR BUILDING THE WIND TURBINES

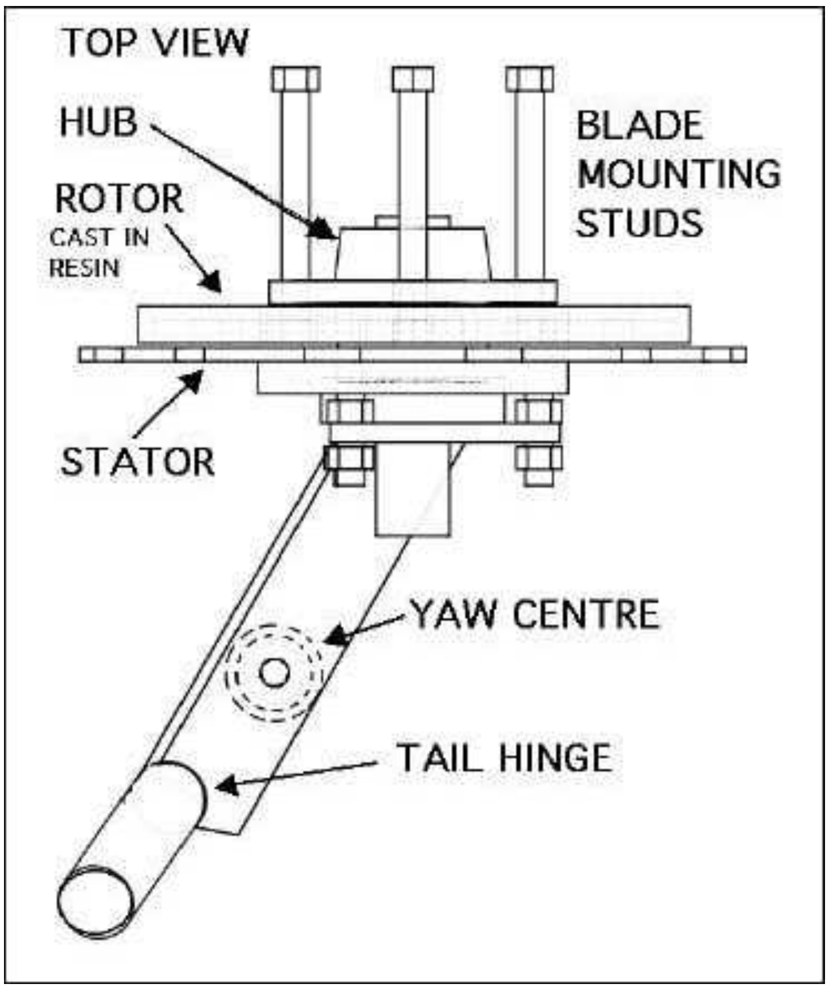
Sizes are in mm	1200	1800	2400	3000	3600	4200
BLADE WOOD (**MINIMUM**) mm						
blade wood width	95	95	125	145	195	225
thickness	35	35	40	45	60	75
Total length	1,800	2,700	3,600	4,500	5,400	6,300
Stainless steel screws	30 @ 25mm	40 @ 30mm	50 @ 30mm	60 @ 30mm	60 @ 50mm	75 @ 50mm
PLYWOOD - fractions of standard sheet (2.4 x 1.2m)	A very rough guide to the amount of plywood needed in different sizes for each turbine for all purposes including the moulds and jigs.					
6 mm	1/4	1/2	1/2	1/2	1/4	1/4
9 mm	1/4	1/4	1/4	1/2	1	1
12 mm	1/2	1/2	1/2	1/2	1/2	1
18 mm	1/4	1/2	1/2	1/2	1	1
STEEL DISKS mm	(only one)	(two disks)	(two disks)	(two disks)	(two disks)	(two disks)
DIAMETER	230	250	300	350	400	450
THICKNESS	6	6	8	10	10	10
STEEL LENGTHS IN mm						
ANGLE 50 x 50 x 6	200	800	900	1,100	1,300	1,500
FLAT BAR 30 x 8	200	700	700	900		
50 x 6		700	600	600	1,500	1,700
100 x 10	100				800	900
STEEL PIPE LENGTHS	These estimates below do not allow for any tower.					
1" nom. 33.4 outer	1,000					
1 1/4" nom. 42.3 outer	200					
1 1/2" nom. 48.3 outer		1,400	1,700	2,000	1,600	1,800
2" nom. 60.3 outer		340	430	530		
2 1/2" nom. 73.O or larger thick wall pipe to fit inside 3”					800	900
3" nom. 88.9 outer					600	700
MAGNETS: 46x30x10mm grade N40 or pref 42 NdFeB magnetised though the 10 mm axis	8	8	24	24	32	32
ENAMELLED COPPER WIRE	1.5kg	2.6kg	3kg	5kg	5kg	7kg
Tough, flexible wire for hooking up the stator and for hanging down tower - see installation section for minimum sizes. Crimp connectors and lugs. Connector blocks. Junction boxes.						
Resin-cored solder wire for stator connections. PVC tape for coil legs, and sleeving for connections. Cable ties.						
Rectifiers. Choose bridge rectifiers rated for at least twice the current and five times the voltage. Connect in parallel if necessary to share current. (Current can be found by dividing power by voltage.) Use best quality PIDG crimp connectors and bolt to a large aluminium heatsink (can be scrap saucepans etc) using ‘semiconductor mounting paste’ between each rectifier and the heatsink body. Diecast aluminium boxes make good enclosures and heatsinks combined for 12 volt rectifiers mounted on turbines.						
Flexible conduit and glands can be used to make a neat job of wiring, especially where the stator has 9 wires out.						
Resin supplies: Polyester or Vinylester resin, Catalyst, Filler: talcum or ATH powder, Fibreglass cloth 100-300g/sqmetres, polish or grease for mould release, Silicone sealant or other caulk, Superglue. The estimates below are very rough, and I strongly suggest you buy plenty extra so you can experiment with mixtures.						
Estimated weight resin	1 kg	2 kg	2.5 kg	3 kg	3.5 kg	5 kg
Estimated weight of powder	500 g	1 kg	1.5 g	1.5 kg	2 kg	2.5 kg
BEARING HUB PCD	100mm	100mm	100mm	125mm	140mm	150mm
WELDING RODS	Quality 2.5-mm or better 3.2-mm general purpose welding electrodes for mild steel					
ANGLE GRINDER DISKS	Grinding, cutting and sanding disks. Chop saw disks and also hacksaw blades					
Grease for bearings – in hub and also yaw and tail hinge. Body filler for defects in castings and blades. Paint.						
Sheet lead for balancing weights for blades. Jigsaw blades, sandpaper,						
Assorted bolts and nuts for fixing tailvane, rectifiers, moulds, and coil winder.						
STAINLESS STEEL FASTENINGS						
THREADED ROD estimated sizes. Also nuts and washers	M10 x 1000	M10 x 1500	M10 or M12 x 1500	M12 x 1500	M12 or M14 x 2000	M14 x 2000

Views of the turbine head

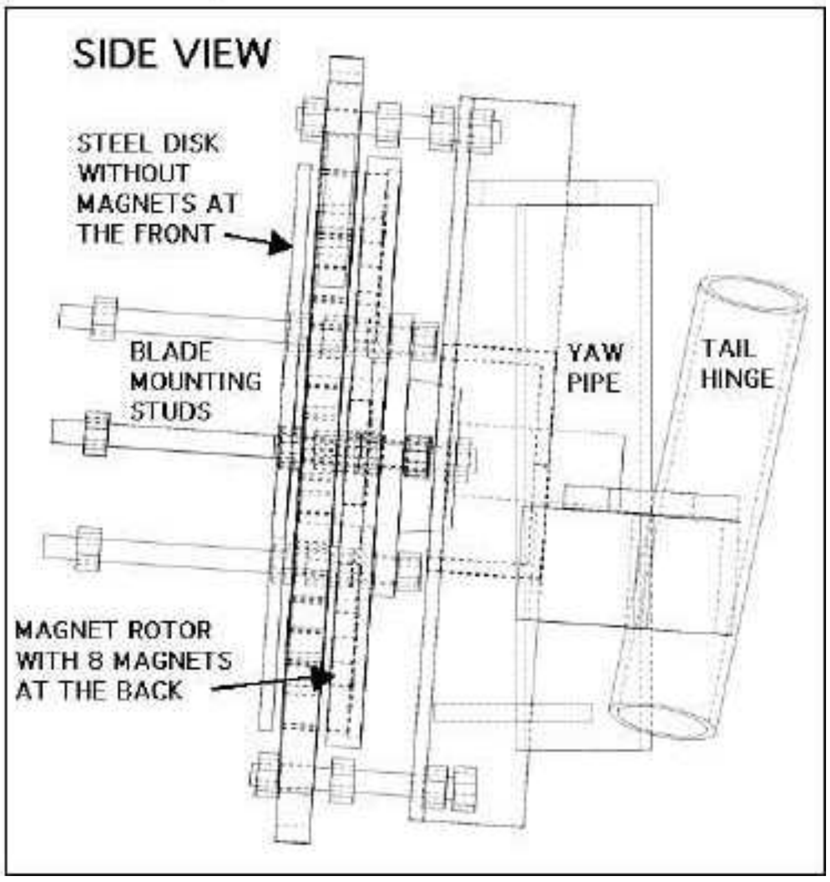
1200 turbine

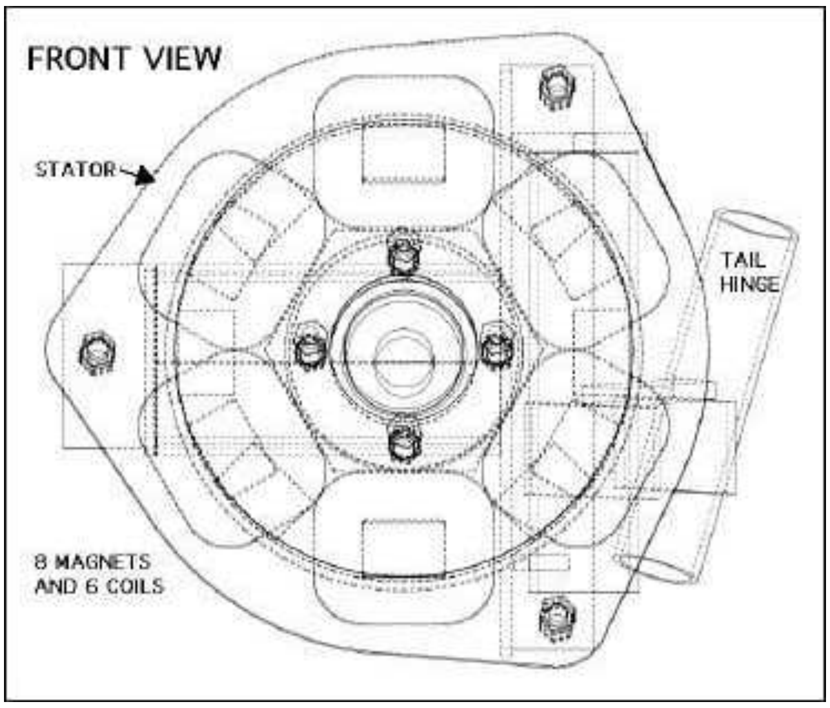


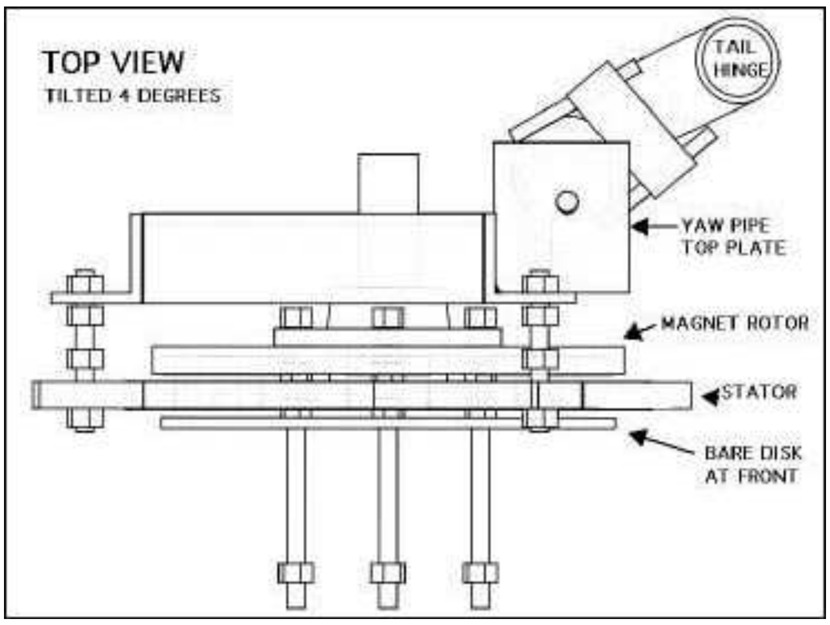




1800 turbine

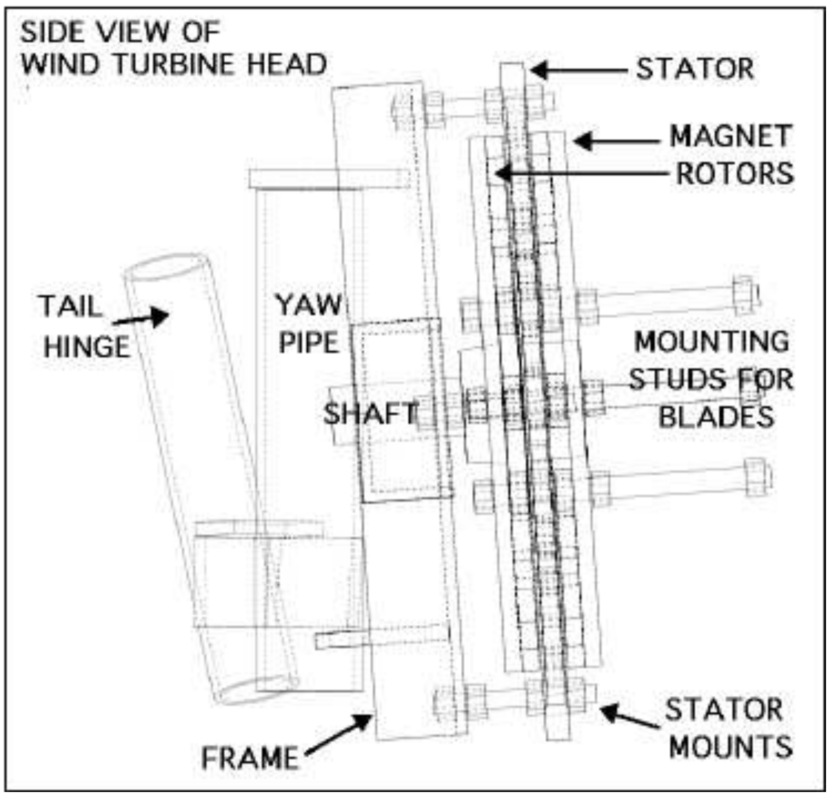


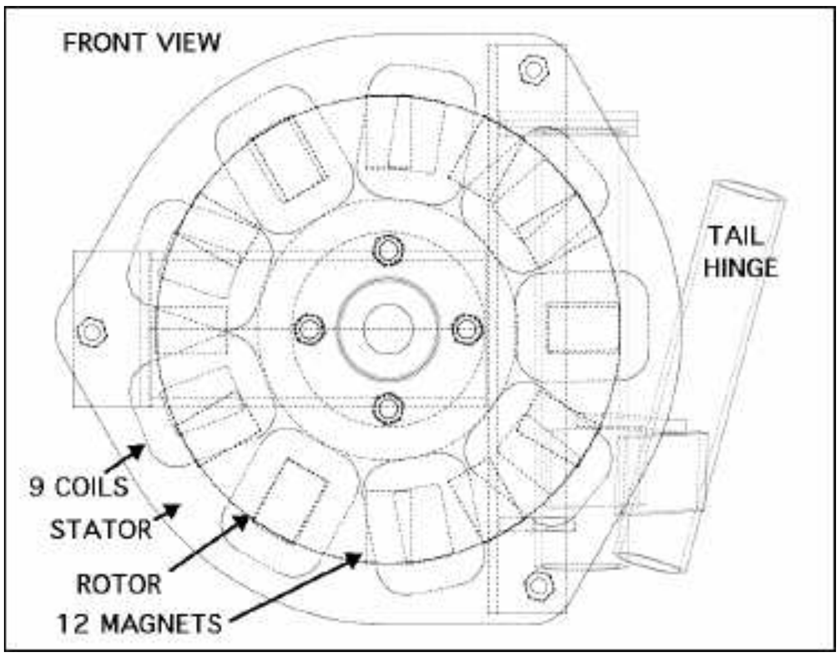


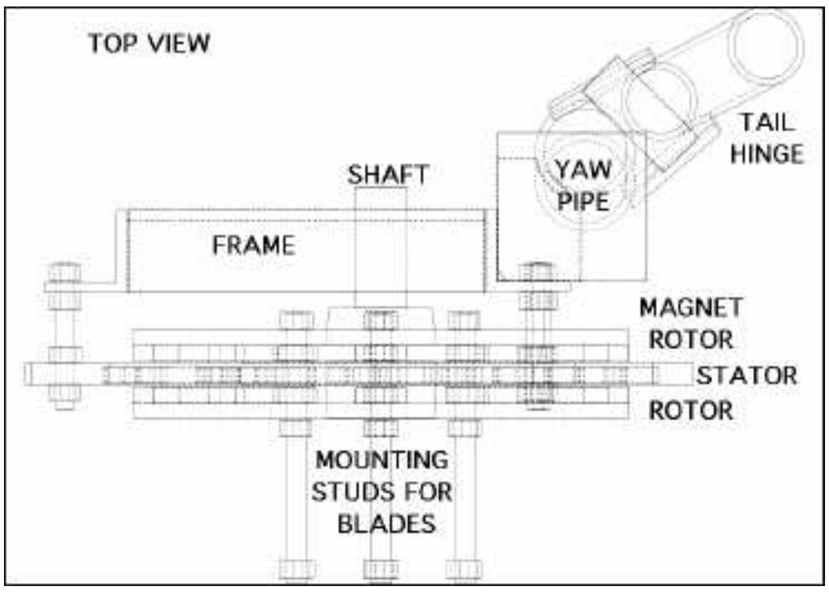


2400 and 3000 turbines

These views do not show the resin on the magnet rotors.







3600 and 4200 turbines