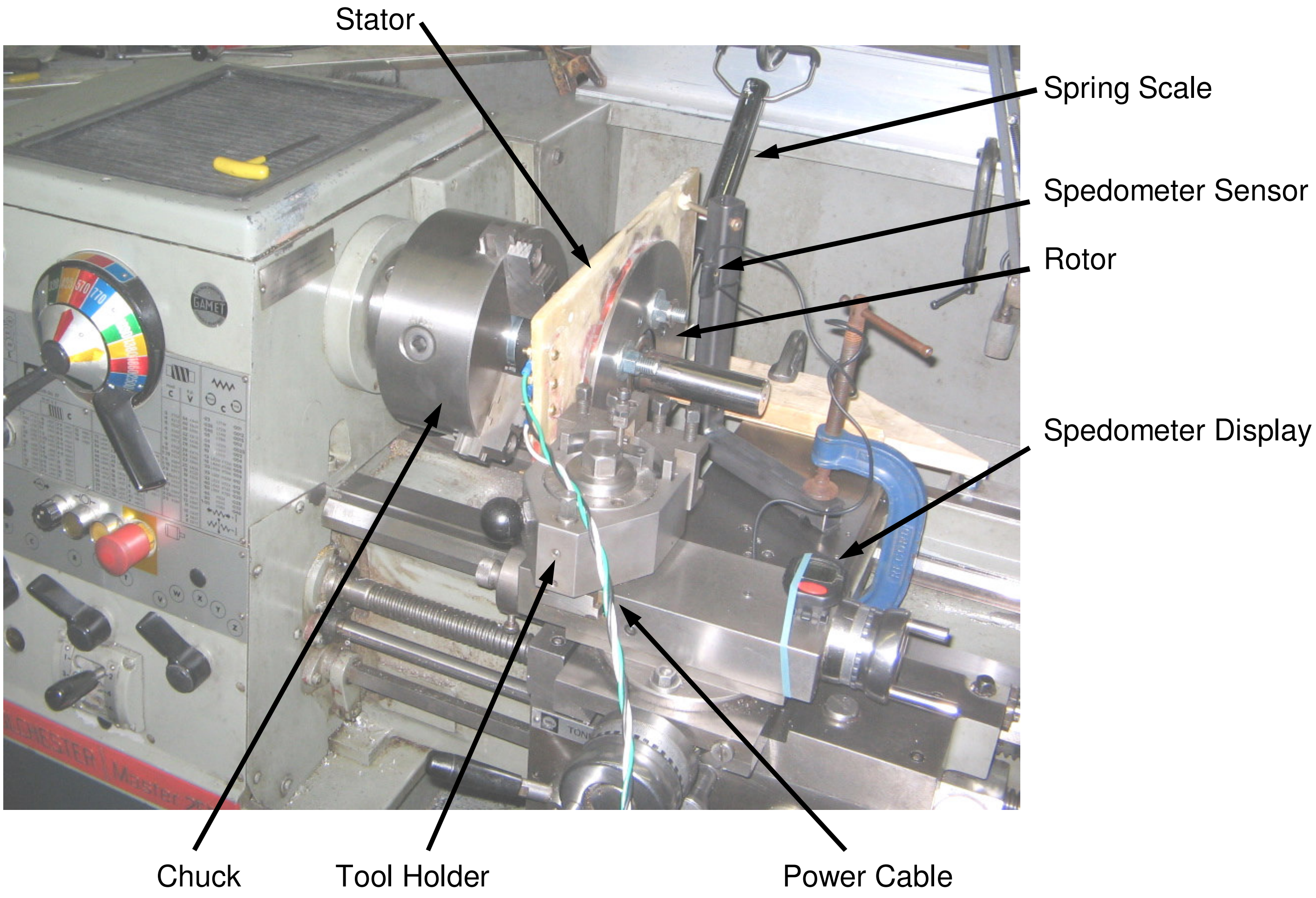
Performance Testing a Homebrew Axial Flux Generator

Following a long design and construction of a permanent-magnet generator, it was time to put it through its paces. I have tried to describe what I did, and the conclusions I made, as carefully as possible, in hopes that it can help novices to build better generators.

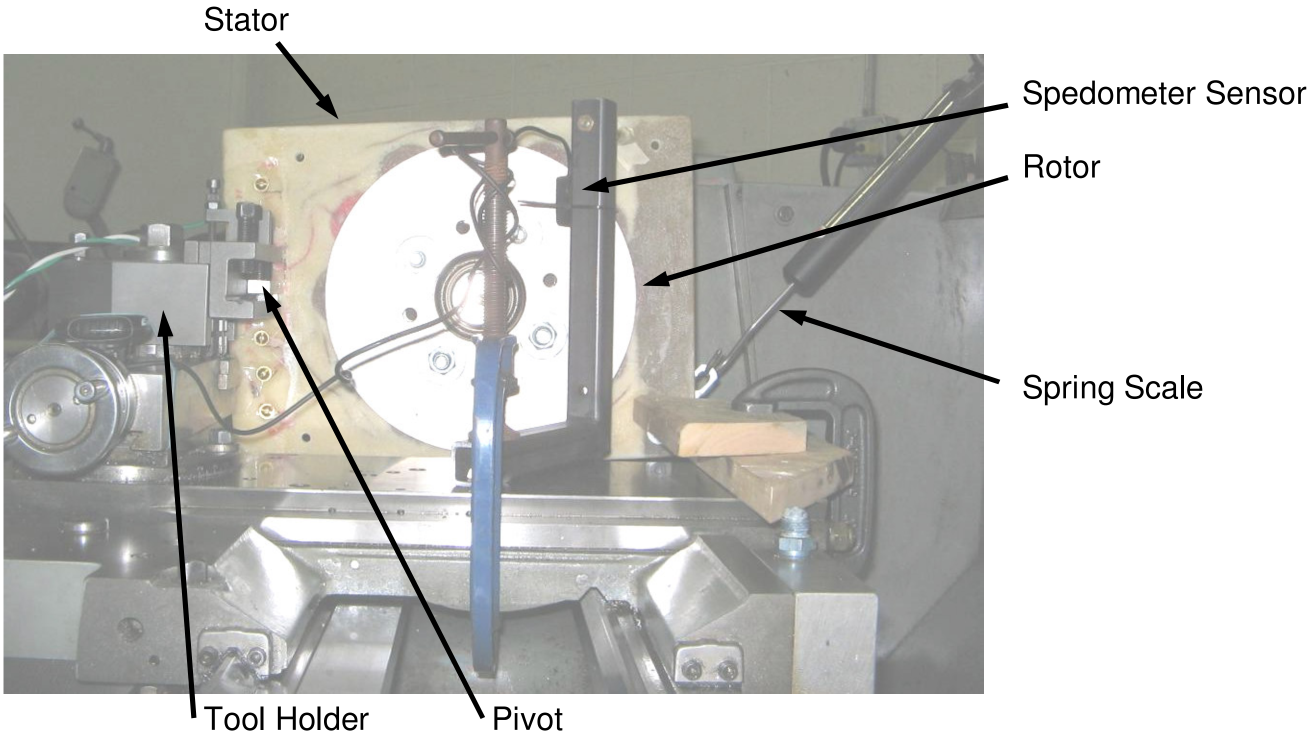
This generator can be desicribed as an Permanent-Magnet Axial-Flux Generator. It consists of magnets arrayed around the edges of two round steel plates mounted, on a hub. These plates spin, with a stationary stator plate, between them. Within the stator plate is a series of wire coils, connected to deliver 3-phase AC. It is intended for use mounted on a windmill. The output power is usually rectified to DC to charge a battery bank for remote power applications.

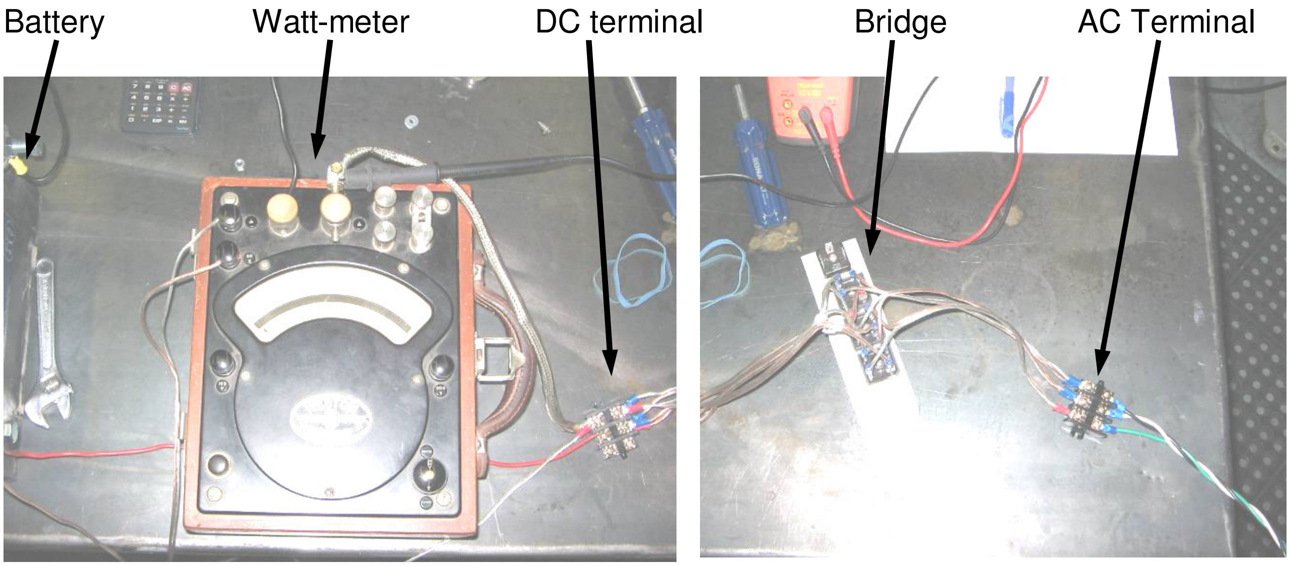
TEST SETUP

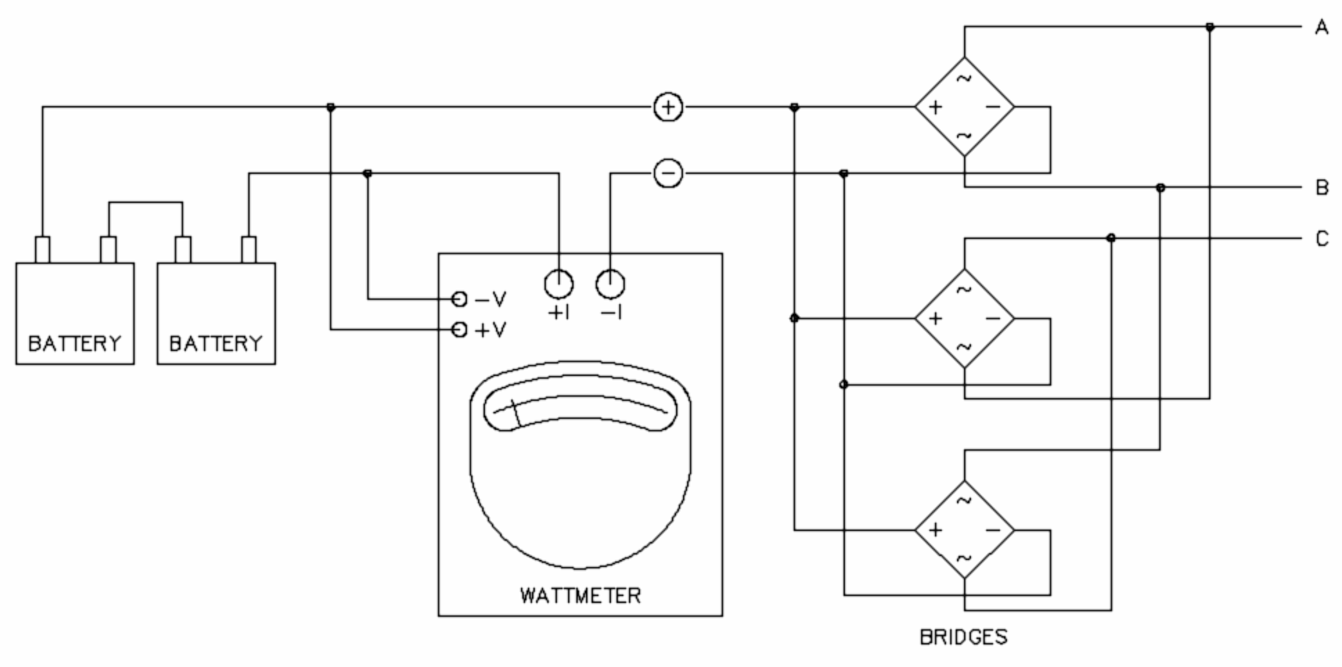


The generator was mounted in the lathe by mounting the rotor in the chuck. The rotors can be turned at any speed the lathe can turn. A speedometer (adapted from a bicycle speedometer) was also installed, but this proved unnecessary. The speed of the 5 HP lathe was not affected by the alternator, which did not demand more than 2 HP.

The stator was mounted in a pivoting fashion to allow a torque measurement at each speed and load tested. With a bolt in the tool-holder holding one side of the stator, and a spring scale connected to the other side, the stator rotated around the bolt, and pulled against the spring-scale. There were no other direct supports for the stator. Indirectly, the stator was confined from moving too close to each rotor by some support blocks. These supports did not prevent the stator from applying the full load from running torque onto the spring scale. This method of mounting the stator required a degree of caution. Being free to move under load, the stator could scuff against the rotor. Fortunately, the fiberglass coverings on the stator protected it well from damage. Fine-tuning of the stator's position was easy, due to it being supported on the tool holder.







The wattmeter is a helpful device for measuring the power of electrical systems. It takes the uncertainties of power factor (AC) and duty cycles (DC) out of the power measurement and displays a simple result. After looking over the data collected, I am very happy I purchased one before trying this test.

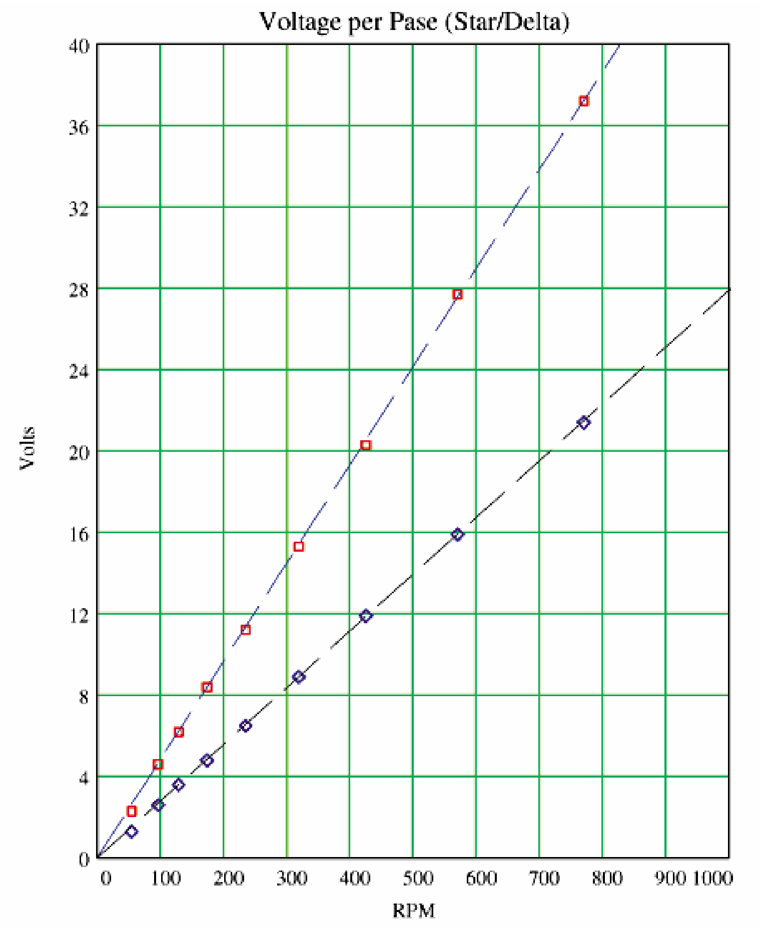
By using the wattmeter, it is not obvious how both current and voltage rise as the EMF in the generator rises. The wattmeter displays only the product of the two. A separate voltmeter was used in parallel with the wattmeter voltage pickups, to keep track of voltage.

It was something of a duplication of effort, but a current shunt was also set up to measure current. A 0.15 Ohm resistor, in the wattmeter's place, was used under identical conditions to see if there was a difference. The difference was clear at currents above 5 Amperes. I realized afterward that the resistance, although low, was enough to affect the charging current in the system, thus reducing the power. This became even more obvious when I remembered that the resistor was dissipating enough power to become warm. Instead of using a resistor, a flat-plate shunt with a resistance < 0.01 Ohm should be used, which will not hamper the generator's efficiency.

The 3-phase AC from the generator (on the right of the diagram above) was rectified through single-phase bridges. The rectified DC was used to charge batteries. Both automotive and deep-cycle batteries were charged, but my results were not different between the two types. If others can detect a difference when charging different types of batteries, it may be because they can charge them at much higher currents than I did, or measure with more sensitivity.

TEST RESULTS

The first runs on the lathe were performed unloaded, at speeds ranging from 54 RPM to 770 RPM. This established the baseline Electromotive Force that the generator creates.



When shown this way, the EMF is obviously a straight line.

Broken down into its constituent factors:

$$\text{emf} = \frac{(0.0483\text{V})(3\text{ phase})}{(\text{RPM})(56\text{ turns})(12\text{ coils})}$$

$$\text{emf} = 0.216\ \frac{\text{mV}}{\text{RPM-turn}} \qquad \text{(in star)}$$

The voltage is dependent on the connection of the generator. The emf above applies to a “STAR” connection. (See appendix).

$$\text{emf} = 0.124\ \frac{\text{mV}}{\text{RPM-turn}} \qquad \text{(in delta)}$$

It is useful to know the values for Delta connections, because connection of the generator in Delta allows higher current delivery. Switching an alternator between Star and Delta permits a generator to operate in two speed ranges. I do not expect to want a Star-Delta switch on this generator, but if I change my mind, I left connections to all 6 phase ends available on the edge of the stator.

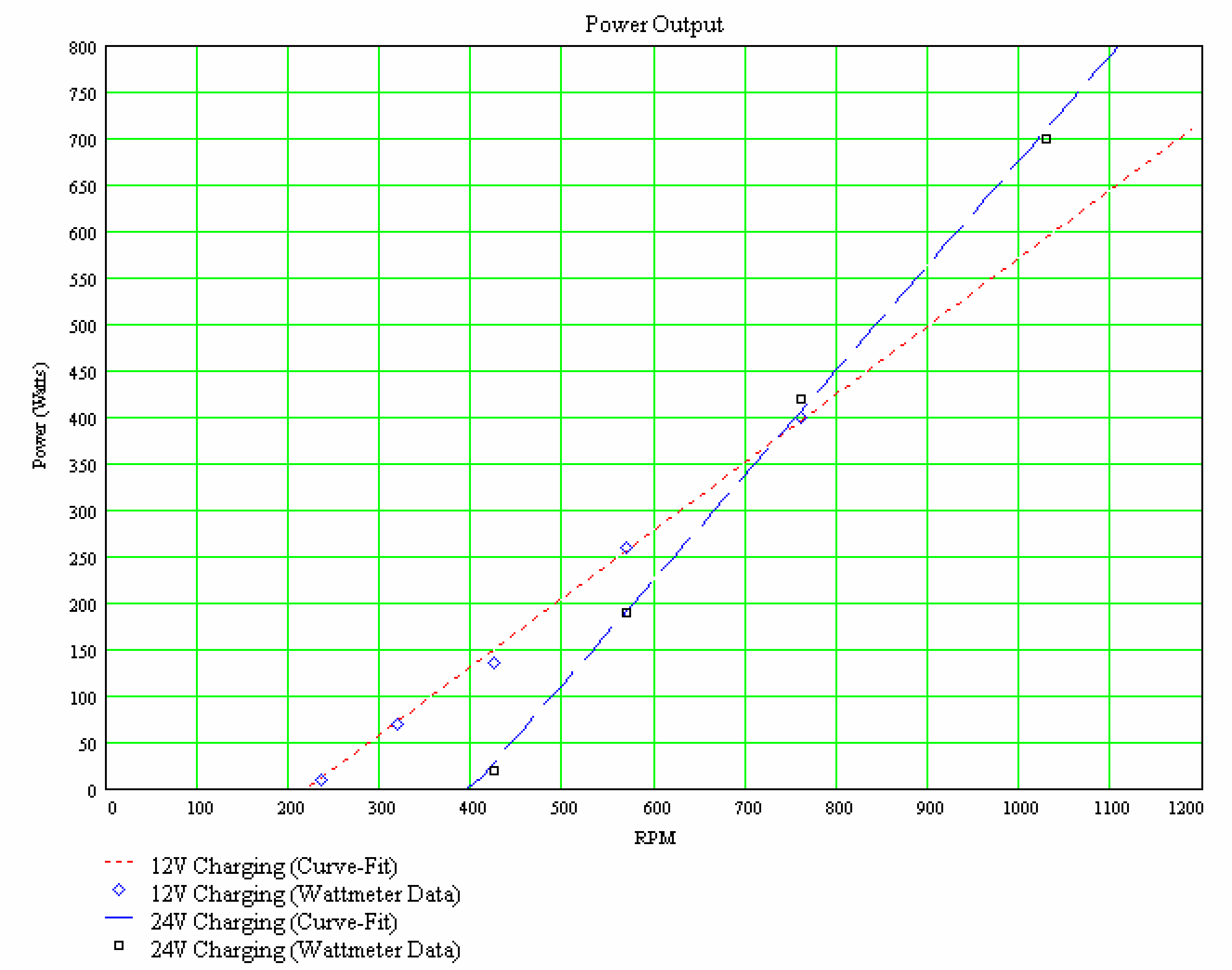
LOAD TESTING

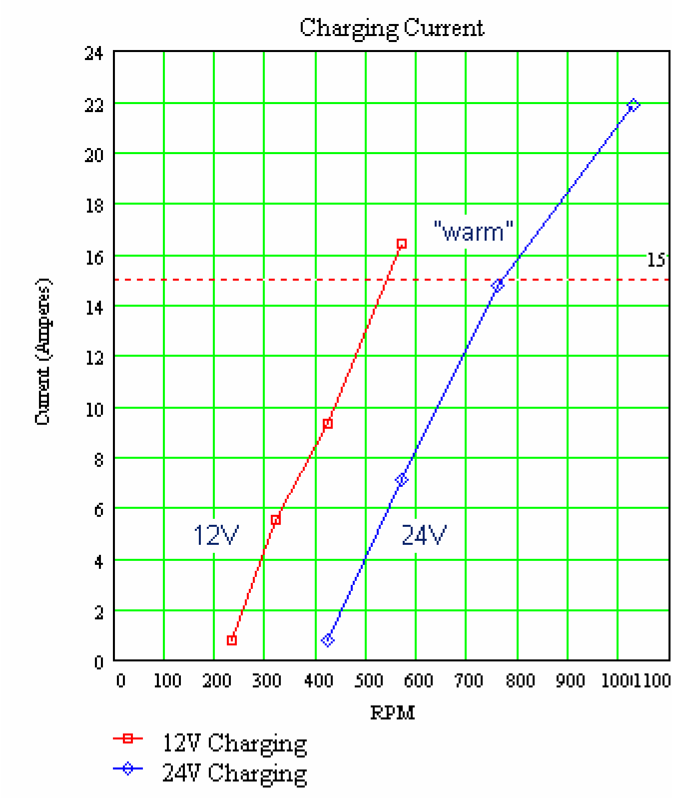
The lathe was run slowly at first, then at increasing speeds, and data was recorded for each step. Places where some data could not be recorded were at low speeds, where the generator would not produce a charging current for the batteries, and at high speeds, where I was concerned for the heat build-up in the stator, and for the stability of the torque measurement set-up.

Broad conclusions that can be made:

	Cut-in Speed	Max. Efficiency Speed	Overload Speed
12V	220 RPM	300 RPM	550 RPM
24V	400 RPM	550 RPM	750 RPM

The power output data for 12V and 24V are plotted below. I have drawn straight lines through the data for “best fit”.



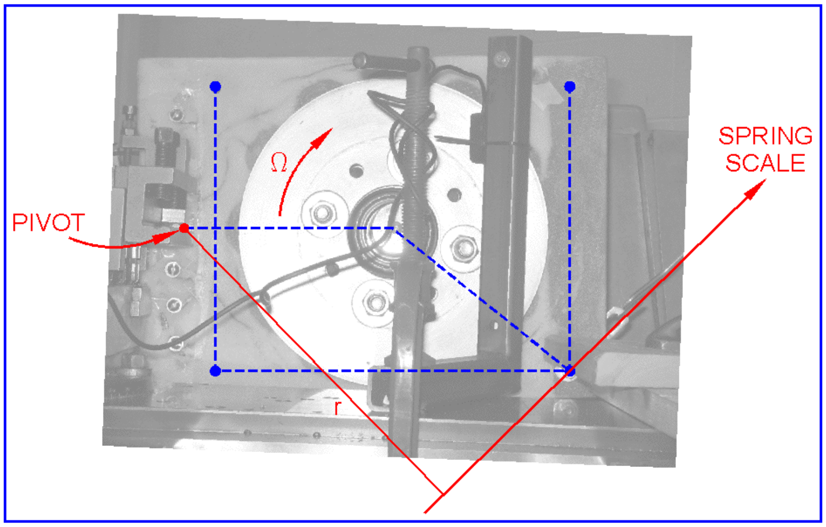


The power curve from the wattmeter is very straight. Because I also measured charging voltage, which rose with increasing EMF, I can show that the current is not quite rising linearly.

After testing at high power, the stator felt distinctly warm. The bridges were also warm. The upper limit of output power was evidently being approached. In the practice, 15 Amperes (when connected in Star “Y”) should not be exceeded, except for brief periods, to avoid damaging the stator. This is near the maximum limit for 18 AWG wiring current load (See Appendix).

INPUT TORQUE MEASUREMENT

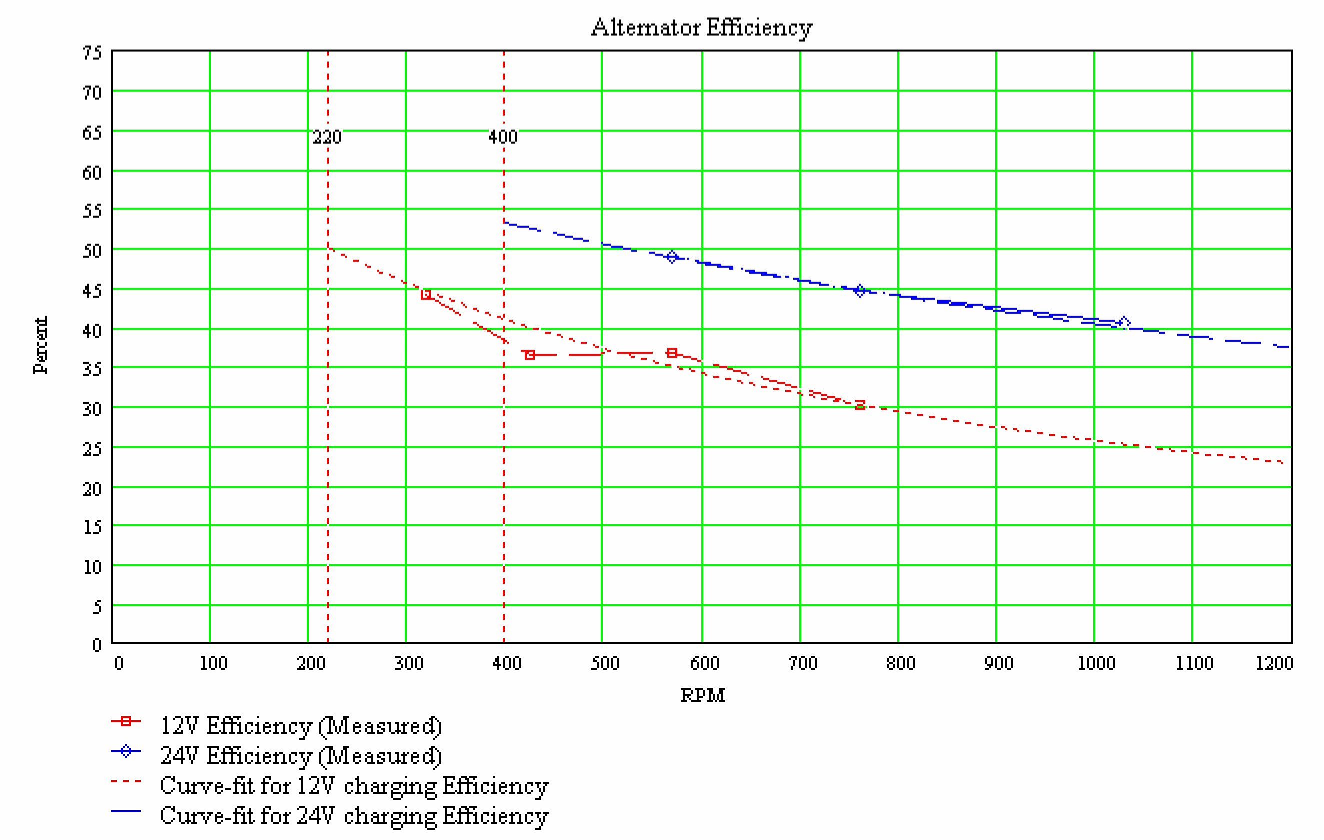
The torque applied to the stator must be measured if the input power is to be found.



The spring scale can only be trusted to within ½ pound. As torque on the stator increases, it turns around the pivot. The geometry of the spring scale’s line of action changes slightly. The lever arm is approximately 10.5 inches, and gets about ½” longer, as the stator is loaded. Assume that the uncertainty of the input power measurements is +/- 15%.

INPUT POWER AND EFFICIENCY

The smooth lines through the data points are only approximations.



The efficiency of the generator increased when charging at higher voltages. Losses are mostly due to heat loss from current, so taking energy from the generator at higher voltage always improves its efficiency. The limit to which this can be of advantage is the increase in RPM required to produce the higher voltage.

The power required to drive the generator was reduced when the resistor was being used to measure current, because it was unloading the generator. It was also reducing its output. So from this point of view as well, it was not a good way to measure output power.

MATCHING THE ALTERNATOR AND PROP

These test have provided enough information to estimate a good size and dimensions for the prop to turn this alternator. Some information about the local winds and atmospheric density is important to making the right choice, as we will see.

I live east of the Canadian Rocky Mountain range, on the Alberta prairie. Winds here are not as strong as in the foothills of the mountains, and ground winds are slowed by terrain which isn't quite flat, either. When I consult the Canadian Wind Energy Atlas I find the mean windspeed for my location is about 4.5 m/sec, or 10 mph. This is really quite low. There are enough times, however, when the wind blows quite strongly, that I doubt I should be trying to capture any low wind power at all, and focus on catching it only when the wind is strong. I have a wind speed & probability distribution for my area that allows me to make some decisions on that point.

To start figuring all this out, put the wind power curve and the alternator power curves on the same chart.

Power in the wind is: $P = (\rho / 2) * (\pi * D^2 / 4) * (V_w)^3 * C_p$

which depend on:

Prop diameter	D
Wind speed	V_w
Air density	ρ
Prop coefficient	C_p

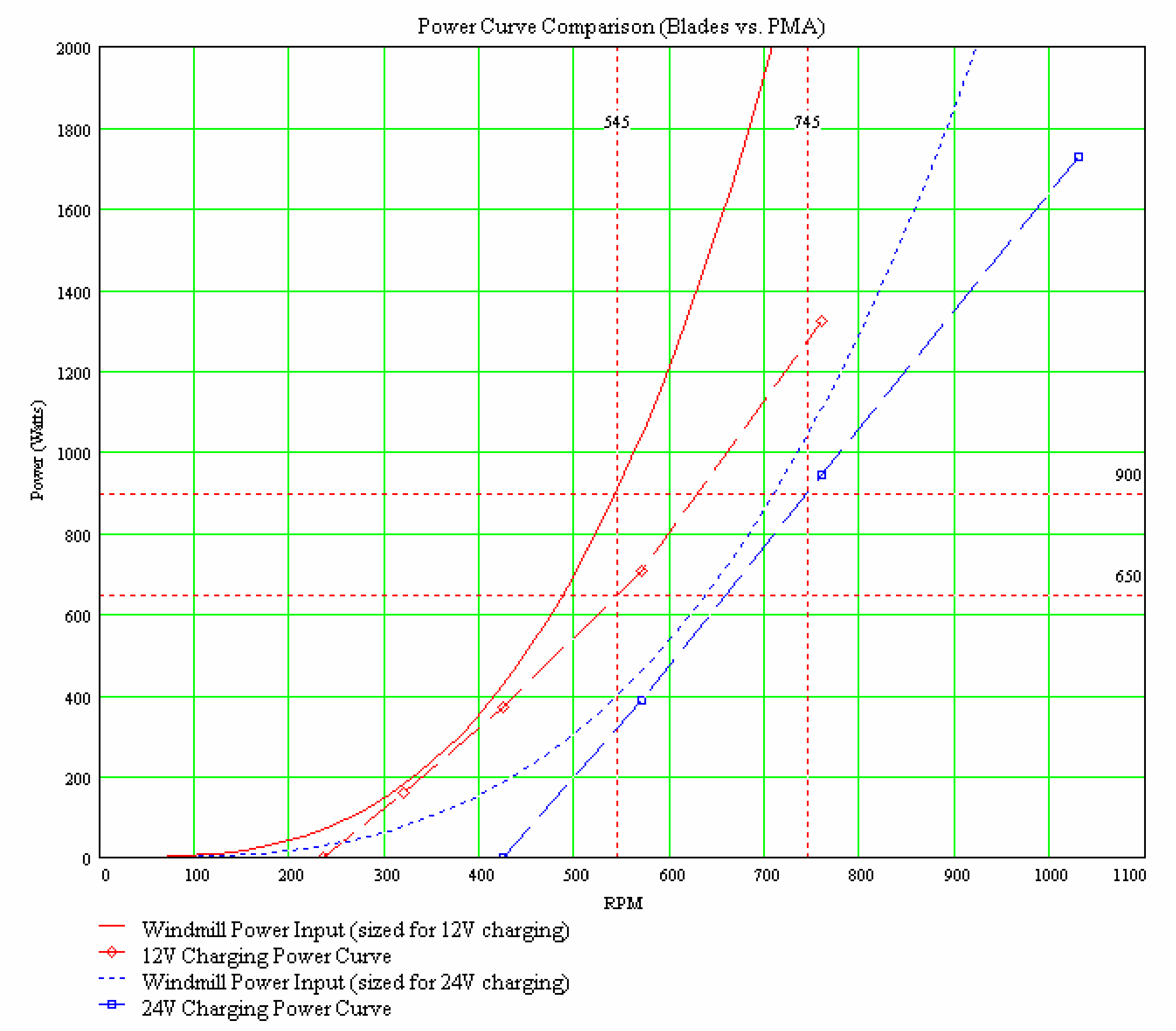
The density of air depends on your altitude. To research your location's air density, use the internet to look up terms like "altitude", "air density", and "standard atmosphere" to find tables. My altitude is 3300 feet above sea level, so my air's density is 90% that of sea level, on average. The propeller's coefficient of efficiency relates to many variables that are hard to really define. It depends on the quality of construction, twisted angle of attack, the airfoil, and how smooth the surface is. Tip shape is less important, although it does reduce noise when done well. Cp can be as low as 20% on an old-fashioned prairie water-pumping windmill, and as high as 50% on commercial turbines that supply the grid. It can't be higher than 59% (the Betz rule).

Instead of expressing the wind power in terms of wind speed, I'm going to convert the formula to an equation using RPM and TSR instead. By doing this, I can plot both wind power and alternator power with RPM on the bottom scale.

$$P_{wind} = (\rho / 2) * (\pi * D^2 / 4) * (RPM * D / 2 / TSR)^3 * C_p$$

This formula can make a curve on a graph, if I pick values for D and TSR. I assume that C_p is about 30%.

Try:	7.6 ft diameter and TSR = 6	for charging at 12 Volts
and:	6.5 ft diameter and TSR = 6	for charging at 24 Volts

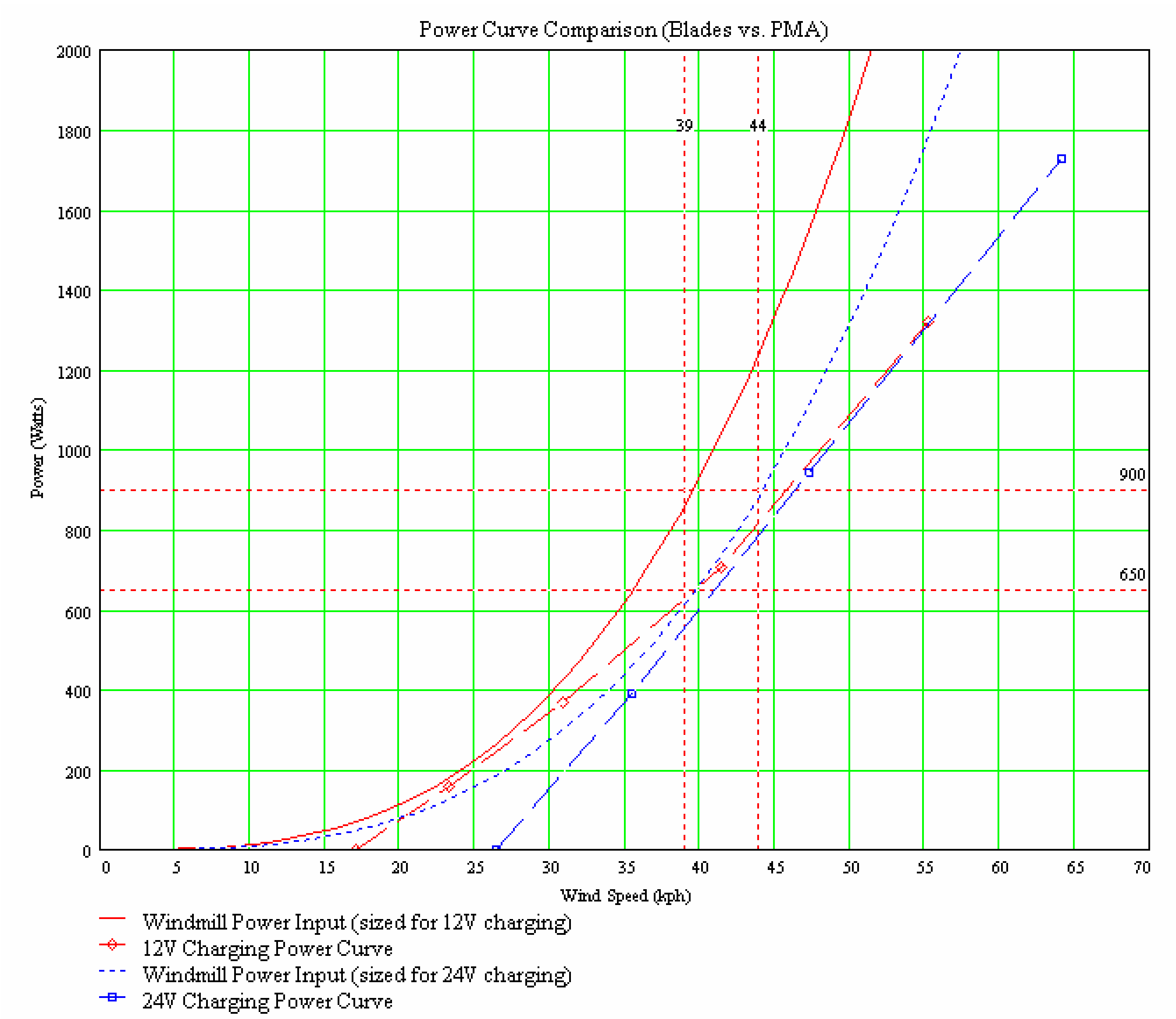


I adjusted the propeller diameters until I got curves that seemed to fit the alternator curves. The prop that charges a 24 V system doesn't have to be as big as a 12V charging system, even though it can develop higher power. The credit lies in the higher ranges of wind speeds.

The wind power curves get close to the alternator power curves, but at high speeds the wind energy grows far faster than the alternator can take it out. The windmill will run faster than TSR=6, or, in other words, less wind is needed to make the alternator turn faster than it would if it was always working at TSR=6. This is probably good for a low-wind area, but in strong winds, the machine will run away if it isn't furled.

The above curves don't tell us what the winds are doing in relation to the power. We can fix this with the original wind power equation, but the speed of the alternator must be converted into an equivalent wind speed:

Again, at TSR = 6 and D = 7.6 ft diameter for charging at 12 Volts
TSR = 6 and D = 6.5 ft diameter for charging at 24 Volts



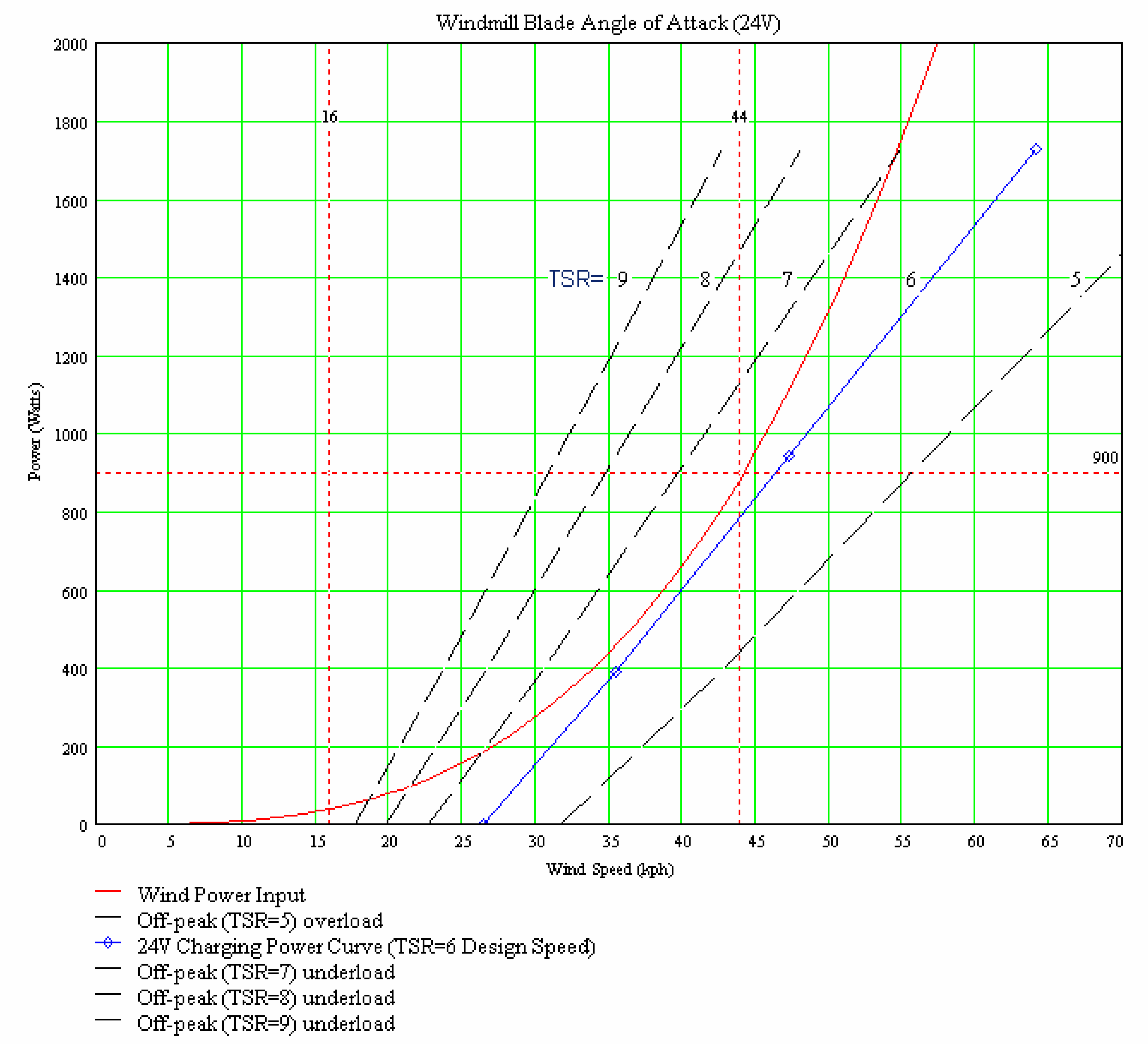
I find it very interesting that the curves fall very close together, plotted this way. The higher-voltage charging system requires a smaller prop, but operates in a higher power range, and a higher RPM range. However, when all that is converted into windspeed, at the same TSR, the operating wind speeds get closer together. The furling speeds are within 5kph of each other.

On the other hand, the 12V and 24V systems do very different things. The 12V starts charging in much lower winds. But it needs to furl itself early. The 24V charging system doesn't start until the storm is really under way, but when it does, it doesn't get overwhelmed until the wind is really going.

TIP SPEED RATIO

Thought we were done? If I haven't lost all of you by now, I will take one last step which will relate wind power, alternator load, wind speed all together with the mysterious concept of "Tip Speed Ratio". You used to think that a windmill blade built to turn at a specific Tip Speed Ratio (TSR) actually will… but it doesn't!

The chart below takes the wind power curve, shown above, and along with it I've plotted the alternator curve, adjusted for different TSR's. Now I can finally put the TSR of a windmill prop on the chart, representing the speed that makes the power IN from the wind MATCH the power OUT through the alternator.



I'll explain what I'm saying with an example. Look for the wind power when the wind blows at 27 kph. The red curve is just passing through 200 Watts. The blue line (with the diamonds), is the data I collected for my alternator, when the RPM is converted to wind speed for a prop running at TSR=6. The alternator running at TSR=6 when the wind is 27 kph is barely at cut-in speed. But that ISN'T what happens in reality.

This alternator isn't powerful enough to load that windmill. It's going to spin faster. The windmill will actually turn at TSR=7 in a 27 kph wind (the next dashed line up), and it's going to take up all those 200 Watts, and convert them to electricity at 50% efficiency. I expect to see 100 Watts (4A @ 24V) in a 27 kph wind. In lower winds, the current won't drop off to zero right away. The mill will produce a little power, even in low winds. By the way, I marked the line at 16 kph for the mean wind speed for my area. Hold onto your hats, eh!

Then, when the wind comes up to, say 40 kph, there's about 650 Watts of power in the wind, and the mill captures it at a TSR just over 6. Convert that speed to RPM and the mill should be turning at about 650 RPM. It could be generating up to 300 Watts at about 45% efficiency.

POWER COEFFICIENT

There's only one factor that's been missed through all of the discussion so far. That's the power coefficient, written as C_p. It gets ignored a lot because it's hard to do anything with the number. After a while, some of us get used to seeing 0.30 or 0.35 tossed around and assume it's constant. The Betz limit has been discussed elsewhere, so I don't need to repeat it, which pegs the maximum at about 59%. What happens in between? I don't know either!

I intend to find out.

To Learn More

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

DIY Projects

Hugh Piggott	www.scoraigwind.com
Dan Bartmann	www.otherpower.com
Ed Lenz	www.windstuffnow.com
The Backshed	www.thebackshed.com/Windmill

Scientific Research

Sandia National Labs	www.sandia.gov/wind/
NREL	www.nrel.gov/wind/
UIUC Airfoil Data	www.ae.uiuc.edu/m-selig/
ECN (Dutch)	www.ecn.nl/en/

Electrical Theory

All About Circuits	www.allaboutcircuits.com/
FEMM (Magnet Models)	www.femm.foster-miller.net/index.html

Commercial Wind Turbine Manufacturers

Bergey Windpower	www.bergey.com/
Southwest WindPower	www.windenergy.com/
Jacobs	www.windturbine.net/
Windmission	www.windmission.dk/index.html
Marlec	www.marlec.co.uk/products/products.htm
Flowtrac	www.nimnet.asn.au/~kali/
African Windpower	www.scoraigwind.com/african36/
AeroMax	aeromag.com/

Wind Energy Associations and Watchdogs

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

Appendix A - Wire Gauge Table

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

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

I would consider the column for "chassis wiring" a hard limit – you could burn up your stator if you overload it. On the other hand, delivering your power from the mill to the battery depends a lot upon the distance between them. Increasing resistance, by increasing the length of the wire, or decreasing the size of the wire, reduces the output of the windmill.

AWG gauge	Diameter Inches	Diameter mm	Ohms per 1000 ft	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission
OOOO	0.46	11.684	0.049	0.16072	380	302
OOO	0.4096	10.40384	0.0618	0.202704	328	239
OO	0.3648	9.26592	0.0779	0.255512	283	190
0	0.3249	8.25246	0.0983	0.322424	245	150
1	0.2893	7.34822	0.1239	0.406392	211	119
2	0.2576	6.54304	0.1563	0.512664	181	94
3	0.2294	5.82676	0.197	0.64616	158	75
4	0.2043	5.18922	0.2485	0.81508	135	60
5	0.1819	4.62026	0.3133	1.027624	118	47
6	0.162	4.1148	0.3951	1.295928	101	37
7	0.1443	3.66522	0.4982	1.634096	89	30
8	0.1285	3.2639	0.6282	2.060496	73	24
9	0.1144	2.90576	0.7921	2.598088	64	19
10	0.1019	2.58826	0.9989	3.276392	55	15
11	0.0907	2.30378	1.26	4.1328	47	12
12	0.0808	2.05232	1.588	5.20864	41	9.3
13	0.072	1.8288	2.003	6.56984	35	7.4
14	0.0641	1.62814	2.525	8.282	32	5.9
15	0.0571	1.45034	3.184	10.44352	28	4.7
16	0.0508	1.29032	4.016	13.17248	22	3.7
17	0.0453	1.15062	5.064	16.60992	19	2.9
18	0.0403	1.02362	6.385	20.9428	16	2.3
19	0.0359	0.91186	8.051	26.40728	14	1.8

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

Appendix C - 3-Phase Connections

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