

Testing the Power Curves of Small Wind Turbines

by Paul Gipe

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Background:

The following article grew out of research for an extensive revision of my book *Wind Power for Home & Business* published by Chelsea Green. The article is essentially a report on how to test small wind turbines and the results of my tests.

These tests began in the spring of 1999 and work on the article began in earnest during the fall of that year. All tests were conducted pro bono, that is, no one paid for the tests. The original article was written, again pro bono, for [Home Power magazine](#) because they are one of the few periodicals that cover small wind turbines. However, HP chose not to publish the article. The article and the decision by HP not to publish it was extremely controversial within the small wind community. As a result, there is an extensive discussion of power curve measurements on the news group [awe-a-wind-home](#). The debate begins at message 2923 and runs through message 3269.

All wind turbine manufacturers mentioned were kept apprised of these tests and copies of the data were forwarded to the manufacturers. Some found substantive errors and corrections were made. Some didn't comment. The data was also sent to several of my peers for review.

An edited version of the article was sold to [WindStats Newsletter](#) and appeared in the Summer 2000 (Vol. 13, No. 3) issue. WindStats, as its name implies, publishes articles and supporting data on the the performance of wind turbines. It's the only publication of its kind in the world. For a pdf version of the article, contact [WindStats](#) directly.

My reasons for testing the turbines are clearly explained in the article. My reasons for selecting the turbines that I did is also explained. Essentially I picked turbines that I've written about and that I could afford.

Disclosure: I paid for all products mentioned. In the early 1980s I was a dealer for Bergey Windpower. I wrote promotional copy for NRG Systems in the late 1980s and I was a contractor to AWEA from 1986 to 1993.

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Power Curves

Power curves. These charts can be found everywhere small wind turbines are advertised. You can see them in Home Power magazine and on the web.

What is a power curve? It's a graph indicating how much power (in watts or kilowatts) a wind turbine will produce at any given wind speed. Power is presented on the vertical axis; wind speed on the horizontal axis.

Can these charts be believed? That's a much more difficult question to answer. American consumers, accustomed to performance labeling on everything from refrigerators to new cars, may assume that data on arcane wind turbine specifications, such as power curves and the mysterious term "rated power," are produced by a nationally recognized testing institute or are at least derived according to some industry standard. They are not.

For years I've fielded the occasional complaint from small wind turbine owners that their wind turbine had failed to live up to its manufacturer's claims. Either the turbines didn't operate reliably or there was a suspicion that the turbines weren't delivering as much power as they expected. While it's true that satisfied customers seldom call to say how great their turbines are running--and there are tens of thousands of small wind turbines in use worldwide--the disturbing calls were real and continue to this day.

It wasn't until I loaded some software from the National Renewable Energy Laboratory that I came across the first hard data that said something was amiss. NREL's Hybrid II software indicated that a popular turbine from a respected manufacturer was delivering only 65% of its "rated power."

Despite exhorting wind turbine buyers in three books and dozens of lectures over two decades to compare wind turbines on the area swept by their rotors (or by simply using rotor diameter), consumers are still smitten with the archaic and misleading concept of "rated power."

Recently World Power Technologies boldly changed the system designating their products and adopted swept area to indicate the size of the their turbines. Encouragingly, I've found owners are using this system when talking about their machines. But as much as I may goad consumers to use swept area, "rated power" nomenclature and the unwarranted emphasis on "power curves" is deeply ingrained. And therein lies the problem. So I decided to test the performance claims of some small wind turbines myself.

The Rating Game

In the advertising wars, the high ground on the power curve that manufacturers try to take is the point at which the wind turbine reaches its "rated" or nominal power. Whether this is important or not relative to how well the wind turbine actually performs in the field is hotly contested.

Wind turbines reach their "rated" or nominal power at their "rated" wind speed in mph or meters per second (m/s). Rated power is not synonymous with peak power, though they are occasionally the same. Rated power and peak power are just two points on a power curve.

Typically the peak power of a small wind turbine is greater than its rated power. For example, the rated power of Bergey Windpower's 850 is 850 watts at 28 mph. Yet its peak power is nearly 1100 watts at 33 mph. Similarly, the Air 403 is rated at 400 watts, but the manufacturer, Southwest Windpower, says it will produce up to 500 watts.

There are no rules, standards, or norms about what wind speed manufacturers may pick to "rate" their small wind turbines. Often in the United States it's 28 mph (12.5 m/s). But manufacturers may pick any speed they choose. If it's less than 28 mph, the turbine will have a lower "power rating" than a wind turbine with a similar sized rotor but with a higher rated speed. In the 1970s it was easy for unscrupulous manufacturers to manipulate this system to make it appear that their turbines were a better buy than competing products. By pushing "rated power" higher they were able to show lower relative costs in \$/kW of rated power (turbine cost/rated power) or they were able to jack up their price--and profits--proportionally.

Rated power at a rated speed is just one point on a wind turbine's power curve, yet many consumers rely on the rated power and the power curve when comparison shopping. But not all power curves are created equal. Some power curves are, to be diplomatic, more "aggressive" than others. While measuring power curves is complicated and costly, it is one of the few means that we have of objectively testing wind turbine performance.

Some argue that few consumers care, so why bother. Andy Kruse at Southwest Windpower notes that most consumers are more concerned about the state-of-charge of their batteries than whether the wind turbine performs as advertised. If their batteries are charged, so what if the turbine doesn't deliver what the manufacturer promised. While this may be true, it ignores the distortion that inflated claims may have on the small wind turbine marketplace. Those who "stretch the truth" by "fudging" on their power curves and rated power gain an unfair marketing advantage over their competitors.

The only way to find out if small wind turbines can do what their manufacturers say they'll do is to test them. In an ideal world, an independent testing agency, Consumers Union (the publishers of Consumer Reports) for example, would certify small wind turbine power curves. There are a number of companies and testing

laboratories that do just that for big turbines. But there's never been enough money in small turbine testing to warrant the attention of the major institutes.

NREL's Wind Technology Center in Colorado occasionally measures power curves. But much of the information collected is considered confidential and proprietary, though the tests are partially paid for with public funds. These test results are not available to the public without a Freedom of Information Act filing.

With this background in mind I set out in the spring of 1999 to try and measure the performance of some small wind turbines at a site in California's Tehachapi Pass. The five turbines I tested were those I've written about in my books. Over time, and as money permits, I hope to test others as well. My purpose was to gain a general idea of whether the turbines were meeting or exceeding their power curves. I wanted to keep the tests as simple as possible so that others could replicate the process. I also wanted to avoid any lengthy testing of reliability or durability-- considerations equally important as power curves when comparing the worth of small wind turbines. One conclusion of these tests is straightforward: none of the turbines I tested consistently exceeded their power curves at all wind speeds. In contrast, big turbines often exceed their power curves.

Standardized Tests

There is an international consensus that the only way to properly test small wind turbines is "in the field." Both the American Wind Energy Association's performance testing standard and the proposed European standard for small wind turbines developed by Britain's IT Power exclude performance measurements of wind turbines in wind tunnels or through truck tests. Neither "truly replicate free-stream conditions," says IT Power. Typically, wind tunnel tests overstate performance. This phenomena was seen several times in the 1970s during development of government-sponsored wind turbines in the United States, notably McDonnell Aircraft's giromill. Typically, consumers will never see the performance measured in a wind tunnel.

AWEA adopted a performance testing standard in 1988. It was specifically compiled for small wind turbines, but the method is similar to that used internationally today to measure the performance of wind turbines of all sizes.

Very few if any large wind turbines sold on the international market can obtain financing without a performance test conducted by an independent testing laboratory. Until recently no one in the United States was internationally recognized to perform such testing, not even NREL.

AWEA's standard was ". . . intended to provide consumers . . . with an equitable basis for comparing the energy production performance and operating characteristics" among different wind turbines. It avoids any discussion of reliability or durability, except as it affects testing of the power curve. (You can't measure a power curve if the turbine's not operating.)

At the heart of the standard is a detailed description of how power curves should be measured. Further, it requires all manufacturers to prepare a "test report" describing the techniques they used to measure their power curve and the results of their measurements. Presumably this report would then be available to the public upon request.

No small wind turbine sold in the United States today complies with AWEA's performance standard. American manufacturers' reluctance to embrace any standards whatsoever goes back to the rebirth of the wind industry in the United States in the mid 1970s. This recalcitrance results from a uniquely American fear that standards stifle engineering creativity.

The first draft of AWEA's performance standard appeared in 1979. After a decade of bickering this standard was finally approved. Two decades after the standard was first proposed there are still no small wind turbines on the U.S. market that comply with its provisions.

Wulf Test Field

My test site is situated among rolling hills at an elevation of 4600 feet (1,400 m) on the north facing flanks of the Tehachapi Mountains. The site is about one mile (1.7 km) north of and 200 feet (60 m) below Oak Creek Pass. The hills form part of the low col that encompasses the Tehachapi Pass Wind Resource Area. Because of its location, the test field experiences periods of extremely high winds during the winter and spring and a high average annual wind speed. (The test field's eastern boundary abuts Enron's Victory Garden wind power plant, one of the largest in the United States, with nearly 1,000 wind turbines.)

Vegetation is sparse and primarily low grass with a cluster of willows in a nearby stream bed. The trees are about 30 feet (10 m) tall. The ridges bordering the shallow valley draining the site are also about 30 feet (10 m) high.

The test field is undeveloped. There are no buildings or other structures. There is no access road, only a track. All equipment and materiel must be transported to the site by four wheel drive vehicle or carried in by hand. During rain or snow the site is inaccessible except on foot. The test field is well suited for demonstrating and testing small, stand-alone wind turbines designed for battery-charging applications at remote sites. (See the article "[Get a Grip \(pdf\)](#)" for more on the test field.)

Bergey Windpower's 850

The Turbines

I tested five turbines: Bergey Windpower's 850, Southwest Windpower's Air 303 with Air 403 blades, Air 403, LVM's Aerogen 6F, and Marlec's Rutland 910-3F. The first turbine tested was BWC's 850.

At the time I ordered the Bergey 850 it was widely considered the Cadillac of mini turbines because of its robustness and cost. With its 8-foot (2.4 m) diameter rotor and 80 pound (36 kg) mass, the Bergey 850 has a specific mass, a measure of the turbine's robustness determined by its mass relative to the area swept by its rotor 50% greater than an Air 303/403.

The Bergey's permanent-magnet generator produces three phase "wild" AC from conventional Ferrite magnets. The wind turbine includes a Variable Charge Controller that rectifies the variable frequency AC to DC for charging batteries. The three-blade, upwind turbine is similar to the two other turbines in the Bergey line: the 1500 and the Excel. The turbine was designed by Karl Bergey and when Karl retired the company discontinued the product. That announcement occurred a few months after I received my unit, #159.

The Southwest Windpower turbine was an Air 303 I bought used from NRG Systems. NRG had operated the turbine for no more than two weeks. I had the turbine reconditioned by SWP for about \$100. They provided the larger 46-inch (1.17 m) rotor now used on the Air 403 and a new charge controller. Consequently my unit was a hybrid Air 303/403, but without the 403's new alternator. I also tested a new Air 403 out of the box.

At 48 inches (1.22 m) in diameter, LVM's Aerogen 6F intercepts 9% more area of the windstream than the Air 403. The Aerogen 6F also uses six blades to the Air's three. It also uses a furling tail (the F in 6F). The Air 303/403 uses a fixed tail vane and no conventional means of overspeed control. At high wind speeds the slender blades of the Air flutter, dissipating energy acoustically.

Southwest Windpower's Air 303
with Air 403 blades

Marlec's Rutland 910-3F is one of the smallest wind turbines on the market. The Rutland 910 uses a six blade rotor about 36-inches (0.91 m) in diameter. Unlike the other machines, the Rutland uses an unusual "pancake" rotor with the rotor and stator embedded in thick plastic. The Rutland rotor intercepts 60% of the area swept by the Air 303/403.

Wind Speed

Measuring power curves is not an exact science. There's a lot of room for error and misinterpretation. Most notable is the sheer difficulty of accurately measuring wind speed. It's not as simple as most think.

The wind industry's meteorologists bludgeon each other with obscure arguments on the accuracy of their anemometers. They pepper their discourse with terms like "slope" and "intercept" and feud over which is right for each of the different anemometers (wind speed sensors) on the market. They even disagree whether "to boot or not to boot" the terminals on the Maximum #40 cup anemometer--the most popular sensor in North America--and the effect this has on the measured wind speed.

Both the American and the proposed European standards for measuring small wind turbine performance require calibrated anemometers with documentation traceable to a national testing authority.

LVM's Aerogen 6F

Marlec's Rutland 910-3F

I chose NRG's Maximum #40 cup anemometer for my tests. At \$75 for the un-calibrated version, and twice that for the calibrated models, these are the least

expensive anemometers on the market. Some meteorologists use sensors that cost \$500 or more.

For my tests of the Bergey I used an un-calibrated anemometer. For measurements on the other four turbines I used a calibrated anemometer. In the future I'll test the two anemometers side by side. But for tests of small turbines replicating actual consumer use I don't feel calibrated anemometers are necessary. Users of small wind turbines are invariably cost conscious. They will nearly always buy the non-calibrated version--if they use an anemometer at all. For wind turbines worth half a million dollars each, the extra cost of calibrated anemometers makes more sense.

Wind Direction

Both the AWEA and European standards require monitoring wind direction during power curve tests. The intent is to identify periods when winds are from a direction where the anemometer is sheltered behind the tower. The standards specify that only those winds from quadrants free of obstructions upstream of the anemometer should be used.

For a backyard (back garden for those in Britain) system, this too is overkill. If the anemometer is in the wake of the tower, the anemometer will see less wind than the wind turbine. This will tend to boost the relative performance of the wind turbine in the manufacturer's favor. For example, if the anemometer "sees" 9 mph, but 10 mph winds strike the rotor, the wind turbine will produce proportionally more electricity than it would at 9 mph. The recording system will log production from actual winds of 10 mph in the loggers 9 mph register. The power curve will appear better than it really is.

The winds in the Tehachapi Pass are nearly bidirectional. Most power producing winds are west northwest. During the summer months and during occasional "Santa Anas," winds are from the opposite direction, east southeast. My anemometers read winds from both directions with a bias toward the prevailing wind direction. I chose not to measure wind direction.

Anemometer Boom

Standard test procedures call for erecting an anemometer mast separate from and upwind of the wind turbine. The intent is to place the anemometer in the freestream just upwind of the wind turbine's rotor.

AWEA's standard places the anemometer 1.5 to 6 rotor diameters upwind of the wind turbine rotor's centerline. For the 8-foot diameter BWC 850 that's 12 feet to 50 feet from the rotor. The proposed European standard for small wind turbines is similar, from 2 to 4 rotor diameters upwind. This puts the measurement mast dangerously close to the spinning rotor, or from 16 to 32 feet in front the BWC 850.

For a scientific laboratory or a certification agency this requirement makes sense. Manufacturers will use data from these measurements to promote their products. The measuring institution will want its test to be as accurate as possible so other

organizations can reproduce their results. They don't want to favor the manufacturer, because this shortchanges consumers, but at the same time they don't want to underestimate performance because this puts the manufacturer at a competitive disadvantage.

My tests were designed as a "first cut" whether or not the turbine approached, met, or exceeded its power curve. I economized where it was in the manufacturer's favor. If the wind turbine performed well and met its power curve under these conditions, the test could be refined later--at greater cost.

Because of the steep hillside site on which I had installed the turbine and the rapidly escalating (skyrocketing might be more like it) cost of this project I took the path of least resistance. I opted to mount the anemometer on a mid-tower boom strapped to the wind turbine tower. **Mick Sagrillo**, an expert on small wind turbines in Wisconsin, recommended placing the boom a minimum of one rotor diameter below the turbine's hub. The tower used for the BWC 850 is nominally 64-feet (19.5 m) tall, consequently the anemometer boom is at a nominal height of 56 feet (17 m). The tower used for the smaller turbines is nominally 44 feet (13 m), the anemometer boom used for testing these machines is at a nominal height of 40 feet (12 m).

Wind speed typically increases with height above the ground. If the 1/7 power law applied, the Bergey wind turbine could see 2% more wind and possibly 6% more power than that at the height of the anemometer. In rough terrain, such as my test site, the increase in wind speed and power with height could be even greater. However, no attempt has been made to adjust the wind speed measured by the anemometer to that possibly seen by the wind turbine. This is to the manufacturer's benefit. The wind turbine could be intercepting winds with 5-10% more power than that indicated by the anemometer.

Initially I installed the anemometer boom at the top guy bracket which I thought was five feet below the hub. Wrong! NRG's tower sections loose about one foot of their nominal length at each joint because the sections slip together. Though I was concerned that the anemometer might give erroneous readings if I'd inadvertently placed it within the air dam or upstream wake in front of the tower, it never occurred to me that the blades might strike the boom. I heard a clicking sound once during the several weeks that it operated in this manner. When I lowered the tower to later reposition the anemometer booms, I noted a little white powder on the top boom. Each blade lost about 1/4-inch at the tip, not quite the width of the leading edge tape; about 1% of the original area swept by the rotor. This incident affected the Bergey 850 only.

Air Density

Air density has a significant effect on wind turbine performance. The power available in the wind is directly proportional to air density. As air density increases the power available also increases.

Air density is a function of air pressure and temperature. Published power curves are typically presented for standard conditions of temperature and pressure so they are readily comparable with one another.

At a standard temperature of 288 degrees Kelvin (273.15 degrees K plus 15 degrees Celsius) and pressure of 760 mm Hg or 1013.25 mb, air density is 1.225 kg/m³ in SI units. Standard conditions in the English system occur at a temperature of 59 degrees Fahrenheit and 29.92 in Hg.

Both temperature and pressure decrease with increasing elevation. Consequently changes in elevation produce a profound effect on air density. The air is less dense and the wind, accordingly, has about 14% less punch at the crest of the Tehachapi Mountains than at Miami Beach.

To account for air density, standard test procedures call for simultaneous measurements of both barometric pressure and temperature. However, pressure sensors are costly, about \$500. Both Second Wind and NRG Systems suggest that a barometric pressure sensor is overkill for home-brew measurement systems. They note that much of the effect air pressure has on air density can be accounted for by elevation. Variations in barometric pressure due to passing weather systems can effect air density by a few percent but this can be accounted for by monitoring local weather.

While changes in barometric pressure affect air density slightly, temperature has a more discernible effect. Air density decreases with increasing temperature. During the summer months average daytime temperatures in the Tehachapi Pass may average 70 degrees Fahrenheit (21 degrees C) or more. This can reduce air density by some 2% relative to standard conditions. Consequently it's important to account for temperature as well elevation during power curve measurements.

To adjust my test site's elevation and temperature for standard temperature and pressure, measured power curves were increased by about 18%, depending upon actual average temperature during the test. (This statement doesn't begin to explain the amount of effort it took to construct the spreadsheet to do this! My thanks to meteorologists Jim Salmon of Zephyr North and Jack Kline of Ram Associates for their invaluable help.)

Loggers

Finding and installing the right sensors needed to measure power curves is only one of many steps. It's necessary to log the collected data for later retrieval and processing. Loggers and their associated hardware don't come cheap, typically \$1,000 to \$2,000 just for the recorder.

If you're a computer whiz like [Michael Klemen](#) in North Dakota or [Hugh Piggott](#) in Scotland you can build your own system from one of those old computers gathering dust in your closet. Klemen monitors the performance of his Whisper H900 and H4500 using a rebuilt Sharp 586 clone and a data translation board that cost him

\$900. He also creates his own software to translate the digital information into something us mere mortals can comprehend. Scoraig Wind Electric's Hugh Piggott uses a Picolog interface with an old 286 laptop.

The loggers of choice for the national laboratories and some university test fields in North America are those made by Campbell Scientific. Both Brian Vick at the U.S. Department of Agriculture's ARS (Agriculture Research Service) Bushland experiment station and Ken Starcher at [West Texas A&M's Alternative Energy Institute](#) use Campbell's CR21X. These are full-fledged data loggers intended for the pros who can program them.

Somewhat less sophisticated yet still versatile are loggers built for the wind measurement industry. NRG Systems and Second Wind build loggers for collecting meteorological data from several sensors. These loggers store data from the pulses of Maximum cup anemometers as well as analog signals from such sensors as wind vanes and power transducers.

I bought a used Second Wind Nomad for \$500 from a colleague in the wind business. The Nomad is easy to use and Second Wind provided excellent support. I haven't used the other instruments.

Measuring Power

There are several ways to measure power: separately measuring voltage and current (volts x amps = watts), or measuring voltage and current together with a power (or watt) transducer. AWEA's standard recommends (though it doesn't require), using a watt transducer.

Voltage can be stepped down to the range digestible by electronic recording devices using a voltage-divider circuit comprised of several resistors. (Second Wind's Nomad records analog signals from 0 to 2.5 volts.) Michael Klemen measures voltage on the wind turbines he's testing in North Dakota using such a divider circuit.

Current can be measured with either a current shunt, like the shunts in Trace power panels used by Bogart Engineering's Tri-Metric meter, or with a Hall-effect transducer. Starcher uses a current shunt at AEI's test field in Canyon, Texas. The Campbell Scientific logger that he uses reads the voltage drop across the shunt as current, then combines this data with the voltage measured separately and records watts. Starcher says that test fields in many of the Third World countries he works with use shunts to measure current because they are cheaper than Hall-effect transducers. Klemen in North Dakota also uses current shunts.

Hall-effect sensors and their signal amplifiers are found in clamp-on ammeters. They are easy to use.

You just pass the conductor being measured through the sensor doughnut. But as Starcher says, they don't come cheap. Ohio Semitronics' Hall-effect transducer and signal conditioner applicable to small wind turbines costs about \$350.

After struggling with a spreadsheet to combine voltage and current, I followed Second Wind's advice and sprung for a power transducer that delivers watts directly to the logger. This greatly simplified life but at more than twice the cost of the current transducer.

Regardless of which method is used, AWEA's standard calls for instruments with an accuracy of at least 3%. International standards typically demand an accuracy of 1%.

Power Accuracy

My Ohio Semitronics PC8-002-01B watt transducer is accurate within 1%. It has an input range of 0-50 volts and 0-100 amps, accordingly the transducer can measure up to 5,000 watts plus or minus 50 watts. To improve the resolution of the transducer I looped the positive cable through the Hall-effect doughnut (sensor).

One loop reduces the transducer's range from 100 amps to 50 amps, or from 5,000 watt to 2,500 watt. At 1% accuracy this is equivalent to +/- 25 watts. On a nominal 1000 watt wind turbine, such as the Bergey 850, this represents about 2.5% of peak power. Two loops through the transducer doughnut cuts the range from 100 amps to 33.3 amps or 1665 watts. At 1% accuracy this is 17 watts.

The consensus among those measuring small turbine performance in the United States is that this is probably good enough. The data acquisition board Klemen uses to monitor his 24 volt Whisper 4500 is accurate within +/- 1.5 amps. That's a resolution of better than 1%. Considering all the inaccuracies confronted when measuring power curves, it's difficult to expect much better.

Power Location

The objective is to measure the turbine's power after all internal losses, so "that only power delivered to the load is measured" according to AWEA's performance standard. In a battery charging wind system this occurs between the charge controller and the batteries. This is as it should be. In the real world it's what we put in our batteries that's important, not what's being produced at the top of the tower.

Load

Measuring power from battery-charging wind turbines present special challenges relative to measuring the performance of wind turbines interconnected with a utility network. The latter presents an infinite load for an interconnected wind turbine. The load, the utility, can consume all the electricity generated. Not so with batteries.

In a typical application, battery storage is finite. When batteries are fully charged, wind turbine charge controllers switch off the load to avoid overcharging and damaging the batteries. Clearly it's futile to try and measure the wind turbine's

performance when the charge controller has stopped charging and unloaded the wind generator. Consequently there must be sufficient load on the batteries so they never become fully charged during the test period. This often entails a diversion controller and a diversion load.

Voltage is a good state-of-charge indicator for lead-acid batteries. Voltage decreases as batteries become discharged, and increases as they are charged. In a typical renewable energy system, battery voltage constantly fluctuates with the state-of-charge.

Unfortunately, the performance of battery-charging wind turbines is partly a function of battery voltage. Scoraig Electric's Hugh Piggott notes that a wind turbine's low wind performance improves as voltage decreases. He says that permanent-magnet alternators need to reach a certain speed to produce the necessary voltage to begin charging the batteries. When battery voltage is low the alternator speed at which charging begins is accordingly lower and the wind turbine's "cut-in" wind speed is lower. In high winds, Piggott says, losses depend on current and you can get more power out of a given current when voltage is high because power is the product of voltage and current.

This complexity has befuddled researchers for many years. The consensus is that voltage must be held relatively constant during performance tests. AWEA's standard specifies that the ". . . load and wiring should be representative of typical customer installations" and should be large enough to maintain the wind turbine's full output within "generally recognized operating limits." For a 24 VDC system the battery charging system should be large enough to limit voltage to below 28.2 VDC. (Incidentally, this is the voltage at which Bergey's Voltage Control System switches off charging and unloads the wind turbine.)

The proposed European standard suggests measuring performance at two voltages: 112% (26.9 VDC), and 96% (23.1 VDC) of nominal battery voltage. This represents batteries that are fully charged, and heavily discharged according to IT Power, the consultants who drafted the standard. They add that voltage should be held within 2% of these values, from 26.4 to 27.4 VDC under "charged" conditions and from 22.6 to 23.6 VDC under "discharged" conditions.

To provide the constant voltage required, Mick Sagrillo suggested an Enermaxer Universal Voltage Controller, which acts as a diversion controller. Whenever voltage reaches a selected value it directs excess current to a diversion load, typically a resistive load. I should have listened to Mick. Instead I succumbed to the lure of vapor ware being pushed by Trace Engineering and it cost me several months of lost time.

Load Controller

Because the Wulf test field is in an area of high fire hazard I wanted an engineered system of protection devices that would essentially meet the National Electrical Code used in the United States. Trace offered two packages that fit the bill: the power

panel and their power module. I opted for the power panel with a 175 amp disconnect, circuit breakers, and a DR1524 inverter so I could hang it on a wall and service it standing up. (Yes, it's overkill for the electronic instruments it powers, but I wanted to check out the power quality of its modified square wave.) Trace also advertised a C60 charge controller that could be used as a diversion controller.

I say "could" because I never received one. When the tractor trailer pulled up with the power panel, the C60 wasn't on it. After several months of waiting I finally called Doug Pratt at Real Goods, my supplier, only to learn that the C60 didn't exist and wouldn't be shipped for months more, if even then. Trace was trying to salvage their reputation by offering Pulse Energy's 60 amp controller. Of course real hardware always costs more than vapor ware. Both the Pulse and Enermaxer controllers cost about 50% more than the advertised price for the Trace C60.

Though Pulse's TC60 can be used as a diversion controller it must be configured in the field to do so. The unit and its documentation are shipped for charge control applications only. While configuration is not difficult I wouldn't call it "user friendly" either. Fortunately a Pulse technician walked me through it and I was able to set the voltage switch point at 26.8 VDC. The Pulse controller diverts surplus current to a 1440 watt Enermaxer air heater built by Alternative Energy Engineering.

Wire Size

The electricity produced by a wind turbine is seldom of benefit at the top of the tower where the turbine is located. The electricity must be transmitted to the point of use before it can provide any benefit. Thus, the cables connecting the wind turbine to the batteries are as integral to a wind power system as the tower the turbine stands atop.

The length, diameter, and material used in the cables connecting the wind turbine to the batteries determines the resistive losses between the wind turbine and the batteries or battery charge controller. These losses are proportional to the type of material (copper has less resistance than aluminum), diameter (thick cable has less resistance than thin cable) and distance to the batteries (short cables have less resistance than long cables). These resistive losses are reflected in the voltage drop between the wind turbine and the batteries.

Manufacturers specify the cable size and material for a range of distances between the wind turbine and the batteries that will allow their wind turbine to perform as designed. For example, Bergey Windpower recommends using #8 AWG copper wire for wire runs up to 300 feet from its BWC 850 to the batteries for its 24 V system. This distance includes the tower. Bergey's operation manual claims that this size cable "will provide no more than a 10% power loss."

Because the intent of performance testing is to replicate what consumers can expect from wind turbines operating in the field, AWEA's performance standard stipulates measuring the power delivered to the load, not at the top of the tower. It does not

take into account any losses between the wind turbine and the batteries, assuming that the wind system is installed to the manufacturer's specifications.

The proposed European standard tries to establish a uniform resistive loss in the cables between the wind turbine and the batteries for ease of comparison between tests, and between turbines. IT Power's draft says that the voltage drop "should be equivalent to 10% of nominal voltage at rated power".

The Air 303/403, the Aerogen 6F and the Rutland 910-3F all rectify three-phase AC at the generator and deliver DC to the tower leads. For the 200 feet of DC cable run to the batteries from the tower used by the micro turbines, I installed #4 AWG copper conductors in accordance with SWP's Air 403 installation manual.

At the base of the Bergey tower I installed a drip-proof fused disconnect according to Bergey's installation manual. And, as recommended by Bergey I installed 15 amp fuses. Southwest Windpower offers no recommendation on disconnect switches, nor do the other micro turbine manufacturers. However, I installed a similar fused disconnect switch for the micro turbines.

Power Loss

Almost immediately after data was first collected on the BWC 850 a serious question arose about the size of the conductors used. The turbine was consistently under performing it's power curve 10% to 15% even after adjusting to standard conditions of temperature and pressure. Scoraig Wind Electric's Hugh Piggott quickly diagnosed the situation and suggested that the conductors from the turbine to the controller were undersized. And sure enough, during a period of high winds the turbine blew the 15 amp fuses as Piggott predicted.

Unfortunately, calculating resistance or power loss due to current flow in 3-phase AC rectified circuits is not as clear cut as I once thought. Even professionals disagree. Bergey Windpower said one thing, Piggott another. To settle the matter, I installed a current transducer on one phase of the AC side of the charge controller. Piggott suggested that on rectified 3-phase circuits, AC phase current should be 0.82 of DC current for low impedance alternators. For high impedance alternators, the AC phase current is nearer 0.74 DC current. And this was the range of results obtained. At high wind speeds, high current, AC phase current was 0.72 times DC current. At low wind speeds and low current flows, AC phase current was more than 0.8 DC current. It certainly was not the 40% implied by the use of 15 amp fuses in the AC circuit that Bergey recommended. Possibly as much as 15% of the total power produced was being lost in the conductors at rated wind speed, and as much as 20% at peak power.

Chart of Power Loss in Conductors to BWC 850

Because few manufacturers explain exactly how much power can be lost in the conductors they recommend for their turbines, I've included calculations of estimated power loss at various wind speeds. These calculations are based on measured current flow and the size, length, and type of conductors used.

Data Sampling

In the old days (20 years ago) data was collected on a strip chart and the observer interpolated or "eyeballed" a line through the scattered dots (data points) on the strip chart. You can still do that today by dumping the data into a spreadsheet program and charting a "scatter plot". You should be able to then use the spreadsheet program's line interpolation functions to draw a line through the scattered points.

The reason the data points are scattered is due to differences between the anemometer's and the wind turbine's inertia. When a gust strikes a lightweight Maximum cup anemometer it begins speeding up almost instantly. However, there is a longer lag between the time a gust strikes a wind turbine rotor and when it begins to respond because of the mass in the blades, hub, generator, and transmission if one is used. The reverse is also true. The anemometer responds more quickly than the wind turbine in lulls. The wind turbine, because of its rotational inertia, will continue spinning and putting out power for a few seconds or more after the gust has passed. This lag, or hysteresis as the engineers call it, makes it difficult to accurately measure a wind turbine's performance without averaging.

Performance standards require correlating power data from a series of wind speed ranges or "bins" across the range of wind speeds of interest. For example one "bin" or register could accumulate measurements from 10 mph to 11 mph. The power data in each bin is then statistically averaged. The right software, such as Second Wind's Insite (DOS) and Winsite (Windows 95), makes quick work of this.

You'll need software to make sense out of the data, and there can be a lot of it. Whatever logger you choose, you'll have to either buy software with it, download free software from the net or create your own. Second Wind's Nomad comes with Insite included. It does the job and is all that you really need. However, they recommend using their \$300 Winsite software instead. Software is actually a critical component because the analysis of wind speed and transducer data is not as straightforward as it might appear.

An area of contention has been the rate at which data from the sensors are sampled and the period of time over which the samples are averaged. The proposed European standard requires sampling data from the sensors at least every two seconds. This sample, they argue, should be representative of fluctuating wind

speed and power. Data from one minute or ten minutes of these two-second samples are then averaged and logged. AWEA's standard simply limits the minimum averaging period to 30 seconds. There's no maximum averaging period.

Second Wind's Nomad samples data every second and can average data over 1, 5, 10, 15, 20, and 30 minute, hourly, and daily periods. Dave Corbus at NREL's Wind Technology Center uses 1 minute and 10 minute averaging periods in his measurements of Southwest Windpower's Air 403. The international standard for large turbines requires 10-minute averages. Cowley says that IT Power has dropped the 10-minute average and opted for the 1-minute average in testing of small wind turbines in the proposed European standard "because of the difficulty getting sufficient data in a reasonable amount of time." Mike Bergey has proposed that AWEA adopt the 1-minute average as part of its revised performance standard.

Duration

The amount of time over which the data is collected and, hence, the total amount of resulting data affects the accuracy of the results. AWEA's standard requires a minimum of 60 samples for wind speed bins less than 28 mph (12.5 m/s), 20 samples for bins from 28 mph to 35 mph (12.5-15.6 m/s), and 10 samples for bins greater than 35 mph (15.6 m/s). Cowley is recommending that the proposed European standard require 30 1-minute samples or one-half hour of data for each wind speed bin. Mike Bergey has suggested that AWEA adopt the same approach.

I opted for one-minute averaging periods and cut bins with less than one-half hour of averaged data.

Advertised Curves

With the exception of Bergey Windpower, no manufacturer provided a table of expected power output relative to wind speed as could be used in a spreadsheet. Southwest Windpower, Marlec, and LVM provided charts. From these charts I manually constructed a table of power versus wind speed by interpolating the points on these curves. This explains why the manufacturers' power curves in the test results are not smooth.

Results

The Air 303 with 403 blades, the Air 403, and the BWC 850 delivered noticeably less than their power curves at rated power when corrected for temperature and pressure. The LVM 6F and Marlec's 910F effectively met their claims at rated power. The LVM 6F and the Ampair 100 were the only machines to exceed their power curves at any time. The Air, BWC, and the LVM machines all substantially underperformed at 10 mph, representative of light winds. In comparison Marlec's 910F was off only modestly.

It is significant among micro turbines that at 10 mph and 15 mph the Ampair 100 meets its power curve; at 20 mph the Ampair exceeds its power curve by 33%; and at 25 mph it exceeds its power curve by 47%.

Most of the Bergey's under performance is attributable to losses in the conductors. However, the conductors were sized to Bergey's recommendations and thus this is what a consumer could expect to receive when similarly following the advice in the installation manual.

The Air 303, even with the 403 blades did not meet any of the three power curves provided by Southwest Windpower. It did exceed its projected performance in the 15 mph bin for Curve 2. As with the Bergey, the conductors were sized to Southwest Windpower's specifications. Unlike the Bergey, the difference between projected performance and that measured can't be explained by losses in the conductors. Tech support indicated that the under performance could be due to "de-Gaussing" of the magnets over time. This unit, serial number 13951, had not operated for any extensive length of time. Before the tests began, the turbine had operated only a few weeks at a low wind site in Vermont.

Because of the under performance of the Air 303 (with 403 blades), I felt obligated to also test the new Air 403. However, it too under performed its advertised power curve. From these tests it appears that the Air 303 is more correctly described as the Air 253 and the Air 403 is more corrected termed the Air 303.

Though the procedures used in these tests don't fully conform to international testing standards, the power curves published by many small wind turbine manufacturers are often not measured according to these standards either. Some published power curves were derived from truck tests, some were from wind tunnel tests, and some were produced by manual data collection.

While my measurement procedures are not up to those of an international testing laboratory, they are certainly as good as that used by many small wind turbine manufacturers, and better than some.

Moreover, my results are more reflective of what an actual consumer can expect. With the exception of the three British machines tested (LMV 6F, Marlec 910F, and Ampair 100), it's unlikely that a consumer can expect to see the performance promised by the Bergey 850 and SWP Air 303 and 403 product literature.

- [**Summary of Power Curve Measurements Relative to Manufacturers' Advertised Power Curves**](#)
- [**Marlec 910F Measured Power Curve**](#)
- [**LVM 6F Measured Power Curve**](#)
- [**Air 303H and Air 403 Measured Power Curves**](#)
- [**Ampair 100 Measured Power Curve**](#)
- [**BWC 850 Measured Power Curves**](#)
- [**Table of Power and Specific Power for Wind Turbines Tested at Wulf Test Field \(100k\)**](#)

Commentary

According to Scoraig Wind Electric's Hugh Piggott, such differences between what the manufacturers say you can expect and what you actually get are not out of the ordinary. In fact, he says, it's fairly typical for small wind turbines.

It's not typical in big turbines. Many if not most wind turbines in the medium-size class (100-1,500 kW) not only meet their power curves, they exceed them--and with good reason. Buyers invest hundreds of thousands of dollars in each turbine and they expect results. (A 500 kW wind turbine will cost \$500,000.) They demand--and get--written guaranties that the turbines will do what their manufacturers say they will do. These guarantees are not empty promises, but legally-binding contracts backed by insurance or the manufacturer's assets. Consequently, manufacturers of the big turbines prefer a margin of safety and shoot to exceed their advertised power curve.

Consumers could demand the same from manufacturers of small wind turbines. It's certainly conceivable that manufacturers can build small wind turbines that will not only do what they say they'll do, but then some.

Equipment

Watt transducer: Ohio Semitronics PC8-002-01B, LRB 5000 Ohm resistor

Anemometer: calibrated and un-calibrated NRG Maximum #40

Logger: Second Wind Nomad with RAM card and 115 VAC power supply

Software: Second Wind Insite and Winsite
Batteries: 4 Trojan T105
Diversion controller: Pulse TC 60 with 60 A CB
Diversion load: Enermaxer 1440 W air heater (60 A x 30 VDC max.)
Protection devices: Trace 175 A power panel with 60 A CB for wind turbine
Source disconnect: drip proof 3 phase fused AC (BWC 850), drip proof fused DC (Aerogen, Marlec, Air).
Inverter (for AC instruments): Trace DR 1524
Visual monitoring: Tri-Metric Battery System Monitor
Wind turbines: BWC 850 with VCS, LVM Aerogen 6F, Marlec Rutland 910F, SWP Air 303 w/ 403 blades.
Towers: guyed 64 ft (nominal) NRG 4.5-inch diameter, guyed 45 ft (nominal NRG 3.5-inch diameter).
Tower conductors: 150 feet #8 AWG stranded copper (BWC 850), 190 ft #4 stranded copper (Aerogen, Marlec, Air).

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