FEATURES

Taming Your Wind Turbine

Power Perfected

Although you can buy off-the-shelf wind power generators these days, they tend to get bad reviews from users. The problem is that harnessing wind energy takes some "taming" of the downstream electronics. In this article, Alexander discusses his characterization project for a small wind turbine. This provides a guide for designing your own wind energy harvesting system.

By
Alexander Pozhitkov, PhD.

Harvesting wind energy in your backyard or on the roof of your house is a lucrative opportunity to save some money by using an alternative to energy from the grid. It may sound like a simple project, especially because you can buy a wind generator from Amazon with or without the electronics included. Interestingly, however, numerous critical reviews give such generators only 1 or 2 stars. There's a reason for such disappointment in small-scale wind generators. It's because harnessing wind energy is not a trivial thing. Figuratively speaking, one must "tame" the turbine and the downstream electronics to get maximum extraction of energy from the wind. Harvesting wind energy with a turbine is the subject of a complicated relationship between turbine load and energy extraction efficiency. If the load is too small, the turbine rotates too fast, resulting in a high aerodynamic drag. If the load is too high, the turbine rotates too slowly, and the wind energy is lost in wake currents.

Adding sophisticated electronics such as a maximum power point tracking (MPPT) charge controller may make things worse, if the MPPT is not done properly. It is much easier to track maximum power point for photovoltaics, where the I-V curve is monotonous and illumination changes relatively slowly. In contrast, with turbines the wind speed is usually variable, thus making MPPT prone to instability. Here I present a characterization project for a small turbine that was conducted at MidNite Solar (**Figure 1**). Readers may wish to use this report as a guide for their own wind energy harvesting.

FIGURE 1
The turbine was mounted on a mast attached to a wooden base placed in the truck bed. The anemometer was placed in front of the turbine. P. Hougardy, a member of the research team at MidNite Solar, is shown next to the truck.

FUNDAMENTALS

Wind carries energy in the moving mass of air. The energy delivered by the wind, like the energy of any other moving body, is:

$$\frac{mu^2}{2}$$

where *m* is mass and *u* is speed. As wind hits turbine blades covering area *A*, the mass of air coming through the blades per second is:

$$\rho \times A \times u$$

where *ρ* is air density. Specifically, in one second, the air extends into a cylinder of length *u* and base area *A*, with the volume of the cylinder *A*×*u*. Altogether, the amount of energy per second, or power delivered by the wind, is:

$$P_W = \frac{1}{2}\rho u^3 A$$

Apparently, the turbine can extract only a portion of wind energy through the rotation of blades, while the rest of the energy ends up as aerodynamic loss. Also, part of the extracted energy is lost in the stator windings as heat. The remainder is the usable energy delivered to the load, for example, batteries. **Figure 2** summarizes energy balance.

For a given wind speed, RPM of the turbine will correspond to the equilibrium achieved between the energy input, energy output and losses. The following equation relates wind energy to the total electric energy produced by the turbine:

$$P_{st} + P_o = \frac{1}{2}\rho u^3 A C_p$$

where C_p is the power coefficient. The power coefficient is determined empirically in a test that varies wind speed and turbine RPM through variable load. C_p is a curve with a maximum. At a low tip-speed ratio or TSR—the ratio between the tangential speed of the tip of a blade and the actual speed of the wind—the energy harvesting is inefficient because of the wake air currents. At a high TSR, the aerodynamic losses are increased due to drag (**Figure 3).** Note: C_p cannot exceed 0.59, the Betz Limit, which is the theoretical maximum efficiency for a wind turbine.

STEP1: SENSE YOUR TURBINE

The first step in taming is to learn the character of your turbine. Specifically, the power coefficient needs to be determined

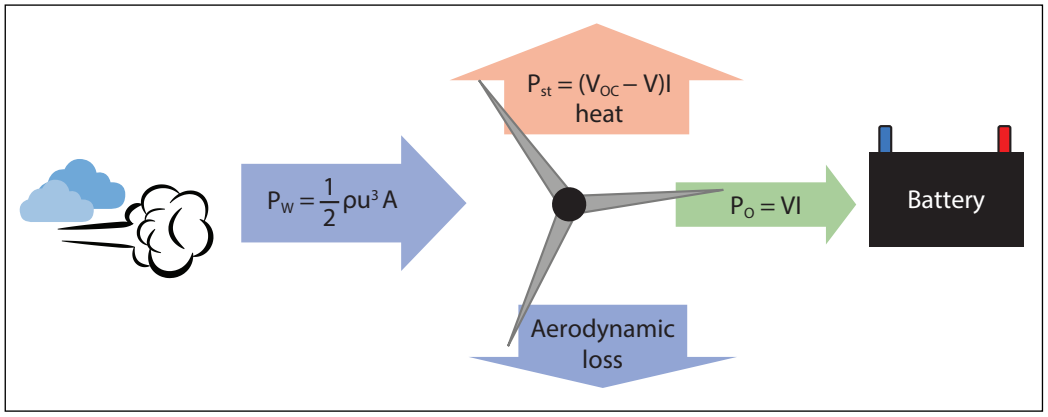

FIGURE 2
Wind energy balance. The power delivered by the wind (P_W) is dependent on the wind speed (u), rotor area (A) and air density (ρ). Aerodynamic loss is dependent on RPM and the shape of the blades. Stator heat loss (P_{st}) is dependent on the turbine operation voltage V, open circuit voltage V_{oc} and the current (I) flowing through the circuit. V_{oc} is directly proportional to RPM. P_o is the usable power delivered into the load.

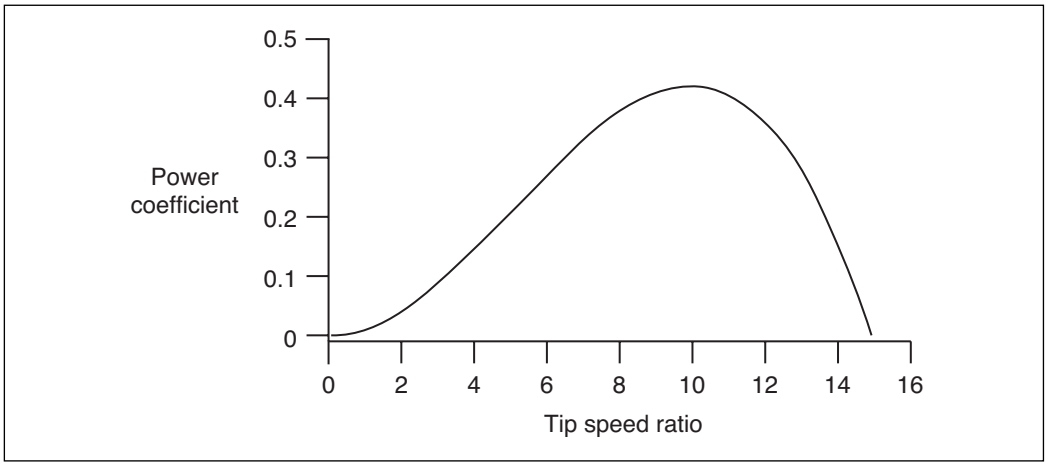

FIGURE 3
An example graph adopted from Manwell et al. [1]. The Tip Speed Ratio, TSR = 2πr(RPM/60)/u, where r is the rotor radius and u is the wind speed.

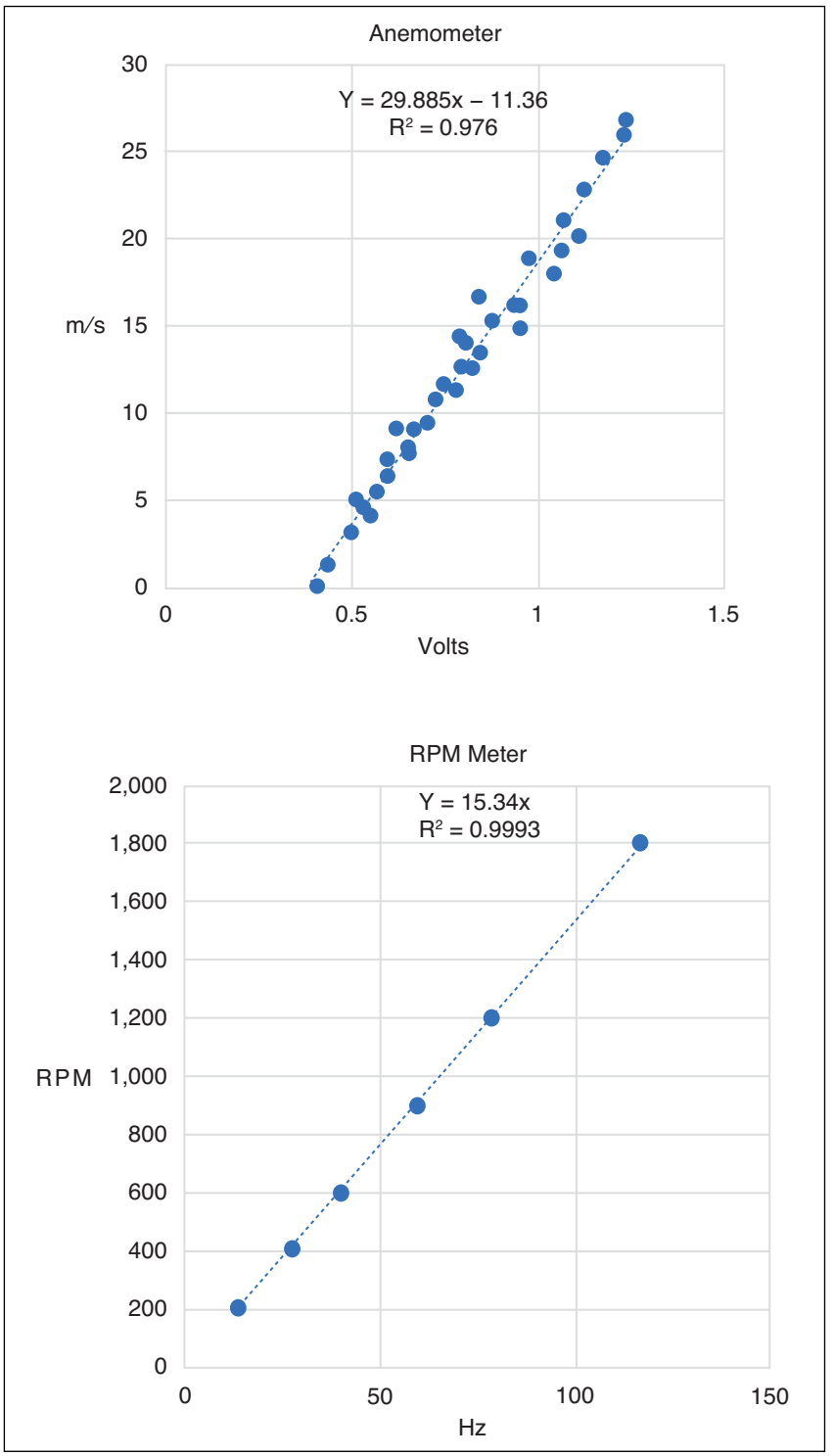

FIGURE 4
Calibration and reproducibility of the anemometer and the RPM meter

For detailed article references and additional resources go to:
www.circuitcellar.com/article-materials
Reference [1] as marked in the article can be found there

RESOURCES

BK Precision | www.bkprecision.com

MidNite Solar | www.midnitesolar.com

empirically. In practice, one must subject the turbine to variable wind speeds and loads while measuring the wind speed, RPM and power output. The turbine might be either installed in its final position so that the corresponding measurements are conducted over a period of several weeks, or it might be "flown" using a truck. We chose the latter (Figure 1).

The turbine was mounted on an approximately 3 m mast, which was firmly attached to a wooden base situated in the bed of our truck. Although the turbine is capable of rotating 360 degrees around its base, an elastic "leash" was attached to the back fin of the turbine to restrict its swivel angle to about 300 degrees. This was done to avoid twisting RPM sensor wires. A wind-speed sensor (anemometer) was placed in front of the turbine at the same height as the rotor axis.

To measure the turbine's RPM, we used an air core RF coil—42 µH 60 Ω—mounted behind the turbine rotor. The rotor magnets generated electricity not only in the turbine windings but also in the RPM meter coil. The frequency of the signal was directly proportional to the RPM. In fact, the signal coming out of the coil was quite fuzzy, given the highly non-homogeneous magnetic field of the magnets. A simple RC filter with a cut-off frequency at about 1 kHz was placed between the coil and a counter. Alternatively, a reed switch and a magnet could be used to measure RPM.

To measure wind speed, we used an analog three-cup anemometer. The anemometer was calibrated by driving our truck on a windless day at various speeds. As you can see from **Figure 4**, both the anemometer and the RPM meter showed high reproducibility and exceptional linearity.

STEP 2: SPINNING WITHOUT LOAD

Along with the aerodynamic characteristics of the turbine, its electrical properties are equally critical. Specifically, the open circuit voltage V_{oc} and windings resistance determine the power yield and loss, respectively. According to Faraday's law of induction, the electromotive force (measured by V_{oc}) is proportional to the rate of the magnetic flux change. Therefore, we would expect V_{oc} to be proportional to RPM. This is indeed the case.

We characterized two aerodynamically identical turbines differing only by the stator windings, and observed the expected linear relationship (**Figure 5**). In our experiments, we used a special stand, allowing the precise control of RPM. However the stand is not

necessary. Given the RPM meter, V_{oc} can be measured when the turbine is driven by wind or "flown" on a truck.

STEP 3: LOAD CHALLENGE

The last and the most critical step in taming the turbine is to investigate its behavior under load. In our experiments, we used a 300 W electronic load from BK Precision. The load was set to a constant voltage mode. During the test, the truck was moving at a constant speed of 15 mph, and the load was set to 5, 10, 15, …, 90 V. After completion of the series, the truck speed was increased. We characterized our turbines up to 35 mph wind speed. The recorded data constituted voltage, current, wind speed and RPM.

There are many possible ways of recording the data simultaneously. In our test, we recorded short video clips of displays of the measuring equipment seen in the same frame. After "flying" the turbine, we transcribed the video clips into actual numbers back at the base.

To make sense out of these numbers, let us consider the following measurement example: Voltage on load = 19.99 V; Current = 4.488 A; Frequency = 61.1 Hz; Anemometer = 0.7163 V. Using the calibration lines in Figure 4, we convert frequency and anemometer output into 895.99 RPM and 10.05 m/s, respectively. We calculate the total power carried by wind at that speed P_w = 460.36 W. That's a lot of watts! Knowing the RPM and the calibration line, we calculate V_{oc} = 39.76 V. Next, we calculate the power coefficient by dividing the total power generated by the turbine (the product of current and the open circuit voltage) by the total power carried by wind, C_p = 0.39. Finally, from the wind speed, rotor radius and RPM, we obtain TSR = 4.51. After collecting many C_p – TSR pairs, we plot the power coefficient curve.

At MidNite Solar we experimented with two turbines that were aerodynamically identical

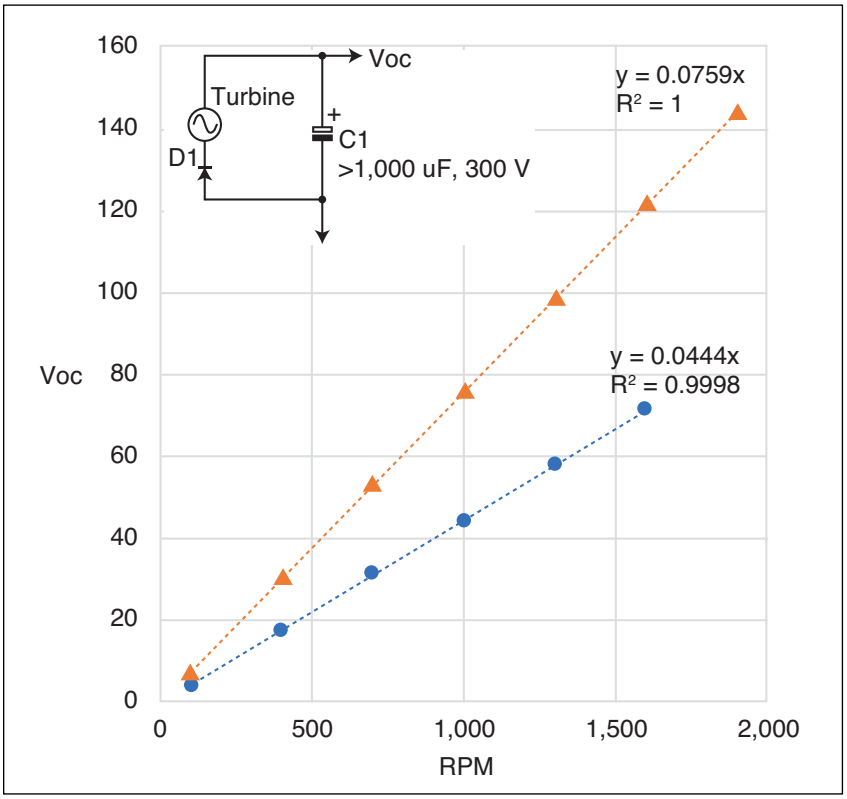

FIGURE 5

Dependency of V_{oc} on RPM. Two different stators were tested. The number of turns in one stator (orange triangles) is about twice than that of the other stator (blue circles).

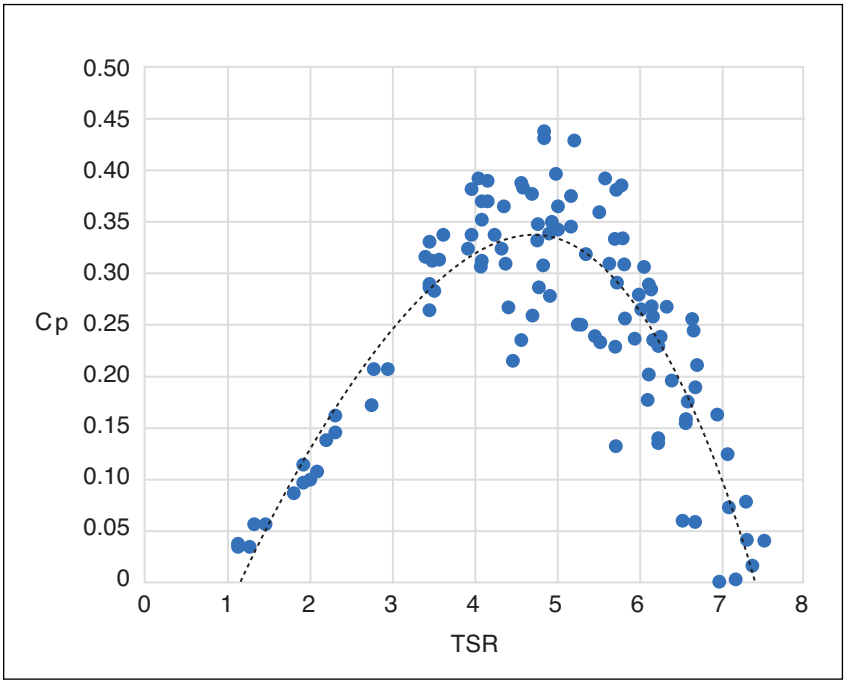

FIGURE 6

Experimental determination of the power coefficient (C_p). Max of the power coefficient is at C_p=0.35, which means that about 35% of the wind energy is extracted.

ABOUT THE AUTHOR

Dr. Alexander Pozhitkov has an MSc degree in Chemistry and a PhD in Genetics from Albertus Magnus University in Cologne, Germany. His expertise is interdisciplinary research involving molecular biology, physical chemistry, software, and electrical engineering. Alex has worked in academia (University of Washington and Planck Institute) and in the private sector (MidNite Solar). Currently, he is a researcher at the City of Hope medical center in Los Angeles CA.

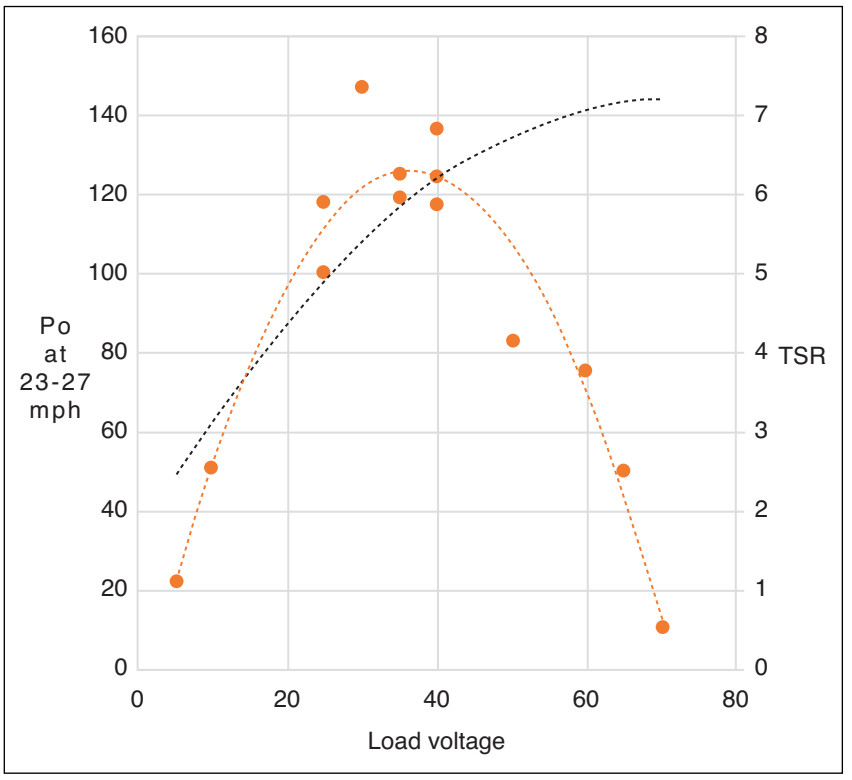

FIGURE 7
Turbine power output versus load voltage at 23-27 mph wind (shown in orange). TSR is shown in black.

but had different windings. It's important to understand that the power coefficient does not depend on the stator windings, because C_p solely reflects upon aerodynamics. With that in mind, we combined the results of the two experiments. The power coefficient curve obtained in our experiments resembles the theoretical one (**Figure 6**) quite well. Apparently, the maximum energy extraction efficiency is 35%, which occurs for a TSR range of 4-6.

STEP 4: OPTIMAL OPERATION

Once the turbine has been characterized, we can determine the optimal load required to provide maximum power extraction. It all depends on the expected wind speed in the location where the turbine will be working. Let us assume that at our location the wind speed is often about 11 m/s (25 mph,) and this is the condition in which we expect some useful power from our turbine. Let us take a slice of the data for wind speeds 23-27 mph from the previous step, and plot the usable power output, P_o, which is the product of the current and the voltage on the load. In this analysis, the stator windings matter. Here we'll show the plot for one specific stator out of the two we characterized. As you can see, the best power output occurs at about 35 V, when TSR reaches approximately 5.7, consistent with the earlier C_p measurements (**Figure 7**). Note that at a different wind speed, a TSR of 4-6 will be attained at a different voltage!

When the turbine is well characterized, two production options are possible. Option one—the simpler of the two—is to load the turbine, expecting a fixed range of voltages and an average wind speed. For example, our turbine could be loaded with a charge controller maintaining input voltage at 30 V to 40 V and assuming average wind speed of 25 mph. Option two is to record the C_p curve into an intelligent charge controller, which is equipped with an input for an anemometer and is capable of determining the turbine's RPM—for example, from the AC frequency. The controller would adjust the load on the turbine such that the TSR is at the maximum C_p.

Regardless of the option chosen, the final arrangement for using a turbine to charge batteries is shown in **Figure 8**. AC produced by the turbine is rectified, supplied to a charge controller followed by a diversion load and terminated at the battery. The diversion load is a microcontroller-driven PWM resistive load, which serves a dual purpose. First, the diversion load protects the battery from overcharging. Second, it keeps the turbine loaded, thus preventing the rotor from reaching excessive RPM.

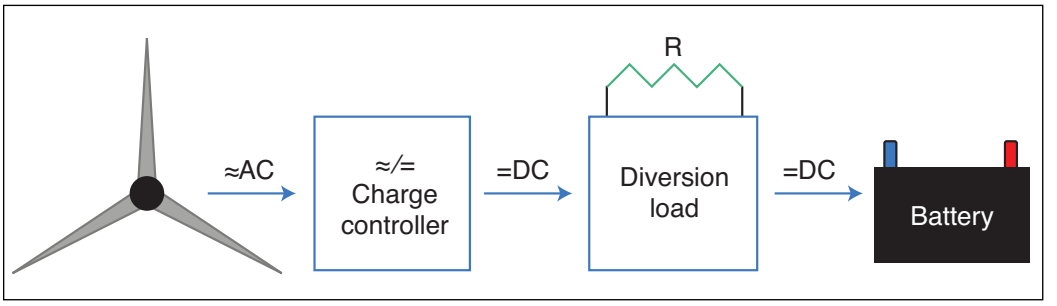

FIGURE 8
Final arrangement for the turbine in production. It is important to place a diversion load to prevent battery overcharge but keep turbine loaded.