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Development and Testing of Commercial Prototype Wind-Electric Battery Charging Station

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DEVELOPMENT AND TESTING OF COMMERCIAL PROTOTYPE WIND-ELECTRIC BATTERY CHARGING STATION

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Abstract

The technical aspects of charging 12-volt (V) batteries with a small permanent magnet wind-turbine generator suggested that a special battery-charging station be developed. Scientists at the National Renewable Energy Laboratory (NREL) conducted research on several possible configurations of wind-electric battery-charging stations. Based on preliminary modeling and test results, the optimal system for this application was the one with individual charge controllers.

This paper presents the development efforts and test results of a commercial prototype wind-electric battery-charging station designed and manufactured by Ascension Technology, a Division of Applied Power Corporation (APC). The system, which is powered by a 3-kilowatt (kW) wind turbine, was tested at the National Wind Technology Center (NWTC). The paper discusses control strategies to improve system performance, and includes recommendations for system integrators based on the testing experience accumulated at the NWTC.

Introduction

In 1998, we successfully completed Phase I of the Wind-Electric Battery-Charging Station (WBCS) Development Project. The tests were conducted at NREL, and the results were encouraging. Some of the modeling and preliminary testing data of Phase I, along with the economic aspects of WBSCs, were presented in another report [1]. Based on Phase I results, the system with individual charge controllers was selected as the most promising one in terms of meeting the system's operational and performance objectives. Phase II of the current project was launched in 1999, soon after the completion of Phase I. NREL granted a subcontract to Ascension Technology to design and fabricate a commercial prototype battery-charging station with individual charge controllers.

This paper is focused mainly on Phase II activities, including system tests developed by Ascension Technology. The system was tested at NWTC during the fall and winter of 1999.

Small Wind Turbines in Battery Charging Application

The performance limitations of permanent magnet wind turbine generators in battery-charging applications are caused by the poor match of the rotor, generator, and load characteristics over most of the operating wind speed range. Several different methods for improving energy capture from wind turbines in this application have been analyzed in other reports [1-3]. In one of the methods, we placed an optimizing direct current (DC)/DC voltage converter between the rectifier and batteries. We can control the current output of the DC/DC converter, which allows us to control the power going to the batteries.

Battery-charging systems are very important in developing countries where rural families cannot afford a solar-battery home system or other electricity options. However, they can afford to own a battery and can pay for it to be charged on a regular basis. Because the typical households that use these batteries are located far from the grid, small wind battery-charging stations can be a cost-competitive option. However, the technical aspects of charging numerous 12-V batteries with a small permanent magnet alternator wind turbine suggest that a special battery-charging station needs to be developed.

NREL conducted research on two different types of wind battery-charging stations: a system that uses one charge controller for the entire DC bus and charges batteries in parallel strings of four batteries each; and one that uses individual charge controllers for each battery. A 10-kW Bergey Excel wind turbine system was tested at the NWTC in a battery-charging station application. Testing revealed certain operational limitations for this application [1]. After that, we developed the "proof-of-concept" system with individual charge controllers and tested it using the dynamometer set-up at the NWTC [1]. We carried out a comparative economic analysis of both system configurations based on steady-state modeling. The analysis demonstrated the superiority of the system with individual charge-controllers over the system with a single charge controller for all batteries. This performance improvement comes at higher system capital cost; however, the cost per charged battery of the system with the individual charge controllers is lower because of better performance characteristics.

Objective

The main purpose of this stage of the project was to develop a commercial battery-charging station with individual charge controllers (DC/DC converters) that are capable of both improving wind turbine performance and providing favorable charging conditions for batteries.

Selection of Converter Configuration

Various options for DC/DC converters to maximize energy capture from wind turbines in battery-charging applications are presented in other reports [3]. The theory of the operation of variable-speed wind turbines with permanent magnet alternators is illustrated in Figure 1. Maximum power from the

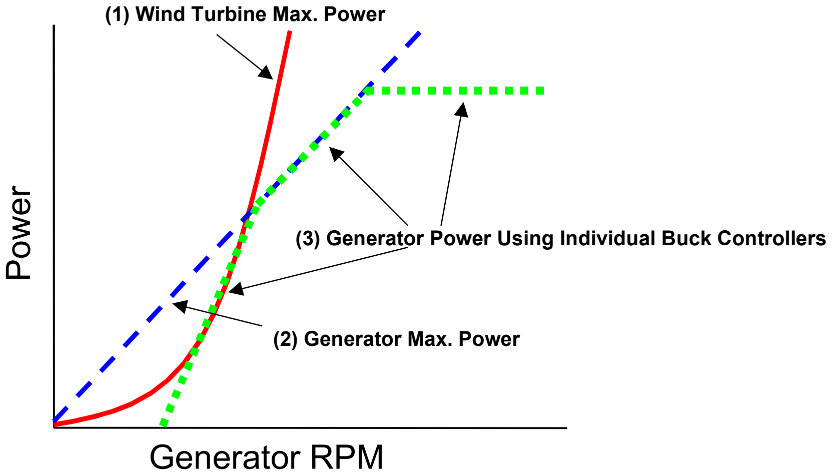

Figure 1. Operation of Buck converter with variable-speed wind turbine

wind turbine is a cubic function of revolutions per minutes (RPM) (curve 1). The permanent magnet alternator is capable of delivering a certain amount of power that is a linear function of RPM (curve 2). To make a system operate at maximum power, power to the load should be controlled in such a manner that the generator power curve matches the wind rotor maximum power curve. This can be achieved only by using a buck-boost converter with series alternating current (AC) capacitors. However, this option appears to be too costly for the given application. The buck converter configuration minimizes the cost of charge controllers and allows us to meet the system's operational requirements. With buck converters, the wind turbine will be able operate along the power curve (3) shown in Figure 1. The operation along curve 3 gives an acceptable approximation of wind rotor maximum power for lower wind speeds and alternator maximum power for higher wind speeds.

The buck-converter-based charge controller that meets the above characteristics was developed by Ascension Technology. The unit is called BCS-1 (BCS stands for Battery Charging Station).

BCS-1 Battery-Charging Station Unit

The BCS-1 is a 200-watt (W) power converter primarily designed to charge 12-V batteries. It has a three-phase full bridge diode rectifier to receive AC power and convert the AC power to DC. It has a DC/DC buck converter operating in current program mode control, which controls the output voltage and current to the battery. BCS-1 is a microprocessor-controlled device that controls the power level at which the converter operates. It has a voltage trim adjustment that can be used to set the maximum output voltage of the unit from 0.0 to 16.0 V DC. It also has a current trim adjustment that can be used to set the maximum output current of the unit from 0.0 to 14.0 amps DC. The unit was primarily designed to operate from the three-phase AC output of a wind turbine.

Multiple BCS-1 units may be connected to a single power source to build battery-charging stations of any size, limited only by the power and energy availability of the power source. BCS-1 units may be co-located or distributed, as long as three-phase power is provided from the power source.

Input voltage to the BCS-1 is 0–64 volts AC, 0–120 Hz. Versions may be provided for DC or single-phase operation, but a reduced input voltage range or output capability may be required.

Input and output specifications of the BCS-1 battery-charging unit are given in Table1.

Table 1. BCS-1 Specifications

Input AC voltage (3-phase)	0–64 VAC
Input AC frequency	0–125 Hz
Maximum output DC (battery) voltage, adjustable	0–16 VDC
Maximum output DC current, adjustable	0–14 A
Maximum output power	224 W
Efficiency	88%

The BCS-1 design also provides the following protective features:

- Reverse battery protection
- Output current limiting, short-circuit and normal operation
- Internal thermal limiting
- Microprocessor controlled Safe Operating Area (SOA) protection
- Amp-hour counting

Possible BCS-1 power sources:

- Wind turbines
- Hydro-generators
- Fuel cells
- Photovoltaics (PV)
- Diesel or gas turbine generators
- Utility power (single- or three-phase)

Possible applications:

- Village electrification, battery charging in village homes
- Battery recharge stations
- Standalone battery charging
- Direct connection to provide regulated power to DC loads

An important design element of the BCS-1 is its ability to share power with other BCS-1 units connected to the same power source. Each unit is capable of controlling its output current in 0.1-amp increments from 0.0 to 14.0 amps. The control function that determines the output current does so in a way that operates the power source near its maximum power point. The exact maximum power point is not determined, nor is total power ever measured by the system, but a priori information about the power source is used to operate close to the maximum power point.

One important characteristic of a constant-voltage battery charger is its ability to control the charge current during finish or taper charging. During normal operation, when the battery is still undercharged, the BCS-1 will control the current going to the battery in such a way that the system operates near it maximum power point. However, when the battery is nearly fully charged, the BCS-1 will immediately enter a voltage-regulation mode. Battery charging will stop when a preset number of amp-hours have been charged into the battery or when the charging current drops far and fast enough while voltage regulation is maintained.

Test Setup

Sixteen BCS-1 units were tested with 3-kW World Power wind turbine at the NWTC (see Figures 2 and 3). The three-phase AC transformer (1:15) is used to bring the turbine voltage down to the range required by BCS-1 specifications. Figure 4 shows a more detailed electrical diagram of the tested configuration. The AC transformer size and transformation ratio may vary depending on turbine power and voltage ratings. Each charging unit consists of a three-phase passive rectifier. The MOSFET transistor controls the DC current, and thus controls the DC power to the battery.

The test setup was equipped with a Labview-based data acquisition system. We monitored the following system parameters:

- Wind speed
- Generator frequency
- AC voltage and total AC current
- AC currents to four individual BCS-1 units
- Charge currents and voltages for four individual BCS-1 units

We calculated the following parameters based on measurement results: total power to all units, power to four individual units; DC power and Ah to four individual batteries; and BCS-1 efficiency. The resistive load bank was used to discharge the batteries.

Figure 2: BCS-1 units

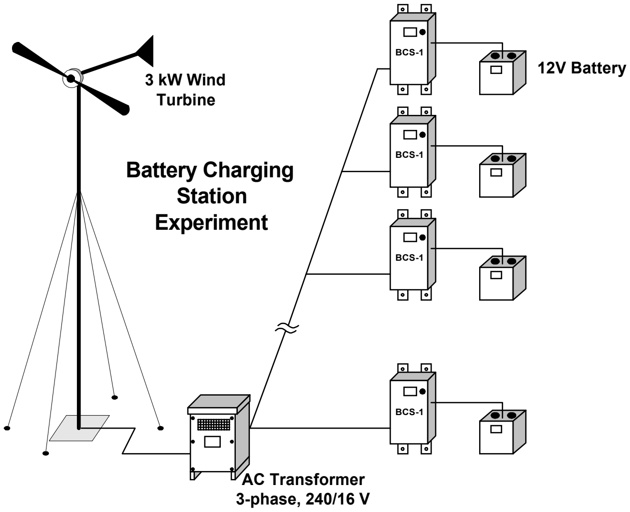

Figure 3. Battery-charging station experiment

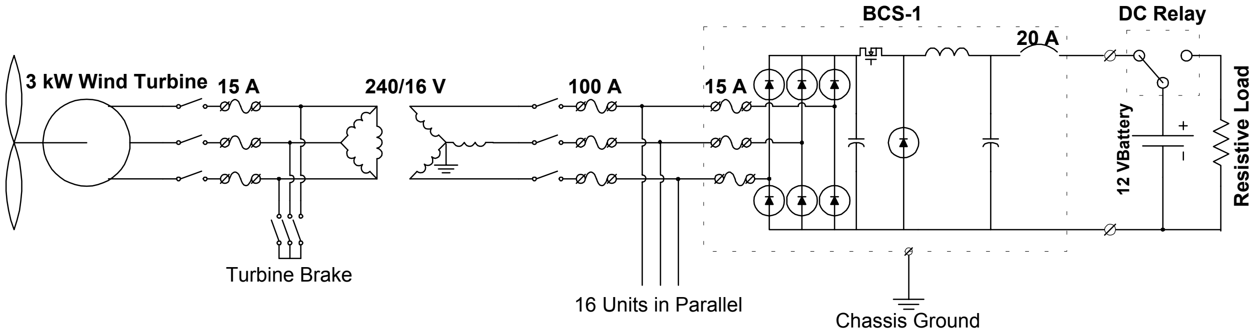

Figure 4. Test setup

Test Execution and Results

The BCS-1 battery charging units, powered by 3-kW World Power wind turbines, were tested at the NWTC from September–December 1999. The measurements were performed during the testing to estimate the BCS-1-based battery-charging station performance under real wind conditions. Test results for the beginning of the charging process, when the batteries are at a low state of charge and able to accept high currents, are shown in Figures 5 and 6. The AC power to all 16 BCS-1 units is increasing with alternator frequency (Figure 5a). At about 100 Hz, each of the chargers reached the maximum output current of 14 amps (about 220 W per unit), so no further increase in power was possible. Above 100 Hz, the power stayed nearly constant at about 3.4 kW. The power output to each of the four monitored units was nearly equal (Figure 5b), indicating that they are able to share power with each other and with the other 12 BCS-1 units, according to design specifications. AC voltage and the total AC current to all 16 units are shown in Figures 5c and 5d, respectively.

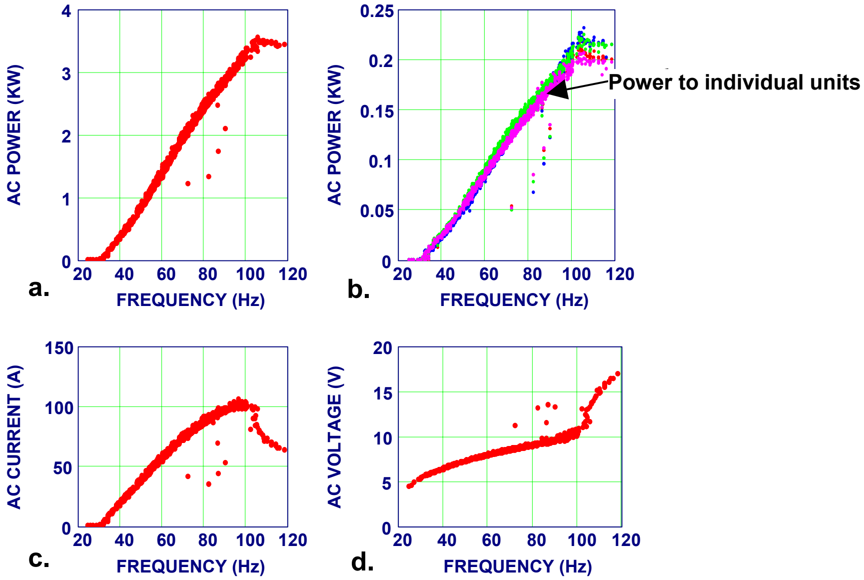

Figure 5. Test results

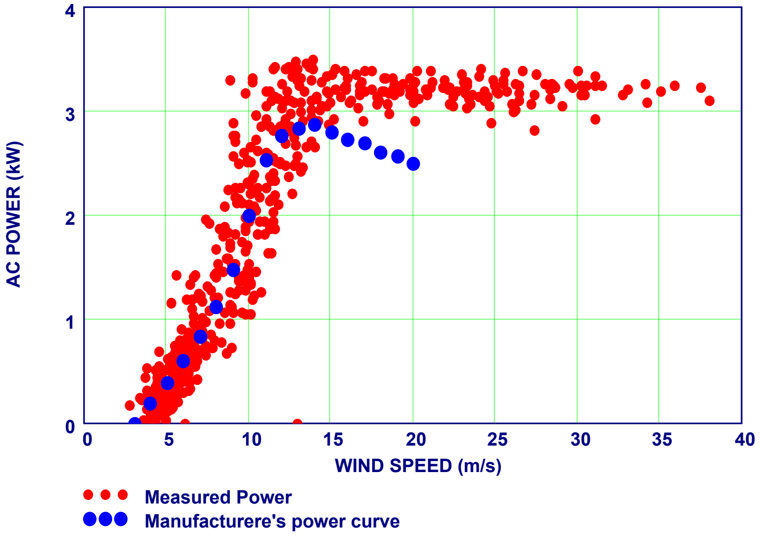

Figure 6. Power Curve

System power as a function of wind speed is shown in Figure 6. The measured power is compared to the published power curve for the World Power 3-kW wind turbine, adjusted for the elevation at the NWTC test site. As seen in Figure 6, the power output of the wind turbine increases with the wind speed until it reaches 3.4 kW at about 12–13 meters per second (m/s). For higher wind speeds (up to 35–40 m/s), the power is nearly constant, with slight a decrease when some units went into voltage-regulation mode. The power curve shown in the figure demonstrates system's capability for stable operation under a wide range of operational wind speeds.

Figure 7 shows the system performance at the end of the charging process. The power output of the wind turbine (Figure 7e) decreased gradually with time, despite high wind speeds (Figure 7a), because the batteries are getting closer to a full state of charge. The alternator starts accelerating, so the frequency and voltage are increasing (Figure 7b and c).

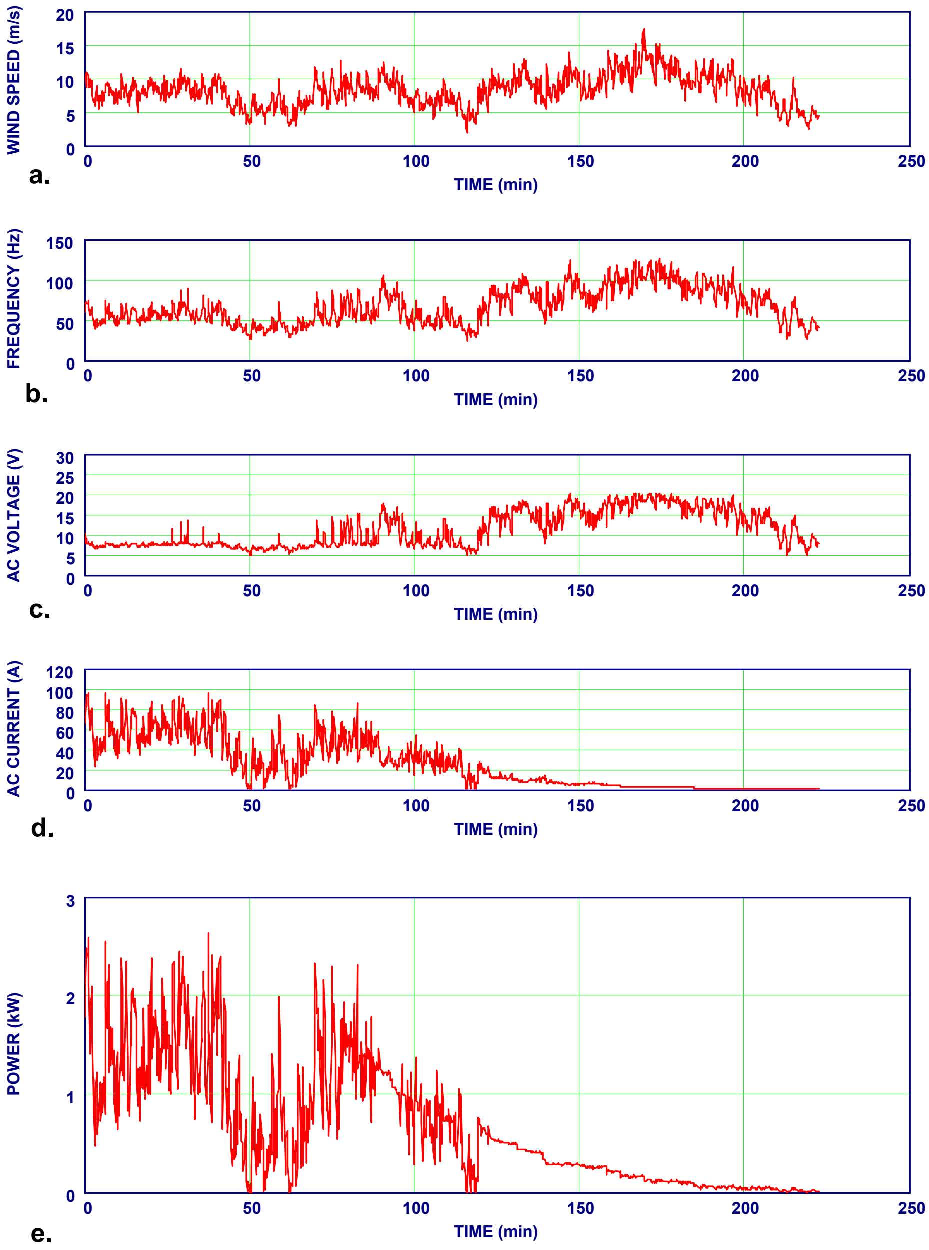

Figure 7. Finish charge profile

Figure 8 gives a closer look at single-battery conditions during the finish charge profile. The BCS-1 unit entered voltage-regulation mode after the battery voltage reached a preset value of 14.8 V. At that point, the BCS-1 started limiting the battery current to keep the voltage at the preset level. Battery charging stopped when a preset number of amp-hours had been charged into battery.

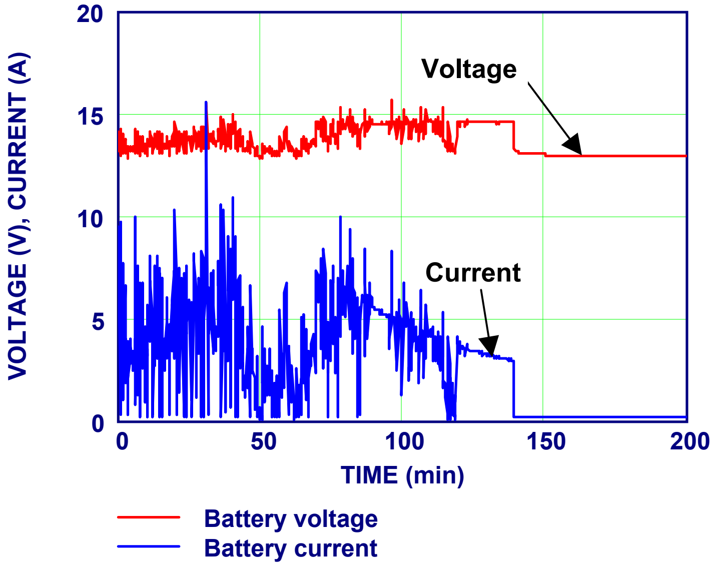

Figure 8. Battery finish charge profile

Optimum Number OF BCS-1 Chargers

The capital cost of a wind-electric battery-charging station is a combination of the capital costs for its individual components: wind turbines and battery-charging units. If the station operator owns the batteries, then that cost should be added to the system capital cost as well. The optimum number of chargers that can be used for a given station depends on 1) the wind resource, 2) wind turbine cost and the number of wind turbines in the station, and 3) a single BCS-1's capital cost

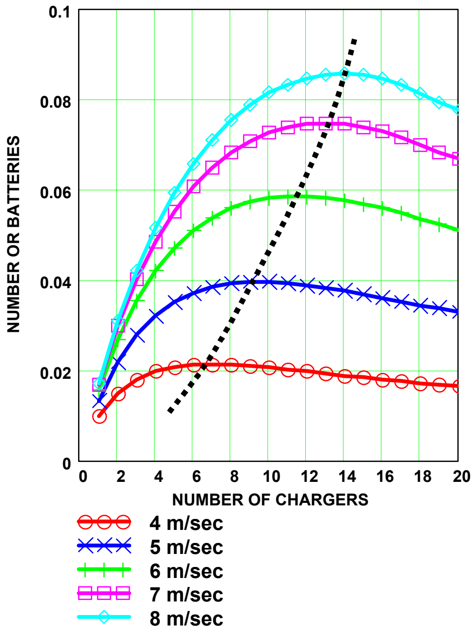

Figure 9. Optimum number of chargers

As an example, presented here is a site-specific analysis for a system that consists of one 3-kW World Power wind turbine. The analysis was done using the Weibull wind speed probability density function (Weibull shape parameter K=2) and a wind turbine power curve (Figure 6). The optimum number of chargers can be determined by dividing the number of batteries charged per month by the system capital cost. The result gives an idea of the number of batteries charged per month per dollar of capital cost (Figure 9) for different annual average wind speeds. We used a capital cost of $300 per

BCS-1 charger in the calculations. The optimum number of chargers is higher for a site with higher wind speed. For example, the optimum number of chargers for a site of 5 m/s average annual wind speed is about 8–10. However, for a site with a higher wind speed of 8 m/s, the optimum number of charges is 14. Figure 10 shows the average number of batteries that can be charged by the system as a function of annual average wind speed. A similar analysis can be done for different configurations.

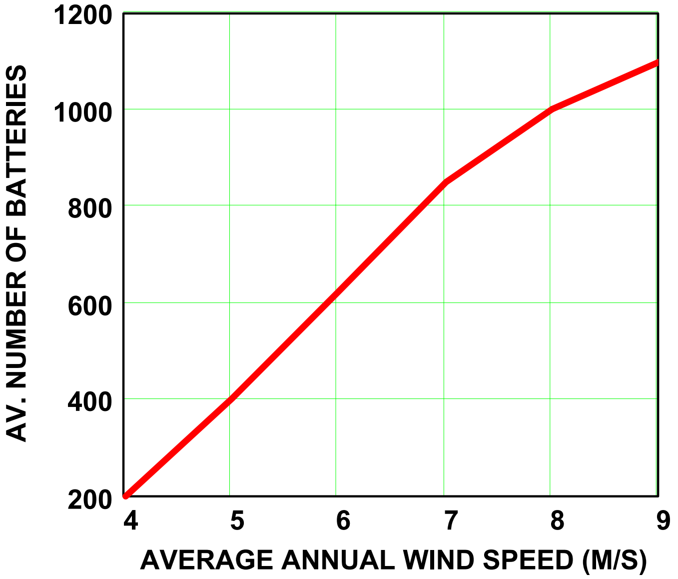

Figure 10: Average number of batteries charged per month

A preliminary comparative economic analysis of various battery-charging options was done in another report [1]. The wind-electric battery-charging station with the BCS-1 charge controllers offers a higher capital cost compared to existing wind-electric battery-charging technologies. However, the cost per charged battery is lower because of better performance. According to preliminary economic analysis, the system with the BCS-1 controllers can offer \$0.25–\$0.27 per charged battery compared to \$0.36 and higher for a traditional system with a single controller. So, the BCS-1-based battery-charging stations can provide a service to a variety of income groups in developing countries.

Conclusions and Future Plans

A simple to operate and robust wind-electric battery-charging station has been developed and tested. The tested configuration can be used as a stand-alone station or as part of an existing wind-diesel hybrid power system.

In the future, we plan to conduct further field testing and detailed studies for the deployment of pilot projects in developing countries.

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