A Hybrid Photovoltaic-Wind Power System for the National Data Buoy Center's Coastal Marine Automated Network

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***Abstract*-The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) operates the Marine Observation Network (MON) for NOAA's National Weather Service (NWS). The MON is a network of land and buoy-based automated platforms that collect and report meteorological and oceanographic measurements and transmit these data in near real-time through the NOAA Geostationary Operating Environmental Satellite (GOES) system. These platforms are traditionally powered by rechargeable batteries that are recharged by photovoltaic panels. The NDBC MON has platforms throughout the coastal United States including Alaska and Hawaii, and some deep ocean areas of the United States. Because of the variety of environments to which these platforms are subjected, traditional photovoltaic power systems have been inadequate in some locations, particularly extreme northern latitudes, where little or no sunlight may be available for charging a photovoltaic power system in winter months. Locations which typically have poor solar charging in winter months often have relatively high prevailing winds. This paper describes the design and testing of a hybrid photovoltaic-wind rechargeable battery power system that employs small, inexpensive wind generators to supplement battery charging on platforms in those locations.**

I. INTRODUCTION

The Marine Observation Network (MON) operated by the National Data Buoy Center (NDBC) in support of National Weather Service (NWS) requirements has experienced substantial growth in the number, type, and frequency of environmental measurements collected. This growth has led to heavy demands on the photovoltaic-rechargeable battery power systems used on MON platforms. An expansion of the MON in northern latitudes, and especially in the Alaskan region, has put increased demand and stress on the MON power system. These same areas require more frequent observations because of the harsh conditions, and it is these conditions that can severely impact the operation of the photovoltaic power system. Platforms in northern latitudes have less available sunlight in winter months, which are the same periods that the measurements made by these platforms are most in demand. In addition, platforms in these locations experience much colder temperatures for longer periods of time, which can reduce output capacity of the power system batteries. These same areas have a relative abundance of winds during the same periods that solar power is at its minimum. Therefore, NDBC developed an experimental, hybrid photovoltaic-wind generator power system design to take advantage of the higher prevailing winds in northern latitudes and supplement the NDBC MON available power. This paper details the design and preliminary results of the first field deployment of this hybrid power system on an NDBC Coastal-Marine Automated Network (C-MAN) station.

II. NDBC POWER SYSTEM DESIGN

NDBC power system designs up to the present have incorporated silicon photovoltaic (PV) solar panels that use sunlight to recharge lead-acid or gel-cel rechargeable secondary batteries. A typical power system is shown in the block diagram in Fig. 1. The power system relies on sunlight to recharge the secondary batteries. When they are recharged and voltage reaches 15.2 volts, the solar panels are switched out of the circuit to prevent overcharging and gassing of batteries. In the absence of sunlight for prolonged periods of time, the secondary batteries can be depleted to the point where the output voltage falls below 11.7 volts, the minimum system requirements, especially during high-demand periods such as data acquisition and data transmission from NDBC platforms. When this occurs, either the system will fail to operate, or a bank of non-rechargeable primary batteries supplies power to recharge the secondary batteries as a backup for solar charging. Stations may or may not have primary batteries for backup, depending on typical solar insolation at a given location. In general, stations at latitudes below 50 degrees north will not have primary batteries for backup, and systems above latitude 50 degrees north will.

This design has been used successfully for many years on NDBC platforms, but recent increases in the number of stations north of 50 degrees north latitude, more sensors, new oceanographic measurement requirements, and increased reporting frequency of required measurements has put heavy demands on this NDBC power system design. In the extreme case of platforms in the Alaska region, sunlight may be available for only a few hours during the day and even when sunlight is available, the sun may be so low on the horizon that it passes through atmospheric haze, reducing efficiency of the solar panels. This puts a much greater demand on the backup primary batteries and can cause them to fail prematurely. It is during these same winter months when NDBC observations are most needed. In the northern latitudes, it is also during winter months that frequent high winds occur, with the Alaska region being an area with some of the highest sustained winds over long periods during winter. NDBC took advantage of commercially available low-cost wind generators used to charge batteries on private

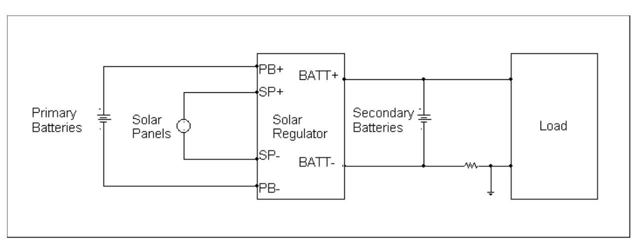

Fig. 1. Block diagram of present NDBC C-MAN power.

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Report Documentation Page

Form Approved
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1. REPORT DATE **01 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **A Hybrid Photovoltaic-Wind Power System for the National Data Buoy Centers Coastal Marine Automated Network**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Oceanic and Atmospheric Administration National Data Buoy Center 1100 Balch Blvd. Stennis Space Center, MS, 39529, USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002146. Oceans 2003 MTS/IEEE Conference, Held in San Diego, California on September 22-26, 2003. U.S. Government or Federal Purpose Rights License**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

sailing vessels and designed a hybrid power system that uses either solar power or wind power, whenever either is available, to recharge secondary batteries. In general, the two sources of energy complement each other.

Two wind generators were chosen for this system: the Rutland 913 and the Ampair Pacific 100. The Rutland generator has a very low wind threshold and can provide power at wind speeds as low as 2.5 meters/second. Power output of the Rutland can be as high as 250 Watts at wind speeds of 20 meters/second. The Ampair Pacific 100 has a slightly higher threshold of 3.5 meters/second and will produce as much as 85 Watts at 20 meters/second.

A block diagram of the NDBC hybrid power system design appears in Fig. 2. This system was designed to use two wind generators connected in parallel with the secondary battery stack. When solar charging is available, a solar regulator will route current to the secondary batteries if secondary battery voltage falls below the minimum system requirement of 11.7 volts. Batteries are recharged by solar power until reaching an operating voltage of 15.2 volts, at which time the solar panels are switched out of the circuit to avoid overcharging, gassing, or damage to secondary batteries. When wind speeds are sufficiently high to produce output current from either or both wind generators to the secondary batteries, the secondary batteries will be constantly charged by the wind generators until reaching 14.1 volts. At this voltage, a pulse width modulator regulator will switch the wind generator or solar output to a load that sinks excess current. The pulse width modulated regulator is temperature compensated, so the nominal 14.1 volt set point to dump excess charging current will vary slightly with temperature, increasing with colder temperatures and decreasing with higher temperatures around the set point.

The excess current sink consists of 6 parallel banks of three series 1 ohm, 50 Watt resistors, so the current sink is capable of dissipating as much as 900 Watts of excess power, which could occur during periods of sustained winds exceeding 20 meters per second with both wind generators producing output and including a safety factor. This is required during times of high sustained winds as the wind generator output can exceed what the secondary batteries require for a full charge. Wind generators have internal diode isolation to prevent secondary batteries discharging through the generators in the event of generator failure due to shorting. The pulse width modulator regulator prevents batteries from discharging through the excess current sink load by disconnecting the load when battery voltage falls below 14.1 volts. This design was chosen in order to test two wind generator types to determine their performance under the same set of conditions

Shunts were present in the return branches of the two wind generators, the solar panels, and the environmental sensing load circuits in order to allow connection of an

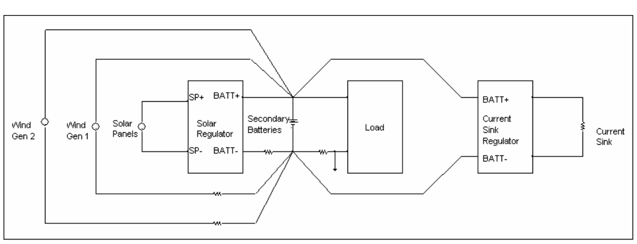

Fig. 2. Block diagram of hybrid solar-wind power system.

independent data logger to monitor wind generator input current and voltage, solar panel input current and voltage, and power consumption by sensor load. In addition, wind speed was sampled by the logger. All of these data were sampled at one Hertz by a data logger and stored to a 500 Megabyte compact flash storage device for later retrieval and analysis.

III. POWER SYSTEM INSTALLATION AND SITE DESCRIPTION

The experimental hybrid solar-wind generator power system was field tested at the NDBC C-MAN station located at Newport, Oregon (NWPO3). There were a number of reasons this site was selected for the field test. NWPO3 is situated at the water's edge of the Pacific Ocean, offering an unobstructed wind field from offshore. In addition, NWPO3 does not have primary batteries as a backup energy source. The station has drive-up access, unlike most other C-MAN sites that require a ship or helicopter for access. NWPO3 is also at relatively high latitude, approximately 45 degrees north, and could be expected to have prolonged periods without solar charging during winter months. Finally, Newport, Oregon is rated a class 6 area for wind power density during the winter season from December to February. A region's wind power density is determined by the American Wind Power Association to be rated on a scale of class 1 to class 7, with class 7 being the highest wind power density and class 1 the lowest. A class 6 area experiences 7 meters/second winds on average at a height of 10 meters, with an average wind power density of 400 Watts per cubic meter [1].

The two wind generators were mounted on a 12.2 meter Rohn tower at a height of approximately 9 meters to avoid any interference to the site anemometers, which are at a height of approximately 13 meters. The current sink of the hybrid power system was exposed to the air to allow maximum cooling of the power dissipating resistors when sustained high winds generate excess charging current. An installation drawing of the C-MAN Rohn tower with wind sensors and wind generators is shown in Fig. 3.

IV. DATA AND RESULTS

A. Performance in High Winds

The hybrid power system was installed at NWPO3 and made fully operational December 17, 2002. A return visit was conducted February 17, 2003. System current, voltage, and wind data sampled at 1 Hertz and stored to non-volatile memory was retrieved for analysis. Station meteorological data received at NDBC in real-time had been exhibiting occasional anomalies, and this prompted the visit in February to determine the cause of the anomalies. Upon testing and inspecting the wind generator system, it was discovered that one of the wind generators, the Rutland 913, was missing its blades. Despite the failed wind generator, all the system wiring was intact, and the second generator was properly functioning. Electrical tests conducted on the system showed that with the exception of the missing blades on one wind generator, the power system was intact and still operating properly. Most notably, the Ampair Pacific 100 wind generator was still providing charging to the power system. The meteorological data anomalies were determined to be caused by the data collection system, most likely the GOES transmitter.

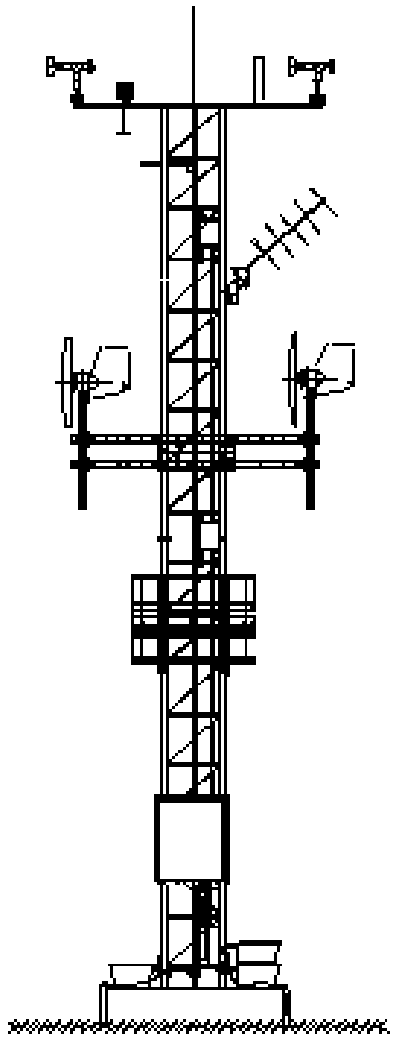

Fig. 3. C-MAN Rohn tower with wind generators.

It is believed that the cause of the failure of the Rutland wind generator blades was a strong winter storm that passed over the station on the morning of December 27. Wind gust data is one of the reported meteorological parameters at NDBC stations. Fig. 4 is a graph of the 5-second average wind gust measured at NWPO3 from the period December 18 to December 31, 2002. On December 27 at 1200 UTC, which is 4:00 am local time, a 5-second average wind gust of 23 meters/second was observed during the passage of the winter storm. This was also when the station began to first exhibit data anomalies. It is believed that a gust during this storm caused catastrophic failure to the Rutland 913.

It was reported [2] that testing of several wind generators to supplement residential power was being conducted at a residence at Cannon Beach, Oregon during the same period. Cannon Beach, Oregon is on the Pacific coast of Oregon approximately 100 miles to the north of Newport, Oregon. One of the generators under test at the Cannon Beach residence was a Rutland 913. The test conductor observed that the same winter storm passed through the Cannon Beach area the morning of December 27, with wind gusts in a range of 18 to 30 meters/second also recorded by meteorological instruments at the residence. These observations were consistent with those observed at NWPO3. The test

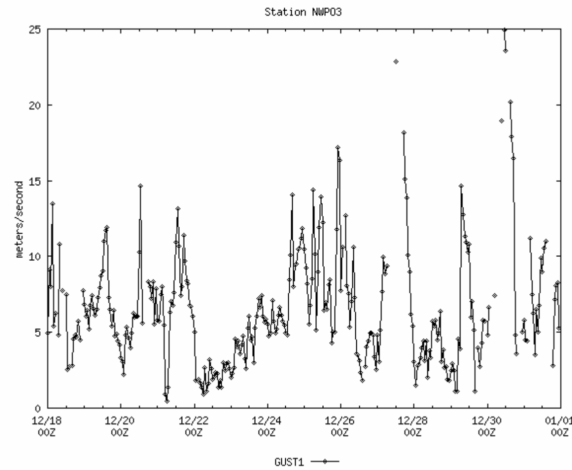

Fig. 4. Five-second average wind gusts from December 18 to December 31, 2002.

conductor reported that the blades of the Rutland 913 under test was destroyed by a wind gust of 28 meters/second during the storm.

B. Results of 1-Hertz Logger Data

The data retrieved from a 1-Hertz data logger that sampled all system voltages and currents from the wind generators and batteries was analyzed at NDBC. This analysis determined that nearly all the logged data had been corrupted with electrical noise. Although high frequency sampled data on each individual component of the hybrid power system was not available as a result of data corruption, other data was available, allowing a performance analysis of the system. The meteorological data collection system records a snapshot sample of system battery voltage, solar charging current, and hourly average wind speed, and transmits these data through the GOES each hour. These data were used to analyze wind generator system performance.

C. Results from Hourly GOES Data Reports

Under normal operating conditions and in the absence of any input power to batteries from either the solar panels or wind generators, a gradual decrease in system battery voltage is expected due to a continual power drain from the batteries by the meteorological data logger and sensors. This power drain is approximately 200 milliamperes, and, during transmission of data to the GOES, 3 ampere for approximately 1 minute added to the 200 milliamperes. This power consumption pattern repeats each hour. With no power input to recharge the batteries, the system battery voltage would gradually decrease over a period of several weeks until the system failed, since this station does not have primary batteries as a backup power source. If solar charging is occurring during the meteorological data acquisition time, this will be reflected by a non-zero solar charging current value reported with the data message through the GOES, and if system battery voltage is below a peak voltage of 12.7 volts DC, then the system battery voltage reported through the GOES will show an increase over that of the previous hour. Since there is no direct indication in these data of input power from wind generators, the system battery voltage increase can be attributed to solar charging only, or to a combination of solar charging and wind charging if the reported average wind speed exceeds the threshold speed of either of the two wind generators. Furthermore, in the absence of solar charging, which is indicated by zero solar charging current reported through the GOES, if the system battery voltage still shows an increase over the previous hour and average wind speed exceeds the threshold speed of either wind generator, one can conclude that the increase in battery voltage must be a result of charging from the wind generators.

Fig. 5 shows two graphs for the period December 18 through December 31, 2002. The upper graph in Fig. 5 is the reported solar charging current (IPCURR) overlaid with system battery voltage (BATT1) and the lower graph shows the average wind speed from anemometer number one (WSPD1) for the day and hour indicated on the x-axis. Times are in Universal Time, Coordinated (UTC). Since NWPO3 is on the west coast of the United States, local time is Pacific Standard Time during the period shown on the graph, so local time is UTC minus 8 hours.

From these graphs, one can see instances where power system charging occurred as a result of solar charging, a combination of solar and wind generator charging, and charging that can be clearly attributed to the wind generators alone. In the upper graph, solar charging is indicated by the lower curve of solar charging current as a function of date and time. The peaks of solar charging occur around 20:00 UTC, which is noon local time. Solar charging falls off to zero on this curve at 00:00 to 01:00 UTC or 4:00 to 5:00 pm local time, consistent with sunset. During night hours and when the indicated wind speed is below the threshold of the wind generators, the general trend of battery voltage decreases. This trend can be seen in the upper graph of the figure from December 22, 00:00 UTC until 16:00 UTC.

From December 22, 00:00 UTC until 16:00 UTC, there was no solar charging since it was night, and indicated wind speed was below the threshold required for either of the wind generators to begin producing power, so no charging was occurring from the wind generators. Since no power system charging was occurring from either source, the system battery voltage steadily decreased from 13 volts to 12.5 volts. System battery voltage increased slightly after 16:00 UTC when weak solar charging occurred during daylight hours, indicating an overcast day. After sunset on December 23, system battery voltage rapidly decayed to 12.5 volts, since no winds above the wind generator threshold occurred to produce output from the wind generators. At sunrise on December 24, strong solar charging occurred, raising system battery voltage to 13.5 volts from 12.5. This voltage increase is entirely attributable to solar charging since winds remained below the threshold speed for wind generator output. During daylight hours of December 25, moderately strong solar charging occurred while wind speed increased to above the threshold of both wind generators, producing a rapid rise in system battery voltage to about 13.5 volts. The more interesting behavior occurred after sunset local time December 26, which was about 00:00 UTC December 27. Wind speed increased rapidly from below the threshold speed of either wind generator to 20 meters/second over a period of four hours beginning after sunset December 26. System battery voltage rapidly increased from 12.6 volts to 13.6 volts over a two hour period. Since this happened after sunset, the increase in system voltage occurred as a result of charging current from the wind generators. This time is about the time that the leading edge of the winter storm arrived at the station, which explains the rapid increase in wind speed. During the 24-hour period from sunset December 26 until sunset December 27, the battery system voltage was maintained at or above 13 volts, despite the load on the system and no solar charging. The input charging current over this period can be attributed exclusively to the wind generators. This demonstrates that the power system can produce significant amounts of charging current. It is likely that during this period, significant amounts of excess charging current were diverted to the current sink, due to the high winds of the storm producing significantly more current than the power system batteries could absorb, but this cannot be confirmed due to the lack of data on this branch of the circuit.

Fig. 6 contains stacked time series plots of overlaid battery system voltage and solar charging current and a separate time series plot of wind speed for the month of January, 2003. Fig. 7 contains stacked time series plots for the period covering February 1 until the first service visit of the station on February 16, 2003.

Data from the month of January in Fig. 6 shows several periods where battery voltage increases are attributable solely to wind generator charging, specifically from January 11 through January 14, and again from January 24 through January 27. For the period February 1 to February 16 in Fig. 7, most of the power system charging was from solar, as wind speeds for that period were lower overall compared to December and January.

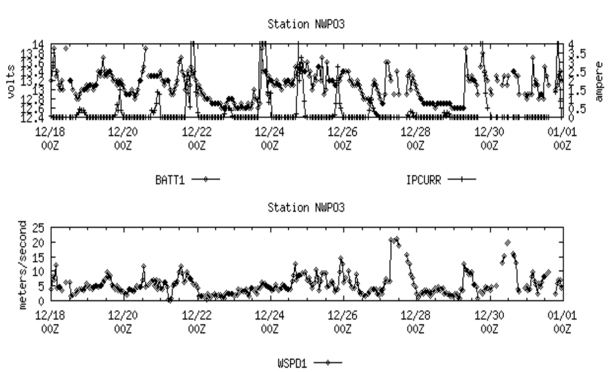

Fig. 5. Stacked time series plots of overlaid power system battery voltage and solar charging compared to wind speed.

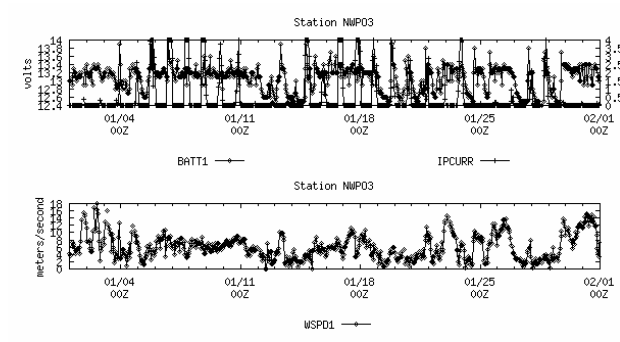

Fig. 6. Stacked time series plots of overlaid battery system voltage and solar charging current compared to wind speed month of January, 2003.

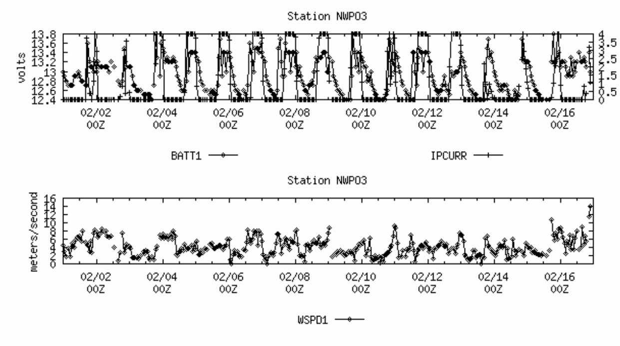

Fig. 7. Stacked time series plots of overlaid battery system voltage and solar charging current compared to wind speed month of February.

Fig. 8 is a comparison of the power system battery voltage for NWPO3 in winter 2001 to 2002 compared to winter 2002 to 2003. The overall battery voltage in the 2002 to 2003 winter months discharges less as a result of the wind generator supplementing solar charging. Since lead-acid and gel-cel batteries perform better when discharge cycles are shallow, supplementing solar charging with charging from wind generators is better for the overall health of the power system. In addition, with the wind generator system, batteries do not remain for long periods at low voltages when there is no solar charging. Average system battery voltage for the two periods was approximately the same, with the wind generator system insignificantly higher by 0.1 volts over the period.

V. CONCLUSION AND FUTURE WORK

Results of testing of a hybrid wind generator-solar charged battery power system on a NDBC C-MAN station has shown that wind generators can add significant charging capacity to stations where wind energy is available. One of two wind sensors tested is capable of surviving sustained gusts exceeding 25 meters/second. Battery charging and discharging cycles in winter months can be improved with wind generators supplementing power system charging.

NDBC is presently adapting the wind generator power system design for buoy applications. Some of the design challenges for this adaptation are placing wind generators sufficiently high off the surface of the ocean for adequate performance while preventing interference to anemometers and corrupting wind measurements from buoys. Another significant challenge for buoy applications is icing in frigid climates. The target region for the hybrid solar-wind generator power systems is the Alaska region. Although most wind generators are designed for frigid climates and remote use, superstructure icing in Alaskan waters is a major obstacle to overcome. For applications in frigid climates, NDBC will explore using the excess wind charging current diverted to the current sink as a source of heat to maintain battery temperature at more optimal levels. Another area of exploration will be using the heat from excess wind charging current to warm solar panels to reduce ice build-up. Finally, developing a reliable design that will perform over long periods in the harsh marine environment is critical to operational use on NDBC buoy platforms. Most small wind generators are designed for the marine environment and use in frigid climates and are used on private sailing vessels and as power for homes in remote regions of Alaska. The NDBC buoy application requires long periods of up to three years without maintenance in a marine environment, so these wind generators are expected to be applicable to buoy platforms.

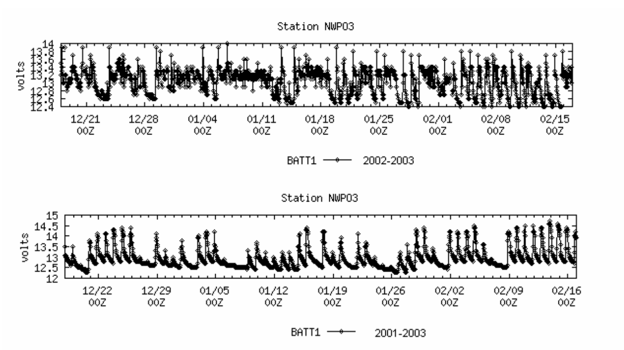

Fig. 8. System battery voltage time series plots for winter 2001-2002 and winter 2002-2003.

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[2] Unknown author. Ocean Solar Web page http://www.oceansolar.com/oceansolar/index.html.