Remote area wind energy harvesting for low-power autonomous sensors

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Abstract—A growing demand for deployment of autonomous sensors and sensor networks is leading to a subsequent increase in the demand for localized, independent energy harvesting capabilities for each node. In this paper, a method of remote area wind energy harvesting is presented, with a focus on an anemometer-based solution. By utilizing the motion of the anemometer shaft to turn a compact alternator, small amounts of power can be harvested from otherwise unavailable sources. Energy harvested is converted to battery potential via a pulsed buck-boost converter operating in discontinuous conduction mode (DCM). It is found that maintaining a constant input resistance at the input port of the converter biases the alternator to operate at its peak power point over a wide range of wind speeds. Results show that power harvesting capability using the discussed alternator and power converter solution are in the range of tens to hundreds of microwatts up to approximately one milliwatt. This power is passed to the central system batteries, providing a trickle-charge. As a result, sensor nodes incorporating this harvesting solution have an increased field lifetime, with little impact on anemometer measurement accuracy.

I. INTRODUCTION

There exists a demand for long-term deployable autonomous sensors over a wide variety of applications. In many cases, power is stored and managed locally, commonly in centralized battery banks or other small energy storage devices. Often, autonomous sensors are designed for outdoor weather and climate monitoring and require placement in areas that may not be easily accessible by maintenance teams to provide battery changes. In fact, power consumption is frequently cited as the primary limiting factor in the duration and performance of autonomous sensor networks [1-3]. For this reason, localized, remote-area power harvesting techniques have become an important amendment to sensors and sensor networks encompassing any number of independent nodes, each requiring an independent energy source.

To expand the duration of time each node can last in the field, alternative methods of remote power capture are under investigation. In this paper, a remote area sensor network which employs a local anemometer for wind speed measurement is considered. Due to the large amount of un-polled or sleep time available at the system anemometer and the nearly continuous motion of the cups, it is feasible to use the motion of the anemometer shaft to drive a small alternator. In turn, the alternator will provide small amounts of rectified and filtered DC power to the central system batteries, trickle-charging the main battery bank over extended periods of time.

Ideally, power must be captured and stored in an efficient manner, with relative power harvesting capability in the hundreds of microwatts range. Due to a low overall system average power consumption rate and the extended periods of time in which the system is in low-power mode, small amounts of power harvested during non-polling or sleep periods should be sufficient to provide a reasonable charge to the main battery bank. In general, it is necessary for the overhead power consumption of the harvesting electronics to be less than the available power for harvest, which varies as a function of wind speed. For this reason, a low power method of electronics control is employed to monitor relative wind speed. At speeds adequate to provide efficient harvesting, the control enables a pulse-based buck-boost converter in series with the generator output and main battery bank. Due to the ability of the system to monitor relative wind speeds and subsequently engage or disengage the charging power converter, a high overall efficiency is maintained at all times.

In the remainder of this paper, an approach to anemometer-based remote area power harvesting is presented and a method of alternator design and employment is discussed. The efficiency and power output of a buck-boost converter controlled to emulate an optimal resistance at its input port and transfer energy to the battery potential for charging is evaluated. The impact of the alternator and converter addition to the system is also evaluated and discussed, as is performance and efficiency of the system over a range of potential wind speeds.
II. POWER AVAILABILITY AND GENERATOR DESIGN

The stability and necessity for a properly designed alternative power management system depends largely in part on the maximum amount of wind power available at the cups of the anemometer. To calculate the theoretical power availability, we begin by using the standard, well known formula for the kinetic energy approximation of a moving system

\[ E = \frac{1}{2} m v^2 \quad [J], \quad (1) \]

where \( m \) is the total mass of air at the anemometer cup and \( v \) is instantaneous wind speed. Since

\[ m = \rho A v \Delta t \quad , \quad (2) \]

the kinetic energy approximation becomes

\[ E = \frac{1}{2} \rho A v^3 \Delta t \quad [J], \quad (3) \]

where \( \rho \) is air density, \( A \) is the single cup face area visible to the wind, and \( \Delta t \) is the period of time over which the calculation is performed. Knowing energy is a product of power and time, the kinetic energy can be converted into power as a function of air density, area, and wind speed, which yields

\[ P = \frac{1}{2} \rho A v^3 \quad [W]. \quad (4) \]

Using known values for air density and cup face area and an estimate of a reasonable wind velocity, the theoretical maximum amount of energy available at the cups of a typical anemometer for a wind velocity of 4.5 m/s (10 MPH) is

\[ P_{4.5\%} = \frac{1}{2} \left(1.225 \frac{kg}{m^3}\right) \left(0.00535 m^{-1}\right) \left(4.5 m/s\right)^3 \]

\[ P_{4.5\%} = 291.61 mW. \quad (5) \]

While this estimation is crude and fails to account for the efficiency of the turbine, the theoretical maximum amount of power available at the cups of the anemometer is sufficient to provide a reasonable amount available for capture. Therefore, it is reasonable to conclude that enough energy is available for capture, even after cumulative system harvesting and conversion efficiency is factored in. For the purposes of this paper, and indeed all wind energy investigations, an estimate of nominal wind speed is required to accurately predict the available wind energy in a local area [4]. Nominal daily wind speed peaks recorded in a sample remote area deployment environment are shown in Fig. 1 (courtesy of C. Seielstad, University of Montana).

A well designed vertical-axis turbine can theoretically capture up to the Betz limit of 33% of the total available power [5], assuming efficient operation is obtained in all working parts throughout the system. The Betz limit for a vertical-axis turbine is somewhat lower than the corresponding limit for a horizontal-axis system, primarily due to a drag-based, as opposed to lift-based, operation. The Betz limit for a well-designed horizontal-axis turbine is 59% [5, 6]. Practically, even well designed turbines operate below their maximum Betz limit [7]. Even if system operation for the vertical-axis system under consideration in this paper were achievable at a fraction of the Betz limit, the maximum reasonably obtainable power is roughly 23 mW. Realistically, a generator design for this application having zero cogging is expected to harvest roughly 2% of the available power after the Betz limit has been applied, or 460 \( \mu W \). This calculation forces an underestimation of generator, converter, and mechanical efficiencies, and realistic harvesting of greater or less than 460 \( \mu W \) is certainly possible, especially at varying wind speeds. Even these conservative estimates lead to a promising amount of available power, where wireless sensor nodes can be designed for operation with average power consumption in the 100 \( \mu W \) range [8].

Several generator designs were considered for use in this application, with the emphasis being on permanent magnet-based alternators. This preference is primarily due to the reduced shaft torque typical in brushless generator designs. For the system anemometer to continue to remain usable as a wind speed measurement tool, the overall load torque placed on the shaft of the measurement system should be minimal and easily correctable. Generator selection is based on several properties, including comparative power production, shaft torque requirements, rectifier necessity, and overall size and weight.

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Fig. 1: Nominal wind speed peaks in a typical deployment location over a period of 24 hours

Fig. 2: Rotor and stator for the axial-flux alternator
For this application, an axial-flux alternator was selected and designed. The design incorporates two axial plates, a stator and a rotor, each 3" in diameter. The stator houses two windings, each comprised of 1250 turns of 38 AWG armored polythermaleze copper wire, with a per-winding resistance of 180 Ω. The rotor houses eight 5/8" diameter neodymium magnets in an alternating pole configuration (see Fig. 2). Both axial plates are concentrically connected via a common ball bearing sleeve. To prevent alternator cogging, no magnetic field shaping techniques were employed. This results in an alternator with a somewhat reduced maximum overall efficiency, but with zero magnetic cogging at the rotor poles. In this application, zero cogging is of much higher importance than overall efficiency, as cogging leads to increased shaft torque at stall and contributes to wind speed measurement error. The alternator design presented in this paper fields a reasonable blend of both with minimal shortcomings.

III. HIGH EFFICIENCY POWER CONVERTER

Maintaining consistent operation at the peak power point of the axial-flux alternator is a requirement for maximum system efficiency. To avoid the overhead control losses associated with traditional peak power tracking techniques, a simple control design is used to maintain a constant resistance at the input port of the power converter [9]. This is an efficient solution so long as the optimal load resistance for peak output power of the alternator remains constant over a range of operating speeds. Experimental measurements for the alternator characteristics are shown in Fig. 3. The load resistance is stepped from 100 Ω to 10 kΩ and the alternator RPM is swept from 60 to 200, corresponding to wind speeds from 2.7 m/s to 8.9 m/s. It can be seen that over a greater than 10:1 range in output power, the optimal load resistance for maximum power remains constant at approximately 1 kΩ.

With the goal of emulating a constant resistance at the input port with minimal control circuitry, a buck-boost converter is used with DCM operation. In addition, the converter is operated in a pulsed mode to maintain resistor emulation while significantly decreasing the power loss of the controller. The overall diagram of the converter and control circuit is shown in Fig. 4, where a two-switch implementation of the buck-boost is feasible since the wind power source can be floating as shown. The switches are implemented using a MOSFET Q₁ and diode D₁, where the diode is used as opposed to a synchronous rectifier in order to reduce the control complexity and associated losses. A low frequency (LF) oscillator controls the pulse frequency, \( f_\text{lf} = 511 \text{ Hz} \), and percent time that the converter is active, \( k = 0.083 \). During the pulse time, the LF oscillator powers the high frequency (HF) oscillator, which drives the converter at a constant frequency, \( f_\text{hf} = 47 \text{ kHz} \) and constant on-time \( t_1 = 10.58 \text{ µs} \) (~50% duty cycle). The inductance is selected as \( L = 220 \text{ µH} \). The resulting emulated resistance is given by

\[
R_\text{emulated} = 2 \cdot L \cdot \frac{T_\text{hf}}{t_1^2} \cdot k = 1 \text{ kΩ}. \quad (6)
\]

All of the control circuitry is powered from the converter output voltage, at the battery. Additional details on the components used in the power converter are given in Table 1. Additional design details, efficiency analysis, and converter options are found in [9].

IV. EXPERIMENTAL RESULTS

In a joint cooperative effort between the University of Colorado and the University of Montana, a series of wireless weather monitoring sensors are under development to provide localized monitoring of conditions during and surrounding wildfires in remote areas [10]. The sensors are deployed in a net-configuration, with each node capable of passing information through various other nodes in a
self-arranging network. Each node is self-contained and incorporates all measurement equipment, communications services, data logging and transmission hardware, as well as onboard power management.

Each node is powered by a pair of centralized AA NiMH batteries operating at a nominal 2.8V and is scheduled to poll its local measurement devices four times per hour, with each polling period lasting approximately 60 seconds. For the remaining time, the central microcontroller is put into sleep mode and all external measurement devices are turned off. Without any extra power management, each node is capable of lasting approximately three to four weeks in the field. It is desired to leave the devices in the field for several weeks to months, which leads to the necessity of the power-harvesting system under discussion. We are also investigating adaptation of alternative sensor hardware to achieve average power consumption less than 30 μW [11], which could operate indefinitely (many years) using the proposed wind power harvesting system, even under light wind conditions.

It is imperative that the addition of any type of generator to the anemometer system have little measurable impact on the accuracy and precision of the anemometer wind speed measurements. To achieve this, the final generator should achieve zero or minimal magnetic cogging between rotor and stator and should require minimal shaft torque to induce rotor motion. A small amount of wind speed measurement error is expected due to the additional shaft torque requirement of an attached alternator. Large or non-linear measurement errors would pose a substantial problem and would require a lookup table-based or similar correction mechanism. Small linear errors, however, pose no substantial problem and a complex correction mechanism would be unnecessary. A well-designed generator should achieve a small, linear error in wind speed measurement.

Investigation of the effect of additional torque requirement added to the shaft of the anemometer, caused by installation of an axial-flux alternator, has shown that minimal wind speed measurement error is observed. At three test wind speeds, the error between speed measurements of the anemometer, both with and without the installed alternator, are found to be minimal and roughly linear. In each case, the error in measurement is found to be approximately 10% (Fig. 5). This error is within a reasonable range and is easily corrected off-line or in the sensor microcontroller.

The output of the alternator, and indeed in any alternating current system, changes polarity with every cycle. For this reason, a full-wave rectifier built from 350 mV schottky diodes is used, with a 220 μF filter capacitor at the output terminals of the rectifier. Rectified and filtered DC power output at a load resistance of 1 kΩ is found to be between 20 μW and 1.02 mW, with DC output voltages varying between approximately 0.15 V and 0.30 V, based primarily on wind speed. This result validates the potential power availability estimate mentioned previously.

A. Incorporation of DCM buck-boost converter

Having validated the power available at the output of the rectifier, the buck-boost converter is incorporated into the system to convert harvested power from primary rectifier voltages to charging-level potential, nominally set at 3.29 V. Experimentally, the power converter is successful at efficiently converting rectifier potential to battery potential, with minimal control losses of approximately 30 μW, drawn directly from the input power.

When connected in series between the rectifier and main batteries and tested over a range of potential wind speeds, conversion efficiency is found to be as high as 71.8%, including control losses (see Fig. 6). The converter
efficiency is greater than 50% down to 80 μW output power with 355 mV input. The converter output power is shown in Fig. 7, with a maximum of 651 μW available at high wind speeds. At lower, more common wind speeds, power output of 5 – 80 μW is obtained. As expected, power output increases nonlinearly with wind speed, corresponding to increased energy availability at the anemometer and reduced impact of the power loss in the converter control circuitry. Addition of this harvesting system will allow each sensor node to remain in the field, uninterrupted, for approximately three to four times longer than present deployments (two to four months) at low nominal wind speeds, typical of the deployment environment. Larger nominal wind gusts would allow for an even longer field-life of each node. Additionally, the power delivered is sufficient for battery-less operation lower power sensors, such as described in [11].

V. CONCLUSION
A unique and effective method of localized remote-area power harvesting for autonomous sensors has been presented, with a focus on an anemometer-based solution. By forcing the input resistance of the power converter to remain constant over a range of wind speeds, the designed alternator is biased to operate at its peak power point over a wide range of wind speeds. The result is an efficient harvesting system capable of providing small amounts of power to charge the central system batteries without adversely affecting the ability of the anemometer to measure wind speeds with a high degree of precision. As a result, each node is capable of an in-field lifetime of approximately three to four times the lifetime of the original system without power harvesting capability.

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REFERENCES