Air-Powered Sensor

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Abstract

This paper describes an application for powering wireless sensors. We use air motion to drive a miniature wind turbine. The intent is to use the device indoors, in air ducts used for heating, ventilating, and air-conditioning. We used commercially available off the shelf components for the airflow turbine. A low-speed, three-phase, brushless DC servomotor was used for the generator. A three-phase bridge constructed from six diodes was used to convert the AC current from the motor to DC current required by low-power sensors. We used a four-inch fan blade for the turbine blade. We conducted a set of tests on the airflow turbine using resistive loads to demonstrate its energy conversion potential. We also showed that it could power a wireless sensor continually.

INTRODUCTION

One of the ideal applications for wireless sensor networks is monitoring and control of systems in buildings such as heating, ventilating, and air-conditioning (HVAC) systems. A potential limitation of wireless sensor technology is sensor power consumption. For commercial buildings, it is necessary for wireless sensors powered by batteries to last several years. Without careful power management, wireless sensors such as those described in [1] may only last five days on a pair of AA batteries.

For HVAC systems, airflow is a potential source of power for sensors. A typical air velocity in an HVAC duct is 1200 feet per minute. The kinetic energy flux (i.e., power) of air moving at that velocity through an area of one square centimeter is 12.4 mW. This is roughly comparable to the energy density of solar cells exposed to direct sunlight [2]. This high energy density offers the opportunity for operating sensors without the need for and limitations of wired power or batteries.

Due to recent developments in the design and development of wireless sensor networks, there has been an increased interest in scavenging energy from ambient sources to power sensors. In [2,3], techniques for scavenging power from vibration are described. Methods for scavenging power from shoe-mounted piezoelectric devices that extract energy from the impacts of heel strikes and flexing of soles is described in [4]. In [5], methods for scavenging power from temperature gradients using thermoelectric elements are described. This technology is less useful for HVAC applications because the energy density is lower and because it is difficult to attain the temperature gradients required to produce high efficiency and significant voltage.

In this paper we describe the design of a miniature airflow turbine intended to be used to supply power to low-power wireless sensors from air motion in HVAC systems. The next section contains the details of the design of the prototype. The subsequent section describes a set of tests that demonstrate the performance of the prototype. The Discussion section covers a number of points that are relevant to the design of devices that scavenge energy from air motion and for energy scavenging systems in general.

DESIGN

We used commercially available components to design a miniature airflow turbine that produces low-voltage DC power from airflow. The turbine uses a commercially available fan blade as a turbine blade, a brushless DC motor operated as a generator, and a three-phase bridge circuit to convert the AC power from the generator to DC power. The characteristics of the motor/generator are shown in Table 1. The motor/generator is a low-speed design, with a high back-emf coefficient. This allows it to produce higher voltages at the lower speeds encountered in this application.

Table 1: Electrical characteristics of motor/generator.

supply volts	no-load speed, rpm	back-emf mVolt/rpm	eff., %	resistance, Ω
12	2660	4.5	65	46.6

With no commutator, the motor produces a three-phase alternating current (AC) output. We used a standard three-phase bridge constructed from six diodes to convert the AC voltage to direct current (DC) voltage. Figure 1 shows a schematic of the three-phase bridge. The bridge circuit takes the three phases from the motor, configured in a wye, and outputs a “DC” voltage with a ripple resulting from the rectification of the AC voltages.

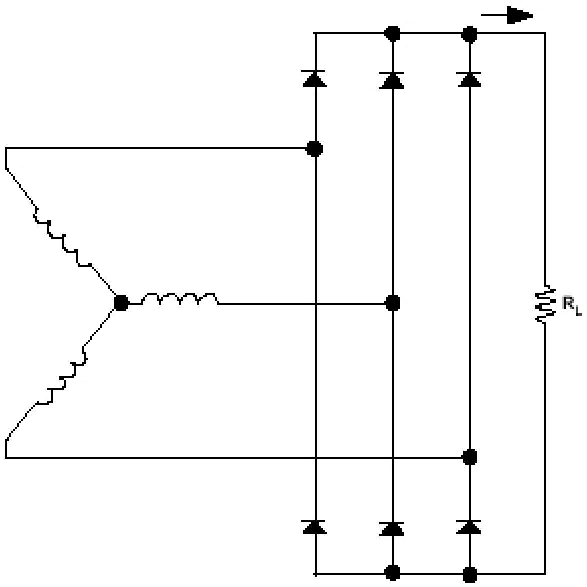

Figure 1: Schematic of three-phase bridge circuit.

Fig 2 shows a picture of the airflow turbine.

Figure 2: Miniature airflow turbine.

RESULTS

We tested the turbine with a range of resistive loads from 2 ohms to 9000 ohms and at three air velocities, 500 feet per minute (fpm), 800 fpm, and 1000 fpm. We measured voltage and current supplied to the load under each condition and computed the power from these measurements. We also used the turbine to power two wireless sensor nodes called “motes”.

Fig 3 shows the voltage versus current for each load at each velocity. Also shown is the voltage and current of a Rene mote and a Mica mote. See [1] for details on the designs details of these motes. The Rene mote was programmed with a low-power radio stack that ran with a 10% duty cycle, which is part of the reason that the Rene mote uses so much less power than the Mica mote. The Mica mote was programmed so that the radio and processor used the maximum amount of power. The results show that the turbine can operate the Rene mote at the highest velocity directly and continuously. It cannot operate the Mica mote even at the highest air velocity.

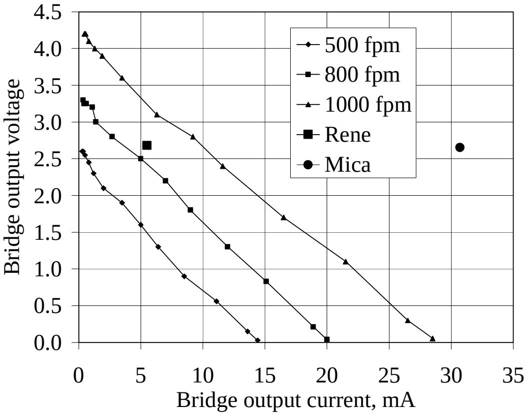

Figure 3: Output at three velocities.

Fig 4 shows the power generated by the turbine as a function of load. The peak power at the medium air velocity is just enough to operate the Rene mote, but the voltage at this load condition is too low for the Rene mote. If the Rene mote were designed with a DC-DC step-up converter in the power supply circuitry, then the turbine would be able to operate it as programmed at the medium velocity.

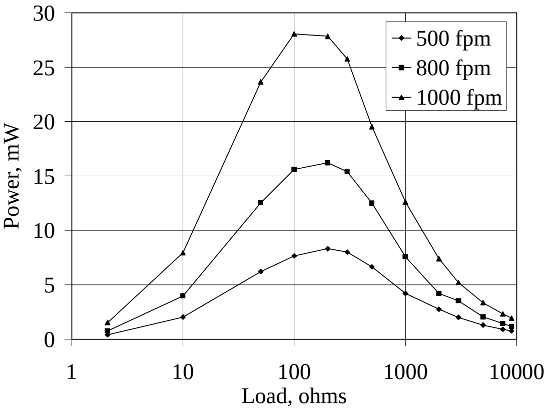

Figure 4: Power versus load at three air velocities.

Fig 5 shows the turbine efficiency as a function of load. The figure demonstrates that the turbine is very inefficient. This is the result of a number of factors, including low motor/generator efficiency, bridge circuit losses, and inefficient blade design. Efficiencies of large wind turbines are typically 20% - 40% [6]. The theoretical limit is 59%. It should be possible to increase the maximum efficiency to 20%, which would allow us to decrease the blade diameter to two inches.

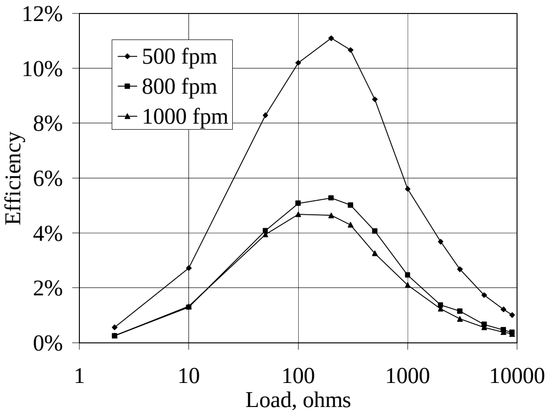

Figure 5: Efficiency versus load at three air velocities.

DISCUSSION

The results reported in this paper clearly demonstrate that enough energy can be scavenged from airflow to power wireless sensors located in air ducts. Under common operating conditions it is possible to continuously operate sensors that are designed and programmed to conserve energy. Note that the amount of energy extracted from the process is small, so that the wind turbine would not detract from the energy efficiency of an HVAC system.

Of course, when air is not moving, it is not possible to power a sensor from airflow. However, there are a number of applications in HVAC systems where this is not a limitation. For all of the sensors in the supply air path of an HVAC system, including supply duct temperature and pressure, flow rate, filter pressure drop, and mixed-air temperature, sensor readings when the fan is off are meaningless. When the fan is on, the velocity is high enough to be used as a power source.

We found that the efficiency of the turbine is low (<10%) for most operating conditions. This low efficiency is caused by a number of factors. First, the efficiency of the motor/generator for the prototype is lower than that available from other vendors. The low efficiency of the motor/generator comes from the fact that it has a high back-emf coefficient in a small package. Another factor contributing the low efficiency is the non-ideal characteristics of the diodes in the three-phase bridge circuit. The diodes do not conduct until they are forward-biased by 0.6 volts, which is a significant fraction of the output of the bridge circuit. The final factor contributing to the low efficiency is the fact that we are using a blade designed to operate as a fan at high speed, not a turbine at low speed. Although we did not test where the greatest inefficiency lies, we suspect that the best opportunity to increase the efficiency resides in using a better blade. The efficiency of low-cost fan blades can be less than 20%. If we could increase the efficiency to 20% it would allow us to decrease the diameter of the blade to two inches.

One way to enable sensors to operate over a wider range of velocities from the power provided by the turbine is to shut off the energy-intensive components (radio and processor) most of the time. The Rene mote, which was programmed with a low-power radio stack operating with a duty cycle of 10%, consumed considerably less power than the Mica, which had all components running at full power. For HVAC applications, it is acceptable for the sensors to report data as slowly as once per minute. By taking advantage of the low data requirements of the application it should be possible to reduce the average power consumption to a level that would allow the device to be powered even at the low-velocity test condition (500 fpm).

There are some times when air velocities may drop below 500 fpm, and yet it may be important for the sensor to operate. It might be desirable in some cases for the sensor to operate from velocities as low as 150 fpm. The turbine design described in this paper will not produce enough voltage for most low-power microcontrollers to operate at such low velocities. However, if the sensor node has a DC-DC step-up converter, it may be possible to operate the sensor at 150 fpm. Extrapolating from the results reported here, we estimate that at very low average power consumption (100 μW), 150 fpm would correspond to a bridge output of 1 volt.

It is common for buildings with legacy control systems to have pneumatic controls. If such a building were retrofit with wireless controls it would be necessary to avoid having to run wire for actuation because doing so would negate one of the main benefits of wireless controls. A solution in this case is wire-free actuation enabled by scavenging energy from air motion to operate the pneumatic actuator. Such a system could use low-power, latching solenoid valves to operate a pneumatic actuator. These valves require as little as 3 mJ of energy to change state. At the winding resistance of the motor/generator and 500 fpm, it would take the turbine less than one second to generate enough energy for one state change. It has been shown in [7] that a flow controller can achieve good control performance with an execution period of one second and a duty cycle of less than 2%, which implies that the turbine should be able to supply ample power for wire-free actuation.

CONCLUSIONS

This paper has demonstrated that air motion is a viable source of energy for powering wireless sensors. The results from testing the prototype indicate that with careful design of the airflow turbine, power supply electronics, and sensor node power management, it should be possible to operate a sensor at velocities as low as 150 fpm. It should also be possible to use the airflow turbine for wire-free actuation when retrofitting pneumatic controls.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0088648. This work was also supported the Center for the Built Environment (CBE) at UC Berkeley. CBE's research is supported by the National Science Foundation and CBE's Industry Partners.

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