SELF-POWERED WIRELESS SENSOR FOR DUCT MONITORING

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Abstract: We report on the development of a self-powered, battery-less wireless sensor aimed at condition monitoring in ducts or pipelines. The device is based around a 2 cm-diameter shrouded wind turbine with a permanent magnet generator built into the shroud and a cavity in the exit diffuser to accommodate the sensor electronics. The present paper is focused on the design and performance of the power conditioning electronics and the radio transmitter. The power conditioner employs a synchronous, rectifying voltage doubler which is self-priming and able to derive a stable DC supply (2 V at 100 μA) from AC input voltages down to 0.5 Vrms. The radio transmitter is a 433 MHz Colpitts oscillator with a loop antenna as the tank inductor.

Keywords: energy harvesting, self-powered, battery-less, wireless sensor, microturbine, oscillator transmitter

INTRODUCTION

Energy harvesting from gas flows has potential applications in wireless condition monitoring, for example in air conditioning systems or gas pipelines. Energy harvesters for air flow have been demonstrated previously [1-4], but most of these have been relatively large and not well suited to installation within a duct. Recently we reported a cm-scale energy harvester aimed specifically at this application. The device is based on a 2 cm-diameter, shrouded turbine with an integrated three-phase, axial flux permanent magnet generator (see Figs. 1 and 2). When configured for single-phase operation (with the three phases connected in series), the 16-pole generator has a total winding resistance of 75 Ω and produces around 430 μVrms per rpm of rotation speed at a frequency of 267 Hz/krpm. The turbine/generator combination can operate at air flow speeds down to 3 m/s and deliver mW power levels of output power for flow speeds in the range 6-10 m/s. The cross-sectional area including the shroud is 8 cm^2, which represents only 1% of the cross-section of a 1 ft diameter duct. Details of the fabrication process and preliminary wind-tunnel test results were previously reported in [5].

In this paper we report on progress towards a complete, battery-less wireless sensor for duct monitoring. Fig. 3 shows a block diagram of the sensor which includes turbine/generator, power conditioning electronics, microcontroller, transducers and ultra-low power wireless transmitter. In the current implementation, air flow speed is inferred from the turbine rotation speed, and there is one additional transducer, an LM94022 temperature sensor [6]. The microcontroller is an ATmega88PA [7] operated with 2 V supply voltage and an internal 128 kHz RC oscillator clock. The wireless transmitter is a custom device based on a 433 MHz Colpitts oscillator with a loop antenna as the tank inductor [8].

At 2 V supply voltage, the nominal active supply currents for the microcontroller, temperature sensor and wireless transmitter, are 30 μA, 5 μA and 60 μA respectively, giving a total power budget for the sensor electronics of just under 200 μW when the transmitter is active. The transmitter supply current value assumes on-off keying with 50% duty cycle.

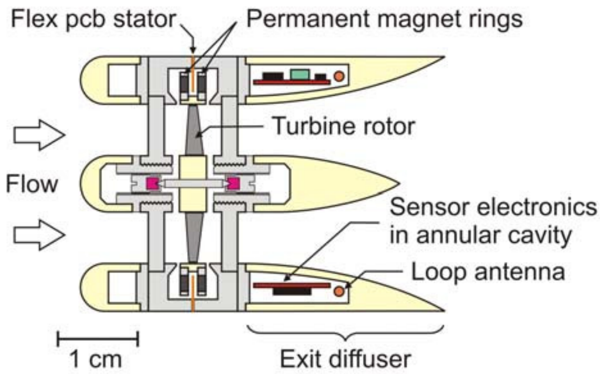


Fig. 1: Schematic cross-section of sensor showing turbine/ generator geometry and cavity for electronics.

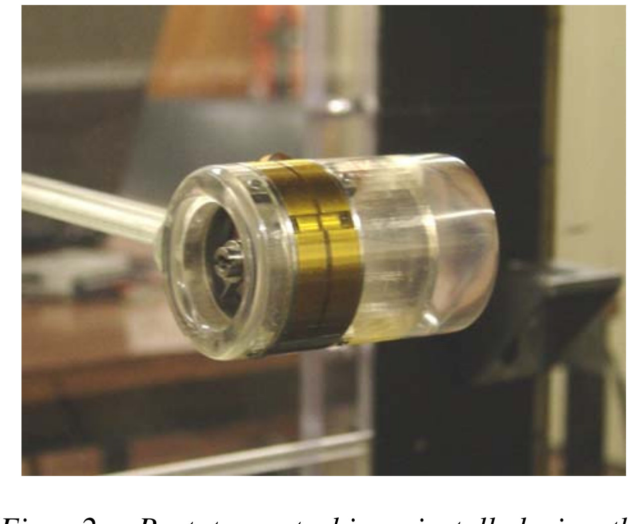


Fig. 2: Prototype turbine installed in the experimental section of an 18" × 18" wind tunnel.

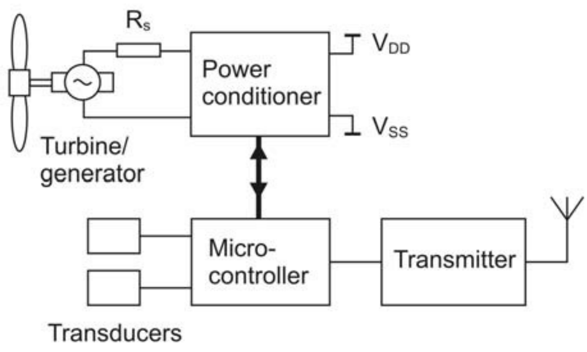


Fig. 3: Block diagram of complete wireless sensor.

POWER CONDITIONING

In the absence of a battery, the power conditioning electronics must be self-priming, and this is challenging for miniature electromagnetic generators because of the low voltage levels produced. We have developed a solution based on a 2-sided synchronous voltage doubler as shown in Fig. 4. The circuit comprises two classic voltage doublers (formed by C1, D1, D2, C2 and C3, D3, D4, C4 respectively), with each diode having an associated parallel mosfet to eliminate the forward voltage. The remaining components provide level shifting for the gate drives to the mosfets where required. The doubler outputs are connected in series, so the DC output voltage (between the V+ and V- terminals) in open circuit is expected to be twice the peak-to-peak open-circuit generator output voltage if there are no diode forward drops or other losses.

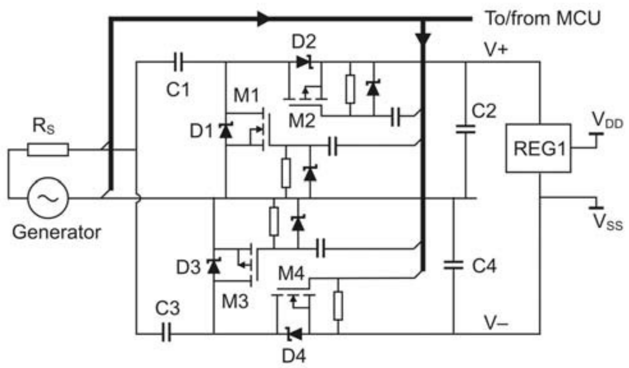


Fig. 4: Power conditioning block based on 2-sided, synchronous voltage doubler.

The idea is that the circuit in Fig. 4 should be passive during priming of the sensor, becoming active once the microcontroller is running and gate voltages are applied to the mosfets. Elimination of the diode forward voltages in active mode is expected to increase the doubler output voltage by about 200 mV per diode (assuming Schottky devices) and hence lower the drop-out flow speed of the sensor i.e. the minimum flow speed at which it will operate. This is an important consideration for sensing in air-conditioning ducts where flow rates are relatively low (typically 3-8 m/sec).

Fig. 5 shows the measured variations of efficiency with generator frequency for a prototype power conditioning circuit operated in both passive and active modes. The diodes D1-D4 in the prototype are Schottky type MBRA120, and the capacitors C1-C4 are all 10 μF ceramics. The capacitor values were not fully optimized, although PSpice simulations were run to establish the range that gave best performance. The mosfets are Vishay types Si1450DH (n-channel) and Si2305CDS (p-channel), selected for low threshold voltage.

The efficiency plotted in Fig. 5 is 100×Pout/Pin, where Pout is the power delivered to a dummy load by the final voltage regulator, REG1, and Pin is the power entering the voltage doubler from the generator. The regulator used for these tests was a 2.047 V voltage reference, type MAX6018_21 [9]. Although intended for use as a voltage reference, the low dropout voltage (200 mV) and supply current (typically 3 μA when unloaded) of this device make it attractive also as an ultra-low power regulator. The dummy load was a 20.47 kΩ resistor which applied a constant 100 μA load to the regulator output, simulating the sensor electronics.

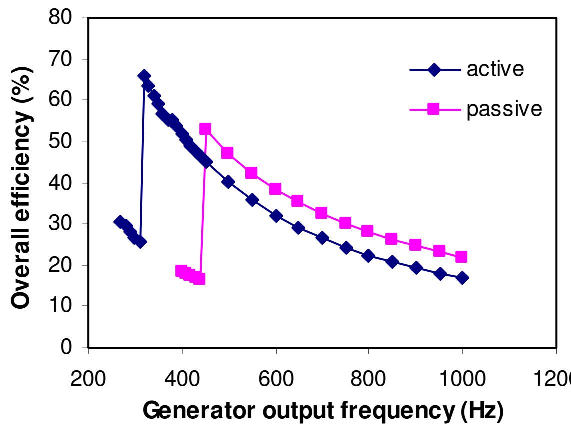


Fig. 5: Conversion efficiencies of conditioner in passive and active modes as a function of generator output frequency.

Both sets of data in Fig. 5 show a dramatic fall in efficiency at low generator frequency. This occurs when the voltage applied to the regulator falls below about 2.25 V and it stops working correctly. The sharp drop in efficiency occurs because the regulator draws a higher supply current under these under-voltage conditions. From the graph it can be seen that the active doubler is able to continue operating effectively to lower frequencies, and also ultimately achieves higher efficiency than can be obtained with the passive circuit. Both of these positive features result from elimination of the diode forward voltage drops in the active doubler. The lowest frequency for which the active circuit can operate is 320 Hz, corresponding to a rotation speed of 1200 rpm and an open-circuit generator output voltage of about 520 mV rms.

The efficiencies of both the active and passive circuits fall with increasing frequency in the normal operating region, and this is primarily due to the fact that a linear regulator has been used at the output. It is important to note in this context that the aim in this work was to achieve high efficiency at low generator voltages, and to minimize the drop-out voltage. The efficiency at higher voltages is unimportant as in this regime there is ample power available from the generator. This justifies the use of a linear regulator at the power conditioner output. When delivering 100 µA of output current, the MAX6018_21 efficiency rises to around 83% as the drop-out voltage is approached, and this is better than can be achieved with a commercial low-power DC-DC converter, even though the latter could be more efficient at higher input voltages.

Generation of the required mosfet gate drive signals is essential for any synchronous rectifier circuit. A common method is to use a comparator to detect the sign of voltage across each mosfet and to switch it accordingly [10]. It can be difficult to switch the mosfets off reliably using this approach because of the low on-state voltage; however solutions to this problem have been demonstrated [11]. In the longer term, we are intending to use the microcontroller to generate the necessary gate drives, with timings estimated based on the measured turbine speed and known loading conditions. For the present paper, however, a simple pulse-position/width modulator circuit was built that allowed the gate pulse timings to be adjusted manually. Fig. 6 shows a captured oscilloscope trace which includes the voltage and current at the conditioner input (Ch1 and Ch2 respectively), along with the gate signals applied to M2/M3 (Ch3) and M1/M4 (Ch4). Driving the mosfets in pairs is not optimal but simplifies the gate drive circuit.

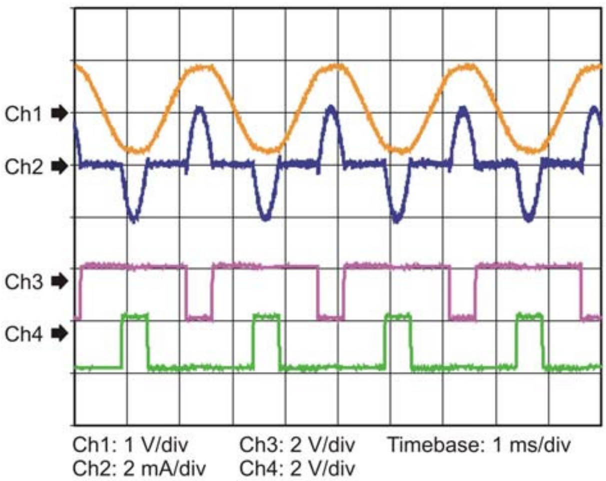
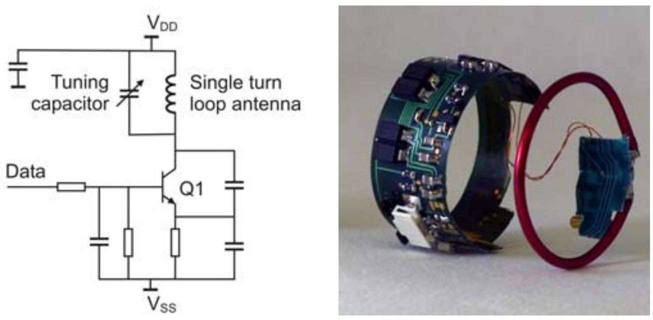


Fig. 6: Scope traces showing power conditioner input voltage (Ch1) and current (Ch 2), and gate drive signals applied to M2/M3 (Ch3) and M1/M4 (Ch4).

The gate drive circuit operated at 2 V with a supply current of 20 to 30 µA, and was powered from the power conditioner output so that no auxiliary power supply was required. The power consumed by the gate drive circuit was not counted as part of the load power, and so was taken properly into account when calculating the efficiency.

RADIO TRANSMITTER

Fig. 7a shows a schematic of the radio transmitter that will be used in initial sensor demonstrations. The circuit is a Colpitts oscillator with a single-turn loop antenna that doubles as the inductor in the resonant tank [8]. This kind of transmitter has a minimal component count and can achieve very low power consumption. However, the transmission range is limited because there is no power amplifier. Also, loading of the antenna by nearby objects can cause significant frequency variations, although this is not an issue for the kinds of applications envisaged in the present work. Fig. 7b shows an assembled transmitter fabricated to fit inside the turbine exit diffuser. The transistor in this circuit is a BFP520 (Infineon Technologies AG) which has a transition frequency of f_T = 45 GHz. A high-Q trimmer capacitor is included to allow tuning of the transmission frequency.



(a) (b)

Fig. 7: Colpitts oscillator transmitter: (a) circuit schematic; (b) prototype (on right) next to other sensor electronics.

Basic tests have been carried out in a normal laboratory environment to establish how the transmission range varies with bias current. The transmitter was modulated by on-off-keying with a square wave, and the received signal was monitored on an oscilloscope as the propagation distance was varied. The receiver was an AM-HRR3-433 super-regenerative receiver module from RF solutions Ltd. Fig. 8 shows a typical result at 1 kbps data rate. With 10 m range, and assuming continuous on-off-keyed transmission with 50% duty cycle, the average current consumption is 60 µA.

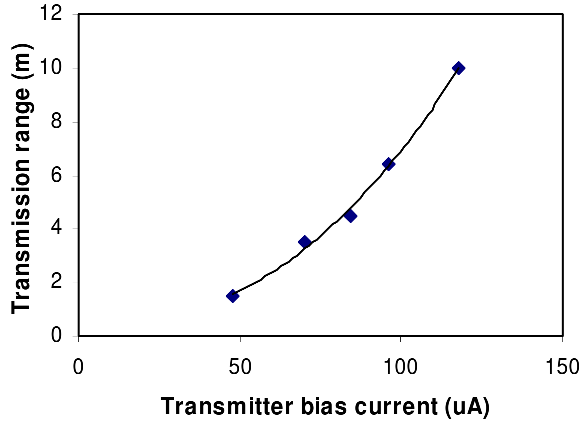


Fig. 8: Measured variation of transmission range with bias current for Colpitts oscillator transmitter.

OVERALL PERFORMANCE

In order to determine the minimum flow speed at which the sensor will operate, it is necessary to consider the power conditioner characteristics in conjunction with those of the turbine. Fig. 9 shows the measured variation of turbine shaft power with rotation speed at different wind-tunnel flow speeds. Also shown is the power that must be developed by the generator (including the dissipation in the winding resistance R_s) in order for the power conditioner to deliver 2 V at 100 μA to the sensor. The latter curve extends down to 1,200 rpm, which is the lowest speed for which the voltage doubler provides sufficient headroom for the regulator. The results suggest that the sensor will operate at flow speeds down to about 4.5 m/s.

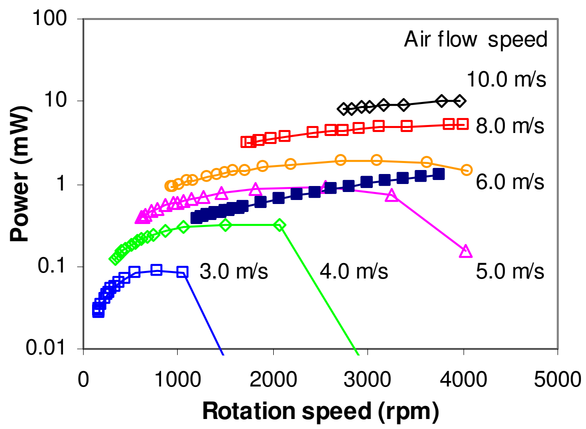


Fig. 9: Variation with rotation speed of (a) measured turbine output power at different air flow speeds (open symbols), and (b) input power requirement of power conditioner (filled symbols).

CONCLUSIONS

We have explored the use of a 2-sided, active voltage doubler for power conditioning in a self-powered, battery-less wireless sensor in which sensor power is supplied by a miniature wind-turbine. The power conditioner can achieve an efficiency of 66% when delivering 200 μW, which is quite respectable and should allow the sensor to operate at flow speeds down to about 4.5 m/s. Currently we are integrating the various sensor parts to produce a demonstrator with a simple point-to-point radio link for data transfer to a nearby data collection node.

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