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IMPLEMENTATION OF A HYDRO ENERGY HARVESTING SYSTEM FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

In the context of the wireless sensor networks (WSN), there are almost no systems using hydric energy harvesting. The purpose of this work is to show a small-scale hydro generator for energy harvesting and the necessary electronics to power WSN nodes. Two systems based on the Pelton turbine were tested in a watercourse, in order to evaluate two modes of operation: continuous and intermittent generation. A circuit was designed that allows WSN nodes to run continuously without batteries by using a small continuous water flow as a power source. A second system was designed to reduce generator wear by only activating it when required by the sensor node.

Keywords: hydric, energy, harvesting, wireless, sensor, networks, water, flow.

INTRODUCTION

The wireless sensor networks (WSN) allow monitoring of various parameters of the physical environment. These networks, with the last decade technological developments, are comprised of small size and low cost sensor nodes, which include sensors, processor, a small radio and a power source (Raghunathan, 2006). Although the RF communication offers flexibility in data transmission on a distributed system, power continues to be supplied mainly by batteries or directly connected to the mains (Woias, 2005). The batteries make possible applications of sensors in remote or difficult to access areas with operation periods of several days to several months, but hardly offer longer operating time (Kulkarni, 2008). One solution is to harvest energy from the surrounding environment (Raghunathan, 2006). The energy harvesting systems must be compact and provide power to the sensor nodes, requiring between one milliwatt to one hundred milliwatts.

In recent years, several options have been considered for energy harvesting from the environment. Most studies have used solar PV to power the sensor nodes in WSN (Raghunathan, 2005). Only a few studies have considered wind and vibration energy harvesting. The flow of water available in some environments offers a high potential for harvesting energy. But while the great potential of this energy source on a large scale is already well known, in the context of WSN, there are few systems that use this energy source. And the solutions available use commercial hydro generators designed for smart gas-based water heater appliances implemented on irrigation water pipes (Morais, 2008).

The water flow may be constant or variable over time. To fill the energy gaps within these variations it is necessary to have an efficient management of energy by the sensor node and to use some type of energy storage (e.g. rechargeable batteries). Super-capacitors may be used instead of batteries, solving issues such as battery memory, limited charging cycles or very fine charge control.

The purpose of this work is to implement a small hydro system for waterfalls to power wireless sensor nodes efficiently with an inexpensive circuit. This involves controlling the energy extraction from water flow in continuous or intermittent conditions and feeding the sensor node directly or through a super-capacitor.

HARVESTING ENERGY FROM SMALL WATER FLOWS

There are some environments that offer plentiful water flow throughout the year. This is the case of the island of Madeira. The hydro-generator is small comparing to the waterfall, so a water capture system must exist to diverge some of the water flow to a hydro turbine. Considering that this water flow can vary daily, is dependent of the season and may contain some debris, it is necessary that the capture system must include a buffer to filter variations of the water flow. This capture system must remove air pockets and filters debris that may clog the hydro turbine system. The solution proposed is presented in Fig. 1. Where a tube is used as a buffer reservoir, where an inclined top filter avoids debris entrance and a hose connected a little above the bottom of the buffer drives the water flow to the turbine. The excess water continues overflows the buffer maintaining the head. The water used by the turbine is delivered back to the watercourse.

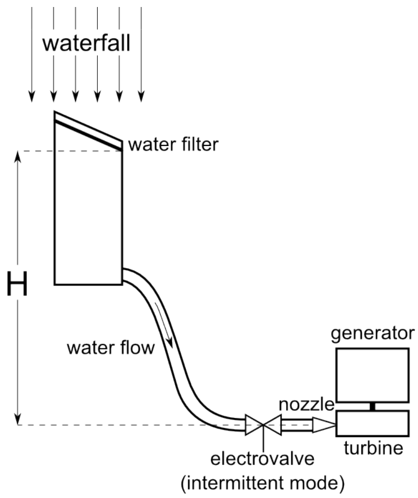

Fig.1 The water flow capture system

It was considered the use of small waterfalls to increase the number of possibilities where to install the system. The desired power production is achieved by varying the head. In a previous work (Azevedo, 2011) it was found that for this purpose the Pelton turbine is the most suitable over the propeller for this application, presenting a higher efficiency for lower flow rates and higher heads.

The hydro generator used in this work is the same as in (Azevedo, 2011) named small pelton generator. This is a reused optical CD drive three-phase motor, with a diameter of 2.5 cm and a height of 0.7 cm coupled to a Pelton Turbine with the same dimensions. Fig. 2 shows the system of the pelton turbine.

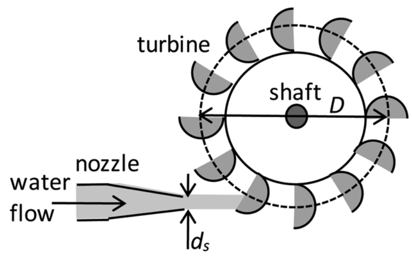

Fig.2 The Pelton hydro turbine.

The available power of a hydro system is given by (Peng, 2007)

$$P_T = \rho g Q H \tag{1}$$

where ρ is the water density (1000 kg/m^3), g is the gravity acceleration (m/s^2), Q is the water flow rate at the turbine (m^3/s) and H is the effective height or head (m).

The usable power can be obtained from

$$P = \eta P_T \tag{2}$$

where η is total system efficiency, including Pelton turbine conversion efficiency, generator efficiency and voltage regulator efficiency. To evaluate the needed head, it is necessary to specify the required power consumption and the inefficiencies of the system.

The theoretical jet velocity for the Fig. 2 configuration is given by (Peng, 2007)

$$v_1 = \sqrt{2gH} \tag{3}$$

and the flow rate is

$$Q = A.v_1 = \frac{\pi.d_s^2}{4} v_1 \tag{4}$$

ZigBee is a very popular wireless communications protocol used on WSNs. It is based on the 801.15.4 standard that defines two types of devices: full function devices that need to be constantly powered on to route network data, and reduced function devices that may enter sleep mode, thus lowering their average power consumption. In this work a commercial ZigBee device known as the XBee was used. This module operates with input voltages between 2.1 and 3.6 V and a current consumption of 40 mA (at 3.3 V) for transmission and reception. With a power consumption of 132 mW a typical battery (2400 mAh) powering this device would only last about 2 days.

Considering a head of H = 3 m, an efficiency of the small pelton generator of η_g = 14%, an efficiency of the power conditioning circuit of η_c = 80%, and defining a power requirement of 132 mW, the minimum water flow Q can be estimated using (2) and (1). For these requisites, it is necessary a minimum water flow of Q = 2.33 L/min. Applying the defined head of H = 3 m and the obtained water flow of Q = 2.33 L/min at (3) and (4), the necessary jet diameter is d_s = 2.54 mm.

SYSTEM ARCHITECTURE

To evaluate the proposed system two modules were developed: one for continuous operation mode and one for intermittent operation mode, differing mainly in the use of a valve to control the water flow (intermittent mode) and the power conditioning subsystem.

In the continuous mode of operation, the water flows continuously from the buffer to the turbine, as shown in Fig. 1, and the module setup follows the block diagram depicted in Fig. 3. The generator is connected to a three-phase rectifier that converts AC voltage to DC, the output is limited by a simple Zener diode to prevent the generator from free running and limit the voltage maximum value to 5.8 V, in order to not exceed the maximum allowable voltage of the next block. Then a step-down converter (TPS62203 from Texas Instruments) regulates the voltage to a stable value of 3.3 V, which is the standard supply voltage of the XBee module. For evaluation purposes of the system efficiency two ADC pins of the XBee were connected to a precision current sensor (MAX9929 from Maxim) and to the voltage output of the three-phase rectifier. The XBee was programed to send a reading of both values every second.

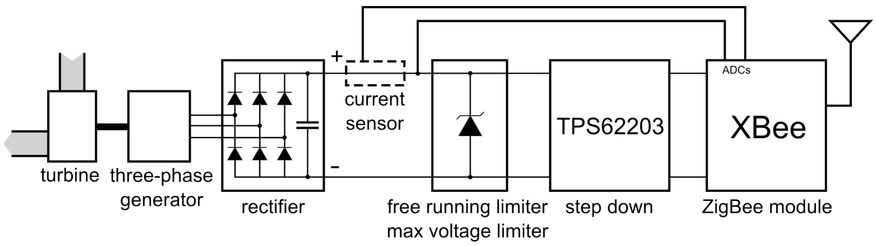

Fig.3 Continuous operation module block diagram

In the intermittent mode of operation, the hydro generator only works during a short period of time, just enough to provide energy for the node to acquire and send the sensor data and to recharge the capacitor in order to offer power to the node during the sleep period (low power period). The water flow is controlled by a latched electro valve installed in the hose of the system as shown in Fig. 1.

The intermittent module follows the block diagram depicted in Fig. 4. After the rectifier there is a voltage regulator that limits the maximum charging voltage of the capacitors to 3.3 V, under the maximum voltage of the XBee module. This voltage regulator was built based on a simple circuit with an AMPOP that switches a Mosfet ON or OFF when the voltage is under or above 3.3 V respectively, thus maintaining the voltage across the capacitor. The voltage reference is given by a Zener diode. This voltage regulator has the advantage of turning itself off when the turbine is not working, since there is no power supply to the AMPOP and the Mosfet stays in a high impedance state. The following block is a super capacitor working as an energy storage device in order to provide power during the sleeping period, the output of the super capacitor feeds the XBee node and a 8-bit microcontroller (ATmega168 from ATMEL), added to control the electro valve and the sleep state of the XBee module.

During tests it was noticed that due to the high value of the Equivalent Series Resistor (ESR) of the super capacitor, the initial capacitor charge current caused a high voltage elevation at the capacitor pins, exceeding the maximum operational voltage of the other components, thus it was chosen to introduce a current limiting inductor and a protection diode at the output of the rectifier.

The electro valve utilized (5110-NC from RPE - Italy) needs a 25ms pulse of 500 mA at 9 V during each operation. Since the current is so high, it will not be possible to feed the system only with the super capacitor, this is due to a high value of the ESR, that causes a high voltage drop across the pins of the super capacitor, thus disabling the system.

Due to this it was developed an auxiliary circuit based on the L293 H-Bridge integrated circuit powered by a 9 V battery. The L293 is controlled by the microcontroller and with a mosfet the component can be switched ON only during valve operation, thus lowering power consumption.

The 9 V battery has a total power capacity of 2.5Wh, since each valve state change lasts 25 ms, the autonomy of the battery can be estimated to a maximum of 80,000 pulses and considering a period of 5 minutes, the battery will last for about 138 days. Considering longer periods of valve state change the battery could last several years, although a precise estimation should include several characteristics as the battery self discharge and battery age.

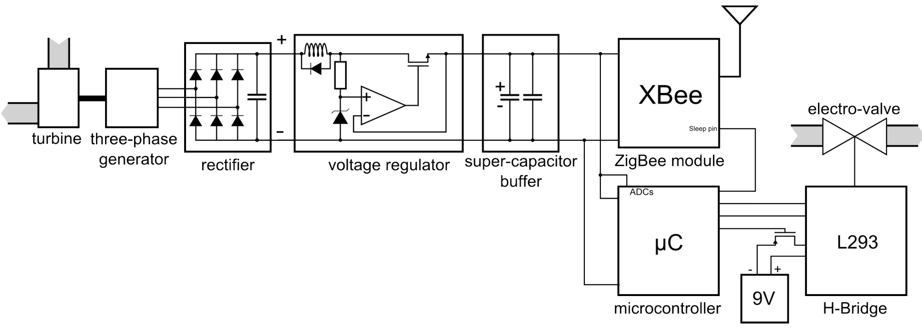

Fig.4 Intermittent operation module block diagram

In order to estimate the necessary capacity of the super-capacitor, the power consumption of the XBee module and microcontroller were registered for different modes of operation, values are shown in Table 1.

Table 1 Power requirements for the node components

Components	Active state (mA, at 3.3 V)	Sleep state (μA, at 3.3 V)	Operation voltage range (V)
XBee	40,27	≤ 10	2.1 – 3.6
microcontroller	5,8	87 (RTC on)	2.7 – 5.5

Considering a 5 minute period of data acquisition, the super-capacitor buffer must have a capacity C that can power the XBee and the microcontroller during the sleep state. During this state the power consumption is around 100 μA at 3.3 V, considering a maximum voltage variation (due to the capacitor discharge) of 0.2 V during a 5 minute sleep period, the capacity required is of 1.63 F. For this two 1.5 F super-capacitors in parallel were used, offering a total capacity of about 3 F.

The operation of the intermittent circuit, shown in Fig. 5, is mainly controlled by the microcontroller program as follows: There is an initial state when the capacitor bank is discharged and nothing is powered, to start the system the operator manually opens the valve, thus starting the initial capacitor recharge operation, after a while the microcontroller activates and takes control of the electro valve and the XBee sleep pin, the system is now self controlled and requires no more user input. During normal operation the microcontroller opens the valve to start recharging the capacitor bank, gathers data, wakes up the XBee module, sends data to the ZigBee network, makes the XBee enter sleep mode, waits for 20 seconds in order to recharge the capacitor bank, after which it closes the electro valve and goes into a low power state that lasts 5 minutes, after which it restarts the autonomous operation cycle.

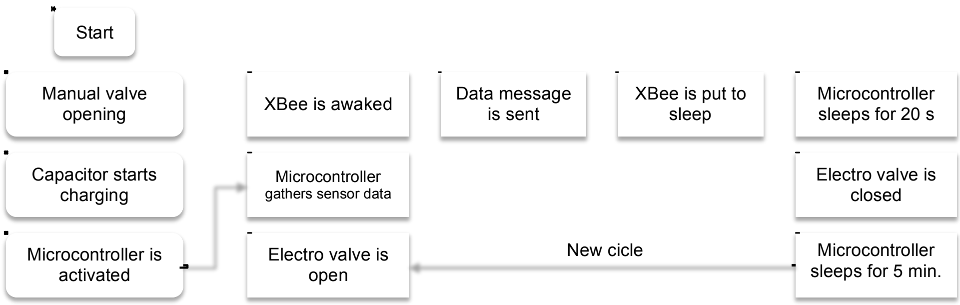

Fig.5 Intermittent operation module flux diagram

RESULTS

The two modes of operation were tested during several days in a real waterfall. In the continuous mode the small Pelton turbine was placed in a small waterfall as shown in Fig. 6a. The goal was to produce enough energy to power a XBee node that is always on and consuming about 135 mW. The required power was obtained for a head of H = 3 m and a flow rate of Q = 2.4 L/min.

a) b)

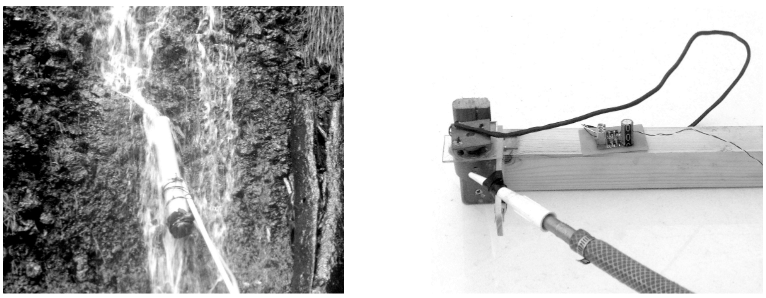

Fig.6 Hydro energy harvesting system a) Water buffer reservoir; b) Hydro generator (including turbine, nozzle, generator and rectifier)

The practical water flow rate obtained is slightly above the estimated value in section 2. This increment was done to account for water flux variations. The registered efficiency of the power conditioning subsystem is shown in Fig. 7. This efficiency varies between 82 % and 88 %. The total efficiency of the hydro generator system was on average 11.5 %.

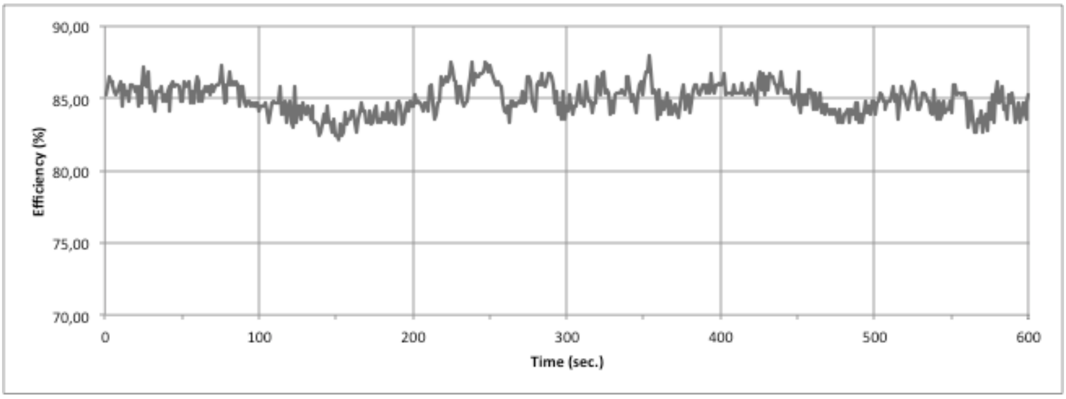

Fig.7 Continuous mode power conditioning subsystem efficiency variation over time

As can be observed the turbulence present in the water flux must be accounted. The power produced varied between 155 mW and 164 mW, giving an efficiency of 88 % and 82 % respectively. Considering that for these values of power the used step-up presents an efficiency of around 94 %, the excess power was consumed by the Zener diode.

In the intermittent mode, the hydro generator only works during an active period of 20 seconds to recharge the super-capacitor. The stored energy feeds the module during a sleep period of 5 minutes. Fig. 8 shows the voltage across the capacitor that supplies power to the circuit during about two periods.

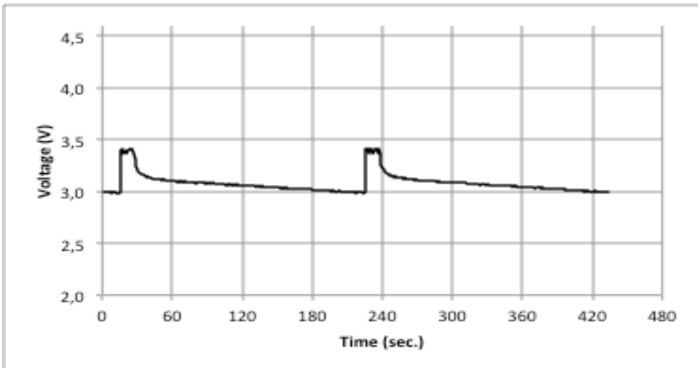

Fig.8 Intermittent mode capacitor voltage variation over time

It can be observed from the picture that the 20 seconds is not enough to charge the capacitors to 3.3 V, but it is verified that this recharge time is enough to store energy for the low power period and the next start-up, since the voltage at the capacitor pins has a variaton of 0.2 V and does not fall under 3 V, as calculated. The discharge rate is mostly due to the high leakage current compared to the current consumption of the components during the sleep period.

Evidence of the high ESR value effect at the charging period is noticed, since the voltage is 0.15 V higher than the real charge voltage level of the super-capacitor. It is also noticed that the simple regulator still allows some variation of the regulated voltage due to the water flux turbulences.

CONCLUSIONS

Two hydro generator systems based on the pelton turbine were developed and tested. In the first system the hydro generator is powering the wireless node in a continuous mode. This is done without using any battery, thus avoiding the battery-associated problems like limited charging cycles. This demonstrates the advantage of hydro systems for energy harvesting compared to other sources of energy that are not always present, requiring a large energy storage device to overcome periods of no production.

In the second system an intermittent mode of operation was designed, where the hydro generator only works during the active state intervals, by being controlled by an electro valve. This allows for less wear of the hydro generator, especially for applications with long periods of inactivity. A super-capacitor is charged during the active interval in order to power the microcontroller throughout the duration of the sleep period and the system start-up of the next cycle. The capacitor value and the active charge time are dependent of the sleep time defined by the WSN application.

In these experiments it was also noticed the importance of super-capacitors with low ESR and a low leakage current, that could improve the system efficiency.

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