A water-powered Energy Harvesting system with Bluetooth Low Energy interface

M. Kroener, K. Allinger, M. Berger, E. Grether, F. Wieland, S. Heller, P. Woias
Laboratory for Design of Microsystems, Department of Microsystems Engineering, Georges-Koehler-Allee 102, 79110 Freiburg, Germany
kroener@imtek.de

Abstract. This paper reports the design, and testing of a water turbine generator system for typical flow rates in domestic applications, with an integrated power management and a Bluetooth low energy (BLE) based RF data transmission interface. It is based on a commercially available low cost hydro generator. The generator is built into a housing with optimized reduced fluidic resistance to enable operation with flow rates as low as 6 l/min. The power management combines rectification, buffering, defined start-up, and circuit protection. An MSP430FR5949 microcontroller is used for data acquisition and processing. The data are transmitted via RF, using a Bluegiga BLE112 module in advertisement mode, to a PC where the measured flow rate is stored and displayed. The transmission rate of the wireless sensor node (WSN) is set to 1 Hz if enough power is available, which is the case for flow rates above 5.5 l/min. The electronics power demand is calculated to be 340 µW in average, while the generator is capable of delivering more than 200 mW for flow rates above 15 l/min.

1. Introduction
The first hydroelectric power plant, converting water flow to electrical energy, began operation in Appleton (Wisconsin) in 1882. While on the larger scale this method has been used for a long period, water-powered energy harvesting systems in the mW-range are pretty rare. Recent research in this field covers smart-water meters [1], and some special generation principles, such as piezoelectric harvesting from vortices [2], and graphene thin film based harvesting in the µW-range [3]. An early version of a water-powered energy-autonomous sensor system has been realized in the lab with a price-awarded student project [4]. The research shown in this paper aims at an expansion of the idea of water-powered WSNs for smart home applications. For reasons of simplicity an off-the-shelf “micro hydro power generator” is used here. The WSN is intended to measure water temperature and flow as a standalone system in the water conduit of a smart home, to determine the total water usage and energy consumption. For this purpose, the recorded data are transmitted to a receiver, processed and displayed continuously. The presented system is limited to water flow measurements only, as the characterization and power management stood in the focus of this demonstrator, as it turned out to be the most complex part.
2. System design and measurements

This system consists of an optimized turbine housing, the generator itself, an electronic power management, the microcontroller-based data acquisition, and a Bluetooth low energy (BLE) transmission unit. The component description is given in detail below.

2.1. Generator and turbine housing

The micro hydro generator used in this project is commercially available (Manufacturer: Yoyo Zeng Shenzhen Slinya Electronic Co., Ltd). The turbine is made from a pot-shaped rotor with turbine blades at the outside, a belt-shaped magnet with six poles at its inner side and a central axis fitting into a brass gliding bearing in the turbine housing. The generator part consists of a three phase design with 9 coils that are mounted liquid-tight in the stator and protrude into the pot-shaped rotor, thus facing the ring magnet at a short distance given by the turbine housing in-between. If water flows through the turbine housing it starts rotating the magnet around the stator, thus inducing a voltage in the stator coils due to the dynamic change of the magnetic field. The data sheet of the original device gives a maximum output power of 10 W, with 80 V output and a maximum water pressure of 1.2 MPa (12 bar). The minimum pressure for rotation of the turbine is specified to 0.06 MPa, i.e. 0.6 bar.

For optimization the turbine housing was replaced by a custom-made brass housing with optimized fluid flow and reduced fluidic resistance (see Figure 1). Instead of the original brass bearing, a PTFE bearing was used to reduce friction losses and uneven rotation. A custom adapter and cover were fabricated from PMMA to embed the stator and to have an optical access to the rotating turbine.

2.2. Power management, data processing and transmission

Frequently, power management in energy harvesting means to optimally distribute a small amount of energy available. In this work particular attention had to be payed to over powering and overvoltage protection. Rectification from the generator’s AC-signal is achieved with Schottky diodes (BAT54SW) on the three-phases. A buffer capacitor was chosen with a capacitance large enough to supply one complete measurement and wireless transmission cycle, an ultra-low-power hysteretic switch enables defined electronics start-up [5], providing under voltage protection. Over voltage protection of the circuit is achieved with a voltage divider and an NMOS transistor (TI CSD17313Q2), which converts abundant power to heat via opening a path to GND for voltages on the buffer capacitor above 5 V. The PCB is shown in Figure 2.

A 16-Bit MSP430FR5949 (TI) microcontroller (µC) is used for data acquisition and processing. It measures the rotational speed of the turbine by measuring the frequency of the AC voltage delivered by the generator. This data is then correlated to external flow rate measurements to get calibrated values. During measurement only the µC is active as a load. Once the data are acquired they are transmitted to a PC via RF, using a Bluegiga BLE112 Bluetooth low energy module in advertisement mode. The advertisement mode transmits the measurement data in the header, elsewhere used to establish a linked connection, which is not done here. Thereby the power
consumption of the whole system is lowered remarkably, because it is only on for 4 ms during a full measurement and transmission cycle. The average power consumption of every part of the electronic is derived from the datasheet values and given in Table 1. The average power consumption with a transmission rate of 1 Hz is 340 µW. We are currently working on a method to assess the power consumption of such a system with high time and low current resolution [6].

### Table 1. Power consumption of the electronic components.

| Component                  | U in V | I in mA | t in ms | Avg. Power P=U*I*t/1s |
|----------------------------|--------|---------|---------|----------------------|
| MSP430 – Active (1 MHz)    | 3.3    | 0.1     | 10      | 3.3 µW               |
| MSP430 – Sleep (LPM3.5)    | 3.3    | 0.00025 | 990     | 0.82 µW              |
| BLE Modul – Sleep (PM2)    | 3.3    | 0.0009  | 996     | 2.96 µW              |
| BLE Modul – Transmit       | 3.3    | 25      | 4       | 330 µW               |
| Sum total                  |        |         |         | ~340 µW              |

2.3. Measurements

The system can be operated from water flow rates between 5.5 l/min and 15 l/min, which lies in the range of household applications. Below flow rates of 5.5 l/min operation is limited, because the voltage generated by the turbine is too low (<4 V), while still approximately 10 mW of power is available. To characterize the system several measurements have been conducted, all in the optimized housing mentioned before:

1. Output power and rotational frequency vs. load resistance for two different flow rates
2. Output power at optimal load resistance vs. rotational frequency of the turbine
3. Pressure drop between inlet and outlet vs. water flow rate

3. Results

The measurement of the generator’s output power as a function of the load resistance, together with the rotational frequency of the turbine is shown in Figure 3. The curve was measured for two different flow rates. The higher flow rate equals to a maximum flow rate of 12.5 l/min, and results in a shifted curve for output power and rotational frequency. Water flow is taken from the building supply. Pressures oscillations at the supply line are reflected in the curves. For these measurements the turbines were uncalibrated with respect to flow rate. As can be seen, the rotational frequency of the turbine decreases from high to low load resistances by about 25 % (e.g. 200 Hz to 150 Hz), i.e., there is a strong feedback of the generator to the fluid flow. A successive measurement calibrates the flow rate versus rotational frequency including the system electronics connected, as is shown in Figure 4. During these measurements only the timer and the comparator module of the microcontroller is active for frequency measurement, to simulate no-load conditions. Only by this the correct flow rate can be determined, which then goes linearly with the rotational frequency of the turbine. The lower limit of 6 l/min was chosen, because from this flow rate on the system is capable of transmitting data once per second. The pressure drop between inlet and outlet, as a function of flow rate were also measured, without electronics connected (see Table 2). The pressure loss for 15 l/min is 360 mbar, while for 5 l/min it was measured to be 30 mbar. This shows the gain in performance achieved by the optimized turbine housing, as the original system, according to the datasheet requires a pressure drop of 0.6 bar for start-up.

![Figure 3. Measured output power (solid) and rotational frequency of the turbine (dashes) vs. load resistance for two flow rates. The optimum load is in the range of the generators internal resistance (185 Ohm). The rotational frequency of the turbine decreases with smaller load resistances.](image)
Table 2. Measured pressure drop between inlet and outlet, with disconnected electronic.

| Flow rate in l/min | 15 | 14 | 13 | 12 | 11 | 10 | 9  | 8  | 7  | 6  | 5  |
|--------------------|----|----|----|----|----|----|----|----|----|----|----|
| Pressure drop in bar| 0.36 | 0.31 | 0.29 | 0.22 | 0.19 | 0.15 | 0.10 | 0.07 | 0.06 | 0.04 | 0.03 |

4. Conclusion and Outlook

A system capable of powering itself from the fluid flow with typical flow rates in domestic application (5-15 l/min) was successfully demonstrated. A great deal of development was put into the power management, with a hysteresis switch cutting off the system electronics from a buffer capacitor for voltages below 3.3 V and enabling operation from ~4 V. The capacitor was laid out such, that one full cycle of measurement and transmission was guaranteed. This ensures, that the BLE module does not undergo any undervoltage situation, which otherwise may be permanently damaged. Since for high flow rates the generator can easily deliver 100 mW and voltages above 20 V, the system electronics was protected by an active shunt resistor, if buffer voltages exceeded 5 V. The turbine shows strong feedback onto the flowrate depending on the electrical load, therefore measurements are conducted with only very light load, i.e. only the microcontroller’s timer and comparator module is used. The power measurements show, that for flow rates of only 4 l/min enough power is available. However, at this rotational speed the generator only produces voltages of ~3.7 V (the voltage drop over the diodes is around 0.3 V), which is too small to charge the capacitor to the needed 4.0 V.

To conserve the energy below and above the supply voltage, in future a small battery will be integrated into the system, in combination, with a Delon voltage-doubler or a buck-boost converter. Further this would allow for more functionality, like a full, synchronized and encrypted BLE connection, unlike the advertisement mode which is currently used to save power. In future several other signal acquisition lines, such as for water temperature and pressure drop will be implemented into the system, which will enable the user to be provided with more data for saving hot water and giving feedback via Bluetooth Apps on the smart phone, or into a home automation system. Perspective even an automatic control of valves could be implemented, for a fast flow regulation in shower rooms (e.g. in a gym), so that the water temperature can remain more constant for all users.

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