Energy Harvesting from Fluid Flow in Water Pipelines for Smart Metering Applications

D Hoffmann¹, A Willmann¹, R Göpfert¹, P Becker¹, B Folkmer¹ and Y Manoli¹,²
¹ HSG-IMIT – Institute of Micromachining and Information Technology, Wilhelm-Schickard-Str.10, 78052 Villingen-Schwenningen, Germany
² Fritz Huettinger Chair of Microelectronics, Department of Microsystems Engineering – IMTEK, Georges-Koehler-Allee 102, 79110 Freiburg, Germany

E-mail: daniel.hoffmann@hsg-imit.de

Abstract. In this paper a rotational, radial-flux energy harvester incorporating a three-phase generation principle is presented for converting energy from water flow in domestic water pipelines. The energy harvester together with a power management circuit and energy storage is used to power a smart metering system installed underground making it independent from external power supplies or depleting batteries. The design of the radial-flux energy harvester is adapted to the housing of a conventional mechanical water flow meter enabling the use of standard components such as housing and impeller. The energy harvester is able to generate up to 720 mW when using a flow rate of 20 l/min (fully opened water tab). A minimum flow rate of 3 l/min is required to get the harvester started. In this case a power output of 2 mW is achievable. By further design optimization of the mechanical structure including the impeller and magnetic circuit the threshold flow rate can be further reduced.

1. Introduction
The application of an automatic remote water meter reading technology requires low-cost, secure and reliable communication solutions being independent from the electricity infrastructure. The wireless M-Bus is one of the possible solutions for water utility companies to address the special requirements of home utilities by providing a technology, which is independent from the electricity infrastructure, in terms both data communication and power supply. In this context a cost-efficient integrated energy harvesting system was developed converting energy from the available water flow in water pipelines. This enables operation of the water meter reading system independently of the main grid and eliminates the need for battery replacement.

Power generation from fluid flow confined in pipelines is not a new concept [1]. In the past, a lot of work has been done in particular in the area of pressurized gas flow. In this case mesoscale turbines with rotational speeds up to 600000 rpm were developed for power generation [2]. However, power generation systems, which can be integrated in conventional water meter devices fulfilling the power requirements of wireless water meter reading solutions based on the wireless M-Bus, are rarely to find. An automatic water meter reading system requires both permanent data acquisition and periodic data

³ To whom any correspondence should be addressed.
communication. This should work independently from the energy available at particular times. As a consequence, an energy harvesting system is required, which generates and stores sufficient energy at times of water flow. Therefore, the energy harvester proposed in this work is based on an impeller wheel, which is directly coupled to an electromagnetic energy transducer. When water flow occurs, the impeller starts to rotate driving the transducer.

2. Design and Implementation
The presented rotational, radial-flux energy transducer incorporates a two-pole ring magnet and three induction coils connected in a star circuit (figure 1a). Iron core elements are used for concentrating the magnetic flux in the coils. The two-pole ring magnet is directly mounted on the impeller wheel. This particular three-phase structure was chosen for the following reasons: low-cost design, increasing the active volume with respect to the given design space, reducing cogging torque and ease of integration into conventional water meter housings including the impeller.

Table 1. Parameters of the radial flux energy harvester.

| Parameter                  | Value   |
|---------------------------|---------|
| Outer diameter of ring magnet | 20 mm   |
| Inner diameter of ring magnet | 6 mm    |
| Height of ring magnet         | 8 mm    |
| Outer coil diameter           | 17 mm   |
| Inner coil diameter           | 9 mm    |
| Coil length                  | 20 mm   |
| Length of iron core           | 17 mm   |
| Wire diameter of coil         | 0.2 mm  |
| Internal resistance of coil   | 37 Ohm  |
The complete design of the radial-flux energy harvester is shown in figure 2. The electromagnetic transducer is mounted directly on top of a water meter housing. When the induction magnet starts to rotate, a magnetic flux inversion in the iron cores are generated. This leads to the induction of a three-phase voltage and current in the coils. The induced voltage is then proportional to the rate of change of the magnetic flux density. With respect to a fixed load resistance connected to the coil, the power output increases with the rotating speed of the induction magnet.

The implementation of the flow energy harvester is shown in figure 2b. The power management and the battery storage are accommodated in the cap, which is mounted on top. The complete system was designed with respect to the given requirements (electrical parameters, robustness, integratability, costs).

For optimizing the coil parameters a parametric system model was developed in Matlab based on analytical equations. The magnetic flux density in the coil was numerically calculated using the FEMM tool (figure 1b). When the magnetic axis of the ring magnet and the axis of one of the coils get aligned, the magnetic flux density becomes maximal. In this case the maximum average magnetic flux density in the coil is 0.38 T. The minimum average magnetic flux density is about 8 µT and occurs when the magnetic axis is orthogonal to one of the coils. For the electrical part of the model a circuit including a single coil and a load resistor was considered. Voltage and power was then calculated with

Table 2. Experimental Measurements: the voltage was measured over the optimum load resistance of 70 Ohm

| Flow rate (l/min) | Pressure drop (bar) | Voltage (V) | Power (mW) |
|------------------|---------------------|-------------|------------|
| 3                |                     | 0.4         | 2          |
| 5                | 0.1                 | 1           | 15         |
| 8                | 0.4                 | 2.3         | 76         |
| 10               | 0.6                 | 3.2         | 150        |
| 12               | 0.9                 | 4           | 228        |
| 15               | 1.4                 | 5.3         | 400        |
| 17               | 1.8                 | 6.2         | 546        |
| 20               | 2.2                 | 7.1         | 720        |
3. Experimental
For experimental characterisation, the axial-flux energy harvester was connected to a conventional domestic water pipe line (4 bar static pressure). In this set-up the flow rate can be varied between 0 l/min and 20 l/min. During the power measurements the pressure drop over the energy harvester was also measured. The voltage and power output were measured over a load resistor, which is connected to a three-phase rectifier. The optimum load resistance was 70 Ohm (see figure 3a). The measurement data is summarized in table 2. For a flow rate as low as 3 l/min a power output of 2 mW was measured. The corresponding pressure drop was not detectable. With increasing flow rate the voltage output and thus the power output increases accordingly. A maximum power of 720 mW was generated at a flow rate of 20 l/min. At this flow rate a pressure drop of 2.2 bar was measured over the energy harvester.

In figure 3b the power output (simulation and experiment) is shown with respect to a load resistance connected to a single coil. The predictions by the simulation model are in close agreement with the experimental results. The power output increases with the flow rate in a non-linear manner.

4. Conclusions
In this contribution we have presented a low-cost rotational radial-flux energy harvester based on a flow-driven impeller wheel and an electromagnetic energy converter incorporating a three-phase coil circuit. The energy converter was designed for easy integration with commercial water flow meters to harvest energy from water flow in domestic water pipe lines. The harvested energy is used for powering smart water meter systems. The power output ranges from 15 mW at 5 l/min to 720 mW at 20 l/min. At flow rates smaller than 5 l/min the power output becomes very low. In this respect, the design of the power characteristic of the energy harvester becomes an important step in line with further device optimization. Here we aim to achieve a more constant power output, which is supposed

![Figure 3](image-url)

**Figure 3.** a) Voltage output over optimum load resistance as a function of flow rate (the three coils are connected by means of a full-wave three-phase rectifier; the load resistor is connected to the output of the rectifier. b) Power output over optimum load resistance (40 Ohm) as a function of flow rate (load resistor is connected to a single coil).
to be less dependent on the flow rate. This can be achieved, for example by a fluidic bypass. To accomplish higher power output at lower flow rates the frequency of the system requires to be increased. This can be realized, for example, by utilizing a multi-pole magnet.

The power management including a battery charging circuit as well as the overall concept of an automatic water meter system will be presented in a separate contribution.

Acknowledgments
The authors would like to thank all project partners for the excellent cooperation. The project is co-funded by the European Commission under reference number FP7-SME-2011-286753.

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