A Literature Review on Self-Powered Fluid Flow Measurement

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Abstract— **This paper aims to provide an overview of the work conducted so far in the domain of Self-Powered Fluid Flow Measurement (SPFFM) systems, with a focus on systems involving the metering of water and Automatic Meter Reading (AMR) abilities. It provides a brief on the key concepts and approaches involving Fluid Flow Measurement in such systems, the challenges around Self-Powering such setups, and avenues for the potential for future work and development in the field.**

INTRODUCTION

Fluid Flow Measurement has been an important part of instrumentation since its advent because of its critical application in the monitoring of Industrial applications. More recently, with the increase in human populace and the growth of cities, its application has extended to the monitoring of water consumption and leakage detection in Water Distribution Networks (WDN) [4]. The technology currently deployed in monitoring such networks involves Manual Meter Reading (MMR) and as we move towards building smart cities, there is a need to replace them with AMR systems. This cuts down labor and maintenance costs, improves accuracy and analysis abilities by centralization, and consequently equips cities and citizens to understand and deal with water supply demand challenges.

However, developing an AMR Fluid Flow Measurement system possesses a new set of challenges:

- The system needs to be electro-mechanical or completely electronic in its construction and hence requires an electric power source.
- It needs to be able to process and transmit the collected data wirelessly.
- The electronics involved need to have waterproofing.
- The system needs to be robust mechanically and electronically.

While there a many who have designed relevant AMR solutions that cater to these needs, there is still one prominent challenge associated with these systems, that is, they often need to be installed at remote locations where power is not accessible. This sets the motivation to pursue the development of AMR-based Self-Powered Fluid Flow Measurement systems. These systems do not require any external source of power and are generally optimized to be powered by using a battery backup and energy harvesting electronics that source from the flow of water.

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OVERVIEW

The first section of this paper will provide a brief background on the fluid flow meters that are relevant to SPFFM systems and their principle of measurement. The second section will provide a review of the latest research & work that has been conducted in the domain SPFFM. The third section discusses the challenges and avenues for future development in the field before concluding.

I. TYPES PRINCIPLES OF FLUID FLOW MEASUREMENT

There is a wide variety of principles and their congruent flow meters that are utilized for the volumetric flow rate measurement.

The most traditionally used are the differential head type flow-meters, with a heavy utilization in industries due to high accuracy, precision, and robustness for a wide variety of industrial applications. These are based on the principle of differential pressure at two points in a fluid due to a difference in fluid velocity. However, they are not very suited for WDNs due to their complex installation requirements, conditions, and maintenance.

A similar reason also follows for Variable Area type Rotameters Meters, in addition to their inaccuracies [2][3], or Mass Displacement type Inertial Mass Flow Meter which in addition require complex conditioning and robustness [3], or Ultrasonic & Electromagnetic type meters which are subject to variables like fluid bubbles, conductivity, and power-consumption [2].

The two more recently developed electro-mechanical fluid flow meters are Vortex and Coriolis flow meters. The former positive-displacement type flow meter has been promising due to its robustness due to no moving parts and high accuracy [2]. It utilizes the von Karman effect which involves the generation of a stream of alternating parallel fluid vortexes by an obstruction shedder, leading to fluid vibrations detected as frequency changes by a transducer. On the other hand, the latter Mass-displacement type, also offers high accuracy and detection of additional variables such as density and viscosity [3], utilizing the conservation of angular momentum of fluid on a free-suspended mass of fluid, detecting its net phase change to small impulses by an actuator.

However, neither has been utilized for the purpose of an SPFFM system to the best of our knowledge yet. The flow meters utilized so far in SPFFM meter designs have been in Turbine-Generator based flow meters [4][5][7][8][9]. This is primarily due to their easy integration with pipes, the relative simplicity of use, reasonable accuracy for WDN, and most importantly the ability to act as a source of power simultaneously.

II. Design Considerations and Approaches

A. Turbine Design

An important consideration to maximize power generation efficiency was the design of the turbine or impeller that rotated the generator. One design used a 7-wheel Pelton wheel steel roller bearing coupled design [4] based on the experimental findings of [7], which concluded that 7-wheel semi-spherical blades with a radian curvature of 0.5 for pipes less than 50 mm in diameter, higher attack angles (0 - 36 degrees) for pipes in the size range 50 - 300 mm, and a double propeller (generator front-back mounted) shaped design for pipes greater than 300 mm, with a perpendicular installation. Furthermore, Miroslav Cink's cross-flow radial turbine design was also presented by [10] to improve efficiency by increasing the fluid's contact time with Turbine and preventing reverse and overflow issues.

B. Generation Design and Power Generation

Generator construction features were critical to maximizing generation and efficiency. All proposed systems involved 3-Phase Generators for maximizing output [4][5][8][9]. [7] suggested surrounding the turbine magnets with a metal ring to reduce flux leakage, reporting an improvement of 300% over for turbines to be installed in large pipes (> 300m).

A roughly linear trend was observed between flow rate and power generation in [4][5][8]. The 12-winding generator design in [4] achieved an efficiency of 50%, generating 5.3 V, 25 mA, and 0.13 W of power for a flow rate of 10 L/min and a maximum of 21 V, 115 mA, and 2.39 W at 45 L/min. [5] used a star-circuit 2-pole ring-magnet induction generator sourced to an 83% efficiency energy harvesting circuitry, allowing a power transfer of 0.15 W at 10 L/min, maxing out at 0.3 W at 19 L/min. [8] designed an 8-Pole 6-Slot coreless cogg-resistance free axial-flux permanent magnet (AFPM) generator rated for 1 W at 1200 RPM, and using only one phase it was able to power its setup that involved no wireless transmission for 720s given an energy harvesting period of 18s at 10 RPS.

Furthermore, [8] [9] also demonstrated the longer terms feasibility of using an existing commercial use 12V-10W micro-turbine generator after little modification to generate sufficient power for an SPFFM system with strong optimizations and a compromise of 1 meter reading per hour with the wireless transmission in the case of [9]. Strong optimizations and analysis were also conducted in [4].

C. Energy Harvesting & Regulation Mechanism

Given that the turbine generators proposed in the reviewed studies involved 3-Phase generators, an efficient mechanism to rectify, use and store this energy was essential. [4] used a full-bridge to rectify the AC phase coupled via a high-freq transformer to charge AAA Na-Cd batteries and isolate the circuit-load from the turbine generator while the electronic circuitry performed other operations, while supply was regulated via an ultra-low dropout regulator to minimize losses. On the other hand [5] presented a more mature design using Lithium polymer batteries and features involving over-voltage protection, deep-discharge protection, battery charging, and monitoring, voltage conversion, and safe-start, active & sleep modes, with the aid of LTC2935 power management IC. Unexpectedly, [8] proposed a battery-free solution that utilized a simple half-wave rectification circuit only utilizing a single phase under the rationale that complete 3-Phase 6 Pulse diode-based or IC-based rectification significantly increased the generator load and consequently torque making it unsuited for operation at lower flowrates, thus bringing into light a unique concern. A 3-Phase 6 Pulse rectifier was also utilized in [9] [10], however no such concerns as those presented in [8] were raised, while [10] did not provide any power analysis results at all.

D. Signal Conditioning

In our review we came across two distinct types of SPFFM systems: one type extracted the power and signal from a 3-Phase turbine flow-meter setup [7][8], while the other type used a small turbine for signal generation, and a relatively larger 3-Phase turbine for power generation [4][5]. The reason for the latter can be speculated around the challenges with AC signal conditioning for accurate detection as seen in [9], where DC rectification of AC signal leads to a voltage drop in the signal and directly detecting the AC signal involved complex filtering techniques for accuracy. In addition, it offered good accuracy only for a flow rate range of 250 - 650 L/hour. Using a separate turbine allowed for a simpler low signal for easier signal processing [4].

E. Calibration

Calibration was not generally a focus point for the scope of most reviewed papers. This is perhaps rooted in the idea that WDNs do not require industrial levels of accuracy. [9] presents only a piece-wise mathematical function between signal voltage and flow rate derived from the experimental data and the accuracy of which is questioned by the paper itself. [9] initially uses a line of best fit based on experimental data of the signal voltage vs tachometer readings, after which the line of best fit was further optimized accuracy by comparing the flow rate and volume of consumption for a fixed volume of water over a time interval.

F. Other Considerations

Another important variable that was found to impact the flow rate accuracy and the flow of water adversely was the pressure loss due to the obstruction that a flow meter or turbine generator device posed by extracting kinetic energy from it. [4] had interesting findings in this regard, and concluded that such a loss was insignificant to have any impact on the flow rate itself or an in-direct inaccuracy.

G. Transmission Method

The last observed consideration for the ARM SPFFM system was found the be the medium of Wireless Transmission. This is an important consideration as wireless transmission can be a major source of power consumption as demonstrated by [4], which utilized the ZigBee technology to achieve an outdoor transmission range of 80 meters and an indoor 30 meters. [5] as a European Commission-funded project, it utilized the Wireless M-Bus Standard doing long-range transmission over the 169 MHz RF band. [8][9] both proposed new technology Bluetooth solutions due to their low power consumption.

III. CHALLENGES AND POTENTIAL DEVELOPMENT AVENUES

In the previous section, we reviewed some of the work that has been done in the domain of Automatic Metering Reading Self-Powered Fluid Flow Measurement systems, and this has enabled us to identify some of the key challenges that revolve around the task and could be worked upon:

- Achieving high flow rate accuracy is still a difficult task because of the challenges associated with complex AC signal conditioning techniques and inaccuracies that are inherited as a consequence of AC-DC Rectification.
- Continuous operation and wireless transmission is still a difficult task and reading needs to be taken and transmitted over large intervals. This is because of high power consumption by sensory devices and more importantly wireless transmission.
- Smart software and hardware integration methods are needed for the optimization of power consumption.
- Long-range wireless transmission still poses a challenge unless on official RF bands, which usually require a very expensive license.
- No method or means of a general or automatic calibration mechanism. Manual Calibration is required for each type of pipe size.
- Reducing moving parts in the system to increase robustness and maintain power efficiency over time.
- Developing auto-calibration methods to cater to multiple pipe sizes.

While keeping these above points in mind we observed that while there were several different approaches and designs that were presented with regard to AMR SPFFM each one of them seemed to improve upon only a few particular aspects. For example, [4][7] only provided good novelty in terms of mechanical turbine design. The results seen with regard to power generation based on generator type did not reflect any strong novelty as the power output results observed were for the most part similar [4][5][7][8][9]. The energy harvesting mechanisms did pose some novelty and bring into light some concerns, [8] reported the issue of a large issue of generator torque under 3-Phase 6 Pulse rectification rendering it unfeasible for low flow rate and was able to function as good as other setups using simple half-wave rectification, in contrast to some form of full-wave rectification as used by others, opening up room for the assessment of these claims. In addition, a wide variety of wireless transmission mediums were also put forth.

In addition to focusing on improving individual factors of SPFFM setup based on these considerations and findings, another avenue for future work could be in the integration and assessment of these presented novelties into a single ARM SPFFM system. Furthermore, there is also fresh room for potential exploration of the feasibility of integrating the relatively new and more accurate flow measurement means such as Vortex or Coriolis into an SPFFM setup.

IV. CONCLUSION

To conclude it was explored that the overall literature on ARM SPFFM seems to be relatively limited for now. This is partly due to the relatively recent but strong need of developing such systems in the context of smart cities and optimizing the usage of essential resources such as water. There is room sufficient room for improving such systems to provide more accurate flow rate measurement, ways of integrating other measurement variables such as density, viscosity, and quality of fluid, integrating more recent flow measurement technologies, means of long-range transmission, etc. These reflect the room for useful work they can contribute to the field and bigger scope of things in novel ways.

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