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Discussion on the development of low power off-grid electromagnetic sensor

***Abstract**. Presented paper describes the problems of the energy consumption limiting the applicability of electromagnetic sensors with electromagnetic sensor dedicated for flow measurements as an example. The initial investigation on the possibilities to use pulse excitation in the estimation of the flow velocity is discussed with respect to the electric model of the sensor as well as a proposal of an autonomous power supply.*

Streszczenie.** Referat prezentuje problematykę zużycia energii ograniczającego możliwości zastosowania czujników elektromagnetycznych na przykładzie elektromagnetycznego czujnika przepływu cieczy. Przedstawiono w nim wyniki wstępnych badań nad możliwością wykorzystania pobudzania impulsowego z uwzględnieniem schematu zastępczego czujnika oraz propozycję autonomicznego układu zasilania. **Ograniczenia możliwości zastosowania czujników elektromagnetycznych na przykładzie elektromagnetycznego czujnika przepływu cieczy

Keywords: electromagnetic sensors, pulse excitation, autonomous supply.
Słowa kluczowe: czujniki elektromagnetyczne, pobudzanie impulsowe, autonomiczne zasilanie.

Introduction

Distributed systems for the environment monitoring are made of measurement stations installed in remote locations, where the power grid is usually unavailable. As a result alternative power sources are necessary, which often rely on renewable energy. Unfortunately such sources do not offer high energy density levels, so the size of power stations are quite considerable. This implies the tendency to minimize the power requirements and simultaneously to increase the efficiency of a power station itself, yet retaining the quality and confidence level of the gathered sensor data.

Measurement stations can include different sensor types, including electromagnetic ones, which inherently require considerable amounts of energy to generate the magnetic field of a required magnitude. A good example of such a sensor is an electromagnetic flowmeter, which pushes both the power supply and signal processing requirements to the limits. The paper presents the initial results of a research aimed at reducing the power requirements of a flowmeter, thus making it possible to use such sensors in a distributed system.

In a broad aspect the presented work is an attempt to modify the existing solutions in order to meet the requirements of wireless measurement networks. By analyzing the problem, two key aspects have been outlined that require a completely new approach. First, a complete modification of measurement algorithm which will enable lower power usage. It requires a totally new way of magnetic field excitation and processing of measurement signal. Second aspect is to provide a suitable power supply based on renewable energy sources, which will make the sensor independent from a fixed power grid.

Status quo of the electromagnetic sensor

Electromagnetic flowmeters, despite their obvious advantages as measurement devices, were never considered to become a part of wireless, distributed sensor networks. The main obstacle was high power requirement, resulting from the need to create the measurement conditions in which the unbiased, low-variance estimator could be applied. Required conditions are traditionally created by such AC excitation of a coil, for which in certain time intervals of flow measurements the derivative of magnetic field is zero. The commonly applied measurement algorithm utilizes then the mean values of the voltages induced across the measurement electrodes in certain time intervals. Other approach, utilizing the Markov estimator, is less restrictive to the magnetic field excitation and provides better ratio of flow measurement uncertainty to the required coil excitation power. Nevertheless the stationary state of the coil excitation current must be maintained regardless of the applied measurement algorithm, which means that the excitation source of relatively high power have to be applied in both cases.

Experimental setup

The idea of low-power excitation of primary transducer coil was tested in a proposed laboratory setup presented in Fig.1, which shows the scheme of a flow channel with exciting coil used for the generation of magnetic field. The channel itself was previously used in earlier research [1-4] where the controlled current source was used for a quasi-constant excitation. Those earlier works made it possible to estimate the power requirements to achieve the desired 2% measurement uncertainty. Only for the measurement period of 0.6 ms it was about 26VA. The total power needed for magnetic field generation and drawn from the power line was about 93VA. Taking into account initial excitation time required for the transient state to disappear (at least 10 periods of 5Hz excitation frequency – 2 seconds) the total energy required for a single measurement is (2[s]+0,6[s])·93[VA]≈240[J]. The analysis presented above leads to the conclusion, that the power supply chain should be as simple as possible in order to achieve fast energy transfer to the coil with minimum number of intermediate stages. As a result, as it is shown in Fig.1 the keyed chemical DC power source was applied witch internal resistance R_w and output voltage at terminals of 12V.

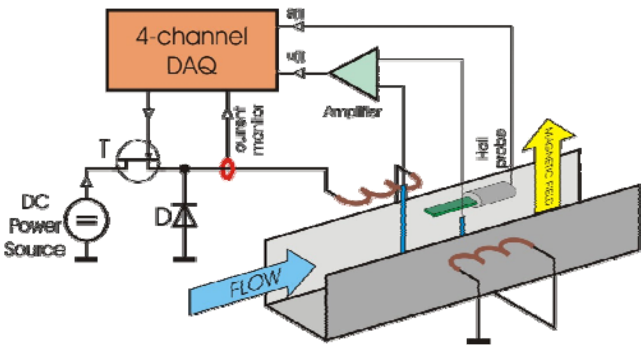

Fig. 1. Experimental setup of the laboratory model.

The recorded values of coil current and voltages across the electrodes provide measurement information and diagnostic data on sensor condition. The amplifier provides high CMRR coefficient, high input resistance (to minimize load effect) and filtering of low-frequency disturbances caused by electrochemical and electro-kinetic processes in a contact zone between moving fluid and the electrode. Electronic keying switch T regulates the energy flow to the coil and it is driven by a control pulse of selected duration. Diode D maximizes the energy transfer and acts as discharge diode, which enables to use the energy of a magnetic field in the time instant when the supplying voltage is cut off.

Electrical parameters of the sensor

Proposed pulsed excitation requires the knowledge about electrical properties of the sensor and the parameters of its equivalent circuit diagram, which is presented in Fig.2.

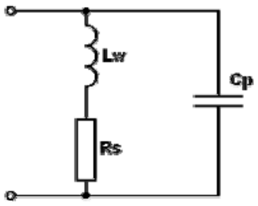

Fig. 2. Substitute scheme of the sensor.

In general case the parasitic capacitance of the coil C_p may be important. This capacitance is a potential cause of energy loss because it is being charged by high-energy current pulses, which in that case do not contribute to magnetic field generation. Large value of parasitic capacitance may require additional forming of excitation current pulses in order to minimize energy loss. Electrical parameters of a laboratory transducer were determined on the basis of resistance and inductance measurements carried in broad frequency range by means of LCR-821 meter by GW Instek. The results show that the inductance is practically constant up to 10 kHz and is equal to the self-inductance L_w. The influence of the parasitic capacitance on the measured inductance of a transducer can be observed above 10 kHz, thus for the low frequency range only self-inductance is considered. Its value, determined as mean value from the measurements conducted in the frequency range up to 3 kHz is L_w=35,24mH. The serial resistance value R_s was measured in a similar manner, giving the result of 3.43Ω. For a diagram presented in Fig.2 the resonant angular frequency ω_{SRF} can be approximated by a following equation:

(1) $$\omega_{SRF} \approx \frac{1}{\sqrt{L_w \cdot C_p}}$$

Then, by approximating the inductance changes with frequency according to the following relation [5]:

(2) $$L(\omega) \approx \frac{L_w}{1-(\omega/\omega_{SRF})^2}$$

It is possible to determine the resonant angular frequency for a given value of L_w and then, on the basis of (1) to calculate the parasitic capacitance C_p. The capacitance value derived by the aforementioned method was 0.21nF. It can be concluded that for such values of electric parameters and step excitation, the stationary state of coil current will be obtained after about 50ms (duration of 5 time constants $L_w/(R_s+R_w)$). Simultaneously the charging of a parasitic capacitance (assuming the coil and leads resistance R_w below 1Ω) will take about 1ns, which is $5\cdot10^7$ times faster. Thus, bearing in mind the duration of applied current pulses, it can be said that the influence of parasitic capacitance charging on energy balance can be neglected in the presented measurement system.

Experiments

In order to test the operation of a flowmeter in a measurement setup shown in Fig.1, the coil currents and induced voltages were recorded for 5 flow velocities and 4 durations of exciting voltage pulses. Data acquisition frequency was set at 10 kHz. Waveforms of the coil current are depicted in Fig.3. From those plots the exponential current escalation can be observed for a step voltage excitation and positive current peaks that corresponds to the opening of the electronic keying switch. The amplitude of those current peaks increases with the duration of excitation pulses. Occurrence of those current peaks is suspected to be the result of energy discharge through the diode which has non-linear internal resistance, lower than the combined resistance of energy source and keying switch.

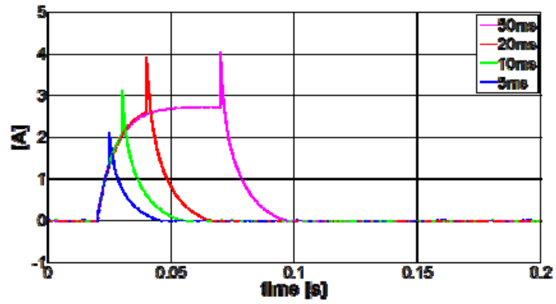

Fig. 3. Current pulses for different durations.

The amounts of energy drawn from the source can be easily calculated for each pulse duration by knowing the voltage and performing numerical integration of the recorded current waveforms. The calculated energy values are presented in Table 1.

Table 1. Energy consumptions for different pulse durations.

[ms]	50	20	10	5
[J]	1.40	0.43	0.15	0.05

The averaged values of induced voltages (which are the output signals of the flowmeter related to flow velocity) are presented in Fig. 4. (excitation pulse duration 20 ms). Due to transformer effect [6] and the influence of measurement amplifier the shape of the recorded waveforms differ from the shape of current pulses. But clear monotonic dependence between the amplitude and flow velocity can be observed, which makes it possible to apply simple measurement algorithm.

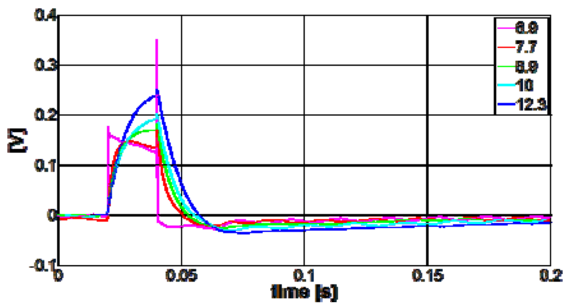

Fig. 4. Induced voltage waveforms for 20ms pulse duration and different flow velocities given in [cm/s].

It can be seen from the Table 1 data that the amount of supplied energy can be reduced by shortening the duration of excitation pulses. Unfortunately such an approach leads to the significant modifications of the shape of output signals which in turn increases the requirements for the applicable measurement algorithm.

Proposal of the power supply

Calculated power requirement for the modified electromagnetic flowmeter is expected to be a several per cent of that required by traditional solutions.

Because of the nature of typical locations where flowmeters are usually installed (remote, with limited availability of fixed power network), the autonomous power supply based on renewable energy is strongly considered, consisting of photovoltaic cells, small wind turbine, fuel cells and classical battery acting as energy buffer and storage. Controlled by an appropriate electronic circuit such a setup is able to provide the required level of electric energy [7]. In Poland the average amount of available solar energy is about 1000 kWh/m^2 per year, meaning about 1600 hours of insolation (5.5 hours a day, on average) that can be used by a solar cell. The main problem, however, is not the low energy density, but significant changes of available energy levels during day, month and year cycles, varying from 18 kWh/m^2 in December to about 155 kWh/m^2 in July. Those factors together with the efficiency of solar cells mean that the delivery of 1W of constant power all year long requires a solar battery with a peak power of 40 W. Wind energy is also very unstable in both time and space. Average wind velocity in Poland is several m/s and it also strongly depends on the region and a height above the ground. It is important, however, that usually wind is stronger when the sky is clouded (the amount of available solar energy is then limited), which makes these two energy sources complementary to some extent. Yet, the application of a backup energy source in the form of a fuel cell seems inevitable.

The proposed concept of an autonomous, hybrid power supply system (Fig. 5) consists of solar panels, wind turbine and a fuel cell with a classic battery (lead-acid or Li-Ion) as an energy storage.

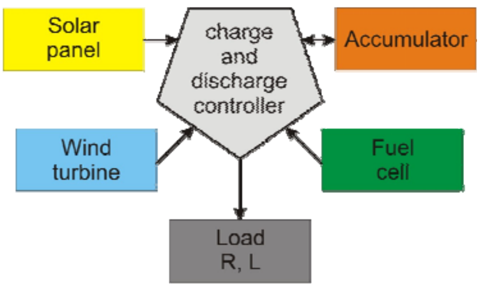

Fig. 5. Autonomous power station for pulse-excited electromagnetic flowmeter

Accumulator charging/discharging process will be controlled by a specialized electronic control circuit, able to optimize the energy transfers taking into account the maximum output power and optimal working conditions of an accumulator. As a result the total system efficiency will be increased, especially during winter season and in case of deep accumulator discharge. The aforementioned control circuit will also supervise the operation of a fuel cell, switching it on to charge the battery and off when the optimal accumulator voltage will be reached. The voltage can be monitored and thus the amounts of energy sent to the accumulator can be precisely adjusted.

In the presented solution the application of a polymer DMFC fuel cell (Direct Metanol Fuel Cell) is proposed. This device uses methanol as a fuel instead of hydrogen. The range of operating temperatures for this type of a fuel cell is from −20 to +45 ^{0}C and theoretical efficiency of 5 kWh per 1 dm^3 of methanol. Assuming real energetic efficiency of 30% the available energy level of 1.5 kWh/dm^3 can be expected. Commercially available fuel cells (like EFOY Pro 600) provide 600Wh per day with 25W of output power and output voltage of 12V or 24V. High-capacity accumulator or a set of supercapacitors can be applied as an energy buffer.

The presented concept of the autonomous, renewable energy power supply and the new method of signal processing for pulsed excitation of electromagnetic transducer can be widely applied for sensor networks, not only for electromagnetic flowmeters.

Conclusions

The final results of the research, apart from the modification of existing design of a flowmeter, will be the development of a whole family of integrated power supply units based on renewable energy sources. Such devices can be adopted not only for electromagnetic flowmeters, but also for other wireless, distributed sensor networks. In Author's opinion the presented solutions will greatly help to overcome the energy issue, one of the main factors preventing the electromagnetic flowmeters from being widely used for flow measurements in open channels. The unique concept of a modified electromagnetic flowmeter will be the meaningful and well-documented result of the conducted research, which will be further, verified experimentally using the prototypes created by and in possession of the Authors.

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