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## Energy consumption estimation of low-power devices using an integrating coulombmeter

**Abstract.** The main problem in designing devices powered with Energy Harvesting is an estimation of energy demand of low-power devices as well as quantity of energy provided by the selected energy transducer in the assumed work conditions. Due to the work characteristic of each block of the device and properties of the measured signal, measurement is not trivial. The paper presents the proposal of the micro-charge measurement device based on an integrating coulombmeter.

**Streszczenie.** Główną trudnością w konstrukcji urządzeń zasilanych energią ze środowiska jest oszacowanie zużycia energii przez urządzenie mikromocowe oraz ilości energii dostarczonej przez wybrany przetwornik w założonych warunkach pracy. Ze względu na charakter pracy poszczególnych bloków oraz właściwości mierzonych sygnałów, pomiar nie jest trywialny. Artykuł przedstawia propozycję układu pomiaru ładunku na bazie kulombometru całkującego. (Szacowanie poboru energii układów mikromocowych z wykorzystaniem kulombometru całkującego).

**Keywords:** micro-energy measurement, energy harvesting, coulombmeter, low-power devices.

**Słowa kluczowe:** pomiar mikroenergii, pozyskiwanie energii ze środowiska, kulombometr, urządzenia mikromocowe.

### Introduction

Energy Harvesting (EH) systems belong to a class of devices collecting the energy available in the environment and supplying it to the powered device. Collecting other forms of energy (such as solar energy, kinetic energy, the energy of mechanical vibrations or electromagnetic field) [1] enables the construction of devices that do not require conventional power sources. They can work in places difficult to access without additional service. This is possible under the condition of an efficient processing of energy from the forms available at the place of installation into electrical energy. Typical applications include sensor network nodes, elements of the installation smart home, recorders of transport conditions, systems for monitoring various parameters [2-5]. Figure 1 presents the concept of the device powered with energy harvesting.

Most similar systems can be divided into three basic blocks [6]. The first is the energy converter converting other forms of energy into electrical energy - it may be a piezoelectric element (vibration), antenna (EM field) or set of thermocouple (temperature difference) [7]. The system can have more than one type of converter. Average energy supplied by the converter normally does not exceed tens of microwatts. It is often received in pulses of hard to predict parameters, so it requires processing and storage. It is the role of energy management block in the composition, which includes specialized DC/DC converter adjusting the source voltage level to the required level by the micropower system. Storage block, in the simplest case, if access to energy is continuous, can consist of a capacitor. If access to energy is irregular, one can use supercapacitors or batteries recharged during periods of surplus energy. The aforementioned two blocks are responsible for the reliable supply of the third – micropower system implementing proper functionality.

The main difficulty in constructing devices powered with Energy Harvesting is an estimation of energy demand of low-power devices [8, 9]. The knowledge of quantity of energy provided by the selected energy transducer in the assumed work conditions is also necessary. The mechanical properties, such as the method of fixing or the resonance of the mechanical converter have an essential influence on the amount of collected energy. The simplest method is the experimental selection of parameters for the specific application.

The energy measurement is required at the connection among each of the three blocks (on Fig.1. it was marked as „E” meter). Due to the nature of the blocks work and the properties of the measured signals, realization of the precise measurement is not trivial, in the paper, Authors propose to estimate this energy by the measurement of the charge consumed by the micropower circuit (or produced by Energy Harvesting source).

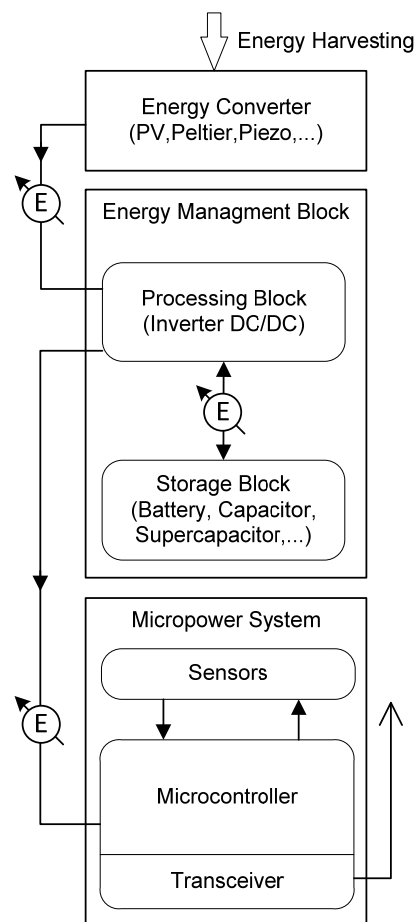


Fig.1. Block diagram of the device powered with energy harvesting from an environment

### Review of micro energy measurement methods

The average power consumption the low-power system is typically calculated in microwatts. Such low power consumption can be achieved even using standard components (microcontrollers), because the device for most of the time is inactive and majority of blocks do not work. States of full activity occur very short, a small percentage of the work time. Accurate measurement of the energy consumed by a typical micropower system is problematic - measuring device must have a large dynamic range. It is assumed that the measured currents can be varied by at least two orders of magnitude. There must be a wide band width due to the fact that a large current is consumed in a very short time (pulse). Similar requirements determine the measurement of the energy supplied from alternative sources. Electrical energy available at the output of converter usually appears irregularly in pulses of varying intensity of current and different voltages. Equally unpredictable is the time characteristics.

Basically, the energy measurement can be made according to the definition (1):

$$(1) \quad E = \int u_s(t) i_s(t) dt$$

where:  $u_s(t)$ ,  $i_s(t)$  – temporary values of supply voltage and current, respectively in  $t$  moment of time.

Integration is performed over the desired period of time giving the estimated energy consumed (or produced) during that period.

It was considered to realize energy measurement according to the block diagram presented in Fig. 2. The method assumes sampling the signals of supply voltage and current and performing multiplication and integration numerically [8].

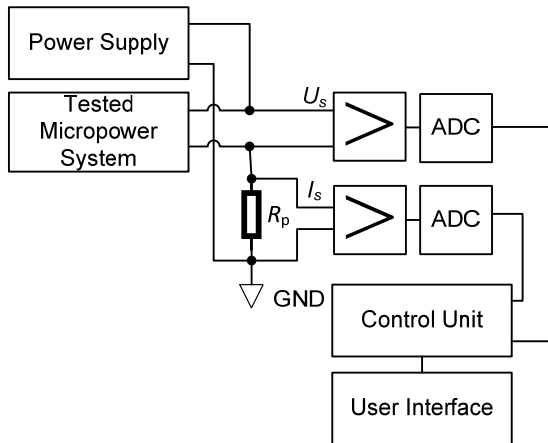


Fig. 2. Block diagram of circuit for energy measurement based on signals sampling and numerical integration

However, such measurement method has a number of drawbacks. According to the sampling theorem, ADC sampling frequency must be at least two times greater than the highest frequency component of the sampled signal. Because of the pulse nature of the waveform, the frequency spectrum is continuous. It means the necessity of anti-aliasing filters use, that is leading to a contradiction. On the one hand, the widest possible range is required, on the other hand, the frequency response must be properly limited. In this construction, a narrow pulse of current of large value would be transmitted with a large error. Another requirement would be a very fast microcontroller in the control unit. A numerical integration errors should be also taken into account.

For the above mentioned reason, it was decided to measure the energy using different approach. Let make an assumption, that during the integration period, the supply voltage can be treated as constant (usually it is in fact stabilized) and equal to  $V_{cc}$  as written in (2):

$$(2) \quad u_s(t) = V_{cc} = \text{const}$$

Rewriting (1) with the use of assumption (2), we obtain (3):

$$(3) \quad E = V_{cc} \int i_s(t) dt$$

The part of equation (3) containing the integral represents the charge consumed by the micropower circuit (or produced by the EH source). The charge counting method concept is shown in Fig. 3.

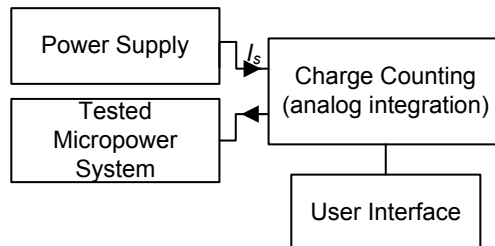


Fig. 3. Block diagram of circuit for energy measurement based on charge counting (analog integration)

Charge counting method gives more reliable results than the voltage and current measurement, even using high-speed A/D converters. In addition, hardware implementation is cheaper (without sophisticated A/D converters), and writing the software effort is lower. Integration takes place in analog in the same measuring system. Measurement of charge can be carried out liberally long directly obtaining the current average for the period. Using the charge meter we can also conduct indirect measurement of energy, avoiding the errors of numerical calculations and only using the properties of the system and passive components.

The paper [10] shows the implementation of a charge measuring method using current mirrors. The method idea is presented in block diagram shown in Fig. 4.

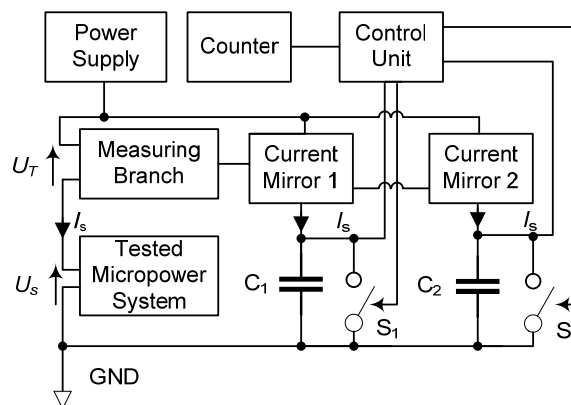


Fig. 4. Realization of charge counting method for energy measurement based on current mirrors

Supply current of the tested system flows through the measuring branch. By dint of the current mirror 1 and 2, the same current charges one of the capacitors  $C_1$  or  $C_2$ . The second capacitor at that time is discharged by a switch  $S_1$  or  $S_2$ . After charging the capacitor to a specified voltage, keys are switched to the opposite position and a portion of

charge stored in the capacitor is counted. The presented idea was evaluated by simulation means as well as experimentally on the realized prototype. The simulations were performed using NI Multisim 14 [11].

Figure 5 prove a linear relationship between the measured current and the charge count, of course, within certain limits.

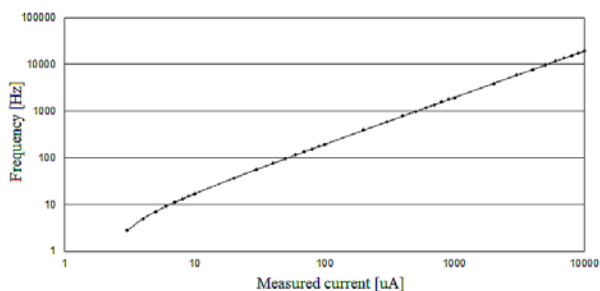


Fig. 5. Relationship between charge counts and current for analog charge integration method

Unfortunately, problematic is using the circuit in this form to measure the amount of energy generated by the EH source, because the measured current is flowing out of the system (delivered to the load which can be a low-power system). The problem is related to the deposition  $U_T$  voltage (about 2 V) in the measurement branch.

#### Modification of the charge counting method using current mirrors

A simple elimination method of the above mentioned disadvantages by using an additional voltage follower and a current source providing an initial polarization is proposed in [12]. Figure 6 shows a block diagram with additional elements.

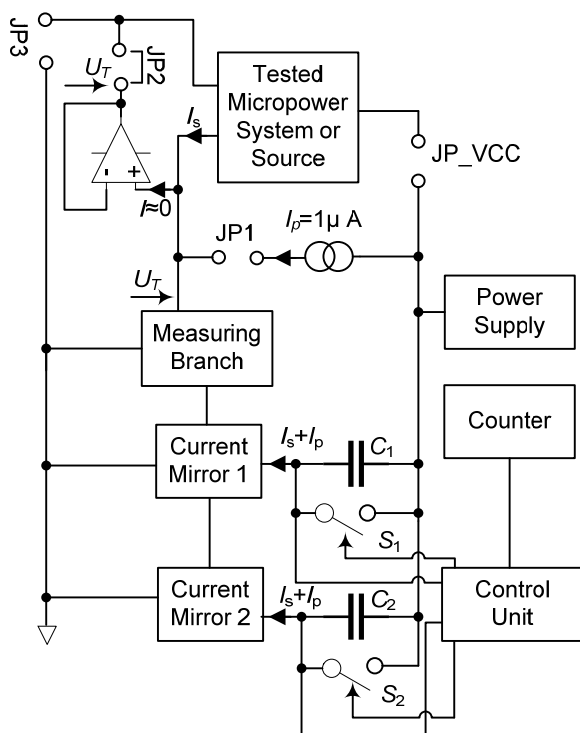


Fig. 6. Block diagram of modified method for energy measurement based on charge counting (analog integration)

Jumper settings are dependent on the currently executing measurement. If a source is being tested we have to use jumpers JP1 and JP2, then current flows between the voltage follower output located on the potential  $U_T$  and the input of the measuring branch, which is also located on this potential through an initial polarization of the current  $I_p$ . To measure current flowing out of the system we have to use jumpers JP\_VCC and JP3.

The schematic diagram of the circuit realizing the modified method is given in Fig. 7. Components of the prototype were selected through simulation tests and verified experimentally in order to minimize thermal drift (especially in the input circuit) and to obtain the best linearity. The transistor T12 and the involved elements form the source of a capability of about 1  $\mu$ A, which pre-polarises input transistors T1 and T2 thus forcing voltage drop close to 1.6 V. Voltage is repeated by voltage follower U4. In order to investigate the correctness of the concept, cheap operational amplifier with modest parameters (LM358) was used. Additional elements allowed the study of sources of lower voltage than  $U_T$ . From the input terminals, measuring system is virtually short-circuit. The measured DC input resistance is less than  $2\Omega$ , so the circuit inclusion between tested energy source and the energy consumer should not significantly interfere the measurement. The voltage drop as seen from the terminals of the measuring is equal to voltage imbalance of the used operational amplifier over the entire range of measured currents (nearly 400 nA to 10 mA). The proposed solution has also disadvantages. Figure 8 shows that the preliminary polarization the system causes permanent shift of the characteristics of current to frequency ratio.

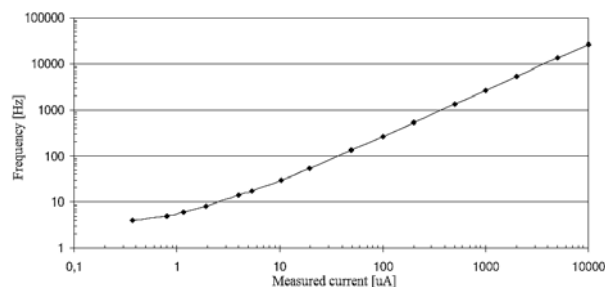


Fig. 8. Relationship between charge counts and supply current  $I_s$  for modified charge integration method

Despite its simplicity and high dynamics (almost 10000:1) measuring system based on current mirrors is cumbersome in practical application: in its original form according to a significant drop in voltage  $U_T$ , which is also a function of the measured current as adequate as after the addition of a voltage follower due to appearing oscillations and the decrease of linearity. The current measurement result „flow” was also observed for currents above 15 mA. It is suspected to be related to the heating of the input transistors. Shown circuit could be well in dedicated solution, where the known values of the currents would be measured, but unfortunately not suitable for building an universal meter. It would also be troublesome changing the measuring range.

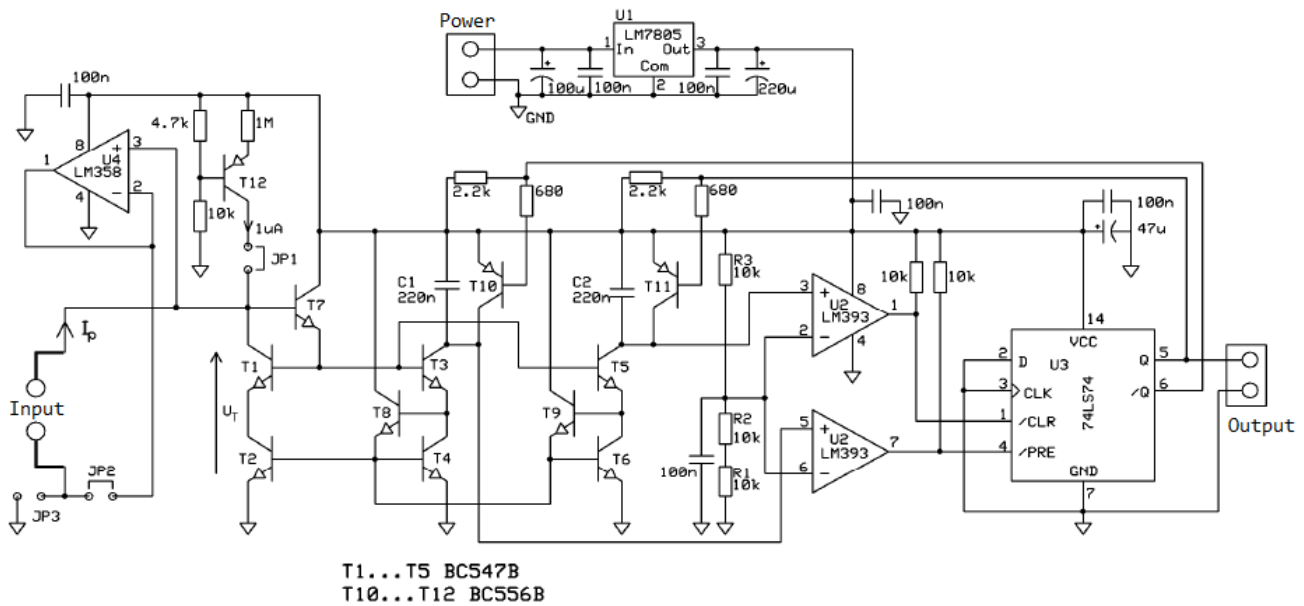


Fig. 7. Schematic diagram of the circuit implementing the modified charge counting method

### Conclusions

Modification, implementation and evaluation of methods based on counting charge for measurement of low-power energy systems were the main objectives of this work.

Based on the idea described in the literature, some improvements were made, expanding the range of applications with the ability to measure sinking currents, produced by EH source and eliminating the effect of voltage drop on the measurement branch by using a voltage follower. Despite the improvements, the system does not provide all the requirements for typical measurements of energy consumption low-power systems, however it forms step to obtain a very efficient tool.

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