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The use of a static electrical energy meter as a transducer of active power to a pulse frequency signal

***Abstract**. Frequency of a pulse signal at the test output of a static electricity meter is proportional to the active power of a connected load. When the consumed power changes, time between adjacent pulses of the test signal changes too, which prevents from obtaining the results of power measurement at regular time intervals. This work presents an algorithm for digital processing of a pulse frequency signal from the test output of a static electricity meter in order to obtain instantaneous values of active power at regular time intervals.*

***Streszczenie.** Częstotliwość sygnału na wyjściu testowym statycznego licznika energii elektrycznej jest proporcjonalna do mocy czynnej dołączonego obciążenia. Gdy ta moc zmienia się, czas pomiędzy kolejnymi impulsami sygnału testowego również się zmienia, co uniemożliwia uzyskanie wyników pomiarów mocy w regularnych odstępach czasu. W pracy prezentuje się algorytm cyfrowego przetwarzania sygnału częstotliwościowego z wyjścia testowego licznika energii elektrycznej w celu uzyskania wartości chwilowych mocy czynnej w regularnych odstępach czasu. (**Zastosowanie statycznego licznika energii elektrycznej jako przetwornika mocy czynnej na impulsowy sygnał częstotliwościowy**).*

Keywords: electricity meter, active power measurement, pulse frequency signal, uniform resampling.
Słowa kluczowe: licznik energii elektrycznej, pomiar mocy czynnej, impulsowy sygnał częstotliwościowy, równomierny resampling.

Introduction

Electrical energy meter is an electrical instrument that measures the amount of electrical energy used by the consumers. Therefore under the current provisions [1], each static electricity meter must have a pulse test output which allows to check its measurement errors with one of the recommended methods [2]. Test signal $y(t)$ of the electricity meter is a sequence of rectangular pulses shown in Figure 1. The number of pulses attributable to 1 kWh of the measured electricity being defined by a meter constant K. The static electricity meter is thus a converter of active power P to a pulse frequency f of the test signal:

$$f = P\frac{K}{3{,}6\cdot 10^6} \quad (1)$$

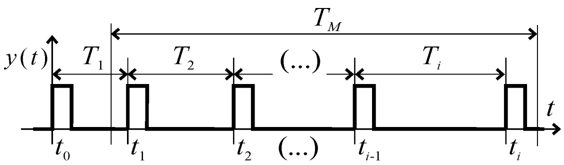

Fig.1. Pulse test signal of the static electricity meter

Measuring the frequency f of the test signal by counting N of its pulses at measurement time T_M (Fig. 1), the active power P of the connected load can be determined:

$$P = 3{,}6\cdot 10^6\frac{f}{K} = 3{,}6\cdot 10^6\frac{N}{K\cdot T_M}\ . \quad (2)$$

For a single-phase electricity meter the maximal frequency f_{max} of the test signal is given by:

$$f_{\max} = U_n \cdot I_{\max}\frac{K}{3{,}6\cdot 10^6}\ , \quad (3)$$

where: U_n - nominal voltage of the electricity meter, I_{max} - maximal current of the electricity meter, K - meter constant.

For a three phase meter this value (3) is three times higher, respectively. In practice, the maximal frequency f_{max} of the test signal of electricity meters for maximal power is of the order of 25 Hz. In order to maintain the frequency quantization error at a level 10 times lower (of the order of 0,1%) than the intrinsic error of the meter, the measurement time T_M should amount to at least 40 seconds, which significantly limits the measurements of fast-changing loads. In such cases, the instantaneous frequency value $f(t)$ should be measured by measuring successive interpulse times T_i (Fig. 1). Then, however, it is not possible to obtain the instantaneous frequency values distributed uniformly in time [3], which makes it difficult to cooperate with voltage circuits of the measuring system [4, 5, 6] and prevents the implementation of algorithms for the frequency [7] and time [8] analyses of signals. The analyses requiring in this case to use the operation of uniform resampling [9, 10].

Processing the test signal of the static electricity meter

The principle of generating the test signal of the static electricity meter is presented in its block diagram (Fig. 2) and in time courses of appropriate signals (Fig. 3).

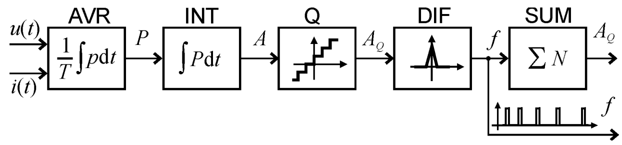

Fig.2. Functional diagram of the static electricity meter

In an averaging unit AVR (Fig. 2), active power $P(t)$ is calculated as an average value of instantaneous power $p(t)$ equal to the product of instantaneous values of voltage $u(t)$ and current $i(t)$. The active power P, integrated in INT block, equal to the measured energy A, is subject, in quantizer block Q, to quantization with a step ΔA_Q. Stepped course of quantized energy A_Q as a sum of unit steps:

$$A_Q(t) = \Delta A_Q\ ent\left(\frac{A(t)}{\Delta A_Q}\right) = \Delta A_Q\sum_{i=1}^{\infty}\mathbf{1}(t-t_i)\ , \quad (4)$$

after differentiation, in DIF block, is a source of δ Dirac pulses having frequency f (1) and representing successive rising edges of the test signal $y(t)$ at moments t_i (Fig. 1):

$$y(t) = \frac{dA_Q}{dt} = \Delta A_Q\sum_{i=1}^{\infty}\delta(t-t_i)\ . \quad (5)$$

Each successive pulse of the test signal $y(t)$ appears at moment t_i when the measured energy A increases by another quantization step $i\cdot\Delta A_Q$ (Fig. 3). The pulses are summed in SUM block, and their number N determines the quantized energy A_Q measured by the meter at time T_M :

(6) $$A_Q = \int_t^{t+T_M} P(t)dt = \int_t^{t+T_M} \Delta A_Q \sum_{i=1}^{\infty} \delta(t-t_i)dt = N \cdot \Delta A_Q \,.$$

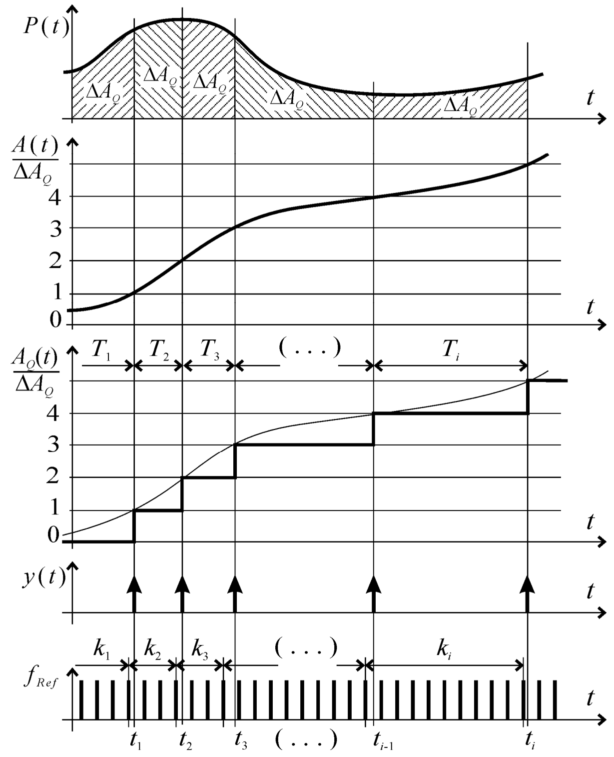

Fig.3. Time courses of signals in the static electricity meter

The appearance, at moment t_i, of another pulse of the test signal of the meter means an increase in energy by a quantum ΔA_Q in relation to the pulse which occurred at moment t_{i-1}. Digitally measuring successive time intervals T_i by filling them with k_i pulses having reference frequency f_{Ref}, successive values of active power P_i can be determined:

(7) $$P_i = \frac{\Delta A_Q}{t_i - t_{i-1}} = \frac{\Delta A_Q}{T_i} = 3{,}6 \cdot 10^6 \frac{1}{K \cdot T_i} = 3{,}6 \cdot 10^6 \frac{f_{Ref}}{K \cdot k_i} \,.$$

The values of active power P_i are not instantaneous values, but they are average values for times T_i, which are obtained at moments t_i distributed nonuniformly in time. In practice, it is more convenient to process the instantaneous values of signals sampled uniformly in time [10], which requires to perform a resampling by approximating the active power values $P(t)$ at intervals between the measured values P_i and by collecting new values at regular intervals [7]. For an unknown form of variation $P(t)$, it is not known to which moments t of time the values P_i can reasonably be attributed only on the basis of the values k_i. However, regardless of the form of $P(t)$, pulses of the test signal always appear exactly at moments t_i, at which the energy $A(t)$ increases by a quantum ΔA_Q, and thus the successive points (t_i, ΔA_{kQ}) allow to unambiguously approximate the course of the instantaneous energy $A(t)$ and then, after differentiating, the course of active power $P(t)$.

First-degree polynomial approximation of energy

For slowly variable signals, it is sufficient to assume that the active power $P(t)$ has a constant value between adjacent pulses of the test signal $y(t)$, and the energy $A(t)$ can be approximated at this interval with a straight line. The procedure for such a case is shown in Figure 4. Two given points A, B define a straight line $A(t)=a_0+a_1t$ which approximates energy at time interval (t_{i-1}, t_i) in which an increase of energy ΔA_Q occurred. To simplify the analysis, point A was placed in the origin of Cartesian coordinate system. After simple transformations [10] and determination of derivative, $P(t)=P_i$ is obtained, for any time $t \in (t_{i-1}, t_i)$. By proceeding analogously for successive interpulse intervals, a stepped line approximating the course of $P(t)$ will be obtained, which allows to determine the samples P_k^R of active power values at moments $t_k^R=kT_R$ uniformly distributed in time with a period T_R of uniform sampling:

(8) $$P_k^R = P\left(t_k^R\right) = P\left(kT_R\right) = \frac{3{,}6 \cdot 10^6}{K \cdot T_i}, \;\; t_k^R \in \left(t_{i-1}, t_i\right).$$

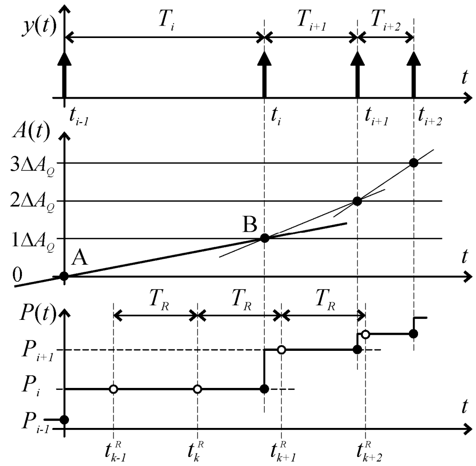

Fig.4. Approximation of instantaneous active energy $A(t)$ with a first-degree polynomial between the two adjacent pulses [10]

Second-degree polynomial approximation of energy

Assuming a linear change of the power $P(t)$ as a function of time, the course of energy $A(t)$ should be approximated with a second-degree polynomial, which requires the assignment of coordinates of three points A, B and C shown in Figure 5, the points being determined by the location of the three successive pulses of signal $y(t)$, distant from each other by times T_i and T_{i+1}, and corresponding to increments of energy $A(t)$ by successive multiples of ΔA_Q at moments t_{i-1}, t_i and t_{i+1}, respectively.

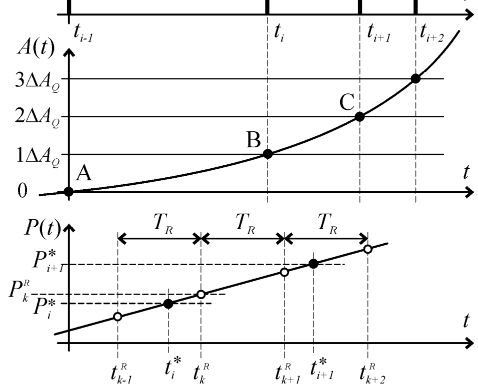

Fig.5. Approximation of active energy $A(t)$ with a second-degree polynomial between the three successive pulses [10]

Three points $(0, 0)$, $(T_i, \Delta A_Q)$, and $(T_i+T_{i+1}, 2\Delta A_Q)$ (Fig. 5) define a system of three equations, its solution being a parabola in the form of $A(t)=a_0+a_1t+a_2t^2$ which describes energy A as a function of time t. After appropriate transformations [10] and having considered a meter constant K, a dependency on energy will be obtained:

$$(9)\quad A(t)=\frac{3,6\cdot 10^6}{K(T_i+T_{i+1})}\left[\left(\frac{T_{i+1}}{T_i}-\frac{T_i}{T_{i+1}}+2\right)t+\left(\frac{1}{T_{i+1}}-\frac{1}{T_i}\right)t^2\right].$$

Derivative of the right side of equation (9) is a polynomial approximating active power $P(t)$ at time moments interval (t_{i-1}, t_{i+1}) on the basis of two adjacent interpulse times T_i and T_{i+1}:

$$(10)\quad P(t)=\frac{3,6\cdot 10^6}{K(T_i+T_{i+1})}\left[\frac{T_{i+1}}{T_i}-\frac{T_i}{T_{i+1}}+2+2\left(\frac{1}{T_{i+1}}-\frac{1}{T_i}\right)t\right].$$

Dependency (10) allows for uniform resampling of the active power signal $P(t)$ by collecting values P_k^R at moments $t_k^R=kT_R$ equally spaced by a uniform sampling period T_R:

$$(11)\qquad P_k^R=P\left(t_k^R\right)=P(kT_R),\; t_k^R\in(t_{i-1}, t_{i+1}).$$

For example, by substituting $T_i=T_{i+1}$ in (10), $P(t)=const.$ will be obtained, which means a constant pulse frequency at interval (t_{i-1}, t_{i+1}). For $T_i\neq T_{i+1}$, dependency (10) allows to determine a moment of time t_i^*, for which $P(t_i^*)=P_i$, i.e. for which the instantaneous value of active power $P(t)$ is equal to the average value P_i measured at time T_i (Fig. 5):

$$(12)\qquad P_i^*=P\left(t_i^*\right)=P_i\;\Rightarrow\; t_i^*=t_{i-1}+\frac{T_i}{2}.$$

First-degree polynomial approximation of active power

Dependency (12) means that, for the linear change of active power, its average value P_i, measured at time T_i, is equal to the instantaneous value P_i^* at moment t_i^*, lying in the middle of the time interval T_i. Therefore, approximating of power $P(t)$ is justifiable at time interval from $t_i^*=t_{i-1}+T_i/2$ to $t_{i+1}^*=t_i+T_{i+1}/2$ for which the instantaneous power takes the values $P_i^*=P_i$ and $P_{i+1}^*=P_{i+1}$, respectively (Fig. 6):

$$(13)\qquad \begin{aligned} P_i^* &= 3,6\cdot 10^6\,\frac{1}{K\,T_i}=3,6\cdot 10^6\,\frac{f_{Ref}}{K\cdot k_i}\\ t_i^* &= t_{i-1}+\frac{1}{2}T_i=\sum_{j=1}^{i-1}T_j+\frac{1}{2}T_i \end{aligned}.$$

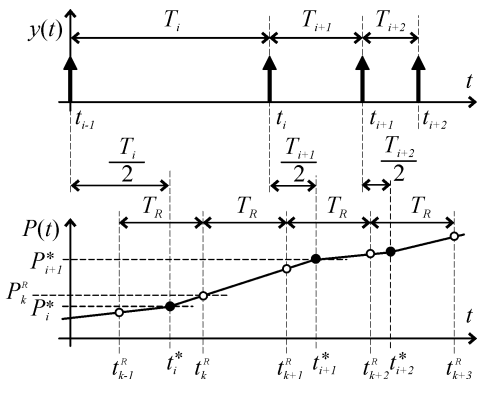

Fig.6. Approximation of instantaneous active power $P(t)$ with a first-degree polynomial between the two adjacent points [10]

Successive points P_i^*, t_i^* (12), shown in Figure 6, determine successive sections of a polyline approximating power $P(t)$ at time intervals from $t_i^*=t_{i-1}+T_i/2$ to $t_{i+1}^*=t_i+T_{i+1}/2$, the polyline allowing for a uniform resampling by collecting power values P_k^R at moments $t_k=kT_R$ equally spaced in time by a uniform sampling period T_R:

$$(14)\qquad \begin{aligned} P_k^R &= P\left(t_k^R\right)=\frac{\left(t_k^R-t_i^*\right)P_{i+1}^*+\left(t_{i+1}^*-t_k^R\right)P_i^*}{t_{i+1}^*-t_i^*}\\ t_k^R &= kT_R,\; t_k^R\in\left(t_i^*, t_{i+1}^*\right) \end{aligned}.$$

Practical use

In order to practical assessment of the proposed solution, an appropriate measurement system was built in accordance with Figure 7.

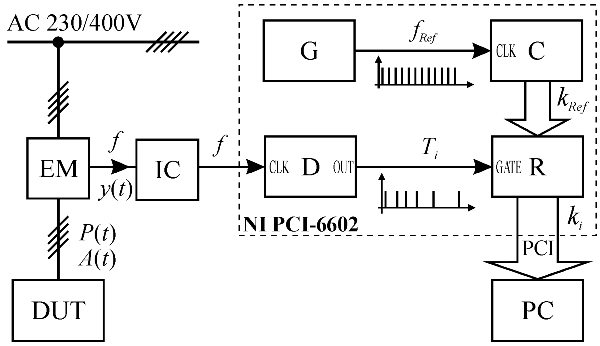

Fig.7. Block diagram of the measurement system with electricity meter working as transducer of active power to frequency

In the realized measurement system the static electricity meter EM and a high speed buffered counters DAQ Card NI PCI-6602 [10] connected to PC computer by PCI bus were used. Electricity meter EM measures the active energy consumed by the device under test DUT. In the DAQ Card two counters are used, the first of them works as frequency divisor D, the second one C is set in buffered period measurement mode [11] and counts reference frequency pulse f_{Ref} from a reference generator G. The test output signal $y(t)$ from the electricity meter EM is fed, through the interface circuit IC, to the CLK input of the divisor D. The output of the divisor is connected to the latch input GATE of the buffer register R, so at each edge of the pulse the current value k_i of the counter C is written to the buffer register R. System must be able to measure each successive times intervals T_i, so buffered period measurement mode was used [12]. Inter-pulse time values are given as $T_i=D\cdot k_i/f_{REF}$, where D is division factor of the divisor D. Then uniform resampling (14) with a period T_R=100ms is performed. Appropriate software was prepared using LabVIEW package.

Interface circuit IC was made according to International Standard [13] which is applicable to passive, two-wire, externally powered pulse output devices to be used in electricity meters. For this purpose is used special open-collector type current interface, so-called S0-Interface [14]. Realized circuit diagram is shown in Figure 8.

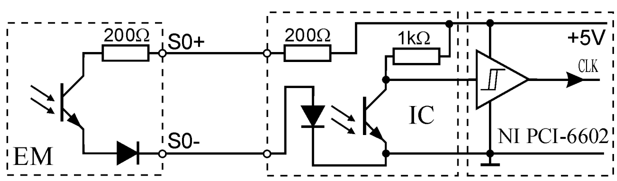

Fig.8. Current interface S0 for transmitting pulses from the electricity meter EM through the interface circuit IC to DAQ-Card

Example results obtained from the measurements realized in presented system are shown in Figure 9. The use of the described algorithm for analysing the power absorbed by a hydraulic press driven with two 22 kW induction motors is shown. An electricity meter with a constant K=1000 pulses/kWh was used, and a uniform resampling (14) with a period T_R=100ms was performed.

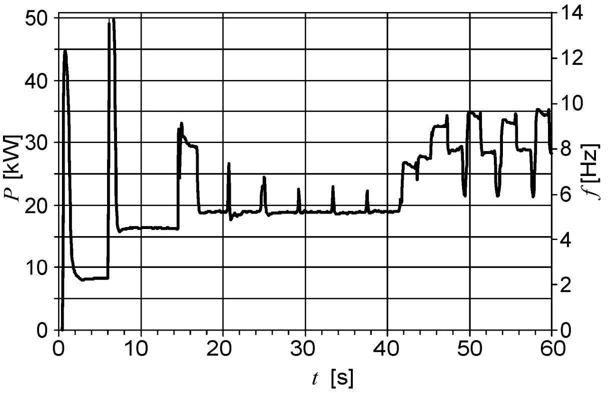

Fig.9. Active power determined on the basis of the test signal of the static electricity meter

In the graph (Fig. 9), during the first 10s, starting of two drive motors, one after the other, is shown. During the next 30s, the press worked at idle, and after 50s from starting, it began a cyclic operation with a period of about 2s. The frequency of the test signal of the meter was then comprised in the range of 6 ... 10Hz, which means the active power being consumed by the cyclic working press in the range of 20 ... 35kW (2).

Summary

The indications of the electricity meters are a basis for the financial settlements for consumed electric energy. Therefore, they are subjected to appropriate regulations and their design must fulfil proper requirements. Thus all static electricity meters must have an output of the test signal allowing for determination of the measurement errors of the meter during its legalization. It also gives additional possibilities of analyzing the load variation in the installation place, as the frequency of the pulse signal on the test output is proportional to the active power of connected load. In order to precisely determine the frequency of the test signal in short time it is required to measure its successive periods. But if the device power changes, the successive results of measurements are obtained in various time intervals. It makes the analysis of load variation in reference to the linear time scale more difficult.

The article presents the range of issues connected with the digital processing of the impulse frequency signal from the test output of the static electricity meter in order to obtain the instantaneous values of the active power in equal time intervals. It has been shown that it is possible to determine instantaneous values of active power at regular intervals on the basis of the frequency of the pulse test signal of a static electricity meter. This requires to adopt a suitable form of a function approximating, with sufficient instantaneous accuracy, the value of active energy. Using the fact that the energy, measured by the meter, increases exactly by the same value (resulting from the meter constant K) at moments of appearance of adjacent pulses of the test signal, the energy may be unambiguously approximated for any moment of time, whereby the time intervals between adjacent pulses of the test signal determine average values of active power distributed nonuniformly in time. An exemplary results of measurements obtained in a real system were presented.

At the end, it should be noted that the basic problem of digital processing in analyzed system with a pulse frequency signal is obtaining results of active power $P(t)$ from measurements of frequency f at times t_i (fig. 3), which is the average value of the frequency for the time from t_{i-1} to t_i and should be assigned to a moment in time lying in the middle of this interval. This is only possible in data processing systems in off-line mode. Unfortunately in the measurement system operating in on-line mode it is impossible to assign processing results to corresponding moments of time, as these results are received after the expiry of the time point to which they should be assigned. This results in impossible to avoid errors in position at the time of single samples. The second problem results from the integrating operation of the transducer with frequency output, whereby in this kind of converters an averaging sampling of signal is implemented, and not, as in other types of ADCs sampling of instantaneous values. Therefore, the value course of a measurand obtains a stepped line, whereby the width of these steps is variable and dependent on the current signal value.

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