Short Papers

Accurate Measurement of Power, Energy, and True RMS Voltage Using Synchronous Counting

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Abstract—The measurement method described in this paper can be applied for the accurate determination of periodic signals. The method relies on adaptation of the measurement time to the period of the measurement signal. The synchronous method is based on dual-slope integration performed according to the synchronization signal (input signal). The first phase of integration is fully synchronized with the input signal. The time of the first phase is also measured. Output voltage of the integrator depends directly on the input signal and the time of the first integration phase. Measurement values are the results of arithmetic operations between the time of the second phase of integration and the measuring time (first phase). With this method, an accuracy of 0.1% can be achieved.

I. INTRODUCTION

With the development of systems which produce electric power with highly distorted waveforms there is an increasing need for accurate measurement techniques and calibration services that cover these higher frequency power signals. Some methods have been described which are based on thermal effects [1] or on sample and hold converters [2].

In this paper a measuring method is presented for power, energy and true RMS of voltage based on synchronous counting. This method has been used in frequency counters [3], and has resulted in a substantial decrease in discretization error. The ± 1 cycle error is eliminated here by synchronized gating. The opening and closing of the main gate of the event counter are synchronized with the input signal and do not truncate any cycle.

The total number of cycles is, therefore, an integral number without ± 1 cycle error. The value of the measured frequency is calculated with a microprocessor.

II. PRINCIPLE OF OPERATION

A block diagram of the system, consisting of an analog and a digital part, is presented in Fig. 1. The analog part converts the input signals U and I into digital values, according to the definitions of power and true RMS voltage:

$$U_{\text{RMS}} = \sqrt{\frac{1}{T_p} \int_0^{T_p} U(t) dt}$$

or

$$P = \frac{1}{T_p} \int_0^{T_p} U(t) dt \quad (1)$$

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in which $U(t)$ and $I(t)$ are the input signals, and T_p is the measurement time (in synchronous method T_p is the time of the first phase of integration also). The multiplication is performed by an analog multiplier, the integration by a dual-slope converter and the calculation by a microprocessor.

The voltage at the output of the dual-slope converter can be described by the following expression (this one described the zero crossing voltage of integration also):

$$U_i = \frac{1}{RC} \int_0^{T_p} kU^2(t) dt - \frac{1}{RC} \int_{T_p}^{T_p+T_x} U_{\text{ref}} dt \quad (2)$$

where k is the multiplication constant of the multiplier. Fig. 2 shows the timing diagrams for a typical input signal. The output voltage of the multiplier is integrated during a time interval T_p , which is synchronized with the input signal using the synchro circuit (Fig. 1).

Upon a start signal from the microprocessor, a timer T_0 generates a pulse of 100 ms, which activates the synchro circuit. This circuit generates the signal T_p after synchronization with the input signal (Fig. 2). The signal T_p controls the gate of the time counter L2. As a result, time T_p is always equal to an integral number of the input signal period: $T_p = nT_{\text{in}}$.

Subsequently, the dual-slope converter integrates the reference voltage U_{ref} during a time period T_x , measured by the event counter L1. Now (2) can be rewritten by

$$\int_0^{T_p} k \cdot U^2(t) dt = U_{\text{ref}} \cdot T_x$$

and

$$\int_0^{T_p} c \cdot U(t) \cdot I(t) dt = U_{\text{ref}} \cdot T_x \quad (3)$$

where c is the multiplier constant for the power measurement. Substitution of (3) in (1) results in

$$U_{\text{RMS}} = \sqrt{\frac{T_x \cdot U_{\text{ref}}}{k \cdot T_p}} \quad \text{and} \quad P = \frac{T_x \cdot U_{\text{ref}}}{c \cdot T_p} \quad (4)$$

This expression is used for the calculation of power and true RMS voltage.

U_{RMS} contains four parameters: T_x , T_p , U_{ref} , and k , where T_x is the time of the second phase of integration, T_p is the time of the first phase of the integration and U_{ref} is the reference voltage of the dual-slope converter U_{ref} divided by k or c are constants which are stored by the microprocessor system and can easily be changed during calibration. The measurement of T_p and T_x is executed by 16-b counters L1 and L2. These time periods are presented by

$$T_p = \frac{L2}{f_{\text{osc}}} \quad \text{and} \quad T_x = \frac{L1}{f_{\text{osc}}} \quad (6)$$

where f_{osc} is derived from a 4 MHz crystal oscillator, and L1 and L2 are the contents of the counters after each measurement. Thus

Fig. 1. Block diagram of microprocessor energy counter.

Fig. 2. Some characteristic curves.

we have:

$$U_{RMS} = \sqrt{\frac{L1}{k \cdot L2}} U_{ref} \quad P = \frac{L1}{cL2} \cdot U_{ref} \quad (6)$$

Equations (5) and (6) are used for the calculations by the microprocessor. The microprocessor reads both counters, divides L1 by L2, multiplies this ratio by the constant U_{ref}/k or U_{ref}/c and performs the square root operation for the RMS voltage calculation. The total error is given by

$$\delta_{U_{rms}} = \delta_{xy} + 0.5\delta_{L1} + 0.5\delta_{L2} + 0.5\delta_{U_{ref}}$$

and

$$\delta_P = \delta_{xy} + \delta_{L1} + \delta_{L2} + \delta_{U_{ref}} \quad (7)$$

where δ_{xy} is the relative error of the multiplier. Those errors could be written in a statistical way:

$$\delta_{U_{rms} stat} = \sqrt{(0.5\delta_{xy})^2 + (0.5\delta_{L1})^2 + (0.5\delta_{L2})^2 + (0.5\delta_{U_{ref}})^2}$$

$$\delta_{P stat} = \sqrt{\delta_{xy}^2 + \delta_{L1}^2 + \delta_{L2}^2 + \delta_{U_{ref}}^2} \quad (8)$$

The errors δ_{L1} and δ_{L2} are the quantization errors of the counters and are equivalent to 1 count. δ_{L2} is almost constant:

$$\delta_{L2} = \frac{1}{L2} = \frac{1}{T_p f_{osc}}$$

$$= \frac{1}{100 \text{ ms } 400 \text{ kHz}} < 2.5 \cdot 10^{-5} \quad (9)$$

$T_p = 100 \text{ ms}$ is the minimum value (in the prepared model).

The quantization error of counter L1 referred to the range is equal to:

$$\delta_{L1} = \frac{1}{T_{x_{max}} \cdot f_{osc}} = \frac{1}{50 \text{ ms } 400 \text{ kHz}} < 5 \cdot 10^{-5} \quad (10)$$

Relative error δ_{L1} depends, of course, on input value. The error of the reference voltage depends on the thermal and time stability and can be less than 0.02%.

The error of the analog multiplier is the most important one. This error depends on the frequency, amplitude, crest factor, temperature, and time (the total error can reach 0.5%). The energy measurement is according to the formula:

$$E = P \cdot t = \frac{1}{cL2} \cdot U_{ref} \frac{L3}{f_{osc}} \quad (11)$$

The time t is measured with a third counter L3 which generates a pulse every 160 ms. This one is stored in the memory, and the microprocessor calculates the actual value of energy with (11). The error of the energy measurement is given by

$$\delta E = \delta_{xy} + \delta_{L1} + \delta_{L2} + \delta U_{ref} + \delta t$$

$$\delta t = \delta_{L3} + \delta f_{osc} \quad (12)$$

Fig. 3. Frequency characteristic of voltage error.

Fig. 4. Amplitude characteristic of voltage error.

Fig. 5. Characteristic of power error.

The formula of the energy error is similar to that of the power error. However, there is an additional component, the time error δ_t (quantization of time and the frequency oscillator error):

$$\delta_{L3} = \frac{1}{2^{16}} = 2 \cdot 10^{-5}; \quad \delta f_{osc} = 10^{-6}/\text{deg}. \quad (13)$$

This means that the time error is negligible.

III. RESULTS

Fig. 3 shows the frequency characteristic of the complete system. The results have been compared with a 745A ac calibrator and a multimeter 3478A (HP). The frequency range of the calibrator is 100 kHz. The input voltage range of the model is 0–7 V. Fig. 3 confirms that the frequency characteristic is flat over a frequency range from a few Hz to 100 kHz, within 8 mV.

This characteristic shows that the synchronous method can be used for other applications, not only for energy at 50 Hz. The error can be reduced by writing a new constant into the memory. Fig. 4 shows the nonlinearity error of the multiplier characteristic. This nonlinearity can be reduced by applying a digital correction function. If the error does not depend on the particular copy of the multiplier, the correction function will be the same for one type of multiplier. The maximum of the nonlinearity is about 8 mV. This means that the relative error referred to the full scale is about 0.1%. The correction function can reduce this error.

The most important characteristic of the energy counter is presented in Fig. 5. It shows the power error as a function of the measured power. Two voltage sources, one fixed and one variable, have been connected to the multiplier. The input power is derived by a precise measurement of these input voltages. The resolution of the power measurement is 1 W, and the power range is 2–200 W.

The relative error in the power measurement is the same as for the voltage measurement, 0.1% of full scale. The quantization error of the energy measurement is equal to:

$$\delta_E = \delta_P \delta_t = 1 \text{ W} \cdot 0.16 \text{ s} = 0.16 \text{ W}_s.$$

The power consumption of the instrument is about 15 W.

IV. CONCLUSIONS

The main advantage of the synchronous method described in this paper is that the measurements are performed exactly according to the definition of power and true RMS voltage. The overall inaccuracy is in the order of 0.1% full scale. The major causes of the inaccuracy are the multiplier and the rest of the analog part dual-slope converter. Such errors could be eliminated by a correction function in the microprocessor part. The prototype of a three-phase meter is being prepared in the Electronic and Biomedical Measurement Devices Laboratory (Institute of Electrical Metrology—Technical University of Wrocław). The synchronous method can also be used for other applications, like a digital power meter, an ac voltage meter and a real $\cos \phi$ meter.

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