

DIGITAL ELECTRICITY METER

*MSc. Rastislav Michálek, MSc. Peter Gábor, MSc. Peter Fuchs, PhD,
Assoc. Prof. MSc. Ján Hribik, PhD, Assoc. Prof. MSc. Miloslav Hruškovic, PhD*

Department of Radioelectronics, FEI SUT, Ilkovičova 3, SK-812 19 Bratislava, Slovakia

Abstract - The description of the designed digital three-phase registration/calibration electricity meter based on the most recent Texas Instruments TMS320C6711 DSP is given. The description of the rms value calculation and the measurement errors are also given.

Keywords: digital electricity meter, DSP, active power, reactive power, apparent power, rms value calculation.

1. INTRODUCTION

Electronic methods of power and energy measurement are based on different principles [1], [2]. The methods suitable for use in digital electricity meters may use Hall effect [3], pulse-width modulation (time-division multiplier) [4], analog multiplying IC [5], three-terminal thermo-converter (TTTC) [6], or digital multiplication [7], to mention only a few published papers. The last mentioned method may use one AD converter with multiplexed inputs, or it may use separate AD converter for each input. The method used in electricity meter depends on the desired accuracy and on the allowed price of the instrument. The following considerations concern digital electricity meters based on digital multiplication.

The basic instruments for the most accurate measurement of electric power and energy are digital electricity meters. Their advantages are obvious: high accuracy, complex net parameters measurements, possibility of remote automated data processing and many other functions resulting from the microprocessor-based digital system possibilities.

Digital power and energy measurement is based on sampling and digitizing of the instant values of the voltage and current in regular time intervals, their arithmetic multiplying in digital form, summation and averaging of the products. With today's high computing power of digital signal processors and fast A/D converters with high accuracy it is also simple to measure the reactive power, phase shift, power factor and apparent power. Because of a nonharmonic character of the power supply in many cases it is necessary to measure also the frequency spectrum of the power network. Digital processing of analogue signals guarantees short- and long-term stability as well as high accuracy of measurement. Usually, digital devices contain auto-calibration techniques and self-test features. Such power and energy measurement is influenced not only by the inaccuracies of analogue circuits but also by the inaccuracy of the

sampling process itself. In the asynchronous sampling method the error can be higher and it needs longer summation time interval for the error to be sufficiently low. The synchronous sampling method gives better results. It requires shorter measuring time but its realization is more complex.

Analogue circuits of the digital electricity meter contain practically the same parts as other types of electronic electricity meters [8]. The voltage channel contains circuits for the net voltages sensing and conditioning to match the requirements of A/D converters. The main parts of the current channel are current-to-voltage converters with the output voltages corresponding with the demands of A/D converters. Both of these channels essentially influence the accuracy and other properties of the whole instrument.

Electricity meters are manufactured by many manufacturers. Digital electricity meters have different measurement and communication possibilities. The accuracy of the best instruments is of the order 0.01 %. The important parameter for a user is also the price of the instrument.

2. ELECTRICITY METER DESCRIPTION

The proposed instrument is able to measure all basic three-phase net parameters including rms values of voltages and currents, active, reactive and apparent power, power factor, net frequency, and energy delivered into the load. It can calculate the frequency spectra using FFT. The results can be announced by the voice output and can be transmitted via infrared and RS 485 interface. There is also a frequency output. Combined in the electricity meter is also three-phase signal generator of voltages and currents.

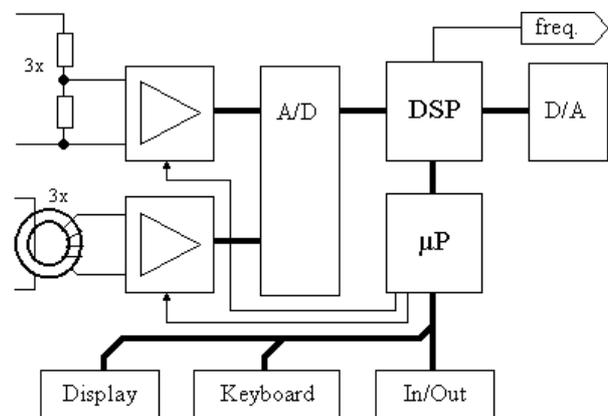


Fig. 1. Block diagram of the designed electricity meter

Block diagram of the proposed instrument for power and energy measurement (PEM 6711) is in Fig. 1. It can be used as a calibration or a registration three-phase electricity meter. Analogue part contains circuits for sensing the net voltages and currents and circuits for conditioning the signals proportional to the net voltages and currents. A block of A/D converters digitizes the signals from the analogue part. The DSP part with the Texas Instruments TMS320C6711 processor makes necessary calculations and signal processing in digital form. It also contains software for signal generation with the output through a D/A converters block and a frequency output with the frequency proportional to the measured power.

Microcontroller board with the Texas Instruments TMS320F243 processor controls the operation of the device. It controls some circuits of the analogue part, displays the results and enables communication with other instruments via standard interfaces. It contains also address decoder and control logic. All the circuits (keyboard, display, DSP) are mapped into its memory what makes the communication very simple. For presentation of time and frequency characteristics, graphical LCD display with the resolution of 240x128 dots is used.

The most important part of the device is the DSP board with a powerful DSP. This part makes all the necessary computations of the system. It controls the communication with A/D converters, generates signals for testing of other electricity meters and stores data in memory. In registration mode the device takes the advantage of a large on-board memory where the measured values are stored. To visualize the results, a communication port with the microcontroller was designed. The microcontroller is the master in the system and it is able to display any data of the DSP on the graphical LCD display [9].

The DSP board receives six input signals from the A/D converters block with sampling frequency $f_s = 50$ kHz (the start of sampling is synchronized with the frequency of the input signals) and calculates rms values of voltage and current, active, reactive and apparent power and power factor

$$U = \sqrt{\frac{1}{T} \int_0^T u^2(t) dt} , \quad (1)$$

$$I = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} , \quad (2)$$

$$S = UI , \quad (3)$$

$$P = \frac{1}{T} \int_0^T u(t)i(t) dt , \quad (4)$$

$$Q = \sqrt{S^2 - P^2} , \quad (5)$$

$$\cos \varphi = \frac{P}{S} . \quad (6)$$

Supplementary values are frequency and energy delivered into the load. Reactive power in (5) also includes distortion power produced by harmonics of $u(t)$ and $i(t)$ of different orders. Reactive power can be also calculated from the equation

$$Q = \frac{1}{T} \int_0^T u(t)i(t + \frac{T}{4}) dt . \quad (7)$$

To set the parameters of the device, calibration procedure can be run. The exact values of the measured voltages and currents must be entered for the device to be able to calculate the correction coefficients. This procedure is not user accessible.

3. RMS VALUE CALCULATION

The definition of RMS value is

$$X_{RMS} = \sqrt{\frac{1}{T} \int_0^T x^2(t) dt} , \quad (8)$$

The real waveform is usually approximated by staircase or a piecewise linear function for average or RMS value calculation, [10]. The RMS value is calculated in staircase approximation by

$$X_{RMS} = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} x_i^2} , \quad (9)$$

and in piecewise linear approximation by

$$X_{RMS} = \sqrt{\frac{1}{3N} \sum_{i=0}^{N-1} (x_i^2 + x_i x_{i+1} + x_{i+1}^2)} . \quad (10)$$

In the first step, the program receives sampled data from the A/D converter. For the sake of high speed, the program makes calculations in the integer form. The maximum value of the data from the A/D converter (16 bit) is $u_{max} = \pm 2^{15} = \pm 32768$. At the minimum frequency $f = 45$ Hz, the number of samples per period is $N = f_s / f = 50 \text{ kHz} / 45 \text{ Hz} = 1111$. Numerical integral calculation gives the rms value

$$U = k \sqrt{\frac{1}{N} \sum_{i=1}^N u_i^2} \quad (11)$$

where k is the range constant. Maximum possible value of the sum in (11) is $V_{max} = N(u_{max})^2 = 1192927166464$. This gives the necessary number of bits $NB = 40.11$. Because the input voltage is not rectangular, the summation is accomplished by a 40-bit register. It makes it possible to work with high speed without losing the information. Calculation algorithm limits are displayed in Fig. 2. For the piecewise linear approximation V_{max} is three times higher and the $NB = 41.7$.

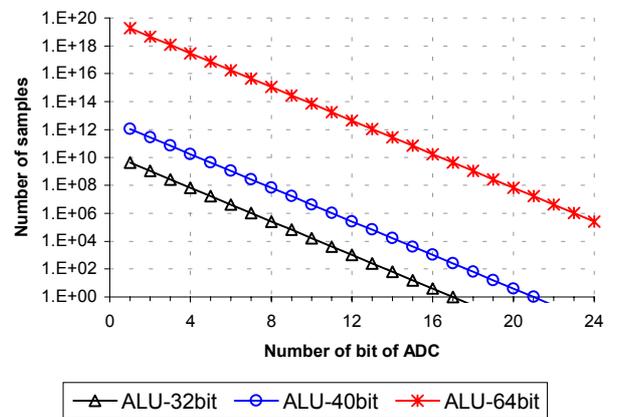


Fig. 2. The influence of the word length on the algorithm limits

In the second step, the sum of the samples during one period is converted from the integer to the floating point. All the following operations are made in floating point. The next summation is the sum of the data from many periods. The number of periods is given parametrically as N_p (the default value is $N_p = 50$, that means one measurement per second). The next operation is the division by the total number of samples and the square root calculation. If the sum of the j th period is V_j

$$V_j = \sum_{i=1}^N u_{N(j-1)+i}^2, \quad (12)$$

then the rms value is

$$U = k \sqrt{\frac{1}{NN_p} \sum_{j=1}^{N_p} V_j} = k \sqrt{\frac{1}{NN_p} \sum_{i=1}^{NN_p} u_i^2}. \quad (13)$$

This algorithm does not require complicated branching in interrupts. Than all of interrupts take equal time to compute. This makes it possible to increase the frequency of calling, that means also sampling frequency or to remove dual calling of interrupt routine.

In this way, the rms values of voltages and currents of all three phases are calculated. Similarly, power is calculated by numerical integral calculation of (4). The apparent power is then calculated from (3), power factor from (6) and the reactive power from (5).

4. ERROR OF MEASUREMENT WITHOUT FREQUENCY SYNCHRONIZATION

Sampling frequency is not usually an integer multiply of the frequency of the input signal. Maximum error of RMS calculation is in the situation, where the sample from the 2nd period is added to the sample set of the 1st period. This sample is $x_{N+1} = x_T$. Measured RMS value is

$$x_{ef}^1 = k \sqrt{\frac{1}{N+1} \left(\sum_{i=1}^N x_i^2 + x_T^2 \right)} \quad (14)$$

The error of measurement is

$$\begin{aligned} \Delta &= \frac{x_{ef} - x_{ef}^1}{x_{ef}} \cdot 100 = \left[1 - \sqrt{\frac{N}{N+1} \left(1 + \frac{x_T^2}{\sum_{i=1}^N x_i^2} \right)} \right] \cdot 100 \\ &= \left[1 - \sqrt{\frac{N}{N+1} \left(1 + \frac{x_T^2}{N \cdot x_{ef}^2} \right)} \right] \cdot 100 \quad \text{in \%}, \end{aligned} \quad (15)$$

which can be simplified to

$$\Delta \cong \frac{1 - \frac{x_T^2}{x_{ef}^2}}{2N} \cdot 100. \quad (16)$$

When starting condition is $(x_i < 0)$ and $(x_{i+1} \geq 0)$, than the value of x_T is very near to zero. Then the error is

$$\Delta = \left[1 - \sqrt{\frac{N}{N+1}} \right] \cdot 100 \text{ in \%}. \quad (17)$$

The condition for zero error ($\Delta = 0$) is

$$|x_T| = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} = x_{ef}. \quad (18)$$

In DSP system it is possible to set variable condition for starting point (x_T) of measurement. This value can be taken from measurement of the previous period. Also, the sampling signal is not synchronized by input signal, that means that the start condition can be $x_T = x(kT_s \pm T_s/2)$, where T_s is sampling period. For sine-wave signal $x(t) = X \sin(\omega t)$ RMS value is

$$x_{ef} = \frac{1}{\sqrt{2}} = X \sin\left(\frac{\pi}{4}\right), \quad (19)$$

and $x_T = X \sin\left(\frac{\pi}{4} \pm \frac{\pi}{N}\right)$. Then

$$\Delta = \left[1 - \sqrt{\frac{N}{N+1} \cdot \left(1 + \frac{2}{N} \cdot \sin\left(\frac{\pi}{4} \pm \frac{\pi}{N}\right) \right)} \right]. \quad (20)$$

5. SIMULATION RESULTS

The above given equations were used in simulation of the error of sampling without synchronization of the sampling signal with the input signal. The simulation was carried in MatLab by using (9) and (10). The results for staircase and piecewise approximation of sine-wave signal are in Fig. 3.

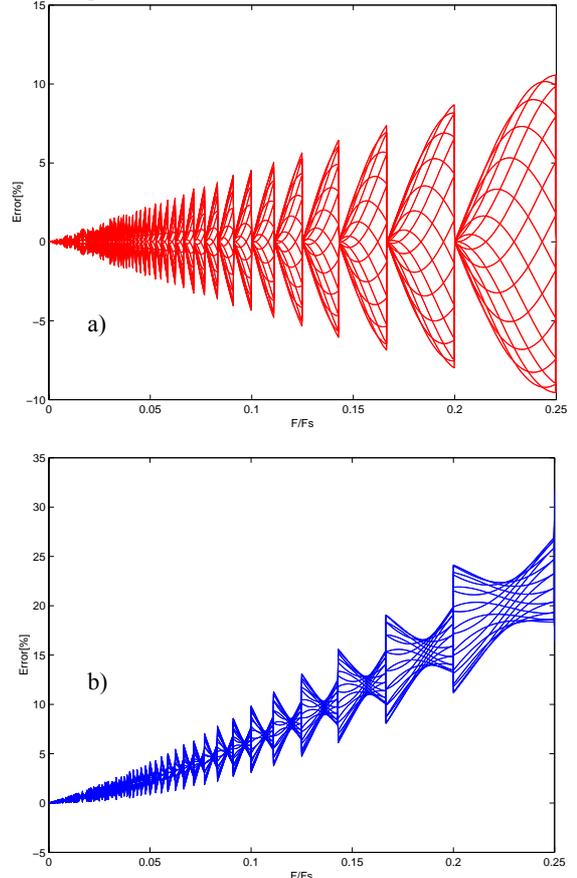


Fig. 3. The effect of sample rate and phase shift on the error of RMS calculation: a) staircase approximation, b) piecewise linear approximation.

For 1000 samples per period, the error calculated when only one period was sampled is 0.05%. If samples from 50 periods are used, the error is 0.001%. The minimum values of errors in Fig. 3a correspond with exactly synchronous sampling.

Errors calculated according to (17) (start of sampling in the instant of zero crossing) and (20) (start of sampling near the RMS value) are in Fig. 4. It can be seen that the error given by (20) is approximately half the value of that given by (17).

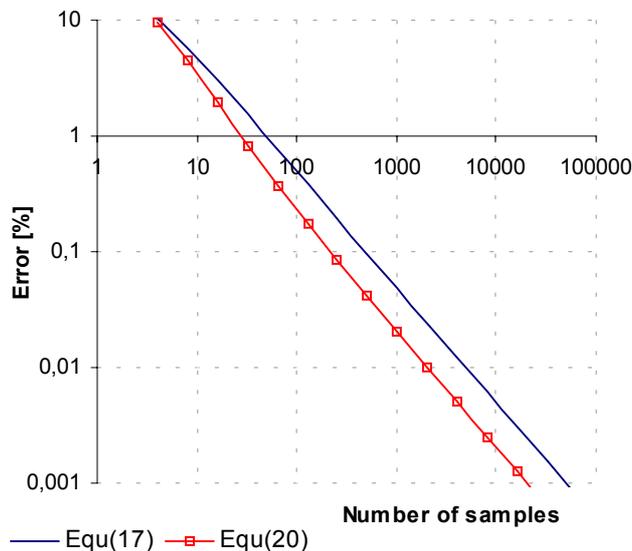


Fig. 4. The effect of the sampling starting level

6. CONCLUSION

Brief description of the designed digital three-phase registration/calibration electricity meter is given. The analogue part of the instrument consists of the signal conditioning circuits for the three voltage channels and three current transformers with the corresponding circuitry for the three current channels. The digital part contains the microcontroller board with the connected keyboard, graphical LCD display and interfaces, the DSP board for the necessary calculations and the separate A/D converters for every voltage and current signals. Modern Texas Instruments TMS320F243 processor and TMS320C6711 DSP were used to get a powerful measuring system. The accuracy obtained in the constructed sample of the electricity meter is better than 0.05 %.

The description of the RMS value calculation and error calculation for asynchronous sampling is also given. The minimum error can be obtained if the sampling starts exactly at the RMS value of the sampled signal. Error calculation was carried out for staircase and piecewise linear approximation of the sine-wave measured signal.

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REFERENCES

- [1] M. Kahmann, „Elektrische Energie elektronisch gemessen: Meßgerätetechnik, Prüfmittel, Anwendungen“, vde-verlag, Berlin, Offenbach, 1994.
- [2] J. Webster (ed.), „Wiley Encyclopedia of Electrical and Electronics Engineering Online“, John Wiley & Sons, Inc., New York, 1999.
- [3] Š. Rapant, P. Babarik, „Electricity Meters Siemens Constructed after Landis & Gyr Dialog of Series ZMD120AS and ZMD120ASs“, *Časopis EE*, vol. 8, no. 1, p. 11, February 2002. (in Slovak)
- [4] S. Kusui, T. Nagai, „A Single-Phase Three-Wire Watt-to-Pulse Frequency Converter Using Simple PWM and Its Accuracy Analysis“, *IEEE Trans. Instrum. Meas.*, vol. 43, no. 5, pp. 770-774, October 1994.
- [5] A. Hashimoto, K. Yasui, S. Kusui, „Self-Calibrating Standard Watthour Meter“, In: Proc. of the Conf. „*Metering and Tariffs for Energy Supply*“, July 3-5, 1996, Conference Publication No. 426, pp. 194-198, IEE 1996.
- [6] T. Lalinský, Š. Haščik, Ž. Mozolová, E. Burian, M. Držik, „The improved performance of GaAs micromachined power sensor microsystem“, *Sensors and Actuators*, vol. 76, pp. 241-246, 1999.
- [7] M.F. Schwendtner, „Digital Measurement System for Electricity Meters“, In: Proc. of the Conf. „*Metering and Tariffs for Energy Supply*“, July 3-5, 1996, Conference Publication No. 426, pp. 190-193, IEE 1996.
- [8] M. Hruškovíc, J. Hribík, „Voltage and Current Channel of Digital Calibration Electricity Meter“, In: Proc. of the Conf. „*New Trends in Signal Processing I*“, VA Liptovský Mikuláš, May 24-26, 2000, pp.3-8.
- [9] P. Fuchs, R. Feranec, P. Gábor, J. Hribík, M. Hruškovíc, D. Považanec, „Digital Three-Phase Registration/ Calibration Electricity Meter“, In: Proc. of the 3rd Internat. Conf. „*Measurement 2001*“, SAS, Smolenice Castle, May 14-17, 2001, pp.66-69.
- [10] M. Sedláček, V. Haasz, „Electrical Measurement and Instrumentation“, Vydavatelství ČVUT, Prague, 2000.

Authors:

MSc. Rastislav Michálek, Phone: +421 2 60291213, E-mail: michalek@elf.stuba.sk,

MSc. Peter Gábor, Phone: +421 2 60291213, E-mail: gabor@elf.stuba.sk,

MSc. Peter Fuchs, PhD, Phone: +421 2 60291775, E-mail: fuchs@kre.elf.stuba.sk,

Assoc. Prof. MSc. Ján Hribík, PhD, Phone: +421 2 60291353, E-mail: hribik@kre.elf.stuba.sk,

Assoc. Prof. MSc. Miloslav Hruškovíc, PhD, Phone: +421 2 60291592, E-mail: hruskovic@kre.elf.stuba.sk.

Department of Radioelectronics, FEI SUT, Ilkovičova 3, SK-812 19 Bratislava, Slovakia, Fax: +421 2 60291213.