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ACCURATE DIGITAL THREE-PHASE ELECTRICITY METER AND GENERATOR

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Abstract – Accurate measurement of parameters of a power network is now possible by digital methods. The description of the proposed and realized instrument based on the digital sampling method is given. It can measure basic parameters of the three-phase power network such as rms values of voltages and currents, powers, energies, power factors, the network frequency and frequency spectra. Its accuracy is better than 0.05%. The instrument can be also used as a generator of three-phase voltage and current signals with selectable phase shifts and higher harmonic components. Questions concerning the accuracy of measurement and error sources are also briefly given.

Keywords: digital electricity meter, DSP, calibration.

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], analogue multiplying IC, [5], three-terminal thermoconverter (TTTC), [6], or digital multiplication, [7], to mention only a few published papers. 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.

Basic instruments for the most accurate measurement of electric power and energy are digital electricity meters. They use digital multiplication of voltage and current samples, [1], [2], received from A/D converters (ADC). They may use one A/D converter with multiplexed inputs, [7], or separate A/D converter for each input signal, [8]. The advantages of such instruments are obvious: high accuracy, short- and long-term stability, complex network parameters measurements, possibility of remote automated data processing, auto-calibration, self-test and utilization of many other functions resulting from the microprocessor-based digital system possibilities. With today‘s high computing power of digital signal processors (DSP) it is also simple to measure the reactive power, apparent power, phase shift, power factor and frequency spectra of the power network signals.

Very important characteristic of electricity meters is their accuracy. It depends on the accuracy of analogue input circuits, the accuracy of the sampling process itself, [9], the accuracy of A/D conversion and the accuracy of digital calculations. In digital sampling electricity meters the measurement error can be simply eliminated in the digital signal processing. In this case the main problem is the stability of the parameters of these parts which handle the measured signals. The analogue input circuits must be constructed using highly stable components. Usually, synchronised or approximately synchronised sampling is used, [9]. A/D conversion with multiplexed inputs of one A/D converter needs a compensation of errors caused by time delay between the multiplied voltage and current samples by means of one of the known methods, [10]. Better way is to use separate A/D converter for each input signal. There are many methods of error correction in digital electricity meters, [11]. Most of these methods use software correction based on calibration process.

Digital electricity meters have different measurement and communication possibilities and different prices. The accuracy of the best instruments is of the order 0.01 % or better.

2. DESIGNED INSTRUMENT DESCRIPTION

Block diagram of the proposed instrument for power network parameters measurement is in Fig. 1, [12]. It contains three input boards with sensors of the network voltages and currents and circuits for conditioning of the signals from the sensors. Analogue board digitizes the input signals and delivers the samples to a DSP board. It also contains digital-to-analogue converters and output amplifiers for signal generation. The DSP board makes necessary calculations and signal processing in digital form. It also generates digital samples of the generated output signals for testing of other electricity meters. Main control board controls some circuits of the input boards and the DSP board, displays the results and operates standard communication interfaces and a matrix keyboard.

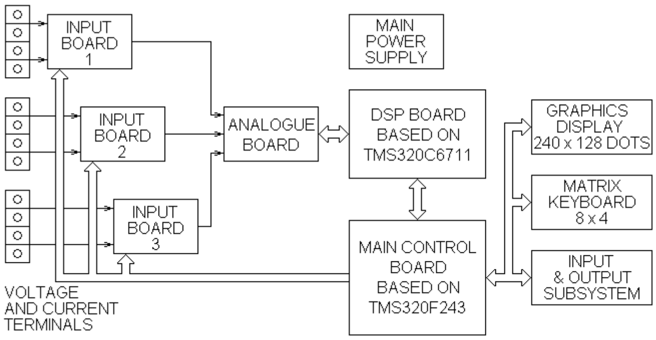

Fig. 1. Block diagram of the designed electricity meter.

2.1. Input board

The concept of the three input boards is shown in Fig. 2. Voltage sensors in the voltage channel scale the levels of the network voltages to get the desired values. These voltage sensors are realized as four-stage resistive voltage dividers. The voltage range is from 30 V to 500 V. Individual outputs of the voltage dividers are switched by a range switch which is controlled by the processor system automatically according to the output values of the A/D converters or according to the desired entered range. Overvoltage protection is a simple way of the voltage limitation in case of the occurrence of inadequate voltage levels. For the sake of low leakage current and high speed these circuits are realized by diodes. Instead of the sensed voltages it is possible to connect calibration values to the inputs of the buffer stages. In this case it is possible to check zero level shifts and to connect and measure precision DC calibration voltage. Inaccurate adjustment of the voltage dividers is compensated by coefficients introduced into the calculation of the input voltages in the processor part. The phase shifts of the voltage channel were immeasurable up to the frequency 2 kHz.

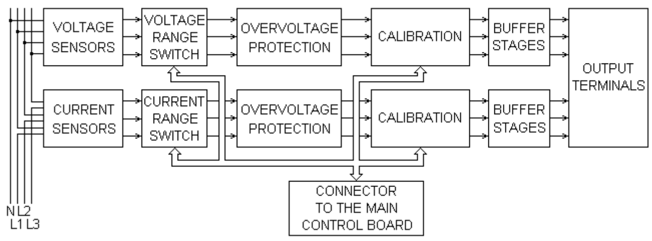

Fig. 2. Block diagram of the input board.

The concept of the current channel is practically the same as the voltage channel. The current sensors are realized as current transformers with metal glass core material followed by the current-to-voltage conversion. There are six current ranges so the total current range is from 50 mA to 120 A. Inaccuracies in the current channel are compensated by the calibration procedure for every current range separately. The phase shifts of the current channel are immeasurable up to the frequency 2 kHz. The attempts have been made to use compensated current transformers, [13], but the better accuracy of the conversion has been overshadowed by the increased noise level and more complicated construction.

2.2. Main control board

The block diagram of the main control board of the designed electricity meter is in Fig. 3. The heart of the board is the Texas Instruments TMS320F243 processor with external memories. It controls the operation of the entire device. It contains also address decoder and control logic. All the circuits (keyboard, display, DSP board) are mapped into its memory so it makes the communication very simple. For presentation of time and frequency characteristics, graphical LCD display with the resolution of 240x128 dots is used.

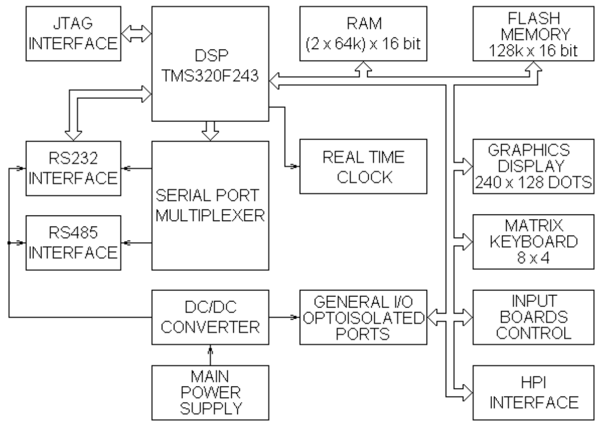

Fig. 3. Block diagram of the main control board.

The processor operates standard communication interfaces such as RS-232 and RS-485, which are multiplexed. The information can be entered into the instrument also through a matrix keyboard. JTAG interface is used when the instrument is programmed (software is emulated). HPI interface is used in communication between the DSP and the main control board. As many other microprocessor-controlled instruments, this electricity meter also contains real time clock and the real time can be used to check the instants the data have been measured.

2.3. DSP board

The most important part of the device is the digital signal processor (DSP) board with a powerful TMS320C6711 DSP, Fig. 4. This part makes all the necessary computations of the system. It controls the communication with A/D converters 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 visualise the results, a communication port with the microcontroller has been 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. The DSP board 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. Signal generation procedure is similar as in DDS systems. The levels of the generated signals are stabilized by feedback from the analogue outputs by means of A/D converters. The frequency spectra of the measured voltages and currents up to the 50^{th} harmonic are calculated using the FFT algorithm.

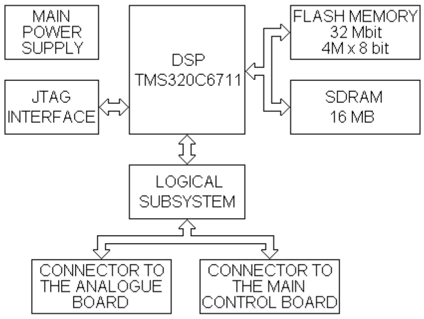

Fig. 4. Block diagram of the DSP board.

The properties of the DSP board:

- powerful floating-point Texas Instruments TMS320C6711 DSP for computation of multiple FFTs and for calculation of measured quantities,
- high speed temporary data memory (8 MByte SDRAM),
- large low-cost program and data memory (4 MByte flash ROM),
- simple control signals and data transfer from the three A/D converters at sampling rate up to 100 kHz,
- simple communication between the DSP and the microcontroller (HPI interface, [14]),
- watch-dog security system,
- JTAG emulation for software development.

2.4. Analogue board

The block diagram of the analogue board of the designed electricity meter is in Fig. 5. Three blocks of A/D converters digitise the signals from the input boards. They contain six 18-bit A/D converters (16 bits used) with approximately synchronised sampling, [9], and sampling frequency f_s = 50 kHz.

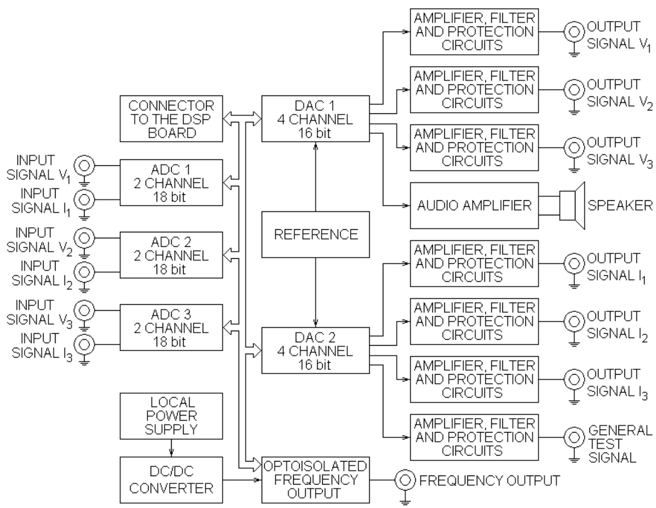

Fig. 5. Block diagram of the analogue board.

This board also converts the digital samples of the generated three-phase signals to the analogue form in two 4-channel, 16-bit digital-to-analogue converters (DAC). These signals are then amplified, filtered and connected to the output terminals. Optoisolated frequency output with the frequency proportional to the measured active power is also a part of the board.

3. ERROR SOURCES IN ELECTRICITY METERS

As mentioned earlier, there are practically four main error sources in digital sampling electricity meters: errors of the analogue input circuits, errors of the sampling process, errors of A/D conversion and errors of digital calculations. In precise instruments, precautions must be used to overcome or eliminate these errors.

The errors caused by the analogue input circuits are mainly inaccurate adjustments of voltage and current sensors, instability and noise of circuits handling the input signals. If stable, these errors can be eliminated by the calibration, where calibration constants are determined and then used to correct the measured values.

The sampling of the real waveform usually approximates the waveform by a staircase or a piecewise linear function. The following equations, which use the staircase approximation, have been used to calculate the power network parameters, [13]:

$$U = k_u \sqrt{\frac{1}{N}\sum_{i=1}^{N} u_i^2} \tag{1}$$

$$I = k_i \sqrt{\frac{1}{N}\sum_{i=1}^{N} i_i^2} \tag{2}$$

$$S = UI \tag{3}$$

$$P = \frac{k_u k_i}{N}\sum_{i=1}^{N} u_i i_i \tag{4}$$

$$Q = \sqrt{S^2 - P^2} \tag{5}$$

$$PF = \frac{P}{S} \tag{6}$$

$$f = \frac{f_s}{N} \tag{7}$$

where k_u and k_i are voltage and current range constants, respectively, f_s is the sampling frequency, and f is the power network frequency.

The approximation increases the error of measurement but because of the symmetry of sine and cosine functions this error may be small. The error increases if the waveform is distorted.

Another problem concerning the sampling process is the synchronization of sampling with the input signals. Usually, synchronised or approximately synchronised sampling is used, [9]. Simple and often used method is to start sampling in the instant of zero crossing of the input voltage or current (approximately synchronised sampling). The error here is caused by the random position of the last sample considering the end of the period, missing or exceeding sample (from the next period). This error depends on the sampling rate and on the averaging time interval.

The errors caused by A/D conversion depend on the number of A/D converters used and on the resolution of A/D converters. Low-resolution A/D converters (low number of bits) cause unacceptable quantisation errors.

Even very fast DSP is not able to make corrections of every sample according to the correction function (for the three-phase system six samples must be corrected per one sampling period and all other calculations and operations must be also done). In this case, usually, only the final calculated values are corrected and, thus, additional errors are introduced, [15].

4. INSTRUMENT CALIBRATION

The calibration of the instrument was performed by a calibration station EKS 05-3 with a software Station, [16]. A reference instrument used was K2006 precise three-phase comparator, [8]. The calibrated quantities were the voltages and the currents of the power network. A phase shift correction was then performed by shifting of the current samples against the voltage samples before their multiplication (power calculation) in the digital signal processing. So, the main importance is to have the accurate measurement of the voltages and the currents. The errors of the voltage and the current measurements after the instrument calibration are in Fig. 6 to Fig. 15.

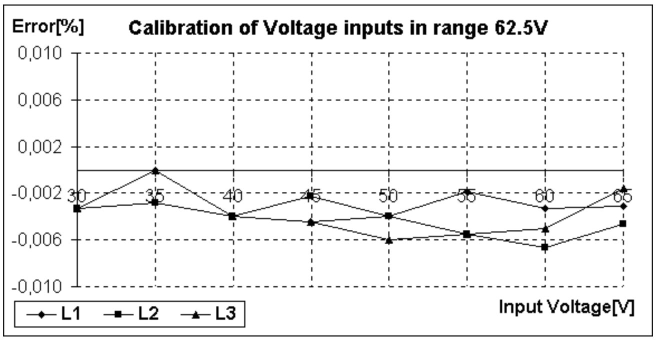

Fig. 6. Errors of the voltage inputs in the range 62.5 V.

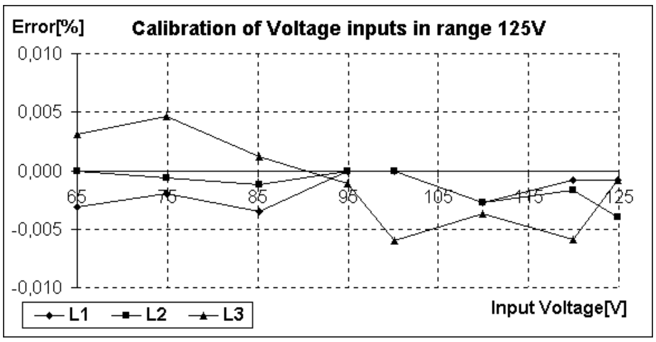

Fig. 7. Errors of the voltage inputs in the range 125 V.

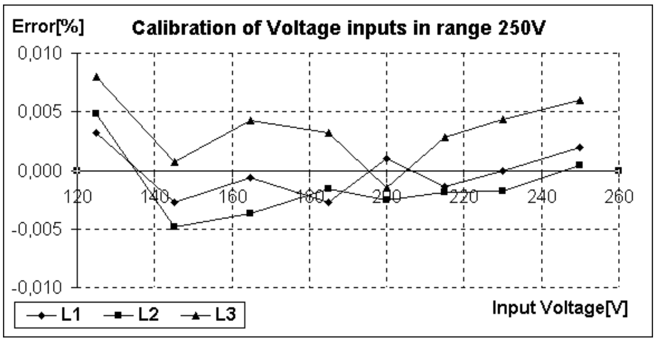

Fig. 8. Errors of the voltage inputs in the range 250 V.

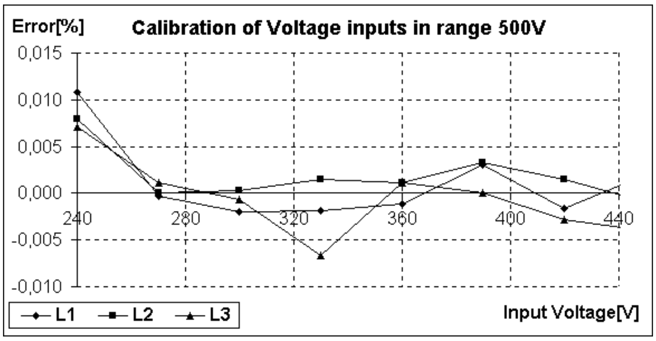

Fig. 9. Errors of the voltage inputs in the range 500 V.

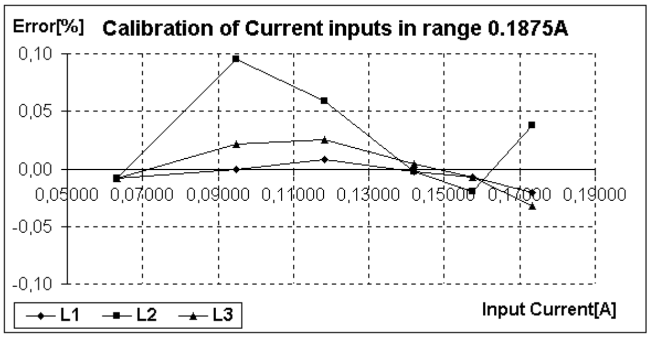

Fig. 10. Errors of the current inputs in the range 187.5 mA.

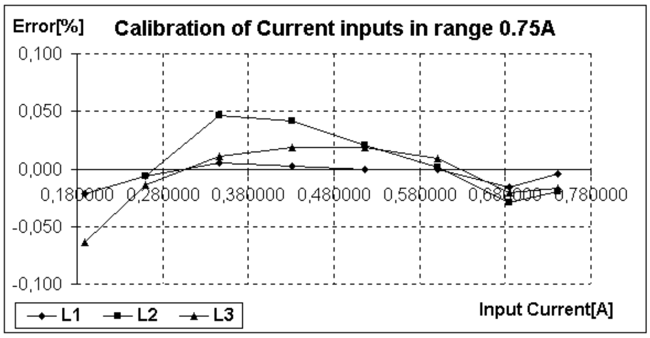

Fig. 11. Errors of the current inputs in the range 750 mA.

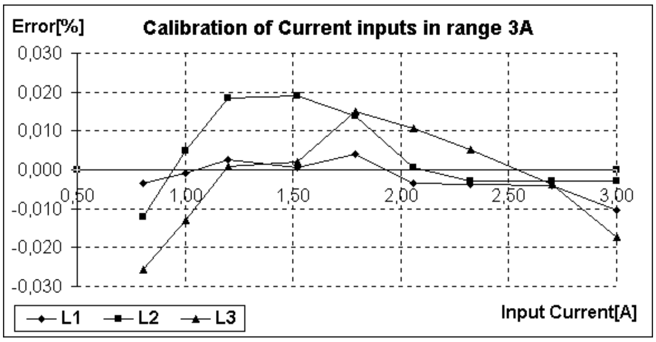

Fig. 12. Errors of the current inputs in the range 3 A.

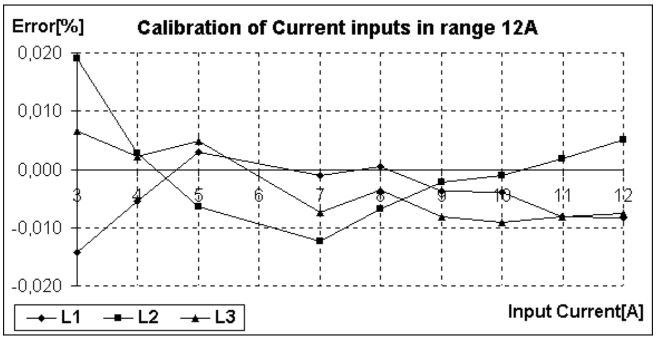

Fig. 13. Errors of the current inputs in the range 12 A.

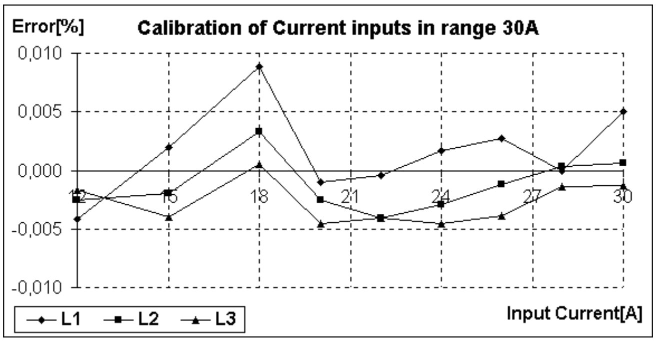

Fig. 14. Errors of the current inputs in the range 30 A.

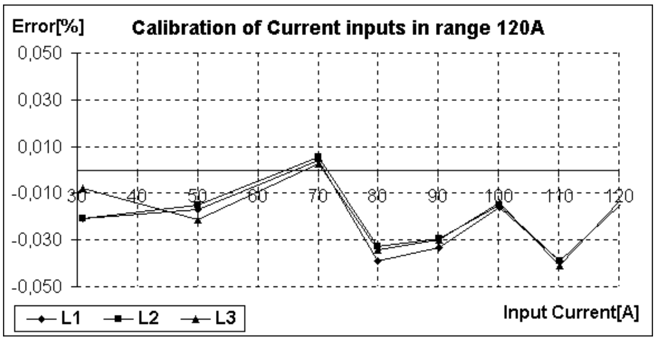

Fig. 15. Errors of the current inputs in the range 120 A.

The phase L2 in Fig. 10 seems to have uncompensated offset error. Low-current end in Fig. 11 has a bit higher error. All other results are within the error range of 0.05 %.

5. CONCLUSIONS

A description of the designed digital three-phase electricity meter and signal generator is given. Modern Texas Instruments TMS320F243 processor and TMS320C6711 DSP were used to get a powerful measuring system. It can measure basic parameters of the three-phase power network such as rms values of voltages and currents, powers, energies, power factors, the network frequency and frequency spectra. Its accuracy is better than 0.05%. The instrument can be also used as a generator of three-phase voltage and current signals with selectable phase shifts and higher harmonic components. Four main error sources in digital sampling electricity meters, namely errors of the analogue input circuits, errors of the sampling process, errors of A/D conversion and errors of digital calculations are briefly explained.

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