Digital Power Network Parameters Measurement

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Abstract. *Exact measurement of the 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 and the network frequency. Questions concerning the accuracy of measurement, error sources, and error correction are also given. A method of calibration based on the frequency output is proposed and its calculation accuracy evaluated by MATLAB.*

Keywords

Digital electricity meter, DSP, power measurement, measurement accuracy, error sources, 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], analog 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 one A/D converter with multiplexed inputs, [7], or they may use separate A/D converter for each input signal, [4]. The advantages of such instruments are obvious: high accuracy, short- and long-term stability, complex net parameters measurements, possibility of remote automated data processing, auto-calibration, self-test and many other functions resulting from the microprocessor-based digital system possibilities. With today‘s high computing power of digital signal processors it is also simple to measure the reactive power, apparent power, phase shift, power factor and the frequency spectrum of the power network signals.

Very important characteristic of electricity meters is their accuracy. It depends on the accuracy of the analog 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 analog input circuits must be constructed using highly stable components. Usually, synchronized or approximately synchronized sampling is used, [9]. A/D conversion with multiplexed inputs of A/D converter must use one of the known methods of compensation of errors caused by time delay between the multiplied voltage and current samples, [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. Analog Circuits of the Electricity Meter

Circuit diagram of the proposed instrument for power network parameters measurement is in Fig. 1, [12]. It contains the circuits for conditioning of the signals proportional to the network voltages and currents. The processor part controls some circuits of the analog part, digitizes the signals, makes necessary calculations and signal processing in digital form, displays the results and generates signals for testing of other electricity meters.

Voltage sensors in the voltage channel scale the levels of the net voltages to the desired values. These voltage sensors are realized as four–stage resistive voltage dividers. The voltage range is from 30 V to 500 V. Single outputs of the voltage dividers are switched by a range switch which is controlled by the processor system according to the output values of the A/D converters. 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 with 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.

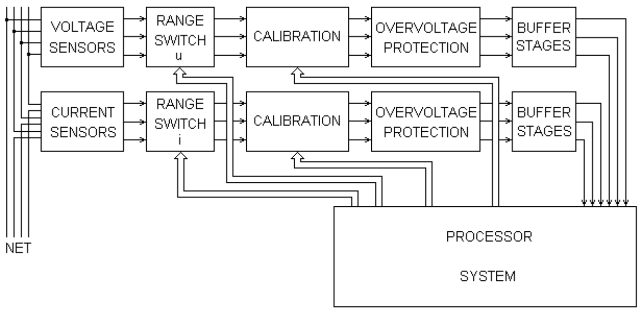

Fig. 1. Block diagram of the proposed digital electricity meter.

The concept of the current channel is practically the same as the voltage channel, Fig. 1. 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, Fig. 2, but the better accuracy of the conversion has been overshadowed by the increased noise level and more complicated construction.

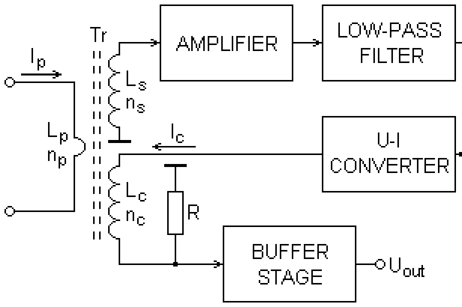

Fig. 2. Block diagram of the compensated current transformer.

3. Digital Part of the Electricity Meter

The block diagram of the digital part of the designed electricity meter is in Fig. 3, [13], [14]. Microcontroller board with the Texas Instruments TMS320F243 processor controls the operation of the device. It contains also an address decoder and control logic. All the circuits (keyboard, display, DSP board) 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. A block of A/D converters digitizes the signals from the analog part. It contains six 18-bit A/D converters (16 bits used) with approximately synchronized sampling, [9], and sampling frequency f_s = 50 kHz. 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 converter block and a frequency output with the frequency proportional to the measured power.

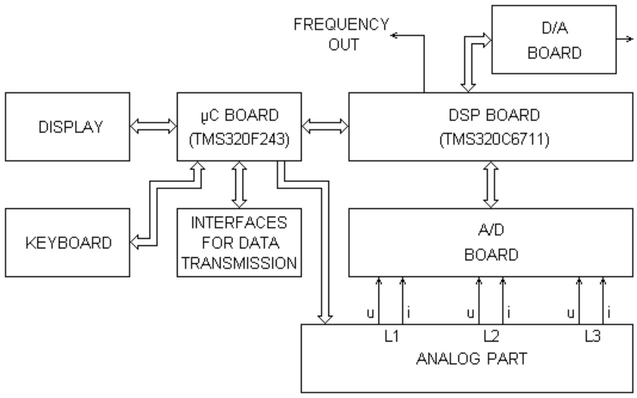

Fig. 3. Block diagram of the digital part of the proposed electricity meter.

The device operates in two modes. In the calibrator mode the following parameters are measured and calculated: rms values of voltages and currents, active, reactive and apparent powers, power factors, network frequency, energy delivered into the load and frequency spectrum of the measured signals. The results are displayed continuously on the display. In the registration mode the measured and calculated parameters are periodically stored in the memory. As a result, time characteristic or electric energy consumption can be obtained. The period of averaging and storing the results is optional. The shortest time interval of voltages, currents and powers calculation is one period of the network signals. The measured average values are displayed on demand. All data can be transferred into an external device via an infrared or RS 232 interface.

The most important part of the device is the digital signal processor (DSP) board with a powerful DSP TMS320C6711. 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 visualize 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. The frequency spectra of the measured voltages and currents up to the 50th harmonic are calculated using the FFT algorithm.

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 of 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),
- watch-dog security system,
- JTAG emulation for software development.

To set the parameters of the device, calibration procedure must be run. The instrument is calibrated using known values of the input quantity. During the calibration a digital processor in the instrument calculates correction coefficients or correction functions which are used to get the correct values of the measured quantity during the measurement. In the proposed instrument the least squares method is used but this procedure is not user accessible.

The following equations have been used to calculate the power network parameters, [15]:

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

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

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

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

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

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

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

where k_u and k_i are voltage and current range constants, respectively. The maximum value of the data from the A/D converter (16 bit) is $u_{max} = \pm\, 2^{15}$. At the minimum power network frequency f = 45 Hz, the number of samples per period is $N = f_s / f$ = 50 kHz / 45 Hz = 1111. The maximum possible value of the sum in equation (1) is $U_{max} = N(u_{max})^2$ and 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. The averaging of samples is accomplished during more than one period. The default number of periods is 50.

Equations (1) and (2) represent staircase approximation of the input signals.

4. Error Sources in Electricity Meters

As mentioned earlier, there are practically four main error sources in digital sampling electricity meters: errors of the analog 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 analog input circuits are mainly inaccurate adjustments of voltage and current sensors, instability and noise of circuits handling the input signals.

The sampling of the real waveform usually approximates the waveform by a staircase or a piecewise linear function. The rms value and the power are calculated in staircase approximation by equations (1) [or (2)] and (4), approximately. In piecewise linear approximation these equations are more complicated, [16]:

$$U = \sqrt{\frac{1}{3N}\sum_{i=0}^{N-1}\left(u_i^2 + u_i u_{i+1} + u_{i+1}^2\right)}\,, \tag{8}$$

$$P = \sqrt{\frac{1}{3N}\sum_{i=0}^{N-1}\left[u_i i_i + \frac{1}{2}\left(u_{i+1} i_i + u_i i_{i+1}\right) + u_{i+1} i_{i+1}\right]}\ . \tag{9}$$

The approximation increases the error of measurement but because of the symmetry of sine and cosine functions this error may be small. Often, simpler equations (1), (2) and (4) may give lower errors than equations (8) and (9). The error increases if the waveform is distorted.

Another problem concerning the sampling process is the synchronization of sampling with the input signals. Asynchronous sampling is not practically used because of its high error or very long averaging time (summation interval), [9]. Simple and often used method is to start sampling in the instant of zero crossing of the input voltage or current (approximately synchronized sampling). Better accuracy can be achieved if the sampling starts in the instant of crossing the rms value of the sampled signal, [17]. It is difficult to realize in a three-phase system or if there is a phase shift between the voltage and the current. The error here is caused by the random position of the last sample compared with the instant of the end of period, missing or exceeding sample (from the next period). The best accuracy, from this point of view, needs synchronization of the sampling frequency with the frequency of the input signal, [2].

If the number of samples, N, used to get the average value is low then the error of measurement increases, [9]. This error depends on the sampling rate and on the averaging time. High sampling rate makes it possible to average the samples with good accuracy even during one period of the power network signal. It is then possible to register even short transitions in power consumption and to change the frequency output after every period of the signal.

The errors caused by A/D conversion depend on the number of A/D converters used and on the resolution of A/D converters. Errors in one A/D converter with multiplexed inputs are caused by time delay between the multiplied voltage and current samples. Low-resolution A/D converters (low number of bits) cause unacceptable quantization 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.

5. Error Correction in Electricity Meters

In digital sampling electricity meters the measurement errors of the analog input circuits 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.

For the sake of calculation simplicity, mainly staircase approximation is used. In symmetrical signals the errors of sampling in one quarter of period are partly compensated in another quarter.

Approximately synchronized sampling with the starting point in the instant of zero crossing of the sampled signal is the usual case in digital electricity meters. If the number of samples used in one summation interval is sufficiently high, then the error of such sampling is low.

Precise instruments use sigma-delta A/D converters with high resolution (over 16 bits) and high sampling rate (tens kSPS). All the measured quantities are then calculated during one period but, usually, the results are averaged again during longer summation intervals to get higher accuracy.

To find out the error of calculation when only the final calculated values were corrected, simplified calculations of the corrected rms values of the net voltage U, current I and the active power P were compared with the calculations where every sample was corrected, [18]. The selected correction function was a linear function of the type $y = ax + b$, where the constant a represents the gain error and the constant b is the offset error. 1000 samples of the voltage and current per period were calculated using the equations:

$$u_i = a_1 U_m \sin(2\pi i/1000) + b_1 , \tag{10}$$

$$i_i = a_2 I_m \sin(2\pi i/1000) + b_2 \tag{11}$$

where $i = 1,2,...,1000$. For simplicity, the values U_{m} and I_{m} were set to unity.

The following equations show the correct use of the correction function:

$$U_1 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{1}{a_1}u_i - \frac{b_1}{a_1}\right)^2} , \tag{12}$$

$$I_1 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{1}{a_2}i_i - \frac{b_2}{a_2}\right)^2} , \tag{13}$$

$$P_1 = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\frac{1}{a_1}u_i - \frac{b_1}{a_1}\right)\left(\frac{1}{a_2}i_i - \frac{b_2}{a_2}\right)\right] . \tag{14}$$

The simplified calculation of the corrected values is given by the equations:

$$U_2 = \frac{1}{a_1}\sqrt{\frac{1}{N}\sum_{i=1}^{N}u_i^2 + b_1^2} , \tag{15}$$

$$I_2 = \frac{1}{a_2}\sqrt{\frac{1}{N}\sum_{i=1}^{N}i_i^2 + b_2^2} , \tag{16}$$

$$P_2 = \frac{1}{a_1 a_2}\frac{1}{N}\sum_{i=1}^{N}u_i i_i + \frac{b_1 b_2}{a_1 a_2} . \tag{17}$$

Because of higher calculation errors of U_2 and I_2 in [18], equations (15) and (16) are modified.

The differences of the corresponding values are the calculation errors given by equations:

$$\delta_u = \frac{U_2 - U_1}{U_1} \times 100 , \tag{18}$$

$$\delta_i = \frac{I_2 - I_1}{I_1} \times 100 , \tag{19}$$

$$\delta_P = \frac{P_2 - P_1}{P_1} \times 100 . \tag{20}$$

These errors were plotted in Fig. 4 and Fig. 5 for different values of the coefficients a_1, a_2 (gain) and b_1, b_2 (offset). The offset is relative, referenced to the amplitude U_m or I_m. It can be seen that the results of calculation of the corrected rms values are the same if the offset coefficient is zero. For nonzero offset coefficient the error increases with the increased offset. On the other hand, higher errors can be seen for lower values of the gain coefficient.

The results of calculation of the corrected power values are also the same if the offset coefficients are zero. For simplicity, the values of a_1 and a_2 (b_1 and b_2) are equal. For nonzero offset coefficients the error increases with the increased offsets. Higher errors can be also seen for lower values of the gain coefficients.

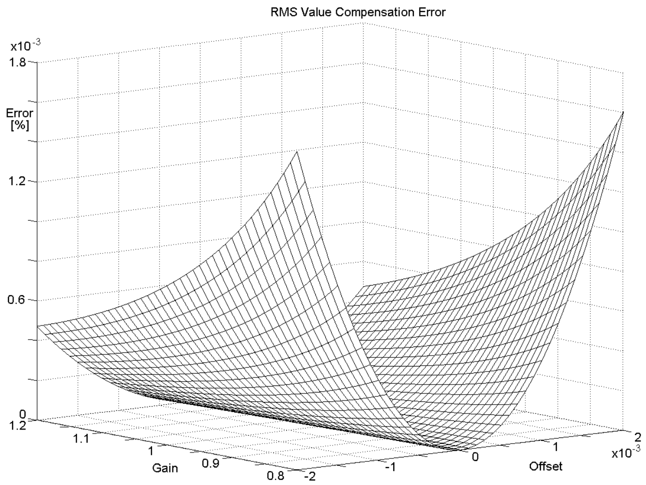

Fig. 4. RMS value correction error of the simplified calculation procedure.

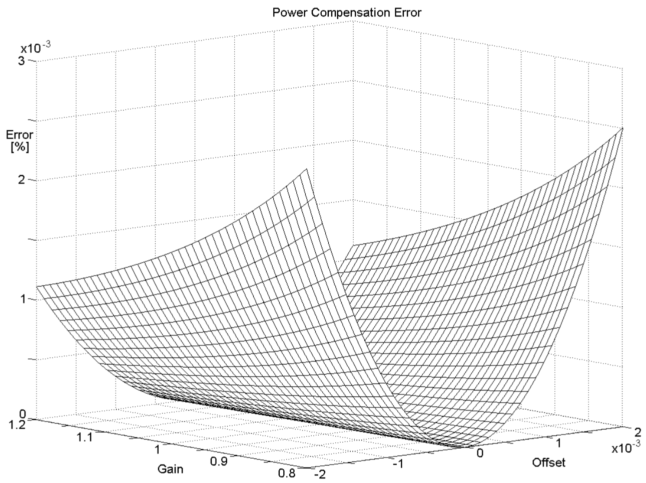

Fig. 5. Power correction error of the simplified calculation procedure.

Fig. 4 and Fig. 5 show that the errors of such simplified calculations are of the order 10^{-3} per cent. They are small enough to use them instead of much more complicated and time-consuming exact calculations.

6. Calibration Problems

Calibration procedure is used to set the parameters of the device and to correct the errors of measurement. The simplest error correction is only the offset correction, which is done by measuring the value of the input quantity with short-circuited input and storing this value in the memory for use as the correction constant. To correct the gain error multiplication coefficient must be evaluated. This needs some reference value of the input quantity to be connected to the input and measured by the instrument. The nonlinear characteristic of such an instrument needs more values of the input quantity to be connected to the input and measured by the instrument. In such case, a nonlinear correction function or a table of correction values must be calculated.

In electricity meters, three calibration procedures must be run, [19]: voltage calibration, current calibration and parasitic phase shift correction. The best way is to carry out the calibration process automatically, using a computer. The computer controls a signal source (sets the desired measured values), reads the necessary values from the calibrated and reference instrument in the same instant, calculates the calibration constants and stores them in the memory of the calibrated instrument. Manufacturers of electricity meters usually have such possibility.

The designed instrument contains an algorithm for voltage calibration using the least squares method. The current calibration can be done using the same algorithm but usually the measured current is not stable. In this case it is necessary to synchronize the measuring time period of the calibrated and the reference instrument or to use mean values. It is also possible to use frequency output of the instrument with the output frequency proportional to the apparent or active power. The frequency proportional to the measured power is compared with the correct value in the precise reference comparator. In this way, the calculated apparent power, S_i, is compared with the correct power value, S. As the voltage is correct (calibrated already) the mean value of the apparent power relative error is the same as the mean value of the current relative error. These errors in a few points over the calibrated current range can be used to calibrate the current by the least squares method.

Simple, lower accuracy electricity meters sometimes do not have the frequency output based on the apparent power. They have only the frequency output based on the active power. In this case the current calibration procedure must be repeated because of its dependence on the phase shift correction. A method was carried out to calculate the current and the parasitic phase shift at the same time, [20].

The measured powers P_i, $P_{i\varphi}$ for two different phase shifts 0, φ are compared with the correct values P, P_φ, respectively, using the frequency output of the instrument. The mean values of the relative errors yield the mean values of the calculated powers:

$$P_i = P(1+\frac{\delta}{100}), \quad P_{i\varphi} = P_\varphi(1+\frac{\delta_\varphi}{100}). \tag{21}$$

The equations to be solved to get the mean values of the measured current and parasitic phase shift are, [19]:

$$P_i = UI_i\cos(\varphi_p)\,,\quad P_{i\varphi} = UI_i\cos(\varphi+\varphi_p) \tag{22}$$

where φ_p is a phase shift between the voltage and the current caused by the input circuits of the instrument and U, I_i are the measured voltage and current, respectively.

Using mathematical formula for the cosine of the sum of two phase angles, [21], and taking into account that φ_p is a small phase shift it is possible to simplify this equations. The simplest solution follows from the well known fact that if x is small then $\sin(x) = x$ [rad] and $\cos(x) = 1$:

$$I_i = \frac{1}{U}\frac{2P_i^3\sin^2(\varphi)}{2P_i^2\sin^2(\varphi)-[P_i\cos(\varphi)-P_{i\varphi}]^2}\,, \tag{23}$$

$$\varphi_p = \frac{P_i\cos(\varphi)-P_{i\varphi}}{P_i\sin(\varphi)}\,. \tag{24}$$

For phase shifts φ_p up to 5° the error of this solution is of the order of tenth per cent as shown in Fig. 6. Here, for starting values of I and φ_p the exact values of powers P_i and P_φ are calculated from equations (22), the values of I and φ_p are calculated again from equations (23) and (24), respectively, and compared with the starting values. The values U = 100 V and φ = 60° were used.

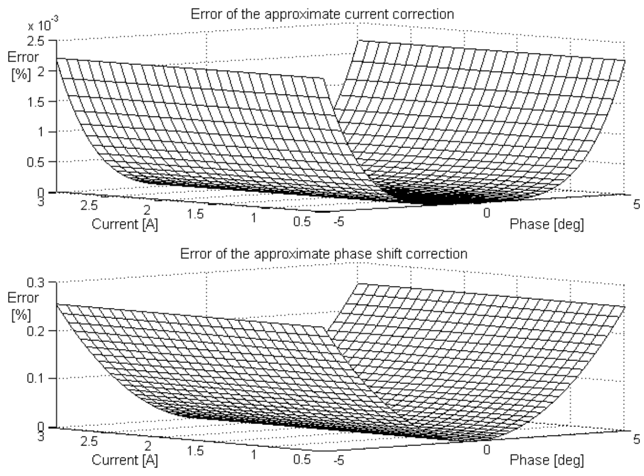

Fig. 6. Errors of the approximate current and phase shift corrections.

Higher precision of the solution is obtained using, [21]:

$$\sin(x) = x-\frac{x^3}{6}\,,\quad \cos(x) = 1-\frac{x^2}{2}\,. \tag{25}$$

In this case equations (22) change to:

$$P_i = UI_i(1-\frac{\varphi_p^2}{2})\,, \tag{26}$$

$$P_{i\varphi} = UI_i\cos(\varphi)(1-\frac{\varphi_p^2}{2})-UI_i\sin(\varphi)(\varphi_p-\frac{\varphi_p^3}{6})\,. \tag{27}$$

Extraction of I_i from equation (26) yields:

$$I_i = \frac{P_i}{U(1-\frac{\varphi_p^2}{2})} \tag{28}$$

and substitution of equation (28) into (27) leads to the cube equation:

$$P_i\sin(\varphi)\varphi_p^3 - 3\left[P_i\cos(\varphi)-P_{i\varphi}\right]\varphi_p^2 - $$
$$-6P_i\sin(\varphi)\varphi_p + 6\left[P_i\cos(\varphi)-P_{i\varphi}\right] = 0\,. \tag{29}$$

The number of real roots of this equation depends on the sign of the expression:

$$D = -2-6\left\{1+\frac{\left[P_i\cos(\varphi)-P_{i\varphi}\right]^2}{P_i^2\sin^2(\varphi)}\right\}^2\,. \tag{30}$$

For $D < 0$ equation (29) has three real roots.

To solve equation (29) three new expressions have been introduced:

$$q = -2\frac{\left[P_i\cos(\varphi)-P_{i\varphi}\right]^3}{P_i^3\sin^3(\varphi)}\,, \tag{31}$$

$$r = \pm\sqrt{2+\frac{\left[P_i\cos(\varphi)-P_{i\varphi}\right]^2}{P_i^2\sin^2(\varphi)}}\,, \tag{32}$$

$$\cos(\alpha) = \frac{q}{r^3}\,. \tag{33}$$

The sign of r must be the same as the sign of q. If the phase angle φ_p is positive, then q is negative and vice versa. Three roots of equation (29) are now given by the expressions:

$$\varphi_{p1} = -2r\cos\left(\frac{\alpha}{3}\right)+\frac{P_i\cos(\varphi)-P_{i\varphi}}{P_i\sin(\varphi)}\,, \tag{34}$$

$$\varphi_{p2} = 2r\cos\left(60-\frac{\alpha}{3}\right)+\frac{P_i\cos(\varphi)-P_{i\varphi}}{P_i\sin(\varphi)}\,, \tag{35}$$

$$\varphi_{p3} = 2r\cos\left(60+\frac{\alpha}{3}\right)+\frac{P_i\cos(\varphi)-P_{i\varphi}}{P_i\sin(\varphi)}\,. \tag{36}$$

Because the expected value of φ_p is near to zero, the proper root must be selected. After finding the value of φ_p from one of equations (34) to (36) the value of the current is calculated from equation (28).

The solution of equation (29) was carried out also in MATLAB under the same conditions as given for the solutions (23) and (24). Fig. 7 shows the calculated error of such solution of the current I_i from equation (28), and Fig. 8 shows the error of the solution of the parasitic phase shift φ_p directly from equation (29).

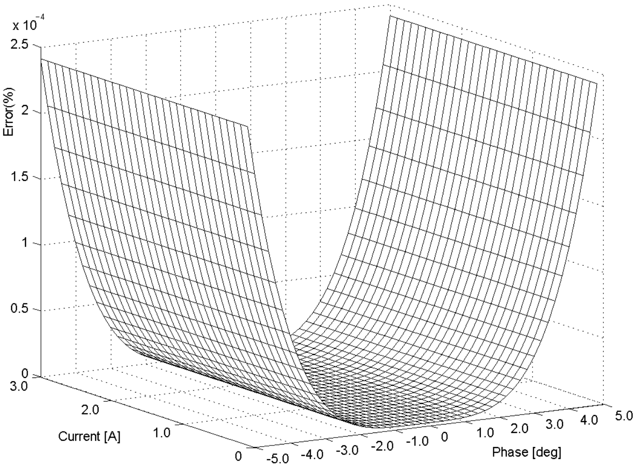

Fig. 7. The calculated error of the current solution.

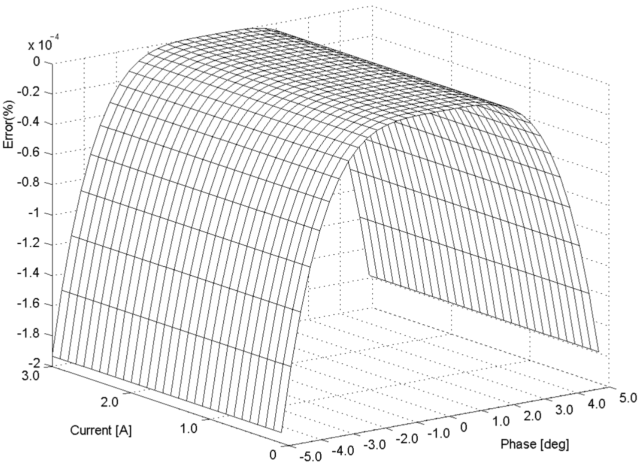

Fig. 8. The calculated error of the parasitic phase shift solution.

It is evident that for φ_p up to 5^o the error of such solution is of the order of 10^{-4} per cent. The error is independent on the current value. The results of the solution given by the direct calculation from equations (28), (34), (35), (36) are similar.

7. Conclusions

Brief description of the designed digital three-phase electricity meter is given. Modern Texas Instruments TMS320F243 processor and TMS320C6711 DSP were used to get a powerful measuring system. Four main error sources in digital sampling electricity meters, namely errors of the analog input circuits, errors of the sampling process, errors of A/D conversion and errors of digital calculations are briefly explained. Error correction precautions are also described and accuracy results of simplified correction calculations are given. Because of low calculation errors (of the order of 10^{-3} per cent), validity of such simplified calculations is proved. Calibration problems in the proposed electricity meter are described. A calibration procedure for the corrections of the measured current and parasitic phase shift between the measured voltage and current based on the active power measurement is given. This procedure enables to calculate the correct values of the current and the phase shift at the same time, thus overcoming the repeating of the current calibration after the phase shift correction. These correct values can now be used in the current calibration and parasitic phase shift correction procedures. The errors of simplified solution are of the order of 10^{-3} per cent for the current calculation but of the order of tenths per cent for the parasitic phase shift calculation. Higher precision method of such calculation was proposed and MATLAB calculations were used to verify this method. The errors of such calculations are of the order of 10^{-4} per cent.

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