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Measurement Over an Interval Method in Measuring and Monitoring of Power Quality

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Abstract: Measuring and monitoring of power quality of supplied electric energy are important links in electro-distribution chain. Modern systems used for this purpose are complex. Goal of this paper is to present a new approach to the measurements of power quality, which can achieve equal or better performances using less complicated hardware. In this paper, we have presented the method of measuring over an interval in measurements of relevant factors of power quality: grid voltage frequency, grid voltage RMS and grid voltage distortion factor. Also given is the analysis of performances from metrology point of view, which shows that the measurement uncertainty of proposed method is many times lower than required, regarding maximum deviations from nominal values, defined by the European norm EN50160.

Keywords: EN50160, Power quality, Measurement uncertainty, Stochastic measurement.

1 Introduction

Measurement over an interval method is an integral approach to the measurements of signals and their parameters. Essentially this method represents generalization of a standard sampling method which we have named measurement in a point, but with totally different metrology assumption. Here it is not necessary for quantization error to be, theoretically, infinitesimally small - its value can be finite or even substantial [1 – 4].

The advantages of measurement over an interval method are:

- high frequency signals measurements;
- measurements of noisy signals;
- measurements of signals requiring high linearity and accuracy.

The characteristics of measurement over an interval method can be combined to achieve accurate results in areas where previously not possible [5 – 7].

Considering that quantization error of this method can be high, method is implemented using A/D converters with low resolution, extreme case is 2 bit or

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even 1 bit resolution. Any characteristic of a signal, under certain conditions, can be measured (calculated) from samples taken over the interval.

In the first paper dedicated to this method [1] almost all important properties are provided:

a) at the input of low resolution A/D converter, using analogue adder, uniform random noise signal, in the range of a quant of the A/D converter, is added to the signal being measured;
b) since measured data is of short word, devices for digital processing (adder, subtractor, multiplier) are also short worded, meaning simple hardware;
c) correctness of digital processing is ensured by using uncorrelated additional (dither) signals in case of above mentioned devices for digital processing.

During measurements on a power grid the natural interval is one or several periods of grid voltage signal. It is shown that even that interval could be determined from low resolution samples obtained by measurement over an interval method [4]. If the interval length is known, the following can be measured: voltage RMS, current RMS, active, reactive, apparent power, etc.

The first device based on this method was a voltmeter. It measured RMS value of AC voltage [8], later a number of devices, prototypes and commercial ones were made. Devices that measure the power quality, measure in frequency (transformation) domain, for standard method of measurement over the interval, had high resolution (6 or 8 bitts) [9, 10].

In this paper it will be shown that the power quality could be measured using 2 bit A/D converters in combination with 2-bit Stochastic digital measurement method (SDMM).

2 Problem Definition

The European norm EN50160 [11], set in year 2000, is the first and major quality standard for supplied electric energy and is a compromise between the suppliers and users of electric energy. Suppliers insist on wide limits and tolerances for parameters of grid voltage and users insist on narrowing them down. That delicate balance is the reason for longevity and stability of EN50160 norm. The intention of the norm is that the grid voltage signal is:

1) sinusoidal,
2) RMS value 230 V,
3) frequency 50 Hz,
4) three phase symmetrical.

The norm defines limits and tolerances as given in **Table 1**.

Table 1
Voltage characteristics of electricity supplied by public distribution systems.

SUPPLY VOLTAGE PHENOMENON	ACCEPTABLE LIMITS	MEASUREMENT INTERVAL	MONITORING PERIOD	ACCEPTANCE PERCENTAGE
Grid Frequency	49.5 Hz to 50.5 z to 52 Hz	10 s	1 week	95% 100%
Slow Voltage Changes	230 V ± 10 %	10 min	1 week	95%
Voltage Sags or Dips (≤1 min)	10 to 1000 times per year (under 85 % of nominal)	10 ms	1 year	100%
Short Interruptions (≤3 min)	10 to 100 times per year (under 1 % of nominal)	10 ms	1 year	100%
Accidental, long interruptions (>3 min)	10 to 50 times per year (under 1 % of nominal)	10 ms	1 year	100%
Temporary over-voltages (line-to-ground)	Mostly < 1.5 kV	10 ms	N/A	100%
Transient over-voltages (line-to-ground)	Mostly < 6 kV	N/A	N/A	100%
Voltage unbalance	Mostly 2% but occasionally 3%	10 min	1 week	95%
Harmonic voltages	8% Total Harmonic Distortion (THD)	10 min	1 week	95%

Voltage RMS value at mains is:

$$U = \sqrt{\frac{1}{T_g} \int_0^{T_g} u^2(t)\,\mathrm{d}t}\,, \tag{1}$$

where

$$u(t) = U_m \sin(\omega t)\,, \tag{2}$$

$$\omega = \frac{2\pi}{T_g}\,, \tag{3}$$

$$f_g = \frac{1}{T_g} = 50\,\mathrm{Hz}\,, \tag{4}$$

$$\frac{U_m}{\sqrt{2}} = 230\,\mathrm{V}\,. \tag{5}$$

Norm EN50160 defines allowed deviations of: frequency, symmetry, shape, current values and continuity of voltage at terminals to the grid.

If we know the values of parameters that are measured and their tolerances, then metrology problem is defining measuring equipment so the measurement uncertainty of each parameter of electric power (voltage) measurement is negligible (at least 3 times less than tolerances defined by EN50160 norm).

The measurement equipment today is digital, meaning it uses a standard sampling method. In this paper we shall, however, use somewhat altered sampling method that enables usage of low resolution A/D converters. This method we have named Stochastic digital measurement method (SDMM) [3, 4]. The essence of this method is to add, to analogue input signal, using analog adder, random uniform noise signal *s* in range of quant of A/D converter and to measure the integral of an input signal (signals) [3]. Formula (1) is suitable for application of the SDMM method.

Note that the input signal to A/D converter, apart from time *t*, also depends on random signal *s*. Therefore, samples after A/D converter that are processed in accordance to (1) depend on *t* and *s*. The idea is to get all the relevant information, for measuring and monitoring of the power quality, extracted from low resolution samples - in the extreme case and the simplest - 2-bit samples. So, we shall be using two bit SDMM.

All measurements, according to EN50160 norm, boil down to three types of measurements:

- measuring the frequency of grid voltage;
- measuring the grid voltage;
- measuring the factor of voltage distortion.

3 Frequency Measurement Using 2-bit A/D Converter

Measurement of the frequency is done using an instrument that has three or six channels, for measuring voltage and/or current frequency in all three phase of the grid. Structure of each channel is very simple and is comprised of several blocks (Fig. 1).

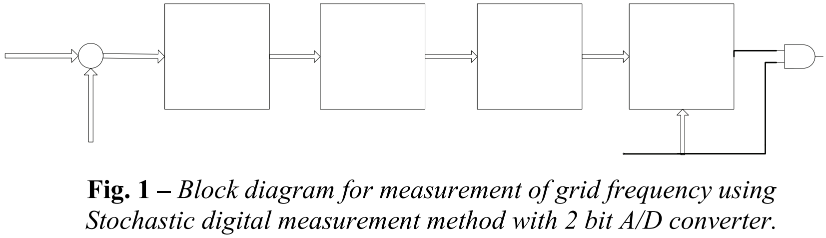

Fig. 1 – *Block diagram for measurement of grid frequency using Stochastic digital measurement method with 2 bit A/D converter.*

Initially, analogue signal $u(t)$, acquired from voltage divider or current sensor (usually current measurement transformer), is added to the white noise (dithering signal h) that has uniform probability density $p(h)$. Resulting signal $y(t)$ is digitalised using 2-bit flash A/D converter, and then passed through FIR filter. After determining the sign of the signal, digital circuit for zero detection (ZCD) gives an information on change of the sign of filtered signal $\hat{u}(n)$. The number of cycles of sampling between two adjacent change of a sign represent the duration of corresponding half-period of a signal. From an average value of duration of half-periods, frequency of the signal $u(t)$ is calculated. Measurement of frequency using above mentioned method is discussed in paper [12], limits of measurements errors are shown, as well as measurement uncertainty of the method.

4 Voltage Measurement Using 2-bit A/D Converter

Standard definition of RMS of grid voltage is given as:

$$U=\sqrt{\frac{1}{T_g}\int_0^{T_g}u^2(t)\,\mathrm{d}t}=\sqrt{\frac{1}{NT_g}\int_0^{NT_g}u^2(t)\,\mathrm{d}t}=\sqrt{\frac{1}{T_m}\int_0^{T_m}u^2(t)\,\mathrm{d}t}\ . \tag{6}$$

As $u(t)$ is measured using 2-bit flash A/D converters, to whose inputs, using analogue adder, uniform random noise s (or h) is added, above formula can be written as:

$$U=\sqrt{\frac{1}{T_m}\int_0^{T_m}u^2(t)\,\mathrm{d}t}=\sqrt{\frac{1}{T_m(s)}\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t}\ . \tag{7}$$

In this measurement the error, unlike measurement using standard digital sampling method where quantization error is negligible, is heavily dependant on random noise s, so

$$\frac{\mathrm{d}U}{\mathrm{d}s}=\frac{1}{2}\frac{\dfrac{\mathrm{d}}{\mathrm{d}s}\left(\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t\right)}{\sqrt{\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t}}, \tag{8}$$

respectively

$$\frac{\mathrm{d}U}{U}=\frac{1}{2}\frac{\dfrac{\mathrm{d}}{\mathrm{d}s}\left(\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t\right)\mathrm{d}s}{\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t}, \tag{9}$$

$$\frac{\mathrm{d}U}{U}=\frac{1}{2}\left[\frac{u^2\left(T_m(s)\right)\dfrac{\mathrm{d}T_m(s)}{T_m(s)}}{\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t}-\frac{\mathrm{d}T_m(s)}{T_m(s)}\right]+\frac{1}{2}\frac{\left(\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}\frac{\partial}{\partial s}u^2(t,s)\,\mathrm{d}t\right)\mathrm{d}s}{\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t}. \quad (10)$$

Since s is random variable, derivative of the third term of above equation doesn't exist, so as in [3] time within interval $t\in\left[0,T_m(s)\right]$ is treated as random variable with uniform distribution, and differential – measurement error of the third term, is treated as a measurement error of the square of RMS value [1 – 3].

$$\frac{\mathrm{d}U}{U}=\frac{1}{2}\left[\frac{u^2\left(T_m(s)\right)}{\dfrac{1}{T_m(s)}\displaystyle\int_0^{T_m(s)}u^2(t,s)\,\mathrm{d}t}-1\right]\frac{\mathrm{d}T_m(s)}{T_m(s)}+\frac{1}{2}\frac{\mathrm{d}U^2}{U^2}. \quad (11)$$

For $u(t)\approx U_m\sin(\omega t)$, where $\omega=\dfrac{2\pi}{T_g}$ follows

$$\frac{\mathrm{d}U}{U}=\frac{1}{2}\left[\frac{u^2\left(T_m\right)}{\dfrac{U_m^2}{2}}-1\right]\frac{\mathrm{d}T_m}{T_m}+\frac{1}{2}\frac{\dfrac{U_m^2}{2}\dfrac{1}{\sqrt{2M}}}{\dfrac{U_m^2}{2}}, \quad (12)$$

where M is defined as

$$T_m=NT_g=MT_s, \quad (13)$$

and M is the number of samples in measurement interval.

As factor

$$0\le\frac{u^2(T_m)}{U_m^2}\le 1 \quad (14)$$

follows that the first summand varies between

$$-\frac{1}{2}\left|\frac{\mathrm{d}T_m}{T_m}\right| \quad \text{and} \quad +\frac{1}{2}\left|\frac{\mathrm{d}T_m}{T_m}\right|. \quad (15)$$

So we get final formula:

$$\left|\frac{\mathrm{d}U}{U}\right|\le\frac{1}{2}\left|\frac{\mathrm{d}T_m}{T_m}\right|+\frac{1}{2\sqrt{2M}}. \quad (16)$$

Note that all values in the above formula were obtained from 2-bit samples obtained by measurements using stochastic digital measuring method (SDMM).

5 THD Factor Measurement

Distortion factor is characterized by a deviation of voltage in terminals on the low voltage grid, from basic sinusoidal waveform. The fundamental harmonic has amplitude U_1 and it is by definition sinusoidal. Then the distortion factor *k* is given by the following equation:

$$k = \frac{\sqrt{U^2 - U_1^2}}{U_1}, \tag{17}$$

where U is the RMS value of voltage at the terminals. The Norm requires that distortion factor is $k \leq 0.08$.

Calculating the error limits for the measurement of distortion factor:

Distortion factor *k* is given by (17), from which follows

$$k^2 U_1^2 = U^2 - U_1^2, \tag{18}$$

respectively

$$(1 + k^2) = \frac{U^2}{U_1^2}, \tag{19}$$

$$\sqrt{1 + k^2} = \frac{U}{U_1}, \tag{20}$$

since *k* is sufficiently small, by series expansion of the above equality we obtain the following expression:

$$1 + \frac{1}{2}k^2 \approx \frac{U}{U_1}. \tag{21}$$

Differentiating the expression for *k* we get

$$k\,\mathrm{d}k = \frac{\mathrm{d}U U_1 - U\,\mathrm{d}U_1}{U_1^2}, \tag{22}$$

so follows

$$\frac{k\,\mathrm{d}k}{1 + \frac{1}{2}k^2} = \frac{\mathrm{d}U U_1 - U\,\mathrm{d}U_1}{U U_1} \tag{23}$$

$$k\,\mathrm{d}k \approx \frac{\mathrm{d}U}{U} - \frac{\mathrm{d}U_1}{U_1}. \tag{24}$$

From this expression the final formula, for error limits for the measurement of distortion factor, follows

$$\left|\frac{\mathrm{d}k}{k}\right| \le \frac{1}{k^2}\left(\left|\frac{\mathrm{d}U}{U}\right| + \left|\frac{\mathrm{d}U_1}{U_1}\right|\right). \tag{25}$$

Note that error limit for the measurement of amplitude of harmonics $\left|\frac{\mathrm{d}U_1}{U_1}\right|$ is given in paper [5].

5 Evaluation of Measurement Uncertainty in Measurements of Power Quality Parameters

For the frequency of sampling $f_s = 500$ kHz, used in double three-phase power analyzer, developed at the Chair for electrical measurements of Faculty of Technical Sciences in Novi Sad, within the TR32019 project, the following evaluation of upper limits of the most important parameters of the power quality based on EN50160 norm are:

1. frequency:

$$\left|\frac{\mathrm{d}T_m}{T_m}\right| = \left|\frac{\mathrm{d}T_g}{T_g}\right| \le \frac{1.3\cdot 10^{-4}\,\mathrm{s}}{10\,\mathrm{s}} = 13\cdot 10^{-6}\,; \tag{26}$$

2. slow changes of voltage:

$$\left|\frac{\mathrm{d}U}{U}\right| \le \frac{1}{2}\left|\frac{1.3\cdot 10^{-4}\,\mathrm{s}}{600\,\mathrm{s}}\right| + \frac{1}{2}\frac{1}{\sqrt{2\cdot 5\cdot 10^5\cdot 600}} = \frac{0.2}{2}\cdot 10^{-6} + 20\cdot 10^{-6} \approx 20\cdot 10^{-6} \tag{27}$$

3. voltage drops:

$$\left|\frac{\mathrm{d}U}{U}\right| \le \frac{1}{2}\left|\frac{1.3\cdot 10^{-4}\,\mathrm{s}}{10\cdot 10^{-3}\,\mathrm{s}}\right| + \frac{1}{2}\frac{1}{\sqrt{2\cdot 5\cdot 10^5\cdot 10\cdot 10^{-3}}} = \frac{1.3}{200} + \frac{1}{200} \approx 1.15\cdot 10^{-2} \tag{28}$$

4. Brakes:

$$\left|\frac{\mathrm{d}U}{U}\right| \le \frac{1}{2}\left|\frac{1.3\cdot 10^{-4}\,\mathrm{s}}{10\cdot 10^{-3}\,\mathrm{s}}\right| + \frac{1}{2}\frac{1}{\sqrt{2\cdot 5\cdot 10^5\cdot 10\cdot 10^{-3}}} = \frac{1.3}{200} + \frac{1}{200} \approx 1.15\cdot 10^{-2} \tag{29}$$

5. Symmetry:

$$\left|\frac{\mathrm{d}U}{U}\right| \le 20\cdot 10^{-6} \tag{30}$$

6. Shape – distortion factor k:

$k = \dfrac{\sqrt{U^2 - U_1^2}}{U_1}$, since $k \le 0.08$, approximate expression applies:

$\left(1 + \dfrac{1}{2}k^2\right)U_1 \approx U$, i.e. $k\,\mathrm{d}k \approx \dfrac{\mathrm{d}U}{U} - \dfrac{\mathrm{d}U_1}{U_1}$, and finally,

$$\left|\frac{\mathrm{d}k}{k}\right| \le \frac{1}{k^2}\left(\left|\frac{\mathrm{d}U}{U}\right| + \left|\frac{\mathrm{d}U_1}{U_1}\right|\right).$$

Follows that

$$\left|\frac{\mathrm{d}k}{k}\right| \le \frac{1}{6400\cdot 10^{-6}}(20+41)\cdot 10^{-6} \approx 9.5\cdot 10^{-3} \approx 1\cdot 10^{-2} \tag{31}$$

It is worth noting that for higher distortion factors limit is lower than the one mentioned above.

6 Discussion

Relation (16) has two summand – the first that depends on accuracy of measurement of upper limit of integral $\left|\mathrm{d}T_m/T_m\right|$ and the second that depends on number of points in measured interval M where $M = T_m/T_s$. Note that M is integer number. For $T_s = 1/f_s = 1/500\,\mathrm{kHz} = 2\cdot 10^{-6}\,\mathrm{s}$ in previous chapter, it can be seen that we get acceptable results for accuracy of measurements of all parameters except $T_m = T_g/2 = 10\,\mathrm{ms}$, brakes, and surges. Accuracy of around 1%, obtained in this case is considered low. Interestingly both summands are in the same order of magnitude so we can influence both of them. Increasing sampling clock: modern technology of electronic components enables that in mixed mode, ASIC chip can increase its clock 20 times. Therefore, 20 times higher sampling rate means 20-fold increase of *M*, so the second summand can be decreased $\sqrt{20} \approx 4.5$ times. Lowering the theoretical limit of the measurement error T_m : theoretical limit [12] can be lowered approximately two times, using FIR filter with two times higher order, more than that doesn't make sense [13], furthermore $\left|\mathrm{d}T_m/T_m\right|$ can be decreased, so accuracy of measuring critical parameters, drops, breaks, surges, can be reduced to 0.35%. *Given the rough limits* (given *in percent*), the increase *of accuracy of about 3 times enables acceptable measurement and control* of *even critical parameters*, *drops*, breaks *and surges.*

With 20 times higher sampling rate accuracy of measuring the distortion factor is 4.5 times higher, so $\left|\mathrm{d}k/k\right| \le 2.1\cdot 10^{-3}$ in that case.

6 Conclusion

In this paper we showed how using 2-bit A/D converters and SDMM method we can measure and monitor parameters, of power quality at the mains, specified by the EN50160 norm. The general formula for voltage measurement at the mains was derived (using SDMM). Frequency and THD factor i.e.

fundamental harmonic measurement data were taken from literature. Developed algorithms were implemented in a dual three-phase power analyzer prototype. Theoretical values of measurement uncertainty match the values achieved for frequency measurements, while measurement uncertainty of voltage and THD are slightly higher, caused by imperfections of external circuits (current measurement transformer etc.).

The complete digital processing is implemented in one FPGA chip, while analogue part (12 2-bit flash A/D converters and one 14-bit D/A converter with accompanying circuits for conditioning) is done in discrete technology. Also analyzed was the possibility of implementing the complete device in one mixed-mode ASIC chip. The conclusion is that it would improve metrological performances, as power quality analyzer by a factor 3–4.5, even though the achieved measurement performances are completely acceptable. Simple 2-bit flash A/D enable multiplication of signals as well as filter operation (FIR filters) without the use of multipliers, so it is possible to use extremely simple procedures for parallel measuring and parallel digital processing. That is very important in a three phase distribution systems.

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