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STOCHASTIC DIGITAL MEASUREMENT METHOD – A STRATEGIC ADVANTAGE IN ELECTRICAL POWER DISTRIBUTION SYSTEM MEASUREMENTS

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Abstract – Stochastic digital measurement method (SDMM) is a method that uses low resolution flash A/D converters, the most common one uses only 2 bit converters. Hence, the instruments that use SDMM are characterized by a very simple hardware, small number of systematic error sources, wide bandwidth, high reliability and robustness. The paper presents the latest results of its application in the power grid measurements. Simple hardware allows easy implementation of parallel measurements and high level of integration of functions of instruments that simultaneously measure multiple quantities – currents and voltages on the multiple channels, as well as derived quantities – power and energy.

Keywords: stochastic, measurement, RMS value, electrical power, electrical energy

1. INTRODUCTION

In paper [1], a comparative analysis of a standard sampling method (measurement in a point) and SDMM method (measurement over an interval) is presented. In power distribution system measurements, especially in systems for protection, a standard sampling method has the advantage over the SDMM because it provides significantly faster results of the required precision and accuracy. The situation in power distribution is completely different, in other words the real-time criterion is not strict, so the SDMM with all its advantages provides results of required precision and accuracy. The latest results of SDMM application are: in [2] – measurement of non-stationary signals, in [3] – measurement of power grid frequency using two-bit flash A/D converter and [4] – power grid harmonics measurement as well as all other quantities derived from harmonics.

Because of great speed of electronic components, SDMM provided competitive results comparing to standard sampling method [5]. Nowadays, situation is even more favorable, because electronic components are approximately two orders faster than in 2000th year. Moreover, it is obtained that already simple devices for processing in SDMM can be even simpler, because stochastic computing can be implemented instead of deterministic computing [6]. Stochastic computing again becomes important topic in the last few years, because its implementation implies dramatically simpler hardware, dramatically more robustness, dramatically greater rejection of the noise and dramatically simpler verification of integrated circuits design.

Smart grid, a major subject in power distribution, assumes that the measurements are precise and accurate, not only of all the important quantities in power distribution, but also the quality of power delivered which is the focus of the research described in this paper.

The key result of SDMM application in Smart Grid is a quadruple three-phase power analyzer – MM4 – that has the ability to measure the quality of delivered power. The MM4 is developed as an element of the redundant measurement system. It can measure, on demand, the power quality parameters, quantity of delivered power in low-voltage distribution transformer station and it enables detection and measurements of power and energy flows.

2. SDMM - SINGLE PHASE POWER AND WATT-HOUR METER

Figure 1. shows a schematic of a single-phase power meter and watt-hour meter. In case the first input signal is phase voltage and the second input signal is phase current, then active power and active energy are measured. When we apply the same signal to both inputs, the square RMS value of the input signal is measured.

When active power is measured, it is described by the relation:

$$\overline{\Psi} = \frac{(2g)^2}{N}\sum_{i=1}^{N}\Psi_1(i)\cdot\Psi_2(i) \approx \frac{1}{T}\int_0^T f_1(t)f_2(t)dt = \frac{1}{T}\int_0^T u(t)i(t)dt = P$$

while it is assumed: $y_1 = f_1(t) = u(t)$ and $y_2 = f_2(t) = i(t)$.

If we do not divide the content of the upper counter from Fig. 1 with N, than for instant M we have:

$$\Psi(M) = (2g)^2\sum_{i=1}^{M}\Psi_1(i)\cdot\Psi_2(i) \approx \int_0^{\tau} f_1(t)f_2(t)dt = \int_0^{\tau} u(t)i(t)dt = E(\tau)$$

so active energy is obtained.

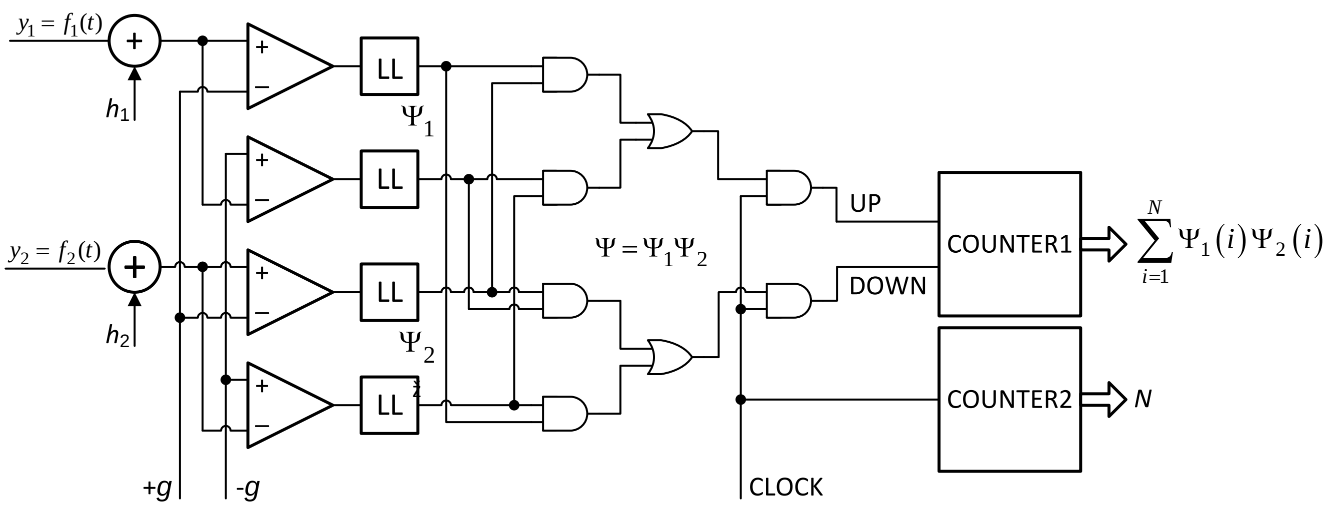

Fig. 1. Schematic diagram of a device that measure the square of RMS (voltage or current) or active power and energy using SDMM.

There is the question about measurement uncertainty of active energy at first place, but also of active power. That question can be on-line answered by the simple hardware shown in [7]. Therefore, there is no need for any further processing – the hardware provides standard data important for measurement of power and energy: (i) information of measurement variable and (ii) information of its measurement uncertainty. This is, of course, much more important for power measurement than for energy measurement, because energy is measured over long time intervals, which is different comparing to power where N has many times smaller value.

Measurement of harmonics assumes that Ψ_2 is being taken from memory, and quantums on channels 1 and 2 - Δ_1 and Δ_2 - are different and $\Delta_2 \to 0$, hence, for cosine component of j[th] harmonic:

$$a_j = \frac{2}{T}\int_0^T f_1(t)\cos(j\omega t)dt \approx \frac{2\Delta_1}{N}\sum_{i=1}^{N}\Psi_1(i)\Psi_{2c}(i)$$, and for sine component:

$$b_j = \frac{2}{T}\int_0^T f_1(t)\sin(j\omega t)dt \approx \frac{2\Delta_1}{N}\sum_{i=1}^{N}\Psi_1(i)\Psi_{2s}(i)$$

Measurement uncertainty for measurement of harmonic components is defined [8] with variances of the average of measurement error *e*:

$$\sigma_{\bar{e}}^2(a_j) = \sigma_{\bar{e}}^2(b_j) \le \frac{\Delta_1^2}{4}\cdot\frac{1}{2N}$$

Active power is, in fact, the mean value of active energy over an (short) interval of time. The fundamental quantity is energy, as an integral quantity, rather than samples of voltage and current, as separable quantities, which is the characteristic of a standard sampling method.

3. MM4 – QUADRUPLE THREE-PHASE POWER ANALYZER

Figure 2. shows two MM4 analyzers monitoring low-voltage transformer station with 8 terminals.

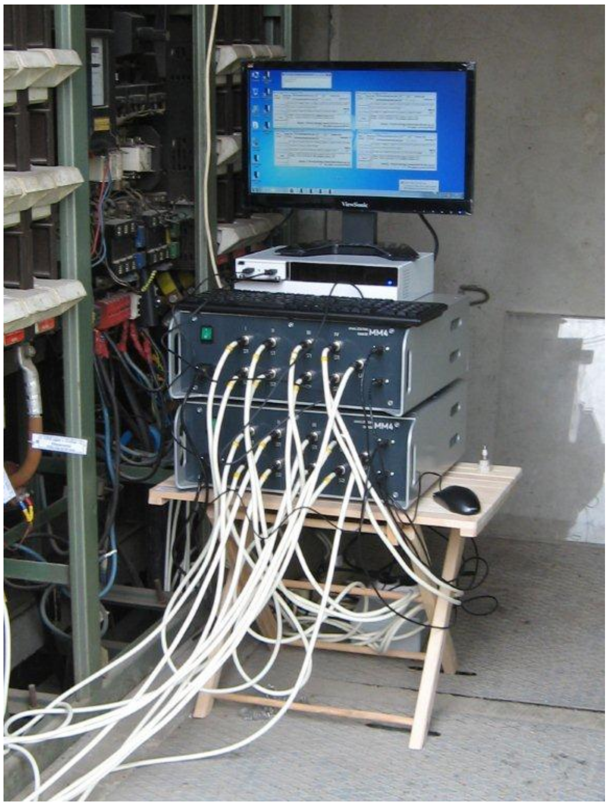

Fig. 2. Two MM4 monitoring 8 lines in distribution transformer station.

Basic accuracy of the MM4 for voltage and current measurements is 0.2 % FS (Full Scale) and for power and energy measurements is 0.5 % FS.

Complete digital part of the MM4 is implemented in a single FPGA chip, whereas the two-bit flash A/D converters (38 of them – 16 for currents and 3 for voltages, two converters per measured quantity) are implemented using analog building blocks. Sampling frequency is 500 kHz and measurement interval is 1 s.

The instruments are in active commercial use. Figure 3. shows the inside of the MM4 instrument prototype.

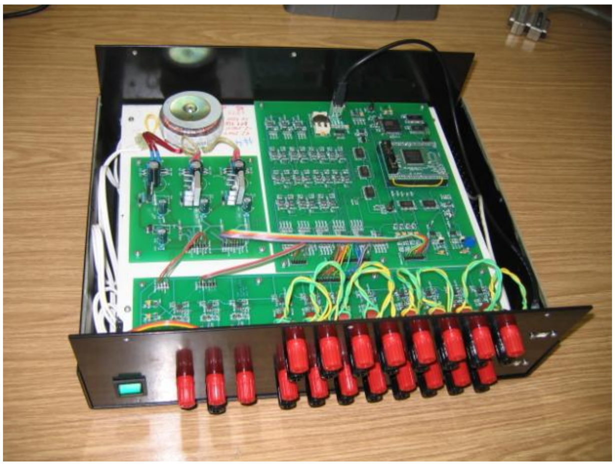

Fig. 3. Prototype of the MM4 power analyzer.

4. THE SUM MEASUREMENT OF POWER AND ENERGY USING THE MM4 - THE PRECISION

One MM4 can measure 16 single phase active powers and energies. Due to a stochastic nature of SDMM, the measurement error is random. Measurement errors on all single-phase channels are mutually statistically uncorrelated, hence the sum of single-phase powers, or energies, behaves according to the Central Limit Theorem. In other words, the precision of the sum is $\sqrt{16}=4$ times greater than the precision of individually measured phase power or energy [9].

In a case of a single three-phase consumer, the effect is analogous, the measurement is $\sqrt{3}=1.73$ times more precise than in the case of a single-phase consumer.

It is interesting to describe hardware (analog and digital) of MM4 instrument. It has 76 analog comparators in 2-bit flash A/D converters; it has 1 DC, precise, thermo-stable voltage reference 2.50000V; it has 38 analog adders; it has two 16-bit D/A converters; it has 2 LFSR generators of stochastic numbers; it has 146 2-input AND and OR circuits in multipliers for power measurement, energy measurement and true RMS measurement; it has 19 of 64-bit up-down counters for measurement of 16 currents and 3 voltages, and it has 16 of 128-bit up-down counters for active power and energy measurement. It has, also, 10kB of ROM memory for basis functions and 6 64-bit integer adders/subtractors – accumulators. It has modest microprocessor for manipulation with measured data, harmonics and communication with supervising computer.

Supervising PC has the internet connection through GPRS router. Complete local access and processing phases are performed by PC. Central SQL database is in command centre. One PC controls 4 MM4, that is 16 terminals in transformation station. If there are more than 16 terminals, another PC can be implemented as well as one router and needed number of MM4. This technologies can be changed with the development of technologies.

We emphasize that this configuration recognizes thermogenic loads with power more than 2kW per phase, and that the methodology of detection of line pole with thermogenic load was developed. The purpose of the system is redundant measurement of electric power and energy flows.

As 22 MM4 devices was delivered to EPS, and one MM4 device measures 16 active powers, while each measured power has stochastic error, complete system measures 22x16=352 active powers. The effect of the delivered system in EPS is that the accuracy of measurement of total power is 0.5 %/sqrt(352), which is approximately equal to 13.7 ppm.

5. SUMMATIVE MEASUREMENT OF POWER AND ENERGY USING THE MM4 - ACCURACY

The accuracy of three-phase measurements of power and energy, as well as voltage and current RMS measurements in SDMM method, that uses two-bit flash A/D converter, on all MM4's channels is defined by one precise, accurate, stable, thermally stabilized DC voltage reference of +2.50000 V. It depends only on this reference, because, all the other systematic errors (the comparator offsets in flash A/D converters as the major ones), can easily be eliminated [10].

The consequence of above mentioned fact is that there is no need for the MM4 calibration. Checking the accuracy of DC voltage reference is sufficient.

6. DISCUSSION

Samples of current (instantaneous) measured values in SDMM are, in general case, accurate but imprecise. Only the large sums of samples give the precise mean value of measured quantity. The fact that values of two-bit flash A/D converter are -1, 0 and 1 enables very simple addition of measured signals, as it can be seen from picture 1. as well as simple MAC (multiply and accumulate) operation in case of harmonic measurements. The hardware for performing these operations is hundreds, even thousands times simpler than in case of implementation of the standard sampling method.

This enables a simple implementation of multichannel device such as MM4 in mixed-mode ASIC chip. A chip that has the functions of double MM4 has been designed.

On the other hand, since there is no need for calibration, implementation in ASIC chip allows significantly higher sampling rate, in mentioned project it is 10 MHz, which means that integrated device is $\sqrt{20} = 4.47$ more precise, i.e. 20 times faster than device from Fig. 2.

7. CONCLUSIONS

SDMM have, as shown in paper, clear advantages in measurements in power distribution.
They are:

- simple and reliable hardware
- simple parallel measurements
- very precise sum measurements
- simple calibration
- simple implementation in mixed-mode ASIC chip
- very accurate measurements of energy over long time intervals

Serial device MM4 has proved itself to be accurate, precise and reliable in exploitation so far.

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