Measurement 98 (2017) 139–150

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Accuracy improvement of the stochastic digital electrical energy meter

Marjan Urekar [a,*], Dragan Pejic [a], Vladimir Vujicic [b], Svetlana Avramov-Zamurovic [c]

[a] University of Novi Sad, Faculty of Technical Sciences, Department of Power, Electronic and Telecommunication Engineering, Trg Dositeja Obradovica 6, Novi Sad, Serbia
[b] Institute of Technical Sciences, The Serbian Academy of Sciences and Arts, Belgrade, Serbia
[c] United States Naval Academy, Annapolis, MD, USA

ARTICLE INFO

Article history:
Received 7 August 2016
Received in revised form 20 November 2016
Accepted 22 November 2016
Available online 23 November 2016

Index Terms:
Stochastic processes
Energy measurement
Smart grid
Accuracy
Measurement uncertainty
Flash ADC
Sampling
Precision

ABSTRACT

The paper describes the problem and a solution for the elimination of the systematic error in a stochastic flash ADC caused by the offset present in fast voltage comparators, when measuring voltage RMS and active power and energy using the stochastic digital measurement method. By the means of simple periodical cross-switching of inverting and non-inverting inputs of used comparators and inverting their digital outputs, it is possible to suppress offset induced error for over 80 dB. Main condition for the method is that input signals (one for voltage RMS measurement, two for power and energy measurements) are stationary during at least two (or even number) of signal cycles. A prototype of a stochastic energy meter was built. It has the offset suppression method implemented, based on the solution proposed in the paper. The prototype was used for measurements in a laboratory, in an industrial plant and on a large power load. The measurement results confirm high accuracy of the instrument and validity of its aforementioned condition. The stochastic digital electrical energy meter prototype has 0.13% accuracy while the stochastic measurement instrument in its core has 0.007% accuracy. High precision and high accuracy of the stochastic instrument enables it to be used as a reference meter for calibration of energy meters at the national level. Full measurement results are presented.

1. Introduction

One of the most important types of measurements today is the active electrical energy measurement in residential and industrial areas. The high consumption of electric energy in a modern society demands accurate measurements of that consumption. Republic of Serbia has the strategic plan of modernizing the national power grid to conform to the EU standards, and smart grid concept is one of the main objectives, in order to increase both economic and energy efficiency. In 2014, Serbia produced 31 900 GW hours (GWh) of electric energy. In comparison, the Netherlands have half the area but produces 3 times more electricity, 98 800 GWh in 2014. In the same year, total net electricity generation figure for all 28 EU countries was 3 032 100 GWh, [1]. The measurement error of only 1% applied to the total net electricity generated in the EU would produce market loss comparable to the total yearly electricity consumption in the Republic of Serbia, or 1/3 of the Netherlands yearly consumption. The measurement error as small as 0.1% at yearly EU level would produce loss equal to the energy consumption in Serbia for 35 days or 11 days for the Netherlands. These examples show that even small errors can produce significant losses, as these measurements are performed over long periods of time (days, months, years). Due to the large order of magnitude of the active electrical energy being measured, it is an imperative that power and energy meters have both high accuracy and high precision, which is achieved by the regular calibration of the instruments. The most common calibration method is the direct comparison with a *reference meter*, an instrument with the accuracy class higher than the one being calibrated.

The best available power grid energy meter in the Serbian power grid is the standard electromechanical (inductive) type instrument with the accuracy class of 0.2%. For the calibration of this instrument, metrological normative asks for a reference meter with at least three times better accuracy (e.g. accuracy class of 0.05%). Development of an accurate and cost-effective reference meter would allow calibration of existing energy meters within the power grid network, without the need for an outside reference laboratory.

Electromechanical energy meters have several disadvantages that must be addressed. The accuracy class of 0.2% must be improved in order to cut the losses of electricity production, but the inductive energy meters with higher accuracy are very rare and expensive. Energy meter in a smart grid must be digital, with various types of communications and connectivity for regulation and readout purposes. Inductive meters have mechanical

---

[*] Corresponding author.
E-mail address: urekarm@uns.ac.rs (M. Urekar).

http://dx.doi.org/10.1016/j.measurement.2016.11.038
0263-2241/© 2016 Elsevier Ltd. All rights reserved.

read-out, making them obsolete in this case. There is a need for a large number of instruments measuring in parallel in a power grid, so the meter must be cost-effective also (price per unit several times lower than the standard inductive meter). Finally, instruments used in a power grid must have long time reliability, as they are expected to work for years or decades (in order to be cost-effective). Inductive meters are difficult for maintenance and prone to mechanical failures over time.

A modern digital instrument betters electromechanical one in every aspect individually, but rarely in all at the same time. There is often a trade-off between accuracy, cost and reliability, so there is a commercial need for an instrument that can consolidate all referred features. With this idea, the stochastic digital electrical energy meter (SDEEM), based on the stochastic measurement instrument (SMI), was developed at the Faculty of Technical Sciences in Novi Sad, [2–4]. Accuracy of the first working prototype was not at the level needed for a reference meter, so the second prototype was produced with the intention to improve the performance. This paper presents the problem analysis and the main method of accuracy improvement in this instrument.

2. Stochastic measurement instrument

The SMI is based on a stochastic flash A/D converter (SFADC) and relies on stochastic theory of measurement over a long time interval, [2,5]. Main characteristic of the SMI is the high precision of measurements (below 100 ppm), and the high measurement accuracy of (200–500) ppm, while using relatively simple hardware. Simple hardware means less sources of systematic error, very high reliability and cost reduction. The theory and simulations show that the SMI performs with both high precision and high accuracy, but the hardware prototype showed lower accuracy (around 1%) during measurements, both in laboratory conditions and in the field. This large discrepancy pointed to a major error in the first prototype, resulting from an unknown source. An electrical power and energy reference meter must have high accuracy (0.2% or better), so the source of measurement error had to be determined, estimated and its influence reduced or eliminated. In order to find the main source of the error, the SMI theory was analyzed in detail and the mathematical model was established, including quantified sources of the error. The solution for the efficient accuracy improvement is described in the paper, as implemented in the second SDEEM prototype. The results of measurements performed on a couple of real-life power loads are presented in order to confirm the efficiency of the implemented solution and the accuracy improvement.

Fig. 1 shows the block diagram of a single-phase SDEEM, based on the SMI shown in Fig. 2. The SMI is the core element of a SDEEM, and it has low voltage inputs. These voltages are proportional to the SDEEM inputs - high voltage and high current of the monitored electrical power load. Input transducers convert these quantities into low voltages suitable for the SMI inputs. Transducers are not covered in this paper, as their errors are included in the total SDEEM error calculated during measurements.

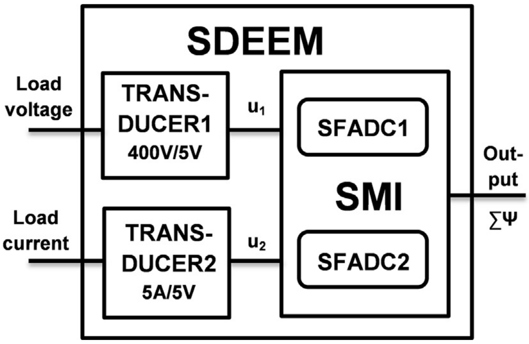

Fig. 1. Block diagram of a single-phase stochastic digital electrical energy meter. Transducers convert input high voltage and high current into low voltages in the range of the SMI inputs.

Three SMIs in parallel are used in one SDEEM for three-phase power grid measurements. The SDEEM voltage range is 400 V RMS and the current range is 5 A RMS. Transducers convert these quantities into the low voltage ac signals suitable for the SMI (with maximum amplitude of 5 V). The output of the SDEEM is a number proportional to the total electrical energy during the measurement period.

The block schematic of the SMI used in the SDEEM prototype is given in Fig. 2, [4]. The SMI input signals are voltages u_1 and u_2, in the range of (−5 to +5) V. The input adder $\oplus$ adds dither signals d_1 and d_2 to input voltages, respectively. The adder is a standard voltage adder with an operational amplifier [6]. Dither signals are random noise signals with the uniform probability density function (PDF), as in Fig. 4b. Dither voltage range is (−2.5 to +2.5) V, and it must be equal to the quantum value of SFADC_1 and SFADC_2. Each SFADC has two bits of measurement accuracy (2-bit SFADC). Dither signals are generated using Pseudo Random Number Generators (PRNG_1 and PRNG_2) and Digital to Analog Converters (DAC_1 and DAC_2). By adding stochastic signal (dither) to the input voltage and by oversampling resulting signal, we effectively increase low resolution of the used SFADC, as shown in [7,8]. We need to calculate the mean of the sequential values of the combined signal, in order to find the value of the input signal.

Fig. 3a shows the transfer function of a 2-bit SFADC.

Digital circuits are synchronized by the clock signal T_0 with the period of 10 μs. During the interval T_0 several functions are performed: (1) a pair of dither values is generated, (2) each dither is added to the corresponding input voltage, (3) conversion is performed in the SFADC, (4) the multiplication of digital values Ψ_1 and Ψ_2 is performed in the multiplier (MULT) section, and 5) the final result $\Psi = \Psi_1 \cdot \Psi_2$ is stored in the accumulator (ACCU) block.

Fig. 4 shows typical voltage waveforms of the SMI. The input u_1 is proportional to the SDEEM input signal with $f = 50$ Hz. The example shown in Fig. 4a is an input signal with 4 V amplitude. Dither signal d_1, with the uniform PDF of voltages in the (−2.5 to +2.5) V interval (Fig. 4b) and the frequency $f_0 = 1/T_0$, is added to the input signal u_1. The resulting sum (Fig. 4c) is sampled at the frequency f_0, using the 2-bit SFADC, resulting in the digital output signal Ψ_1. The 2-bit SFADC uses only two voltage comparators (Fig. 3), hence this type of ADC has only three possible output values, encoded as {−1, 0, +1}. Fig. 4c shows two voltage levels (dashed lines at −2.5 V and +2.5 V), corresponding to the SFADC_1 threshold levels. If the combined signal (sum of the input and dither voltages) is above +2.5 V, the SFADC output is "+1". For inputs below −2.5 V, output is "−1". When the input is in between these two values, output value is "0". In similar manner, input signal u_3 with 3 V amplitude, produces the output of the SFADC_2. Fig. 4d and f show SFADC_1 and SFADC_2 outputs. For a positive value of the input

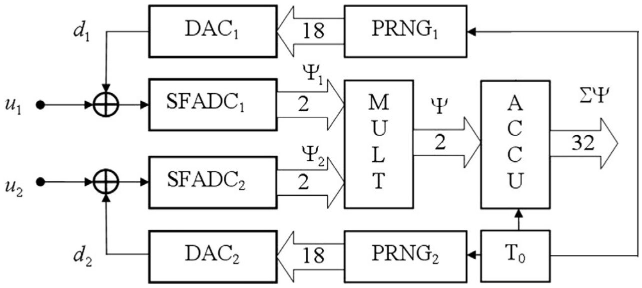

Fig. 2. Block diagram of the SMI in the core of the SDEEM.