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IEC class 0.5 electronic watt–hour meter implemented with first-order sigma–delta converters

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Abstract

This paper presents a design of a precise electronic watt–hour meter implemented with first-order sigma–delta analog-to-digital converters. An efficient digital signal-processing circuit is introduced into the design where the whole signal processing is performed directly on an oversampled signal, eliminating the necessity for a decimation filter. It is shown that Gaussian noise, added to the input signal of sigma–delta modulators, decorrelates quantization error of first-order sigma–delta modulators and thus substantially reduces measurement error at low-signal amplitudes. The effect of added noise is analyzed by extensive behavioral simulations for various input signal amplitudes and for various input noise levels. The results show that IEC accuracy class 0.5 can be achieved with first-order sigma–delta converters and digital signal processing in the sigma–delta domain.

Keywords: Sigma–delta modulation; Digital signal processing; Digital filters; Electrical energy measurement; Mixed-mode simulation; Noise analysis

1. Introduction

An integrated, accurate electronic watt–hour meter requires precise analog to digital converters and relatively complex digital signal-processing circuitry in order to satisfy accuracy requirements over its entire measurement range. By taking into account the specifics of electric energy measurement, some design parameters of watt–hour meter subcircuits can become less stringent. The idea of the implementation of a watt–hour meter, implemented with two first-order sigma–delta ($\Sigma\Delta$) converters, is based on the following facts: (a) input signal amplitude of one of the two converters is close to its full-scale input range, (b) inherent noise of analog elements inside switched-capacitor $\Sigma\Delta$ modulator decorrelates otherwise discrete quantization noise spectrum of the first-order $\Sigma\Delta$ modulator, and (c) product of two filtered signals from $\Sigma\Delta$ modulators is integrated over relatively long time interval.

Oversampled $\Sigma\Delta$ modulators are usually interfaced to a digital signal processor at a Nyquist rate by a decimation filter. When digital processing is done directly on an oversampled $\Sigma\Delta$ signal, a decimation filter could be eliminated and the complexity of digital circuit could be reduced. An efficient approach to implement IIR filters in $\Sigma\Delta$ domain is presented in [1,2], where all internal state variables are remodulated by a digital $\Sigma\Delta$ modulator. Instead of using complex second-order digital $\Sigma\Delta$ modulator to perform remodulation, simple first-order digital $\Sigma\Delta$ bitstream generator similar to [3] is used at this work. A series of bitstream adders [4], connected as two-quadrant delta multipliers [5,6] are introduced as the scalers of feedback $\Sigma\Delta$ signals into the filter structure, further reducing required silicon area of a digital signal-processing circuit.

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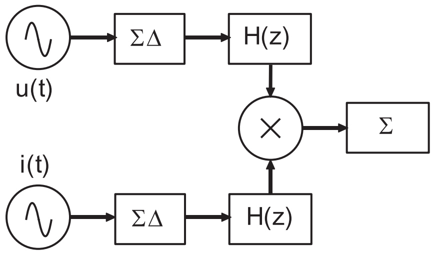

Fig. 1. Main parts of an electronic watt–hour meter.

Analog interface circuitry of a conventional electronic watt–hour meter employs higher-order $\Sigma\Delta$ modulators that occupy a large part of an integrated circuit area. To reduce the size, it is recommended to use the simplest form of analog subcircuits, with their non-idealities compensated by digital signal processing. The simplest form of a $\Sigma\Delta$ modulator used in an analog interface is the first-order $\Sigma\Delta$ modulator [7]. Based on its simplicity, stability [8], and low power consumption, a strong motivation to construct a precise watt–hour meter using first-order $\Sigma\Delta$ modulators emerges.

In the following sections, architecture of an electronic watt–hour meter is presented. After a brief system overview, its digital signal processor is described. A two-quadrant delta multiplier is extended into a full four-quadrant $\Sigma\Delta$ multiplier that can be used to multiply modulated digital representations of $u(t)$ and $i(t)$ signals. The same multiplier structure can be used as a bitstream generator in the $\Sigma\Delta$ integrator. These two blocks, an $\Sigma\Delta$ integrator and a two-quadrant delta scaler, represent basic building blocks in the implementation of a digital filter in the $\Sigma\Delta$ domain.

In the second part, performance degradation due to the quantization error of a first-order $\Sigma\Delta$ modulator is analyzed. Following this analysis, a decorrelation of quantization error when Gaussian noise is added to the input signal is presented. Behavioral simulations with various noise levels added to the input signal are performed and an optimum noise level is chosen as a compromise between remaining error and spreading of simulated results. This noise is generated by appropriate size of an input switched capacitor. Our simulated and measured results show that required accuracy can be achieved by using first-order $\Sigma\Delta$ modulators connected to simple digital filters, implemented in $\Sigma\Delta$ domain.

2. System overview

Main parts of a digital electronic watt–hour meter are shown in Fig. 1. Input AC signals $u(t)$ and $i(t)$ that correspond to measured AC voltage and AC current, are routed to first-order $\Sigma\Delta$ modulators. Their outputs are processed by two equivalent digital filters. Filtered signals from the voltage and current channel are multiplied together in the four-quadrant $\Sigma\Delta$ multiplier and the product is integrated in final integrator. The integrated value is used to calculate measured energy in regular time intervals.

The presented watt–hour meter uses a di/dt current sensor (Rogowski coil). To compensate the frequency dependency of a current sensor, additional integration of a current signal is needed in the signal path before multiplication with the voltage signal. A setup, where voltage signal is taken in its serial form from the first integrator of a voltage channel filter and where current signal is taken in its parallel form from the second integrator of a current channel filter is used. In this setup, the voltage signal is integrated once, and the current signal is integrated twice, so frequency dependency of a current sensor is eliminated. The signal frequency band from 45 to 65 Hz is relatively low when compared to the clock frequency of a digital part, therefore digital integrators can be treated as ideal integrators.

The modulator in the current channel of a watt–hour meter operates over large dynamic range. Its input signal amplitude ranges from the modulator full scale (FS) down to $\frac{1}{1000}$ of FS. At each operating point, an average value of measured energy should not exceed the declared percentage error of 0.5% in case of IEC accuracy class 0.5 [9], which is a difficult goal to achieve with first-order $\Sigma\Delta$ modulators.

3. Four-quadrant ΣΔ multiplier

The basic processing element in the sigma–delta domain is a simple circuit, called "delta full adder" (DFA), introduced as a processing element for delta modulated [5] and sigma–delta modulated [4] signals. A series of connected DFAs could be used to construct a four-quadrant $\Sigma\Delta$ multiplier circuit, similar to a two-quadrant delta multiplier [6].

The multiplication constant α of a four-quadrant multiplier could be written in the form of

$$\alpha = \alpha_1 2^{-1} + \alpha_2 2^{-2} + \cdots + \alpha_q 2^{-q}, \tag{1}$$

where $\alpha_i = -1$ or +1, for each $i = 1, 2, \ldots, q$. Concerning Eq. (1), the product $\alpha \cdot x(t)$ could be written as

$$\alpha \cdot x(t) = \Big(\alpha_1 x(t) + \Big(\alpha_2 x(t) + \\ + \Big(\ldots + \Big(\alpha_q x(t) 2^{-1}\Big)\ldots\Big) 2^{-1}\Big) 2^{-1}\Big) 2^{-1}. \tag{2}$$

A special sequence $\{I_n\}$ is introduced, where $I_n = -I_{n-1}$ and where I_n takes two discrete values of +1 and −1. This sequence is defined as an idle delta sequence of a constant function $i(t) = 0$.

From the properties of DFA [6], where nth member of its output sequence is labelled as $S_n = (X_n, Y_n)$ and where $\{(X_n, \pm Y_n)\}$ is a delta sequence of $2^{-1}[x(t) \pm y(t)]$, a delta sequence $\{P_n\}$ of the product $\alpha \cdot x(t)$ can be determined from Eq. (2) as

$$P_n = \Big(A_n^{(1)}, \Big(A_n^{(2)}, \Big(\ldots, \Big(A_n^{(q)}, I_n\Big)\ldots\Big)\Big)\Big),$$
$$A_n^{(i)} = \alpha_i X_n. \tag{3}$$