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Measurement of active power by time domain digital signal processing

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ABSTRACT

This paper compares DSP time domain algorithms of one-phase active power measurement by non-coherent sampling that are superior to some frequency domain algorithms in active power estimation of non-sinusoidal signals. The measurement bias, uncertainty and sampling time necessary for the required accuracy are compared for various data windows with the use of simulations and measurements. Both monofrequency and multifrequency signals are dealt with. Analytical formulas are presented for the active power bias for rectangular and general cosine windows and for standard uncertainty of active power measurement. A simple method is described for correction of the multiplexing delay in power measurement using multiplexing DAQ boards. The information from this paper can also be used for measuring energy consumption and three-phase power.

1. Introduction

The active power can be found by numerical processing of current and voltage samples, either in the time domain or in the frequency domain. The definition of the active power of a periodic signal (voltage and current) requires the integration of instantaneous power over one period. The classical time domain algorithm is therefore based either on estimating the signal period and subsequent equidistant sampling of one signal period, or an integer number of signal periods, or on using measurement time covering many signal periods that are needed to decrease sufficiently the uncertainty of measurement caused by the energy leakage due to non-coherent sampling. The accuracy with which the signal period is known in the first case influences the uncertainty of the active power estimation.

A phase-locked loop can sometimes be used to enable coherent sampling [1]. However, coherent sampling is not normally provided for in practical applications. In the case of non-coherent sampling, the well-known signal energy leakage occurs in the frequency domain, and windowing and various interpolations are used in DFT if the signal is processed in this domain [2–5]. A detailed analysis of power measurement focused on frequency domain processing can be found in [6].

An interesting alternative to windowing and processing the windowed signal in the frequency domain is signal windowing and further signal processing in the time domain. DFT is not used in this case. This procedure allows much broader window selection than frequency domain procedures based on interpolated DFTs. It is much simpler when measuring the power of multifrequency signals than the frequency domain method based on geometrical summing of the signal harmonic component powers found as products of the RMS values of voltage and current and the cosine of the phase difference of the same harmonic components of voltage and current, as described in [6]. It should be mentioned that windowing a signal means here windowing the sequence of instantaneous power samples, i.e. the sequence of products of the voltage and current samples taken in the same time instants. The fundamental time period of instantaneous power is half of the fundamental period time of the voltage and current waveforms.

This paper analyses the DSP algorithms of one-phase active power estimation and also includes information about the power estimation uncertainty caused by data acquisition channel quantization noise (and by any other additive external noise). It does not deal explicitly with

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the voltage and current transducers that are often placed in practical measurements in front of data acquisition units.

2. Finding active power in the time domain

Active power estimation for analog or digitized signals is based on the relation

$$P' = \frac{1}{T_M}\int_0^{T_M} v(t)i(t)\mathrm{d}t \cong \frac{1}{N}\sum_{n=0}^{N-1} v(n)i(n) \quad (1)$$

where P' is an estimation of the active power, T_M is time of measurement (in the classical approach, one signal period or an integer number of signal periods), $v(t)$ and $i(t)$ are continuous-time voltage and current, and $v(n)$ and $i(n)$ are sequences of voltage and current samples. The product $v(t)\cdot i(t) = p(t)$ is instantaneous power, and the product $v(n)\cdot i(n)$ is a sample of the instantaneous power $p(n)$ in time $n\cdot T_S$, T_S being the sampling period. N is the number of acquired samples, and $T_M = NT_S$. The measurement time can also be expressed as

$$T_M = (M+\lambda)\cdot T_{sig} \quad (2)$$

where (the positive integer) M is the number of integer periods sampled, T_{sig} is the signal period, and λ is the decimal part of the last period sampled ($0 \leqslant \lambda < 1$). There is $P' = P$ for $\lambda = 0$ (coherent sampling), and $P' \neq P$ for $\lambda \neq 0$. The difference between P' and P is the bias of the measured active power P influencing the uncertainty of active power measurement in the time domain caused by non-coherent sampling. The relative bias of P estimation can be expressed as

$$\delta'_P = \frac{P'-P}{P} = \frac{P'}{P} - 1 \quad (3)$$

For sinusoidal voltage and current defined as

$$v(t) = V_m \sin\omega t, \quad i(t) = I_m \sin(\omega t - \phi) \quad (4)$$

the instantaneous power can be expressed as

$$p(t) = \frac{V_m I_m}{2}\cos\phi - \frac{V_m I_m}{2}\cos\phi\cdot\cos(2\omega t) - \frac{V_m I_m}{2}\sin\phi\cdot\sin(2\omega t) = P - P\cos(2\omega t) - Q\sin(2\omega t) \quad (5)$$

The first term (the DC component of the instantaneous power) in (5) is the active power P, while Q is the reactive power, and the oscillatory components with circular frequency 2ω are zero after integration, according to (1) in the case of coherent sampling. For low power factor $\cos\phi$ the first two terms are also low.

Using (2) and (3), the relative bias of the active power for the sinusoidal signal component can be expressed as

$$\delta'_P = -\frac{\sin(4\pi\lambda) - tg\phi[1-\cos(4\pi\lambda)]}{4\pi(M+\lambda)} \quad (6)$$

where ϕ is the load phase (i.e. the phase difference between the sinusoidal voltage drop across the load and the load current). The bias is zero for coherent sampling ($\lambda = 0$), and can be surprisingly large for non-coherent sampling for low power factors (because of the high value of $tg\phi$ in the numerator of (4) and due to the low value of P in (3)).

The dependence of the relative bias of the active power on the relative time of sampling (time related to voltage and current period) is shown in Fig. 1 for selected values of the load phase ϕ. Note the zero values of the bias for integer numbers of signal periods and for $i + 0.5$ periods, i being positive integer numbers.

The bias is zero for the integer number of instantaneous power periods sampled, and the instantaneous power period is half of the voltage and current period. The wave-

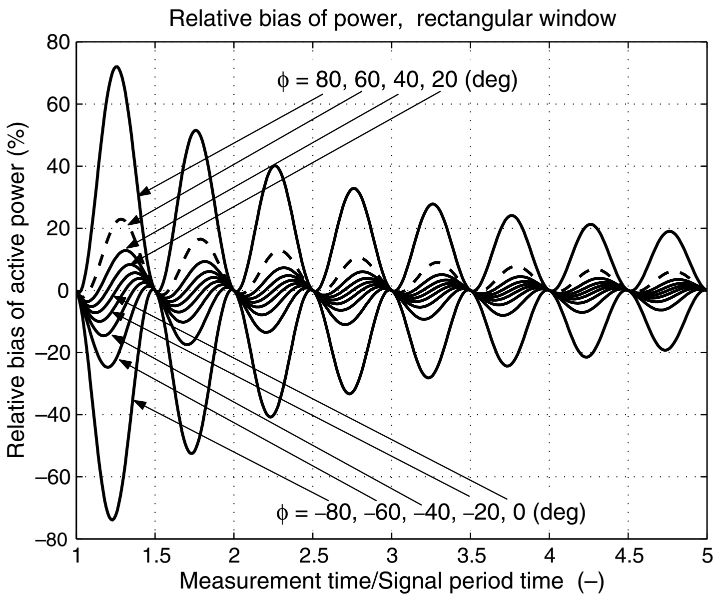

Fig. 1. Bias of active power for a rectangular window.