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The influence of sampling parameters on accuracy of capacitance measurement in the method based on DSP

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Abstract-The paper presents the method of measurement of impedance parameters based on measurement signals sampling and DSP. The influence of main sources of uncertainty and errors on capacitance measurement accuracy has been analysed. The following have been included: non-synchronous sampling of two measurement signals proportional to current and voltage on impedance under measurement, A/D converter resolution and total number of collected samples. The results of simulations have been presented.

I. Introduction

In the recent years, the method based on measurement signals sampling is used for impedance parameter measurement more and more frequently. The signal parameters can be determined thanks to digital signal processing (DSP) [1-3]. The instruments using this method are realised on the basis of data acquisition card (DAQ) installed in personal computer and connected external module. The block diagram of LCR meter, realised by authors on the basis of above presented method, is shown in Fig. 1.

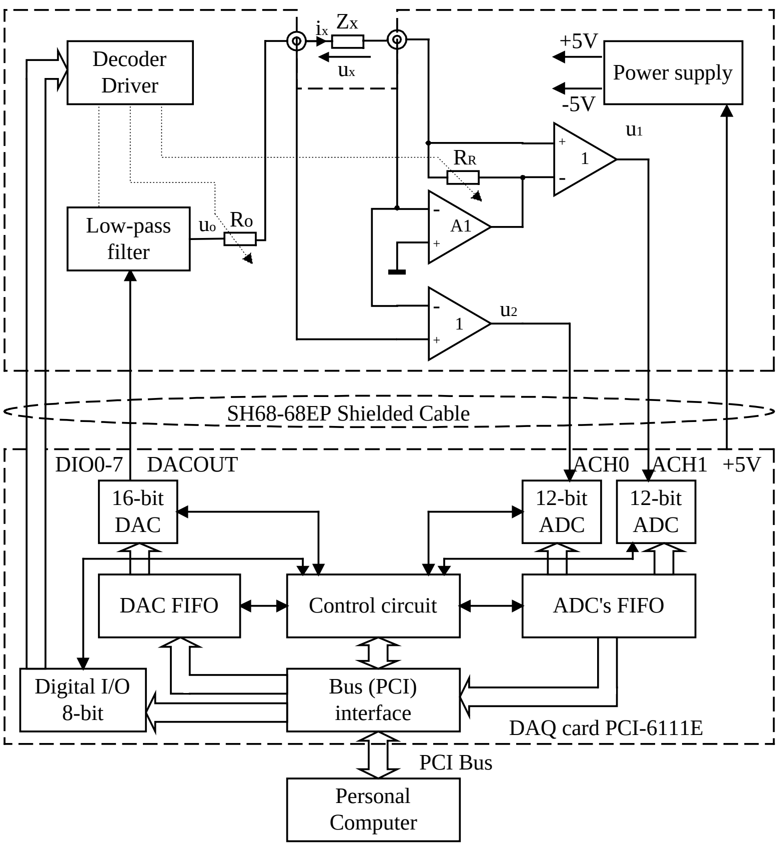


Figure 1. Block diagram of LCR meter

The external module consists of an input circuitry, in which two signals are extracted: current (u_1~i_x) and voltage (u_2~u_x) on the impedance under measurement. The amplifier A1 realises current-to-voltage converter, and amplifiers labelled "1" are differential amplifiers with gain equal to 1.The resistor R_o protects the device from Z_x shortcut. Decoder/driver allows selecting correct range resistor R_R and low-pass filter adequate to measurement range and measurement frequency, respectively.

The signals are sampled and quantised by A/D converters located on DAQ card. In next step, the real and imaginary parts of vector representing signals u_1 i u_2 are calculated from collected samples by means of discrete Fourier transform (DFT). The procedure was analysed in [4], so in the paper it is presented only briefly.

Assuming linearity of the object under test, the extracted in input circuitry voltages u_1 and u_2 are sinusoidal. On the other hand, due to used method of signal generation and acquisition, N collected samples contain exactly L periods of perturbing signal u_o, what proves that the spectral leakage doesn't appear and only one (L), non-zero line exists in the Fourier spectrum. The values of real and imaginary parts vector representation of both voltages can be thus determined from (1).

$$\begin{aligned} \mathrm{Re}(U_1^L) &= \sum_{m=0}^{N-1} u_1^m \cdot \cos(\frac{2\pi \cdot m \cdot L}{N}), \qquad \mathrm{Im}(U_1^L) = \sum_{m=0}^{N-1} u_1^m \cdot \sin(\frac{2\pi \cdot m \cdot L}{N}), \\ \mathrm{Re}(U_2^L) &= \sum_{m=0}^{N-1} u_2^m \cdot \cos(\frac{2\pi \cdot m \cdot L}{N}), \qquad \mathrm{Im}(U_2^L) = \sum_{m=0}^{N-1} u_2^m \cdot \sin(\frac{2\pi \cdot m \cdot L}{N}). \end{aligned} \tag{1}$$

The impedance modulus and phase can be calculated on the base of (2):

$$\phi = \mathrm{arctg}\frac{\mathrm{Im}(U_2^L)}{\mathrm{Re}(U_2^L)} - \mathrm{arctg}\frac{\mathrm{Im}(U_1^L)}{\mathrm{Re}(U_1^L)}, \qquad |Z_x| = \frac{\sqrt{(\mathrm{Re}(U_2^L))^2 + (\mathrm{Im}(U_2^L))^2}}{\sqrt{(\mathrm{Re}(U_1^L))^2 + (\mathrm{Im}(U_1^L))^2}} \cdot R_R. \tag{2}$$

This allows determining values of the measured element parameters (e.g. for capacitor: C, G, D) in relation to equivalent circuit of two-terminal network of measured impedance Z_x. For example, assuming parallel connections of capacitor C and resistor R, their values can be determined on the basis obtained impedance modulus and phase of from (3).

$$C = \frac{1}{|Z_x| \cdot \omega} \cdot \sin\ \phi, \qquad R = \frac{|Z_x|}{\cos\ \phi}, \qquad \text{where}: \omega = 2 \cdot \pi \cdot f_{meas}. \tag{3}$$

To improve the measurement accuracy it is necessary to minimise errors caused by sampling and quantising of measurement signals. Due to this fact, the paper is aimed to analyse main sources of error influencing the accuracy of capacitor measurement.

II. The analysis of the sampling and quantisation process

The important problem analysed in the paper is synchronous sampling of signals u_1 i u_2, which allows determining of Z_x impedance from the definition.

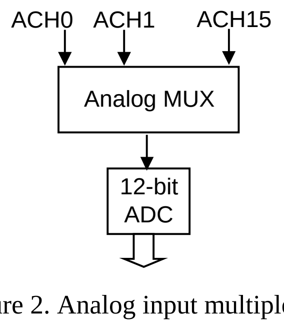
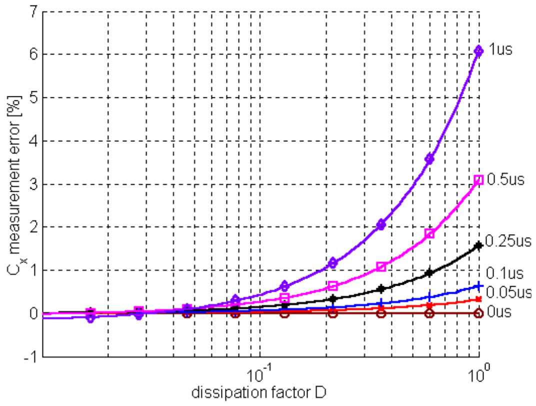


Figure 2. Analog input multiplexer in multichannel low-cost DAQ card

The presented in Fig. 1 LCR meter utilises DAQ card PCI-6111E from National Instruments equipped with two A/D converters, making possible simultaneous sampling of signals u_1 i u_2. This card is much more expensive than popular DAQ cards (like PCI-6052E, PCI-6040E, PCI-6030E) with one A/D converter and 8 or 16 channels input multiplexer (see Fig. 2).

When using sequential sampling, additional systematic error of impedance parameter measurement will appear. For example, relative error of capacitance measurement of the capacitor in the parallel equivalent circuit caused by time shift τ between acquisition of signal u_1 sample and signal u_2 sample is presented in Fig. 3. The simulations have been done assuming 16-bit A/D converter working with 1V full scale at 1MHz sampling frequency. The 1nF capacitor was measured with range resistor R_R=1kΩ and measurement signals with amplitude of 1V, 100 samples were collected during one period of signal. The graph was prepared as a function of C_x measurement error due to changes of dissipation factor (D), with time shift as a parameter. The simple rule can be formulated: for the same measurement frequency, the greater time shift, the greater error caused.



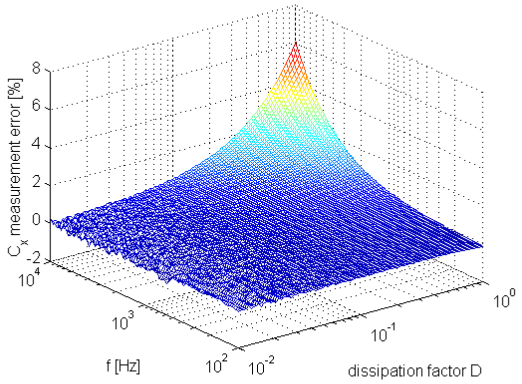


Figure 3. The influence of time shift between samples on capacitance measurement error

Figure 4. The capacitance measurement error as a function of frequency and dissipation factor

Figure 4 presents the measurement error as a function of a measurement frequency and dissipation factor changes. The figure was prepared for the worst case above presented – assuming 1μs time shift between sampling of voltage and current signals. One can see that measurement error increases when measurement frequency or dissipation factor increases. It can be noticed that the cards with multiplexed inputs can be used for lower frequencies or correction of the phase must be used.

Next, the analysis of the resolution of the AD converter has been performed. The simulation was done for some typical values of resolution, which can be found in commercially available ADCs. Other parameters were identical like in the previous case.

Analysing the curves one can notice that for low resolution ADC (8 bit) fluctuation of error can be observed due to quantisation error, especially when measurement range is only partially utilised. In that case the current proportional signal is lower so quantisation errors are much meaningful. With increasing ADC resolution, the quantisation error decreases and achieves values below 0.3% when using 12-bit ADC. Further increasing of ADC has negligible influence on improvement of the measurement accuracy. This allows to use DAQ cards equipped with 12-bit ADC, which are cheaper then 16-bit ones or which offer higher sampling rates at the same price.

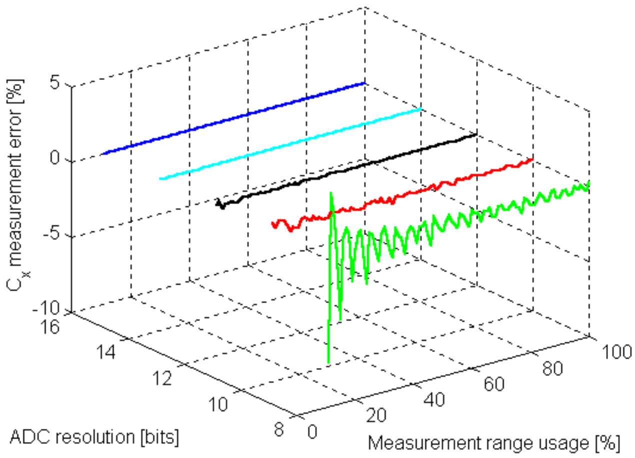


Figure 5. The C_x measurement error in relation to ADC resolution and measurement range usage

Next parameter to be analysed is a number of samples collected during acquisition process. When we assume ideal condition of the measurement, there are no constrains for selecting number of samples. Of course, we need to collect at least one period of the measurement signal in order to correct reconstruction of the signal spectrum. To estimate number of acquired samples, it is necessary to reconstruct the real measurement condition. The current signal is much sensitive on noises especially induced from power lines e.g. existing at 50Hz frequency. In performed simulation, the current signal was disturbed by 10mV amplitude 50Hz noise. Figures 6 and 7 presents the results of simulations for two different measurement frequencies: 550Hz (Fig. 6) and 1100Hz (Fig. 7). The graphs show the influence of samples number and measurement range usage on the C_x measurement accuracy.

It can be seen that error is minimised to 0 when the total number of acquired samples implies the total acquisition time, which is the multiplication of the noise signal period – the multiplication of 20ms. In the presented examples this happens when the number of samples is the multiplication of the 110 and 220, respectively. The presented graphs create similar representation like for integrative voltmeters.

The noise rejection ratio increases when the number of samples increases even when the acquisition time is not the multiplication of noise period. The worse situation exists in case of lower signals e.g. when the range usage is less ten 30%, for higher range usage rates, the influence is less critical.
When the acquisition time is not the multiplication of the period of noise signal, the noise signal causes spectral leakage and the results are erroneous.

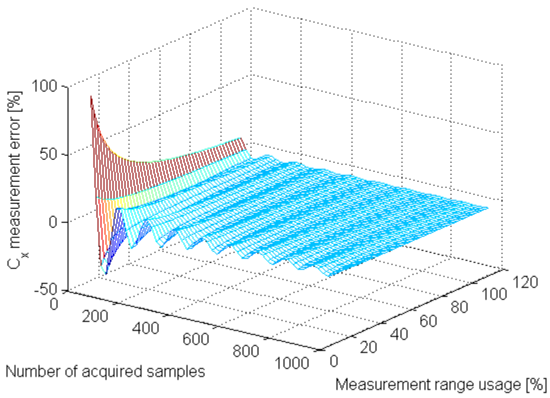


Figure 6. The influence of number of acquired samples on capacitance measurement error f_{meas}=550Hz, f_{noise}=50Hz

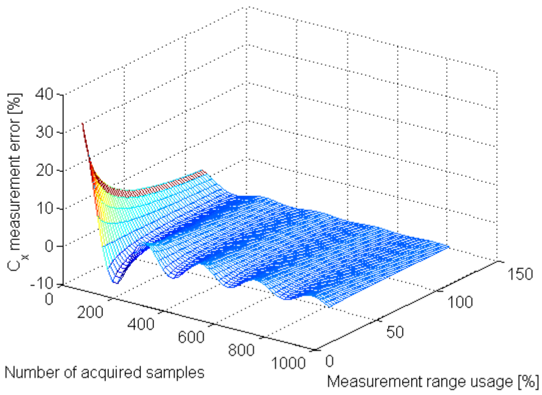


Figure 7. The influence of number of acquired samples on capacitance measurement error f_{meas}=1100Hz, f_{noise}=50Hz

It can be assumed that the number of acquired samples should be as great as possible. But this leads to very long acquisition time. In order to keep acquisition time short, the number of samples should be selected in connection with sampling frequency, to assure the acquisition time to be a multiplication of the period of noise signal.

III. Conclusions

The methods based on measurement signals sampling are used for impedance parameter measurement more and more frequently. The signal parameters can be determined thanks to DSP. This allows reducing the role of analog circuits and shifting the main task to digital hardware and software, of course. It is especially important when measuring at very low frequencies. The time stability and repeatability of parameters of analog circuit can be not satisfying.
One of the possible solutions is the usage of DAQ card mounted in personal computer. There are many available cards on a market with different properties and more or less adequate prices. Taking into account hints presented in the paper, the user can choose right card suitable to specific application at acceptable price. In most of application 12-bit ADC are enough so why to use 16-bit DAQ card which is more expensive or slower. The simultaneous sampling of current and voltage signal is better than sequential sampling available on DAQ cards with analog input multiplexer, but when we know that the time shift between samples exists, we can use correction in a software minimising errors caused by time shift between samples of both signals. The number of acquired samples can be reduced when assuring acquisition time to be a multiplication of the noising signal period.

References

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