Low-Loss Capacitance Measuring Method by Synchronous Detection

Oana MUNTEAN

Technical University of Cluj-Napoca, Faculty of Electrical Engineering

Abstract: *This paper presents a method for measuring low-loss capacitors by synchronous detection. By using synchronous detection is possible to measure the capacitance at different frequencies. Starting with a measurement circuit and taking account of its design conditions, two applications are developed. First application refers to very small values capacitors measurement and second application refers to high values capacitors measurement. At the same time the circuit can be extended to measure the information contained in amplitude.*

Keywords: *synchronous detection, Hilbert transform, capacitance measurement*

1. INTRODUCTION

Capacitors are available in several constructive versions: parallel-plate, cylindrical, coil, multilayer. The version of parallel-plate capacitor is found in the construction of very small values capacitors. Multilayer version is used when it is desired to obtain higher values of the capacity at close characteristics of flat capacitors. The highest values of capacities encountered in practice are obtained from electrolytic capacitors [1], [16].

There are various schemes for measuring capacity [17]:

- Capacimeter consists of a variable frequency oscillator, a frequency splitter and a measure floor. Capacities are measured in the range $100\ \text{pF} - 1\ \mu\text{F}$.
- Series Sauty Bridge is used to measure the small losses capacity.
- Nernst Bridge is used for measuring capacitors with high losses.
- Schering Bridge is used to measure high voltage capacitors.

The method proposed in this paper becomes important because it offers the possibility of measuring capacity at different values of frequency. It is considered that the resistance loss of the measured capacitor is very small, negligible. Two applications are developed.

The first application proposes a method for very small capacity measurement together with the measuring circuit and its initial design conditions. Design condition is given to ensure the measurement of very small capacity of a capacitor with low losses. The circuit consists of an operational amplifier, a synchronous detector, a phase shifter and an electronic voltmeter.

The second application proposes a method for high capacity measurement together with the measuring circuit and its initial design conditions. Design condition is given to ensure the measurement of high capacity of a capacitor with low losses. The circuit consists of an operational amplifier, a synchronous detector and an electronic voltmeter.

Generally, the circuits presented in this paper are used to measure capacity but can be extended to measure the information contained in amplitude. DC component obtained at the output of the synchronous detector contains information of the capacitance to be measured.

2. THEORETICAL CONSIDERATIONS

Measurement of very low values capacities

Let there be the circuit in the figure 1 utilized for very low values capacities measurement.

“ECV” is the electronic voltmeter, “SD” represents a synchronous detector and “AO” the operational amplifier. The input signals in synchronous detector are: the voltage at the output of the operational amplifier and the voltage phase shifted with an angle of 90°.

The synchronous detector consists of a multiplier and a low pass filter as can be seen in the Figure 2.

“M” stands for multiplier and “LPF” stands for low pass filter. $\underline{\hat{E}}$ represents the Hilbert conjugate of $\underline{E}$.

Synchronous detector consists of a multiplier and a low pass filter [2-3]. There are two measures at the entrance of the synchronous detector: the voltage at the output of the operational amplifier and the voltage phase shifted with an angle of 90°. In multiplier the input signals multiplication occurs. The resulting voltage is passed through a low pass filter. At the output of synchronous detector the DC resulting voltage component is obtained. This DC voltage is measured by an electronic voltmeter. The measured value contains information about the capacitor capacitance[12-15].

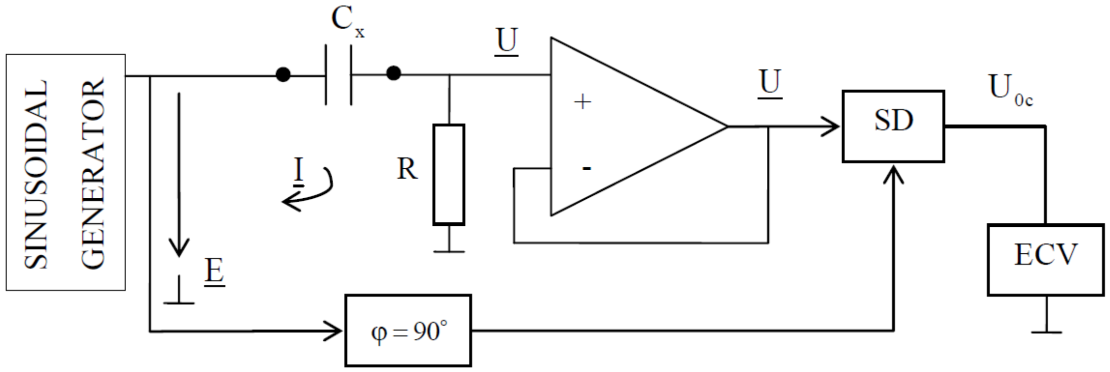


Figure 1 Circuit for very low value capacities measurement

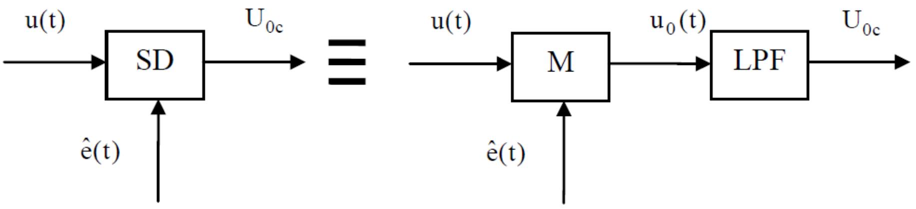


Figure 2 Synchronous detector

Design condition is given to ensure the measurement of very small capacity of a capacitor with low losses. The capacitor impedance is way higher than the resistance.

$$C_x <<\to X_C = \frac{1}{\omega_0 C_x} >> R \qquad (2.1)$$

Circuit is supplied with a sinusoidal voltage. A phasor is two ways attached to a sinusoidal voltage:

$$\underline{E} \leftrightarrow e(t) = E\sin(\omega_0 t) \qquad (2.2)$$

Hilbert conjugate of $e(t)$ is calculated:

$$\hat{e}(t) = E\sin(\omega_0 t - \frac{\pi}{2}) \qquad (2.3)$$

Circuit current is:

$$\underline{I} \leftrightarrow i(t) = \frac{E}{Z}\sin(\omega_0 t + \varphi) \qquad (2.4)$$

Considering (2.1) circuit impedance becomes:

$$Z = R + \frac{1}{j\omega_0 C_x} \cong \frac{1}{j\omega_0 C_x} \qquad (2.5)$$

Of the last two equations one can see that $\varphi = \pi/2$. Thus, the current in the circuit becomes:

Current amplitude contains the capacity C_x information. There was an amplitude modulation.

Voltage at the entrance of synchronous detector is [4-5], [7-8]:

$$u(t) = Ri(t) = E\omega_0 C_x R\sin(\omega_0 t + \frac{\pi}{2}) \qquad (2.6)$$

Operations that take place in synchronous detector are:

$$u_0(t) = u(t)\hat{e}(t) \qquad (2.7)$$

$$u_0(t) = KE\omega_0 C_x R\sin(\omega_0 t + \frac{\pi}{2})E\sin(\omega_0 t - \frac{\pi}{2}) \qquad (2.8)$$

$$u_0(t) = \frac{1}{2}KE^2\omega_0 C_x R[\cos(\pi) - \cos(2\omega_0 t)] \qquad (2.9)$$

At the synchronous detector output the DC component U_{0c} is obtained:

$$U_{0c} = \frac{1}{2}KE^2\omega_0 C_x R \qquad (2.10)$$

DC component obtained at the output of the synchronous detector contains information on the capacitance to be measured. The capacitance can be determined from (2.11):

$$C_x = \frac{2U_{0c}}{KE^2\omega_0 R} \qquad (2.11)$$

Measurement of high values capacities

Let there be the circuit in the figure below: where "ECV" is the electronic voltmeter, "SD" represents a synchronous detector and "AO" the operational amplifier. The input signals in synchronous detector are: the voltage at the output of the operational amplifier $\underline{U}$ and the voltage $\underline{E}$ [12-15].

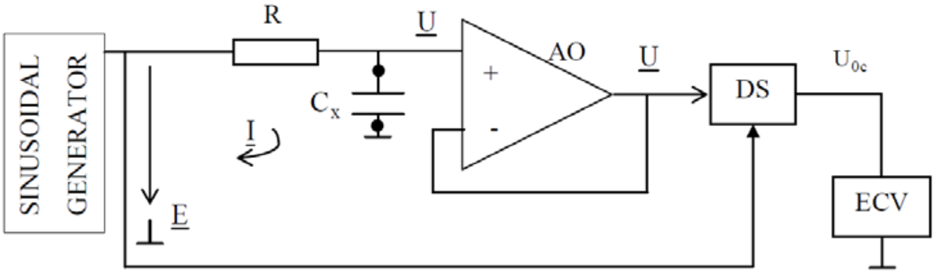


Figure 3 Circuit for high value capacitors measurement

The synchronous detector consists of a multiplier and a low pass filter as it can be seen in the Figure 2.

Design condition is given to ensure the measurement of high capacity of a capacitor with low losses. In this case the impedance of the capacitor is very low compared with the resistance.

$$C_x >>\rightarrow X_C = \frac{1}{\omega_0 C_x} << R \qquad (2.12)$$

Circuit is supplied with a sinusoidal voltage given by (2.2) and the circuit current is:

$$i(t) = I\sin(\omega_0 t) \qquad (2.13)$$

Considering the design condition (2.13), circuit impedance becomes:

$$Z = R + \frac{1}{j\omega_0 C_x} \cong R \qquad (2.14)$$

Of the last two equations one can see that $\varphi = 0$. Thus, the current in the circuit becomes:

$$i(t) = \frac{E}{R}\sin(\omega_0 t) \qquad (2.15)$$

Current amplitude contains the capacity C_x information. It can be said that there was an amplitude modulation.

Voltage at the entrance of synchronous detector is [4-5], [7-8]:

$$u(t) = \frac{1}{\omega_0 C_x} i(t) = \frac{1}{\omega_0 C_x}\frac{E}{R}\sin(\omega_0 t) \qquad (2.16)$$

Operations that take place in synchronous detector are:

$$u_0(t) = u(t)e(t) \qquad (2.17)$$

$$u_0(t) = K\frac{1}{\omega_0 C_x}\frac{E}{R}\sin(\omega_0 t)E\sin(\omega_0 t) \qquad (2.18)$$

$$u_0(t) = \frac{1}{2}K\frac{1}{\omega_0 C_x}\frac{E^2}{R}[\cos(0) - \cos(2\omega_0 t)] \qquad (2.19)$$

Signal obtained is taken through a low pass filter and the DC component (U_{0c}) is determined:

$$U_{0c} = \frac{1}{2}K\frac{1}{\omega_0 C_x}\frac{E^2}{R} \qquad (2.20)$$

DC component obtained at the output of the synchronous detector contains information on the capacitance to be measured. The capacitance can be determined from (2.21):

$$C_x = \frac{1}{2}K\frac{1}{\omega_0 U_{0c}}\frac{E^2}{R} \qquad (2.21)$$

3. APPLICATIONS

3.1. Application for measuring very low values capacities

Let there be the circuit in the figure below used for very low value capacities measurement: Where “Analog block” gives the time continuous signal $u(t)$ and $e(t)$. These signals are taken thru an “A/D System” (Analog to Digital System) and the discrete signals $u[n]$ and $e[n]$ are obtained. With the block “H” the Hilbert conjugate of $e[n]$ is determined. “LPF” represents the Low Pass Filter. It can be seen that there is a direct multiplication of the sequences $u[n]$ and $\hat{e}[n]$ [6], [9].

Let there be the next values:

$$R = 2[\Omega]\,;\, C_X = 10^{-9}[F]$$
$$E = 10[V]\,;\, f_0 = 10^4[Hz] \qquad (3.1)$$

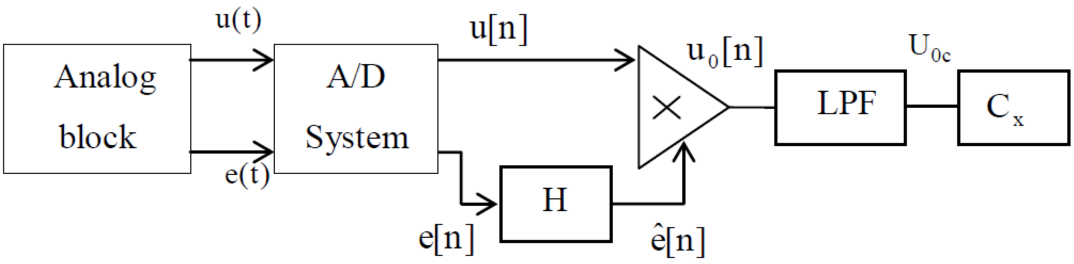
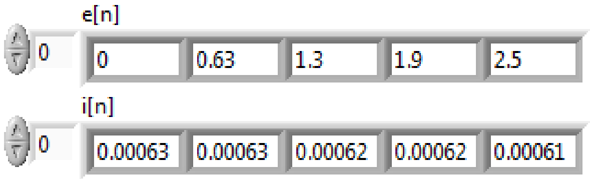


Figure 4 Circuit for measuring very low value capacities

From A/D system there are the following data sequences:



e[n]

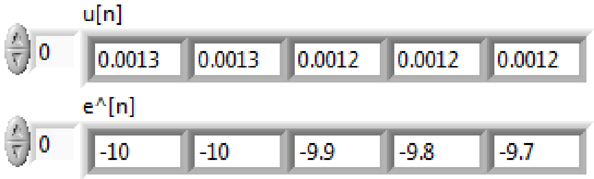
0	0	0.63	1.3	1.9	2.5

i[n]

0	0.00063	0.00063	0.00062	0.00062	0.00061

At the entrance of synchronous detector there is the discrete signal $u[n]$ and the discrete signal $e[n]$ phase shifted with $\pi/2$.

$$u[n] = Ri[n] \tag{3.2}$$



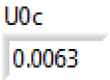
u[n]

0	0.0013	0.0013	0.0012	0.0012	0.0012

e^[n]

0	-10	-10	-9.9	-9.8	-9.7

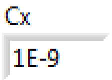
By applying a 4th order Butterworth low pass filter with $1.15 \cdot 10^{-5}$ [Hz] cutoff frequency the DC component U_{0c} is obtained:



U0c

0.0063

From U_{0c}, using the relation (2.11) the capacitance C_x can be determined:



Cx

1E-9

User interface for very low values capacities measure can be seen in figure 6:

Discrete signal $u_0[n]$ is obtained by multiplication of the above signals:

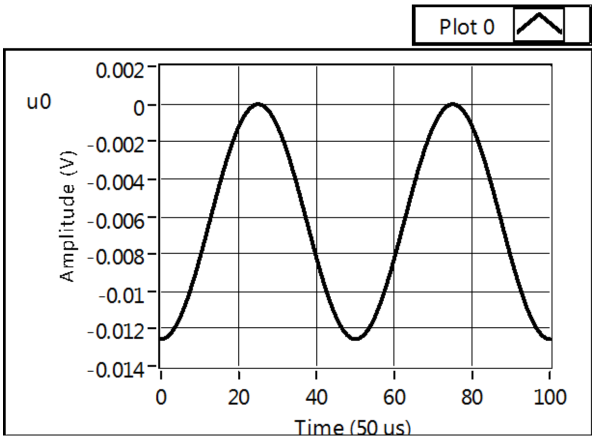
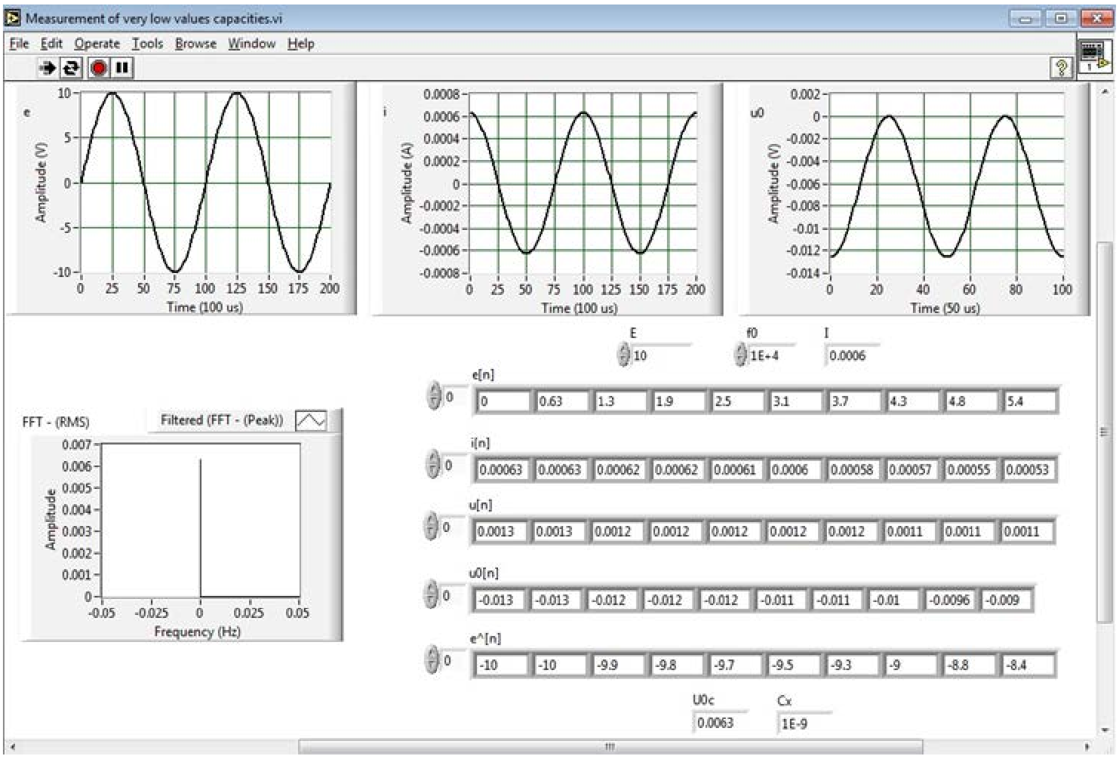


Figure 5 Discrete signal $u_0[n]$

At the exit of LPF there is a curve that stabilizes at the value U_{0c} given by "FFT - (RMS)".

The method for measuring very low capacities was implemented in LabView software and can be seen in Figure 7 [10-11]:



E 10

f0 1E+4

I 0.0006

e[n]

0	0	0.63	1.3	1.9	2.5	3.1	3.7	4.3	4.8	5.4

i[n]

0	0.00063	0.00063	0.00062	0.00062	0.00061	0.0006	0.00058	0.00057	0.00055	0.00053

u[n]

0	0.0013	0.0013	0.0012	0.0012	0.0012	0.0012	0.0012	0.0011	0.0011	0.0011

u0[n]

0	-0.013	-0.013	-0.012	-0.012	-0.012	-0.011	-0.011	-0.01	-0.0096	-0.009

e^[n]

0	-10	-10	-9.9	-9.8	-9.7	-9.5	-9.3	-9	-8.8	-8.4

U0c 0.0063

Cx 1E-9

Figure 6 LabView interface application for very low values capacities

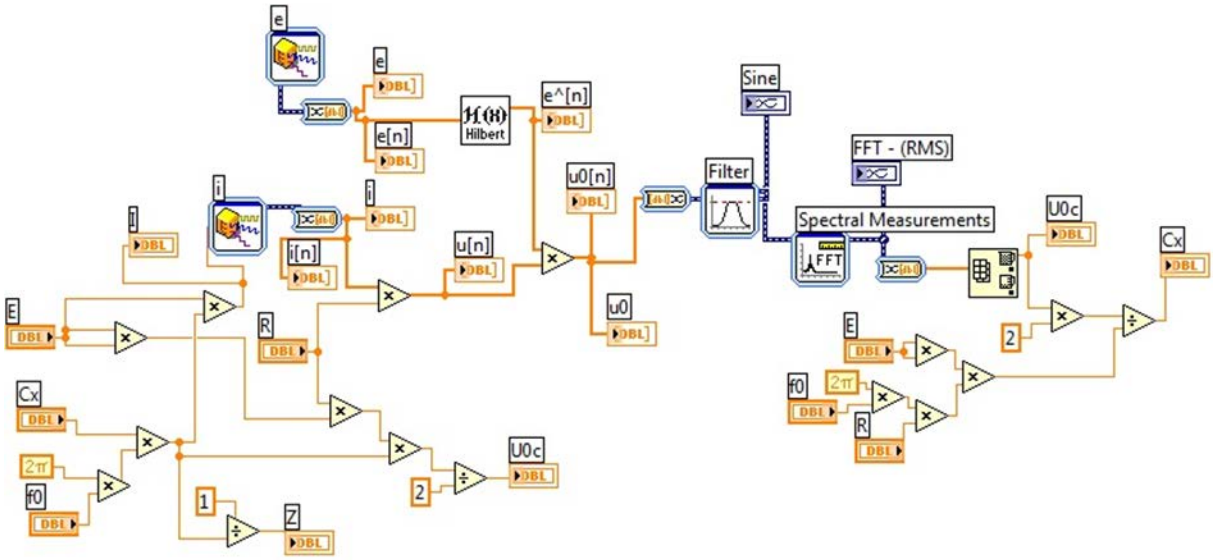
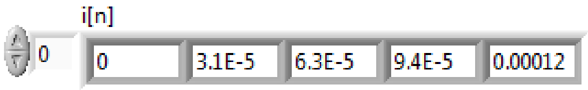


Figure 7 Application for measuring very low values capacities

3.2 Application for measuring high values capacities

Let there be the circuit in the figure below used for high values capacities measurement:

The Discrete signal $i[n]$ is:



i[n]

0

0	3.1E-5	6.3E-5	9.4E-5	0.00012

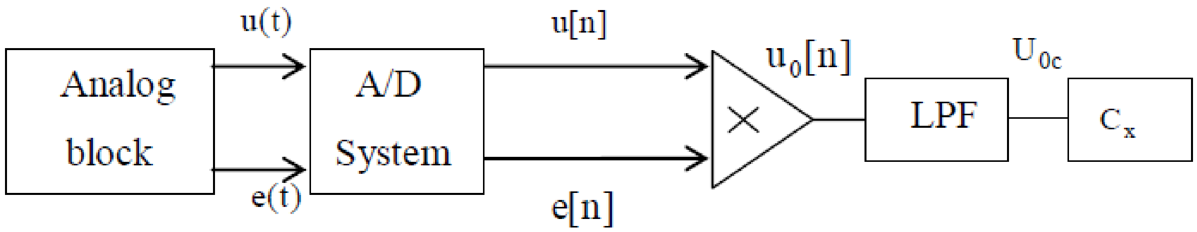


Figure 8 Circuit for high value capacitors measurement

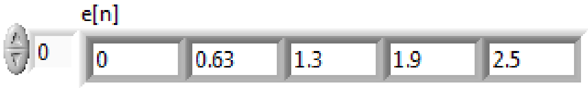
Where “Analog block” gives the time continuous signals: $u(t), e(t)$. These signals are taken thru an “A/D System” (Analog to Digital System) and the discrete signals $u[n]$ and $e[n]$ are obtained. “LPF” represents the Low Pass Filter. It can be seen that there is a direct multiplication of the sequences $u[n]$ and $e[n]$ [6], [9].

Let there be the next values:

$$R = 20[k\Omega]\,;\, C_x = 10^{-4}[F]$$
$$E = 10[V]\,;\, f_0 = 10^{6}[Hz] \qquad (3.3)$$

From A/D system there are the following data sequences: $e[n]$ and $i[n]$.

The Discrete signal $e[n]$ is:



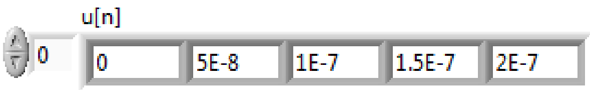
e[n]

0

0	0.63	1.3	1.9	2.5

At the entrance of synchronous detector there is the discrete signal $u[n]$ and the discrete signal $e[n]$. The signal $u[n]$ is:

$$u[n] = \frac{1}{\omega_0 C_x} i[n] \qquad (3.4)$$

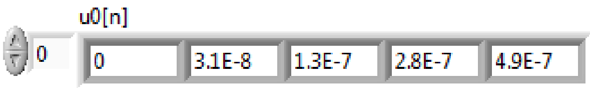


u[n]

0

0	5E-8	1E-7	1.5E-7	2E-7

Discrete signal $u_0[n]$ is obtained by multiplication of $u[n]$ with $e[n]$ and it can be seen in figure 8:



u0[n]

0

0	3.1E-8	1.3E-7	2.8E-7	4.9E-7

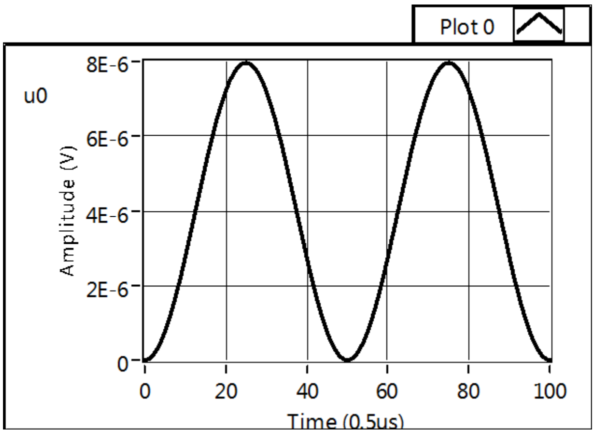
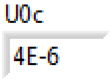


Figure 9 Discrete signal $u_0[n]$

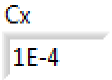
By applying a 4th order Butterworth low pass filter with $1.15 \cdot 10^{-5}$ Hz cutoff frequency the DC component U_{0c} is obtained:



U0c

4E-6

From U_{0c}, using the relation (2.21) the capacity can be determined:

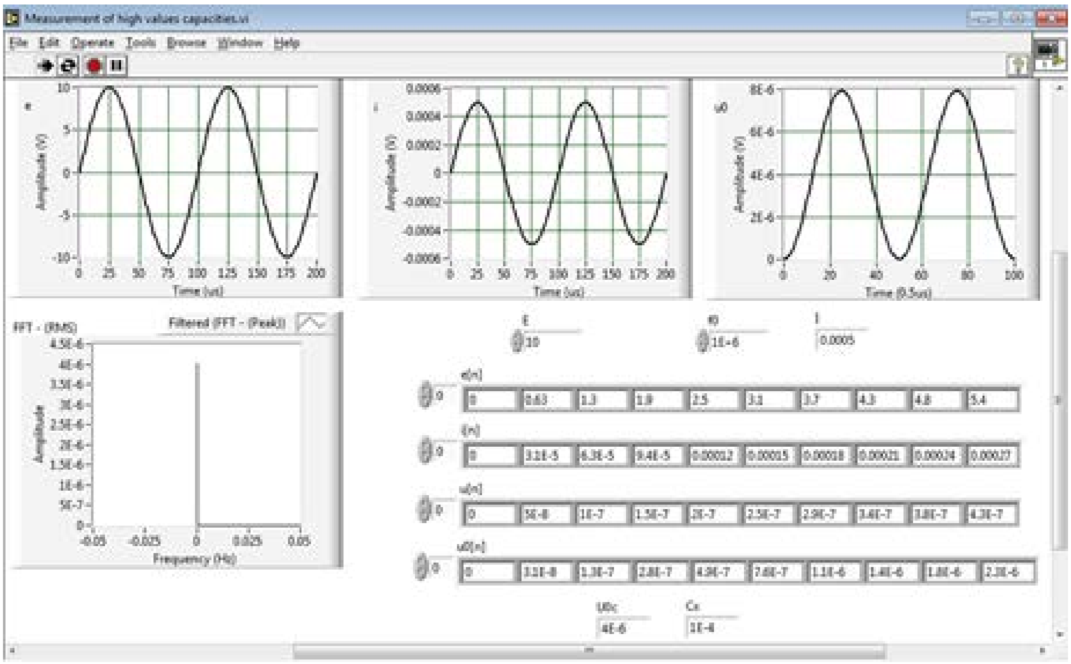


Cx

1E-4

User interface for high values capacities measurement can be seen in figure 10:

At the exit of LPF there is a curve that stabilizes at U_{0c} given by "FFT - (RMS)" The method for measuring high values capacities was implemented in LabView software and can be seen in Figure 11:



E 10

f0 1E-6

I 0.0005

e[n]: 0, 0.63, 1.3, 1.9, 2.5, 3.1, 3.7, 4.3, 4.8, 5.4

i[n]: 0, 3.1E-5, 6.3E-5, 9.4E-5, 0.00012, 0.00015, 0.00018, 0.00021, 0.00024, 0.00027

u[n]: 0, 5E-8, 1E-7, 1.5E-7, 2E-7, 2.5E-7, 2.9E-7, 3.4E-7, 3.8E-7, 4.3E-7

u0[n]: 0, 3.1E-8, 1.3E-7, 2.8E-7, 4.9E-7, 7.6E-7, 1.1E-6, 1.4E-6, 1.8E-6, 2.3E-6

U0c 4E-6

Cx 1E-4

Figure 10 LabView interface application for high values capacities measurement

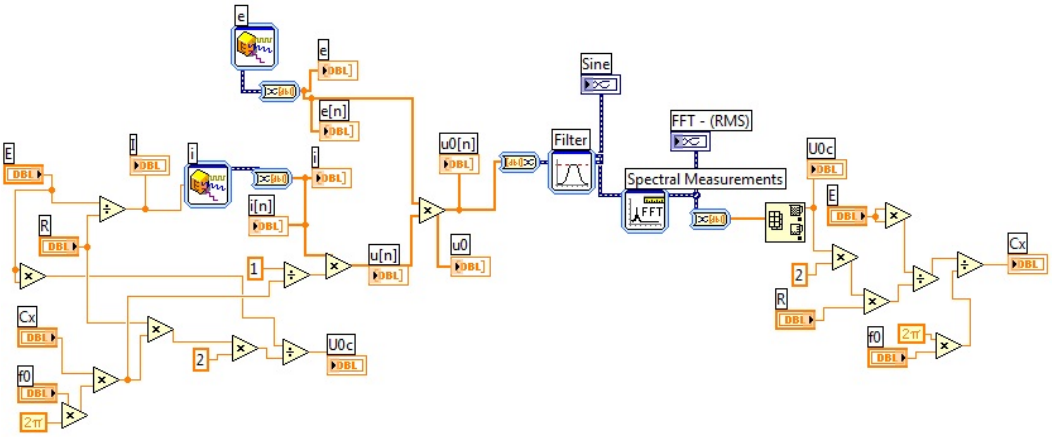


Figure 11 Application for measuring high values capacities

4. CONCLUSIONS

In this paper was presents a method for measuring low-loss capacitors by synchronous detection. The method proposed in this paper offers the possibility to measure capacities at different levels of frequency. The resistance loss of the capacitor to be measured was considered very small, negligible. Two applications have been developed.

In the first application a method for very small capacity measurement together with the measuring circuit and its initial design conditions were presented. Design condition was given to ensure the measurement of very small capacity of a capacitor.

In the second application a method for very small capacity measurement together with the measuring circuit and its initial design conditions were presented. Design condition was given to ensure the measurement of high capacity of a capacitor.

Generally, the circuits presented in this paper are used to measure capacity but can be extended to measure the information contained in amplitude. It has been shown that the DC component obtained at the synchronous detector output contains information on the capacitance to be measured.

ACKNOWLEDGEMENTS

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Oana MUNTEAN

Place/date of birth: Tg-Mureş, Mureş, Romania/28.01.1986
Educational background:
2011-present: Doctoral studies in engineering science
2009-2011 Master - Modern Computer Aided Design Techniques in Electrical Engineering
2005-2009 Engineer - Faculty of Electrical Engineering
Technical University of Cluj-Napoca, Cluj-Napoca, Cluj, Romania