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METROLOGICAL ANALYSIS OF CHARGE - TRANSFER CAPACITIVE TRANSDUCER IN THE PRESENCE OF RESISTANCE

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Abstract: *One of the major tasks in the design of measuring transducers is improving their accuracy in real conditions. Above all, this problem makes it necessary to evaluate the impact that various non-idealities have on the work of the measuring device. This study points that the presence of active resistance in the input of capacitive transducers, realizing the charge-transfer method, influences the measured result. With a configuration, composed of four analogue switches, the magnitude of the occurring in this case additional error depends on: the value of resistance in the input; the value of the capacity, which is the object of the measurement; the frequency and the phase offset of the clock signals, controlling the switches. The conditions under which error does not exceed 0,1% have been defined and a simple equation, by which its value can be assessed in the general case, has been validated. Presented results are useful in the design and implementation of industrial capacitive transducers.*

Keywords: Capacitive transducer, resistance, methodological error

1. INTRODUCTİON

The charge-transfer method (CTM) is one of the three most common methods of measuring capacity, used in the modern industrial transducers [1-6]. With this method the capacity *C* being the object of measurement, switches between two or more nodes from the circuit of the measuring device. Knowing the potentials φ_1, φ_2 of the nodes, to which connection has been established before the switching and having the potentials φ_3, φ_4 of the nodes, after that, it is possible to define the capacity by measuring the charge transfer.

$$\Delta q = C.\left[(\varphi_1 - \varphi_2) - (\varphi_3 - \varphi_4)\right] \tag{1}$$

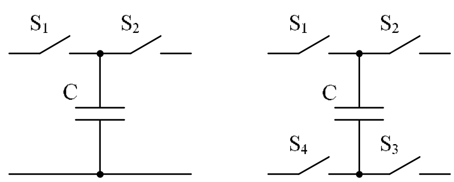

Figure 1. Configuration of two and four switches, used in capacitive CTs.

$$C = \frac{\Delta q}{(\varphi_1 - \varphi_2) - (\varphi_3 - \varphi_4)} \tag{2}$$

In most cases the active resistance of the circuits, formed during the switching, is definitive for the rate by which the charge is transferred form the capacity transducer (CT) to the capacity and backwards. This imposes that C stays long enough in each of the two positions. Otherwise it is possible that

$$\Delta q < C.[(\varphi_1 - \varphi_2) - (\varphi_3 - \varphi_4)] \quad (3)$$

The use of Eqn (2) under the condition of Eqn (3) is related

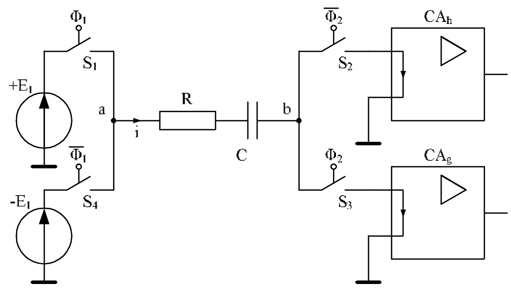

Figure 2. Generalized representation of the input circuit of a CT with four switches.

to a methodological error, whose magnitude is the subject of analysis in this paper.

2. APPLİCATİON AND ANALYSİS OF THE CHARGE - TRANSFER CAPACİTY MEASURİNG METHOD İN THE PRESENCE OF RESİSTANCE

With the CTM normally the commutation in the front-end circuit of the CT is realized by means of two or four switches (Fig.1) [5-11]. The reasons for the appearance of active resistance in this part of the circuit of the CT could be different. Resistors, having 50÷100Ω resistance and connected in series with C, protect inputs of the CT against ESD (electrostatic-discharge) [12]. Resistances are inherent to the elements, themselves, composing the input circuit of the CT (analogue switches, operational amplifiers etc.) or are part of the equivalent circuits of the sensors connected to CT. [5,13-15]. Paper [5] considers the behavior of CTs, realizing the CTM by means of two switches, when the effects of an active resistance in the input circuit are presented by a resistor R, connected in series to the measured capacity C. The solution of this problem with a CT, containing four switches, can be found by considering the scheme, given in Fig. 2. The analogue switches are controlled by two clock signals: Φ_1 and Φ_2 (Fig.3). During the first part of the period of switching T_{cl}, the switches S_1 and S_3 are closed. C is connected to the source of voltage $+E_1$, as well as to the input of the charge amplifier CA_g. In the time interval (t'_0, $t'_0+\Delta t'$), $\Delta t'=T_{cl}/2$ the voltage u_C increases, reaching value of E_2 at the end of the first half. During the second part of the period S_1 and S_3 are open, while S_2 and S_4 are closed. C is connected both to the source of voltage $-E_1$ and to the input of the charge amplifier CA_h.

In the time interval (t''_0, $t''_0+\Delta t''$), $\Delta t''=T_{cl}/2$ the voltage u_C decreases, reaching the value of E_3 when the second cycle of period is completed. After that the processes are repeated.

Taking into account both the above discussion and the scheme in Fig.2, we can find the voltage u_C over the capacitor C in the following way:

$$R.i + u_C = u_{ab} \quad (4)$$

$$R.C.\frac{du_C}{dt} + u_C = u_{ab} \quad (5)$$

where u_{ab} is the voltage at the nodes a and b. During the first part of the period $u_{ab}=E_1$ and the differential Eqn (5) has a solution [16]:

$$u_C = E_1 + A_1.\exp\left(-\frac{t - t'_0}{T}\right) \quad (6)$$

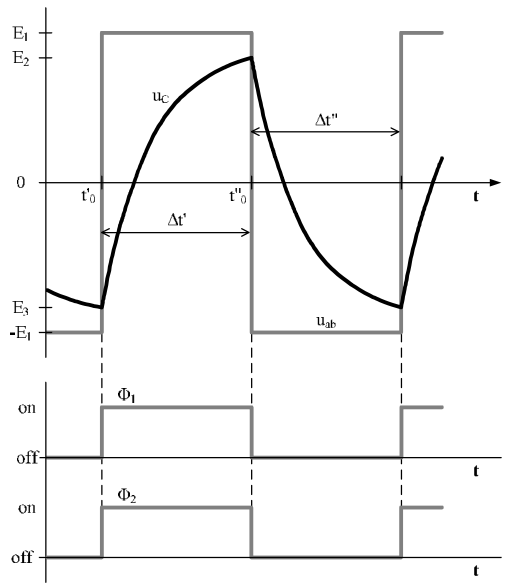

Figure 3. Graphical representation of the voltage u_C, u_{ab}, Φ_1 and Φ_2 at a steady state mode of operation of the measuring transducer.

$$t'_0 \le t \le t'_0 + \Delta t'$$

where T=$R.C$. The integration constant A_1 at a steady state mode is defined by the condition $u_C(t'_0+)=u_C(t'_0-)=E_3$:

$$u_C = E_1 - (E_1 + E_3).\exp\left(-\frac{t - t'_0}{T}\right) \quad (7)$$

$$t'_0 \le t \le t'_0 + \Delta t'$$

Then, from Eqn (7) it is obtained for $t=t'_0+\Delta t'$:

$$E_2 = E_1 - (E_1 + E_3).\exp\left(-\frac{T_{cl}}{2.T}\right) \quad (8)$$

The same way, considering the processes during the second part of period, it is proved that:

$$E_3 = E_1 - (E_1 + E_2).\exp\left(-\frac{T_{cl}}{2.T}\right) \quad (9)$$

From the last two equations it is directly established that:

$$E_3 = E_2 \quad (10)$$

$$E_2 = E_1.\frac{1-\exp\left(-\frac{T_{cl}}{2.T}\right)}{1+\exp\left(-\frac{T_{cl}}{2.T}\right)} = E_1.th\left(\frac{T_{cl}}{4.T}\right) \quad (11)$$

From Eqn (10) and Eqn (11) the charge, which the capacity transfers to the amplifiers CA_g and CA_h within a switching period, can be found:

$$\Delta q_g = C.\left(E_2 - (-E_3)\right) = 2.C.E_1.th\left(\frac{T_{cl}}{4.T}\right) \quad (12)$$

$$\Delta q_h = C.\left(-E_3 - E_2\right) - 2.C.E_1.th\left(\frac{T_{cl}}{4.T}\right) \quad (13)$$

For the purposes of the measurement either the charge quantities q_g, q_h or their difference can be used:

$$Q = \Delta q_g - \Delta q_h = 4.C.E_1.th\left(\frac{T_{cl}}{4.T}\right) \quad (14)$$

In all three cases the application of Eqn (2) for capacity calculating in the presence of resistance will lead to the occurrence of an error. For example, when Eqn (14) is used, the relative deviation is

$$\delta = \frac{\frac{Q}{4.C.E_1} - \frac{Q}{4.C.E_1.th\left(\frac{T_{cl}}{4.T}\right)}}{\frac{Q}{4.C.E_1.th\left(\frac{T_{cl}}{4.T}\right)}}$$

$$\delta = th\left(\frac{T_{cl}}{4.T}\right) - 1 \quad (15)$$

It can be seen from Fig.5 that at T/T_{cl}=0,1, δ≈1%. To keep the error under 0,1% it is required that the time constant T of the formed RC circuit is approximately 15 times smaller than the period T_{cl}.

3. METROLOGİCAL ANALYSİS OF CAPACİTİVE TRANSDUCER REALİZİNG THE CHARGE - TRANSFER METHOD WİTH PHASE - SHİFTED CLOCK SİGNALS

The previous paragraph analyzes the behavior of the CT when sequences Φ_2 and Φ_1 are in the phase. Besides, there are controls in the practice in which the clock Φ_2 outruns Φ_1 by the time equal to $\theta.T_{cl}$, $0<\theta\le 0{,}25$ (Fig.4) [5,8-10]. At $\theta\neq 0$ the capacity C connects to the corresponding charge amplifier before u_C reaches E_2 and E_3 respectively (Fig.3). The amount of the charge, going into CA_g within a one full cycle of the switching is

$$\Delta q_g = C.(E'_2 - E'_3) \quad (16)$$

and into CA_h it is:

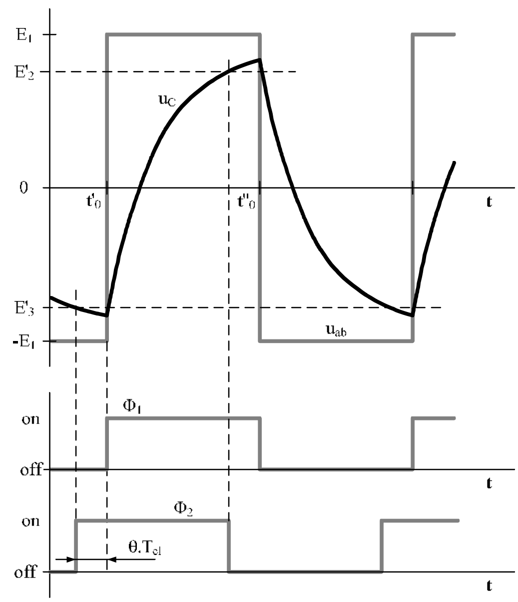

Figure 4. Graphical representation of the voltage u_C, u_{ab}, Φ_1 and Φ_2 at a steady state mode of operation and $\theta \neq 0$.

$$\Delta q_h = C.(E'_3 - E'_2) \quad (17)$$

where

$$E'_2 = E_1 - (E_1 + E_3).\exp\left((1-2.\theta).\frac{T_{cl}}{2.T}\right) \quad (18)$$

and

$$E'_3 = E_1 - (E_1 + E_2).\exp\left((1-2.\theta).\frac{T_{cl}}{2.T}\right) \quad (19)$$

For the purposes of the measurement either Eqn (16), Eqn (17) or their difference can be used:

$$Q = \Delta q_g - \Delta q_h = 4.C.E_1.th\left((1-2.\theta).\frac{T_{cl}}{4.T}\right) \quad (20)$$

In all three cases the application of Eqn (2) for capacity calculating in the presence of resistance will lead to the occurrence of an error. For example, when Eqn (20) is used, the relative deviation is

$$\delta = th\left((1-2.\theta).\frac{T_{cl}}{4.T}\right) - 1 \quad (21)$$

Fig. 5 shows the error δ for different values of θ. It can be seen that the error increases with θ: at T/T_{cl}=0,1 and θ=0,125, the error is about -5% and at T/T_{cl}=0,1 and θ=0,25 it exceeds -15%.

The error δ is not a positive number for the whole

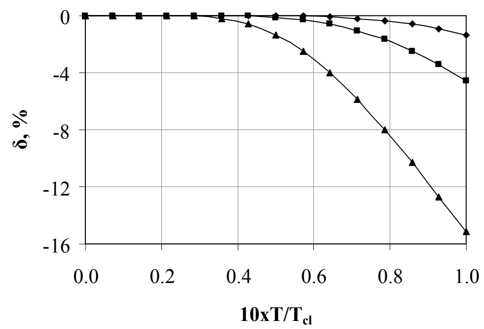

Figure 5. Graphical representation of the error $\delta=\delta(T/T_{cl})$, for different values of θ: —◆— θ=0, —■— θ=0,125, —▲— θ=0,25.

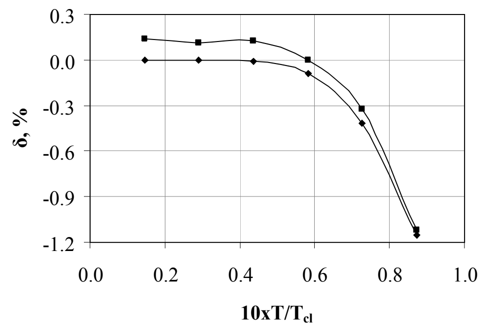

Figure 6. Graphical representation of the error $\delta=\delta(T/T_{cl})$, obtained at θ=0,05, R=1kΩ and C=100÷900pF. —◆— theoretical results; —■— experimental results.

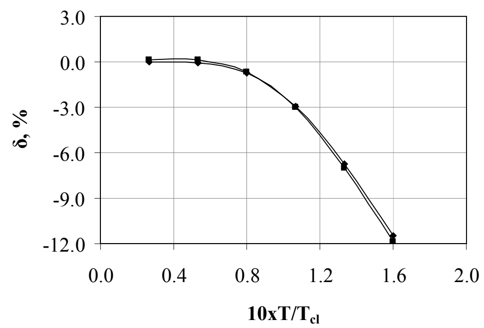

Figure 7. Graphical representation of the error $\delta=\delta(T/T_{cl})$, obtained at θ=0,05, R=1,9kΩ and C=100÷900pF. —◆— theoretical results; —■— experimental results.

range 0≤θ≤0,25. It means that in the presence of the resistance $R \neq 0$ in the input, the value of the capacity, defined in accordance with Eqn (2), will always be less than the value of the real one.

Experimental validation of the Eqn (21) has been conducted by means of the CT, described in [5]. At clock frequency equal to 100kHz (T_{cl}=10μS) and at relative shift θ=0,05, the capacity of reference capacitors, in series to which different resistors are connected, has been determined. The results are shown in Fig.6 and Fig.7. The maximum absolute deviation between the experimental and the theoretical results does not exceed 0,1÷0,5%.

4. CONCLUSİON

The analysis, given in this work, shows that the presence of active resistance *R* in the input circuit influences the operation of the capacitive measuring transducers, realizing the charge-transfer method. With the use of a configuration composed of four analogue switches the magnitude of the occurring additional error δ depends on: the value of *R*; the value of the capacity C, which is the object of the measurement; the clock frequency $1/T_{cl}$ and the relative shift θ. At θ=0 and $R.C/T_{cl}<15$ the error δ does not exceed 0,1%. In all other cases it can be analytically assessed by means of the Eqn (21).

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