# CAPACITANCE METER

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*This paper presents a Capacitance Meter (CM) with fast serial digital output. The CM is intended to be used as a flexible solution for interfacing multiple capacitive sensors with maximum value 1pF. A cable capacitance of up to 1nF can be tolerated. Two different modes of measurement are available – normal and fast. The conversion time is 39μs and 64μs for fast and normal mode, respectively. The resolution in normal mode, with cable capacitance less than 400pF, is better than 14 bits. A special multi-slope A-to-D conversion is used, which at the end of the conversion process transforms itself into sigma/delta conversion. The interface is realized on a PCB with a Single Euro-board format. Six sensors can be interfaced in programmable sequence. The power consumption is less than 1W.*

**Keywords:** Capacitance-to-digital converter, multi-slope ADC, charge amplifier

## 1. INTRODUCTION

Capacitive sensor interfaces with standardized and easy to read output have been for many years the primary goal of numerous research and development efforts. As such are considered the solutions with frequency output [1-4]. Their typical disadvantages are - (1) relatively slow sensor readout speed (only a few conversions per second); (2) dependence of the readout time on the value of the measurand [4].

Another trend is the direct conversion of capacitance into digital code, in which the measured capacitance makes part of the analog-to-digital converter [5-7]. Recently Analog Devices introduced its integrated CDC series – AD7745/6/7, based on a 24 bit sigma/delta core cell [8]. A disadvantage of AD7745/6/7 is the low measurement rate (<100 meas/s) and limited cable capacitance that can be tolerated.

In this paper a fast capacitance meter (CM) is presented, intended to be used as a flexible solution for interfacing multiple capacitive sensors with maximum capacitance of 1pF. A cable capacitance up to 1nF can be tolerated. There are 2 modes of measurement – normal and fast. A multi-slope A-to-D conversion is used, which at the end of the conversion process transforms itself into a sigma/delta conversion. Six sensors can be interfaced in programmable sequence.

## 2. THEORY OF OPERATION

### 2.1. Principle of measurement

The CM block diagram is presented in Fig.1. The measurement is done by applying a reference excitation voltage at the measured capacitance (17), and by measuring the stored charge in it. The unknown charge is amplified by an input

amplifier (2) and is summed with a charge with opposite polarity, which is generated by the reference circuits (3) and (4). The sum is fed to an integrator (6). The output of the integrator is monitored with a comparator (7). The state of the comparator controls the reference charge generators (3) and (4) in a manner to keep the integrator output (6) at 0V. This condition is achieved when the reference charge is equal to the amplified input charge. Knowing the amount of the reference charge, the gain of the input amplifier and the excitation reference voltage, the value of the unknown capacitance can be defined.

Two reference charge generators are used to reduce the conversion time. Generator (4) feeds 16 times more charge and is used for coarse input charge compensation. The fine compensation is done with a second charge generator (3).

The reference charge is counted with 12-bit up/down counter (13). It has two "enable" inputs, "x1" (counter value is changed by 1) and "x16" (counter value is changed by 16). The count direction is determined by the "Up/Down" input. The count direction is controlled by the polarity of the reference charge. In this way the value of the 12-bit counter tracks the amount of reference charge fed to the integrator. Knowing the value of the counter before and after supplying reference voltage to the measured capacitance, one can calculate the amplified input charge by simply subtracting both counter values.

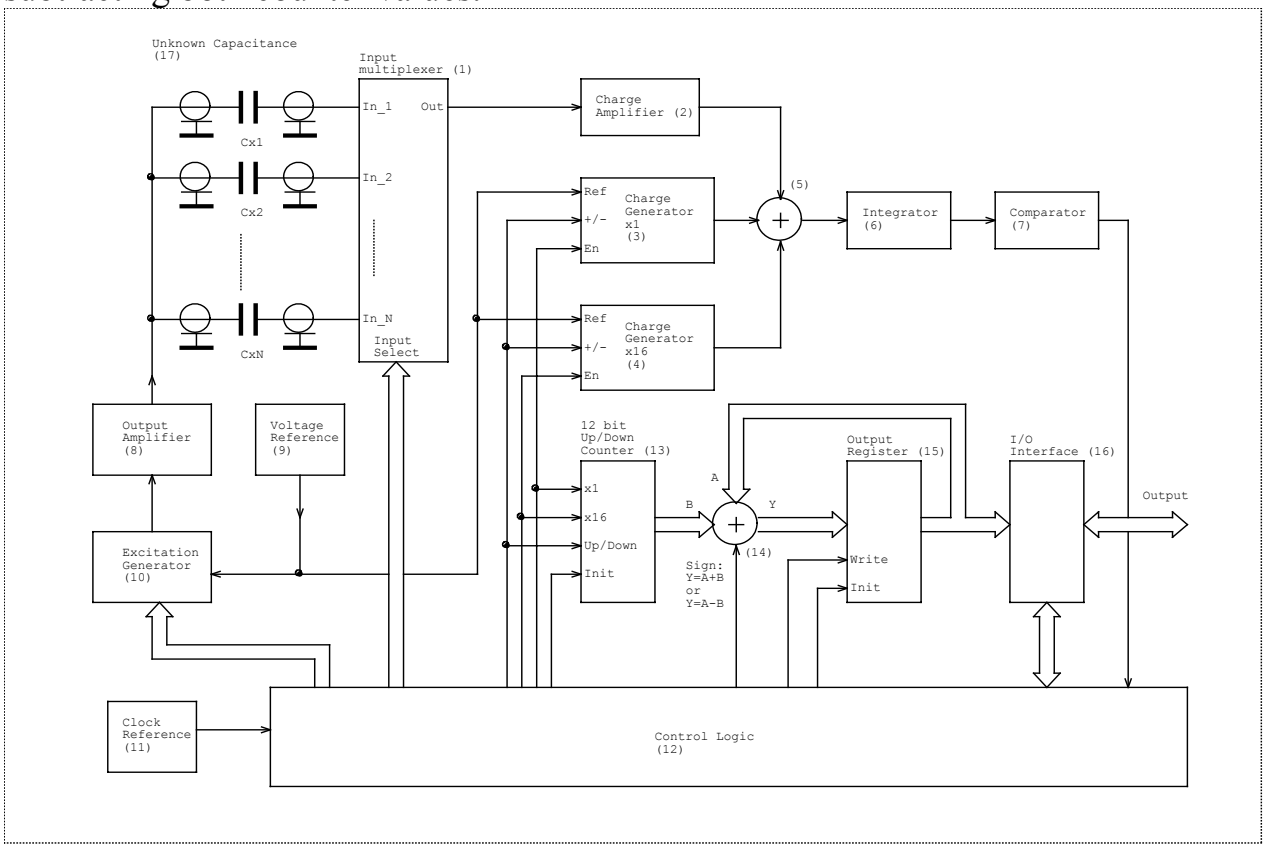


Fig 1. Block diagram of the capacitance meter.

To increase the resolution, the value of the 12-bit counter is sampled 16 times (Fast mode) or 64 times (Normal mode) during the input tracking and all samples are summed/subtracted to/from the value in the output register (15).

The measurement is done in two cycles using both directions of the excitation voltage change. In this way the input offset voltages and the low frequency noise of the input amplifier and the integrator are cancelled.

The excitation voltage generator (10) and the reference charge generators (3) and (4) use a common voltage reference (9). Therefore, slow variations of the reference voltage don't influence the accuracy of the capacitance meter.

**2.2. Implementation**

A simplified electric circuit of the analog part of the CM is shown in Fig.2 with a timing diagram presented in Fig.3. The function of the circuit is the following:

- During time interval $t_1$-$t_2$ the control logic uses the fine reference charge generator (Analog MUX1 and $R_4$) to keep the output of integrator $A_2$ at 0V by monitoring the output of the comparator $A_3$. Because of the input noise, the output of the integrator is not constant and for this reason the value of the charge tracking counter varies. To minimize this effect, the counter is sampled multiple times and the samples are averaged to find the starting value $N_1$.
- At moment $t_3$ the excitation voltage $V_{04}$ is switched from negative to positive value and a charge proportional to $C_X$ is transferred to $C_1$. Immediately $C_1$ starts discharging through $R_1$. While $C_1$ is discharged by $R_1$, $C_3$ is charged through $R_2$ with current proportional to the current through $R_1$. In this way $C_3$ receives the charge from $C_x$ multiplied by the ration $R_1/R_2$. In this way a charge amplifier is realized.
- In the time interval $t_5$-$t_9$ the coarse and the fine charge generators discharge the integrator A2.
- During time interval $t_{10} - t_{11}$ the fine charge generator is turned on and its polarity is controlled depending on the comparator output in a way to keep the output of integrator $A_2$ at 0V. During this time the charge counter is sampled multiple times and the samples are averaged. The difference between the final average value $N_2$ and the starting average value $N_1$ of the counter is proportional to the amount of reference charge transferred to the integrator, which is equal to the amplified charge of $C_x$.
- During time interval $t_{12} - t_{22}$ is performed the second half cycle of the measurement, this time with the opposite transient direction of the excitation voltage. During this half cycle the charge counter starts with averaged value $N_3$ and ends with averaged value $N_4$. The value of the unknown capacitance $C_X$ is found using the values of the counter $N_1$, $N_2$, $N_3$ and $N_4$ as described below.

Based on the principle of operation of the CM and the transfer functions of the functional blocks, the following relation for the unknown capacitance is derived:

$$C_x = \frac{t_{CLK}}{4K_R R_1}\frac{R_2}{R_3}\frac{R_6}{R_5+R_6}\left(N_2 - N_1 - N_4 + N_3\right) \quad (1)$$

where $t_{CLK}$ is the clock period, $K_R$=16 is a constant, $N_1$ and $N_3$ are the averaged start values of the charge counter, $N_2$ and $N_4$ are the averaged final values of the counter for the first and second half cycles, respectively.

Equation (1) shows that the reference components in this circuit are time, absolute value of one resistor ($R_1$) and the ratio between the resistor pairs ($R_2$ , $R_3$ and $R_5$ , $R_6$).

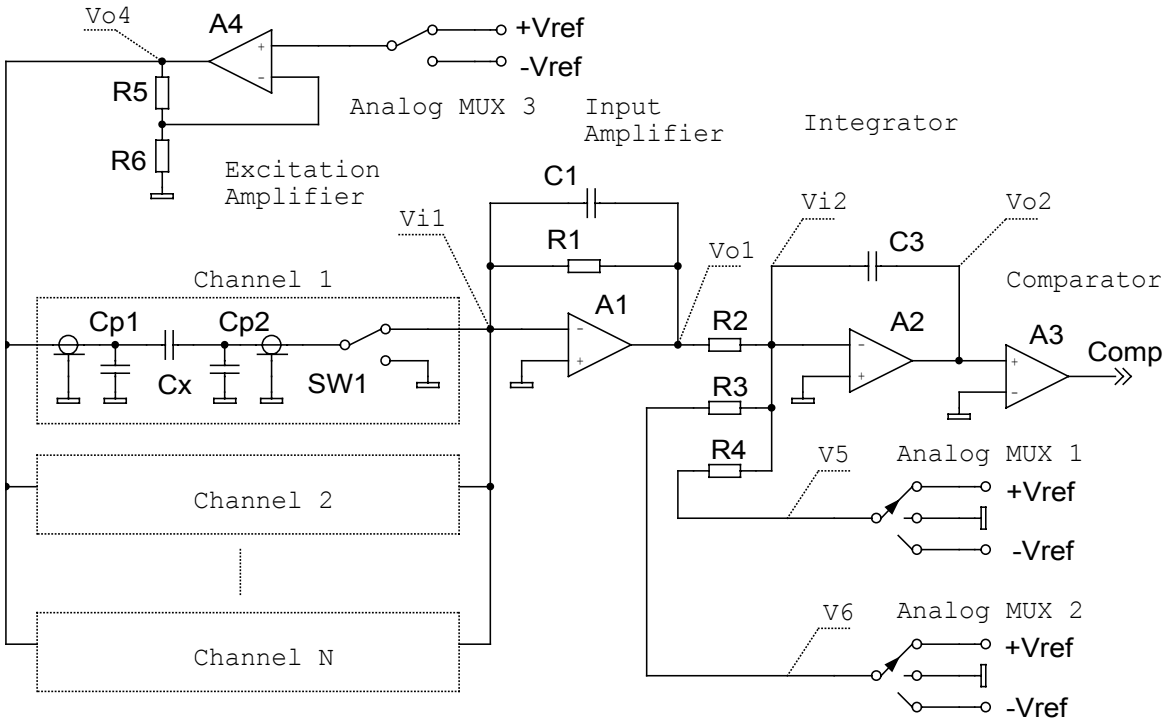


Fig. 2. A simplified electric circuit of the analog part of the CM.

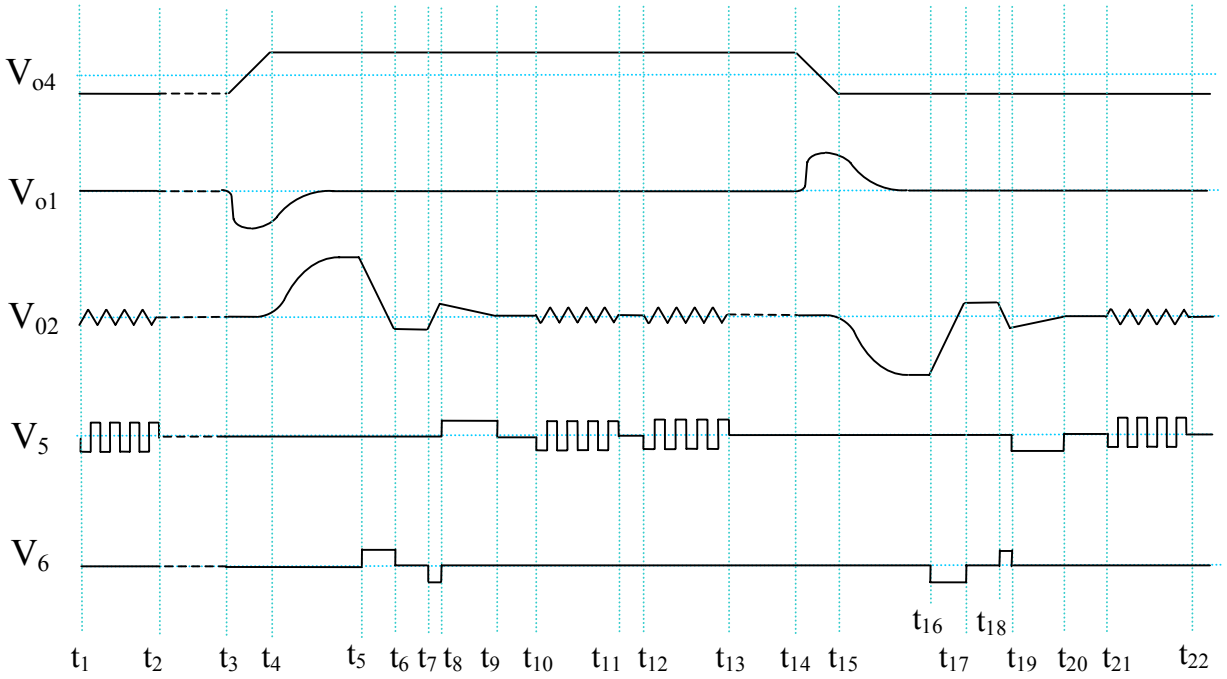


Fig.3. Timing diagramm of the CM operation.

All of these components are available in high precision versions, which ensures a high initial accuracy of the CM and guarantees stability over temperature and time.

### 2.3 Mon-idealities

Equation (1) is derived assuming ideal conditions. In reality there are a number of factors which could have effect on the performance of the CM:

- Offset voltage and offset/bias currents of the OpAmps. If the two half cycles of the measurement period are equal, the offset voltages and currents are cancelled;
- Charge injection of the input analog switches and the switches in the charge generators. Special measures are taken to minimize this effect;
- Noise. Thanks to the charge amplification, the dominant noise source is the input noise of the charge amplifier, especially when longer cables are used. A very low noise OpAmp is selected - AD8065;
- The limited speed of the charge amplifier brings an error during switching of the excitation voltage and may cause instability when longer cables are used. To avoid this effect a composite solution AD8065/AD8031 is implemented.
- Dielectric absorption of the integrating capacitor. It adds an effect of 'memory' in the circuit, which results in dependence of the current measurement result on previous measurements. To minimize this error, a capacitor with low dielectric absorption is used for the integrator circuit.

### 3. Realization and Experimental Results

A demonstrator of the CM is realized and tested on a PCB with a Single Euro format (see Fig. 4). A cable capacitance of up to 1nF (~10m coax cable) can be tolerated. The conversion time in fast mode is 39μs and in normal mode is 64μs. The maximum power consumption is less than 1W.

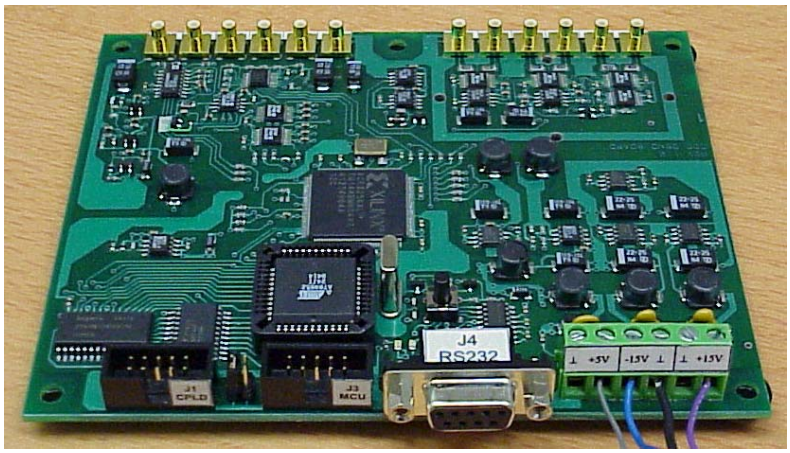

Fig 4. A demonstrator of the capacitance meter.

The integral non-linearity was measured by using four shielded capacitors with approximate values: C1=22fF, C2=58fF, C3=204fF and C4=554fF. To eliminate the uncertainty related to the absolute values of the measured capacitors, a standard approach was used with measuring different combinations of capacitors, i.e. C1+C2, C2+C3, C3+C4, C1+C2+C3+C4, etc., and comparing the results. It appeared that in most of the cases the resolution was a limiting factor to define the non-linearity. A non-linearity was noticed, when all four capacitors were connected in parallel. Its value was less than 0.1%.

The temperature dependence of the conversion coefficient of the capacitance meter was tested in the temperature range 24°C to 62°C. The measured temperature coefficient is less than -11.5 ppm/K.

The offset of the capacitance meter was measured with zero input capacitance $C_x$, in normal and fast mode, with and without shielding of the input charge amplifier. The results are presented in Table1.

Table 1. Measured offset with zero input capacitance

| Offset value (Cx= 0) | No shield | Shield |
|---|---|---|
| Normal mode | 0.013 fF | -0.028 fF |
| Fast mode | 0.008 fF | -0.033 fF |

Figure 5 shows the resolution of the CM, expressed in bits, as a function of the cable capacitance.

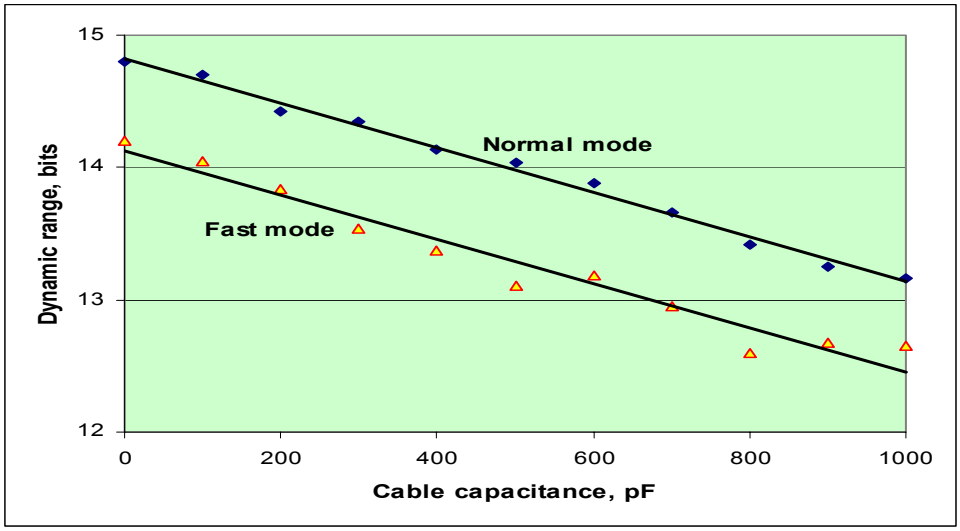


Fig. 5. Dynamic range (rms) of the capacitance meter versus cable capacitance.

## 4. REFERENCES

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