Abstract

The universal interfacing integrated circuit for direct capacitance-to-digital and capacitance-to-frequency (period, time interval)-to-digital conversion suitable for various capacitive sensing elements is newly presented in the paper. Measurement results have successfully verified the functions and performance of the proposed circuit. The capacitance range is from 50 pF to 100 µF. The worst case relative error for reported results is not more than ±0.7%. Any capacitance-to-frequency converters can be also connected to the designed universal sensors and transducers interfacing circuit. The relative error for the further frequency-to-digital conversion is constant in the whole frequency range and not exceeds ±0.0005%.

Keywords: capacitance-to-digital converter; capacitance-to-frequency converter; universal sensors and transducers interface

1. Introduction

Capacitive sensing elements are widely used in humidity, level, pressure, acceleration, position, proximity, biosensors, chemical sensors and transducers. In such sensor systems, physical, chemical or mechanical quantities are converter into capacitance values, which further should be converter into digital by an electronic circuit. As it was written in [1], successful commercial exploitation of highly miniaturized capacitive sensors is often inhibited by the presence of parasitic effects such as environmental noise and parasitic capacitance. Therefore, to alleviate the problem, it is important to integrate readout, interfacing and converting circuitry as directly as possible.

Commercially available capacitance humidity sensor Minicamp 2 (GE Sensing) has a capacitance range from 165.7 to 261.87 pF; humidity sensor KFS33-LC (Hydrogen’s Instruments, GmbH) - from 305 to 355 pF; humidity sensor DSHS07 (Smarted) - from 280 to 380 pF and humidity sensor SMTHS10 from the same company has the capacitance range from 40 to 240 pF; capacitance humidity sensor with carbon nitride detecting element – from 350 to 900 pF [1]. Humidity sensors for technical gases as nitrogen, argon, helium, oxygen, hydrogen, etc. have typical capacitance range from 1 to 2.5 nF. However, existing, available on the market integrated circuits for capacitance-to-digital conversion have limited capacitance ranges and/or low accuracy. For example, integrated capacitance-to-digital converters AD7745/46 [2], AD7747 [3] and AD7150/51/52/53 [4] from Analog Devices have capacitance ranges that do not exceed one-two tens pF. The capacitance converters of AD715X Series have only 12-bit resolution. A capacitance meter based on the PIC16C622 microcontroller has also narrow capacitance range from 1 to 999 nF [5]. It does not cover a pF capacitive range and has a low accuracy (±3.39% average relative error). In the RLC meter, based on virtual counting technique, a sufficient accuracy is achieved only if capacitances are not too large or too small [6].
High metrological performances for capacitance-to-digital conversion are reported in [7-9] but in the limited ranges of humidity sensors (from 10 to 330 pF, from 100 to 150 pF and from 149 to 206 pF respectively). Hence, a design of simple, universal, single chip capacitive sensor electronic interfacing circuit with high metrological performance and wide measuring range is an important and timely task.

2. Capacitance-to-Digital Converter

The universal sensors and transducers interfacing (USTI) integrated circuit (Fig.1) can work in a capacitance-to-digital conversion mode. It is based on a three-signal measurement technique, (initially published in [10]) at which the offset, reference and measurand values are converted into three time intervals by internal capacitance-to-time converter base on the internal comparator. The unknown capacitance should be calculated according to the following equation:

\[ C_x = \frac{N_x - N_{off}}{N_{ref} - N_{off}} \cdot C_{ref}, \]  

where \( N_x, N_{off} \) and \( N_{ref} \) are the numbers of reference frequency pulses counted during the measurand, offset cancellation and reference measurement stages respectively; \( C_{ref} \) is the precision reference capacitor.

The direct capacitive interface needs only a few external components as a reference capacitor \( C_{ref} \) and resistor \( R \) (Fig.2).

\[ R \geq \frac{0.002}{C_{ref}}. \]  

The charging time (in seconds) should be calculated as
The charging time can be set up with the help of USTI’s command “Wnn”. The value of $C_{ref}$ also should be set up with the help of appropriate USTI’s command Ei.f, where "i.f" is the fixed point decimal number: "I" is the integer part (1 to 12 decimal digits) and "f" is the fractional part (0 to 12 decimal digits). An example of USTI’s commands for capacitance-to-digital conversion for RS232 serial interface, slave mode is shown in Fig. 3.

In the master communication mode the charging time should be set up with the help of external switches N0, N1, N2. In this mode the result at the converter’s output will be presented as $C_x/C_{ref}$. In order to get the actual capacitance, such result must be multiplied by $C_{ref}$. Oscillogram on the SMPL pin for is shown in Fig. 4.

> M11 ; Capacitance measurement mode
> E0.00000000012543 ; Reference set up $C_{ref}$ = 125.43 pF
> W00 ; Set up the charging time (100 µs)
> S ; Start Measurement
> C ; Check the measurement status:
 r ; returns 'b' - in progress; 'r' - ready
> R ; Get the result

0.000000000155

Fig. 3. USTI commands for capacitance measurements (RS232 interface).

3. Experimental Results and Discussion

The universal capacitance-to-digital converter was applied to the measurement of capacitance in a wide range from 50 pF to 100 µF. Preliminarily, the USTI has been calibrated at laboratory temperature range in order to eliminate an additional systematic error due to a quartz oscillator trimming inaccuracy (calibration tolerance) and a short term temperature instability. The USTI has been connected to a PC, where terminal software Terminal v1.9b was running under Windows XP operation system. Each of capacitance $C_x$ was measured 100 times in order to compare obtained results with reported in literature, for example, in [8]. The actual capacitance has been measured by the high precision LCR meter GW Instek LCR-819 with the basic accuracy 0.05 % or better, which also has been preliminary calibrated. The measurement results for 152.22 pF and 1.9279 µF are shown in Fig. 5, 6 respectively. The maximum relative error does not exceed ± 0.7 % in the worst case. The experimental results have confirmed the average relative error ± 0.036 % (which is in 20-100 times less than the reported in [5, 6]) in the comparative measuring range (Table 1, gray color).

$T = 2200 \times C$  \hspace{1cm} (3)
In addition, the USTI can work with any known capacitance-to-frequency converters, for example [11-13], in a wide frequency range. In such cases converters’ outputs should be directly connected to any of two USTI’s channels for frequency-time measurements. The relative error for frequency-to-digital conversion ≤ ±0.0005 %. The USTI produces true digital output according to three popular sensor systems interfaces.

4. Conclusions

A simple, cost-effective universal capacitance-to-digital converter based on the Universal Sensors and Transducers Interface circuit has the average relative error ± 0.036 % in a wide capacitance range from 50 pF to 100 µF. In addition, the USTI can work with any known capacitance-to-frequency converters. In such cases their outputs should be directly connected to any of two USTI’s channels for frequency-time measurements. The relative error for the further frequency-to-digital conversion is constant in the whole frequency range and not exceeds ±0.0005 %.

Due to designed USTI integrated circuit the acceptance of capacitive technology will be continuously increasing in various applications during next years.

Acknowledgements

This research and development was funded by the European Commission in the frame of Marie Curie Excellence Chairs (EXC) project MEXT-CT-2005-023991 Smart Sensors Systems Design (SMARTSES).

References