Low Value Capacitance Measurement System with Adjustable Lead Capacitance Compensation

Gautam Sarkar, Anjan Rakshit, Amitava Chatterjee, Kesab Bhattacharya

***Abstract*—**The present paper describes the development of a low cost, highly accurate low capacitance measurement system that can be used over a range of 0 – 400 pF with a resolution of 1 pF. The range of capacitance may be easily altered by a simple resistance or capacitance variation of the measurement circuit. This capacitance measurement system uses quad two-input NAND Schmitt trigger circuit CD4093B with hysteresis for the measurement and this system is integrated with PIC 18F2550 microcontroller for data acquisition purpose. The microcontroller interacts with software developed in the PC end through USB architecture and an attractive graphical user interface (GUI) based system is developed in the PC end to provide the user with real time, online display of capacitance under measurement. The system uses a differential mode of capacitance measurement, with reference to a trimmer capacitance, that effectively compensates lead capacitances, a notorious error encountered in usual low capacitance measurements. The hysteresis provided in the Schmitt-trigger circuits enable reliable operation of the system by greatly minimizing the possibility of false triggering because of stray interferences, usually regarded as another source of significant error. The real life testing of the proposed system showed that our measurements could produce highly accurate capacitance measurements, when compared to cutting edge, high end digital capacitance meters.

***Keywords*—**Capacitance measurement, NAND Schmitt trigger, microcontroller, GUI, lead compensation, hysteresis.

I. Introduction

DEVELOPMENTS of capacitive transducer systems have been an important area of research for quite some time now. Many of these capacitive transducers are employed for measurement of physical quantities like motion, force, acceleration, torque, position and pressure [2]-[6], [10]. One of the specific categories of capacitive sensors that require sophisticated instrumentation based measurement systems is the measurement of low valued capacitances either in its individual capacity or in a differential form [7]-[9]. Very often these capacitance measurements are to be carried out in the low pF range and the sensitivity of the system developed is required to be very high. The low capacitance measurements specially suffer from the problems of stray capacitances [9]. These stray capacitances mainly arise between the capacitance electrodes and the earthed, shielding screen which is primarily used to protect the capacitor electrodes from the influence of external electric fields. Another important source of errors in low value capacitance measurement arises due to the presence of lead capacitances which become comparable with the original capacitance under measurement, when considered in pF order. The other primary important factors to be considered for low value capacitance measurement are problems due to drift and offset errors, ambient temperature errors, maintenance of satisfactory level of sensitivity, range of frequency of operation, cost of development etc.

The methods commonly employed for low capacitance measurement include methods involving AC bridges, charge/discharge methods, oscillation and resonance based methods [9], [12], relaxation based method [11] etc. One of the earliest forms of the AC Bridges was Schering bridges which later formed inspiration for development of various ratio-arm bridges. The later versions of the bridge circuits attempted to improve upon the basic problem associated with bridge circuits that they were not capable of providing sufficient stray-immunity. The charge/discharge method essentially employs the method of charging the unknown capacitance up to a certain voltage level using a switch S_1 e.g. a CMOS switch and then discharging that capacitor using another switch S_2. This differential circuit arrangement gained popularity because it can reduce drifts caused by common inputs and it is capable of providing good accuracy even for high frequency operation in the range of MHz. In oscillation methods RC or LC oscillators can be used to provide a frequency as a function of the unknown capacitance and a frequency to voltage converter can be used to measure the unknown capacitance [9]. Although these methods are quite simple and accurate for medium capacitance measurement, they are not that efficient for low capacitance measurement as they cannot eliminate the effect of stray capacitance in their measurement system. The resonance method can provide a good measurement alternative for capacitance as well as its parallel loss component but it is an elaborate method and not suitable for dynamic capacitance measurements, especially in online measurement scenario. Present-day electrical capacitance tomography (ECT) systems, like the system in [13], are very often based on charge/discharge method which employs integrators. These integrators are main sources of drift and offset errors which prove hazardous for such measurement systems.

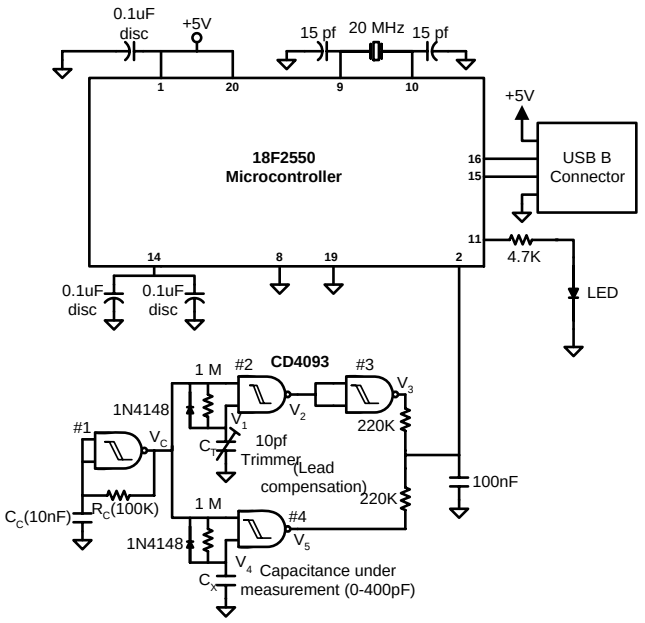
The present work proposes the development of a new, improved, low value capacitance measurement system that promises to minimize many hazardous effects, known so far, in these measurements. Our proposed scheme basically works on the principle of the charge/discharge method but it does not involve any integrator and hence the problems of drift and offset errors are largely taken care off. This novel scheme proposes a new concept of employing quad two-input NAND

Gautam Sarkar, Anjan Rakshit, Amitava Chatterjee, and Kesab Bhattacharya are with the Department of Electrical Engineering, Jadavpur University, Kolkata, India (e-mail: sgautam63@ yahoo.com).

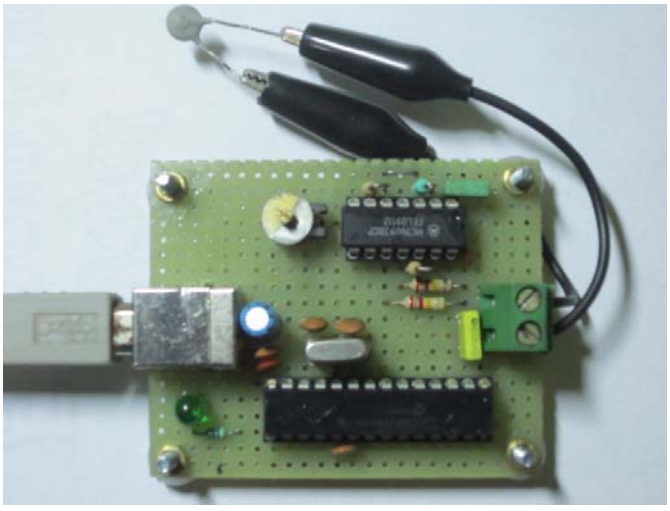
Schmitt trigger circuits CD4093B with hysteresis [14] and the system has been successfully built for measurement of capacitance over a long range of 0 – 400 pF. The present capacitance measurement system is inspired by our previous work reported in [1] where the capacitance measurement was carried out employing two monostable multivibrators in differential form. However the system developed in [1] essentially produced a nonlinear variation of output with input and required a separate neural network to perform sensor linearization. The present system developed in this work proposes a significant improvement where the input-output relation of the measurement system is essentially a linear one and does not require any additional incorporation of a linearization module. The measurement system employs a differential mode of unknown capacitance measurement and the method offers an automatic technique of lead capacitance compensation, already described as a significant source of stray capacitance error in such low capacitance measurement system. For any such measurement system, one has to measure the output, only a single time in the very beginning, with no unknown capacitance connected and set this as the trimmer capacitance initial value. For any subsequent capacitance measurement, in differential form, this initial value of trimmer capacitance set will automatically perform compensation of stray capacitance in form of lead capacitance. Any possibility of false triggering of the quad circuits is eliminated by employing hysteresis in the Schmitt trigger circuits which enhances reliability of the measurement system. The system has been configured as a highly sophisticated one where a PIC 18F2550 microcontroller [15] is used for the purpose of analog voltage data acquisition and this works in conjunction with a graphical user interface (GUI) based system developed in a PC that converts this voltage back to the unknown capacitance, performs all necessary corrections and processing on that information, and provides the user with real time, online display of capacitance under measurement. This system has been implemented for a series of real life measurements of capacitances over the range for which it has been developed and the results have been compared with the measurements carried out using a sophisticated, high end digital capacitance meter. It has been demonstrated that our proposed, low cost system produces measurements with high accuracies and it could improve the performance of the digital *C* meter by more than 55%. The measurement system developed has high flexibility and can be used for several other purposes with minimum modification in the circuit e.g. for direct voltage indication, for usage as a transducer system, for development of electrical capacitance tomography (ECT) system etc.

The rest of the manuscript is organized as follows. Section II describes the Schmitt trigger based low capacitance measurement system proposed and developed in this work. Section III details how the PIC microcontroller and the PC based modules work hand in hand with the analog-digital measurement system to provide online, real-life measurement acquisition and display. The experimental results are presented in Section IV. Conclusions are presented in Section V.

II. Schimitt-Trigger Based Low Capacitance Measurement System



(a)



(b)

Fig. 1 (a) The proposed capacitance measurement system in block diagram form and (b) photograph of the actual system developed

Fig. 1 (a) shows the low capacitance measurement system in its block diagram form comprising quad two-input NAND Schmitt trigger circuit CD4093B [14] and PIC 18F2550 microcontroller [15] and Fig. 1 (b) shows the photograph of the actual measurement system developed. The unknown capacitance under measurement is shown as C_X in the diagram and the circuit can be utilized for measurement of an unknown capacitance in the range 0-400 pF. This capacitance is measured in a differential form with reference to a trimmer capacitance C_T. The output voltage is measured ideally as a linear function of the differential capacitance $(C_X - C_T)$.

The Schmitt trigger, in its basic form, acts as a threshold circuit employing positive feedback [16]. The circuit uses two threshold voltages for the purpose of triggering and utilizes the effect of hysteresis. For a Schmitt trigger in non-inverting configuration, the output triggers to a high state when the input crosses a chosen threshold voltage and the output triggers to a low state when the input dips below another chosen threshold voltage. For any intermediate state of the Schmitt trigger, the output will retain its old state. In CD4093B each of the four Schmitt trigger circuits functions as a two-input NAND gate where they have Schmitt trigger action on both inputs. Let the threshold voltage for positive going signal be denoted as V_{T+} and the threshold voltage for the negative going signal be denoted as V_{T-}. Then the hysteresis voltage (V_H) is given as:

$$V_H = V_{T+} - V_{T-} \quad (1)$$

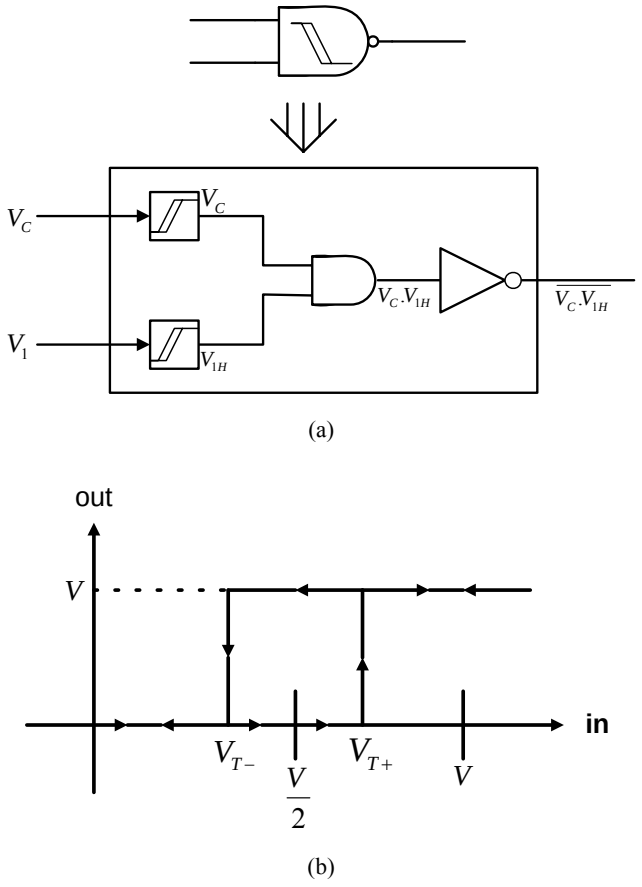


Fig. 2 (a) Detail circuit of a NAND gate based Schmitt-trigger circuit and (b) its input-output characteristic

NAND gate #1 operates in a stable mode to generate clock signal V_C. Let V be the output voltage of the NAND gate #1 (i.e. $V_C = V$) in ON condition and here it is chosen as $V = 5$V. This also corresponds to the maximum value of the instantaneous analog output voltage from the CD4093B system (denoted as V_0). In CD4093B, the hysteresis is implemented such that each overall NAND gate circuit behaves like a Schmitt-trigger circuit with inverting configuration where each individual input to a given NAND gate is subjected to hysteresis with non-inverting configuration. Fig. 2 (a) shows the detail circuit behavior for a representative NAND gate based Schmitt-trigger circuit (the circuit here is shown for NAND gate #2). The two inputs for this NAND gate circuit are V_C and V_1 and they are individually both subjected to hysteresis with non-inverting configuration. This produces two outputs with V_C remaining unchanged and V_1 producing V_{1H} as the output from the hysteresis unit. These two outputs are then fed as inputs to a conventional NAND gate circuit whose output is produced as $\overline{V_C \cdot V_{1H}}$, which is equivalent to the output of a Schmitt trigger circuit with hysteresis in inverting configuration. Fig. 2 (b) shows the input-output characteristic of such a Schmitt-trigger circuit, with hysteresis.

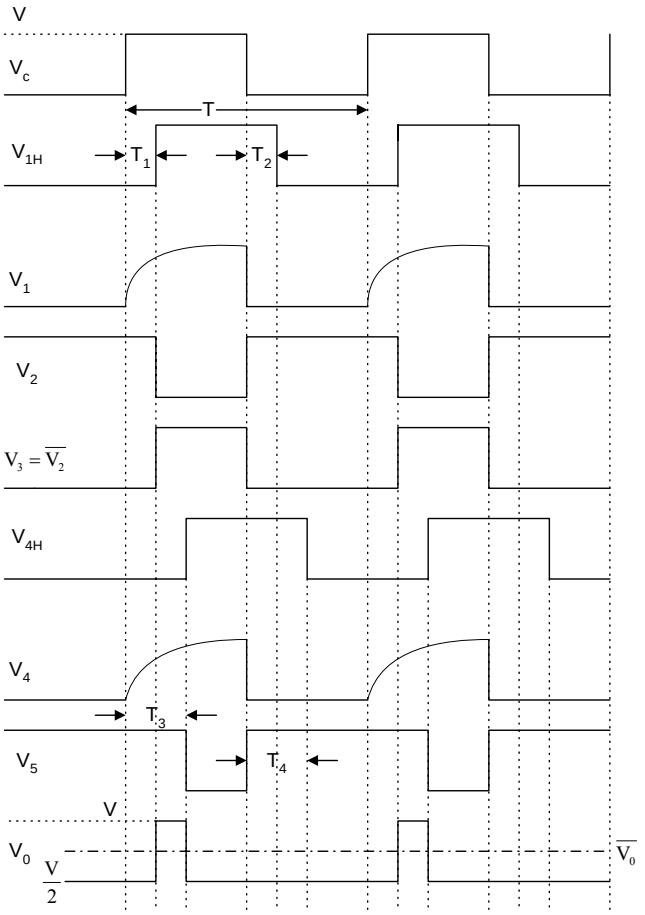


Fig. 3 Voltage waveforms at different points in our developed CD4093B based measurement system

Fig. 3 shows the voltage waveforms at different component Schmitt trigger outputs within CD4093B for our measurement system and also the output voltage generated. V_C shows the output voltage of the NAND gate #1 which toggles between its OFF state (i.e. 0 volts) and its ON state (i.e. V volts). The output from the hysteresis unit in NAND gate #2 corresponding to the input for V_1 i.e. V_{1H} shows a time lag of

T_1 on the rising edge of V_C and a time lag of T_2 on the falling edge of V_C. This T_1 is a function of the charging time for the trimmer capacitance C_T and T_2 is a function of the discharging time for the trimmer capacitance C_T. The circuit will act in such a fashion that C_T will start charging when V_C rises from zero to V, charges to its full capacity and stays there as long as V_C stays at V, and then, as soon as V_C falls from V to zero, C_T starts discharging. The circuit is so designed by us that it connects a diode at the input side corresponding to V_1 input such that the above mentioned discharge takes place very fast and T_2 is considered negligible compared to T_1. This incorporation of diode adds a novelty in our circuit which eliminates a significant source of error due to nonlinearity. It is a common practice that, for such capacitance measurements, no diode is incorporated in the input side and, hence, every time there is a finite time taken for the capacitor discharge. The discharged voltage never reaches zero in a finite time because of which, in the next charging cycle, the voltage starts growing from an offset value which gives rise to error in measurement. The incorporation of the diode helps in sharp discharge of the capacitance which ensures that, every time the charge cycle begins, the voltage starts to grow from an initial value of zero. The T_1 and T_2 are given as [2]:

$$T_1 = RC_T \ln\left(\frac{V}{V_{T+}}\right) = K_1 C_T \tag{2}$$

Fig. 3 shows how the voltage across C_T i.e. V_1 rises and falls with the variation in V_C. The NAND gate #2 has V_C and V_1 as its two input and this Schmitt-trigger circuit produces its output voltage V_2. This voltage V_2 falls from 'high' state to 'low' state when V_C is high and C_T charges such that V_1 exceeds V_{T+}. V_2 is maintained at this 'low' state until V_C falls to zero. This causes C_T to start discharging and V_2 instantaneously rises from 'low' state to 'high' state. V_2 is maintained at this 'high' state until the next time V_C is high and C_T charges to a voltage greater than V_{T+}. Then again V_2 falls from 'high' state to 'low' state and this process of toggling continues.

The NAND gate #3 in Schmitt-trigger configuration has both inputs supplied by V_2. Hence its output V_3 will be, basically, a complementary form of V_2 i.e. $V_3 = \overline{V_2}$. The NAND gate #4 in Schmitt-trigger configuration will operate in a similar manner as the NAND gate #2. The two inputs arrive from voltage V_C and the voltage appearing across the capacitance C_X under measurement, denoted as V_4. The output from the hysteresis unit in NAND gate #4 corresponding to the input for V_4 i.e. V_{4H} shows a time lag of T_3 on the rising edge of V_C and a time lag of T_4 on the falling edge of V_C. The output voltage from the NAND gate i.e. V_5 shows a time lag of T_3 on the rising edge of V_C and instantaneously rises from 'low' state to 'high' state when V_C falls. The time T_3 here is a function of the charging time for the unknown capacitance C_X and the time T_4 is a function of the discharging time for C_X. Here also, the circuit is so designed by us that it connects a diode at the input side corresponding to V_4 input such that the corresponding discharge takes place very fast and T_4 is considered negligible compared to T_3. The unknown capacitance C_X will start charging when V_C rises from zero to V, charges to its full capacity and stays there as long as V_C stays at V, and then, as soon as V_C falls from V to zero, C_X starts discharging. Then T_3 is accordingly calculated as:

$$T_3 = RC_X \ln\left(\frac{V}{V_{T+}}\right) = K_1 C_X \tag{3}$$

The two output voltages V_3 and V_5, from the Schmitt-trigger configurations 3 and 4 respectively, feed the two extreme ends of two equal resistances $R_1 = R_2 = 220$ kΩ, connected in series potential divider configuration and the output voltage (V_0) of this analog-digital capacitance measurement system is tapped from the junction point of the two resistances R_1 and R_2. The variation of V_0 with time is also depicted in Fig. 3. There are situations when either $\{V_3 = V; V_5 = 0\}$ or $\{V_3 = 0; V_5 = V\}$. In those situations, $V_O = \frac{V}{2}$. During other times, $\{V_3 = V; V_4 = V\}$. Then, in those situations, $V_O = V$. Hence for large durations, V_0 will remain as $\frac{V}{2}$ and, for small durations, V_0 will be V. Hence the average value of V_0 i.e. $\overline{V_O}$ will vary between $\frac{V}{2}$ and V. Higher the duration V_0 stays at V, higher will be the average value $\overline{V_O}$. The duration of how long V_0 will stay at V will depend on the relative values of T_3 and T_1. Higher the difference ($T_3 - T_1$), longer will V_0 stay at V, and, hence, higher will be $\overline{V_O}$ and vice versa. Ideally, the difference ($T_3 - T_1$) varies linearly with the difference ($C_X - C_T$). The output average voltage $\overline{V_O}$ is given as:

$$\overline{V_O} = \frac{V}{2} + \frac{V}{T}(T_3 - T_1) = \frac{V}{2} + \frac{V}{T}(K_1 C_X - K_1 C_T) = \frac{V}{2} + \frac{V}{T} K_1 (C_X - C_T) \tag{4}$$

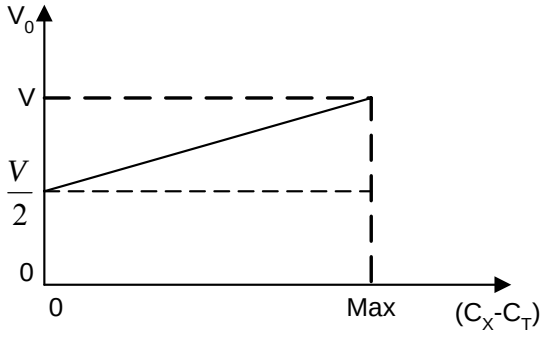


Fig. 4 Variation of output voltage V_0 with differential capacitance ($C_X - C_T$)

Fig. 4 shows how V_0 varies with ($C_X - C_T$). This linear curve essentially shows that the output voltage is a linear version of the input capacitance under measurement. The offset of $\frac{V}{2}$ is a fixed value of 2.5 volts and it can be easily subtracted in

software. In order to achieve an output average voltage directly as a function of the unknown capacitance, without an offset of $\frac{V}{2}$, one could have connected the outputs V_3 and V_4 to the two inputs of another logic gate and the output V_0 could have been tapped from the output of this logic gate. However we did not opt for this option to reduce the chip count and also to avoid any mismatch in thermal characteristic. The mode of employing the required correction using software is, hence, justified as a more convenient solution. Hence the proposed arrangement produces a very convenient means of capacitance measurement, and, ideally, in this situation, a direct linear calibration is achievable and no additional linearization procedure is required.

The proposed measurement system also gives the flexibility of achieving flexible, wide range control characteristic. This range control is achieved as a desirable feature with variation in the frequency of operation. The range of operation is proportional to the time period of V_C (T). The system operates in such a fashion that with increasing frequency, the range of capacitance measurement decreases and, conversely, with decreasing frequency, the range of capacitance measurement increases. This change in operating frequency can be easily achieved by varying either the 100 KΩ resistance (R_C) or the 10 nF capacitance (C_C) or by choosing a suitable combination of them for the NAND gate #1 based Schmitt trigger circuits.

One possible source of significant errors in capacitance measurement is the presence of lead capacitances. Especially for low capacitance measurements, of pico Farad order, the lead capacitances become significantly large in comparison with the unknown capacitance under measurement. Our proposed arrangement offers an automatic lead capacitance compensation arrangement by incorporating a differential measurement scheme. The unknown capacitance is measured with respect to the trimmer capacitance. Assuming that both the unknown and the trimmer capacitances get affected by similar nature of lead capacitances, a measurement of C_X in $(C_X - C_T)$ form automatically ensures that the effects of lead capacitances will be greatly minimized, if not completely eliminated. The trimmer capacitance is employed in manually adjustable form such that it can be flexibly varied to compensate for lead inaccuracies. In the beginning of each unknown capacitance measurement, without any unknown capacitance being connected and with trimmer capacitance being set as zero, a measurement of unknown capacitance is carried out. If this measurement produces a non-zero capacitance value, then this value will arise because of lead capacitance errors. Then this lead capacitance is manually set as the trigger capacitance and the actual measurement of the unknown capacitance is carried out. Ideal employment of this methodology should nullify (practically greatly minimize) the effect of lead capacitances on the final reading.

Another possible source of error in practical situation is the fact that the voltages V_c, V_2, V_3, V_5 and, hence, V will not undergo instantaneous rise or fall in their states or voltage levels. This is because of the presence of finite rise time and fall time of logic gates which, in practical scenario, can never be made equal to zero. The incorporation of diodes at the inputs of NAND gates #2 and #4 to provide fast discharge paths for C_T and C_X respectively remedies the situation greatly. Further improvement in the linearity characteristic can be achieved by employing sophisticated software based linearization/compensation procedures.

Another possible argument for the choice of quad Schmitt-trigger circuit in place of four simple NAND gates is that the incorporation of the hysteresis in the individual circuits plays an important role from the point of view of reliability of operation. In any such measurement system, presence of each bare lead can act as an aerial and pick up stray electromagnetic interferences. If ordinary logic gates were employed, these interferences might have caused frequent, unwanted triggering of the gates. Hence the incorporation of hysteresis, specifically in form of Schmitt-trigger configurations, greatly minimizes the possibilities of false triggering and hence it ensures improved reliability for the measurement system.

III. PIC Microcontroller And PC Based Online Measurement

The capacitance measurement system is so designed that it can be used for graphical user interface (GUI) based online measurement purpose where, for a physical capacitance under measurement, the unknown capacitance is available as a direct read out in a PC. With this objective in mind, the PIC 18F2550 microcontroller shown in Fig. 1 (a) is employed for data acquisition purpose. The microcontroller reads the average output voltage $\overline{V_O}$ through its input pin 2 and sends it in digital form through the output port using the USB architecture. PIC 18F2550 is an enhanced flash, high performance, nano Watt technology microcontroller [3], which is equipped with USB interface. A software is additionally developed in PC, using Visual Basic platform, that directly acquires this voltage value from the microcontroller output, converts it from digital to its corresponding analog form and calculates the unknown capacitance C_X. The instantaneous value of this unknown capacitance is calculated by employing (4) where the offset is eliminated and the linear relation is utilized to determine C_X from the available knowledge of V, T, C_T and K_1. The instantaneous value of C_X is then converted to a steady state form by employing exponential averaging technique where high frequency oscillations in the values of C_X are eliminated. This values of C_X is then displayed online for the real life capacitance under measurement. Fig. 5 shows the GUI form developed in the PC side where the user has the flexibility to start and stop the communication between the hardware and the software, both indigenously developed in our laboratory, for capacitance measurement, as per his/her requirement.

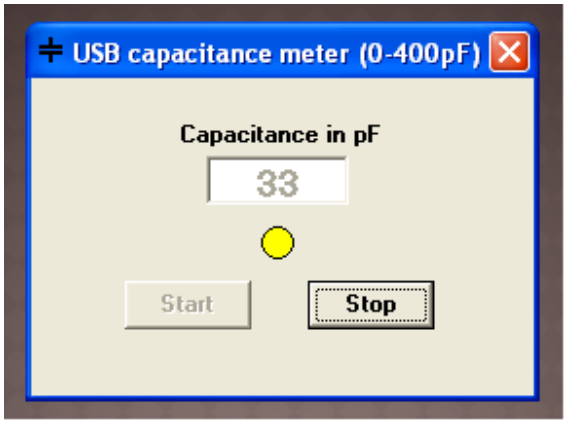


Fig. 5 The GUI form developed in the PC side for online measurement and display of the unknown capacitance

Algo. 1. Main routine in PIC microcontroller

BEGIN

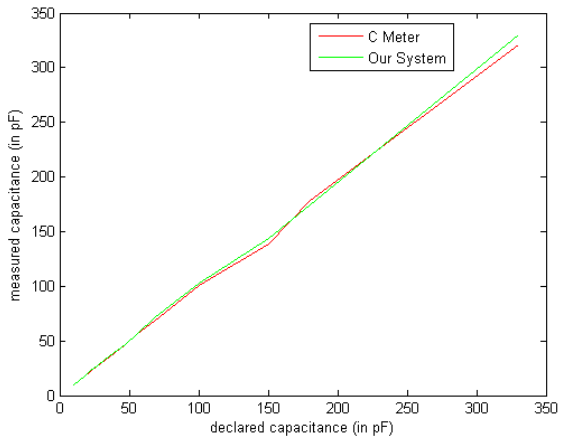
1. Create *adval* to store result.
2. Configure ADCIN parameters e.g. number of bits in the result, sampling time in μs, etc.
3. Set PORTA for all input by configuring TRISA register accordingly.
4. Set ADCON1 and ADCON2 registers to set the RC clock and right justify the result.
5. Initialize PORTC and set TRISC register accordingly.
6. Initialize USB interface.
7. **WHILE** (USB_IN_*Buffer* is Empty)
   Service USB port regularly
   Specify USB_IN_*Buffer* Size
   Read USB_IN_*Buffer* from the USB Port
   ENDWHILE
8. **IF** (USB_IN_*Buffer*[0] = = 0)
   Read Channel information from USB_IN_*Buffer*[0] to *adval*
   Extract the *adval* information to put the high byte in USB_IN_*Buffer*[1] register and low byte in USB_IN_*Buffer*[0] register
   ELSE
   Initialize USB_IN_*Buffer*[0] = 0
   Initialize USB_IN_*Buffer*[1] = 0
   Initialize PIN 0 of PORTC
   ENDIF
9. Prepare voltage data in digital form.
10. Output the voltage data through the USB port.
11. **GO TO** 7 and wait for next channel request.

END

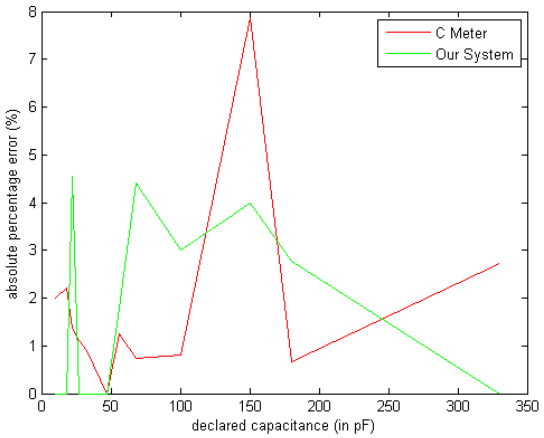
Algorithm 1 shows how the microcontroller is employed for data acquisition and data processing purpose. This microcontroller based data acquisition system is developed as a single channel device with 10 bit ADC resolution. Here the request for data is sent from the PC end to the microcontroller end as a two byte data and the response value is also sent from the microcontroller to the PC end as a two byte data. The microcontroller waits for any channel information input that may arrive at its USB port input. Once this channel request arrives, accordingly it prepares the corresponding output port to output the voltage data through the USB port to the PC. After completion of this data output the microcontroller again waits for any new channel information input and this process continues.

IV. Experimental Results

Once the entire set up is ready with its hardware components and software in both the microcontroller end as well as the PC end, the system is put to real-life testing. Several capacitance values were tested over the range of 0 – 400 pF at an operating frequency of 960 Hz. To compare the performance in terms of accuracy of the developed system, the true, declared value of each capacitance under measurement was checked using a sophisticated, high end Digital Capacitance Meter (Make: METRAVI; Model No.: DCM–1502) and it was also measured using our developed measurement system. Fig. 6 (a) shows the variations of the capacitances under measurement in terms of (a) values measured using capacitance meter and (b) values measured using our system, plotted against declared values of the respective capacitances. To make a closer comparison, Fig. 6 (b) shows corresponding plots of absolute percentage error values compared using the declared value as the reference for each measurement undertaken. It can be seen that the maximum absolute percentage error is approximately 4.5% using our system, which is significantly less than the maximum absolute percentage error obtained using the C meter, which is approximately 7.9% over the entire range of measurements carried out. This yields an improvement in accuracy of more than 43% over the results achievable using a sophisticated C meter and this indicates that our proposed system is capable of providing highly accurate measurement of low capacitance values and it can be very effective in providing automatic lead compensation satisfactorily.



(a)



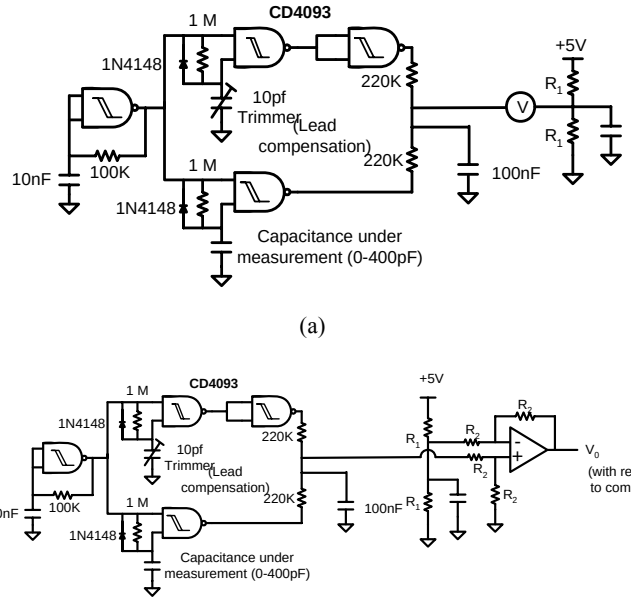
(b)

Fig. 6 (a) Results obtained using digital C meter and our proposed system, vis-à-vis declared values (b) Absolute percentage errors obtained using digital C meter and our proposed system, from respective declared capacitances

V. Conclusion

A highly accurate and low cost setup for measurement of low capacitance in the Pico Farad range has been presented in this work. The arrangement utilizes a combination of sophisticated hardware and software systems where quad two-input NAND Schmitt trigger circuit CD4093B with hysteresis is employed for capacitance measurement that essentially employs a charge/discharge method of capacitance measurement. The hysteresis enables the system to avoid any false triggering because of stray interference and the differential mode of capacitance measurement facilitates to make measurement with automatic lead compensation. A PIC 18F2550 microcontroller is employed for data acquisition and a GUI based software in the PC end interacts with the hardware system and the microcontroller through USB interface to display real-time capacitance measurement values. This system has been developed for a capacitance range of 0 – 400 pF. The experimental results demonstrated that the proposed system could provide highly accurate measurements comparable with those of a high end, sophisticated digital capacitance meter.

As mentioned earlier, the development system can be used for other measurement schemes, employing minimum modification for a variety of applications e.g. for direct voltage indication, for use as a transducer, for ECT systems etc. The circuits in Fig. 7 show such sample systems that can be developed for (a) direct voltage indication and (b) for development of a transducer system. Here these systems can be developed deleting microcontrollers and USB interface and adding very simple additional circuitry as shown in Fig. 7 (a) and (b).



(a)

(b)

Fig. 7 Possible application of the development system as (a) a voltage indicator and (b) a transducer system

References

[1] A. Chatterjee, S. Munshi, M. Dutta, and A. Rakshit, "An artificial neural linearizer for capacitive humidity sensor," Proc. 17th IEEE Instrumentation and Measurement Technology Conference (IMTC 2000), Baltimore, USA, May, 2000.

[2] M. Yamada, T. Takebayashi, S. Notoyama, and K. Watanabe, "A switched-capacitor interface for capacitive pressure transducer," IEEE Tran. Instrumentation and Measurement, vol. 41, no. 1, pp. 81-86, February 1992.

[3] F. N. Toth and G. C. M. Meijer, "A low-cost, smart capacitive position sensor," IEEE Tran. Instrumentation and Measurement, vol. 41, no. 6, pp. 1041-1044, December 1992.

[4] Y. C. Chung, N. N. Amarnath, and C. M. Furse, "Capacitance and inductance sensor circuits for detecting the lengths of open- and short-circuited wires," IEEE Tran. Instrumentation and Measurement, vol. 58, no. 8, pp. 2495-2502, August 2009.

[5] J. C. Lotters, W. Olthuis, and P. Bergveld, "A sensitive differential capacitance to voltage converter for sensor applications," IEEE Tran. Instrumentation and Measurement, vol. 48, no. 1, pp. 89-96, February 1999.

[6] A. L. Hugill, "Displacement transducers based on reactive sensors in transformer ratio bridge circuits," Journal of Physics E: Sci. Instrm. vol. 15, pp. 597-606, 1982.

[7] D. Mariolo, E. Sardani, and A. Taroni, "Measurement of small capacitance variation," IEEE Tran. Instrumentation and Measurement, vol. 40, no. 2, pp. 426-428, April 1991.

[8] D. M. G. Preethichandra and K. Shida, "A simple interface circuit to measure very small capacitance changes in capacitance sensors," IEEE Tran. Instrumentation and Measurement, vol. 50, no. 6, pp. 1583-1586, December 2001.

[9] S. M. Huang, A. L. Stott, R. G. Green and M. S. Beck, "Electronic transducers for industrial measurement of low value capacitances," Journal of Physics E: Sci. & Instrum., vol. 21, pp. 242-250, 1988.

[10] Y. Masuda, M. Nishikawa, and B. Lchijo, "New methods of measuring capacitance and resistance of very high loss materials at high frequencies," IEEE Tran. Instrumentation and Measurement, vol. IM-29, pp. 28-36, 1980.

[11] K. Kobayashi, S. Okamoto, and M. Sukigara, "A capacitance relaxation method for studying surface states at the semiconductor-liquid junction," J. Electroanal. Chem., vol. 225, pp. 79-92, 1987.

[12] A. C. Corney, "A universal four-pair impedance bridge," IEEE Tran. Instrumentation and Measurement, vol. IM-28, pp. 211-215, 1979.

[13] J. K-Rasmussen and W. Q. Wang, "A compact electrical capacitance tomography system," Proc. IEEE International Workshop on Imaging Systems and Techniques (IST 2008), Chania, Greece, September 10–12, 2008.
[14] CD4093BM CD4093BC Quad 2-Input NAND Schmitt Trigger. Texas Instruments, Literature Number: SNOS369A.
[15] Online. *ww1.microchip.com/downloads/en/devicedoc/39632c.pdf.*
[16] Online. *http://en.wikipedia.org/wiki/Schmitt_trigger.*

Gautam Sarkar received the B.Tech. and M. Tech. degrees in electrical engineering from Calcutta University, Kolkata, India, in 1999 and 2001, respectively. He is currently an Assistant Professor in the Department of Electrical Engineering, Jadavpur University. His current research interests include electrical capacitance tomography, digital signal processing, internet-based instrumentation and design of real-time systems. He has authored or coauthored almost 15 technical papers, including 3 international journal papers.

Anjan Rakshit received the M.E. and Ph.D. degrees in electrical engineering from Jadavpur University, Kolkata, India, in 1978 and 1987, respectively. He is currently a Professor in the Department of Electrical Engineering, Jadavpur University. His current research interests include digital signal processing, internet-based instrumentation, smart instrumentation, intelligent control, and design of real-time systems. He has authored or coauthored almost 70 technical papers.

Amitava Chatterjee received the B.E., M.E., and Ph.D. degrees in electrical engineering from Jadavpur University, Kolkata, India, in 1991, 1994, and 2002, respectively. In 1997, he joined the Department of Electrical Engineering, Jadavpur University, where he is currently an Associate Professor. In 2003, he received the Japanese Government (Monbukagakusho) Scholarship and visited Saga University, Saga, Japan. From November 2004 to November 2005, he was with the University of Electro-Communications, Tokyo, Japan, on a Japan Society for the Promotion of Science (JSPS) Post-Doctoral Fellowship for Foreign Researchers. In March-May, 2004, and in May-June, 2009, he visited University of Paris XII, Val de Marne, France, as an invited Teacher. His current research interests include intelligent instrumentation and control, image processing, robotics, signal processing, and stochastic optimization techniques. He has authored or coauthored more than 90 technical papers, including 65 international journal papers.

Kesab Bhattacharya received the B.E., M.E., and Ph.D. degrees in electrical engineering from Jadavpur University, Kolkata, India, in 1982, 1984, and 2000, respectively. He is currently a Professor in the Department of Electrical Engineering, Jadavpur University. His current research interests include Electric Field Computation and Optimisation of High Voltage Systems. He has authored or coauthored almost 25 technical papers, including 8 international journal papers.