

A Picofarad Capacitance Meter Based on Phase-Sensitive Demodulation for Tomography Application

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Intisari – Electrical capacitance volume tomography (ECVT) adalah suatu teknik pencitraan berdasarkan nilai kapasitansi dari suatu objek. Untuk memberikan citra dari objek kaji yang representative, sistem ECVT membutuhkan metode yang mampu mengukur nilai kapasitansi dalam orde pikofarad (pF). Level resolusi tersebut menimbulkan kesulitan bagi alat pengukur kapasitansi umum yang komersial, sehingga menjadi kebutuhan untuk adanya metode special dengan rangkaian pengkondisi sinyal yang khusus. Alat pengukur kapasitansi berbasis phase sensitive demodulation (PSD) dibuat untuk mengatasi isu tersebut, dan alat ini kemudian dibandingkan dengan karakteristik alat pengukur kapasitansi berbasis pengaturan Arduino komersial. Alat pengukur kapasitansi berbasis PSD yang dirancang memiliki nilai akurasi sebesar 97,894%, ketepatan sebesar 0,704 pF, sensitivitas sebesar 0,1197 V/pF, linieritas dengan koefisien determinasi sebesar 0,9983 dan stabilitas sebesar 0,028 pF/menit. Sebagai perbandingan, alat pengukur kapasitansi berbasis Arduino memiliki nilai ketelitian sebesar 97,943%, ketepatan sebesar 0,027 pF, linieritas dengan koefisien determinasi sebesar 0,9999 dan stabilitas sebesar 0,04 pF/menit. Pengujian dilakukan menggunakan sensor ECVT 8 elektrode dengan menggunakan bahan dielektrik udara dan air. Pasangan elektroda terdekat pada kondisi media dielektrik udara memiliki nilai kapasitansi 2,62218 pF untuk alat ukur berbasis PSD dan 3,4027 pF untuk alat ukur berbasis Arduino, sedangkan pada kondisi media dielektrik air ia memiliki nilai kapasitansi 9,8229 pF untuk alat ukur berbasis PSD dan 9,1069 pF untuk alat ukur berbasis Arduino. Pasangan elektroda terjauh pada kondisi media dielektrik udara memiliki nilai kapasitansi 0 pF untuk alat ukur berbasis PSD dan 0,0798 pF untuk alat ukur berbasis Arduino, sedangkan pada kondisi media dielektrik air ia memiliki nilai kapasitansi 4,652 pF untuk alat ukur berbasis PSD dan 0,1224 pF untuk alat ukur berbasis Arduino.

Kata kunci : Kapasitansi meter, resolusi pikofarad, PSD, Arduino, ECVT

Abstract – Electrical capacitance volume tomography (ECVT) is an imaging technique based on the object's capacitance value. To provide a representative image of the object under study, the ECVT system requires a method that can measure the capacitance value in the order of picofarads (pF). This level of resolution poses a difficulty for typical commercial capacitance measuring devices, hence raising the need for a specialized method with dedicated signal conditioning circuitry. The capacitance meter based on phase-sensitive demodulation (PSD) is made to solve the aforementioned issue and it is then compared with the characteristics of a capacitance meter-based commercial Arduino setup. The designed PSD-based capacitance measuring device has 97.894% accuracy, precision of 0.704 pF, sensitivity of 0.1197 V/pF, linearity with a coefficient of determination 0.9983, and stability of 0.028 pF/min. In comparison, the capacitance meter based on Arduino has 97.943% accuracy, precision of 0.027 pF, linearity with a coefficient of determination 0.9999, and stability of 0.04 pF/min. Testing is done on an 8-electrode ECVT sensor using dielectric materials of air and water. The nearest electrode pair on the condition of air as the dielectric medium has a capacitance value of 2.62218 pF for PSD-based measuring devices and 3.4027 pF for Arduino-based measuring devices, while the pair of electrodes on the condition of water as a dielectric medium has a capacitance value 9.8229 pF for measuring device based on PSD and 9.1069 pF for Arduino-based measuring devices. The opposite and farthest electrode pair on the condition of air as a dielectric medium has a capacitance value of 0 pF for PSD-based measuring devices and 0.0798pF for Arduino-based measuring devices, while the pair of electrodes on the condition of water as a dielectric medium has a capacitance value of 4.652 pF for PSD-based measuring devices and 0.1224 pF for Arduino-based measuring devices.

Keywords: Capacitance meter, picofarad resolution, PSD, Arduino, ECVT

I. INTRODUCTION

Medical, industrial processes, geology, security systems, and other fields need ways to see inside objects non-invasively (without damaging) or non-intrusively (without inserting a tool). Electrical capacitance volume tomography (ECVT) is an imaging technique based on the capacitance value of an object that utilizes the principle of parallel plate capacitive sensing [1]. Only the dielectric constant between the plates is affected when the plate spacing and area are kept constant. The difference in the value of this dielectric constant, which will be the basis of the object between the plates, can be reconstructed through an image processing technique. ECVT consists of three main parts: the

capacitance sensor, the data acquisition system, and the computer for control and image processing [2].

Capacitance measurement is an important means of acquiring a fundamental quantity of interest with diverse applications. This includes liquid level sensing [3], flow measurement [4], and sensor interface platforms [5]. In previous studies, there were four circuit methods used to obtain capacitance values from electrical capacitance tomography (ECT) sensors, namely charge–discharge circuit [6], ac-based circuit [7], active differentiator-based capacitance transducer circuit [8] and phase–sensitive demodulation circuit (PSD) [9]. The charge–discharge method uses the time required for charging and discharging a capacitance to determine its value. However, the charge

injection into the input circuit will degrade the measurement's performance. An ac-based circuit excites capacitive plates using a sinusoidal signal and infers the capacitance value from the signal's response, but this demands a complex implementation to sample a full-wave high-frequency signal. On the other hand, an active differentiator employs a filter configuration, thus introducing another time delay which makes the measurement relatively slower.

Phase-sensitive demodulation circuit (PSD), also known as lock-in amplification, has been employed to enhance the accuracy and sensitivity of capacitance measurements. It is a method that extracts amplitude and phase information from a modulated signal. Its operation entails the application of an ac voltage signal to a capacitive sensor, leading to capacitance modulation. By precisely synchronizing measurements with the modulation frequency, this technique can separate the capacitance-related signal from background noise, ensuring high sensitivity and accurate measurement [10].

This research was conducted to determine the characteristics of a PSD circuit-based capacitance meter compared to that of an Arduino-based capacitance meter and to measure the capacitance value of the 8-electrode ECVT sensor in the order of picofarads.

II. METHODOLOGY

This study has stages described in a flowchart, as shown in Figure 1. Capacitance measuring instruments are designed in two scenarios: PSD-based and Arduino-based systems. These systems are tailored to accept measurement ranges between 0 pF to 40 pF. In the PSD-based system, firstly the sinusoidal signal synthesis is tested to cover an operating frequency of 500 kHz with an amplitude of 16 Vpp. Then current-to-voltage converter is tested to ensure the input-output current-voltage relationship. Afterward, the amplification is tested for its gain and phase performance. Analog multiplier functions are evaluated to determine whether the output is a true multiplication between the input signal and reference signal. Subsequently, a low-pass filter is tested to reject the ac component while preserving the DC component.

On the other hand, the implementation of an Arduino-based system lies mainly in the software to count the time constant required to charge the capacitor. This transient time is related to the capacitance value. Both systems will be tested by using capacitors of various values (1 pF– 40 pF) as the device under test. In addition, the measurement is repeated regularly within one hour of the timespan. From tests, the instrument's characteristics such as accuracy, precision, sensitivity, and stability are derived. Lastly, both PSD and Arduino-based systems are then tested to measure the capacitance value of the 8-electrode ECVT sensor containing a dielectric medium.

In measuring capacitors using Arduino, the pins of the capacitor being measured are connected to pins A0 and A2 of Arduino [11]. This circuit of this method is shown in Figure 2 where CT is the capacitor being tested. First, the

circuit is connected with a voltage at A2 = 0 volts. When A2 is given 5 volts, current will flow through both capacitors. The voltage at A0 will be obtained by 1% of the final value for 30 ns. The value obtained at A0 is proportional to the ratio of CT divided by the total capacitance of C1 + CT.

As for the PSD instrument, the design is shown in Fig 3. It consists of a direct digital synthesis (DDS) [12], a high-pass filter (HPF) + amplifier, a current-to-voltage (CV) converter [13], inverting amplifier, an analog multiplier, and a low-pass filter (LPF). In this PSD method, DDS generates the source signal as a voltage. This voltage has dc offset value which must be rejected using HPF such as a capacitor. In the preceding stage, the signal should be amplified to a sufficient level for exciting the capacitive electrodes. The signal from the electrode will be in the form of current, thus CV converter and another amplifier are required for further processing in the voltage-based analog multiplier. The LPF rejects the high-frequency components, leaving only the DC component that suits the internal ADC capability of the microcontroller.

The capacitance measurement value (C_x) can be obtained by using a computation that has been explained thoroughly in [9] utilizing (1). Where V_0 is dc output from low pass filter (V), C_f is feedback capacitor (F), A is input signal amplitude, A_v is the gain factor of the amplifier, and α is the phase shift (degree).

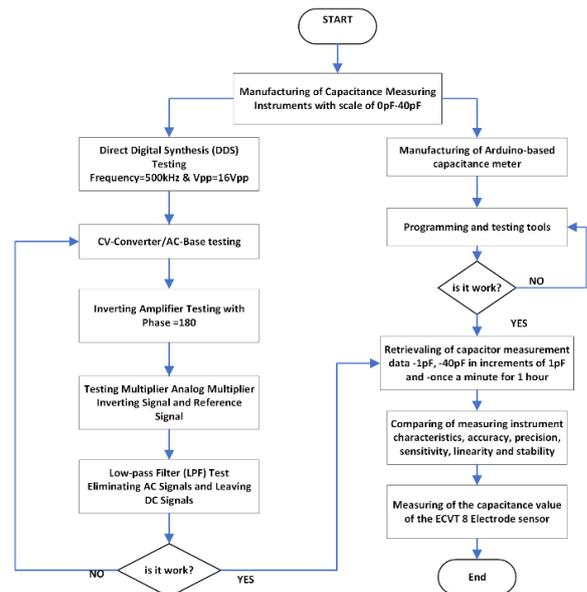


Figure 1. Flowchart of the study

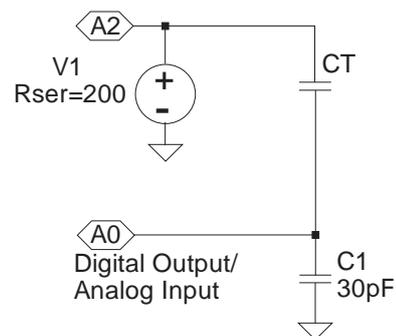


Figure 2. Capacitance measurement circuit with Arduino

$$C_x = \frac{20V_0 C_f}{A^2 A_p \cos \alpha} \tag{1}$$

The instrument's accuracy is the measuring system's ability to indicate the approach to the actual value of the object being measured. Another definition of accuracy is the closest value to reading pertinent with quantity being measured against the actual price so that the level of measurement error becomes smaller. Drift is related to the variability of instruments used at the time of measurement. To determine accuracy, the data obtained is processed using (2). Where A is accuracy, C_x is measured capacitor (F), and C'_x is measurement value (F).

$$A = 1 - \left| \frac{C_x - C'_x}{C_x} \right| \tag{2}$$

$$\%A = \bar{A} \times 100\%$$

The precision of the measuring instrument is the closeness of the individual measurement values that are distributed around the average value or the spread of the individual measurement values from the average value. A measuring instrument that has good precision does not guarantee that the measuring instrument has good accuracy. Another definition of precision is the level of similarity of values in a group of measurements or several values where measurements are made repeatedly with the same instrument.

The precision value is obtained by calculating the difference between the average capacitance value of the measurement results. Calculation of precision uses (3). where C is the average measured capacitor (F) and C_x is the measured capacitor (F).

$$P = \sum_{x=1}^n \left| \frac{C - C_x}{n} \right| \tag{3}$$

Sensitivity is the ratio between the output signal or instrument response to changes in the measured input variable. On the other hand, it usually requires the output value of the instrument reading to be directly proportional to the value of the measured object. The sensitivity value is obtained from the average value of the change in the signal V_0 (V) to changes in C_x (F). Calculation of the sensitivity value uses (4).

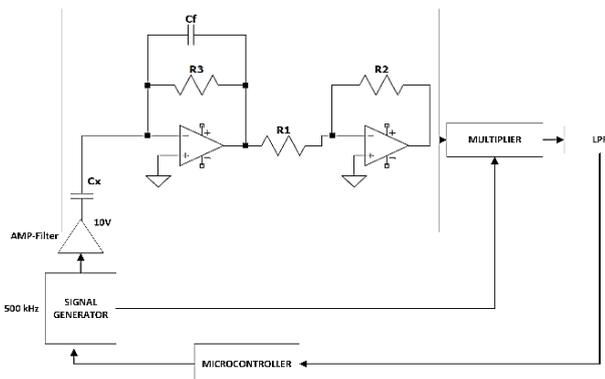


Figure 3. PSD-based capacitance meter design block diagram

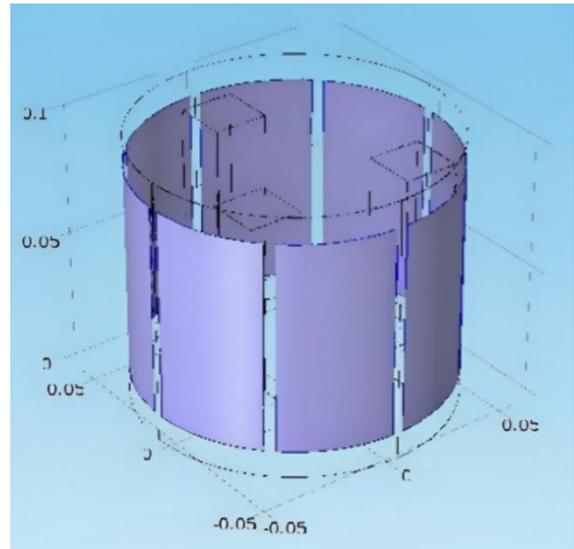


Figure 4. Design of 8-Electrode ECVT Sensor

$$S = \sum_{x=1}^n \left| \frac{V_x - V_{x-1}}{C_x} \right| \tag{4}$$

The stability of the measuring instrument is characterized by the variability of the measurement results or reading results, which are free from the influence of random variations. The stability is shown by the measurement results that do not change during the measurement. The data is processed to find the drift value using (5), where drift (D , in F/minute) represents the stability value.

$$D = \frac{\Delta C_x}{t} = \sum_{t=1}^T \left| \frac{C_x - C_{x-1}}{t} \right| \tag{5}$$

Figure 4 illustrates the ECVT 8-electrode sensor comprises eight copper plates measuring 4 cm long and 8 cm wide, circumventing a tube with a diameter of 11.385 cm [14].

III. RESULT AND DISCUSSION

The PSD-based capacitance measuring instrument has five parts. The first is a DDS, the second is a CV converter, the third is an inverting amplifier, the fourth is an analog multiplier, and the fifth is an LPF. The finished design is shown in Fig. 5. The AD9850 DDS module was programmed using Arduino Uno R3 to produce an output signal with a frequency of 500 kHz. Figure 6 shows the AD9850 output signal obtained using a digital oscilloscope.

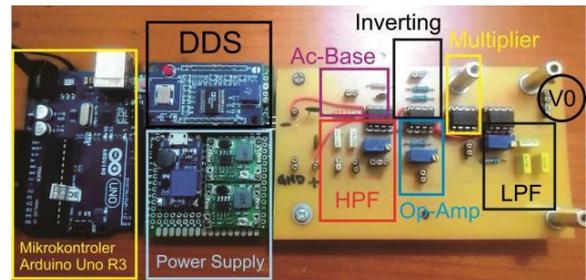


Figure 5. PSD-based capacitance meter

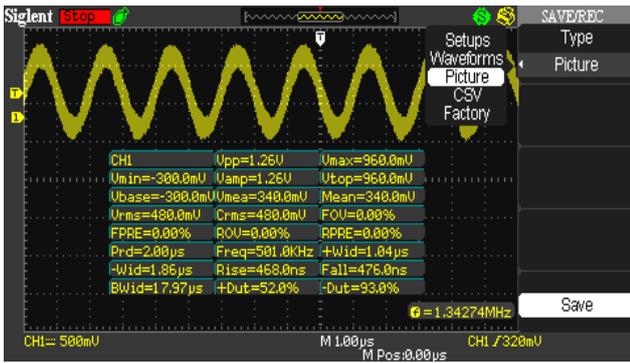


Figure 6. DDS AD9850 signal

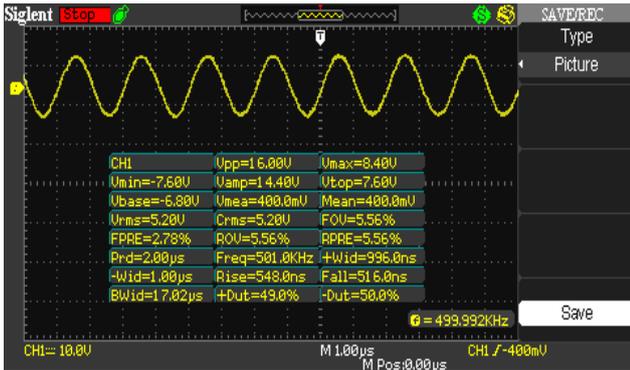


Figure 7. Signal gain by 18x to provide 16 Vpp

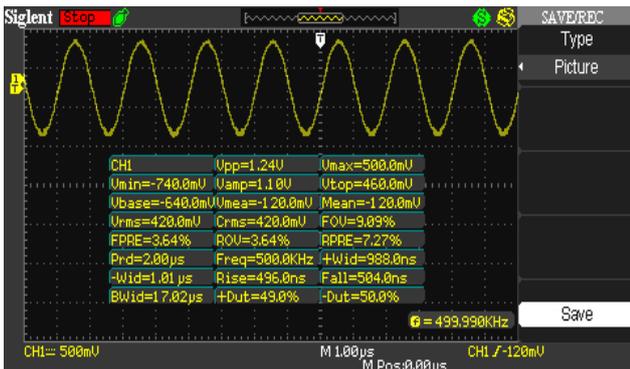


Figure 8. Output signal of CV converter

The required input signal as an excitation signal for the CV circuit was a sine signal with an amplitude of 18 Vpp and a frequency of 500 kHz. Additionally, an HPF was needed to dampen the existing offset voltage, and a signal amplifier with 18 times gain was also needed. Figure 7 shows that the offset has been damped, and the signal has been amplified to 16 Vpp.

The circuit converted the excitation signal from DDS into a signal whose magnitude corresponds to the measured C_x value. Figure 8 shows the output signal of the CV converter with the signal amplitude changing to 1.24 Vpp and Vrms changing to 420 mV for the 1 pF capacitor.

The signal that has passed through the circuit experienced a phase shift of 180°. The phase change was anticipated by using a unity gain inverter circuit. Figure 9 shows the phase change of the signal after passing through the inverting amplifier. An analog multiplier multiplied the information signal with the excitation signal, as represented in Figure 9,

colored yellow and blue respectively. The output signal obtained after going through the multiplier can be seen in Fig. 10.

An LPF filtered the high-frequency signals and passed low-frequency signals. The output signal from the LPF can be seen in Fig. 11. The Vrms value obtained from the LPF output was 100 mV for a capacitor value of 1 pF. In the experimental data, the Vrms value from the LPF output was used as the value of the variable V_0 to determine the value of the measured capacitor (C_x).

Capacitance measurement experiments using Arduino Uno R3 were carried out by programming Arduino with a capacitance measurement program, and then the results were displayed on the serial monitor in the Arduino IDE. The test was done using capacitors between 1 pF to 40 pF with an increase of 1 pF to obtain data for determining the measuring instrument characteristics. Figure 12 shows the scheme of measuring capacitance using the Arduino Uno.

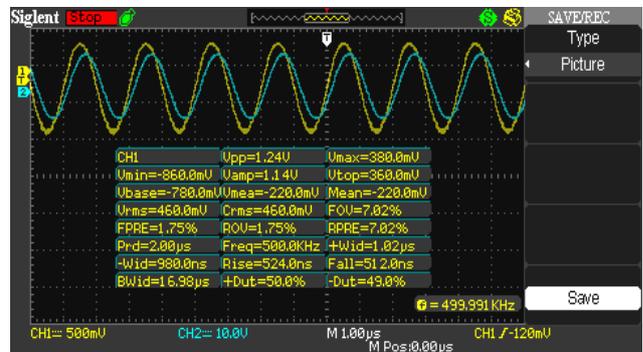


Figure 9. Inverting amplifier output signal (yellow) and excitation signal (blue)

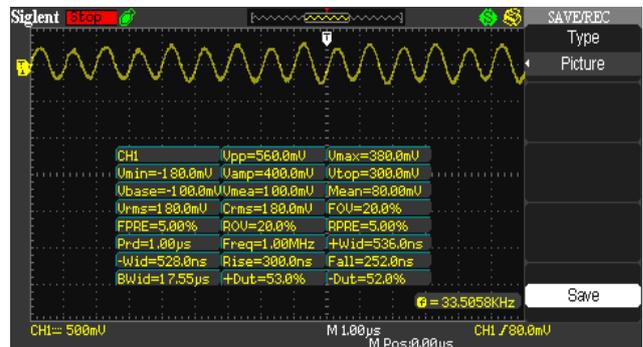


Figure 10 Multiplier output signal



Figure 11 Low-pass filter result signal

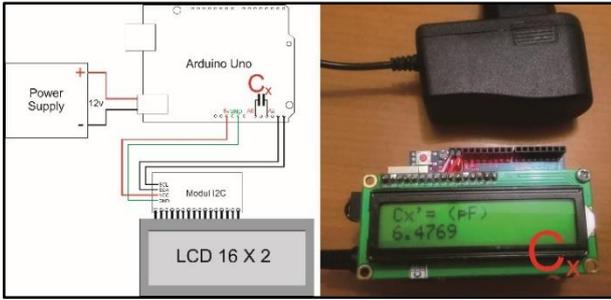


Figure 12. Arduino-based capacitance meter test

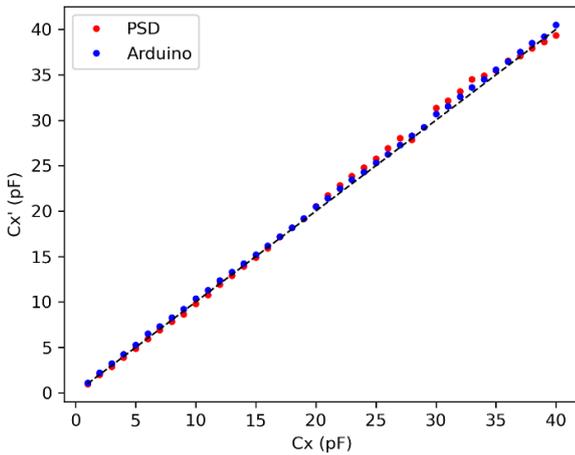


Figure 13. Graph of measurement results against true values

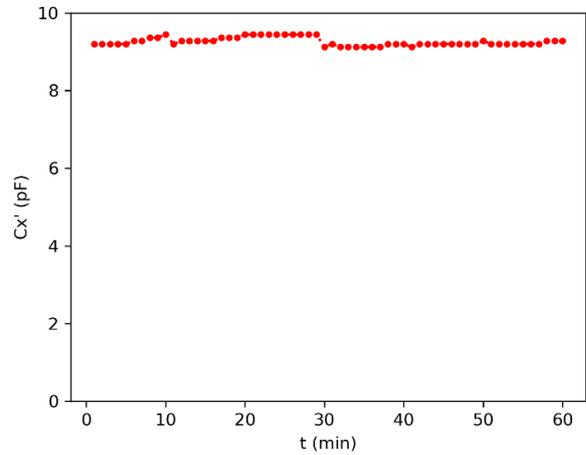
The instrument’s accuracy can be found by comparing measurement results (C'_x) against true capacitor values (C_x) from 1 pF to 40 pF in 1 pF increments. Figure 13 shows the results. The accuracy of the PSD-based capacitance meter obtained after processing the data was 97.894%, whereas the accuracy value of the Arduino-based capacitance meter was 97.943%. The precision of the PSD-based capacitance meter was 0.704 pF, whereas that of the Arduino-based capacitance meter was 0.027 pF. Furthermore, the sensitivity in this experiment can only be measured in the PSD-based measuring instrument experiment because the Arduino-based measuring instrument does not have data on changes in the V_0 signal to changes in C_x . The resulting sensitivity value for a PSD-based system was 0.1197 V/pF.

Figure 13 shows the capacitance measurement from both methods is linear. The blue graph shows the linearity line of the PSD-based system with regression $R^2 = 0.9983$, the equation $y = 1.0206x - 0.1418$ with an average error of 2.106%. The red graph shows the linearity line of the Arduino-based system with regression $R^2 = 0.9999$, the equation $y = 1.0073x + 0.1391$ with an average error of 2.057%.

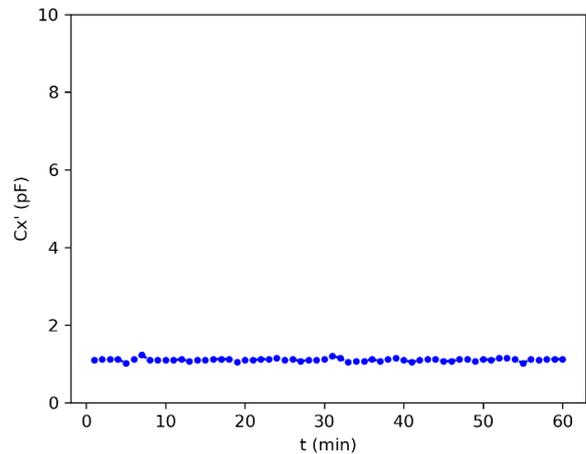
The stability value was calculated by taking measurement data for the capacitor value that is closest to its original value (in this case, 9 pF for a PSD-based circuit and 1 pF for an Arduino-based circuit) for 60 minutes while recording changes in the capacitance value every one minute. Figure 14 shows a graph of the stability in measuring reference capacitors for both capacitance-measuring circuits. The stability value of the PSD-based capacitance meter is 0.028

pF/minute, while the stability value of the Arduino-based capacitance meter was 0.04 pF/minute.

A comparison of characteristics such as precision, accuracy, sensitivity, linearity, and stability of the two measuring instruments is shown in Table 1.



(a)



(b)

Figure 14. Stability graph: (a) capacitance meter based on psd, (b) capacitance meter based on arduino.

Table 1. Comparison of the measuring method’s characteristics

Parameter	Method	
	PSD Circuit	Arduino
Accuracy	97.894%	97.943%
Precision	0.704 pF	0.027 pF
Sensitivity	0.1197 V/pF	-
Linearity	$R^2=0.9983$ $y=1.0206x-0.1418$	$R^2=0.9999$ $y=1.0073x+0.1391$
Stability	0.028 pF/min	0.04 pF/min

The next test used the 8-electrode ECVT sensor on two dielectric materials. The first is with the air medium or ‘empty’ condition, and the second is water medium or ‘full’ condition. Figure 15 shows the capacitance measurement scheme on the 8-electrode ECVT sensor. The test results with the 8-electrode ECVT sensor were analyzed by taking data on the capacitance values of a pair of two electrodes that were adjacent and so on until the opposite pair, alternately for every independent pair combination up to 28 data in total. Figure 16 shows the order in which data is collected, from the nearest pair of electrodes to the farthest pair of electrodes.

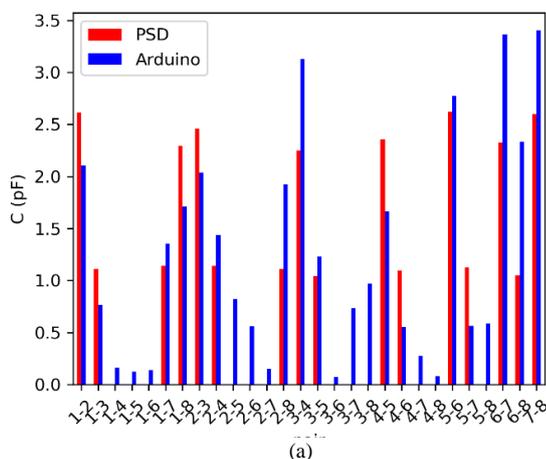


(a)

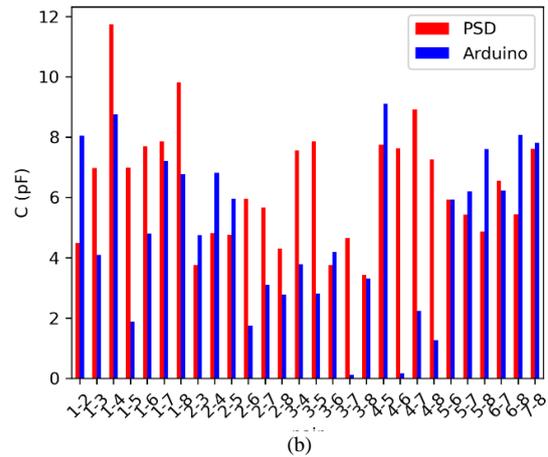


(b)

Figure 15. ECVT sensor measurement: (a) empty condition, (b) condition filled with water.



(a)



(b)

Figure 16. Electrode pair capacitance values: (a) empty conditions and (b) conditions with water objects

V. CONCLUSION

A capacitance measuring instrument based on the PSD circuit has been successfully designed and tested for picofarad-order measurement level. The accuracy of the PSD-based circuit is 97.894%, while the accuracy of the Arduino-based circuit is 97.943%. The precision of the PSD-based circuit is 0.704 pF, while the precision of the Arduino-based circuit is 0.027 pF. The sensitivity of the PSD-based circuit is 0.1197 V/pF. PSD-based circuits are linear as reflected by the coefficient of determination 0.9983, while Arduino-based circuit linearity has a coefficient of determination 0.9999. The stability of the PSD-based circuit is 0.028 pF/minute, while the stability of the Arduino-based circuit is 0.04 pF/minute. The designed capacitance measuring instrument also has been tested in the 8-electrode ECVT sensor. The results for air and water as medium comply with the respective dielectric constant for both objects.

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