A LOW COST ANALOG LOCK-IN AMPLIFIER FOR CAPACITANCE MEASUREMENTS

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ABSTRACT

Precise measurement of sensor signals is important for any control application. Measurement oflow voltage AC signals in noisy environment is quite difficult as the signals are buried in noise.To guarantee accurate measurement of signals buried in noise, this paper presents a low costanalog lock-in amplifier. The lock-in amplifier uses the phase sensitive detection (PSD) property to extract the signals buried in noise. Using this lock-in amplifier unknown capacitances in the range of 100pF to 1000pF aremeasured by locking in the signals from a I-V converter with a reference signal .The capacitorunder measurement is present in the I-V converter. The accuracy of the measurement of capacitance is 98%.

Keywords -- Averaging Filter, Lock –in amplifier, Phase sensitive detection, I-V converter, Zero Crossing Detector

I.INTRODUCTION

Sensors are employed in a wide variety of applications and environments. Sensors of small size and low energy generally provide low levels of output signals under the presence of a noisy environment and so a reliable signal processing operation is necessary to get the relevant information [1]. For example in many control applications,the environment is noisy and the signal from the sensor is very small in amplitude than the noise amplitude. As a resultthe signal to be measured is corrupted by the noise. In such a scenario, a linear filtering is not sufficient to extract the relevant signal information generally [1], [2].To extract these signals from noise, there have been several reports on techniques such as lock-in amplifiers, signal averagers, box car integrators, waveform educators, auto-correlators and cross-correlators [1].A lock-in amplifier can be used to extract the signals buried in noise provided the signal frequency is known [1], [2],[3]. The signal frequency is used as a reference to single out the relevant data from the noise corrupted signal. Lock-in amplifiers have been traditionally used in physics laboratories for a long time in a wide variety of applications as low level optical experiments, acoustical and cross talk measurements, electron spectroscopy, radio astronomy, neurologic research, feedback control of lasers, complex impedance measurements, optical pyrometry, hot wire anemometry and photon counting [4].Resistive and capacitive sensors are used in many applications and in some cases the signals from them are low in amplitude whereby they are corrupted by noise. The project was done primarily to check the applicability of the lock in amplifier for capacitance based cryogenic liquid Hydrogen (LH_2)level sensor calibration.The cryogenic LH_2 level sensor's capacitance varies between 212pF and 525pF with liquid Nitrogen (LN_2) as the cryogen as reported in [5].Hence in this paper we describe the design of a low cost lock-in amplifier which can be used for capacitive impedance measurements.

II. LOCK-IN AMPLIFIER

Lock in amplifiers can be considered as special kind of AC voltmeters which extract the amplitude of an AC signal at a reference frequency, f_0, even when the signal amplitude is very weak and smaller than the environmental noise [1]. It is basically a phase sensitive band pass filter [6].It uses a phase sensitive detection to extract the signal buried in noise and giving a DC output proportional to the amplitude of the required AC input signal [7]. The system reduces noise by rejecting the noise frequencies which are not synchronised with the reference signal frequency,$f_{0.}$Hence it is important for the lock-in amplifier to have the knowledge of a pure reference signal frequency, $f_{0.}$

Fig. 1 shows the block diagram of the lock-in amplifier. It consists of a signal generator, Phase shifter, mixer and an averaging filter also called an RC Low pass filter. It is constructed with complete analog components such as TL084 op-amps and MC14016B analog switches. To measure resistive impedance, the reference signalis directly given to the zero crossing detectors and to measure capacitance the reference signal is 90° phase shifted and given to the zero crossing detectors. The resistor or capacitor under measurement is connected to the inverting input terminal of the I-V converter.

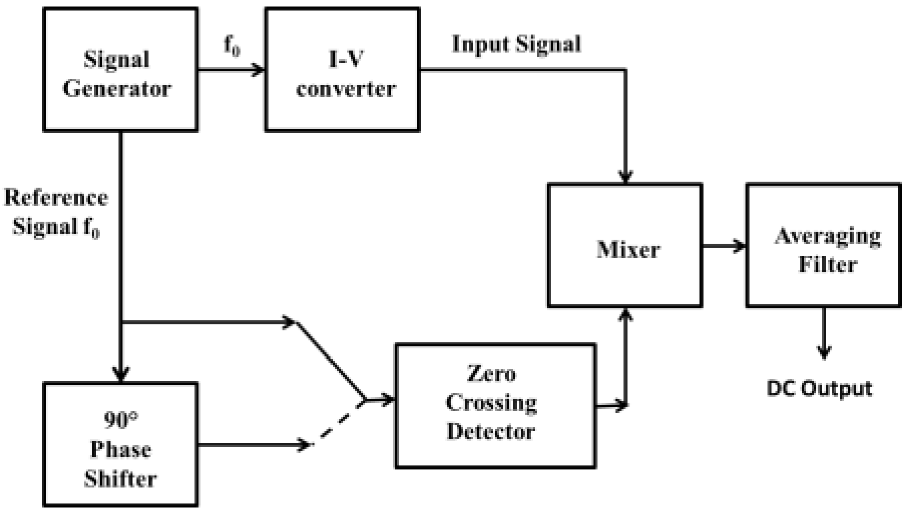

Figure 1 Block diagram of the lock-in amplifier

III. DESIGN AND WORKING OF THE LOCK-IN AMPLIFIER

3.1 I-V Converter

The I-V converter converts the given input current to a proportional output voltage. Fig.2 shows the schematic diagram of the I-V converter. An input sinusoidal reference signal (V_{IN}) of frequency f_0, generated by the signal generator is given to the capacitor (C_X) under measurement. Since the non-inverting terminal of the op-amp is connected to ground, the inverting input terminal of the op-amp is kept at virtual ground. The current flowing through the capacitor (C_X) also flows through the feedback resistor R_F. The voltage (V_{O1}) across R_F is proportional to the current through the capacitor (C_X). The output voltage (V_{O1}) of the I-V converter is 90° phase shifted with respect to the voltage V_{IN} and also inverted.Since the current through the capacitor (C_X) and the current through the resistor (R_F) are same, they can be equated to calculate the Capacitance value of the capacitor, C_X.The V_{IN} and V_{O1} are peak values.

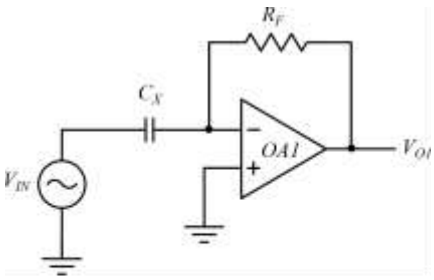

Figure 2 Schematic diagram of I-V converter

The current through the capacitor is calculated as followed.

: $i_{CX} = i_{RF}$ (1)

: $i_{CX} = 2\pi f_0 C_X V_{IN}$ (2)

: $i_{RF} = V_{O1}/R_F$ (3)

: $C_X = \left(\frac{1}{2\pi f_0 R_F V_{IN}}\right) \times V_{O1}$ (4)

3.1.1 Effect of Stray capacitances in I-V converter

There are two stray capacitances C_{S1} and C_{S2} are present in the I-V converter as shown in the Fig.2 but they don't have any effect on the output of the I-V converter. It is because the stray capacitance C_{S1}loads the input source and as long as the source impedance is very low, C_{S1} has no effect on the output voltage V_{01}. Since stray capacitance C_{S2}appears between Virtual ground and ground there is no current flows through it. So C_{S1} and C_{S2} have no effect on the output voltage (V_{O1}) of the I-V converter.

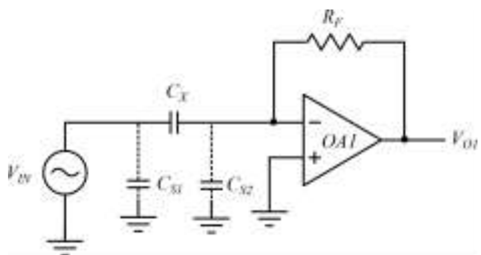

Figure 2 Stray capacitances in I-V converter

3.2 Mixer

The mixer shown in Fig. 3 is also known as the phase sensitive detector or the synchronous demodulator.The output (V_{O1}) of the I-V converter is given as the input to the mixer. The mixer is nothing but an operational amplifier which works as a non-inverting amplifier during the positive cycle of V_{O1} and works as an inverting amplifier during the negative half cycle of V_{O1}.To accomplish this, switches S2 and S3 must be closed during the positive half cycle of V_{O1} and opened during the negative half cycle of the V_{O1}. Similarly, switches S1 and S4 must be closed during the negative half cycle of V_{O1} and opened during the positive half cycle V_{O1}. The control (CNT1) to the switches S1,S4 is given by the zero crossing detector constituted by OA3 and the control (CNT2) to the switches S2, S3 is given by the zero crossing detector constituted by OA4 as shown in Fig.4. Resistances R5, R6, R7 and R8 are chosen to be equal for unity gain.

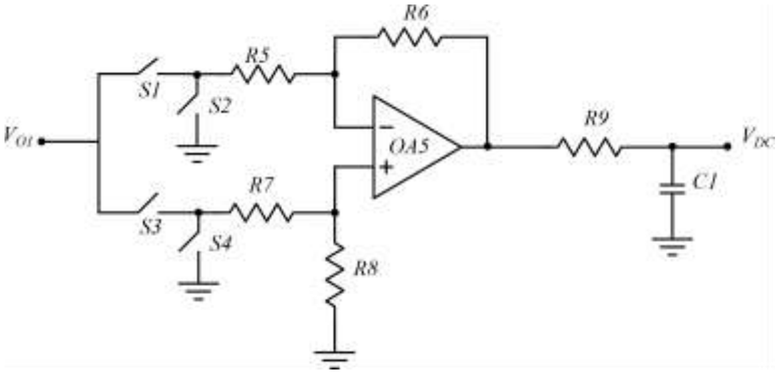

Figure 3 Circuit diagram of the mixer and averaging filter

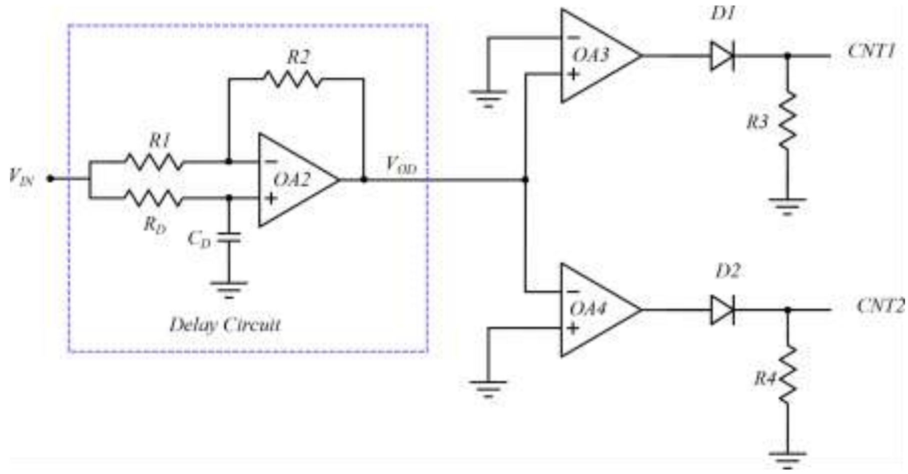

Figure 4 Phase shifter and Zero crossing detectors

3.3 Phase shifter

The phase shifter also known as the delay circuit, is shown in Fig. 4. It provides a delay of up to 90° either varying R_D or C_D. In this design the capacitor is kept at a constant value and the resistance value of R_D is varied to obtain the 90° phase shift. The phase shifter provides the phase matching between the reference signal (V_{IN}) and capacitor signal (V_{O1}) by phase shifting V_{IN} by 90°. The output (V_{OD}) of the phase shifter is given to the zero crossing detectors for the control of mixer operation.

3.4 Zero crossing detectors

Fig. 4 shows the zero crossing detectors OA3 and OA4. The output (CNT1) of the zero crossing detector OA3 goes high during the positive half cycle of V_{OD} and goes low during the negative half cycle of V_{OD}. The output (CNT2) of zero crossing detector OA4 goes high during the negative half cycle of the signal V_{OD} and goes low during the positive half cycle of V_{OD}.

3.5 Averaging filter

The averaging filter is nothing but a low pass RC filter. The output of the mixer is a fully rectified wave of the output of the I-V converter. This fully rectified wave is given as input to the averaging filter constituted by R9 and C1 as shown in Fig. 3. The output of theaveraging filter (V_{DC}) is a DC signal proportional to the amplitude required AC signal (V_{O1}) of the capacitance C_X under measurement. For this the RC time constant of the averaging filter must be greater than the lowest noise frequency. The noise whose frequency is generally high, is filtered by the low pass filter. The relation between the required AC signal amplitude (V_{O1}) and the V_{DC} is given by the following expression.

: $V_{DC} = 2V_{O1}/\pi$ (5)

Rearranging (5) gives

: $V_{O1} = V_{DC} \times \frac{\pi}{2}$ (6)

Substituting (6) in (4) the capacitance value is obtained.

IV. EXPERIMENTAL RESULTS ON THE LOCK-IN AMPLIFIER

To analyse the performance, the designed analog lock in amplifier was tested using high accuracy laboratory instruments. A sinusoidal voltage (V_{IN}) was applied to the capacitor (C_X) under measurement.Fig.5 shows the input signal and output of the I-V converter. The output (V_{O1}) of the I-V converter, which is the signal of the capacitance under measurement, was 270° out of phase with the input (V_{IN}), where the 90° phase shift was provided by the capacitor (C_X) and the remaining180° phase shift was provided by the inverting op-amp of I-V converter.The output (V_{O1})of the I-V converter was given to the input of the mixer and the mixer switches were operated in phase with V_{O1} by shifting the input (V_{IN}) to the zero crossing detector by 90°.Fig.6 shows the input and output at the mixer. The fully rectified wave shows the satisfactory functionality of the mixer. The output of the mixer signal has the amplitude V_{O1} and the noise.The noise is removed by averaging the mixer output signal with RC low pass filter. The resultant average value (V_{DC}) was measured using the Keithley193A system DMM (digital multimeter) and it was used to calculate the capacitance of the capacitor (C_X) using the following expression.

:$C_X = \left(\frac{1}{4f_0 R_F V_{IN}}\right) \times V_{DC}$ (7)

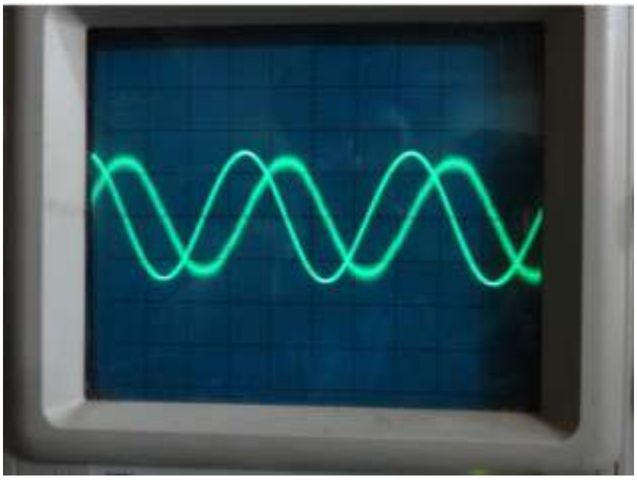

Figure 5 Input and output waveforms of the I-V converter

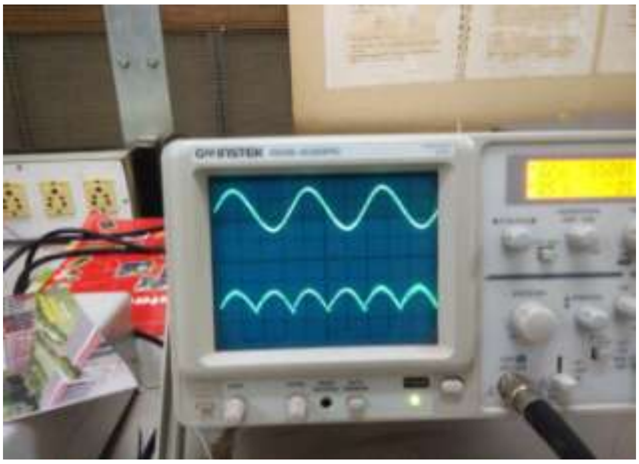

Figure 6Measurement result at the input and output of the mixer

Two known capacitances covering the range of capacitance type cryogenic Liquid Hydrogen(LH_2) level sensor's capacitances (212pF – 525pF)were measured with the input sinusoidal signal(V_{IN}) of 0.8V peak amplitude, frequency (f_0) of 2.19 KHz and a resistor (R_F) of 100 kΩ. The measurement results are given in the following TABLE.1. The results show the designed lock in amplifier can be used to calibrate the capacitance type cryogenic Liquid Hydrogen (LH_2) level sensor satisfactorily.

TABLE 1. Actual and measured capacitance values

S.No	Actual Capacitance Value (pF)	V_{DC} (mV)	Measured Capacitance Value (pF)	% of Error
1.	110.5	76	109.15	-1.22
2.	1110	764	1091.5	-1.7

V. CONCLUSION

The designed low cost analog lock-in amplifier can measure unknown capacitances within the range of 100pF to 1000pF with an error of less than ±2%, by effectively filtering out the noise. The experimental results show the lock in amplifier can be used to calibrate capacitance type cryogenic Liquid Hydrogen (LH_2) level sensor satisfactorily. The lock in amplifier can be used to measure unknownresistive impedances also. In future the analog lock in amplifier can be fabricated in an integrated chipwith capacitive and resistive sensors for integrated sensor module applications.

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