Design of a Lock-in Amplifier with Current-Mode Oscillator

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ABSTRACT

The lock-in amplifier can be used in instrumentation systems as a part of the conditioning circuit that optimizes and supports the signals coming from sensors, being capable of measuring the electrical impedance (or admittance) of such sensors, by exciting them with a local oscillator. In industrial environments and research laboratories, it is important to ensure that the level of current passing through the sensor, usually called Device Under Test (DUT), does not exceed the tolerance and safety limits: 10 mA to 30 mA. In this paper, we proposed the design of a lock-in amplifier with a current-mode oscillator to ensure that the current level is below the tolerance limits. A current-mode Wien oscillator was used based on Current Conveyors, a current-mode building block. Through simulations and experimental measurements, we could check the operation of the designed circuit, pointing out some comparisons with the traditional lock-in amplifier with voltage-mode oscillator.

Keywords

Lock-in Amplifier. Current-Mode Circuit. Current Conveyor.

1. INTRODUCTION

Instrumentation systems are essential in industrial and research environments. The signals extracted from the sensors are transmitted to the conditioning circuit which gives support to the sensors and optimizes the signals for future processing operation. The lock-in amplifier can be used as a part of the conditioning circuit. It is a circuit that enables the measurement of extremely small signals, even when they are immersed in noise by detecting the phase difference between two signals with the same frequency. It can be used to measure the impedance of sensors, exciting them with a local oscillator [1-3]. The current level of the exciting signal (reference signal) cannot exceed the tolerance and safety limits prescribed by the International Electrotechnical Commission (IEC) 60479 and 60947: 10 mA to 30 mA [4]. For this reason, it is important to control the current level that passes through such sensors, usually called Device Under Test (DUT). In order to achieve this requirement, a lock-in amplifier with current-mode oscillator can be implemented in the system. Current-mode circuits are circuits in which the information is represented by a current signal instead of voltage signals [5], ensuring a greater control on the current level.

In this paper, a lock-in amplifier with current-mode oscillator was designed using Current Conveyors, a current-mode building block. Some comparisons were made between the traditional lock-in amplifier with voltage-mode oscillator and the proposed lock-in amplifier with current-mode oscillator.

2. THE LOCK-IN AMPLIFIER WITH CURRENT-MODE OSCILLATOR

2.1 Current Conveyor: a current-mode building block

Current-mode circuits overcome the constant gain-bandwidth product of the op amps in voltage-mode circuits, providing higher bandwidth and speed. Furthermore, it provides a greater control on the current level of the circuit.

Current Conveyors are current-mode building blocks that simplify the design of current-mode circuits in the same way as Operational Amplifiers (op amps) in the design of voltage-mode circuits. One type of Current Conveyor that can be used to design current-mode oscillators is the Positive Second Generation of Current Conveyor (CCII+). The Current Conveyor is capable of transport current from two terminals (X to Z) with different levels of impedance. Figure 1 shows a CCII+ diagram.

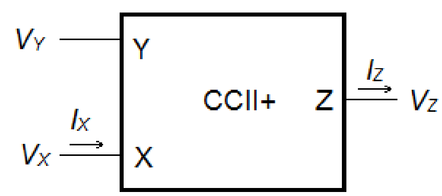

Figure 1. Positive Second Generation of Current Conveyor (CCII+)

The Y terminal has high input impedance working as a voltage input terminal. The X terminal has low impedance working as a current input (or voltage output) terminal and Z terminal has high impedance working as a current output terminal. The voltage of X terminal follows the voltage from Y terminal. There is no current passing through Y and the current passing through the Z terminal is the same one from the X terminal. The equation that relates the voltages and the currents of the CCII+ is given by:

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & R_X & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \end{bmatrix} \qquad (1)$$

Where R_X is the impedance of X terminal. For the ideal case, R_X = 0. The CCII+ can be implemented by AD844 from Analog

Devices. Figure 2 shows the internal configuration of the AD844 where a CCII+ is followed by a voltage buffer [6].

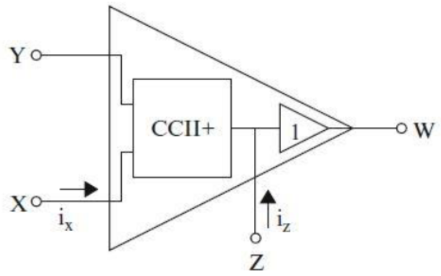

Figure 2. The internal configuration of AD844 [6]

Due to its versatility in working in both current and voltage mode, the CCII+ can be used to implement several analog functions. One of the applications of the CCII+ that is useful in the design of current-mode oscillators is the realization of a voltage controlled voltage source (VCVS) as shown in Figure 3. [7]. The first CCII+ determines the gain of the VCVS and the second one works as a voltage buffer. This configuration can replace the gain stage of an oscillator loop, providing a current output at the Z terminal of the second CCII+.

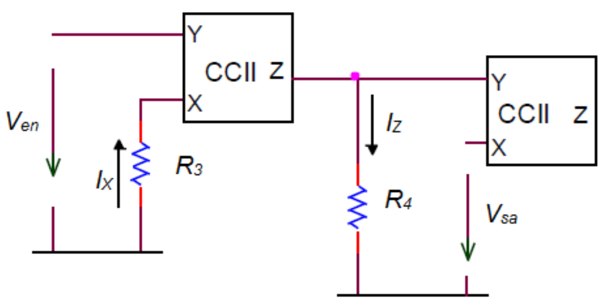

Figure 3. A CCII+ based voltage controlled voltage source [7]

2.2 The current-mode oscillator

One way to design a current-mode oscillator is to replace the voltage amplifier of the oscillator by a Current Conveyor based voltage amplifier which contains a current-mode output terminal as shown in Figure 3 [8]. The Wien oscillator is an oscillator that produces a sinusoidal signal with high harmonic purity. A current-mode Wien oscillator is shown in Figure 4 where its gain stage a was implemented by a voltage controlled voltage source based on CCII+. The Z terminal of the second Current Conveyor is a current-mode output terminal and the X terminal is a voltage-mode output terminal.

The oscillation condition and the oscillation frequency are given by:

$$1+\frac{R_1}{R_2}+\frac{C_2}{C_1}=\frac{R_4}{R_3}=a \qquad (2)$$

$$\omega=\frac{1}{\sqrt{R_1C_1R_2C_2}} \qquad (3)$$

A non-linear control mechanism can be used to control the amplitude of the oscillation. A practical approach is to use two diodes and an additional resistor beside of R_4 [9].

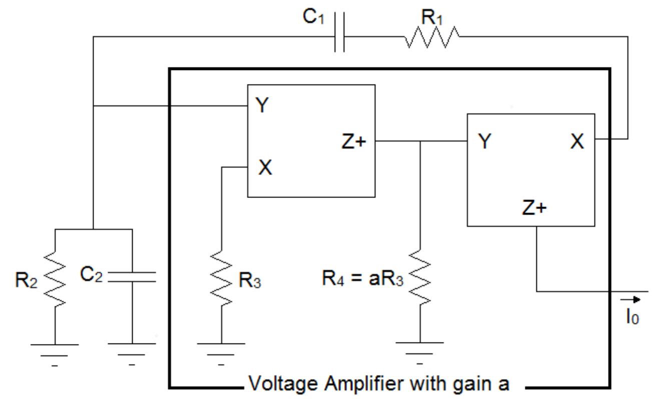

Figure 4. Current-mode Wien oscillator [8].

2.3 Lock-in amplifier with current-mode oscillator

The lock-in amplifier with current-mode oscillator differs from the traditional lock-in amplifier with voltage-mode oscillator for having a current-mode oscillator that excites the DUT with a current signal I_{ref}. The block diagram of this lock-in amplifier is shown in Figure 5. It was used the current-mode Wien oscillator using two CCII+ shown in Figure 4. The signals I_{ref} and V_{ref} present a phase difference ξ. We want to measure the impedance of the DUT:

$$Z(\omega,V)=R(\omega,V)+\frac{1}{j\omega C(\omega,V)}=|Z(\omega,V)|\angle\theta \qquad (4)$$

The output signal can be written as:

$$V_{out}=K|Z(\omega,V)|\cos(\varphi-\xi-\theta) \qquad (5)$$

$$\varphi-\xi=0\rightarrow V_{out}=K|Z(\omega,V)|\cos\theta=KR(\omega,V) \qquad (6)$$

$$\varphi-\xi=90^\circ\rightarrow V_{out}=K|Z(\omega,V)|\sin\theta=-\frac{K}{\omega C(\omega,V)} \qquad (7)$$

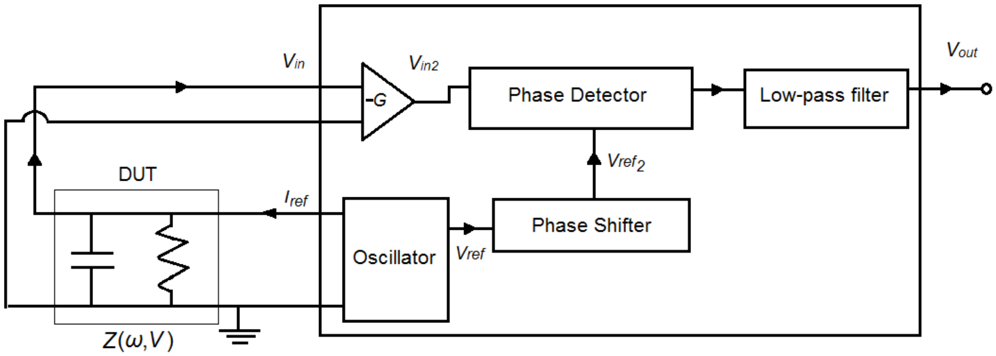

Figure 5. Block diagram of a lock-in amplifier with current-mode oscillator.

Where $K = 4GB/\pi$, G is the gain of the input amplifier and B is the amplitude of I_{ref}. It is important to note that lock-in amplifier with current-mode oscillator measures the impedance directly, while the lock-in amplifier with voltage-mode oscillator measures the admittance directly. One can adjust the phase φ of V_{ref} through the Phase Shifter.

3. METHODOLOGY

To accomplish the objectives of this work, first we simulated the circuit of Figure 5 analyzing the output signal when the impedance of the DUT is varied, to obtain the value of K. Then it was verified if the current signal I_{ref} is bellow the safety and tolerance limits. After, we assembled the circuit in a printed circuit board (PCB) plotting its calibration curves, i.e., its measurement range.

4. RESULTS AND DISCUSSION

The oscillator used in the proposed lock-in amplifier is the Wien current-mode oscillator, shown in Figure 4, which components were set to produce a sinusoidal signal with frequency of f = 15.5 kHz. The oscillator has two output mode signals: voltage-mode and current-mode depending on the impedance value of the output terminal. The phase shifter was implemented by an op amp all-pass filter with a variable resistor. The input amplifier was an op amp inverter amplifier with gain G = 10. The op amp used was uA741 from Texas Instruments. The phase detector was implemented by AD630 from Analog Devices, a switching controlled mixer. The RC low-pass filter has a cutoff frequency of 160 Hz. The power supply was a symmetrical DC voltage source ±9 V.

4.1 Simulation Results

To verify that the designed circuit followed (5), a pure resistive DUT was used in the simulation. Figure 6 shows the output signal V_{out} as a function of the resistance of the DUT. The data follow a linear behavior until R_{DUT} = 5 kΩ, where it starts to saturate. The calibration curve was plotted from the points that presented a linear behavior. The angular coefficient of the calibration curve is $K = 0.98 \times 10^{-3}$ A.
The simulated reference current I_{ref} has an amplitude of B = 80 µA obeying the safety limits.

4.2 Experimental Results

The designed lock-in amplifier was assembled in a PCB as shown in Figure 7. The measured reference current was 64 µA, that is similar to the simulation value, 80 µA.

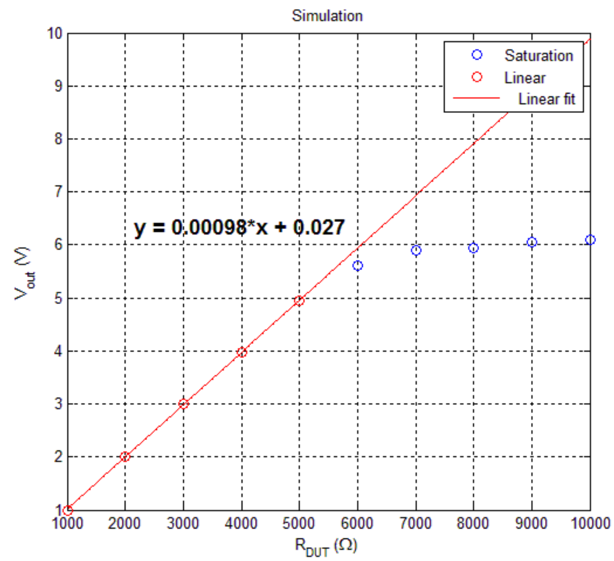

Figure 6. Simulation of the output signal as a function of the resistance of the DUT

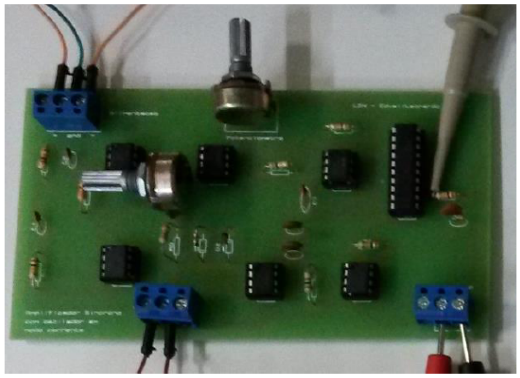

Figure 7. Designed circuit assembled in a PCB.

Calibration curves were plotted to analyze the measurement range of the circuit and to verify if the circuit follows (5) and (6). Figure 8 shows the calibration curve for a pure resistive DUT and Figure 9 for a pure capacitive DUT. The calibration curves are the linear fit of the experimental data that have a linear behavior.

From the calibration curves, we could check that the designed lock-in amplifier can measure resistances bellow 13 kΩ and capacitances above 500 pF for a frequency of 15.5 kHz and an input gain of $G = 10$. The values of K in those curves are 0.36 x 10^{-3} A and 0.34 x 10^{-3} A, which are relatively near to the simulation result $K = 0.98 \times 10^{-3}$ A.

The traditional lock-in amplifier with voltage-mode oscillator can measure the admittance of the DUT directly, differently from the designed lock-in amplifier with current-mode oscillator that measures directly the impedance of the DUT, being capable of measuring low resistances and high capacitances.

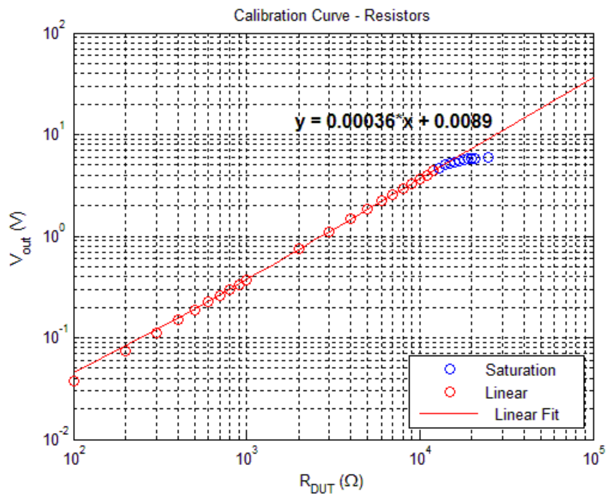

Figure 8. Calibration Curve for resistors

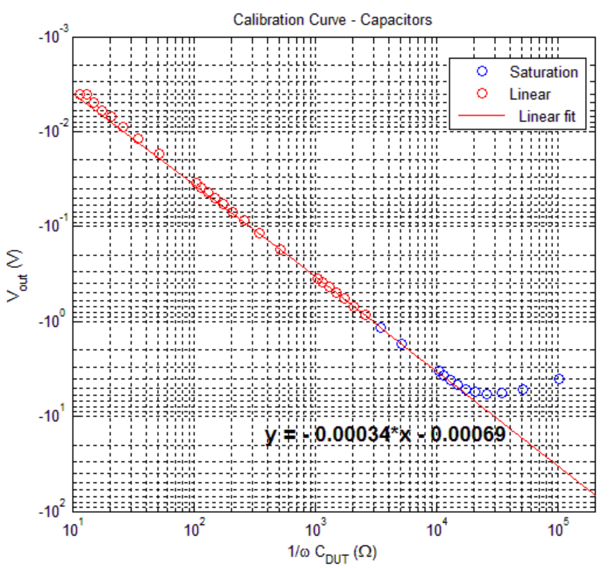

Figure 9. Calibration Curve for capacitors

4.3 Expanding the measurement range

The designed lock-in amplifier can be modified to provide a larger measurement range, increasing f or decreasing G or B. For instance, adjusting $G = 1$ and $f = 30.1$ kHz, it is possible to measure resistances bellow 50 kΩ as shown in Figure 10, ten times larger than the simulation results from Figure 6.

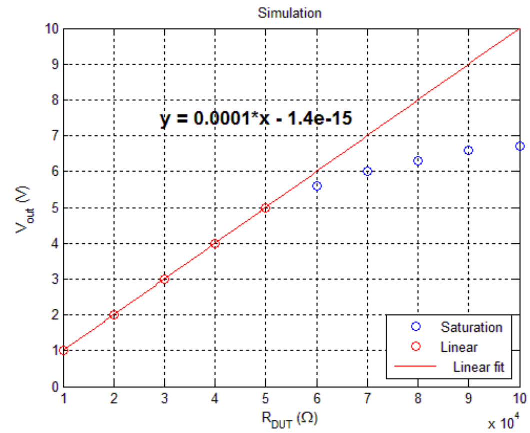

Figure 10. Simulation of the output signal as a function of the resistance of the DUT for *G* = 1 and *f* = 30.1 kHz

5. CONCLUSIONS

A lock-in amplifier with current-mode oscillator was designed obeying the safety and tolerance limits. Simulation and experimental results supports that correct operation of the circuit. It was showed that the designed lock-in amplifier with current-mode oscillator can measures directly the impedance of the DUT, being capable of measuring low resistive and high capacitive sensors. The designed circuit can be adjusted to obtain a larger measurement range.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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