Research Migration Project

https://esim.fossee.in/research-migration-project

The Research Migration Project is an initiative of FOSSEE, IIT Bombay that promotes the use of eSim for reproducing published research circuits originally implemented using proprietary simulation tools. The objective is to migrate these validated designs to eSim to build an open source resource database.

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Affiliation / Institution : Department of Electrical and Electronics Engineering, Vellore Institute of Technology (VIT) Bhopal University, Madhya Pradesh, India.

Title of the circuit : Analog Lock-in Amplifier for Weak Signal Detection

Theory/Description : Lock-in amplifiers utilize the phase-sensitive detection (PSD) technique to isolate a data signal at a specific reference frequency. In PSD-based systems, noise signals at frequencies other than the reference frequency are rejected, meaning they do not significantly affect the desired signal information. The PSD technique is fundamentally based on the synchronous rectification of the data signal, governed by a control signal that determines the amplification sign. When both the data and control signals share the exact same frequency and phase values, the data signal becomes full-wave rectified at the output. Subsequently, a low-pass filter is employed to extract the average value of this processed signal, thereby cancelling the noise and recovering the desired signal information.

Because this fundamental technique requires a perfect match in phase, phase dependency (which often occurs with capacitive sensors) can be eliminated by employing a dual-phase lock-in architecture. This dual-phase architecture adds a second lock-in amplifier branch controlled by a reference signal that is shifted by 90 degrees. To enable single-supply operation (e.g., 3V for battery-operated embedded systems), the system utilizes a quadrature oscillator to provide the 90-degree phase-shifted control signals, and a DC offset is added to center the data signals within the supply range before mixing and low-pass filtering.

Reason to reproduce with eSim : Reproducing this circuit using eSim is highly valuable as it demonstrates the design of a complete, dual-phase analog lock-in amplifier optimized for a single 3V supply, which is critical for battery-operated wireless sensing networks. Simulating

this system in an open-source environment provides immense educational value by allowing users to verify how phase-sensitive detection can successfully recover small AC sensor signals from extreme noise environments with a signal-to-noise ratio below 0.025. Furthermore, eSim is perfectly suited to simulate and verify the circuit's specific building blocks, such as the quadrature oscillator that eliminates phase dependency and the digitally switched analog mixers that are modified to handle 1.5V DC-offset signals.

Expected Outcome/outputs : The simulation is expected to demonstrate the successful recovery of a small AC signal that is heavily buried in noise, regardless of phase dependency. The measurable outputs of the circuit will be two distinct DC signals (V01 and V02) that represent the low-pass filtered, synchronously rectified outputs from the dual-phase branches, both centered around a 1.5V DC offset. The circuit's performance will be validated by applying the extracted DC voltages to the mathematical recovery formula:

$$A = \frac{\pi}{2}\sqrt{(V_{01} - 1.5V)^2 + (V_{02} - 1.5V)^2}$$

which calculates the noise-free amplitude (A) of the original sensor signal. Ultimately, the simulation should verify the system's ability to accurately recover signal information even when the Signal-to-Noise Ratio (SNR) is below 0.025 (meaning the noise amplitude is up to 40 times higher than the data signal), with a measurement error of less than 9%.

Circuit Diagram(s) :

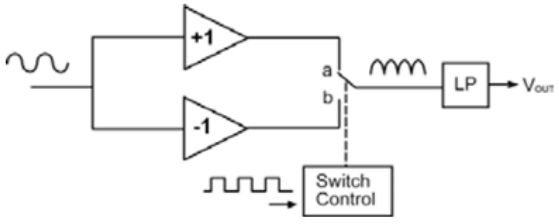


Fig. 1: Digitally switched analog mixer, and the low-pass filter that provides the data signal average value

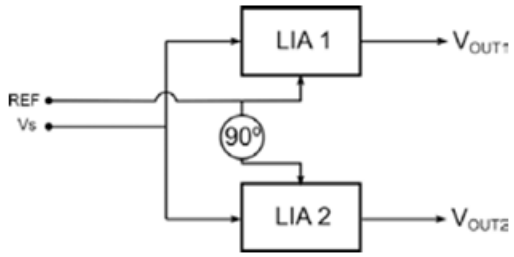
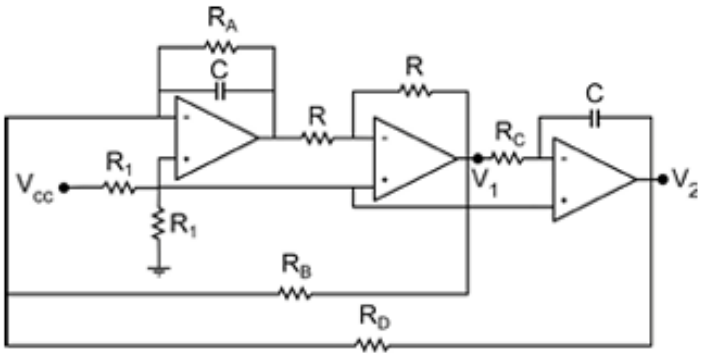
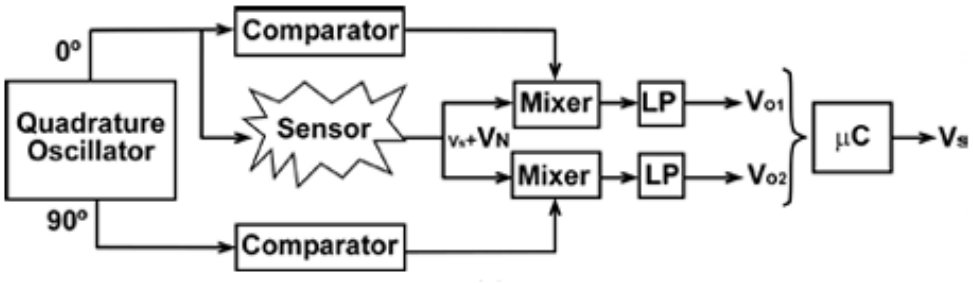


Fig. 2: Dual-phase lock-in block diagram

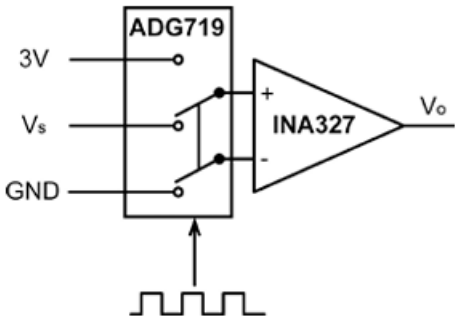


Quadrature oscillator. V1 and V2 are the 90º phase shifted control signals

Block Diagram (s) :

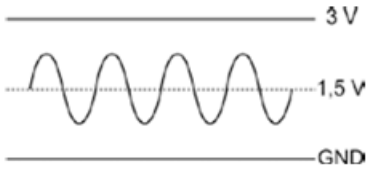


Block scheme of the proposed lock-in system

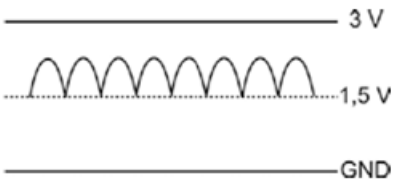


- An input consisting of target sensor data plus noise is centered at a 1.5V DC offset and fed into two parallel signal mixers.
- A local quadrature oscillator generates two 140 Hz reference sine waves shifted by 90 degrees.
- Comparators convert these reference sine waves into square waves to control the switching of the respective signal mixers.
- The synchronously rectified outputs from the mixers are passed through 1 Hz low-pass filters to extract the DC average values V01 and V02 while rejecting AC noise.

Expected Results (Input, Output waveforms and/or Multimeter readings) :



Input signal to the mixer



Rectified output signal

Inputs:

- An AC sensor data signal heavily masked by noise (capable of reaching a Signal-to-Noise Ratio of 0.025), centered around a 1.5V DC offset.
- Two 140 Hz reference sine waves with a 90-degree phase shift and a 1.5V DC offset level, generated internally by the quadrature oscillator.

Intermediate Waveforms:

- Square wave control signals produced by the comparators from the oscillator's sine waves.
- Synchronously rectified transient waveforms at the output of the two signal mixers, which invert the signal around the 1.5V axis depending on the square wave control state.

Final Outputs:

- Two stable DC voltages (V01 and V02) measured at the output of the 1 Hz low-pass filters.
- These DC voltage readings will contain the 1.5V offset and the extracted average values, which can be mathematically combined to verify the noise-free amplitude of the original sensor signal with an estimation error below 9%.

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Research Paper/Journal/etc. :

Title : A complete low voltage analog lock-in amplifier to recover sensor signals buried in noise for embedded applications

Author : M. Gabal*, N. Medrano, B. Calvo, P. A. Martínez, S. Celma, M. R. Valero

Page No. : 74-77

Link : [PDF] A complete low voltage analog lock-in amplifier to recover sensor signals buried in noise for embedded applications | Semantic Scholar

Source/Reference(s) :

- Stanford Research Systems, "Lock-in amplifiers, Appl Notes", Data Sheets, 1999. *(This corresponds to the Application Note #3 we discussed earlier, which provides excellent theory on phase-sensitive detection).*
- Meade, M. L., "Lock-in Amplifiers: Principles and Applications", Peter Peregrinus Ltd, 1983.
- National Instruments, "NI USB-621x User Manual", 2009. *(Referenced for the DAQ board used to simulate the low SNR sensor environment)*.

- Data sheets for the specific commercial ICs used in the experimental setup: Analog Devices ADG719 (SPDT switch) and Texas Instruments INA327 (Instrumentation Amplifier).

Note: Fields marked with an asterisk (*) are mandatory and must be filled for successful submission.