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Lock-In Amplifier Simulation using Multisim

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Abstract
Lock-in amplifiers are extremely important for demodulation of signals as the stability of output in lock-ins is very assuring and the extraction the weak signal from the attenuated noisy signal makes the signal processing very simple. Lock-in amplifiers work under the principle of orthogonality of sinusoidal functions. They are phase sensitive, thus it allows us to get the phase of the input signal as well. In this experiment, a model of lock-in amplifier was simulated using Multisim software. Later, it was tested in a noisy environment. A phase-detection was also done using dual phase lock-in amplifier. The amplification factor was calculated for both lock-ins and they have come to be 2.46 ± 0.07 and 2.41 ± 0.09. The simulation works fine under all tested conditions, thus making this experiment a success.

1 Objectives

1. To design circuits of single-phase and dual-phase lock-in amplifiers in multisim software.
2. To calculate the amplification factor of both circuits.
3. To calculate the phase of the provided signal using dual-phase lock-in amplifier.
4. To calculate the signal-to-noise ratio and determine the effectiveness of the lock-in amplifiers.

2 Introduction

A lock-in amplifier is a device which is capable of extracting signals in a defined frequency band around a provided reference frequency, efficiently rejecting all other frequency components. It was first discovered in the 1930's and has been in use commercially since the mid 20th century. Lock-in amplifier is one of the most useful and cost-effective electrical component that has been in use for a long time. It has an ability to detect and measure both signal amplitude and phase, even when the noise is a million times higher than the signal. The working principle of a lock-in amplifier is discussed in details in next sections,

3 Working Principle

Lock-in amplifiers use the knowledge about a signal's time dependence to extract it from a noisy background. A lock-in amplifier performs a multiplication of its input with a reference signal, also sometimes called down-mixing or heterodyne/homodyne detection, and then applies an adjustable low-pass filter to the result. This method works because of the orthogonality properties of a sine function. When a sinusoidal function of frequency f_1 is multiplied with another frequency f_2, which is not equal to f_1, the result becomes zero. Instead, when a frequency f_1 is multiplied with same frequency, the result becomes $\frac{1}{2}V_1V_2cos\theta$, where V_1 and V_2 are the amplitudes of given signals and θ is the phase difference between them. This method is termed demodulation or phase-sensitive detection and isolates the signal at the frequency of interest from all other frequency components. The reference signal is either generated by the lock-in amplifier itself or provided to the lock-in amplifier and the experiment by an external source. The reference signal is usually a sine wave but could have other forms, too.

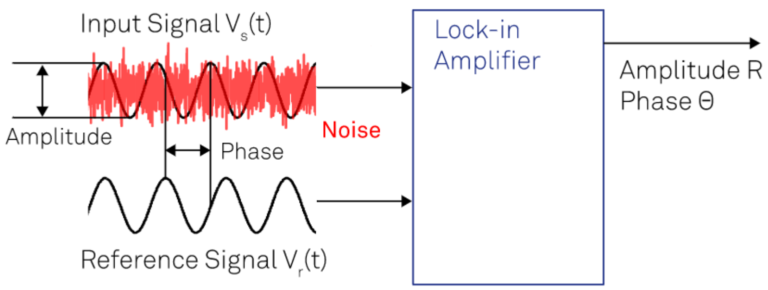

Figure 1: The lock-in amplifier can extract signal of given reference frequency and tell us both phase and frequency of the signal.

In a double phase lockin amplifier, two lockins (say, X and Y) are used with 90° phase difference between them. Now, if $R = \frac{1}{2}V_1V_2$; then output of lockin X is $Rcos\theta$ and output of lockin Y is $Rcos(90° - \theta) = Rsin\theta$, where θ is the phase difference between given signal and lockin X. Now, we can get the phase independent resultant $R = \sqrt{X^2 + Y^2}$ and phase difference $\theta = \operatorname{atan2}(Y, X)$.

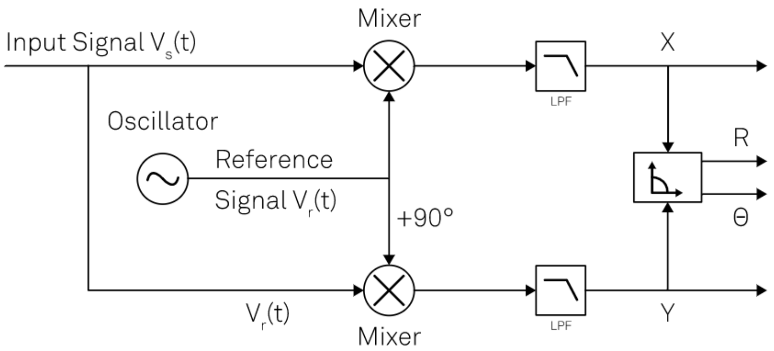

Figure 2: A schematic diagram of a double-phase lockin amplifier.

4 The Circuit Components

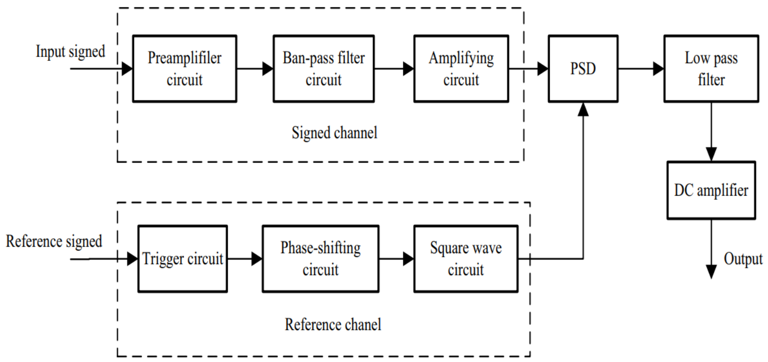

Figure 3: Lock-in amplifier internal frame diagram

The internal frame diagram of a lockin amplifier is given in diagram 3. The signal channel is passed through three major circuits, a preamplifier circuit, a band-pass filter circuit and another simplifying circuit.

4.1 Preamplifier

Since weak signals are more prone to getting mixed with the noise, a preamplifier circuit is used. Preamps are electronic amplifiers that convert a weak electrical signal into an output signal strong enough to be noise-tolerant and strong enough for further processing. Preamplifier circuits are low noise, high gain circuits with dynamic range of features. This design uses two integrated operational amplifiers, this circuit has a peripheral circuit is simple, high input impedance, can effectively suppress common mode interference characteristics. The circuit design is shown in figure 4.

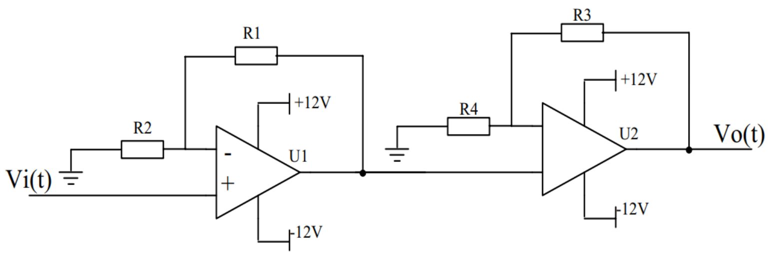

Figure 4: Circuit diagram of a preamplifier

4.2 Band-pass filter

A band-pass filter is used for separating the signal from both lower and higher frequencies, it comprises of both a low pass filter and a high pass filter. In other words, we can say that it is a combination of both. It allows through components in a specified band of frequencies, called its passband but blocks components with frequencies above or below this band. A schematic diagram is shown in figure 6.

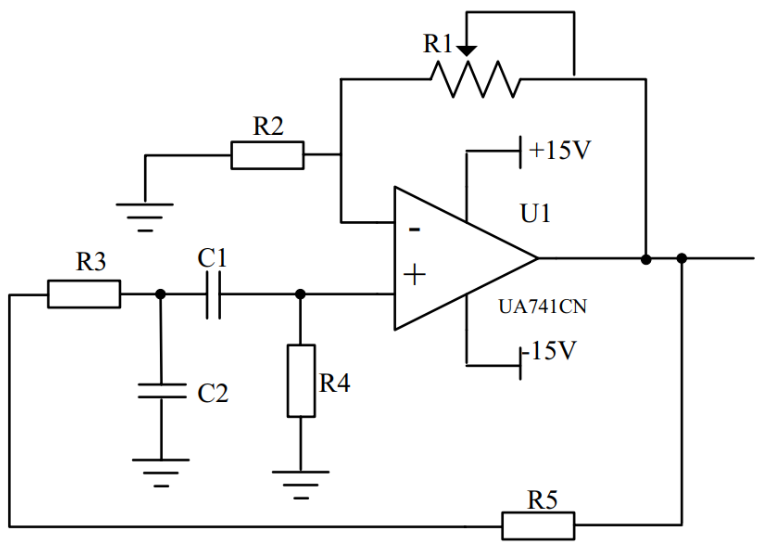

Figure 5: Circuit diagram of a Band-pass filter

4.3 AD 630 IC

The AD630 is a high precision balanced modulator/demodulator that combines a flexible commutating architecture with the accuracy and temperature stability afforded by laser wafer trimmed thin film resistors. A network of on board applications resistors provides precision closed-loop gains of ±1 and ±2 with 0.05% accuracy. These resistors may also be used to accurately configure multiplexer gains of 1, 2, 3, or 4. External feedback enables high gain or complex switched feedback topologies.

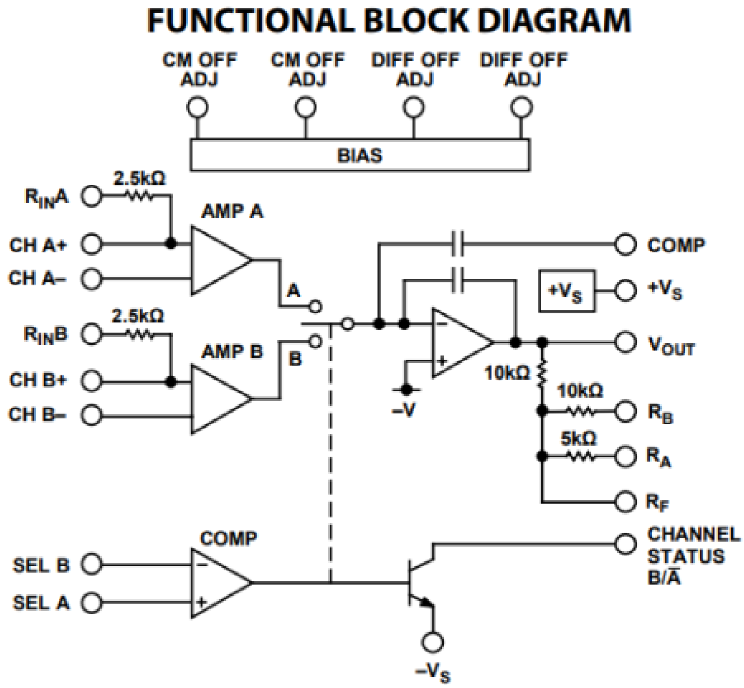

Figure 6: Functional Block Diagram of AD630

The AD630 can also be thought of as a precision op amp with two independent differential input stages and a precision comparator that is used to select the active front end. The rapid response time of this comparator coupled with the high slew rate and fast settling of the linear amplifiers minimize switching distortion. The AD630 is used in precision signal processing and instrumentation applications that require wide dynamic range. Although optimized for operation up to 1 kHz, the circuit is useful at frequencies up to several hundreds of kHz.

Other features of the AD630 include pin programmable frequency compensation; optional input bias current compensation resistors, common-mode and differential-offset voltage adjustment, and a channel status output that indicates which of the two differential inputs is active.

4.3.1 Working of AD630

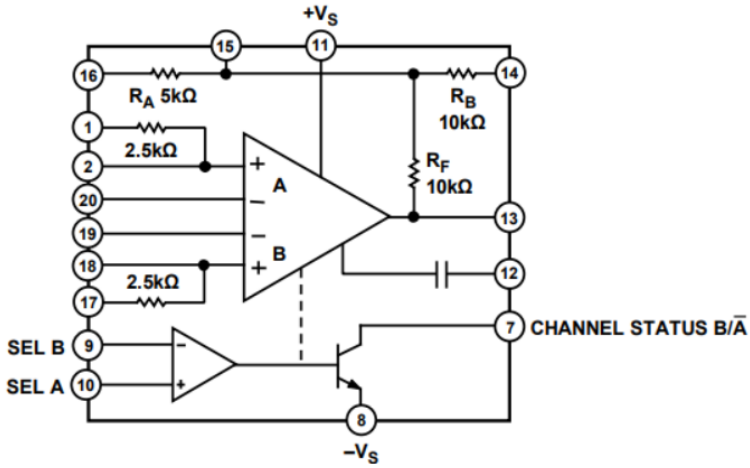

Figure 7: Pin Diagram of AD630

The pin diagram of AD630 is shown here in figure 8. The basic mode of operation of the AD630 may be easier to recognize as two fixed gain stages, which can be inserted into the signal path under the control of a sensitive voltage comparator. When the circuit is switched between inverting and noninverting gain, it provides the basic modulation/demodulation function. The AD630 is unique in that it includes laser wafer trimmed thin-film feedback resistors on the monolithic chip. The configuration shown in Figure-5 yields a gain of ±2 and can be easily changed to ±1 by shifting RB from its ground connection to the output. When Channel B is selected, the RA and RF resistors are connected for inverting feedback as shown in the inverting gain configuration diagram in Figure 7.

The amplifier has sufficient loop gain to minimize the loading effect of RB at the virtual ground produced by the feedback connection. When the sign of the comparator input is reversed, Input B is deselected and Input A is selected. The new equivalent circuit is the noninverting gain configuration shown in Figure 7. In this case, RA appears across the op amp input terminals, but because the amplifier drives this difference voltage to zero, the closed-loop gain is unaffected.

4.3.2 Circuit Description

The simplified schematic of the AD630 is shown in Figure 24. It has been subdivided into three major sections, the comparator, the two input stages, and the output integrator. The comparator consists of a front end made up of Q52 and Q53, a flip-flop load formed by Q3 and Q4, and two current steering switching cells Q28, Q29 and Q30, Q31. This structure is designed so that a differential input voltage greater than 1.5 mV in magnitude applied to the comparator inputs completely selects one of the switching cells. The sign of this input voltage determines which of the two switching cells is selected.

The collectors of each switching cell connect to an input trans-conductance stage. The selected cell conveys bias currents i22 and i23 to the input stage it controls, causing it to become active. The deselected cell blocks the bias to its input stage, which, as a consequence, remains off. The structure of the trans-conductance stages is such that it presents a high impedance at its input terminals and draws no bias current when deselected. The deselected input does not interfere with the operation of the selected input ensuring maximum channel separation.

Another feature of the input structure is that it enhances the slew rate of the circuit. The current output of the active stage follows a quasi-hyperbolic sine relationship to the differential input voltage. This means that the greater the input voltage, the harder this stage drives the output integrator, and the faster the output signal moves. This feature helps ensure rapid, symmetric settling when switching between inverting and noninverting closed loop configurations.

The output section of the AD630 includes a current mirror load (Q24 and Q25), an integrator voltage gain stage (Q32), and a complementary output buffer (Q44 and Q74). The outputs of both trans-conductance stages are connected in parallel to the current mirror. Because the deselected input stage produces no output current and presents a high impedance at its outputs, there is no conflict. The current mirror translates the differential output current from the active input trans-conductance amplifier into single-ended form for the output integrator. The complementary output driver then buffers the integrator output to produce a low impedance output.

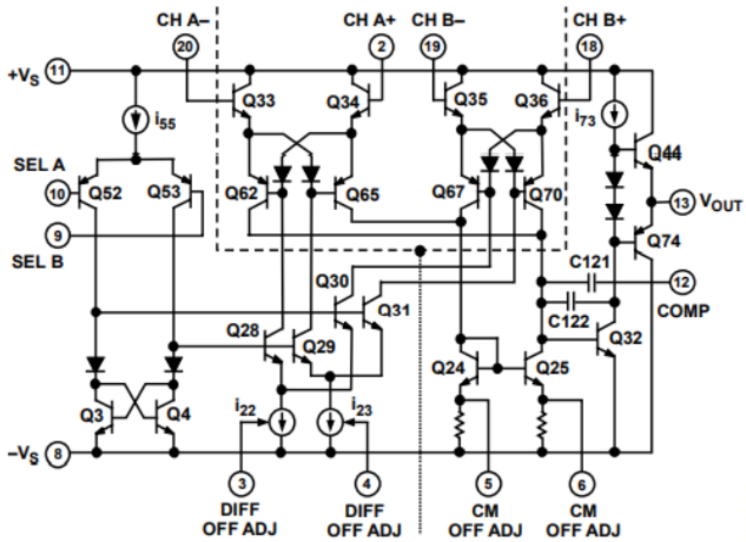

Figure 8: Another schematic Diagram of AD630

4.4 Phase-sensitive Detector

Phase sensitive detection is the core of the lock-in amplifier.The design uses AD630 as a phase sensitive detector. AD630 signal processing applications include balanced modulation and demodulation, synchronous detection, phase-sensitive detection, quadrature detection, lock-in amplifier and square wave multiplication. Here apply its phase-sensitive detection function, which has the function of integration, ease of operation and other advantages, suitable for lock-in amplifier circuit. Phase-sensitive detection circuit shown in Figure 9.

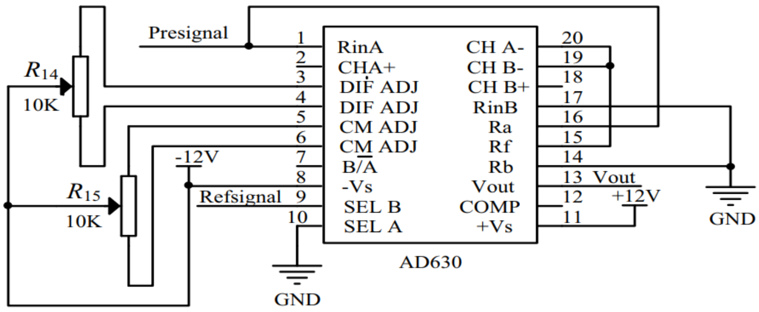

Figure 9: AD630 in circuit

4.5 Low-pass filter

Another RC low-pass filter is added after the circuit. The cutoff frequency of the filter is given by,

$$f_C = \frac{1}{2\pi RC} \tag{1}$$

where R is the resistance and C is the capacitance used in the circuit. We can change the cutoff by changing these values.

4.6 Amplifying Circuit

The amplifying Circuit consists of three integrated operational amplifiers, where N1 and N2 (Figure 9) are two performance consistent with the integrated operational amplifiers with input common form symmetric balanced differential amplifier input stage, N3 constitute a double-ended input single-ended output of the output stage for further N1 and N2 suppress common mode signal, and meet the needs of the ground load. The circuit diagram is shown in Figure 24.

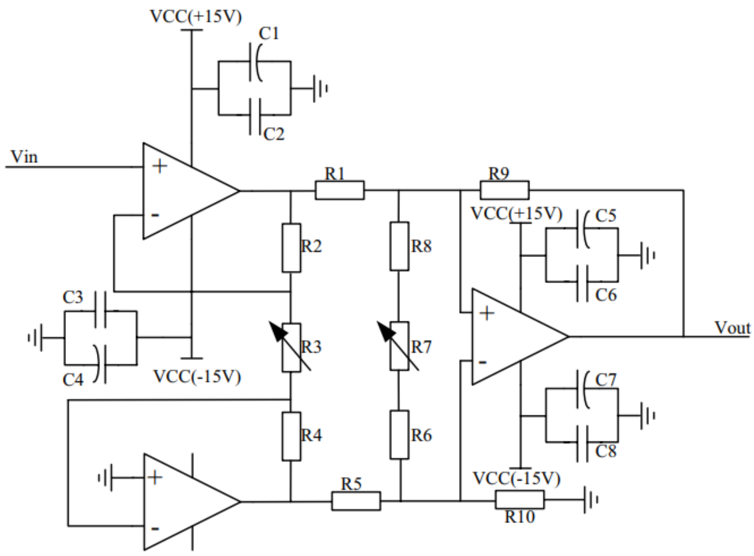

Figure 10: Circuit Diagram of Amplifying Circuit

5 Working Formulae

1. **Amplification Factor:**
   The Amplification factor is given as the ration of the output signal voltage to the input signal voltage. It is a dimension-less quantity. The slope of V_{input} vs V_{output} curve gives the amplification factor (μ).
   $$\mu = \frac{\text{Output voltage in } V}{\text{Input voltage in } V} \tag{2}$$

2. **Phase detection with double phase lock-in amplifier:**
   If the in-phase and out-phase lockin amplifiers in dual-phase lockin amplifier circuit gives the outputs X and Y respectively, then,
   $$R = \sqrt{X^2 + Y^2}$$
   $$\theta = tan^{-1}(\frac{Y}{X}) \tag{3}$$

here θ is the phase difference with X lockin.

6 Circuit Diagrams

The circuits are designed in Multisim. It allows us to use commercially available electronic components and make our desired circuits. The designs are attached below.

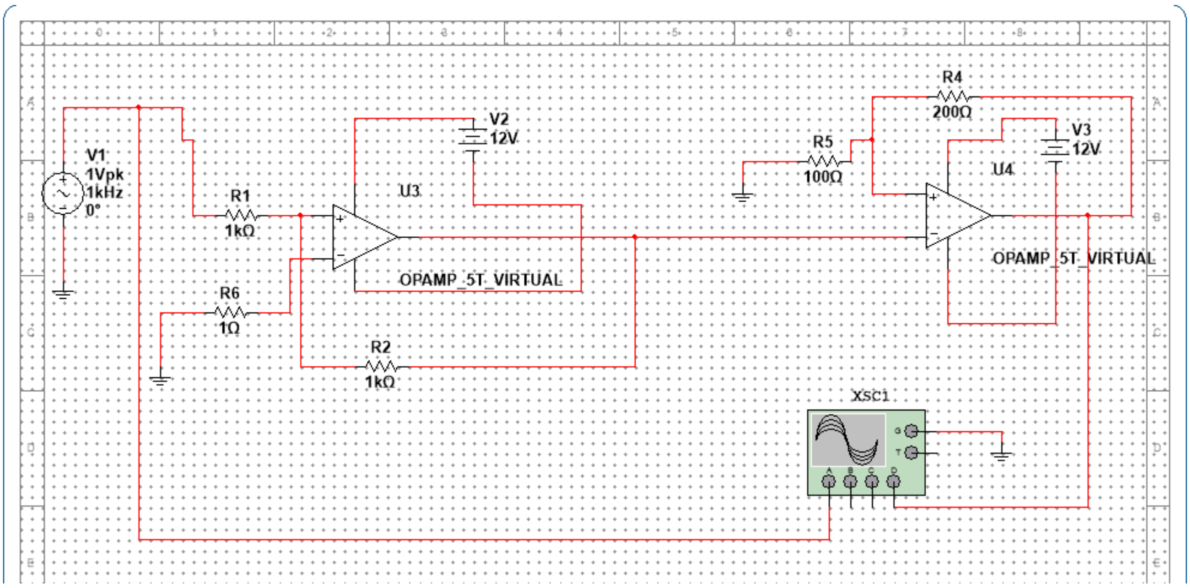

Figure 11: Circuit Diagram of Pre-amplifying Circuit

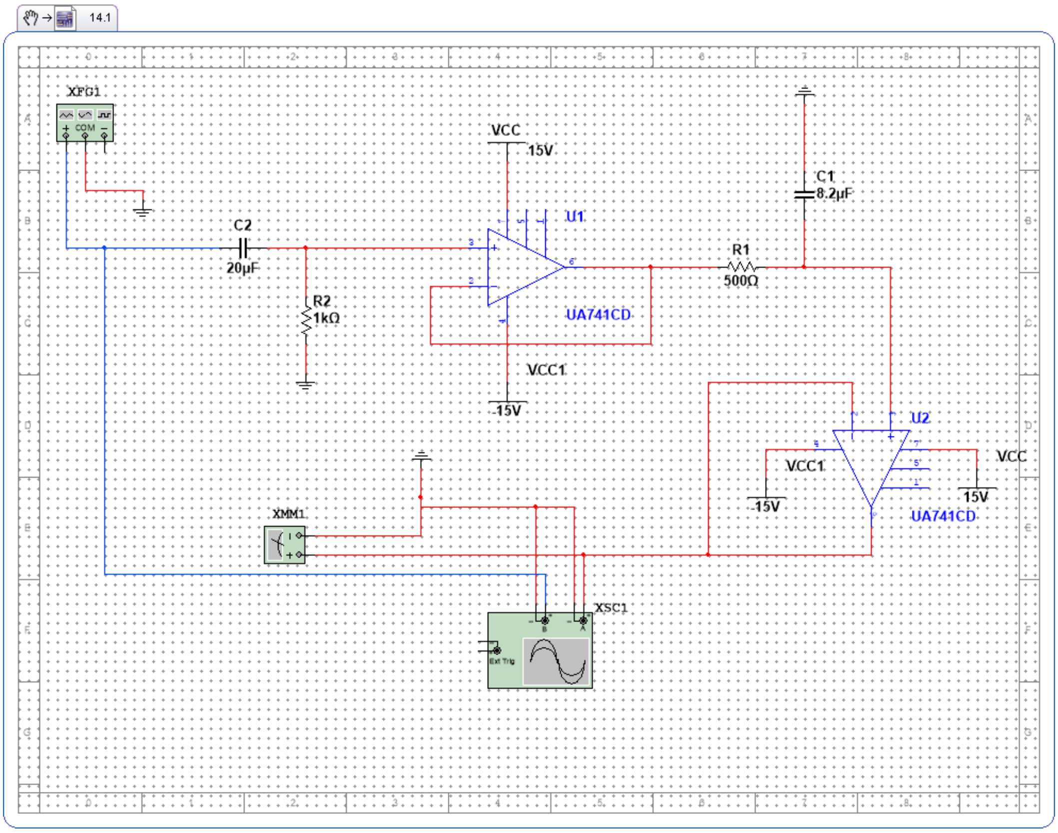

Figure 12: Circuit Diagram of Bandpass Circuit

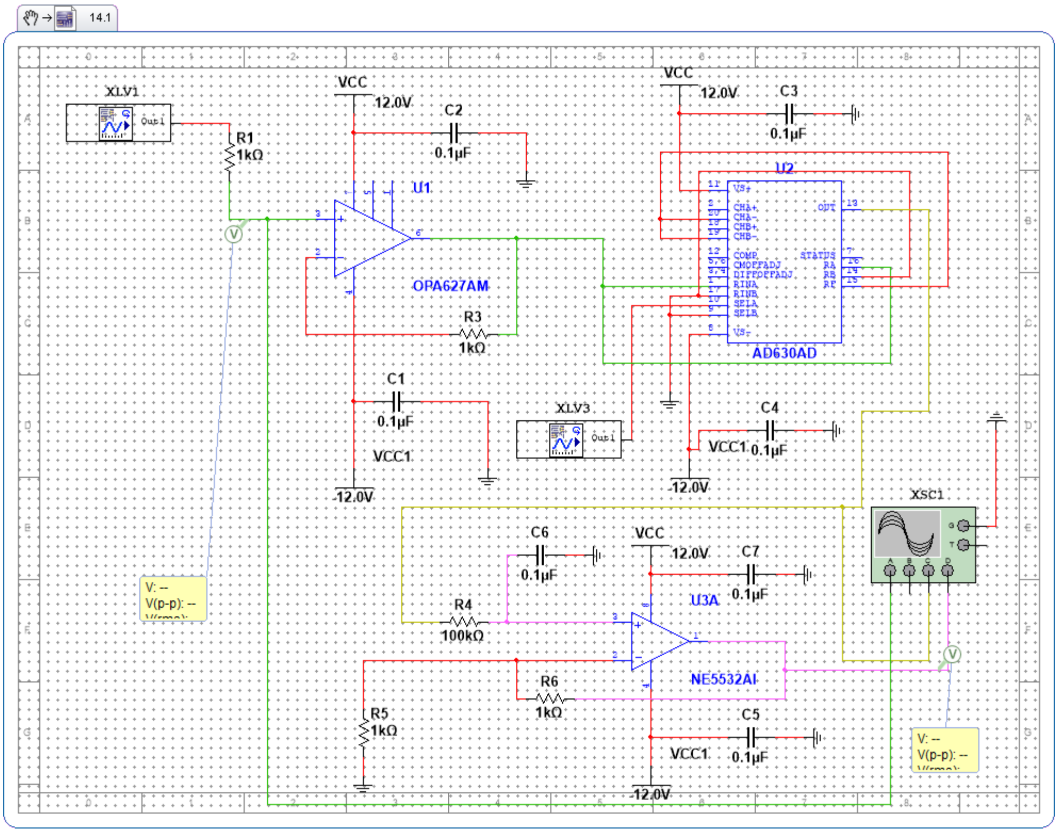

Figure 13: Circuit Diagram of Single Phase Lockin Circuit

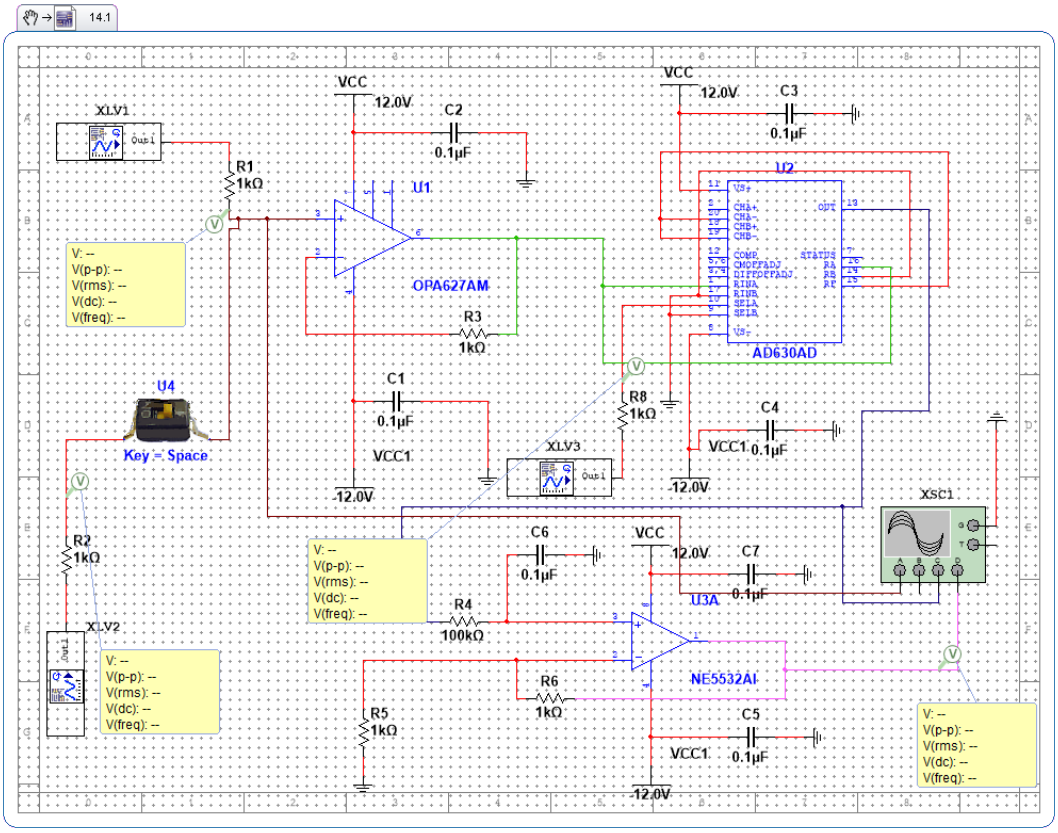

Figure 14: Circuit Diagram of Single Phase Lockin Circuit when used in a noisy source

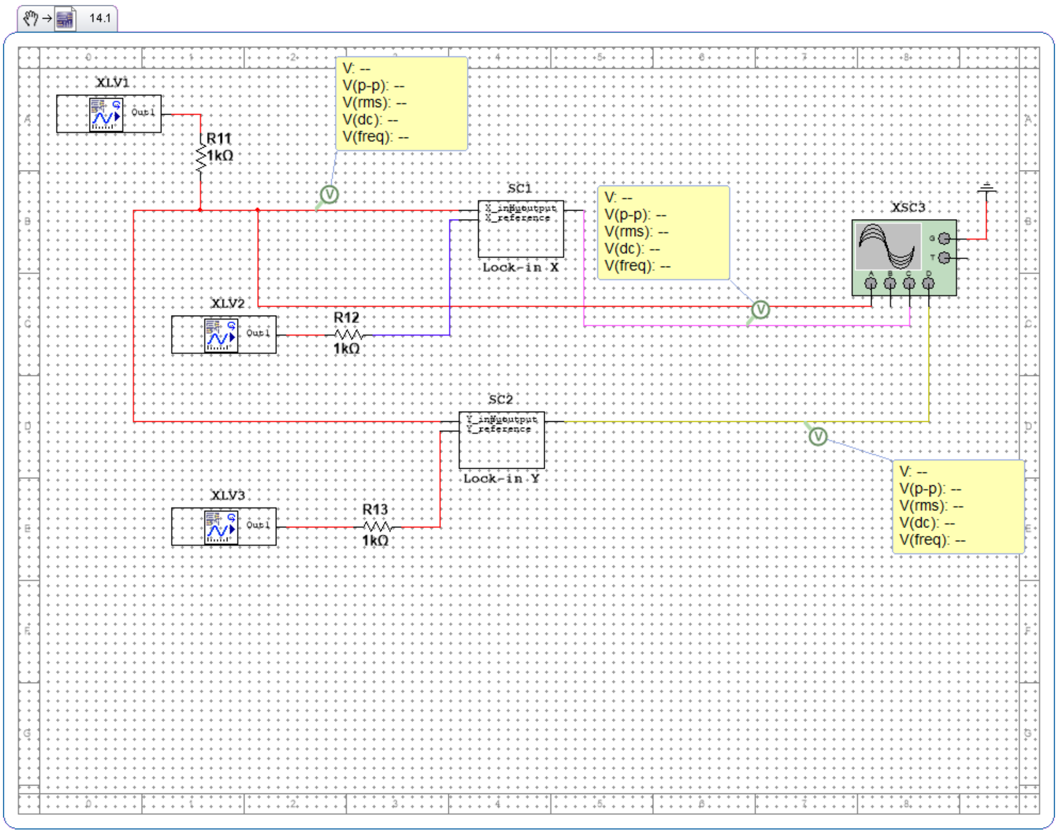

Figure 15: Circuit Diagram of Double Phase Lockin Circuit

7 Observations

7.1 Single-Phase Lock-in Amplifier

The output curves at oscilloscope for different phase shifts in single-phase lock-in amplifiers are shown in the following graphs.

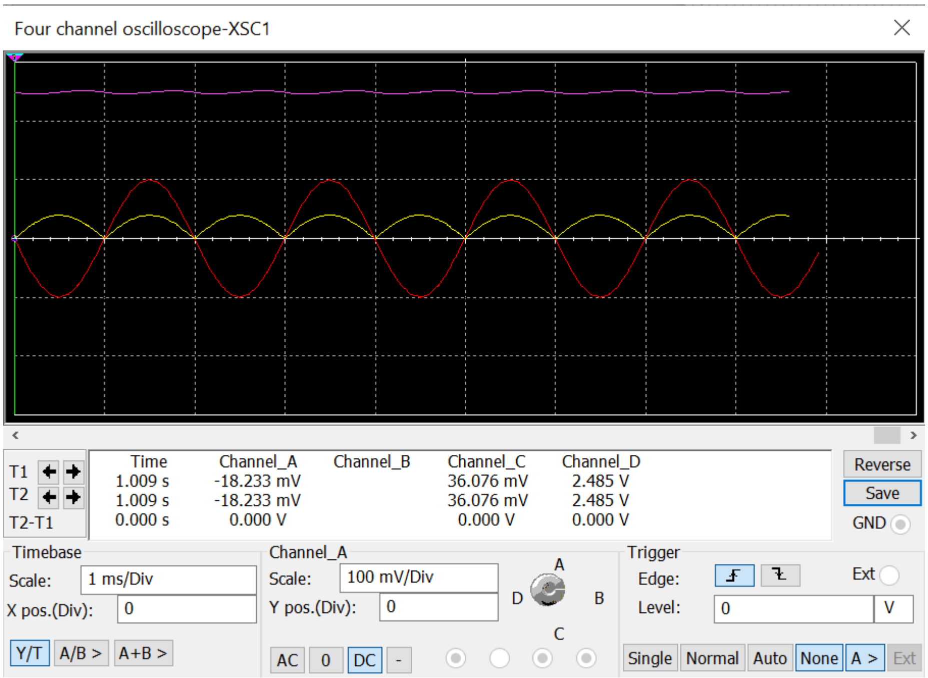

Figure 16: Oscilloscope curves for 0° phase-shift

In the diagram, the red sinusoidal curve is input source, the green one is when input source is multiplied with reference voltage in AD630 and the blue one is DC output.

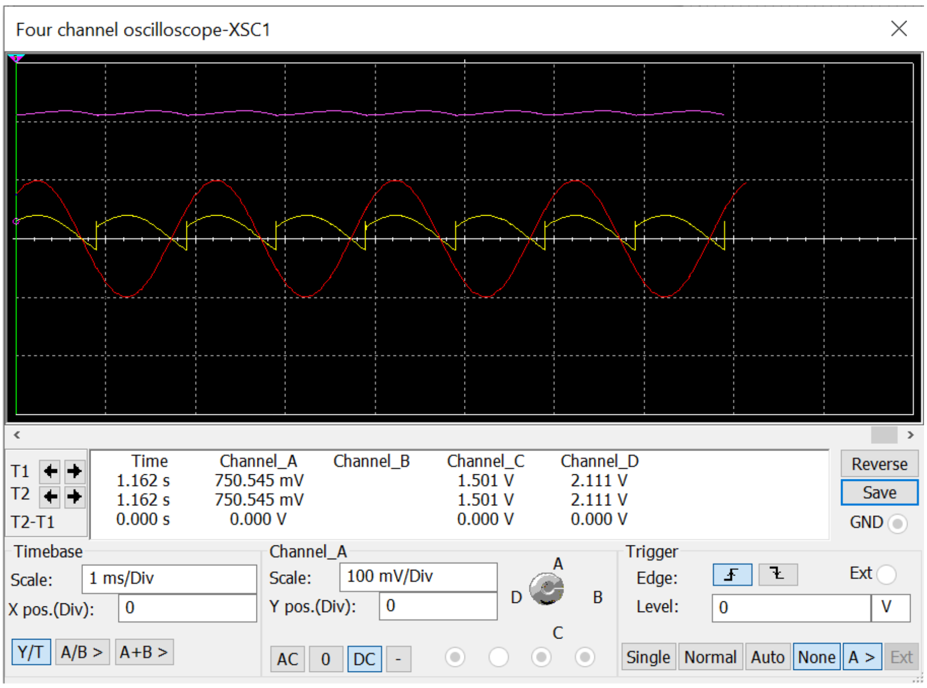

Figure 17: Oscilloscope curves for 30° phase-shift

When we increase the phase-shift, the multiplied AD630 output becomes distorted and the DC output comes down.

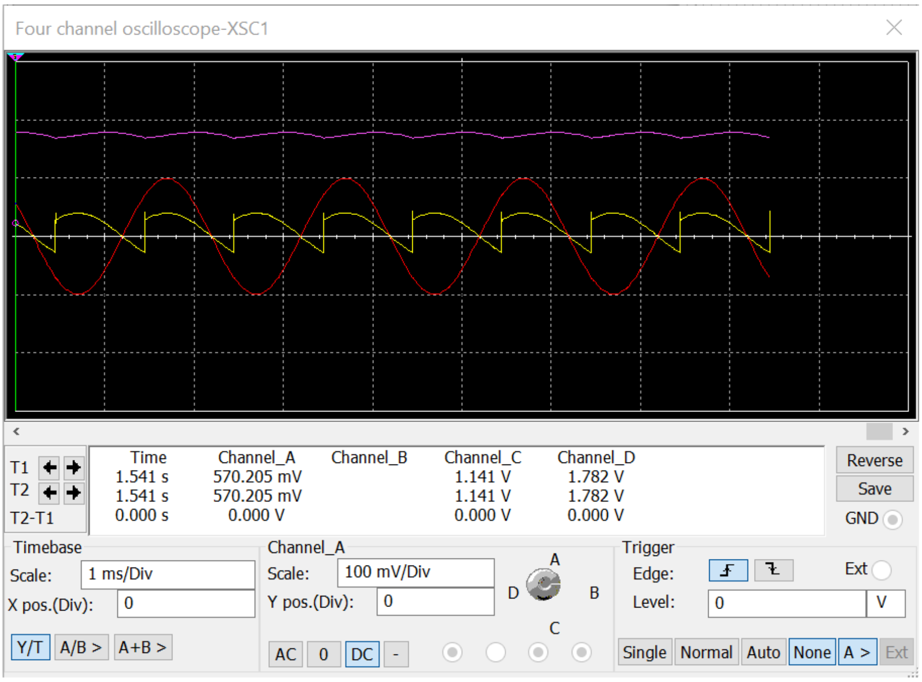

Figure 18: Oscilloscope curves for 45° phase-shift

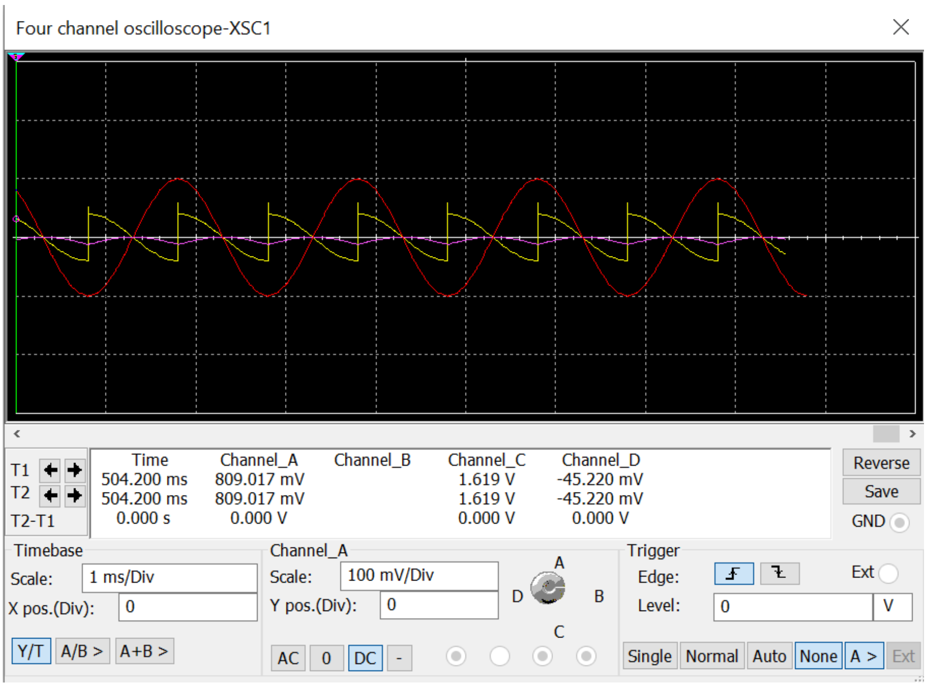

Figure 19: Oscilloscope curves for 90° phase-shift

At 90° phase-shift, the source and reference are completely out-of phase and the area between the multiplied curve and X-axis above and below axis is equal, i.e. integrated AD630 output is zero. As a result, the output DC is also zero.

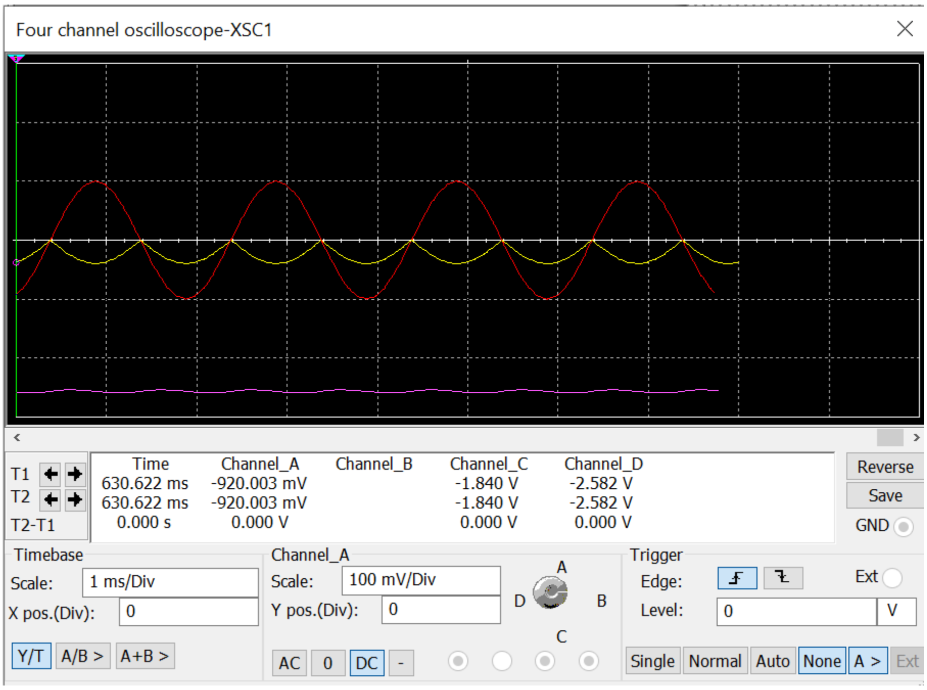

Figure 20: Oscilloscope curves for 180° phase-shift

At 180° phase-shift, the only part that will remain after multiplication are $sin(2\pi fkt)$ and $sin(2\pi(-f)kt)$. As a result, the output will be equal to zero phase-shift, but with opposite sign.

7.2 Dual-Phase Lock-in Amplifier

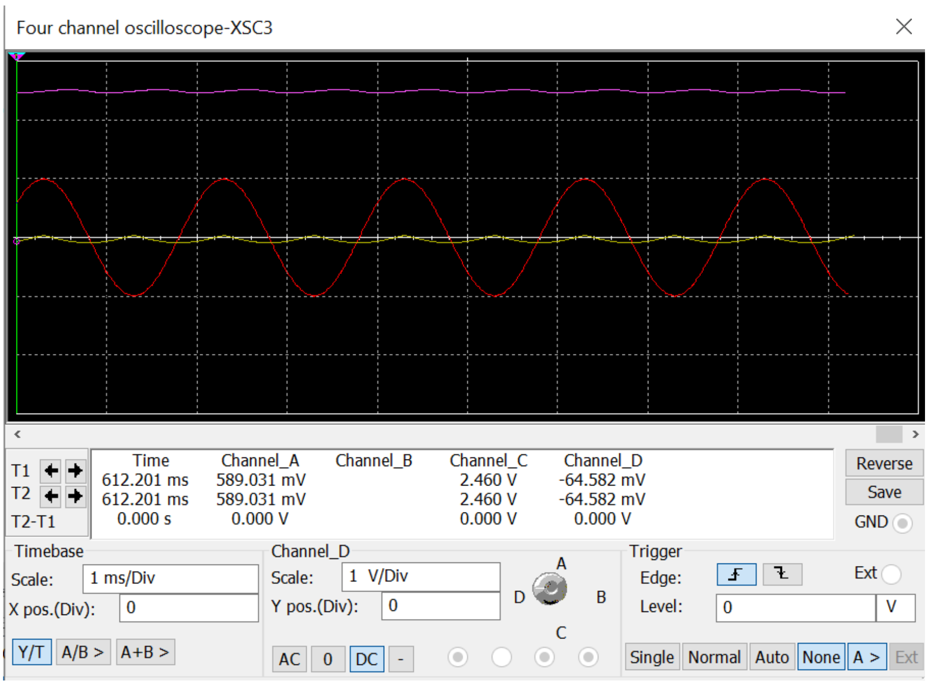

Figure 21: Oscilloscope curves for dual-phase lockin with 0 phase-shift

In this dual-phase output, the blue line is output of lockin X, completely in phase, while the green one is output of Y, which is completely out of phase.

8 Data in Tabular Format

For a constant reference frequency, 500 Hz, the input voltage was changed and the DC output was recorded to get the amplification factor.

Table 1: Table between input and output voltage
f= 500 Hz

$V_{in}(mV)$	$V_{rms}(mV)$	$V_{output}(mV)$
100	70.1	213
200	140	466
300	**210**	**719**
400	281	971
500	351	1220
600	480	1480
700	491	1690
800	561	1980
1000	701	2490
1250	876	3100
1500	1051	3600
1750	1227	4300
2000	1402	4820
2500	1753	6170
3000	2103	7470

Later, a noise of frequency 490 Hz was introduced and the percentage error was measured.

Table 2: Table between input and output voltage in presence of noise

V_{in}	V_{rms}	V_{output}	V_{output}	Percentage Change
(mV)	(mV)	without noise (mV)	with noise (mV)	
100	70.1	213	215	0.938967
300	210	719	724	0.695410
500	351	1220	1235	1.229508
1000	701	2490	2501	0.441767
1500	1051	3600	3610	0.277778
2000	1402	4820	4829	0.186722

For the dual phase lockin, data was taken with constant input voltage 1V and constant input phase 30°.

Table 3: Dual phase lockin amplifier with constant Voltage

$V_{input}(V)$	Input phase	$X_{output}(V)$	$Y_{output}(V)$	R (V)	Phase (rad)	Phase (deg)
1	0	2.43	-0.043	2.430380423	0.0176936266	1.013770129
1	10	2.4	0.385	2.43068406	0.159061502	9.113552748
1	30	2.15	1.21	2.467103565	0.5126102596	29.37040441
1	45	1.76	1.74	2.47491414	0.7796839399	44.67259911
1	60	1.23	2.14	2.468299009	1.049137655	60.11115976
1	90	-0.03	2.47	2.47018218	1.558651175	89.30413406

Table 4: Dual phase lockin amplifier with constant phase

$V_{input}(V)$	Input phase (deg)	$X_{output}(V)$	$Y_{output}(V)$	R (V)	Phase (rad)	Phase (deg)
0.1	30	0.18	0.086	0.1994893481	0.4457123126	25.53743439
0.2	30	0.399	0.214	0.4527659439	0.4922958955	28.20647708
0.5	30	0.994	0.587	1.154385118	0.533436996	30.56368851
0.7	30	1.472	0.838	1.693820534	0.5175351022	29.6525771
0.9	30	1.895	1.048	2.165485858	0.5051698232	28.94409881
1	30	2.14	1.21	2.458393785	0.5146052776	29.48471052

9 Plots

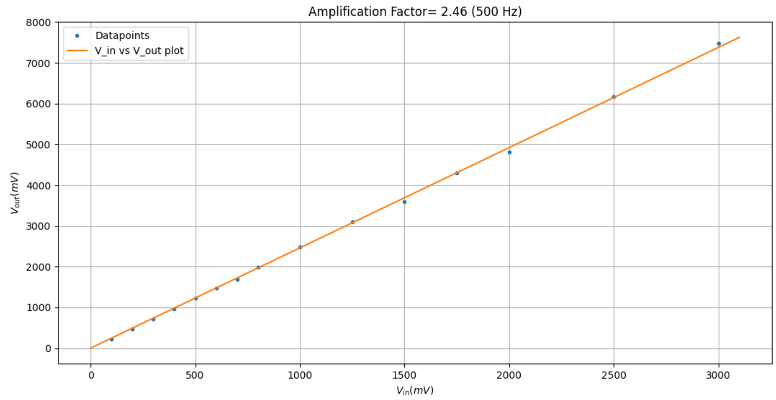

Figure 22: The input vs output voltage curve for single phase lockin amplifier

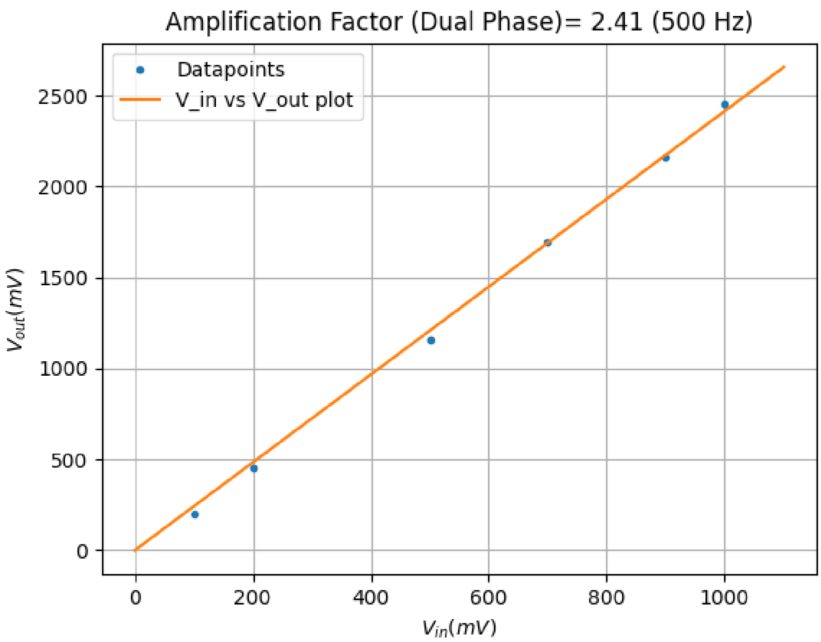

Figure 23: The input vs output voltage curve for dual phase lockin amplifier

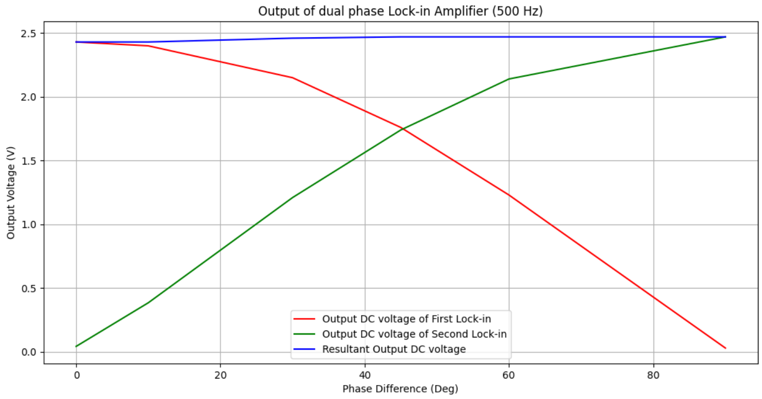

Figure 24: A comparison curve between output in X and Y lockin with resultant output

The green curve is for first lockin, which is in phase initially, but goes out of phase as we increase the input phase. It is the complete opposite for the other lockin. The resultant output remains constant throughout the experiment.

10 Results

1. **Amplification Factor:**

   - The amplification factor for single-phase lockin amplifier at 500Hz has come out to be **2.46 ± 0.07**.
   - The amplification factor for dual-phase lockin amplifier at 500Hz has come out to be **2.41 ± 0.09**.

2. **Phase-detection**
   The phase-detection in dual-phase lock-in works perfectly. From Table 4, we can see that the average percentage change in phase detection is less than 2%.

3. **Noisy Environment**
   Table 2 shows that the lock-in simulation works fine in presence of external noise. The percentage change is listed in table and it is around 1%.

11 Discussion

In this experiment, signal channel, reference channel, bandpass filter, amplifying circuits were designed using multisim software. Finally, the lockin amplifiers were designed by combining those. The simulation works fine in noisy environment and the lock-in can be used to measure phase as well. The amplification factor is quite low though, but it can be changed using different values of resistors and capacitors, thus changing the gains. There are not many sources of error, as it is a simulation model. However, there are always some errors with electrical components and they are present here as well.

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