Chapter 48
An Analog Automatic Lock-In Amplifier for the Accurate Detection of Very Low Gas Concentrations

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We propose here a new analog lock-in amplifier to be utilized in sensor interfaces for the detection of very low quantity of dangerous gases. When compared to other commercial systems in the literature, the proposed scheme shows an automatic operation, consisting in the self-alignment of the relative phase between input and reference signals. This functionality is continuously guaranteed, both at power-on and for any variation of the input noisy signal phase and amplitude during the working time. The proposed lock-in has been designed to work at a specified reference frequency (77 Hz), suitable for gas sensor applications and that avoids interferences with 50 Hz net frequency and its harmonics. The system has been tested using the carbon monoxide as gas to be revealed. With respect to the simple resistive gas sensor interface implemented by a resistive voltage divider, the improvement given by the proposed lock-in amplifier for the system sensitivity is of a factor of about 80, while the resolution, starting from about 5 ppm, has been enhanced to a theoretical value of about 0.05 ppm.

1 Introduction

The lock-in technique measures the magnitude of a signal, buried into noise, in a very narrow frequency bandwidth, while rejects all the components of the signal outside it. It shows better performance than a simple filtering operation, because of the automatic tracking that allows lock-in amplifiers to give effective quality

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factor Q values (a measure of filter selectivity) over 100,000, whereas a normal band-pass filter does not give a Q greater than 50.

In sensor interface design, sometimes it is necessary to maximize the system resolution to reveal very low quantities of toxic gas concentrations. In this sense, the lock-in amplifier can be employed when the measurand shows a very small amplitude, also lower than noise level.

Commercial lock-in amplifiers, as well as ad-hoc lock-in solutions recently proposed in the literature [1, 2], typically of digital kind, have high dimensions and costs, since they are based on DSP. In this sense, especially in sensor applications, the analog kind of the signal to be revealed suggests, when the signal-to-noise ratio is about less than unity, the use of analog lock-in systems [3–6].

Traditional lock-in amplifiers (both analog and digital) have the characteristic of requiring, at power-on as well as during its working time, the manual zeroing of the output signal, related to the "in-quadrature" (90°) condition (initial phase alignment) between input and reference signals. Then, the manual activation of a switch gives a $-90°$ phase shift, achieving the required "in-phase" condition that allows to read a non-zero output voltage proportional to the mean value of the input signal, typically buried into noise.

The here presented automatic analog lock-in amplifier, which represents an advance of the topology proposed in [6] (patent pending [7, 8]), overcomes this disadvantage, being the "in-phase" condition always and continuously guaranteed by an automatic operation, ensured by a suitable feedback. Preliminary experimental measurements have been conducted on the designed system (implementing a PCB prototype based on a commercial operational amplifier as active block and precise passive components) using carbon monoxide (CO) as testing gas and FIGARO TGS2600 as commercial sensor. The achieved results have confirmed the correct functionality of the designed amplifier, as well as the system capability to reveal very small signals coming from resistive sensors with a good sensitivity and resolution improvements.

2 The Proposed Solution: The Automatic Lock-In Amplifier

The proposed analog automatic lock-in architecture, at block level, is shown in Fig. 48.1. Each block, internally, has been implemented through commercial discrete active and passive components. The system continuously provides the required "in-phase" condition by means of an automatic operation (phase self-alignment) given by suitable feedback connections. The final blocks of the proposed architecture are low-pass filters that perform a DC extraction ensuring the specific improvement of system resolution. The amplifier presents two AC inputs and three DC outputs: the two calibration outputs must be zero, in this case the measured value $V_{O,MEASURE}$ is proportional to gas concentration.

Figure 48.2 depicts an example of the measured main signals $V_{O,MEASURE}$ and $V_{O,CALIBRATION}$ (the lock-in time responses) when an input clean signal has been

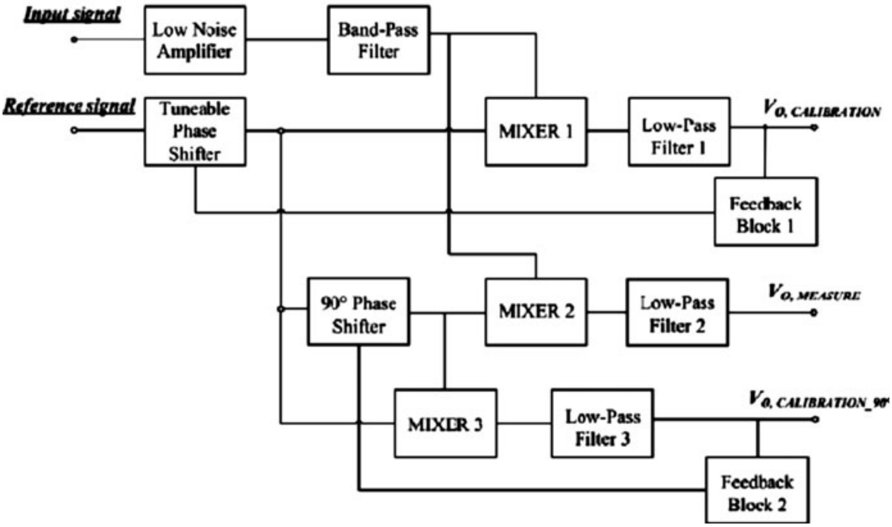

Fig. 48.1 The block scheme of the proposed automatic analog lock-in amplifier

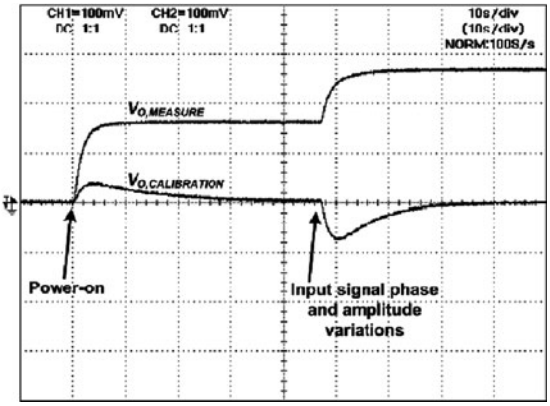

Fig. 48.2 Automatic analog lock-in time responses: system self-alignment at power-on followed by input signal phase and amplitude variations (ΔV_{IN} =2 mV; $\Delta\varphi$ = 20°)

applied, showing the system self-alignment at its power-on and when amplitude (2 mV) and phase (20°) variations have simultaneously occurred.

3 Experimental Measurements

The proposed lock-in amplifier has been implemented through a PCB prototype for preliminary experimental measurements. It has been tested by the set-up scheme reported in Fig. 48.3 to detect the presence of toxic gas into a closed chamber, in

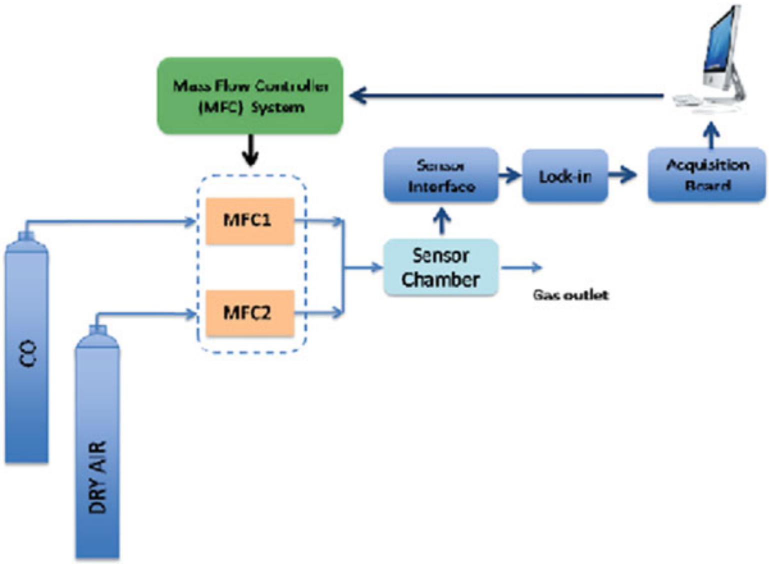

Fig. 48.3 Experimental set-up for the *CO* detection through the commercial resistive gas sensor FIGARO TGS2600

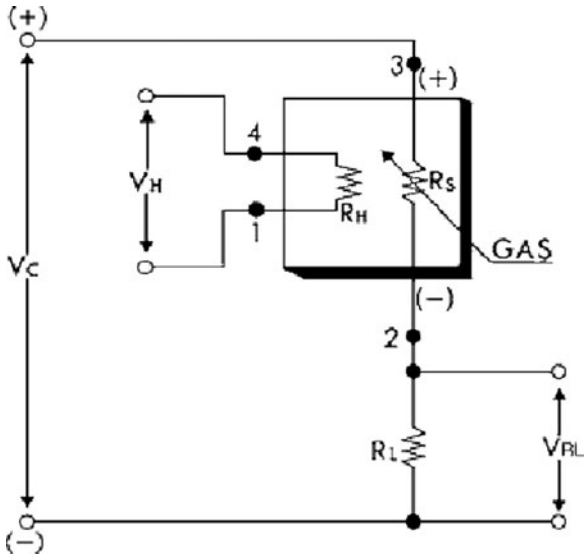

Fig. 48.4 FIGARO TGS2600 mounting scheme

particular *CO* (10, 20 and 30 ppm). The resistive gas sensor (R_S) FIGARO TGS2600 has been supplied through a 77 Hz sinusoidal voltage signal having 30 mV maximum amplitude (V_C, with a DC level of 5 V), in series with a reference load resistance, R_L, valued 10 kΩ, as sown in Fig. 48.4. The heater resistance R_H has

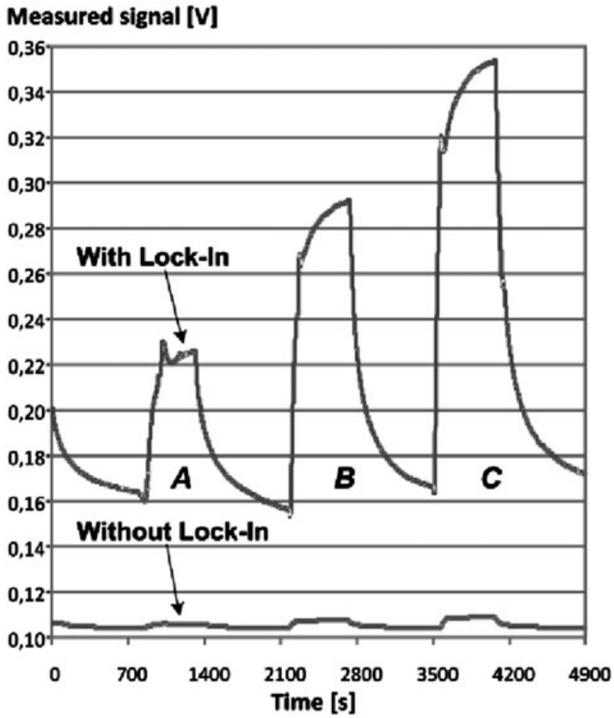

Fig. 48.5 Measured time response of the extracted DC voltage signal at the proposed lock-in output and voltage signal at the system input vs. time for different *CO* concentrations (A = 10 ppm, B = 20 ppm, C = 30 ppm)

been powered with a DC voltage level V_H equal to 5 V. In repeated measurement sessions, for 9 minutes into a closed chamber, a mixture of dry air and *CO* at different concentrations, alternated with a 14 min of dry air only, has been fluxed.

Figure 48.5 shows typical system time responses, considering both input and output DC lock-in amplifier signals for different *CO* concentrations, as detailed in Table 48.1, where the mean values of the sensor resistance have been determined over all the experimental measurements. These voltage signals have been revealed and acquired through a DAQ board, with a sampling rate equal to 1 s, allowing to estimate both the gas sensor resistance value and its variation, under the presence of different *CO* concentrations. Through a straightforward analysis of the experimental results, the sensitivity improvement given by the proposed lock-in amplifier results to be of a factor of about 80 (circuit input sensitivity ≈0.08 mV/ppm; circuit output sensitivity ≈6.5 mV/ppm), while the resolution, starting from about 5 ppm (system input resolution), has been enhanced to a theoretical value of about 0.05 ppm (system output resolution), achieving an improvement factor of about 100 for a measured noise level of about 0.30 mV.

Table 48.1 Experimental results achieved through the fabricated PCB prototype with related sensor resistance (R_S) estimation (see Fig. 48.5)

Measurement time [min]	*CO* concentration [ppm]	Mean sensor resistance $< R_S >$ [kΩ]
0–14 Initial cleaning	(Dry air only)	128
14–23 (A) Dry air + CO mixture	10	91
23–37 Cleaning	(Dry air only)	130
37–46 (B) Dry air + CO mixture	20	69
46–60 Cleaning	(Dry air only)	129
60–69 (C) Dry air + CO mixture	30	56
69–83 Final cleaning	(Dry air only)	129

4 Conclusions

The proposed fully-analog automatic lock-in amplifier has been demonstrated to be suitable for sensor interface applications and, in particular, for very low gas concentration detection. It has shown the capability to perform a phase self-alignment between the input and reference signals so to provide continuous and accurate measurements of the input signal amplitude. The designed system improves the minimal resolution of the sensor front-end, allowing the detection of very small sensor resistance variations, corresponding to very low quantity of target gas concentrations. These performances can be particularly useful in detecting some kind of toxic gases where also the presence of reduced quantities can be particularly dangerous.

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