CIRCUIT ARRANGEMENT TO MITIGATE INTERFERENCE IN THEMEASUREMENT OF SMALL MAGNETIC FIELDS

Enrique Zothner[1]*, Julio G. Zola[2]

[1] Laboratorio de Instrumental y Mediciones - Dto. de Electrónica - FIUBA, Buenos Aires, Argentina.
[2] Laboratorio de Circuitos Electrónicos - Dto. de Electrónica - FIUBA, Buenos Aires, Argentina.

*e-mail: ezothn@gmail.com

ABSTRACT

The measurement of very low intensity magnetic fields in the ultra-low frequency range (less than 10 Hz), brings with it the need to mitigate the influence of interfering magnetic fields, especially the 50/60 Hz (electrical grid) present at the antenna. The front amplifier is connected to a magnetic antenna, which is used for the detection of weak ultra-low frequency fields, it has a very high gain (above 100 dB), and therefore the residual field of the electrical grid saturates the amplifier, not allowing the measurement or subsequent filtering of the incoming signal. The purpose of this paper is to evaluate different circuit arrangements, based on the introduction of a feedback loop in the circuit. The loop is closed through an auxiliary coil coaxial with the receiving magnetic antenna in order to reduce the interfering signal. Both the level of spurious signal reduction and the stability of the amplifier will be analysed taking into account the addition to the circuit of analog filters, digital filters or a phase-locked loop into the feedback loop.

Keywords: Amplifier, Antenna, EMI, Feedback, Interference, Magnetic Field, PLL, Electrical Grid

RESUMEN

La medición de campos magnéticos de muy baja intensidad en rangos de frecuencia ultra baja (Menos que 10 Hz), trae consigo la necesidad de mitigar el ruido generado por campos magnéticos interferentes, especialmente los de 50/60 Hz (red eléctrica) presentes en la antena. El amplificador frontal está conectado a una antena magnética, que se utiliza para detectar campos débiles de frecuencia ultra baja, tiene una ganancia muy alta (sobre 100 dB), y en consecuencia el campo residual de la red eléctrica satura el amplificador, impidiendo la medida o el filtrado subsiguiente de la señal de entrada. El propósito de este trabajo es evaluar diferentes arreglos de circuitos, basados en la introducción de un bucle de retroalimentación en el circuito. El bucle es cerrado por medio de una bobina coaxial auxiliar con la antena receptora magnética con el objetivo de reducir la señal interferente. Tanto el nivel de reducción de la señal espuria como la estabilidad del amplificador serán analizados, teniendo en cuenta la adición del circuito de filtros análogos, filtros digitales o bucles de fase cerrados en el bucle de retroalimentación.

Palabras Claves: Amplificador, Antena EMI, Retroalimentación, Interferencia, Campo Magnético, PLL, red eléctrica.

1. Introduction

An amplifier has been designed for the detection of weak magnetic fields ultra-low frequency range, which receives the induced voltage from a 300 turns loop antenna (magnetic antenna) (Fano *et al,* 2017).

The characteristics of this amplifier are (Gray *et al,* 2009):

- Low equivalent input noise: less than 1 µV.
- High gain: greater than 100 dB.
- High common mode rejection greater than 100 dB.
- Bandwidth: up to 30 Hz.

Under these conditions, the scattered 50/60 Hz fields from the electrical grid, can be found in all environments and can be so high that they can saturate the amplifier and thus it cannot detect weak signals of ultra-low frequencies (Fig. 1) (Schaffner Group, 2013; Zothner *et al*., 2018). The frequency of 50 Hz will be taken in the examples for the rest of this paper (it is the frequency used in our country, Argentina).

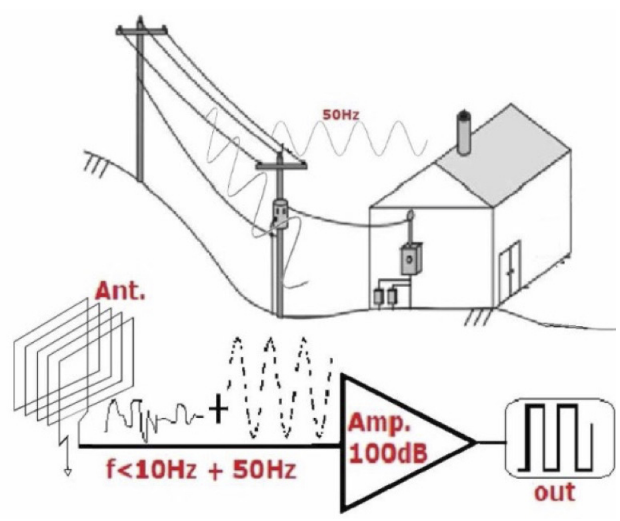


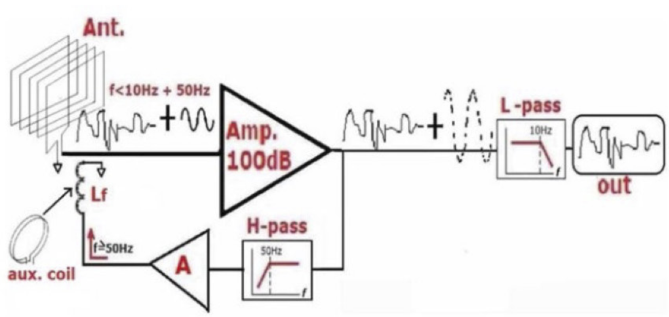
Figure 1. Saturation of the high gain amplifier due to interfering signals that mask the measurement of weak fields.

The simple solution of adding an input low pass filter to eliminate the 50 Hz would bring the following disadvantages:

- Active filter: it would be difficult to implement given the levels of interfering signal, which could add noise to the input of the amplifier.
- Passive LC filter (not RC since it would add noise to the amplifier input): this solution would require the introduction of several low-pass LC networks to achieve adequate attenuation, which would make the filter very complex and bulky to reach a bandwidth of at least 10 Hz.

The solution to reduce the gain of the amplifier also reduces the interference as well as the sensitivity of the measurement system.

To avoid degrading the amplifier characteristics we connect a feedback through a magnetic loop of 4 turns at its input, Lf, coaxial with the magnetic antenna and electrically isolated from the input amplifier as illustrated in Figure 2.



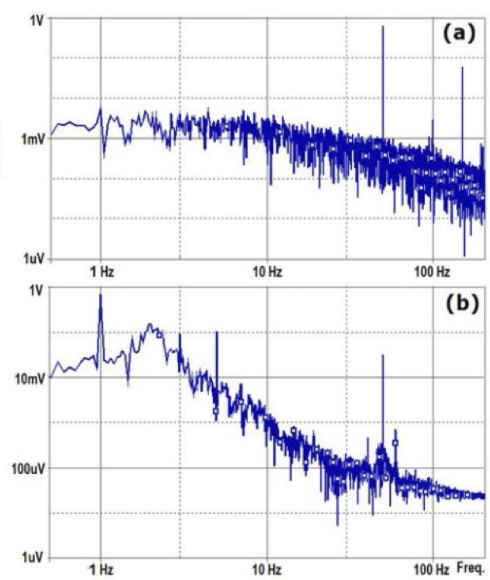


Figure 2. An arrangement using a magnetic coupling feedback and an analog high-pass filter. (a) Amplifier response without feedback through Lf. (b) Amplifier response with feedback through Lf.

This feedback injects a current to Lf from the amplifier "A", in opposition to the interfering 50 Hz signal. Since the signal is in the range of ultra-low frequencies, a high-pass filter is necessary for the feedback to attenuate only signals with frequencies of 50 Hz and above and it does not affect the gain of the signals to be measured. That is to say, for ultra-low frequencies the feedback loop will be open or will be very weak. Therefore, the current in the auxiliary coil reduces the 50 Hz interfering signal at the input amplifier. Complete elimination is not necessary (residual 50 Hz can be observed), since this frequency will be reduced later by a filter. In this way, the maximum gain of the high gain amplifier can be used in the presence of 50 Hz interfering fields.

It should be noted that a feedback loop without electrical isolation is not suitable, direct signal injection at the amplifier input would not only affect its noise level but also the input impedance.

2. Circuit arrangements analysis

Our purpose is to measure very low intensity magnetic fields by means of a loop antenna connected to a high gain low noise amplifier in the presence of 50 Hz magnetic fields. The power supply of the amplifier is isolated from the battery by a DC to DC converter.

The amplifier has a feedback loop according to the arrangement shown on Figure 2, a first-order high-pass filter with a cut-off frequency between 40 and 50 Hz was used. Figure 2 shows the spectrum of the output signal without feedback (Fig. 2a) and with feedback (Fig. 2b). 1Hz and 5Hz fields (40dB lower than the 50 Hz field) were injected at the magnetic antenna. The saturation effect of amplifier is shown in Figure 3a due to the high level of the 50 Hz and its harmonic components. Figure 2b shows the effect of the feedback: attenuating the interfering signal and amplifying 1 Hz and 5 Hz.

As stated, this first circuit arrangement was made using a first order filter in the feedback loop. However, this filter has an attenuation slope of 20 dB/decade and reduces the gain (around 12 dB at 10 Hz) of the amplifier at frequencies of interest.

To increase the 50 Hz attenuation of the previous circuit by adding a multi-pole high-pass filter would not be adequate, since the phase shift of the signal would make the circuit unstable. In our case, an arrangement with a fourth order filter makes the circuit unstable and oscillate at 80 kHz, close to the resonance frequency of the magnetic antenna, with a second order filter an oscillation was observed at 600 Hz. If we need to mitigate a more severe interference, with higher amplitudes of the 50 Hz magnetic spurious field, an improvement is necessary.

Two new circuit arrangements are shown:

The first circuit arrangement proposed is a digital solution. The output of the amplifier is connected to an analog to digital converter (A/D) and then to a digital high-pass filter or digital band-pass filter in real time, with a very steep slope (Fig. 3) (Rabiner, Rader, 2018; Analog Services, 2016). Then the signal is transformed back to analog by means of a digital to analog converter (D/A) and then is injected to Lf through amplifier “A”.

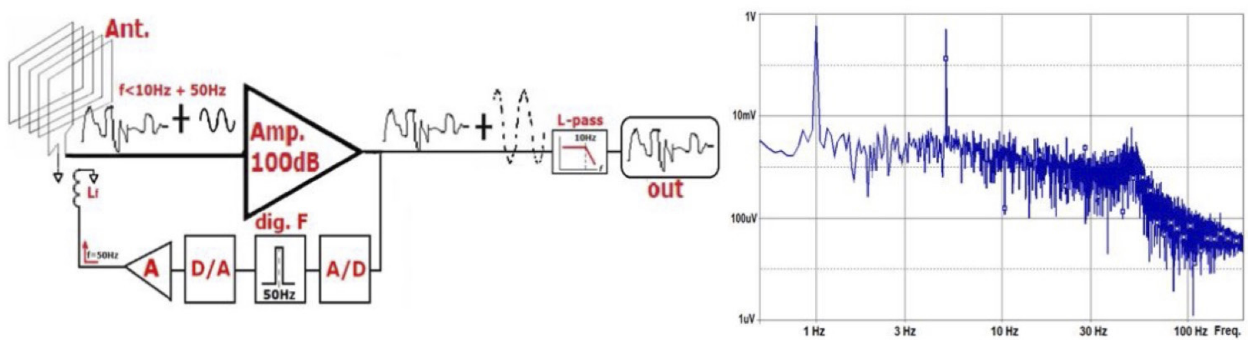


Figure 3. An arrangement using a magnetic coupling feedback loop and a digital band-pass filter and amplifier response of this arrangement.

With a digital filter we can have as many poles as necessary only changing the software appropriately, having the possibility of varying their coefficients to optimize the response (Sherry, 2013). We can add as many poles in the programming, since it is not necessary for the response to be flat.

The output signal of the digital filter (50 Hz) is applied to the auxiliary coil Lf through amplifier “A”, in opposition to the interfering input signal. Thus, when the interfering signal and the feedback signal are added by magnetic coupling, the amplitude of the interfering signal is reduced to the input of the high gain amplifier. In this way, this amplifier will not saturate in the presence of 50 Hz fields (much greater than the ultra-low frequency weak fields).

The amplitude of the 50 Hz signal at the output of the high gain amplifier will be regulated by the feedback. That is, the output signal of amplifier “A” will adapt to the conditions of the interfering signal at the measurement site.

The Figure 3 shows the simulation of the amplifier response, where the almost complete elimination of the 50 Hz signal can be observed.

The second circuit arrangement proposed is an analog solution, with a phase locked loop (PLL) as shown in Figure 4. This circuit could be simpler than the digital filter arrangement but it could add distortion and noise to the measurement system.

A PLL is a circuit capable of generating an oscillation whose phase is referred to an input signal. A feedback loop compares the phase between v1 and v2 (Fig. 4a) (Miyara, 2005).

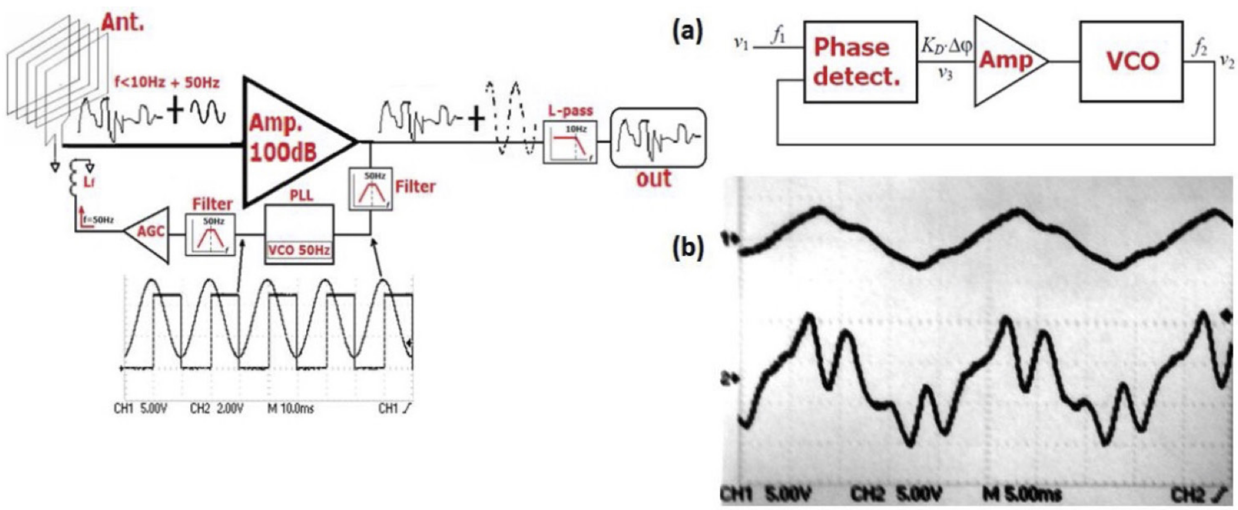


Figure 4. Circuit arrangement using a magnetic coupling feedback and a PLL. (a) PLL basic diagram. (b) Output signal without (top) and with (bottom) PLL into the feedback loop.

The phase detector produces a signal $KD\Delta\varphi$ proportional to the phase difference between the input signal v1 and the signal v2 generated by the voltage controlled oscillator (VCO). The VCO produces a frequency f2 that varies linearly with its input voltage. The equilibrium state is reached when the filtered and amplified KDDΔφ signal causes the VCO to oscillate at exactly the same frequency as the input f1.

For a proper operation of the PLL system it is necessary to have a 50 Hz signal at the output of the high gain amplifier Morgan, 2003. The 50 Hz signal amplitude should be small enough at the output of the high gain amplifier to ensure that it is working within its linear zone, so a suitable filter can remove the 50 Hz later. The output frequency of the PLL will be around 50 Hz. To set a minimum required level of the spurious signal at the amplifier output; an automatic gain control (AGC) must be used to inject the appropriate level at Lf. The AGC will inject the 50Hz signal to Lf (in opposition to 50 Hz input signal).

As shown in Figure 4, filters will be used to improve the behavior of the system if necessary. It should be noted that the free running frequency of the VCO must be adjusted between 40 Hz and 60 Hz. The output of the high gain amplifier is connected to the input of the phase detector.

The Figure 4b shows the output signal without PLL (top) and with PLL (bottom) into the feedback loop. In the bottom waveform it can be seen the mitigation of 50Hz component.

Additional feedback loops can be added to mitigate the harmonic components of the 50 Hz, specially the second and third harmonics. This can be done by adding two more loops with PLLs, adjusted at 100 Hz and 150 Hz, respectively.

It should be noted that preliminary tests have been realized on this arrangement and the next step will be to adjust the phase shift in the arrangement feedback loop.

3. Conclusions

The detection of ultra-low frequencies weak magnetic fields requires the use of very high gain amplifiers, and it is necessary to mitigate the 50/60 Hz spurious interfering signal, to prevent the saturation of the amplifier.

In this paper, different circuit arrangements were proposed, they are based on the feedback of the interfering signal through a magnetic coupling loop:

Arrangement 1: with a high-pass analog filter.

Arrangement 2: with a digital filter.

Arrangement 3: with a PLL.

The arrangement "1" is the simplest, although it affects the bandwidth and the gain of the amplifier. Increasing the order of the filter can cause instabilities and oscillation in the circuit.

The arrangement "2" achieves the best solution, but its implementation is complex and expensive. Even so, this arrangement should be studied in detail for critical measurement systems according to the relationship between useful and interfering signal levels.

In the arrangement "3" it is important to pay attention for possible effects of signal distortion.

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