

PCB-ACB2 Board for AC Voltage and Current Sensing.

A description including signal-conditioning and calibration associated circuits.
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1. Introduction

The PCB-ACB2 board allows users to acquire instantaneous voltage and RMS (*Root Mean Square*) current magnitudes from conventional 230VAC lines. Outputs are isolated and prepared for connection to an A/D (analog to digital) converter. Although initially designed for use with renewable (wind and solar) energy conversion systems and sinewave or modified-sinewave inverters, this board can easily be adapted for home or industrial use.

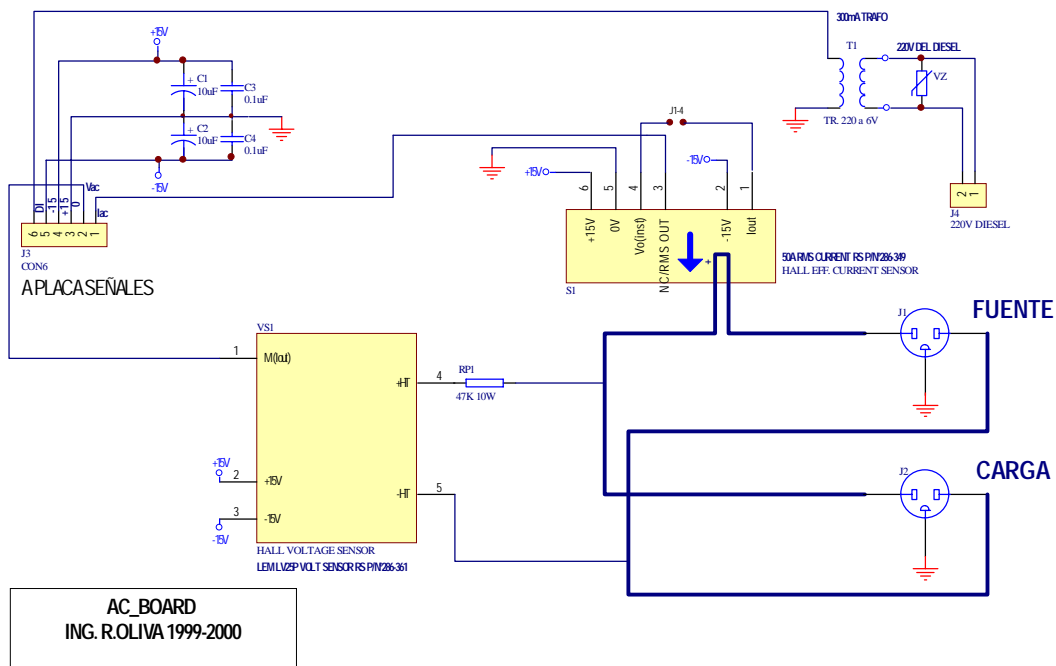


Figure 1: Schematic for PCB-ACB2

The PCB-ACB2 board uses Hall-effect sensors for voltage and current assessment. These sensors require regulated supplies of +/-15V CC at less than 100mA currents. The galvanically isolated outputs on CON6 are: V(iac), I(Vac). With the RMS current sensor installed (type LEM-RS 286-349 for 50A), V(iac) output is 1V DC for maximum (full scale) line current. The voltage sensor (LEM type LV25P / RS 286-361) output I(Vac) is 25mA nominal for maximum primary voltage excursion (depending on R1). Measurement of a voltage from the secondary output requires the use of a measurement resistor, as described in 2. This board is usually

panel-mounted within the line-switch cabinet, and connects to the rest of the data acquisition system through a shielded cable. An additional signal-conditioning circuit is discussed in [2.](#), to transform the measurement magnitudes $V(Iac)$, $I(Vac)$ into adequately filtered 0-5Vdc ó 0-10Vdc, compatible with most commercial A/D converters. As will be shown, this circuit can include amplifiers, a precision rectifier / gain block for pure sinewave line voltage measurements, or an integrated RMS/DC converter for arbitrary line voltage waveforms.

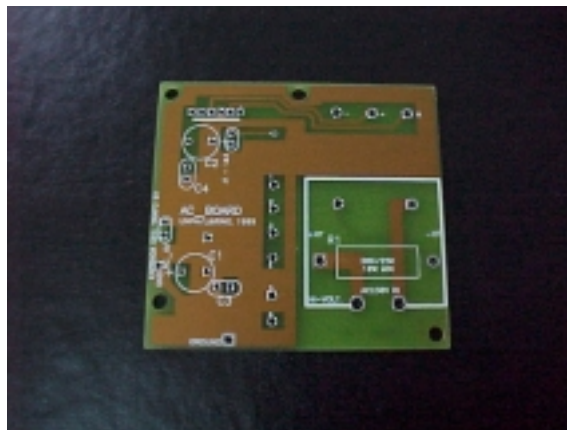


Figure 2 - PCB-ACB2 with no components installed.

The Hall sensors, manufactured by Swiss-based LEM Inc. can be obtained through *L&R Ingeniería*, in Argentina through *Yel S.R.L.* (www.yel.com.ar) or elsewhere through *RS Components* authorized dealers. These are the greatest cost components of the circuit.



Figure 3: PCB-ACB2 in a sensing circuit.

A small transformer added to the circuit is used to sense the presence of backup power systems, such as diesel/gas generators. The output of this transformer (6V) is rectified as shown in [2.](#), producing a logic value of 0V (off) or 5V (on). Further, in [3.](#) and [4.](#) a series of unit-conversion and calibration procedures are described to illustrate typical end-user applications of the PCB-ACB2.



2. Signal-Conditioning Circuits

The PCB-ACB2 board provides low-level, galvanically isolated signals proportional to the instantaneous voltage and RMS current magnitudes fed into the load under test. Most applications will however require additional signal conditioning to allow these signals to be fed to an A/D converter. The actual circuit will depend on user requirements, but typical circuits are presented here (figure 4) that can be used for 12-bit or less resolution converters.

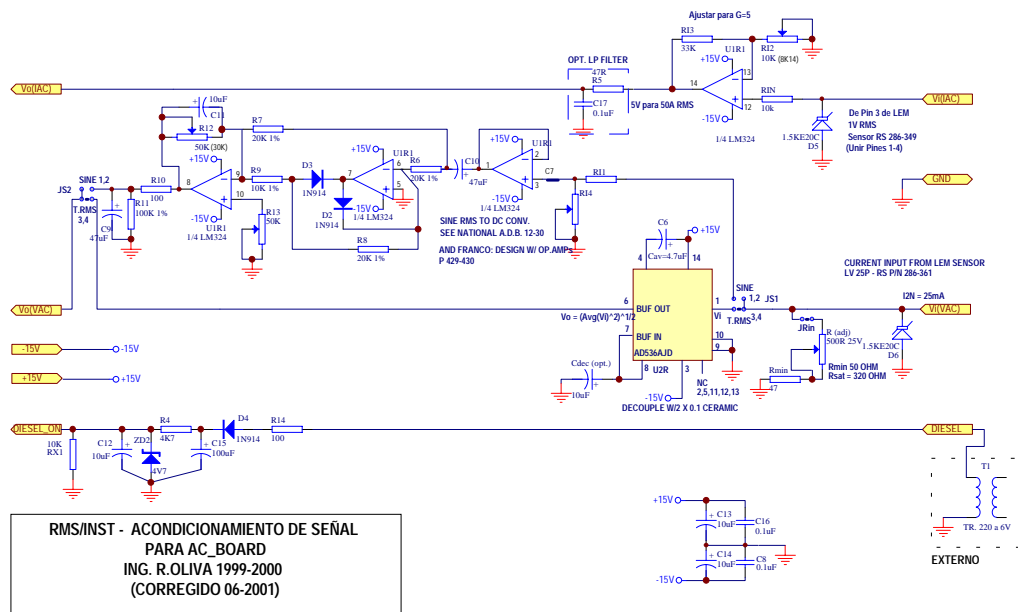


Figure 4 - Typical Signal-Conditioning Schematic.

2.a. I(RMS) conditioning: The signal from the I(RMS) AC current sensor, with a full-scale value of 1V DC is processed with non-inverting amplifier of gain $G=5$. This provides a full-scale value of 5Vdc, compatible with the input of conventional A/D converters. Some comments about this circuit:

- If the measured current in ARMS is less than 50A peak, two (or more) turns of cable around the Hall effect sensor can increase the resolution. For instance, two turns of cable will provide 1Vdc output for a value of 25ARMS full scale. In figure 3, the maximum cross-section of 10mm² cable is shown for a 50A peak system. Smaller section cables can be used for lower current systems, allowing for greater number of turns and lower values of full-scale current. Of course, the default and calibration values seen by the CPU must be corrected accordingly.
- The input impedance of real-world A/D Converters must be taken into consideration. In our case, the MAX197 converter used has a relatively low (a few kOhm) and variable input impedance, so the value of R in the low-pass output filter (R5/C17) is kept very low, to avoid errors. A lower frequency, first-order filter will require and additional voltage follower to buffer

the greater R value. In any case the 1Vdc full-scale signal is relatively noise-free if shielded cable running less than 3m is used.

c) D5 is a 20V, unidirectional transient-supressor diode.

d) The quad operational amplifier used (a low cost LM324) can be replaced by more accurate industry-standard replacements if greater DC-offset precision is required (e.g. OPA470 from Burr-Brown).

2.b. I(VAC) conditioning: The output signal from the LV25P Hall voltage sensor, installed as shown in figure 1 on the PCB-ACB2A is an alternating current, proportional to the instantaneous line voltage. It's nominal value I_{2n} is 25mA. To convert this current into a measurable voltage, the input resistors $R_{(adj)}$ and R_{min} are used. The LEM LV25P datasheet recommends a maximum load of 320 Ohm, for I_{2n} up to 50mA. Since our I_{2n} is half that, the combination of $R_{(adj)}=500$ plus $R_{min}=47$ Ohm does not produce sensor saturation.

The rest of the signal conditioning circuit depends on the waveform of the line voltage. If the available supply produces a near-perfect sinewave, as in most cities, diesel/gas generators or true-sinewave inverters, the JS1, JS2 jumpers are used in position SINE. This activates a classic, low cost RMS sine to DC converter. In other cases where the waveform is distorted (such as the voltage produced by inexpensive inverters), an integrated RMS/DC converter such as the AD536A [ref.3] can be used by setting JS1,JS2 to the T.RMS position, as shown in diagram of figure 4. At a cost of around u\$s50, this IC is not cheap, but produces directly a DC signal proportional to the RMS voltage present on pin 1, for arbitrary voltage waveforms with great accuracy.

2.c.1. JS1,JS2 in SINE option: In this configuration, 3 operational amplifiers work as a buffer / precision rectifier / amplifier chain to obtain a DC output proportional to the True RMS value of a perfect sinewave voltage. The scheme can be mathematically described as follows: first, with the buffer/full-wave rectifier we obtain the average V_{avg} of the sinewave voltage $v(t)$ of frequency f and period $T=1/f$, or

$$V_{avg} = \frac{1}{T} \int_0^T |v(t)| dt \quad (\text{eq.1})$$

By replacing here the value of the voltage with $v(t) = V_m \sin(2\pi ft)$, where V_m is the peak value, we obtain:

$$V_{avg} = \frac{2}{\pi} V_m \quad (\text{eq.2})$$

Since the RMS value of a sinewave signal can be calculated with

$$V_{rms} = \left(\frac{1}{T} \int_0^T (v(t))^2 dt \right)^{\frac{1}{2}} = \frac{V_m}{\sqrt{2}} \quad (\text{eq.3})$$

we can relate (eq.2) and (eq.3) to obtain the value of V_{rms} from the average:

$$V_{rms} = \frac{\pi}{2} \frac{1}{\sqrt{2}} V_{avg} = 1.11 V_{avg} \quad (\text{eq.4})$$

This value of 1.11 is obviously only valid for sinewave signals, and can be adjusted using preset R12 in the circuit shown in figure 4. Further discussion of these calculations can be found in ref. [1] and ref.[2].

Finally, the output indicated as Vo(VAC) produces the DC level proportional to the RMS value of the line voltage, as required. The magnitude is around 7Vdc for 230VAC, so an A/D range of 0 to 10V is used.

2.c.2. JS1,JS2 in T.RMS option: In this case the voltage signal is fed into an integrated RMS/DC converter of type AD536AJ (ref.[3]) manufactured by Analog Devices. This device computes internally the correct value of (eq.3), regardless of the waveform of the voltage. This is true with certain restrictions regarding duty cycle and form factor of the waveform, but these should not present a problem at 50 or 60Hz with the line voltages of most equipment. Operation of the AD536AJ is optimized at a level of 7 VRMS, which produces an output of 7VDC with minimum *ripple*. This *ripple* can be further reduced by adding an electrolytic capacitor C_{dec} of value 10uF, (-) to ground, at the pin 7-8 junction as shown in figure 4.

3. Engineering Units (EU) Conversion and Calibration

The conversion of data using the PCB-ACB2 is strongly dependent on the application. Further, some kind of calibration of the measurements is often necessary. A typical application with a 12-bit A/D converter will be presented, supposing the availability of Floating Point operations on the processor side. A discussion of the "two-point calibration method" (see 4. and ref.[5]) is also included, to allow for minimum average reading errors in the system.

To illustrate the conversion procedure, a conversion structure as shown in figure 5, (see ref.[4]) will be supposed. Here, the symbol U.I. stands for Engineering Units, meaning physical magnitudes (e.g.: Temperature in °C, pressure in hPa, etc.). The "front end" or input circuit includes a sensor (*transductor*) with a conversion gain G_T (V/U.I.), an amplifier with a voltage gain A_V , an adder for a bias voltage V_B , a filter, an ideal multiplexer and the n-bits A/D converter, with a reference voltage FSV.

The conversion gain G_T can have units of Volts/U.I. or alternatively an intermediate unit X, such as current or frequency, so G_T will be in units of [X/U.I.] This can be true for many sensors that produce not a voltage, but a frequency or current output proportional to the physical magnitude. In these cases, the gain A_V will not be adimensional but rather [V/X].

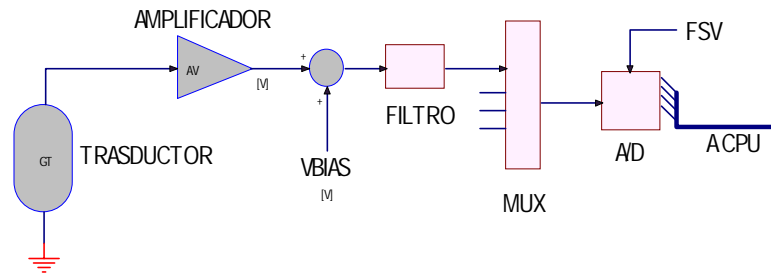


Figure 5 - Typical A/D conversion scheme

The mathematical expression for the A/D counts (between 0 and 2^n-1) will be given by:

$$ADC_{counts} = \frac{(U.I. * G_T * A_V + V_{BIAS}) * (2^n - 1)}{FSV} \quad (\text{eq.5})$$

Whatever the intermediate unit X, it should be noted that the proposed scheme requires that the product $U.I.*G_T*A_V$ have units of voltage [V]. From (eq.5), the programmer can obtain an expression for the measured magnitude in Engineering Units, as follows:

$$U.I. = \frac{\frac{ADC_{counts} * FSV}{(2^n - 1)} - V_{BIAS}}{G_T * A_V} \quad (\text{eq.6})$$

Real-time calculations can be simplified by arranging this equation as follows:

$$U.I. = (ADC_{counts} + C_{offset}) * G_{conv} \quad (\text{eq.7})$$

where the coefficients shown have the following expressions:

$$G_{conv} = \frac{FSV}{G_T * A_V * (2^n - 1)} \quad [\text{U.I./counts}] \quad (\text{eq.8})$$

$$C_{offset} = - \left(\frac{V_{BIAS} * (2^n - 1)}{FSV} \right) \quad [\text{counts}] \quad (\text{eq.9})$$

An advantage of (eq.7) is that it allows for an easy procedure to add calibration values to the physical value computation. This is extremely useful because most sensors, amplifiers, and other components show a dispersion of values of G_T , A_V . For each sensor, the program can require the user to make a first-time (or periodical) calibration procedure to produce "corrective coefficients" that are stored in non-volatile memory and used subsequently. The modified expression is as follows:

$$U.I. = (ADC_{counts} + C_{offset} + C_{cal}) * G_{conv} * G_{cal} \quad (eq.7b)$$

where the corrective coefficients have the following default values:

$$G_{cal} = 1.0 \text{ [U.I./count]}$$

$$C_{cal} = 0 \text{ [count]}$$

which do not disrupt the measurement if no calibration is performed.

Part of the output of a spreadsheet calculation of the theoretical coefficients C_{off} , G_{conv} for channels I_{ac} and V_{ac} (supposing an output from PCB-ACB2A, and a signal-conditioning circuit such as figure 4) is shown in figure 6. In this system, a 12-bit ($n=12$) MAX197 A/D converter with an internal multiplexer is supposed. Input ranges for each of the 8 channels can be individually selected, so FSV values of 5V for I_{ac} (channel 6 with a range of 0-5V) and 10V for V_{ac} (channel 7 with a range of 0-10V) have been used.

The I_{ac} channel must measure RMS current, so a LEM/RS 286-349 sensor was selected, producing an output of 1Vdc for a full-scale current of $I_{fs}=50A$ RMS. As mentioned in 2.a., the resolution can be incremented by increasing the number of turns of the cable around the sensor (this is possible only if the cable is thin enough!) For example, with two turns, the range is $I_{fs}/2 = 25A$ RMS for 1Vdc output. The spreadsheet shows the calculation of **resolution** of the sensor, as $I_{fs} / (2^n - 1)$, but this value is not required for (eq.8,9). What the spreadsheet shows as G_{trsd} is what we call G_T , and G_A what we call A_V in (eq.8). We use $V_B = 0$, since bias voltages are not required for this circuit. So calculations proceed as follows:

$$C_{d\ I_{ac}} = -0.0 * 4095 / 5.0V = 0 \quad \text{[counts]} \quad (eq.8)$$

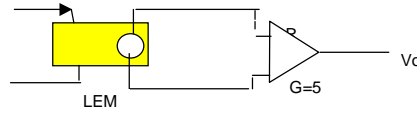
$$G_{d\ I_{ac}} = (5.0 / ((1/50) * (5) * 4095)) = 0.01221 \quad \text{[ARMS/count]} \quad (eq.9)$$

For V_{ac} channel we require RMS voltage, but we shall suppose a pure sinewave on the line side. A Hall-effect LEM/RS 286-361 instantaneous voltage sensor will be used. The output of this sensor is an isolated secondary current of $I_{2n} = 2.5 * I_{1n}$, where I_{1n} is the primary current produced by the limiting power resistor R1. The calculations shown on the spreadsheet are for a nominal line voltage of 230V AC RMS. Since we suppose a pure sinewave, the equations used in 2.c.1. (eq.2,3,4) are applicable. The instantaneous alternating current I_{2n} is converted to a voltage using resistor R_m , which as shown in figure 4 is formed with $R_{(adj)}=500$ in series with $R_{min}=47$ Ohm. Since the A/D converter requires a DC voltage, the alternating voltage is fed into

Canal Iac

Tipo: Sensor LEM RS 286-349 Canal lógico ch6
Configuración: Salida de tensión 1VDC para 50A RMS, requiere Amplificador
Salida para FSV: 5 [V]

I Max= 50.00 [ARMS]
Resolucion= 12.21 [mA/LSB]
FSV= 5.00 [V]
2ⁿ-1= 4095
Gtrasd= 1/50 [V/Arms]
GA= 5.00 [V/V]
Vbias= 0.00 [V]
AD Range 5VUNIP



$$\text{ADCcounts} = \frac{(\text{Ieu} * \text{Gtrasd} * \text{GR} + \text{Vbias}) * 2^n - 1}{\text{FSV}}$$

Coeficientes Default Calculados para Formula Labrosse:

$$\text{EU} = (\text{ADCcounts} - \text{Cd}) * \text{Gd}$$

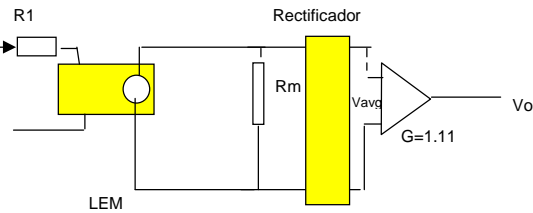
Representation en Setup
Cd Iac= 0 [cuentas] 00000000 (*1000)
Gd Iac= 0.01221 [Arms/cuenta] 000012210 (*1e6)

Canal Vac

(Mod. 22.2.2000)

Tipo: Sensor LEM RS 286-361 Canal lógico ch7
Salida de SW4548E - Suponemos Senoidal Pura
Configuración: Salida de corriente I2n=2.5(I1n). Para V1n = 230V RMS, R1=47K (10W)

R1 = 47000 [ohm] (22.2.2000)
Rm = 500 [ohm] (22.2.2000)
v1n = V1sen(wt) V1 = 324.3 [V]
i1n = I1n sen(wt) I1n = 0.0069 [A]
i2n = I2n sen(wt) I2n = 0.01725 [A]
v2n = V2sen(wt) V2 = 8.625 [V]
Vavg=2/PI*V2 Vavg = 5.49084554
Vo=1.11Vavg V0 = 6.09483855
Gtotal= Vo/v1rms Gt = 0.0264993



Vac Max= 300.00 [VRMS]
Resolucion= 73.26 [mV/LSB]
FSV= 10.00 [V]
2ⁿ-1= 4095
Gt= 2.6499E-02 [V/Vrms]
G= 1.00 [V/V]
Vbias= 0.00 [V]
AD Range 10VUNIP

$$\text{ADCcounts} = \frac{(\text{Ieu} * \text{Gtrasd} * \text{GR} + \text{Vbias}) * 2^n - 1}{\text{FSV}}$$

Verificacion Cd,Gd	
ADCraw	EU
0000	0.00
0500	46.08
1000	92.15
1500	138.23
2000	184.31
2500	230.38
3000	276.46
3500	322.54
4000	368.61
4095	377.37

Coeficientes Default Calculados para Formula Labrosse:

$$\text{EU} = (\text{ADCcounts} - \text{Cd}) * \text{Gd}$$

Representation en Setup
Cd Vac= 0 [cuentas] 00000000 (*1000)
Gd Vac= 0.0921535 [Vrms/cuenta] 000092153 (*1e6)

figura 6 - Planilla para cálculo de Coeficientes

a precision rectifier and finally to an amplifier of gain 1.11, as described in **2.c.1.** This allows for a transducer gain $G_T = 0.0264993 [V/V_{RMS}]$.

For this channel, an FSV of 10V has been selected, allowing for a range of 0 to 10V of the A/D converter. The value $G=1$ is what is called A_V in (eq.8). As before, $V_B = 0$, and therefore the computed values are as follows:

$$C_{d \text{ Vac}} = -0.0 * 4095 / 10.0V = 0 \quad [\text{counts}] \quad (\text{eq.8})$$

$$G_{d \text{ Vac}} = (10.0 / ((0.0264993) * (1) * 4095)) = 0.092153 \quad [VRMS/count] \quad (\text{eq.9})$$

4. Two Point Calibration Method

This method is used for the calibration of most sensors with a linear response. The procedure compares two measurements made with external instruments of known precision at different points, using (eq.7b). and later the values of G_{cal} , C_{cal} can be computed from the equations. Suppose these two measurements are $U.I._1$, $U.I._2$ and the corresponding count values of the A/D are C_1 and C_2 . So, replacing in (eq.7b) :

$$U.I._1 = (C_1 + C_{offset} + C_{cal}) * G_{conv} * G_{cal} \quad (eq.10)$$

$$U.I._2 = (C_2 + C_{offset} + C_{cal}) * G_{conv} * G_{cal} \quad (eq.11)$$

Changing the sign of (eq.11), and adding the result to (eq.10), the following can be obtained:

$$G_{cal} = \frac{1}{G_{conv}} \left[\frac{U.I._1 - U.I._2}{C_1 - C_2} \right] \quad (eq.12)$$

$$C_{cal} = \frac{U.I._1}{G_{conv} * G_{cal}} - C_1 - C_{offset} \quad (eq.13)$$

A possible implementation of the required calculations can be seen in the flow diagram shown in Appendix I. Basically, the routine shown requires the user to make two successive measurements, and to input the known values of $U.I._1$ y $U.I._2$ taken with an instrument of known precision. After each measurement the program saves the corresponding count values C_1 and C_2 . If the sequence finishes correctly, calculations similar to (eq.12,13) are performed.

The flow diagram follows the logic of a routine written in C language. The main program provides the routine a pointer called HPtr, which allows access to a structure (data array) for each A/D channel, later saved in non-volatile memory. A better understanding of the routine's process follows from observing the template for this structure:

```

struct calib {
    UBYTE   ch; /* Channel Number, for internal use */
    char    Name[CAL_NAMELEN]; /* Channel name.. fixed for version */
    char    Label [CAL_LABELLEN]; /* Channel label, user modif.. */
    char    SensorTyp[CAL_SENSOR_TYPLEN]; /* Sensor Type, mfg.. Serial */
    char    ADCRange[CAL_ADCRANGELEN]; /* String indicating range of ADC */
    UBYTE   ADCRng; /* Same as MAX197, A10 rng val.. */
    char    Units[CAL_UNITSLEN]; /* String for Units used in EU.. */
    BOOLEAN CalY_N; /* Calibrated or not.. */
    char    CalDate[CAL_DATELEN]; /* .. and when. */
    BOOLEAN EnabledY_N; /* Can be bypassed, or disabled.. */
    char    EURange[CAL_EURANGELEN]; /* String indicating EU range.. */
    FP      C_Def; /* Default Count of ADC for Channel */
    FP      G_Def; /* Default Gain in Labrosse formula */
    FP      C_Cal; /* Calibr. Count of ADC for Channel */
    FP      G_Cal; /* Calibr. Gain in Labrosse formula */
};

```

Because of implementation problems, (eq.12,13) are not used directly in the flow diagram.

The coefficients are calculated by first obtaining C_{cal} with two possible cases, as follows:
a) A simple operation if $U.I._1 = 0$ (it is quite common to select a first value of 0.0)

$$C_{cal} = -(C_1 + C_{offset}) \quad (\text{eq.14})$$

b) An equation quotient of (eq.10,11) if $U.I._1 \neq 0$. This is as follows:

$$\frac{U.I._1}{U.I._2} = \frac{(C_1 + C_{offset} + C_{cal}) * G_{conv} * G_{cal}}{(C_2 + C_{offset} + C_{cal}) * G_{conv} * G_{cal}} \quad (\text{eq.15})$$

$$C_{cal} \left(\frac{U.I._1}{U.I._2} \right) - C_{cal} = C_1 + C_{offset} - \left(\frac{U.I._1}{U.I._2} \right) (C_2 + C_{offset}) \quad (\text{eq.16})$$

meaning that the first coefficient is:

$$C_{cal} = \frac{C_1 + C_{offset} - \left(\frac{U.I._1}{U.I._2} \right) (C_2 + C_{offset})}{\left(\frac{U.I._1}{U.I._2} - 1 \right)} \quad (\text{eq.17})$$

and for both cases a) and b), it follows that:

$$G_{cal} = \frac{1}{G_{conv}} \left[\frac{U.I._2}{C_{offset} + C_2 + C_{cal}} \right] \quad (\text{eq.18})$$

These are the expressions used in the flow diagram. In all cases, 0 values for any denominators are checked before division operations. If the user finds the process to be correct, the values of G_{cal} and C_{cal} are saved in non-volatile memory. In each successive CPU boot process, these values are read and applied to the (eq.7b) expression, for the computation of measurements on each channel.

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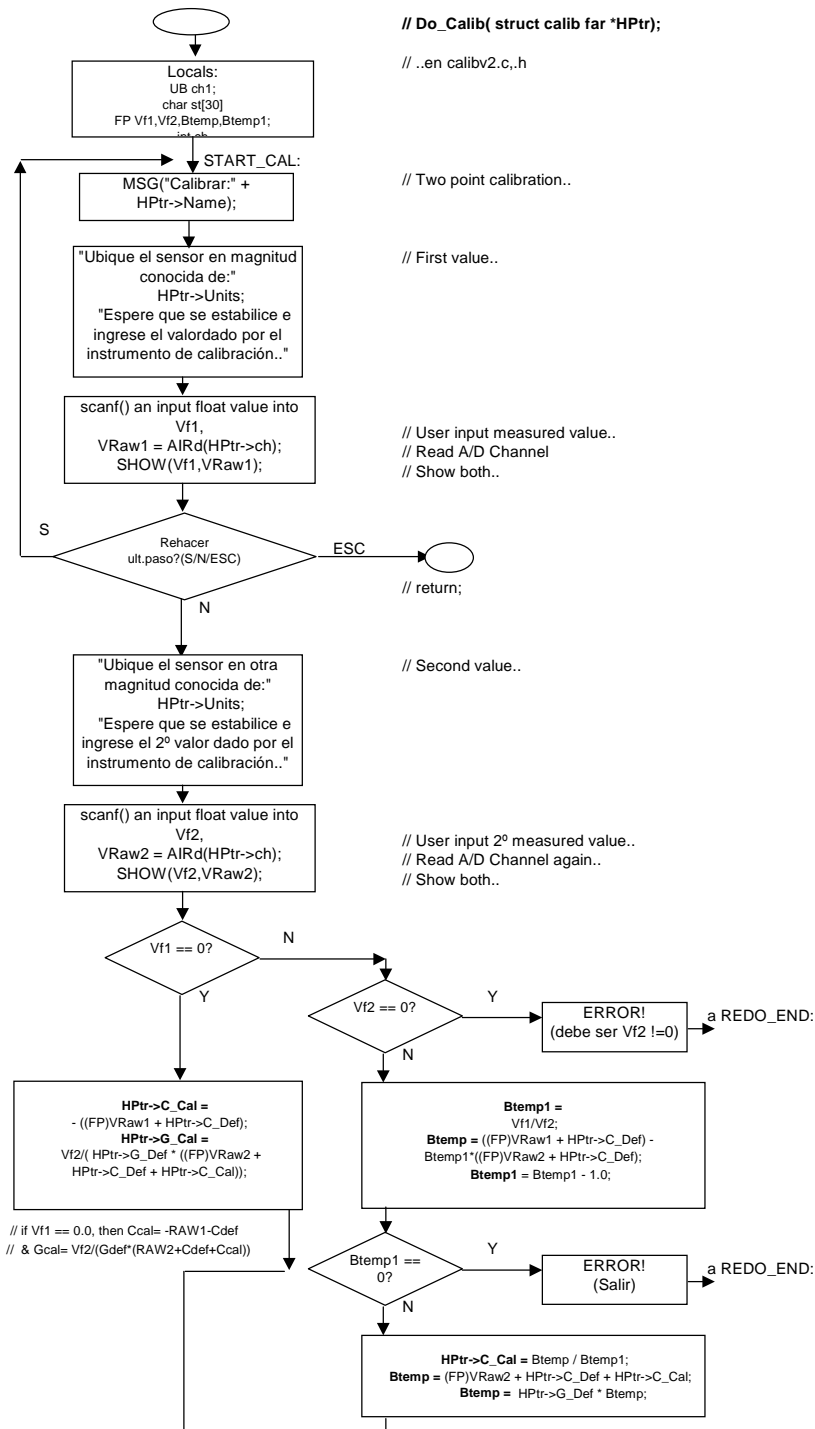
T. DE LOQUI 58 - 9400 RIO GALLEGOS

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- [ref.4] Labrosse, Jean J.: *Embedded System Building Blocks, 2nd Edition*. Jean J. Labrosse, R&D Books KS, US 2000. ISBN 0-87930-604-1
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APPENDIX I: BLOCK DIAGRAM - TWO POINT CALIBRATION METHOD



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