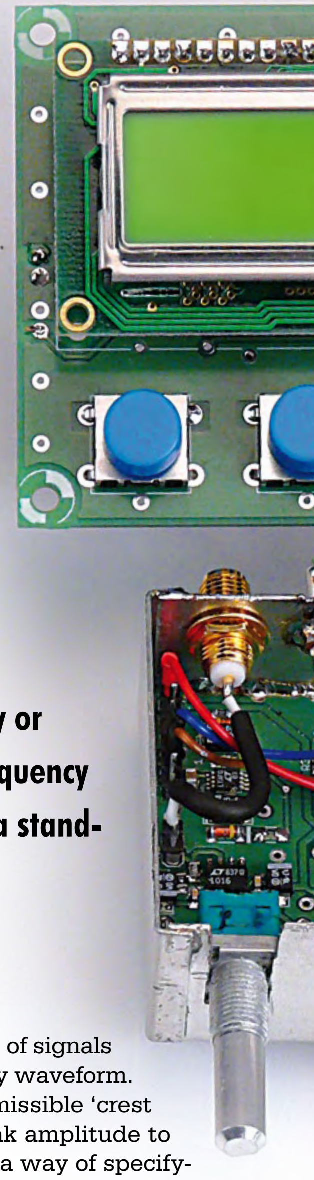
True RMS Digital Voltmeter

with frequency counter



Kai Riedel (Germany)

Many simple function generators do not offer the facility to measure either the frequency or the amplitude of the output. The module described here fills that gap, displaying the frequency and RMS amplitude of a signal on a two-line LCD panel. The circuit can also be used as a stand-alone true RMS voltmeter with frequency measurement.

A wide range of frequency counter designs has been published in Elektor [1]. None of these, however, has offered the ability to measure the amplitude of the input signal. Measuring the RMS (root-mean-square) amplitude properly is more than matter of applying full-wave rectification, averaging, and multiplying by a suitable magic constant, the method used in low-cost multimeters. The magic multiplication factor used in these meters is correct if the input waveform is a pure sine wave, but the error in the reported value increases as the input waveform deviates from the pure sinusoidal shape. Table 1 shows the degree of error for a few example waveshapes. The instrument described here can determine the true RMS amplitude [2] (or 'effective value') of signals with practically any waveform. The maximum permissible 'crest factor' (ratio of peak amplitude to RMS amplitude) is a way of specifying for what kinds of waveforms can have their RMS value measured with sufficient accuracy: for the true RMS converter used here the maximum crest factor (for an overall accuracy of 1 %) is 4.

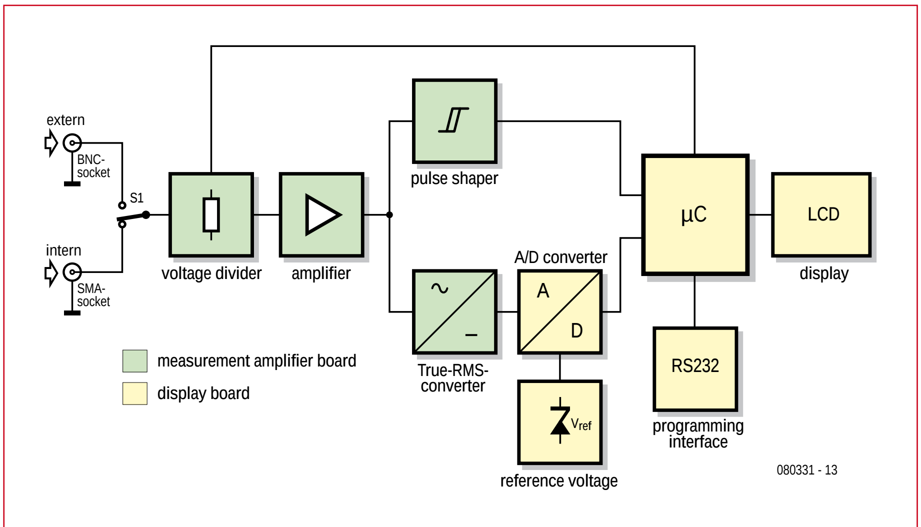


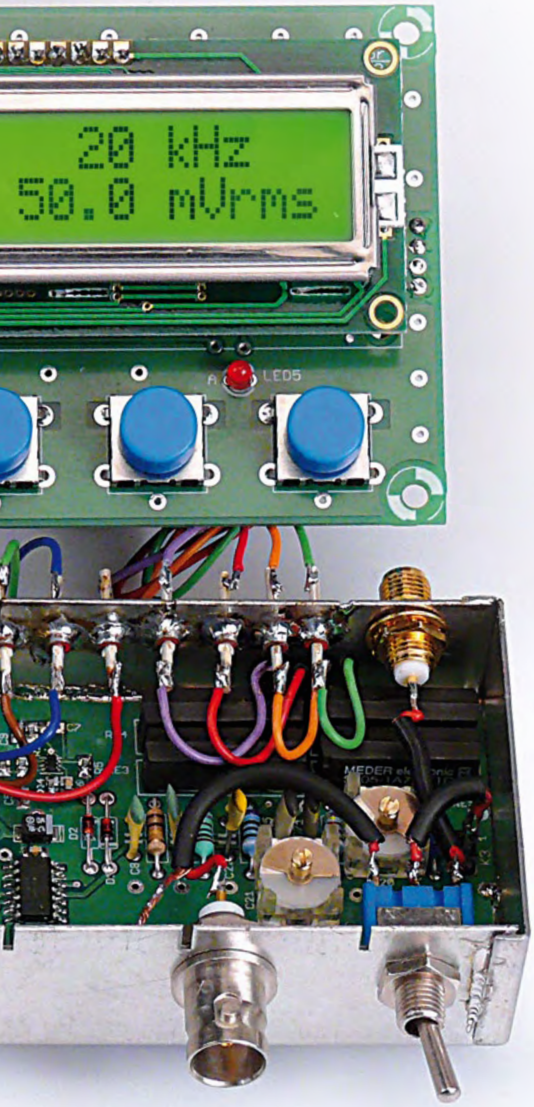
Figure 1. Block diagram of the meter.

The circuit

The principle of operation of the circuit can be understood using the block diagram (**Figure 1**). The system is divided into two main modules: the input amplifier and the display board.

The input circuitry consists of a switchable voltage divider with subsequent amplifier and a true RMS converter. Alongside this is a pulse shaper used in measuring the signal frequency. The amplifier is needed because the error in the output of the true RMS converter increases noticeably at input levels of 5 mV or less.

The display module includes the processing circuit, consisting of a



Main Characteristics

- **Four measurement ranges: 0.1 V, 1 V, 10 V, 100 V**
- **Voltmeter bandwidth: 20 Hz to 1 MHz (basic accuracy ±1.0 % of full scale)**
- **Frequency counter bandwidth: 1 Hz to 10 MHz (typ.), 25 MHz (max.) (±timebase error)**
- **Minimum input voltage for counter: approximately 50 mVRMS**
- **Input impedance: ≥ 1 MΩ || ≤ 50 pF**
- **Counter timebase: 100 ms, 1 s**
- **Adjustable trigger level: approximately ±0.15 V**
- **Autoranging (may be disabled)**
- **Offset correction and calibration facility**
- **Automatic scaling of frequency display**
- **Voltage displayed as RMS value or peak-to-peak value (for sinusoidal input)**
- **Crest factor: ≤4**
- **Two measurement inputs**

Table 1. Mean absolute value versus RMS

We assume a mean signal amplitude of 1 V. 'SCR' stands for Silicon Controlled Rectifier, or thyristor: we use this as shorthand for the waveforms found in AC phase angle control circuits.

Wave shape	Crest factor	True RMS value [V]	Error in using mean absolute value [%]
Sine	1.414	0.707	0
Square, 50 %	1.0	1.0	+11.0
Triangle	1.73	0.577	–3.8
SCR, 50 %	2	0.495	–28
SCR, 25 %	4.7	0.212	–30

microcontroller, LCD panel, analogue-to-digital converter and an RS-232 interface.

Figure 2 shows the circuit diagram of the input amplifier module, where the parts of the block diagram can clearly be seen. As the input voltage is AC, a frequency-compensated voltage divider is used. Without this, the voltage divider would form a low-pass filter with the input capacitance of the subsequent circuit, which would severely limit the maximum frequency of operation. To avoid various potential problems associated with matching and with high input voltages, relays are used to switch the voltage divider. The output of the divider is matched to the amplifier using a classical impedance conversion stage using a dual field-effect transistor. This guarantees good stability down to DC (see [3]).
To allow for operation up to high frequencies the main amplification is carried out in three stages. The amplifier used, the ADA4862-3 [4] has internal frequency compensation and consists of three opamps, which, connected in series, deliver an overall gain of 8. A particular feature of this device is its very good linearity: gain variation is within 0.1 dB up to a frequency of 65 MHz.

The output of the amplifier feeds IC3, an RMS-to-DC converter [5][6], and IC4, a high-speed comparator [7]. Potentiometer P1 allows the switching threshold of the comparator to be adjusted slightly. If it is desired to process signals with a greater DC component, we recommend adding a series high-voltage capacitor of (for example) 330 nF before the input amplifier circuit.
According to its datasheet, the Linear Technology LTC1968 RMS-to-DC converter has a 3 dB bandwidth of 15 MHz. The arrangement in our circuit broadly follows the manufacturer's recommendations. Capacitor C15 allows the response time of the converter to be set. A smaller value can be used to reduce the response time, but this will increase the error in the result at frequencies below 100 Hz. C14 ensures that only the AC component of the signal is processed.

Display module using R8C

The display module is based around the popular R8C/13 microcontroller from Renesas (see **Figure 4**). The wiring of the microcontroller (with programming over the RS-232 interface, crystal and LCD panel) follows the circuits from the R8C series published in Elektor from February 2006 [8][9]. IC2 is an external 20-bit analogue-to-digital (A/D) converter [10]. It uses the delta-sigma conversion technique and can effectively suppress the ripple that appears superimposed on the output of the RMS-to-DC converter. To sim-

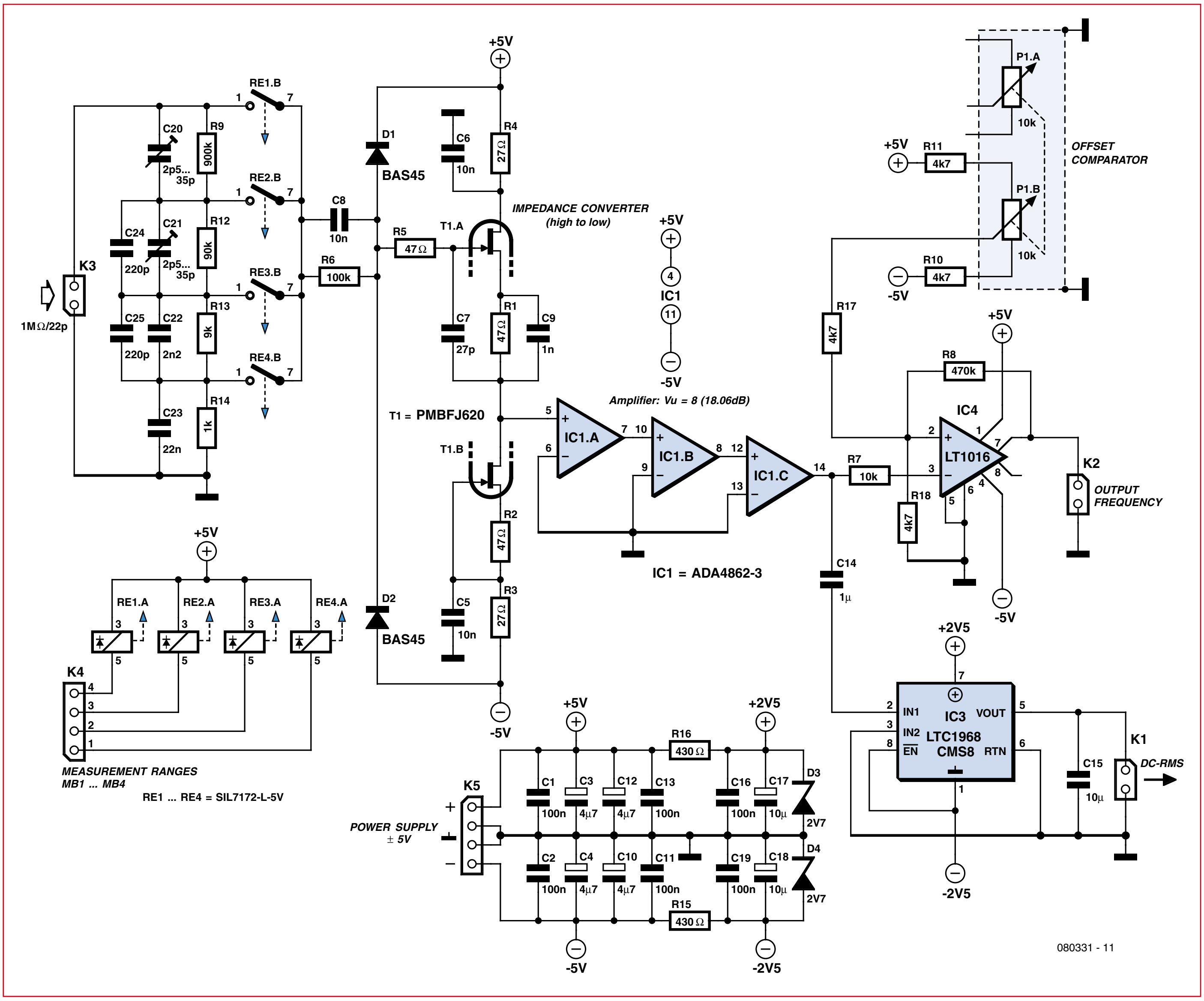


Figure 2. Circuit diagram of the amplifier module, including voltage divider, amplifier and RMS-to-DC converter.

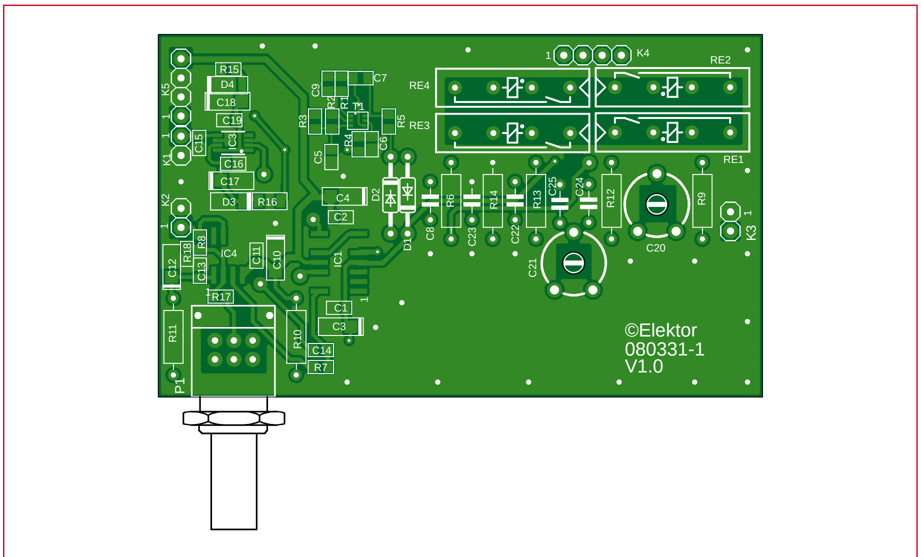


Figure 3. Printed circuit board for the amplifier.

COMPONENT LIST

Measurement Amplifier

Resistors

R1,R2, R5 = 47Ω (SMD 0805)
R3,R4 = 27Ω (SMD 0805)
R6 = 100kΩ
R7 = 10k (SMD 0805)
R8 = 470kΩ (SMD 0805)
R9 = 900kΩ 0.1%
R10,R11 = 4kΩ7
R12 = 90kΩ 0.1%
R13 = 9kΩ 0.1%
R14 = 1kΩ 0.1%
R15 = 430Ω (SMD 0805)
R16 = 430Ω (SMD 1206)
R17 = 4kΩ7 (SMD 0805)
R18 = 4kΩ7 (SMD 0805)

Two ways to calibrate

Method 1:

1. Connect an oscilloscope to the output of IC1 in the amplifier module, using a 10:1 probe.
2. Connect K4.1 to ground: this sets the highest voltage division ratio.
3. Apply a symmetrical squarewave with an amplitude of around 1 V to the junction of resistors R12 and R13. This can be obtained, for example, from the calibration output of the oscilloscope.
4. Now the value of C25 must be selected to obtain as accurate as possible a squarewave on the oscilloscope screen. The value given in the circuit diagram is a good starting-point. One approach is to fit a 100 pF capacitor for C25 and then try adding 100 pF and then 220 pF capacitors in parallel. If you have good eyesight and a steady hand you can solder these as SMDs on the reverse of the board: this makes it easier to change them later.
5. Enable the next measurement range by grounding K4.2.
6. Apply the squarewave signal to the junction of R9 and R12.
7. Adjust trimmer C21 appropriately. Repeat for C20.

Method 2:

Follow steps 1 and 2 above and then apply a symmetrical squarewave to the amplifier module input. Now adjust C25, C20 and C21 until an accurate squarewave appears at the output of IC1. Since the choices of values for C25, C20 and C21 jointly affect the response in each measurement range, considerably more trial and error is required than in the 'textbook' approach described above. Nevertheless, the author has found that it can quickly lead to good results.

It is of course possible to start using method 1 and then use method 2 to make final fine adjustments.

plify the required calculations the A/D converter is provided with a 2.048 V reference voltage (IC3). An important factor is the temperature coefficient of this device: at 10 ppm/°C, we have a variation in the reference voltage of 0.02048 mV/°C.
The A/D converter outputs its conversion results to the R8C over an SPI port. Frequency measurement is carried out by feeding pulses into the CNTR0 counter input of the microcontroller. For this to work, the pulse width must be at least 40 ns and the period at least 100 ns. This means that we can measure frequencies of up to 10 MHz without a prescaler.
Four pushbuttons are provided for the user interface. Pressing S1 switches to manual ranging mode (automatic ranging then remaining disabled until the next reset). S2 switches the timebase (and hence sample rate) between 1 s and 100 ms. The current state is indicated by an LED. An extended press on S3 will perform an offset correction; and S4 switches the readout to peak-to-peak amplitude for sinusoidal signals.
Pin P01 on the microcontroller is connected to test point TP1, which is used in calibrating the module.

P1 = 10kΩ (Alps type 290061)

Capacitors
C1,C2,C11,C13,C16,C19 = 100nF (SMD 0805)
C3,C4,C10,C12 = 4µF7 10V (293D/A)
C5,C6 = 10nF (SMD 0805)
C7 = 27pF (SMD 0805)
C8 = 10nF
C9 = 1nF (SMD 0805)
C14 = 1µF 10V (SMD 0805)
C15 = 10µF 10V (SMD 0805)
C17,C18 = 10µF 10V (293D/A)
C20,C21 = 2.5-35pF trimmer (C-TRIMM808-7.5)
C22 = 2nF2
C23 = 22nF
C24,C25 = 220pF

Semiconductors
IC1= ADA4862-3 (SMD)
IC3 = LTC1968CMS8 (MSOP-8)
IC4 = LT1016CS8 (SO-8)
D1,D2 = BAS45 (1N4148)
D3,D4 = BZW55-2.7 (SMD)
T1 = Dual FET PMBFJ620 (NXP)

Miscellaneous
Re1–Re4 = SIL7271-L 5V or MEDER SIL05-IA72-7ID
K1,K2,K3 = 2-way pinheader
K4,K5 = 4-way pinheader
2x SMA case socket
Metal case e.g. TEKO # 372
BNC case socket
Miniature rocker switch
7x 1nF feedthrough capacitor
PCB # 080331-1, see www.elektor.com/shop

Construction

The overall construction of the unit is shown in the wiring diagram (**Figure 6**) and in the picture of the prototype (main photograph). Observe correct polarity on the relays (the '+' symbol on the package and the dot on the printed circuit board). The dual FET is fitted correctly when the dot on its package (indicating pin 1) is next to the dot on the board.

The circuit should be built in a metal enclosure to minimise interference (**Figure 7**). The DC signals are connected to the input amplifier via feedthrough capacitors, and the signals being measured are connected using SMA or BNC connectors. The output of the comparator (which is a squarewave) is also taken via an SMA connector. If the module is to be built inside a function generator, the generator's output should be connected to the SMA input of the module using a screened cable.

The LCD, the four pushbuttons and the timebase indicator LED are all mounted on the front side of the display board, with all the other components on the back. This allows the board to be mounted in an enclosure as a self-contained module.

Software

We will only describe the structure of the software in broad outline here. Further details can be found in the source code itself and in the file 'Dokumentation_Software.chm' (created using the free software tool Doxygen). Source, hex and help files are of course available for free download from the website for the project [11].

The software makes use of various timers and interrupts (timers X, Y and Z, and the key input interrupt). If a calibration sequence has already been

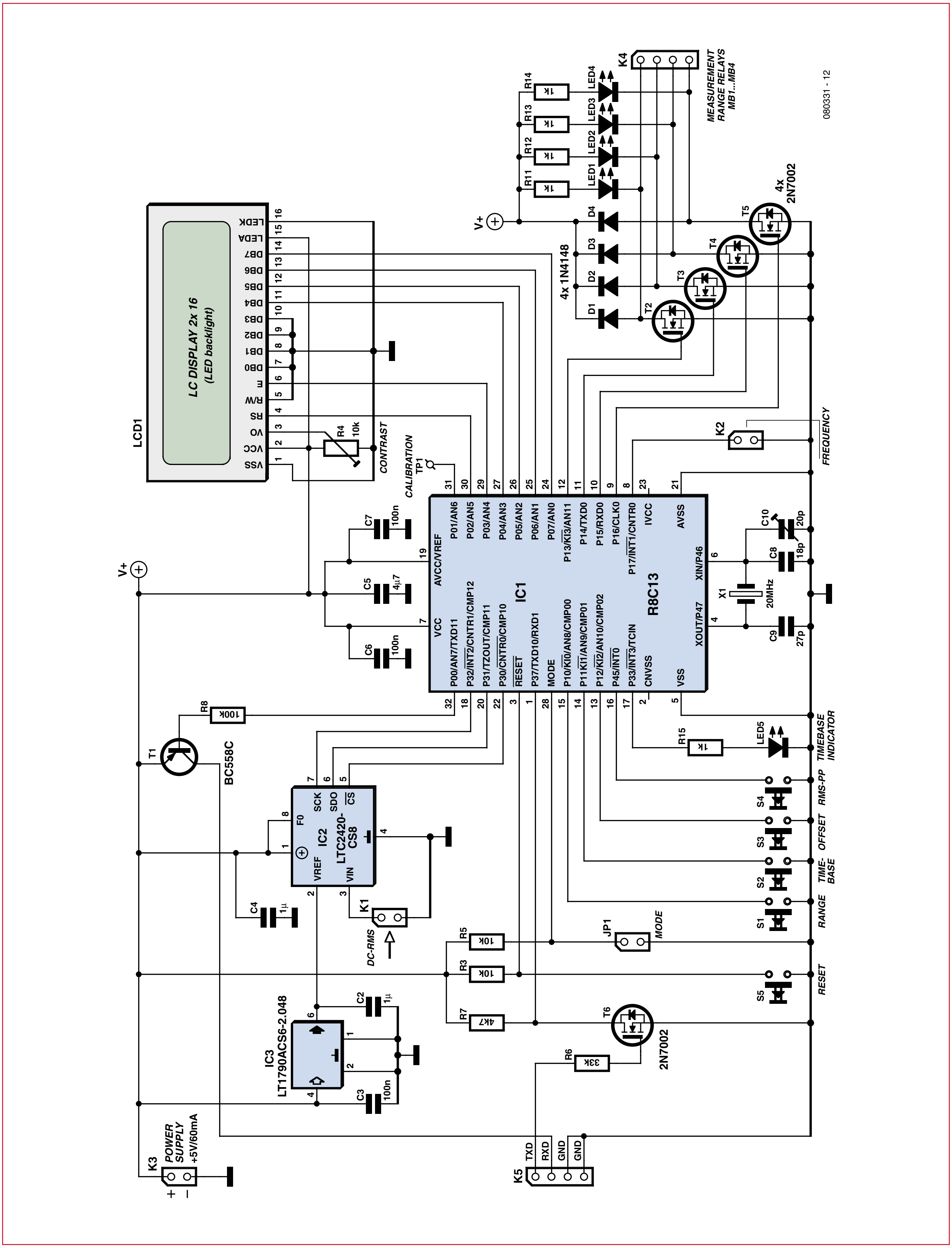


Figure 4. Circuit diagram of the display board with microcontroller, display, A/D converter IC2 and voltage reference IC3.

performed at some point, the first thing the software does when power is applied is to load calibration and offset values from the microcontroller's flash memory; otherwise default values are loaded (and the display shows 'LOAD DEFAULTS'). The microcontroller then goes into an idle mode. TimerX is configured in event counter mode and counts the pulses on the CNTR0 input. An interrupt is triggered when the counter overflows. The interrupt routine that gets called then increments a counter variable. When the TimerZ interrupt is triggered (this depends on the timebase setting, and can be every 100 ms or every 1 s) the frequency and voltage values are calculated and output.

Calculation of the frequency takes into account the values in the counter variable, in TimerX, and in the TimerX prescaler. The voltage is determined by reading the A/D converter over the SPI port. Twelve of the possible twenty bits of A/D converter resolution are enough for the calculation, which automatically takes into account the gain of the amplifier and the measurement range.

Because of the lag in the RMS-to-DC converter, automatically finding the optimal measurement range takes a few seconds, during which the display shows 'Busy'. If an overrange occurs the module will automatically switch to the next higher range for safety reasons, and the display will show 'Overflow'. This automatic switch happens also in manual mode, although the unit will remain in manual mode after the range change.

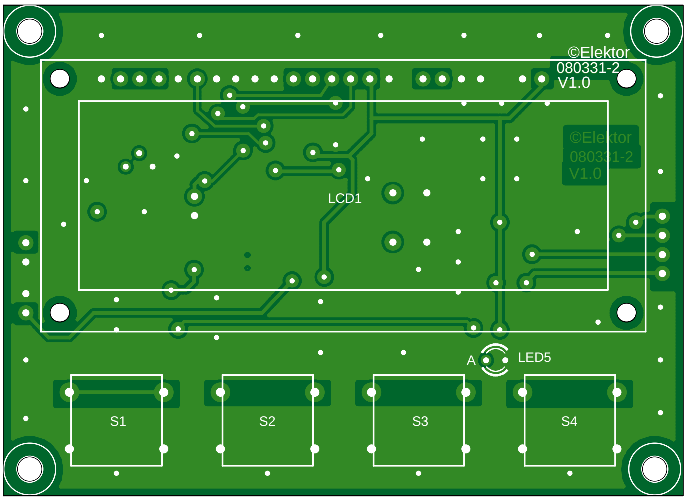


Figure 5. Printed circuit board for the display.

COMPONENT LIST
Display board

Resistors
R3,R5 = 10kΩ (SMD 0603)
R4 = 10k
R6 = 33k (SMD 0603)
R7 = 4kΩ7 (SMD 0603)
R8 = 100kΩ (SMD 0603)
R11,R12,R13,R14 = 1kΩ (SMD 0805)
R15 = 1kΩ (SMD 0603)

Capacitors
C2,C4 = 1µF 10V (SMD 0603)
C3,C6,C7 = 100nF (SMD 0603)
C5 = 4µF7 10V (SMD 0603)
C8 = 18pF (SMD 0603)
C9 = 27pF (SMD 0603)
C10= 20pF trimmer (C-TRIMMCTZ3)

Semiconductors
IC1 = R8C13 (R5F21134FP, LQFP32)
IC2 = LTC2420CS8 (SO-8)
IC3 = LT1790ACS6-2.048 (SOT23-6)
D1..D4 = 1N4148 (SOD-323)
T1 = BC558C (SOT-23)
T2–T6 = 2N7002 (SOT-23)
LED1–LED4 = LED, green (SMD 1206)
LED5 = LED, 3mm

Miscellaneous
LCD1 = LCD 2×16
JP1 = 2-way pinheader and jumper
K1,K2,K3 = 2-way pinheader
K4,K5 = 4-way pinheader
X1 = 20MHz quartz crystal, HC-49US12SMD
S1-S4 = pushbutton (Schurter # 1241.1614)
S5 = pushbutton (6mm)
PCB # 080331-2, see www.elektor.com/shop

The finishing touches

We shall discuss setting up the amplifier and the display board separately. Programming the microcontroller for the display board is described briefly in the text box 'Programming'.
Calibrating the amplifier is a somewhat more involved task (see text box). An oscilloscope, a digital voltmeter (ideally one that can make true RMS readings) and a sinewave generator are required.

First make a simple check that the RMS-to-DC converter and the comparator are working correctly. Then connect the two modules together as shown in **Figure 6**. With the input short-circuited a press of S3 will store the currently displayed value as the calibrated offset voltage (and the display will show 'OFFSET SAVED', followed by '0.0 mV').

Now apply a sinewave with an RMS value of 100 mV to the input. Connect test point TP1 to ground and the voltage readings for the lowest measurement range will be calibrated (with display 'CALIBRATION OK'). The frequency of the sinewave signal should be chosen to obtain best accuracy from the voltmeter being used for comparison.

Calibration is now complete, and the unit can be put to use.

Programming

1. Connect the RS-232 interface to a PC.
2. Fit mode jumper JP1.
3. Briefly press the reset button once: this activates the microcontroller's boot loader.
4. Load the program 'FreqCounter.mot' [11] into the microcontroller using the Renesas Flash Development Toolkit in 'Basic' mode.
5. Remove the mode jumper.
6. Briefly press the reset button. The program will then start up using default parameter values.

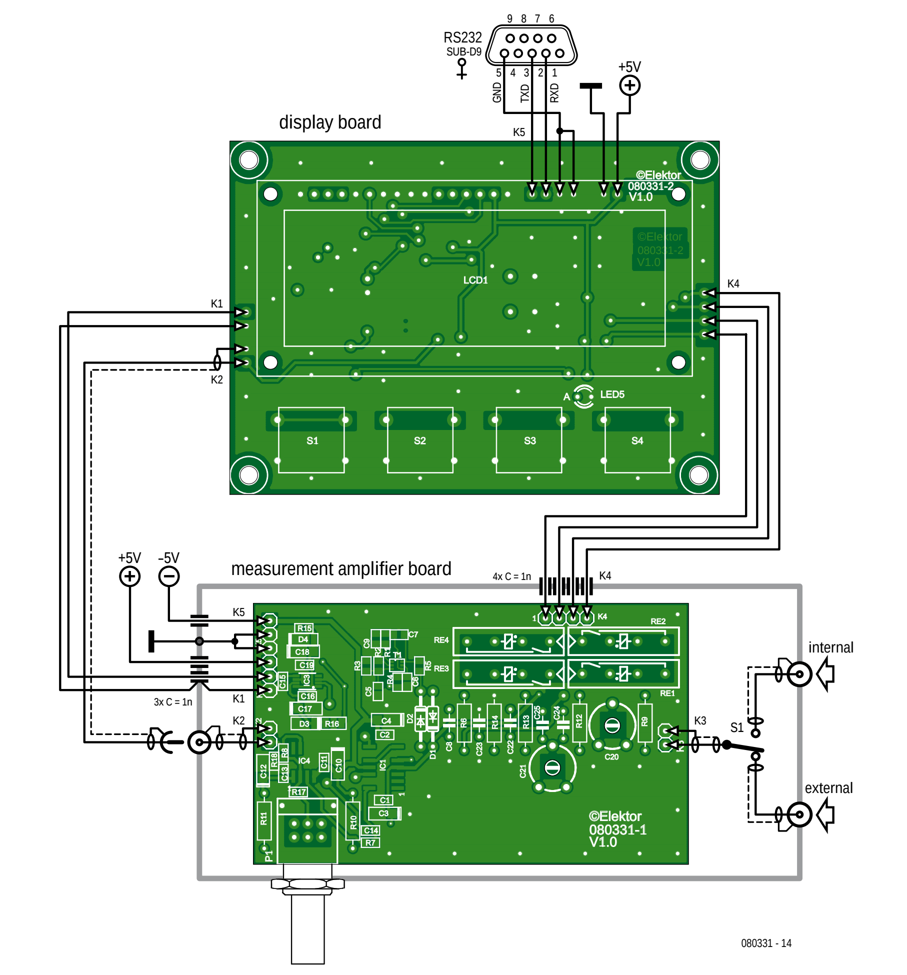


Figure 6. Overall wiring diagram.

Other possibilities

The module can be constructed in the form of a stand-alone voltmeter or it can be built into a function generator. In the latter case, rather than going via the input amplifier circuit, the synchronisation output of the generator can be connected directly to the microcontroller. The measured frequency can be used to index a stored table to allow correction for the frequency response of the instrument.

Another possibility would be to arrange for the software to output readings over the RS-232 port for further processing.

The microcontroller has 16 KB of program memory, of which around 5 KB is used. This gives plenty of room to implement new features. Readers are welcome to contact the author [12] or Elektor with their ideas.

(080331-I)

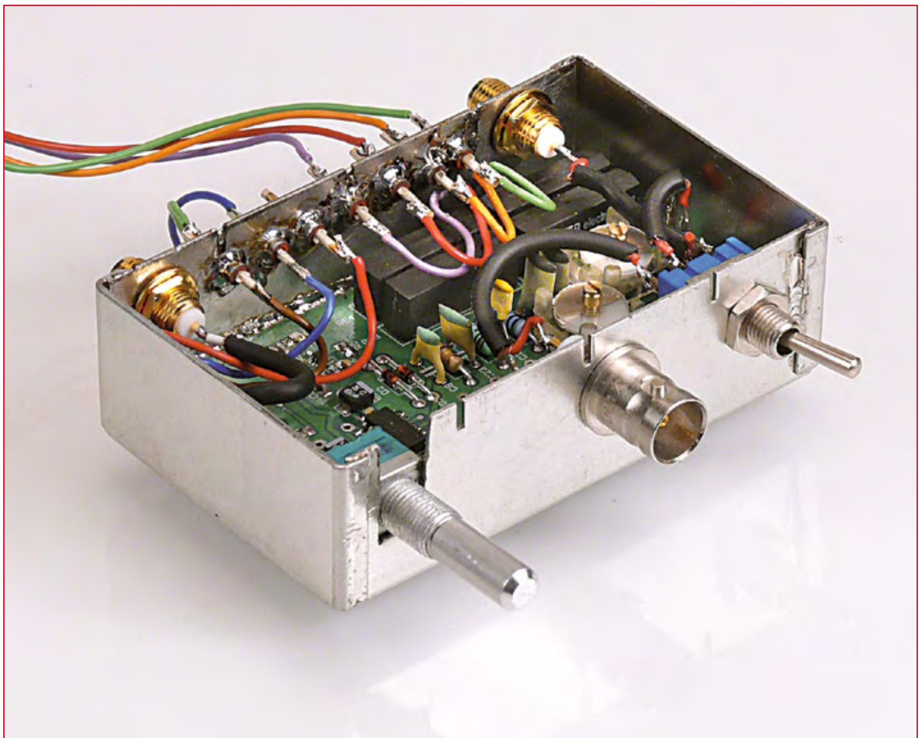


Figure 7. The measurement amplifier should be built into a metal casing..

Internet links

[1] http://www.elektor.com/070954-I

[2] http://en.wikipedia.org/wiki/Root_mean_square

[3] http://tietze-schenk.com/tsbook.htm

[4] http://www.analog.com/en/audiovideo-products/video-ampsbuffersfilters/ada4862-3/products/product.html

[5] http://www.linear.com/pc/productDetail.jsp?navId=H0,C1,C1154,C1086,P7526

[6] http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1154,C1086,P170 1,D24931

[7] http://www.linear.com/pc/productDetail.jsp?navId=H0,C1,C1154,C1004,C1012,P 1225

[8] http://www.elektor.com/050179-2

[9] http://www.elektor.com/050179-3

[10] http://www.linear.com/pc/productDetail.jsp?navIdhttp://www.elektor.com/080331=H0,C1,C1155,C1001,C1152,P1823

[11] http://www.elektor.com/080331

[12] kairiedel@yahoo.de