VK-8 RMS CONVERTER

The used conversion method is based on the thermal action of an alternating current. Average power dissipated in a heater doesn't depend on frequency and waveform of the flowing current, it exactly corresponds only to the root-mean-square value of this current. To measure the RMS value of an AC voltage, it first should be converted to current and for that an input amplifier usually is necessary. Just its broadband capability defines the upper frequency limit of the carried out RMS measurement and figures up to 100MHz are here quite attainable.

Thermo-couple is the most widespread element to sense the heating and produce an output DC signal for further processing, but the faced difficulties in this case often outweigh the virtue of handling broadband signals of heavily distorted waveform. The disadvantages include a considerable, up to 5s thermal inertia, low (not exceeding 20mV) DC output level, restricted (10dB) range of input AC voltages and at last square-law transfer characteristic. The latter can be linearized with the help of the second thermo-couple and heater operating in DC conditions, but here the necessity of matching the two thermo-devices arises.

In this design, the above problems are solved by using a single optocoupler whose lamp turns heating to light which acts on a photoresistor, the DC voltage across that resistor then being compared with a reference level (not necessarily stable).

As a key converting element, this optocoupler has a satisfactory settling time (less than 1s) and high output signal level (about 1,5V), it is supplied in turn by short alternating and direct current injections. Each of these currents is controlled effectively and independently, but is determined by the same, mentioned-above reference, therefore their RMS values always will be set and then with high accuracy maintained equal, even in conditions of variable temperature, supply voltages etc. Current at which this thermal equilibrium is achieved is chosen about 10mA, close to its optimum for the given opto device.

CIRCUIT OPERATION

The simplified circuit diagram of the RMS converter is represented in Fig. 1.

Input AC voltage V_{INA} is buffered (A_1), attenuated (R_1, R_2) and then amplified (A_2). The output alternating current I_{OUTA} is fed through the closed S_{1A} , S_{1B} to a switchable load L which does not influence this current, as the gain defining network (R_4, R_5) takes the feedback voltage sample from a stable resistor R_{01}. Assuming that A_1 and A_2 are ideal op amps, the relationship between I_{OUTA} and V_{INA} can be written as:

$$I_{OUTA} = V_{INA} \times \frac{R_2}{R_1 + R_2} \times \frac{R_{34} + R_5 + R_{01}}{R_{34}R_{01}} ,$$

here R_{34} is a parallel arrangement of R_3 and R_4, R_1 contains a variable photoresistor R_{L1} shunted by 47kΩ, while shunting R_2 by R_6 is negligible and the latter is omitted.

During this so-called AC phase of operation lasting about 0,7s, the Q output of generator G (point A) goes low and the state of associated analogue switches is following: S_{1A} , S_{1B} , S_{3B} are closed and S_{2A} , S_{2B} , S_{3A} - open. At that time the above alternating current I_{OUTA} flows through the filament lamp L which sends light to a photoresistor R_{L2}, the optocoupler output V_D being taken from point D.

The set reference V_{REF} (about 1,5V) is compared with V_D at the inverting input of A_5 and their difference passes to op amp A_6 configured in this phase as an integrator. The integrator output produces a current energizing LED of the second, call it LED optocoupler whose photoresistor R_{L1} is included to the input AC attenuator.

The closed control loop automatically varies the attenuation until reaching $V_D = V_{REF}$, the reference being chosen for setting I_{OUTA} at a level of about 10mA. This level is attainable in the whole 0,1-1V RMS range of input AC voltages and, as gain of the broadband amplifier A_2 is fixed (about 38 with the components shown), the degree of attenuation might serve a measure of the applied AC input. Unfortunately, the accuracy of keeping I_{OUTA} isn't very high because of V_{REF} fluctuations and drift of the converting optocoupler transfer characteristic with temperature, time and other factors.

To avoid this, the second, DC phase of operation is introduced. During its 0,3s, the state of all the switches is opposed to that of the AC phase, so the optocoupler is supplied by a DC current I_{OUTD}. Here the second control loop including the same optocoupler, the same V_{REF} and A_5, but also integrator A_8 and amplifier A_4 is closed, and setting I_{OUTD} is carried out according to the simple relationship

$$I_{OUTD} = \frac{V_{IND}}{R_{02}} ,$$

where V_{IND} is the integrator A_8 output.

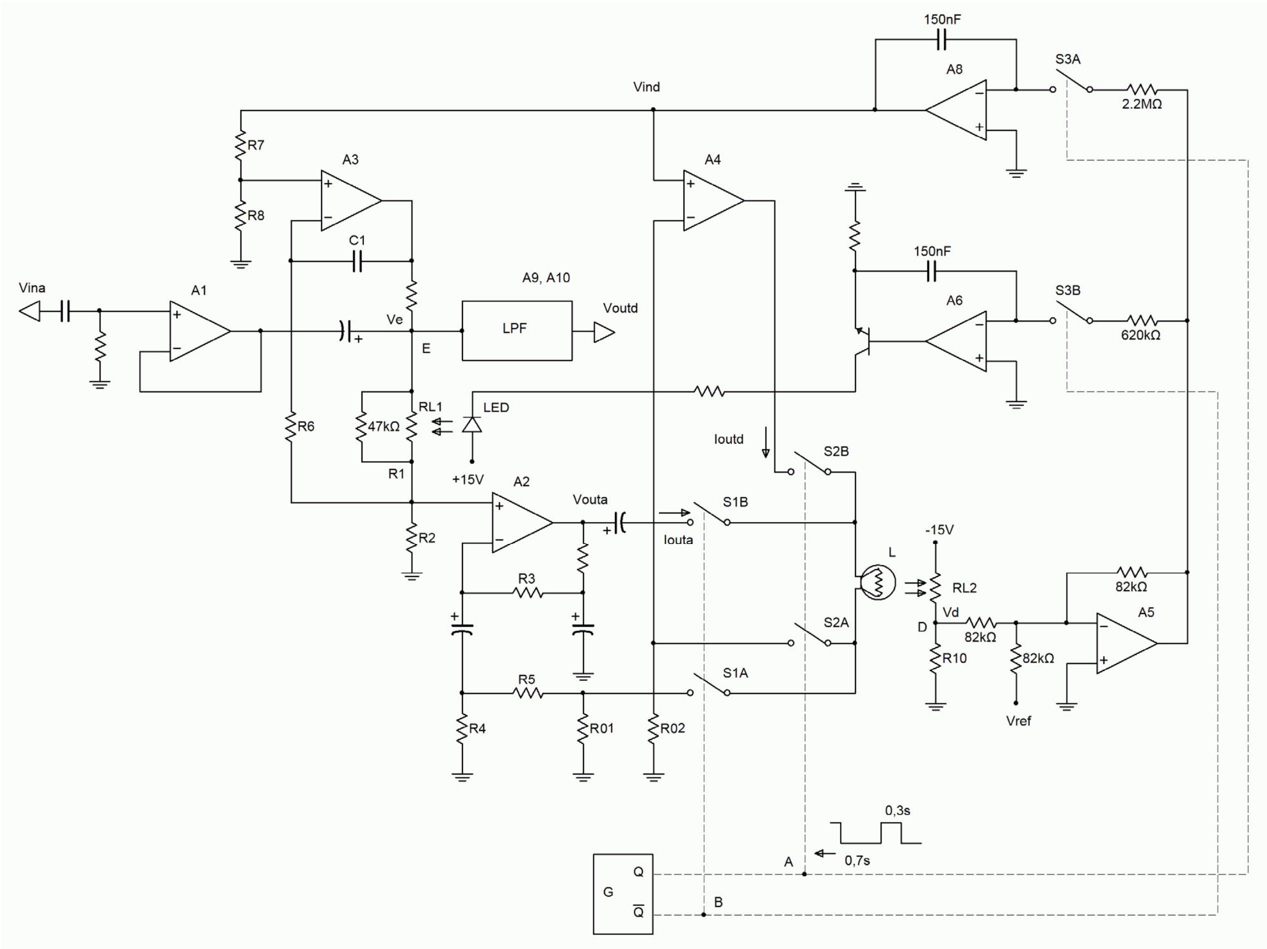

Fig.1. RMS converter - simplified circuit diagram.

The main result of the described two-phase operation is equality of the RMS values of the alternating I_{OUTA} and direct I_{OUTD} currents, its accuracy depending only on the control loops' performance which is determined by offset voltage and open-loop gain of the op amps involved.

The achieved equality $I_{OUTA} = I_{OUTD}$ doesn't suffer the above drawbacks of the converting optocoupler and reference V_{REF} because of the continuous character of switching.

Controlling in the two loops is performed in turn, it means that in every moment only one loop is closed. The other must remember its preceding settled state, otherwise their smooth operation will be broken. The open switches S_{3B}, S_{3A} configure in turn A_6 and A_8 as analogue memories. Chosen durations of the operation phases (0,7s and 0,3s) satisfy a trade-off - they are short enough for A_6 and A_8 to store the settled outputs on corresponding capacitors without degradation and for the optocoupler and V_{REF} - not to be subjected to any perceptible drift.

At the same time they are long enough for the system to respond to a disturbance, the first phase being longer as the AC loop handles variable AC input voltages, while the DC loop is running practically in the steady-state mode (variations of V_{IND} indicate only to the above imperfections of the optocoupler and V_{REF}).

To produce a DC output which could watch the state of the input attenuator and hence the level of AC input, op amp A_3 is employed. It amplifies the applied fraction of DC voltage V_{IND} with the gain just equal to the AC attenuation because the used resistors R_1, R_2 are the same. This results in the DC-component of voltage V_E at point E. The AC-component V_{INA} remains unchanged, as it sees the output of A_3 which here behaves itself as a low-pass filter whose cut-off frequency (8Hz) is determined by $R_6 C_1$.

Pure DC output V_{OUTD} of the converter is obtained after passing V_E through a forth-order Bessel filter (A_9, A_{10}) chosen for its optimum settling time. The filter turnover frequency is 2,4Hz and the AC products are suppressed effectively - about 60dB even at the lowest (20Hz) frequency.

Expression for V_{OUTD} is

$$V_{OUTD} = V_{IND} \times \frac{R_8 (R_1 + R_2)}{(R_7 + R_8) R_2} .$$

Combining it with the previous formula gives:

$$I_{OUTD} = V_{OUTD} \times \frac{R_2}{R_1 + R_2} \times \frac{R_7 + R_8}{R_8 R_{02}} .$$

As $I_{OUTA} = I_{OUTD}$, their expressions must be equal too:

$$V_{INA} \times \frac{R_2}{R_1 + R_2} \times \frac{R_{34} + R_5 + R_{01}}{R_{34}R_{01}} = V_{OUTD} \times \frac{R_2}{R_1 + R_2} \times \frac{R_7 + R_8}{R_8R_{02}}.$$

Exclusion of such a variable term as R_1 (along with R_2) is of vital importance and leads to:

$$V_{OUTD} = V_{INA} \times \frac{R_{02}}{R_{01}} \times \frac{(R_{34} + R_5 + R_{01})\, R_8}{R_{34}(R_7 + R_8)}.$$

The final simplification comes when choosing $R_{02} = R_{01}$, $R_8 = R_{34}$ and $R_7 = R_5 + R_{01}$. Slight adjustment of R_7 allows to set the desired exact equality of the RMS value of AC input and the obtained value of DC output:

$$V_{OUTD} = V_{INA}.$$

ACCURACY

Accuracy of maintaining the last equality depends on various factors. However, thanks to the applied circuit tricks, such crucial parts of the converter as its optocouplers have been excluded from the main contributors of measurement errors.

Indeed, running the led optocoupler simultaneously and the converting optocoupler quasi simultaneously in two processes, AC and DC, ensures the conversion accuracy not to be affected by kind and stability of their transfer characteristics. This considerably simplifies also the choice of the optocouplers, these devices can be obtained by putting together separate components. The required for that are a pair of cadmium sulfide photoresistors with a minimum cell resistance of not more than 1kΩ and settling time not exceeding 100ms, a miniature 6V/20mA filament lamp and at last a miniature red LED.

The only two errors associated with the optocouplers have been encountered. First of them is a slight nonlinearity of photoresistor R_{L1} included in the input attenuator. Increasing R_{L1}, along with rising the AC and DC voltages simultaneously applied to it, more clearly reveals this effect which is due to the property of the photoresistor's light sensing material. At the top end of the 0,1-1V RMS input dynamic range, the nonlinearity error reaches ±0,1%.

The second error is caused by AC modulation of photoresistor R_{L2} used in the converting optocoupler. At low working frequencies, the thermal inertia of filament lamp L becomes insufficient and a ripple of the emitted light intensity appears. This results in R_{L2} modulation and then in the ripple of DC output of the optocoupler, the ripple frequency and amplitude being correspondingly twice and inversely proportional to the frequency of AC input V_{INA}. The error would be ±1% at 20Hz but further I will show how it has been reduced at least to ±0,2%.

The ultimate conversion relationship $V_{OUTD} = V_{INA}$ is obtained by bringing into proper correlation the values of R_{01}, R_{02}, R_3, R_4, R_5, R_8 and by final adjustment of R_7. Long-term stability of these resistors directly determines the conversion accuracy, so to guarantee the latter not to be affected by time, temperature etc, metal film ±0.5% resistors should be used. This eliminates the need of any periodic calibration.

Most numerous are the so-called static errors of the RMS converter. The key condition of running the converting optocoupler is equality of its DC output and reference V_{REF}, i.e. $V_D = V_{REF}$, the accuracy of its maintaining depending on such DC characteristics of the involved op amps A_4, A_5, A_6, A_8 as offset voltage, bias current and open-loop gain. Fortunately, V_{REF} =1,5V is high enough to ignore for example the input offset of A_5, which for the used OP07H doesn't exceed 0,1mV, so its trimming is unnecessary.

Notably lesser are the DC voltages applied to the inputs of op amp A_3 and final low-pass filter (A_9, A_{10}), both stages forming the converter's DC output V_{OUTD}. They are correspondingly 50mV and 0,1-1V, so the input offset of OP07H leads here to such maximum static errors as ±0,2% and ±0,1%. They further can be easily reduced to negligible levels by the adjustments provided in A_3 and A_{10}.

At low working frequencies, the error caused by the residual AC ripple of output V_{OUTD} is added to the above modulation error. The used smoothing forth-order low-pass filter with its 2,4Hz turnover frequency allows to retain this error within ±0,2% even at the lowest 20Hz frequency.

At high frequencies, the errors associated with amplifiers A_1, A_2 become dominating and the highest attainable bandwidth limit may be roughly taken as a frequency at which open-loop gain of amplifier A_2 falls to 60-80. Accuracy largely depends also on the amplifier slew rate and stray capacitances in the whole route of passing AC signals.

The achievements in creating broadband op amps make it possible to widen the converter bandwidth up to 30MHz, but when turning to the discrete technique, a good bit higher figure can be obtained. In the author's prototype, A_2 is an all-discrete FET input amplifier with an open-loop gain of 1000 at 1MHz and a slew rate of 300V/μs. The achieved total accuracy of the RMS converter is better than ±0,3% at frequencies from 20Hz to 20kHz and ±0,5% - from 20Hz to 100kHz in the whole 0,1-1V RMS range of AC inputs with up to 10:1 crest factor. The accuracy remains still high (±1%) at 1MHz, being reduced to ±5% at 10MHz.

CIRCUIT DETAILS

As can be seen from the converter's full circuit diagram (Fig.2), a certain part of circuitry is employed to keep the total settling time within 1,5s in the whole 0,1-1V RMS range of AC inputs. The used diode-resistive networks reduce the integrators' time constants, speeding up the start of controlling when sharp input disturbances occur.

To provide optimum completion of the controlling process for any V_{INA} , the AC control loop contains an automatic attenuator R_{26}, Q_{12} which reduces excessive gain within the loop when R_{L1} is high and the current through the LED optocoupler needs a low output of integrator A_6 . The less this output and its fraction applied to op amp A_7, the less the on-resistance of the two matched JFETs biased equally by A_7, one of them (Q_{12}) shunting the integrator input. This damps an oscillation tending to appear at V_{INA} levels of more than 0,3V RMS and ensures the controlling process to be fast-settling aperiodic.

If during the AC phase of operation considerable changes of the AC input take place, the system must respond to them, not being interrupted by the following DC phase. Forcing flip-flop U_{6A} to stay in the former state for about 2s is carried out by a high going output pulse of monostable U_{6B}, the necessary triggering signal for the latter being derived from the output of A_5 and then amplified and formed by Q_8 and U_{5A} .

The two-phase operation is ceased at all when the input AC voltage drops below about 70mV RMS, the integrator A_6 output reaches a maximum for the given op-amp level and the system looses its ability to maintain the current balance in the converting optocoupler. In this case U_{6A} stops generating and gives at its Q output a steady high level corresponding to the closed DC control loop and to sending the direct current I_{OUTD} to the optocoupler. The inhibiting signal applied at that time to the S input of U_{6A} is obtained via U_{5B} from a simple comparator on Q_6 which is on when the peak-detected AC output becomes less than the set emitter potential. To avoid incorrect results of conversion in this mode of operation, the output of Q_6, inverted by U_{4C}, enables switch U_{3C} to shorten the input of A_4 . This removes the DC-component of V_E and the converter output V_{OUTD} is turned to zero.

The continuous, not affected by any switching AC output V_{OUTA} is normally about 4V RMS, but its short dropping occurred during abrupt transitions of the AC input (particularly from maximum to minimum) has no influence on the generating U_{6A} , as NOR-gate U_{5B} allows to do that only if the system fails to reach the balance $I_{OUTA} = I_{OUTD}$, and the integrator A_6 output is therefore maximum.

Voltage V_{OUTA} is also applied to an amplifying and clipping integral long-tail pair Q_9 -Q_{10} which along with U_{4D} forms a synchronizing signal for U_{6A} . The necessity of such synchronization is dictated by the effect of AC modulation of photoresistor R_{L2}, which is caused by the alternating nature of the passing through lamp L current I_{OUTA} and manifests itself largely at the lowest frequencies. As a result, a certain AC signal is present at the input of integrator A_6 and its capturing, done at the moment of completing the AC phase of operation, leads then to periodic variations of photoresistor R_{L1} and ultimately to unstable output V_{OUTD}. This phenomenon is practically eliminated if commencing every phase coincides with the AC signal zero-crossing, just what the synchronization performs.

The final contribution to the total settling time of the converter is done by the output DC amplifier A_3 and output filter (A_9, A_{10}). The introduced delays don't exceed correspondingly 0,7s and 0,5s (for a 0,1% settling accuracy) and, although overlapping, they are an inevitable payment for the attained accuracy of conversion at low, down to 20Hz frequencies.

ADJUSTMENT

Before using exotic broadband amplifiers and driving the RMS converter at radio frequencies, it's reasonable to test and adjust the circuit in the audio range, with the help of for example a widespread OP37 or even TL082 chosen as A_1 , A_2.

First the required operational point of the converting optocoupler (a 10mA current through its lamp) should be set, whether it is a ready available device or made from the recommended above separate parts. For that, force the converter to run all the time in its DC mode by seating the disconnected S input of flip-flop U_{6A} to +15V supply via a 15kΩ resistor. Choose R_{10} to obtain voltage across R_{02} near to 2V and then check the equality of absolute values of voltages V_D and V_{REF} (at about 1,5V) applied to summing amplifier A_5 .

To set flip-flop U_{6A} to the steady state corresponding to the AC mode of operation, ground its S input and seat the disconnected R input to +15V. Apply a 1kHz 100mV RMS test signal to the converter input and choose R_{30} to obtain the DC voltage across it within 4,5-5,5V, at the same time the AC signal on R_{01} being near to 2V RMS. Observing this signal on an oscilloscope, make sure that it remains unchanged after the settling process caused by a 20dB step increase of AC input V_{INA} (to 1V RMS). If amplitude ringing occurs, damp it by adjustment of trimmer R_{39} and then observe the reverse process, when V_{INA} drops to 100mV RMS. Its duration must be within 0,5s, otherwise continue the optimization.

Restore the circuit initial connections and check its two-phase operation, monitoring pulse signals at the outputs of generator U_{6A} when input V_{INA} is within 0,1-1V RMS. Adjust trimmer R_{51} to cease the generation when V_{INA} is less than 70mV RMS. Apply an AC input V_{INA} =1V RMS and set its exact output DC equivalent V_{OUTD} by adjustment of R_{47}. Reduce V_{INA} to 100mV RMS and compare it first with the DC component of voltage V_E (at point E) and then - with the converter output V_{OUTD} . The first difference, if takes place, can be removed by offset trimming of op amp A_3 , the second - by offset trimming of the output filter (A_{10}).

Imitating all the possible transitions of AC input, measure the DC output settling time, its value of less than 1,5s confirming the correctly made component choice and circuit adjustment.

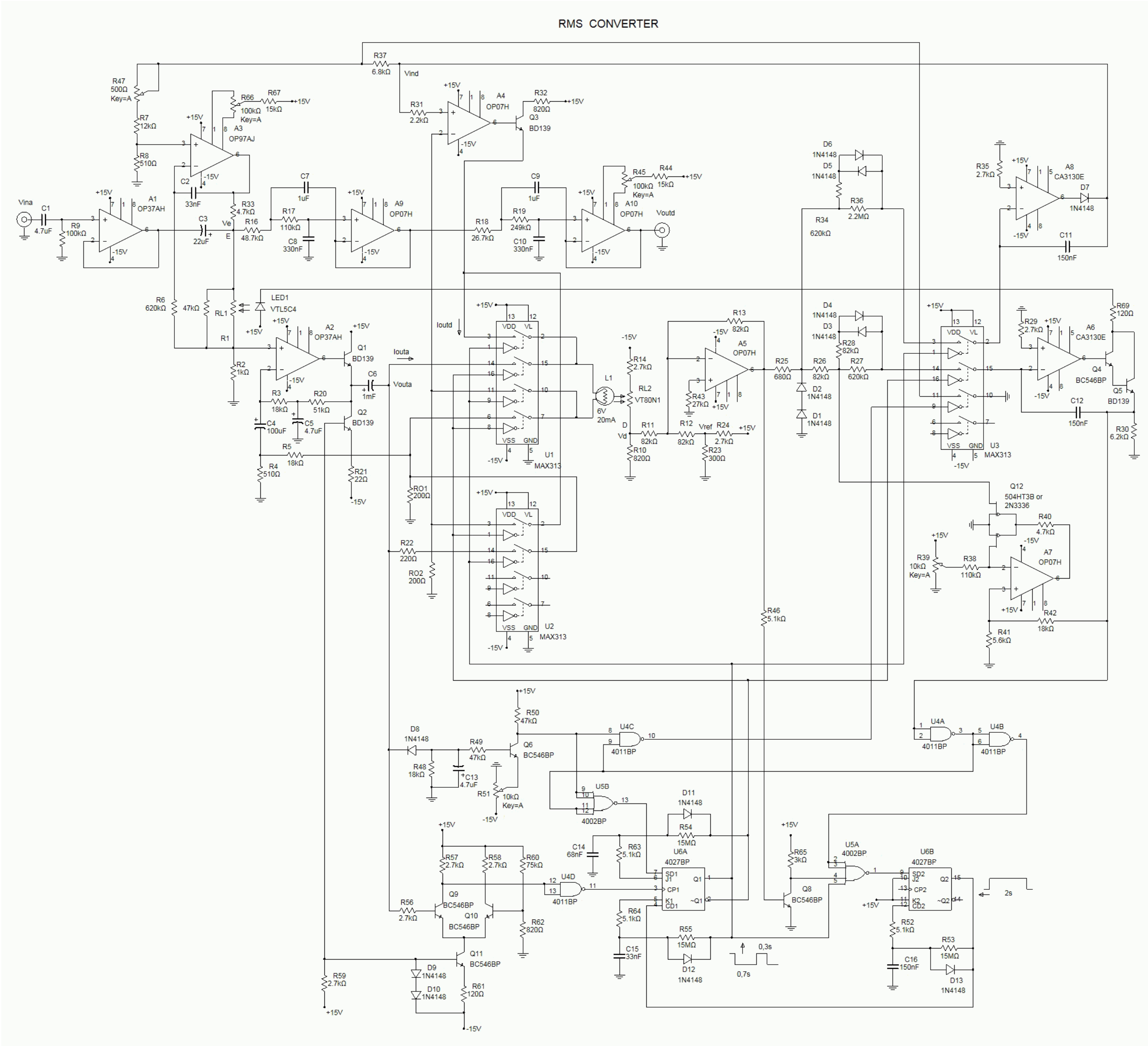

Fig.2. RMS converter - full circuit diagram.

Finally, the accuracy of maintaining the conversion relationship $V_{OUTD} = V_{INA}$ should be evaluated at several, particularly near to the ends, points of the input 0,1-1V RMS range and at the lowest, mid and highest frequencies of the expected bandwidth.

To widen the dynamic range of RMS measurements, the converter should be preceded by a broadband amplifier or attenuator.

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