Accurate Measurement of the RMS Value by Means of an Analog Multiplier-based RMS-to-DC Converter

Daniel Belega, Robert Pazsitka, Dan Stoiciu

Department of Measurements and Optical Electronics, University Politehnica Timisoara, Bv. V. Parvan, Nr. 2, 300223, Timisoara, Romania,
email: {daniel.belega@upt.ro, robert.pazsitk@upt.ro, dan.stoiciu@upt.ro}

***Abstract* – This paper investigates the influence of the accuracy of the op-amp used by the square root circuit on the accuracy of the root mean square (rms) measurement achieved by means of an analog multiplier-based rms-to-dc converter implemented using the direct method. The rms measurement accuracy achieved using the internal op-amp of the multiplier is compared through experimental results with that achieved using more accurate op-amps, namely TL082 and OPA277. The analyzed rms-to-dc converter is implemented using the Texas Instruments Analog System Lab Kit (ASLK) PRO board equipped with MPY634 analog multipliers. The experimental data are obtained by means of a dedicated experimental setup.**

Keywords* – *analog multiplier, error analysis, op-amp, rms-to-dc converter

I. INTRODUCTION

The root mean square (rms) value is a very important parameter of an ac signal since it provides information about its energy. For a periodic ac signal $v_{in}(t)$ the rms value is defined as:

$$V_{in,rms} = \sqrt{\frac{1}{T}\int_0^T v_{in}^2(t)dt}, \quad (1)$$

where $T = 1/f$ is the period of the signal.

The method used for measuring the rms value according to its definition is called the direct or explicit method [1, 2]. This requires three basic operations: square, average, and square root. A low cost solution for implementing the direct method is to use analog multipliers to perform the square and square root operations [3-5]. Fig. 1 shows the schematic of the analog multiplier-based rms-to-dc converter which implements the direct method [5].

The first multiplier provides the squared input signal divided by its Scale Factor (*SF*), that is v_{in}^2 / SF. The signal is then applied to an RC low-pass filter, used as an integrator. The filter cut-off frequency should be much smaller than the frequency of the input signal.

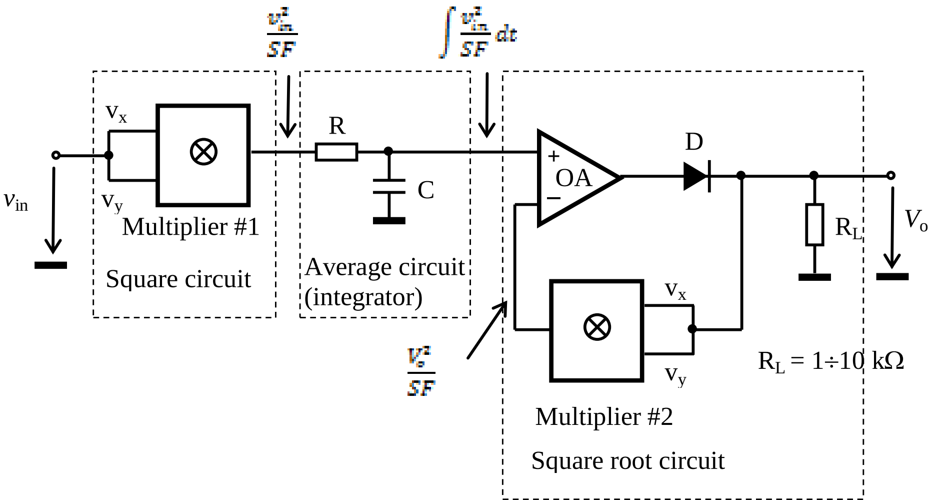


Fig. 1. Schematic of the analog multiplier-based rms-to-dc converter which implements the direct method

The square root circuit contains the second multiplier, an op-amp, the diode D, and the load resistor R_L. The second multiplier provides the squared output signal V_o^2 / SF. The diode D and resistor R_L are used to avoid the latch-up (i.e. the saturation of the output op-amp to its negative limit). The output dc voltage V_o, is almost equal to the rms value of the input signal $V_{in,rms}$, because the voltages applied to the inverting and non-inverting inputs of the op-amp differ only by the offset voltage. Thus, the accuracy of the rms measurement depends also on the accuracy of the op-amp. Its offset voltage should be very small. The op-amp can be either the one inside the second multiplier or an external one. In most applications the first choice is used.

A low-cost precision analog multiplier which can be used to build the above rms-to-dc converter is MPY634, manufactured by Texas instruments [4]. It is worth noticing that the offset voltage for the internal op-amp of the MPY634 multiplier is not specified in its data sheet [4]. Therefore, it is interesting to compare the rms measurement accuracy of the rms-to-dc converter based on MPY634 multipliers which uses the internal op-amp with those achieved using different external op-amps. This is the aim of this paper. The rms-to-dc converter is implemented using the Texas Instruments Analog System Lab Kit (ASLK) PRO board [6]. This board is intended to be used by students to learn how to design an electronic system based on op-amps, analog multipliers, and digital-to-analog converters and to determine its performance [6, 7]. The external op-amps used in the converter are those of the dual TL082 [8], denoted as TL082A and TL082B, and the OPA277 [9]. These op-amps have been chosen due to their moderate (TL082) and very small (OPA277) offset voltages. The analysis is performed by means of experimental data obtained through a dedicated experimental setup.

II. THE RMS-TO-DC CONVERTER BASED ON THE MPY634 ANALOG MULTIPLIERS

Two MPY634 are used as multipliers #1 and #2 in Fig. 1. They belong to the ANALOG MULTIPLIER section situated in the middle part of the ASLK PRO board. This section contains three such analog multipliers (see Fig. 2).

The bandwidth of the MPY634 multiplier increases and its offset voltages decrease when its *SF* increases [4]. Hence, the *SF* of each MPY634 multiplier is set to its maximum value, which is equal to 10. This is obtained leaving the Scale Factor pin unconnected [4]. It is worth noticing that the offset voltages of the input amplifiers *X*, *Y*, and *Z* of the MPY634 multiplier have a typical value of 25 mV and a maximum value of 100 mV [4]. These values are high. Therefore, in the case of small signals the accuracy of the rms measurement achieved by the rms-to-dc converter based on the MPY634 multipliers is low. The typical value for the Slew-Rate (*SR*) of the MPY634 multiplier is 20 μV/s.

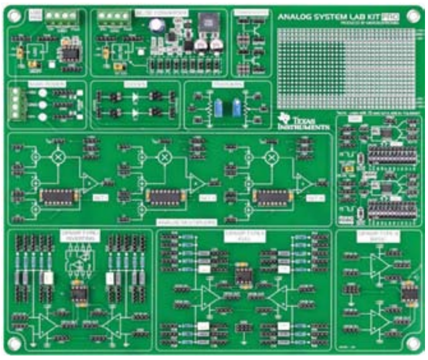


Fig. 2. ASLK PRO board

The external TL082A and TL082B op-amps are the OP3A and OP3B op-amps belonging to the dual op-amp TL082 situated in the OPAMPTYPE III BASIC section of the ASLK PRO board. The external OPA277 is connected in the bread board area of the ASLK PRO board. The typical and maximum offset values for the TL082 op-amps are 3 mV and 15 mV, respectively [8], while those for the OPA277 op-amp are 10 μV and 20 μV, respectively [9].

We consider: R = 10 kΩ, C = 10 μF, R_L = 10 kΩ, and a 1N4148 diode. The capacitor is connected in the bread board area, the resistors are from the ASLK PRO board, and the diode is connected in the DIODES Section of the ASLK PRO board.

III. EXPERIMENTAL RESULTS

The accuracy of the rms measurements achieved when the internal op-amp or the external TL082A, TL082B, or OPA277 op-amps are used is analyzed by means of experimental data achieved using the experimental setup shown in Fig. 3. It should be mentioned that the digital storage oscilloscope (DSO) is used to see the variations which occur in the output of the rms-to-dc converter. It is used in the DC mode coupling.

Fig. 4 shows the absolute value of the relative rms measurement errors as a function of the rms of the input signal $V_{in,rms}$ obtained when the internal op-amp or the external TL082A, TL082B, or OPA277 op-amps are used, in the case of sine-waves (Fig. 4a) and 50% duty cycle square-waves (Fig. 4b). $V_{in,rms}$ ranges from 0.3 to 4.5 V and the frequency of the input signals is equal to 1 kHz. The relative rms measurement error is calculated as:

$$\delta\,(\%) = \frac{V_o - \hat{V}_{in,rms}}{\hat{V}_{in,rms}} \cdot 100, \qquad (2)$$

where V_o is the output dc voltage measured by the BK5491A Digital MultiMeter (DMM) and $\hat{V}_{in,rms}$ is the reference value for $V_{in,\ rms}$ measured by the Keysight 34465A DMM.

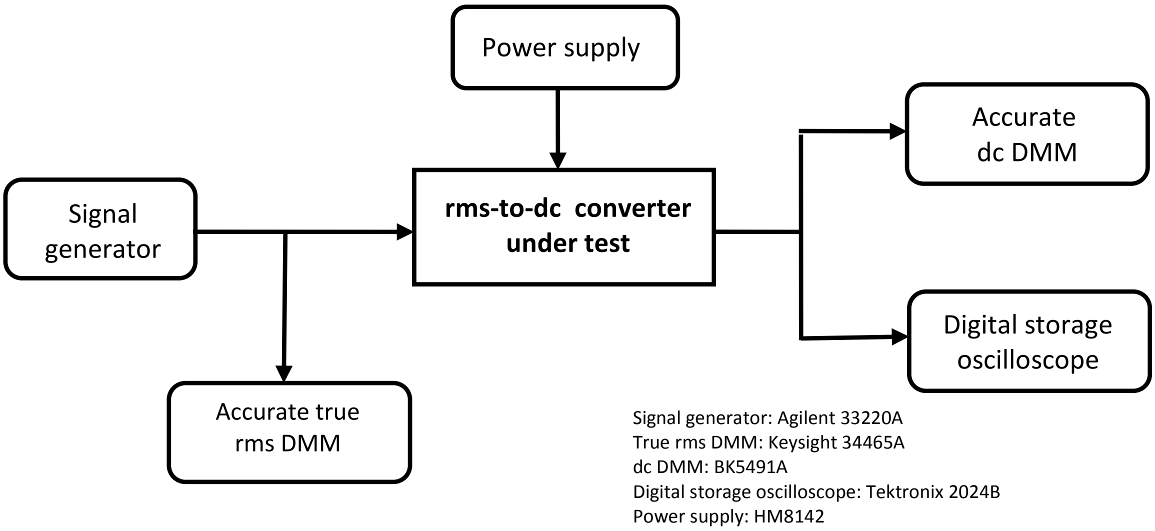


Fig. 3. Experimental setup used to determine the accuracy of the rms-to-dc converter based on the MPY634 multipliers

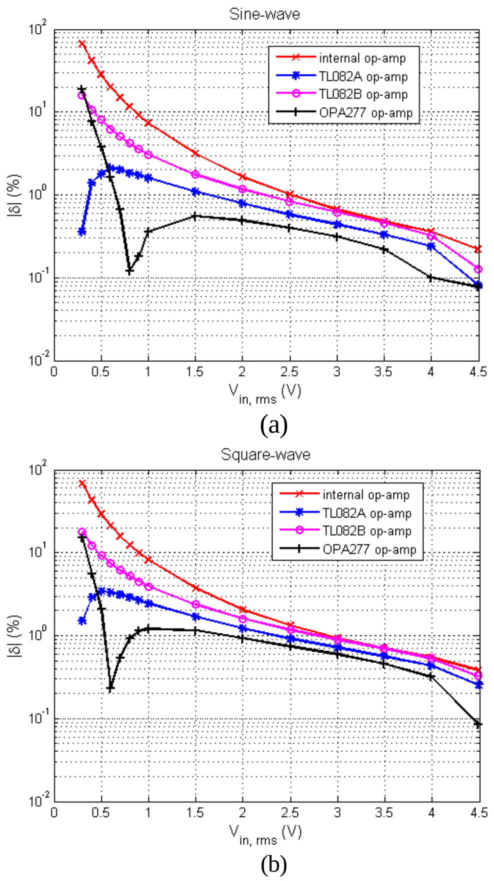
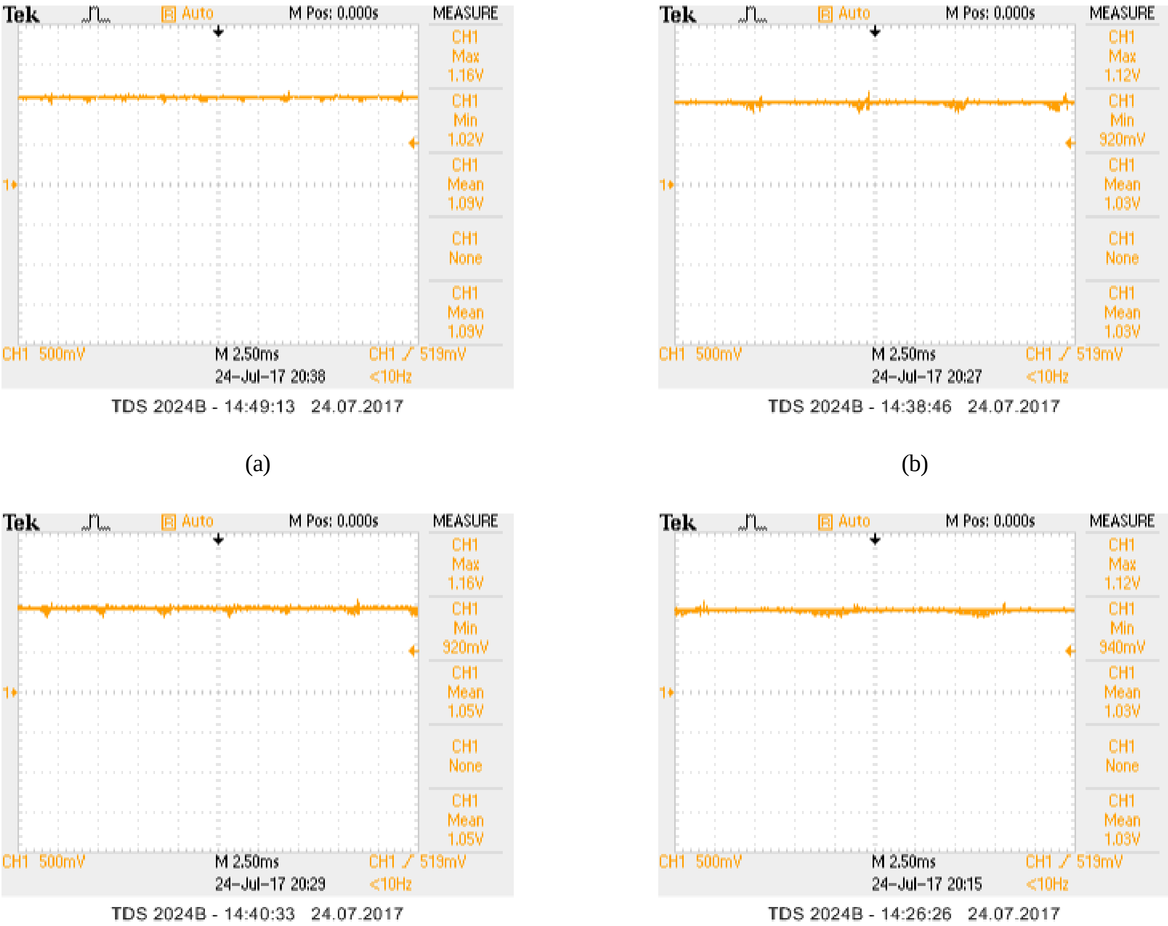


Fig. 4. Absolute value of the error δ achieved by the rms-to-dc converter based on the MPY634 multipliers and different op-amps versus the rms of the input signal in the case of sine-waves (a) and 50% duty cycle square-waves (b) input signal. The frequency of the test signals is equal to 1 kHz

From Fig. 4 it follows that the rms of the input signals are accurately determined when all considered op-amps are used only for $V_{in,,rms}$ much higher than the offset voltages of the input amplifiers of the MPY634 multipliers. In this case the rms measurement errors decrease as $V_{in,rms}$ increases. The same behaviour is achieved for small $V_{in.,rms}$ when the internal op-amp and the TL082B op-amp are used. Conversely, when the TL082A and OPA277 op-amps are used there occurs a minimum value for the rms measurement errors at a small value of $V_{in,rms}$. This behaviour is the result of a favourable combination of magnitudes and signs of the offset voltages of the input amplifiers of the MPY634 multipliers and those of the TL082A and OPA277 op-amps. It is interesting to note that the TL082A and TL082B op-amps, belonging to the same TL082 dual-amp, have different behaviours. The TL082A has better performance than the TL082B. By comparing Fig. 4a and Fig. 4b it follows that the rms values of the sine-waves are more accurately measured than those of the square-waves since the latter have their energy located in the peaks [2]. The best performance is achieved when the OPA277 op-amp is used. In this case when $V_{in,rms} > 0.8$ V we have $|\delta| < 0.56\%$ for sine-waves and $|\delta| < 1.2\%$ for square-waves.

Fig. 5 shows the output dc voltage V_o of the analyzed rms-to-dc converter visualized by the DSO for the four op-amps considered, for 1 kHz sine-waves with $V_{in,rms} = 1$ V. The spikes in the output voltage seen in Fig. 5 can be the result of the op-amp input impedances mismatch, which lead to common mode signals. The smallest spikes are obtained when the internal op-amp is used. Higher spikes, of almost the same magnitude, are obtained when the external op-amps are used. Also, in Fig. 5 it can be observed that the difference between the mean values of the output voltage V_o measured by the DSO and the ideal $V_{in,rms}$ is small for OPA277 and TL082A, while for TL082B and the internal op-amp it is higher, as expected from Fig. 4. It is worth noticing that the same behaviour as in Fig. 5 was observed for square-wave input signals.



(a) (b)

(c) (d)

Fig. 5. The output voltages of the of the rms-to-dc converter based on the MPY634 multipliers visualized by the DSO when the internal op-amp (a) or the external TL082A (b), TL082B (c), or OPA277 (d) op-amps are used in the case of sine-wave input signals with $V_{in,rms}$ = 1 V and 1 kHz frequency

Moreover, the rms measurement accuracy achieved by the analyzed rms-to-dc converter has been investigated as a function of input signal frequency. Fig. 6 shows the results for the four considered op-amps in the case of sine-waves with $V_{in,rms}$ = 2 V and frequency going from 0.1 to 200 kHz.

In Fig. 6 we can seen that the errors $|\delta|$ are almost constant up to 10 kHz, and then they increase with frequency. The best performance is obtained for OP277, despite its smallest *SR* parameter. By considering a limit of 1% for the error $|\delta|$ the bandwidth achieved with OPA277 is about 50 kHz, while with TL082A it is about 30 kHz. For the two other op-amps the errors $|\delta|$ are higher than the above limit. It should be mentioned that the same behaviour as in Fig. 6 can be observed for square-wave input signals, with the remark that the errors $|\delta|$ are higher.

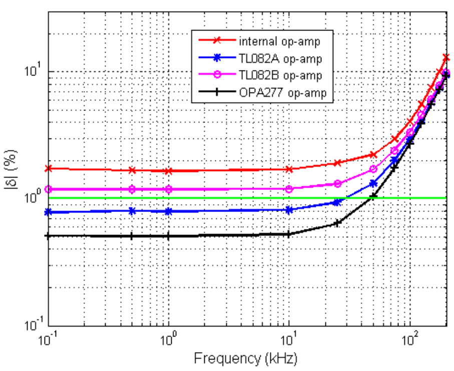


Fig. 6. Absolute value of the error δ achieved by the rms-to-dc converter based on the MPY634 multipliers and different op-amps versus frequency in the case of sine-waves input signals with $V_{in,rms}$ = 2 V

As specified before, for small input signals the rms is not accurately determined since the voltage offsets of the input amplifiers of the MPY634 multipliers are high. A possible solution to overcome this is to *a-priori* amplify the input signals with an appropriate gain to get amplified signals in a range for which the rms-to-dc converter provides accurate rms measurements. Then, the rms value is obtained by dividing by the gain the output dc voltage. This solution is verified in practice for signals with $V_{in,rms}$ ranging from 0.25 to 0.8 V when the OPA277 op-amp is used. A voltage buffer is used to avoid attenuation of the input signal. The output of the buffer is connected to the input of an inverting amplifier with a gain of 5. Thus, the rms of the amplified signal ranges from 1.25 to 4 V, where, as results from Fig. 4, the analyzed rms-to-dc converter provides accurate rms measurements. The voltage buffer and the inverting amplifier were implemented using the OP3A and OP1B op-amps from the OPAMP TYPE III BASIC and OPAMP TYPE I INVERTING sections of the ASLK PRO board. Both op-amps are from dual op-amp TL082. The resistors connected in the feedback loop and to the inverting input of the inverting amplifier are R_{25} and $R_{41} + R_{21}$, respectively. The values of the above resistors measured with the Keysight 34465A DMM are equal to 9.98219 kΩ and 1.99502 kΩ, respectively. The gain of the inverting amplifier is equal to the ratio of the above resistor values. The rms value of the input signal is determined by dividing the measured output dc voltage by the above gain.

Fig. 7 shows the absolute value of the error δ achieved in this case as a function of $V_{in,rms}$ when sine-waves or 50% duty cycle square-waves are used as test signals. The frequency of these signals is equal to 1 kHz.

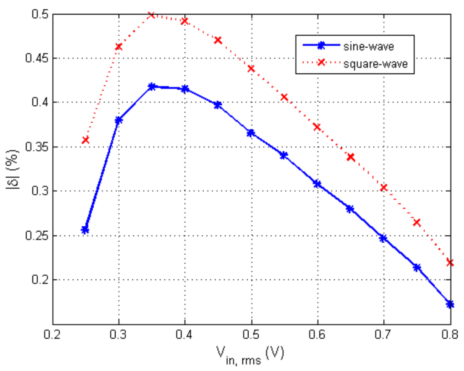


Fig. 7. Absolute value of the error δ achieved by the rms-to-dc converter based on the MPY634 multipliers when the external OPA277 op-amps is used versus the rms of the input signal for sine-waves and 50% duty cycle square-waves (b). $V_{in,rms}$ is in the range [0.25, 0.8] V and the frequency of the test signals is equal to 1 kHz

In Fig. 7 it can be seen that the rms values of both signal types are accurately determined. By comparing the results shown in Fig. 7 and Fig. 4 it follows that the errors $|\delta|$ obtained using the amplified signals are close to those obtained using the non-amplified signals with $V_{in,rms}$ in the range [1.25, 4] V. Also, for amplified signals the rms values of the sine-waves are more accurately measured than those of the square-waves, as expected.

Further, for accurate rms measurements of signals with $V_{in,rms} < 0.25$ V an appropriate amplification should be considered.

IV. CONCLUSIONS

In this paper it has been shown that to achieve accurate rms measurements with the rms-to-dc converter based on the MPY634 multipliers an external op-amp with very small offset voltage should be used by the square root circuit. Such an op-amp is the OPA277, which has been used in this work. In this case it has been shown that accurate rms measurements are achieved when $V_{in,rms} > 0.8$ V. For smaller values of $V_{in,rms}$ a solution to achieve accurate rms measurements is to amplify the input signals. The gain should be chosen to ensure that the rms values of the amplified signals are accurately measured by the considered rms-to-dc converter.

Future work will focus on the comparison of the performance of the rms-to-dc converter analyzed in this paper with that of the dedicated rms-to-dc converter integrated circuits, which have a combined total of offset errors smaller than 1 mV [2].

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