ANALOG DEVICES

RMS to DC Conversion Application Guide

$$rms = \sqrt{\frac{1}{T}\int_0^T [f(t)]^2\,dt}$$

2ND Edition

RMS TO DC CONVERSION APPLICATION GUIDE

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INTRODUCTION

This Application Guide sets forth the principles of operation of the AD536A, AD636, and AD637 integrated circuit true rms to dc converters and shows many practical applications circuits for these devices. The low cost, low power consumption and high (laser trimmed) accuracy of these integrated circuits make rms computation a practical and accessible technique for extracting a measure of the power or the standard deviation of a waveform. Previously, the high cost and relative complexity of using modular, hybrid, or discrete component rms converters had tended to make "true rms" something of a laboratory curiosity restricted to specialized instruments.

In addition to specific applications, this guide also briefly covers the mathematics of rms and offers a comparison between various implementations of the rms equation, e.g., thermal, implicit and explicit computation, and the more commonly used "average" rectified value *non* rms detector. We hope that this background information will help remove some of the mystique of rms computation and assist the designer in applying the various Analog Devices rms converters and rms measurement in general in a creative and knowledgeable manner.

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SECTION I

RMS-DC CONVERSION – THEORY

BASIC DEFINITIONS

Definition of rms

RMS or Root Mean Square is a fundamental measurement of the magnitude of an ac signal. Its definition can be both practical and mathematical. Defined practically: the rms value assigned to an ac signal is the amount of dc required to produce an equivalent amount of heat in the same load. For example: an ac signal of 1 volt rms will produce the same amount of heat in a resistor as a 1 volt dc signal. Defined Mathematically: the rms value of a voltage is defined as:

$$E_{rms} = \sqrt{\text{AVG.}\,(V^2)}$$

(The above is a simplified formula–equivalent to the standard deviation of a zero average statistical signal.) This involves squaring the signal, taking the average, and obtaining the square root. The averaging time must be sufficiently long to allow filtering at the lowest frequencies of operation desired.

Definition of Crest Factor

The crest factor of a waveform is a ratio of its peak value to its rms value. Signals such as amplitude symmetrical squarewaves or dc levels have a crest factor of one. Other waveforms, more complex in nature, have higher crest factors (see Table 1).

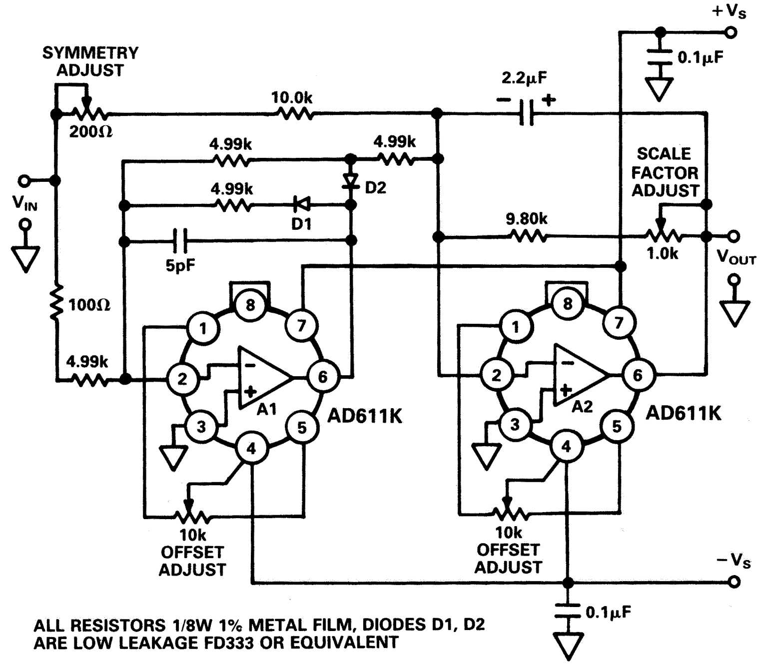
Rectifier or MAD Method of ac Measurement

The most common method of measuring the magnitude of an ac signal is the precision rectifier or average responding approach which is actually a measure of the mean absolute deviation (MAD) or "ac AVERAGE" of a waveform. The gain or scale factor of the system is usually calibrated to the ratio of rms to MAD for sinewaves. This works fine as long as the input waveform is an undistorted sinewave; for any other waveform, the ratio of rms/MAD changes, and serious errors develop.

For these reasons, the precision rectifier method (see Figure 1) provides only a relative measure of the amplitude of non-sinusoidal waveforms.

Waveform 1 Volt Peak	**RMS**	**MAD**	**RMS/MAD**	**Crest Factor**
Undistorted Sinewave	$\frac{V_{PEAK}}{\sqrt{2}} = 0.707$ Volts	$\frac{2V_{PEAK}}{\pi} = 0.636$ Volts	$\frac{0.707}{0.636} = 1.11$	$\frac{V_{PEAK}}{V_{rms}} = 1.414$
Symmetrical Squarewave	$\frac{V_{PEAK}}{1} = 1.00$ Volts	$\frac{V_{PEAK}}{1} = 1.00$ Volts	$\frac{1.00}{1.00} = 1.00$	$\frac{V_{PEAK}}{V_{rms}} = 1.00$
Undistorted Triangle-Wave	$\frac{V_{PEAK}}{\sqrt{3}} = 0.580$ Volts	$\frac{V_{PEAK}}{2} = 0.500$ Volts	$\frac{0.580}{0.500} = 1.155$	$\frac{V_{PEAK}}{V_{rms}} = 1.73$

Table 1. RMS, MAD and Crest Factor Chart



ALL RESISTORS 1/8W 1% METAL FILM, DIODES D1, D2 ARE LOW LEAKAGE FD333 OR EQUIVALENT

Figure 1. A Precision (MAD) Rectifier

For a graphic comparison of the performance of an MAD rectifier vs. a true rms converter over varying duty cycles see Figure 10 in Section II of this guide.

METHODS OF TRUE RMS-DC CONVERSION

Thermal rms-dc Conversion

Thermal conversion is the simplest method in theory; yet, in practice, it is the most difficult and expensive to implement. This method involves comparing the heating value of an *unknown* ac signal to the heating value of a *known* calibrated dc reference voltage (see Figure 2). When the calibrated voltage reference is adjusted to null the temperature difference between the reference resistor (R_2) and the signal resistor (R_1), the power dissipated in these two matched resistors will be equal. Therefore, by the basic definition of rms, the value of the dc reference voltage will equal the rms value of the unknown signal voltage.

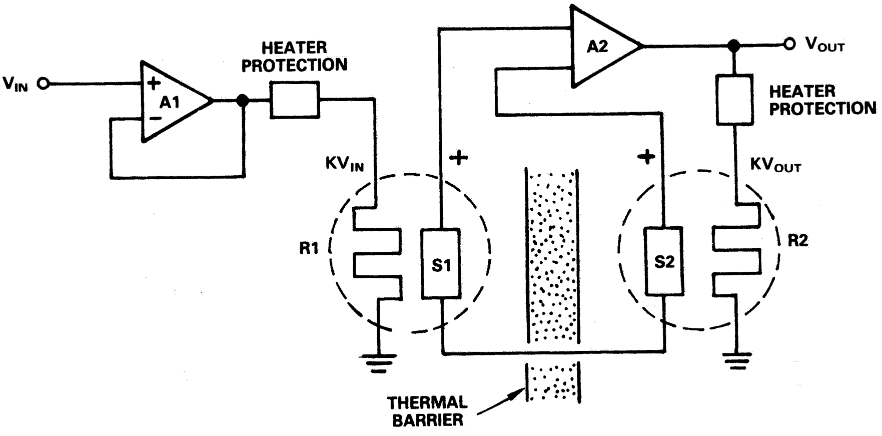


Figure 2. A Thermal rms to dc Converter

Each thermal unit contains a stable, low-TC resistor (R_1, R_2) which is in thermal contact with a linear temperature to voltage converter, (S_1, S_2); an example of which would be a thermocouple. The output voltage of S_1 (S_2) varies in proportion to the mean square of V_{IN}; the first order temperature/voltage ratio will vary as $K\ V_{IN}/R_1$.

The circuit of Figure 2 typically has very low error (approximately 0.1%) as well as wide bandwidth. However, the fixed time constant of the thermal unit ($R_1\ S_1$, $R_2\ S_2$) limits the low frequency effectiveness of this rms computational scheme.

In addition to the basic types discussed, there are also variable gain thermal converters available which can overcome the dynamic range limitations of fixed gain converters at the expense of increased complexity and cost.

Various Computing Methods of rms-dc Converters

Direct or Explicit Computation

The most obvious method of computing rms value is to perform the functions of squaring, averaging, and square rooting in a straight-forward manner using multipliers and operational amplifiers. The direct or *explicit* method of computation (Figure 3) has a limited dynamic range because the stages following the squarer must try to deal with a signal that varies enormously in amplitude. For example, an input signal that varies over a 100 to 1 dynamic range (10mV to 1V) would have a dynamic range of 10,000 to 1 at the output of the squarer (squarer output = 1mV to 10 volts). These practical limitations restrict this method to inputs which have a maximum of approximately 10:1 dynamic range. System error can be as little as ±0.1% of full scale using a high quality multiplier and square rooter. Excellent bandwidth and high speed accuracy can also be achieved using this method.

Indirect or Implicit Computation

A generally better computing scheme uses feedback to perform the square root function implicitly or indirectly at the input of the circuit as shown in Figure 4. Divided by the average of the output, the *average* signal levels now vary *linearly* (instead of as the *square*) with the rms level of the input. This considerably increases the dynamic range of the implicit circuit, as compared to explicit rms circuits. For a more detailed explanation of implicit rms computation, see AD536A and AD637 theory of operation, page 4.

Some advantages of implicit rms computation over other methods are fewer components, greater dynamic range, and generally lower cost. A disadvantage of this method is that it generally has less bandwidth than either thermal or explicit computation. An implicit computing scheme may use direct multiplication and division (by multipliers), or it may use any of several log-antilog circuit techniques.

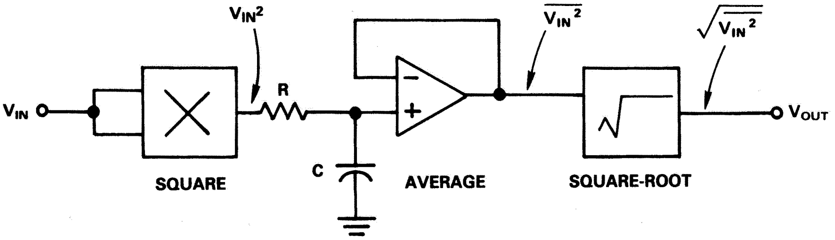


Figure 3. The Explicit Computation Method

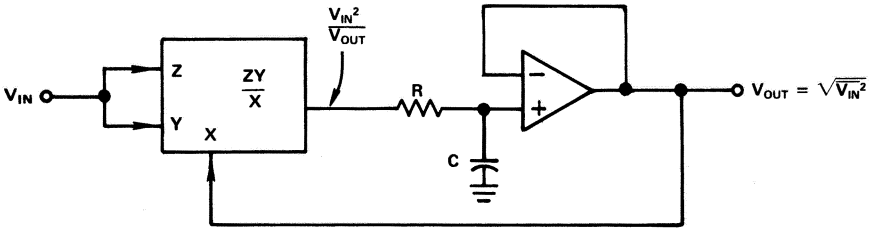


Figure 4. The Implicit Computation Method

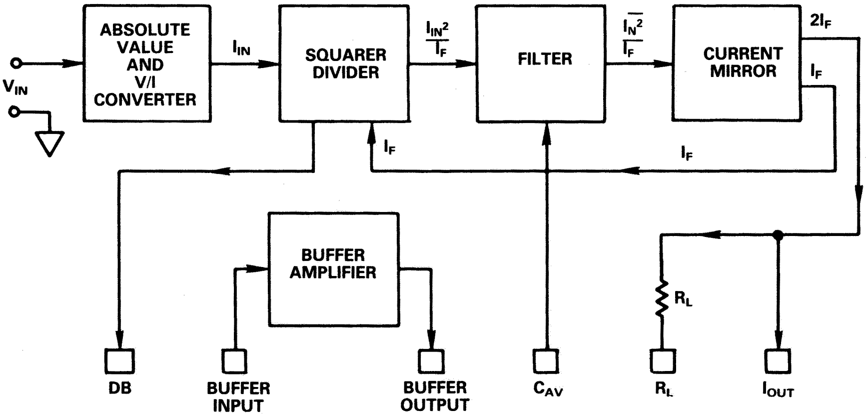


Figure 5. AD536A/AD636 Block Diagram

MONOLITHIC RMS TO DC CONVERTERS – PRINCIPLES OF OPERATION

AD536A – Wide Range rms Converter

The AD536A uses an implicit method of rms computation employing an absolute value V/I converter, a squarer/divider, low pass filter, precision current mirror, and an output buffer (see Figures 5 and 35). It features a 10 volt full scale input range.

The voltage input to the AD536A is first processed by an absolute value circuit (a precision rectifier) which has a single polarity output. This output drives a voltage to current converter (an operational amplifier) whose current output, I_{IN}, is the rectified input signal.

Current I_{IN} drives a squarer/divider, which performs both the squaring and square rooting functions in one stage by utilizing feedback from the current mirror. The feedback current, I_F, is divided into the squared input current, I_{IN}^2, using log-antilog circuits. Since dB or decibels are a function of the log of a signal, a dB output for the AD536A is derived from this squarer/divider stage. The output from this stage, I_{IN}^2/I_F, is averaged by a low pass filter consisting of an internal resistor and an externally-connected filter capacitor. This filtered signal drives the current mirror which provides the feedback current, I_F, and the output current, $2I_F$. The output current is set at twice the feedback current to develop the desired output voltage for the device using its internal 25kΩ resistor, R_L. The I_{OUT} pin of the AD536A gives a current output of 40μA per volt of rms input signal. Grounding the R_L pin gives a voltage output of 1 volt dc per volt rms input. The unity gain buffer amplifier may be used to provide a low impedance voltage output for either the I_{OUT} or dB output function.

AD636 – Low Power/Low Level Operation rms Converter

The AD636 low-power rms converter is very similar to the standard AD536A, however, it is optimized for low level, low power operation in portable instruments; it features a 200mV full scale input range.

AD637 – High Performance rms Converter

The AD637 has higher accuracy than the AD536A, an extended frequency response, and a −3dB bandwidth as high as 8MHz (see Table 2). This converter (Figure 6) uses an inverting low pass filter stage to provide a buffered voltage output whose averaging time constant is independent of input signal level (unlike the AD536A and AD636).

In addition to improved overall performance, the AD637 contains two unique features: a denominator input provision which allows this rms converter to operate as a squarer, mean squarer, root sum of squares (vector sum) and also facilitates low frequency (<10Hz) measurement. A second feature, an optional chip select provision, allows the user to power-down the rms converter to conserve power when it is not being used (as in portable meters on dc ranges). The chip select is normally *on* and must be pulled *low* to a TTL input level of 0.8 volts or less to put the rms converter in the stand-by state reducing its power consumption by 7 to 1. For normal operation without the chip select provision, this pin should be left floating. The output (pin 9) goes to a high impedance state when the chip select is low.

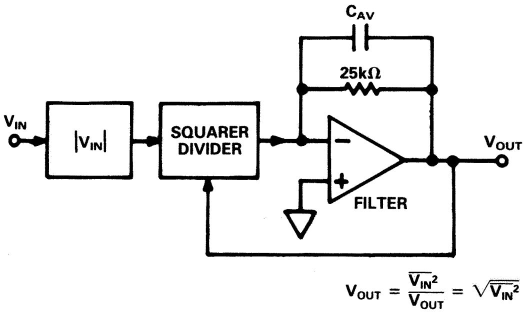


Figure 6. AD637 Filter/Averaging Diagram

This analog "three state" operation permits the outputs of several AD637s to be connected in parallel and allows the desired channel to be selected by pulling its chip select high, thus creating an active multiplexer. Like its predecessors, the AD637 full wave rectifies the input signal voltage using an absolute value circuit. As shown in Figure 7, the next section of the converter takes the log of this dc signal and doubles it, performing a squaring operation. The squared output of this section then passes on to a divider stage where the log of the rms output V_{OUT} is subtracted from the log of the squared input signal. An exponential section then takes the antilog leaving: V_{IN}^2/V_{OUT}.

This is applied to the final section of the rms converter, a filter stage which takes the average of this processed signal leaving: $\overline{V_{IN}^2/V_{OUT}}$.

And since at the output:

$$V_{OUT} = \frac{\overline{V_{IN}^2}}{V_{OUT}}$$

then:

$$V_{OUT} = \sqrt{\overline{V_{IN}^2}}$$

(V_{OUT} times both sides of the equation)

This is, by definition the rms value of the input voltage.

Some additional comments:

The denominator input is normally connected to the V_{OUT} pin, as shown by the dotted lines in Figure 7, to perform the V_{IN}^2/V_{OUT} function. However, if the denominator input, which controls the scale factor, is connected to a fixed dc voltage, V_{EXT}, the output will be: $\overline{V_{IN}^2}/V_{EXT}$. This is equal to the mean square of the input divided (or multiplied if $-V_{EXT}$ is used) by a fixed scale factor (see µP-Controlled Squarer section).

The filter stage of the AD637 consists of an operational amplifier/integrator whose averaging time constant is set by its internal on-chip 25kΩ feedback resistor and an external averaging capacitor, C_{AV}. The RC_{AV} time constant should be chosen to be longer than the period of the lowest frequency being measured, yet short enough to allow tolerable settling time. Since the filter stage output impedance is low, further output buffering is not necessary. The on-chip buffer amplifier is normally needed only in applications where an active filter is required to further reduce the output ripple (see Filters and Averaging section.)

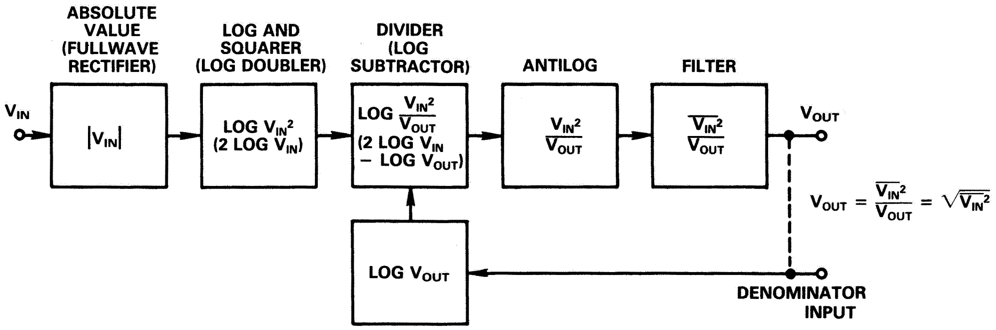


Figure 7. AD637 Block Diagram