

RMS to DC Conversion Application Guide

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

2ND Edition

RMS TO DC CONVERSION APPLICATION GUIDE

2ND Edition

by

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and
Lew Counts**

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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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TABLE OF CONTENTS

SECTION I: RMS-DC CONVERSION – THEORY	1
BASIC DEFINITIONS	1
Definition of rms	1
Definition of Crest Factor	1
RECTIFIER OR MAD METHOD OF AC MEASUREMENT	1
METHODS OF TRUE RMS-DC CONVERSION	2
Thermal rms-dc Conversion	2
Various Computing Methods of rms-dc Converters	3
Direct or Explicit Computation	3
Indirect or Implicit Computation	3
MONOLITHIC RMS TO DC CONVERTERS – PRINCIPLES OF OPERATION	4
AD536A – Wide Range rms Converter	4
AD636 – Low Power/Low Level Operation rms Converter	4
AD637 – High Performance rms Converter	4
SECTION II: RMS TO DC CONVERSION – BASIC DESIGN CONSIDERATIONS	7
ACCURACY OF RMS-DC CONVERTERS	7
“Static” Errors – rms-dc Converter Static Errors and Their Effect on Overall Accuracy	7
Bandwidth Considerations	9
EXTERNAL OFFSET AND SCALE FACTOR TRIMMING	10
FILTERS AND AVERAGING	12
Introduction	12
Averaging and Filtering Time Constants	12
DC Error and Output Ripple	12
The Standard rms Connection	14
Design Considerations – Error Versus Ripple	14
FILTERING VERSUS SETTLING TIME	15
Settling Time Versus Input Level – AD536A and AD636 Only	15
Using a One Pole Filter to Reduce Ripple and Overall Settling Time	16
Settling Time Approximations When Using a Post Filter	17
THE TWO POLE OUTPUT FILTER	18
DETERMINING THE COMBINED ERROR OF THE RMS MEASUREMENT SYSTEM	18
USING THE INTERNAL BUFFER AMPLIFIER TO ISOLATE THE FILTERING CIRCUIT	19
THE EFFECTS OF SYMMETRY, DC OFFSET, AND DUTY CYCLE OF INPUT	20
WAVEFORMS ON THE REQUIRED VALUE OF C_{AV}	20
ERROR VERSUS CREST FACTOR	21
AD536A	21
AD636	21
AD637	21
SINGLE SUPPLY OPERATION	21
AD536A	21
AD636	22
AD637	22
THE DECIBEL OUTPUT PROVISION	22
Basic Operating Principles	22
AD536A/AD636 Temperature Compensation	23
AD637 Temperature Compensation	24

SECTION III: RMS APPLICATION CIRCUITS	25
AUTOMATIC GAIN CONTROL (AGC)	25
An rms – AGC Amplifier	25
An Audio rms – AGC Amplifier	26
INSTRUMENTATION	28
A Low Cost True rms Digital Panel Meter	28
A Portable High Impedance Input rms DPM and dB Meter	29
A Low Power, High Input Impedance db Meter	30
A Modem Line Monitor	31
DATA ACQUISITION	32
A Programmable Gain rms Measurement System	32
Low Level rms Measurement Using an rms Instrumentation Amplifier	33
RMS NOISE MEASUREMENT	35
Introduction	35
The Effects of Input Coupling on Input Filter Performance	35
Determining the Noise Gain of Input Filter	35
A Cookbook Procedure	35
Determining the Exact Noise Gain	36
Processing Noise with an rms Converter	36
Selecting the Value of C_{AV}	36
A Practical Noise Measurement Circuit	36
LOW FREQUENCY MEASUREMENT	37
Introduction	37
A Low Frequency rms-dc Converter Circuit	38
An Ultra Low Frequency rms-dc Converter Circuit	38
MICROPROCESSOR-CONTROLLED RMS FUNCTIONAL CIRCUITS	40
An rms Converter Circuit with a μ P-Controlled Averaging/Settling Time Constant	40
Using a VMOS FET to Quick-Reset an rms Converter Circuit	41
A μ P-Controlled Analog Squarer Circuit	42
MISCELLANEOUS MATHEMATICAL COMPUTATIONS	43
Vector Summation Using the AD637	43
POWER MEASUREMENT	44
Introduction	44
Of Volt-Amperes, Watts, and Vars.	44
Practical Power Measurement	45
APPENDIX A: TESTING THE CRITICAL PARAMETERS OF RMS CONVERTERS	47
Introduction	47
Testing Accuracy Versus Crest Factor	47
Testing ac Accuracy	48
Testing dc Conversion Accuracy	48
Testing dc and ac Linearity	48
USE OF CROSSPLOTS TO SPEED TESTING OF RMS CONVERTERS	49
Introduction	49
Setting Up the Crossplot Test System	49
Evaluation of Crossplot Patterns	50
AN RMS CROSSPLOT TESTER	51
Circuit Description	51
Calibration	52
APPENDIX B: INPUT BUFFER AMPLIFIER REQUIREMENTS	53
The Necessity of an Input Buffer	53

Using the AD536A/AD636 Internal Buffer Amplifier as in Input Buffer	53
Bootstrapping an rms Converter's Internal Buffer Amplifier	54
What is Bootstrapping?	54
Some Precautions	55
Buffer Amplifier Output Stage Considerations	55
AD637 Input Buffer Amplifier Requirements	56
Bandwidth and Slew Rate Limitations	56
Buffer Amplifier Frequency Compensation	58

APPENDIX C: COMPUTER PROGRAMS FOR DETERMINING COMPUTATIONAL ERRORS, OUTPUT RIPPLE, AND 1% SETTLING TIME OF RMS CONVERTERS	59
Introduction	59
Program #1 – rms Converter Ripple/Error Program	59
Program #2 – rms Converter Combined Settling Time Program	61

TABLE OF ILLUSTRATIONS

Table 1. RMS, MAD, and Crest Factor Chart	1
Table 2. Condensed rms Converter Specifications Table	7
Table 3. Number of RC Time Constants (τ) Required for AD536A, AD636, AD637 rms Converters to Settle to Within Stated % of Final Value	17
Table 4. A “Cookbook” Capacitor Selection Chart for Various Input Waveforms	20
Table 5. Capacitor Selection Chart for SCR Input Waveforms for a Maximum of 1% Worst-Case Averaging Error	20
Figure 1. A Precision (MAD) Rectifier	2
Figure 2. A Thermal rms to dc Converter	2
Figure 3. The Explicit Computation Method	3
Figure 4. The Implicit Computation Method	3
Figure 5. AD536A/AD636 Block Diagram	4
Figure 6. AD637 Filter/Averaging Diagram	5
Figure 7. AD637 Block Diagram	5
Figure 8. Maximum Error vs. Input Level AD637K and AD536AJ rms Converters	8
Figure 9. Static Errors in rms to dc Converters	8
Figure 10. Error vs. Duty Cycle AD637 rms Converter and MAD ac Detector	9
Figure 11. AD536A High Frequency Response	10
Figure 12. AD636 High Frequency Response	10
Figure 13. AD637 High Frequency Response	10
Figure 14. External Offset and Scale Factor Trimming for the AD536A	11
Figure 15. External Offset and Scale Factor Trimming for the AD636	11
Figure 16. AD637 External Offset and Scale Factor Trimming	11
Figure 17. Typical Output Waveform for Sinusoidal Input	12
Figure 18. AD536A/AD636 Standard rms Connection	13
Figure 19. AD637 Standard rms Connection	13
Figure 20. Error/Settling Time Graph for Use with the Standard rms Connection	14
Figure 21. Comparison of the Level of dc Error to that of the Ripple Amplitude — AD536A/AD637	14
Figure 22. AD536A Settling Time vs. Input Level	15
Figure 23. AD636 Settling Time vs. Input Level	15
Figure 24. Error/Settling Time Graph for Use with 1 Pole Output Filter Connection	16
Figure 25. AD536A/AD636 with a 1 Pole Output Filter	16
Figure 26. AD637 with a 1 Pole Output Filter	17
Figure 27. AD536A/AD636 with a 2 Pole Output Filter	18
Figure 28. AD637 with a 2 Pole Output Filter	18
Figure 29. Error/Settling Time Graph for Use with 2 Pole Output Filter	19
Figure 30. AD536A Error vs. Crest Factor	21
Figure 31. AD636 Error vs. Crest Factor	21
Figure 32. AD637 Error vs. Crest Factor	21
Figure 33. AD536A Single Supply Connection	21
Figure 34. AD636 Single Supply Connection	22
Figure 35. AD536A/AD636 Simplified Schematic	23
Figure 36. A Simplified Schematic of the dB Output Circuitry Common to the AD536A, AD636 and AD637 rms Converters	23
Figure 37. AD536A/AD636 Temperature Compensated dB Output Circuit	24
Figure 38. AD637 Temperature Compensated dB Circuit	24

Figure 39. An rms AGC Amplifier	25
Figure 40. Input vs. Output – rms AGC Amplifier	26
Figure 41. An Audio rms AGC Amplifier	27
Figure 42. Input vs. Output – Audio rms AGC Amplifier	27
Figure 43. A Low Cost True-rms DPM	28
Figure 44. A Portable, High Z Input, rms DPM and dB Meter Circuit	29
Figure 45. A Low Power, High Input Impedance dB Meter	30
Figure 46. A Modem Line Monitor – A Telephone Line dB Meter	32
Figure 47. A Programmable Gain rms Measurement System	33
Figure 48. Noise in an Unbalanced System	34
Figure 49. Noise in a Balanced System	34
Figure 50. An rms Converter with an Instrumentation Amplifier Preamp	34
Figure 51. A Functional Breakdown of an rms Noise Measurement System	35
Figure 52. The Effects of Input Coupling on the Overall Response of an Active Input Filter	35
Figure 53. A Practical Audio Noise Measurement Circuit	37
Figure 54. A Low Frequency rms-to-dc Converter Circuit	38
Figure 55. An Ultra-Low Frequency rms-to-dc Converter Circuit	39
Figure 56. A μ P-Controlled Averaging/Settling Time rms Converter Circuit	40
Figure 57a. A Quick-Reset rms-to-dc Converter Circuit Especially Suited for Low Frequency Measurements	41
Figure 57b. Oscilloscope Photo Showing the rms Output Over Time Using a $10\mu\text{F } C_{AV}$	41
Figure 58. A μ P-Controlled Two Quadrant Analog Squarer	42
Figure 59. A Vector Summation Circuit	43
Figure 60. The Upper Trace of the Scope Photo is the Root Sum of the Two Triangular Waves that are Shown in the Lower Trace	44
Figure 61. A Block Diagram of a Practical Power Measurement System	45
Figure 62. Apparent Power Measurement Using an rms Converter	46
Figure 63. A Crest Factor Test Setup	47
Figure 64. Testing ac Accuracy	48
Figure 65. Testing ac Accuracy – Alternate Method	48
Figure 66. Testing dc Conversion Accuracy	49
Figure 67. A Crossplot Test System	49
Figure 68. An Ideal Crossplot Pattern	50
Figure 69. Two Amplifiers are Used in this Typical Absolute Value Circuit	50
Figure 70. Input Offset in Absolute Value Circuit	50
Figure 71. Input Offset in Absolute Value Circuit	50
Figure 72. Offset at Amplifier Output	50
Figure 73. Oscillation/Instability	51
Figure 74. An rms Crossplot Tester	51
Figure 75. Good Linearity	52
Figure 76. Poor Linearity	52
Figure 77. A Simple Input Buffer Connection Using the Internal Buffer Amplifier of an rms Converter	53
Figure 78. AD536A Internal Buffer Amplifier Relative Output Response vs. Frequency	53
Figure 79. An Improved Input Buffer	54
Figure 80. Using the Internal Buffer Amplifier as a Bootstrapped Input Buffer	54
Figure 81. AD536A, AD636, AD637 Internal Buffer Amplifier Simplified Schematic	55
Figure 82. The Effect of $R_{E \text{ equivalent}}$ And R_L on the Maximum Output Swing of the AD536A, AD636 and AD637 Internal Buffer Amplifier	55
Figure 83. AD536A, AD636, AD637 Internal Buffer Amplifier – Ratio of Peak Negative Output Swing to $-V_S$ vs. $R_{E \text{ external}}$ for Several Load Resistances	56
Figure 84. AD637 rms Converter with External 4MHz High Impedance Input Amplifier	56

Figure 85. Minimum Slew Rate Required from an Input Buffer Amplifier Driving a 5MHz rms
Converter in Volts/Microsecond 57
Figure 86. AD637 with AD711 Input Buffer Amplifier – 3dB Bandwidth vs. Input Level 58

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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

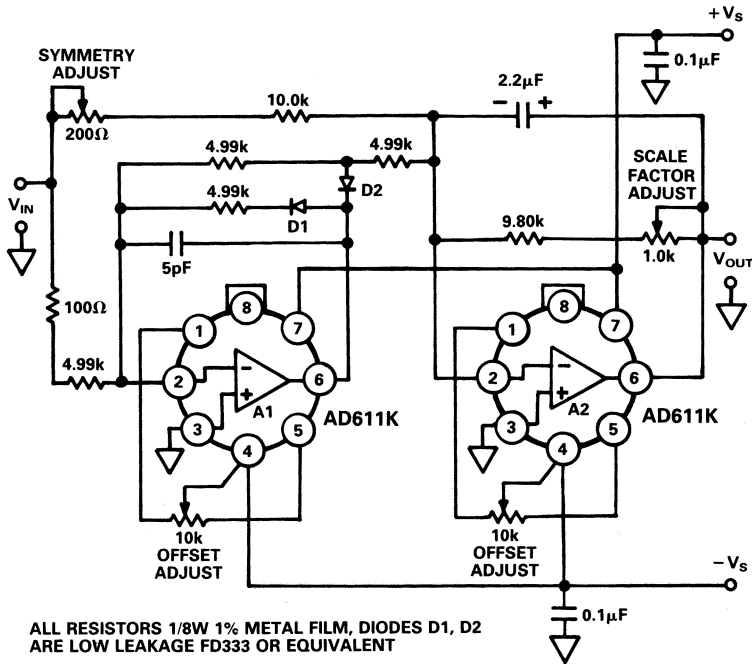


Figure 1. A Precision (MAD) Rectifier

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 com-

paring 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.

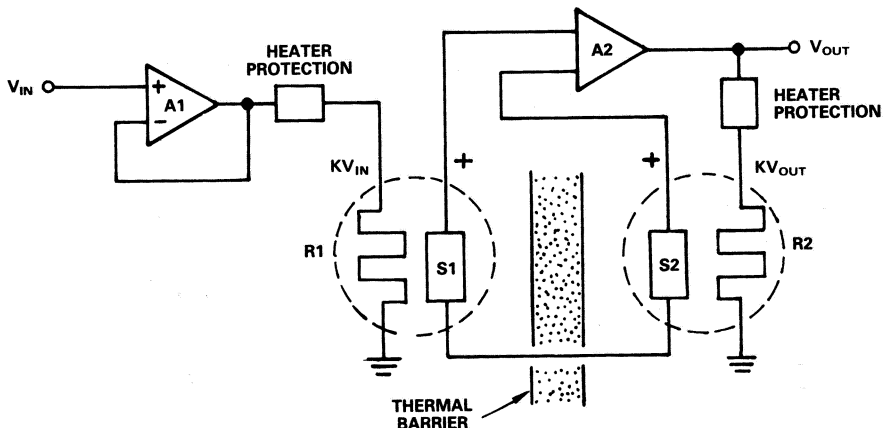


Figure 2. A Thermal rms to dc Converter

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 $\pm 0.1\%$ 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.

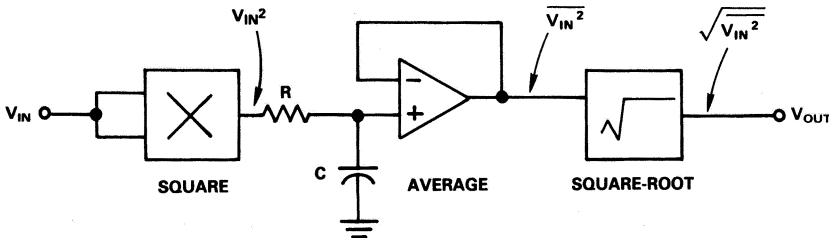


Figure 3. The Explicit Computation Method

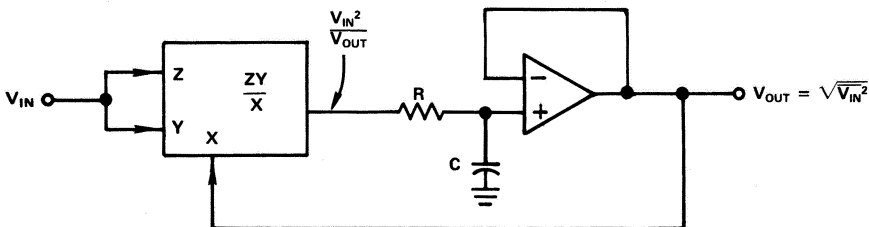


Figure 4. The Implicit Computation Method

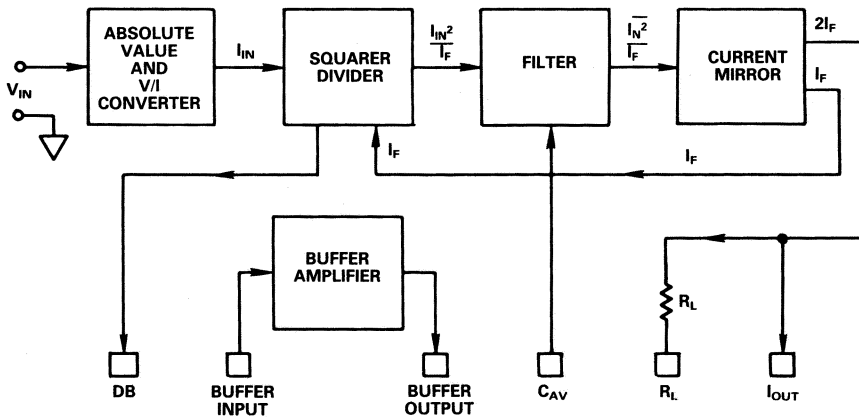


Figure 5. AD536A/AD636 Block Diagram

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 25k Ω resistor, R_L . The I_{OUT} pin of the AD536A gives a current output of 40 μ A 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 -3 dB 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.

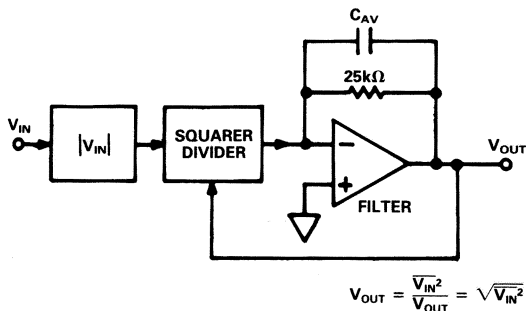


Figure 6. AD637 Filter/Averaging Diagram

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:

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

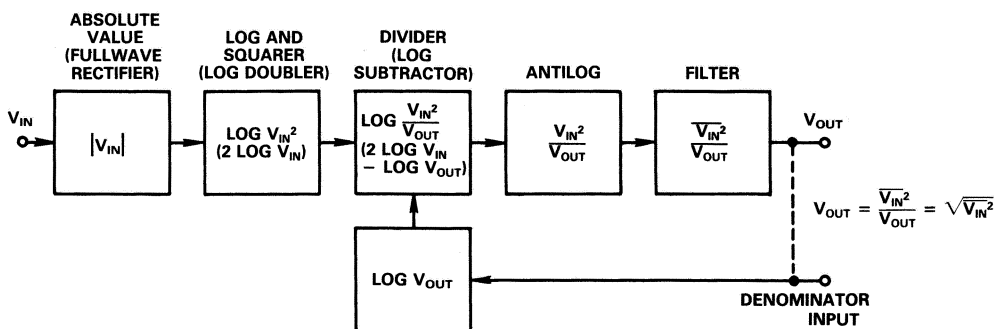


Figure 7. AD637 Block Diagram

then:

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

(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 $25k\Omega$ 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.)

