A Digital Multimeter Using the ADD3501

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INTRODUCTION

National Semiconductor's ADD3501 is a monolithic CMOS IC designed for use as a 3 ½-digit digital voltmeter. The IC makes use of a pulse-modulation analog-to-digital conversion scheme that operates from a 2V reference voltage, functions with inputs between 0V and ±1.999V and operates from a single supply.

The conversion rate is set by an external resistor/capacitor combination, which controls the frequency of an on-chip oscillator. The ADD3501 directly drives 7-segment multiplexed LED displays, aided only by segment resistors and external digit buffers. The ADD3501 blanks the most significant digit whenever the MSD is zero; and, during overrange conditions, the display will read either +OFL or −OFL (depending on the polarity of the input.)

These characteristics make the ADD3501 suitable for use in low-cost instrumentation. An example of such use is the inexpensive, accurate, digital multimeter (DMM) presented here—an instrument that measures AC and DC voltages and currents, and resistance.

CIRCUIT DESCRIPTION

Figure 1 shows the circuit diagram of the ADD3501-based DMM, and Table I summarizes its measurement capabilities. Since the accuracy of the ADD3501 is ±0.05%, the DMM's performance is mainly determined by the choice of discrete components.

Supporting the ADD3501 is a DS75492 digit driver, an NSB5388 LED display, and an LM340 regulator for the V_{CC} supply. A 2V reference voltage—derived from the LM336 reference-diode circuitry—permits the 3 ½-digit system a 1 mV/LSD resolution (i.e., the ADD3501's full-scale count of 1999 or 1999 mV).

DC Voltage Measurement. The DMM's user places the (+) and (−) probes across the voltage to be measured, and sets the voltage range switch as necessary. This switch scales the input voltage, dividing it down so that the maximum voltage across the ADD3501's V_{IN} and V_{IN}—pins is limited to 2V full-scale on each input range. The ADD3501 performs an A/D conversion, and displays the value of the DMM's input voltage. The instrument's input impedance is at least 10 MΩ on all DC voltage ranges. Except for the 2V range, the DMM's survival voltage—the maximum safe DC input—is in excess of 1 kV. On the 2V range, the maximum allowable input is 700V.

AC Voltage Measurement. Switching the DMM to its AC VOLTS mode brings the circuit of *Figure 2* into function. This circuit operates as an averaging filter to generate a DC output proportional to the value of the rectified AC input; this value, in turn, is ''tapped down'' by R5 to a level equivalent to the input's rms value, which is the value displayed by the DMM.

Op amp A3 is simply a voltage follower that lowers the input-attenuator's source impedance to a value suitable to drive into A4. This impedance conversion helps eliminate some of the possible offset-voltage problems (the A4 input-offset-current source impedance IR drop, for example) and noise susceptibility problems as well. C1 blocks the DC offset voltage generated by A3.

A4 and A5 comprise the actual AC-to-DC converter; to see how it works refer again to *Figure 2*, and consider first its operation on the negative portion of an AC input signal. At the output of A4 are 2 diodes, D1 and D2, which act as switches. For a negative input to A4's inverting input, D1 turns on and clamps A4's output to 0.7V, while D2 opens, disconnecting A4's output from A5's summing point (the inverting input). A5 now operates as a simple inverter: R2 is its input resistor, R5 its feedback resistor, and its output is positive.

Now consider what happens during the positive portion of an AC input. A4's output swings negative, opening D1 and closing D2, and the op amp operates as an inverting unity-gain amplifier. Its input resistor is R1, its feedback resistor is R3, and its output now connects to A5's summing point through R4. D2 does not affect A4's accuracy because the diode is inside the feedback loop.

A positive input to A4 causes it to pull a current from A5's summing point through R4 and D2; the positive input also causes a current to be supplied to the A5 summing point through R2. Because A4 is a unity-gain inverter, the voltage drops across R2 and R4 are equal, but opposite in sign. Since the value of R2 is double that of R4, the net input current at A5's summing point is equal to, but opposite, the current through R2. A5 now operates as a summing inverter, and yields—again—a positive output. (R6 functions simply to reduce output errors due to input offset currents.)

Thus, the positive and negative portions of the DMM's AC voltage input both yield positive DC outputs from A5. With C2 connected across R5 as shown, the circuit becomes an averaging filter. As already mentioned, the tap on R5 is set so that the circuit's DC output is equivalent to the rms value of the DMM's AC voltage input, which is the value converted and displayed by the ADD3501

DC Current Measurement. To make a DC current measurement, the user inserts the DMM's probes in series with the circuit current to be measured and selects a suitable scale. On any scale range, the DMM loads the measured circuit with a 2V drop for a full-scale input.* The ADD3501 simply converts and displays the voltage drop developed across the DMM's current-sensing resistor.

*This drop may be reduced to 200 mV; refer to the last section of this application note.

TECHNICAL SPECIFICATIONS

DC VOLTS	< ±1% ACCURACY
RANGES	2V, 20V, 200V, 2 kV
INPUT IMPEDANCE	2V RANGE, >10MΩ
	20V TO 2 kV RANGE, 10MΩ
AC RMS VOLTS	< ±1% ACCURACY
RANGES	2V, 20V, 200V, 2 kV
	(40 TO 5 kHz SINEWAVE)
DC AMPS	< ±1% ACCURACY
RANGES	200 μA, 2mA, 20 mA, 200 mA, 2A
AC RMS AMPS	< ±1% ACCURACY
RANGES	200 μA, 2 mA, 20 mA, 200 mA, 2 A
OHMS	< ±1% ACCURACY
RANGES	200 Ω, 2 kΩ, 20 kΩ, 200 kΩ, 2 MΩ

Note 1: All V_{CC} connections should use a single V_{CC} point and all ground/analog ground connections should use a single ground/analog ground point.

Note 2: All resistors are ¼ watt unless otherwise specified.

Note 3: All capacitors are ±10%.

Note 4: All op amps have a 0.1 μF capacitor connected across the V+ and V− supplies.

Note 5: All diodes are 1N914.

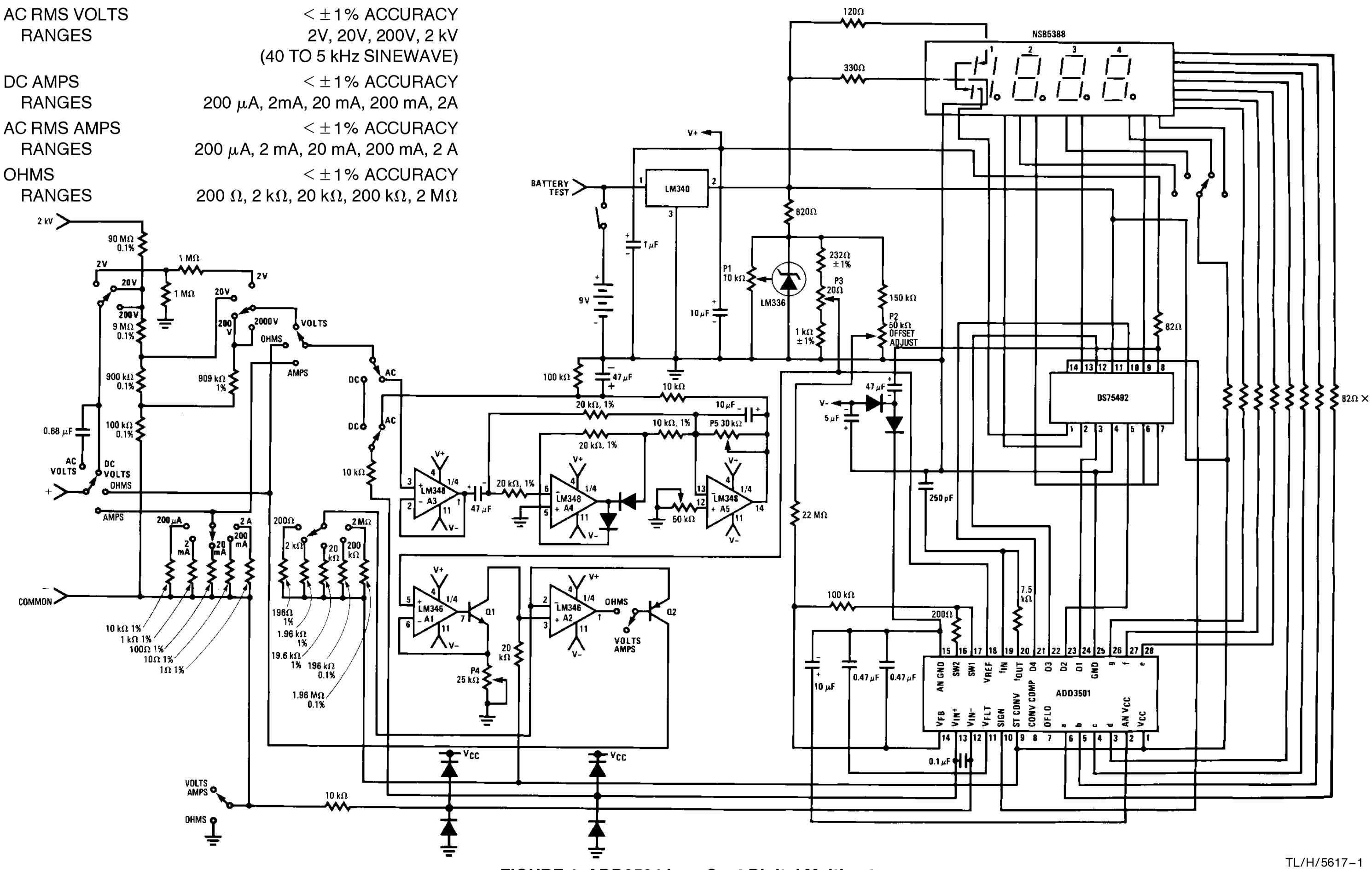

FIGURE 1. ADD3501 Low Cost Digital Multimeter

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AC Current Measurement. AC current measurements are made in a way similar to DC current measurements. The DMM is switched to its AMPS and AC settings. The in-circuit current is again measured by a drop across the DMM's current-sensing resistor, but now the AC voltage developed across this resistor is processed by A3, A4, and A5—exactly as described for AC voltage measurements—before being transferred to the ADD3501. Again, the DMM displays an rms value appropriate for the AC signal current being measured.

Resistance Measurement. This DMM measures resistance in the same way as do most multimeter: it measures the voltage drop developed across the unknown resistance by forcing a known, constant-current through it. Suitable scale calibration translates the voltage drop to a resistance value.

The resistance measurement requires the generation of a constant-current source that is independent of changes in V_{CC}, using the 2V, ground-referred reference voltage. The circuit of *Figure 3* accomplishes this.

In *Figure 3*, A1 establishes a constant-current sink by forcing node A to V_{REF}, the voltage level at A1's non-inverting input. With node A held constant at V_{REF} (2.000V), current through R2 is also fixed—since Q1's collector current is determined by the αI_E product—thus establishing V1 as

$$V1 = V_{CC} - \alpha(V_{REF}/R1)R2 \qquad (1)$$

Note that V_{REF} is derived from the LM336—a precision voltage source. Equation (1) shows, then, that (all else remaining constant) V1 varies directly with changes in V_{CC}; i.e., V1 tracks V_{CC}. The A1/Q1 pair thus establishes a voltage across R2 that floats, independent of changes in the ground-referenced potentials (V_{CC} and V_{REF}) that define it.

Now look at the A2/Q2 circuitry. The closed-loop operation of A2 tries to maintain a zero differential voltage between its input terminals. A2's non-inverting input is held at V1; thus, A2's inverting input is driven to V1. The current through R_L (Q2's emitter current) is therefore $(V_{CC} - V1)R_L$. Since V1 tracks V_{CC}, then $(V_{CC} - V1)$ - the voltage drop across R_L—is constant, thus producing I_{SOURCE} (*Figure 3*)—the constant source current needed for the resistance measurement.

Note, that varying R_X will not affect I_{SOURCE} so long as the voltage drop across R_X is less than $(V1 - V_{BE2})$. Should V_{RX} exceed $(V1 - V_{BE2})$, Q2 would saturate, invalidating the measurement. The ADD3501 eliminates this worry, however, because as soon as the drop across R_X equals or exceeds the 2V full-scale input voltage the ADD3501 will display an OFL condition.

Finally, SW1 (*Figure 3*) is required as part of the VOLTS/AMPS/OHMS mode selection circuitry; in the VOLTS/AMPS position it prevents Q2's base-emitter junction pulling the V− supply to ground through A2.

TABLE I. DMM PERFORMANCE

Measurement Mode	Range 0.2	2	2	200	2000	Frequency Response	Accuracy	Overrange Display
DC Volts	—	V	V	V	V	—	≤ 1% F.S.	± OFLO
AC Volts	—	V_{RMS}	V_{RMS}	V_{RMS}	V_{RMS}	40 Hz to 5 kHz	≤ 1% F.S.	+ OFLO
DC Amps	mA	mA	mA	mA	mA		≤ 1% F.S.	± OFLO
AC Amps	mA_{RMS}	mA_{RMS}	mA_{RMS}	mA_{RMS}	mA_{RMS}	40 Hz to 5 kHz	≤ 1% F.S.	+ OFLO
Ohms	kΩ	kΩ	kΩ	kΩ	kΩ	—	≤ 1% F.S.	+ OFLO

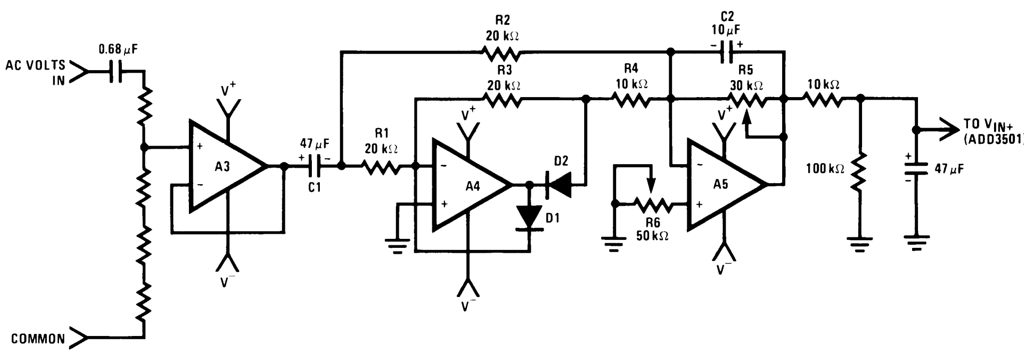

FIGURE 2. AC/DC Converter

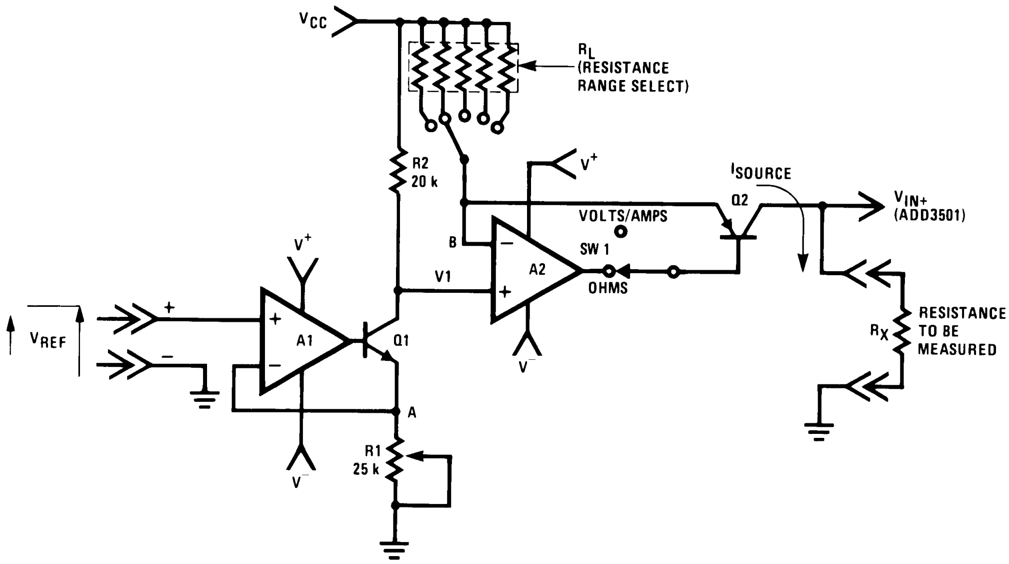

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FIGURE 3. Constant-Current Source

CALIBRATION

Calibrate the DMM according to the following sequence of operations:

	1.	Adjust P1 until the cathode voltage of the reference diode, LM336, equals 2.49V. This reduces the diode's temperature coefficient to its minimum value.
DC Volts 2V Range	2.	Short the (+) and (−) probe inputs of the ADD3501 and adjust P2 until the display reads 0000.
DC Volts 2V Range	3.	Apply 1.995 volts across the (+) and (−) probe inputs and adjust P3 until the display reads 1.995.
Ohms 2 MΩ Range	4.	Select a precision resistor with a value near full-scale or the 2 MΩ range, and adjust P4 until the appropriate value is displayed.
AC Volts 2V Range	5.	Apply a known $1.995V_{rms}$ sinewave signal to the DMM and adjust P5 until the display reads the same.

PC BOARD LAYOUT

It is imperative to have only one, single-point, analog signal ground connection for the entire system. In a multi-ground layout, the presence of ground-loop resistances will cause the op amps' offset currents and AC response to have a devastating effect on system gain, linearity, and display LSD flicker. Similar precautions must also be taken in the layout of the analog and high-switching-current (digital) paths of the ADD3501.

A FINAL NOTE

The digital multimeter described in this note was developed with the goals of accuracy and low cost. For the high-end DMM market segments, however, improvements to the basic circuit of *Figure 1* are possible in the following areas:

1. Expand the VOLTS mode to include a 200 mV full-scale range;
2. Decrease the full-scale current-measurement loading voltage from 2V to 200 mV; and,
3. Provide a true-rms measurement capability.
4. Increase resolution by substituting the ADD3701—3 ¾-digit DVM chip—which is interchangeable and provides a maximum display count of 3.999.

The first 2 improvements involve a dividing down of the ADD3501 feedback loop by a ratio of 10:1, which reduces the 2V full-scale input requirement to 200 mV. This not only allows a 200 mV signal between the ADD3501's V_{IN+} and V_{IN-} inputs to display a full-scale reading, but implies that the maximum voltage dropped across the current-measuring-mode resistance also will be 200 mV. Note, though, that the values of the current-measurement resistors must be scaled down by a factor of ten.

Additionally, a 200 mV full-scale input implies a resolution of 100 μV/LSD. At such low input levels, the DMM may require some clever circuitry to eliminate the gain and linearity distortions that can arise from the offset currents in the AC-to-DC converter.

The third possible improvement—the reading of true-rms values—can be implemented by replacing the AC-to-DC converter of *Figure 2* with National's LH0091, a true-rms-to-DC converter, and appropriate interface circuitry.

REFERENCES:

1. ADD3501 Data Sheet.
2. LH0091 Data Sheet.
3. LM336 Data Sheet.
4. Application Note AN-20.
5. ADD3701 Data Sheet.

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