How to use digital voltmeter modules

Part 2

In this concluding part of the series, Ray Marston shows how to use 3½-digit LCD DVM modules to build a multimeter and measure temperature, capacitance, frequency and a whole lot more.

Ray Marston

IN PART 1 I explained the basic characteristics and usage rules of 3½-digit LCD digital voltmeter modules and showed how these units can be used to measure voltage, current and resistance.

This part kicks off with the complete circuit of a five-function, 25-range digital multimeter and continues by showing how these modules can be used to give accurate measurement of temperature, capacitance, frequency and various other parameters. It finishes up with some vital hints on actually constructing projects that are designed around the modules.

A 25-range multimeter

Figure 21 shows how the circuits of Figures 15 to 20, in Part 1, can be joined together to make a complete five-function 25-range multimeter. Table 3 details the ranges/functions of the meter.

The reader should have little difficulty in following the Figure 21 circuit. Functions are selected by SW1, ranges by SW2. SW1a connects the inputs to the voltage, current or resistance measuring networks, and SW1d activates the ac/dc converter or energises the 'ohms' circuitry when necessary.

Voltage ranges are selected by SW2a, current ranges by SW2b, and resistance ranges by SW2c.

SW2d and SW2e control the decimal point

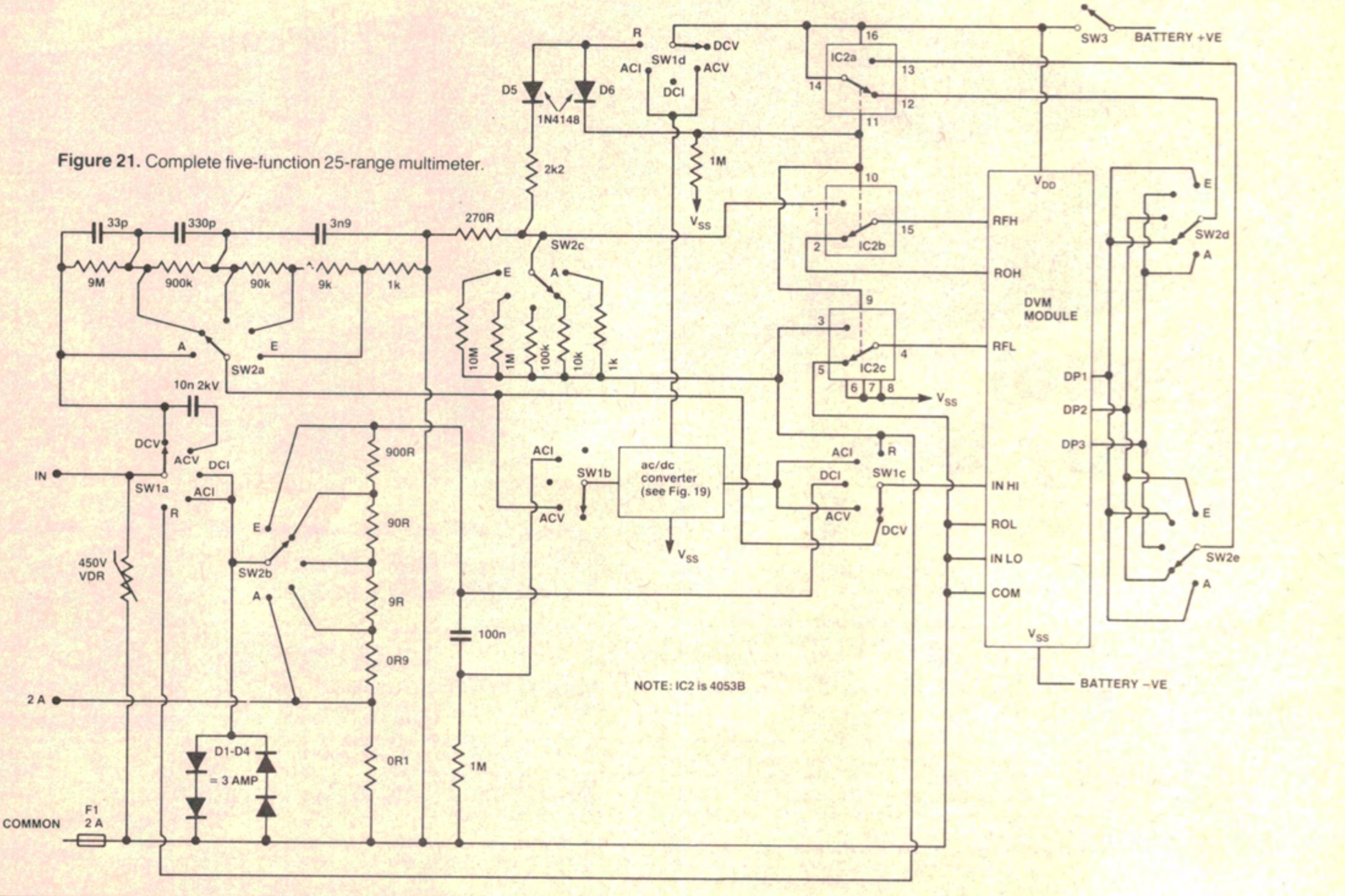


Figure 21. Complete five-function 25-range multimeter.

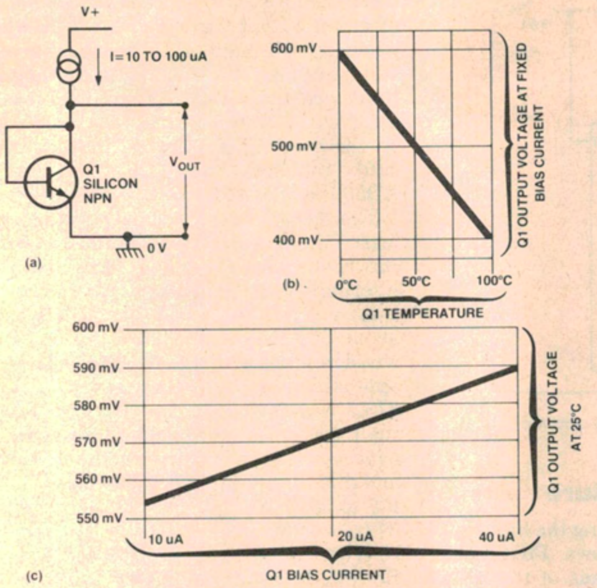


Figure 22. When a transistor is connected as in (a), its output voltage varies at a rate of about −2 mV/°C as shown in (b). The output voltage also varies with drive current as shown in (c).

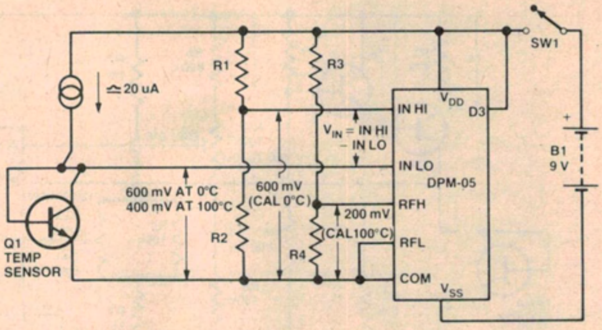


Figure 23. Basic digital thermometer circuit using an idealised (Figure 22b) transistor sensor.

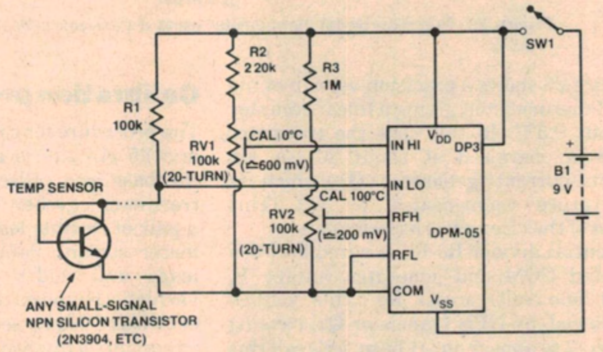


Figure 24. Simple digital thermometer using a transistor sensor. Linear accuracy is about 1.5°C.

positions on each range, the appropriate switch being selected automatically by IC2a. IC2b and IC2c control the basic configurations of the DVM module. IC2 (a triple two-way analogue switch) is activated via SW1d.

Digital thermometers

A DVM module can be made to act as a wide-range (−50°C to +150°C) digital thermometer by feeding the output of a linear voltage-generating temperature sensor to its inputs. Two suitable types of sensor are readily available; the first of these is the ordinary bipolar silicon transistor and the second is a dedicated IC. In either case, the resulting digital thermometer has a temperature discrimination of 0.1°C. Linear accuracy varies from 0.5°C to 1.5°C, depending on the sensor and circuitry used.

Because of the low mass of a transistor sensor, the device has a thermal response time some 10 to 100 times faster than a normal mercury thermometer. When used to measure a sharp change in the temperature of free air, a transistor-sensor circuit typically settles to within 0.1°C of the new temperature in less than one minute; a mercury thermometer takes some 20 minutes to attain the same accuracy.

Transistor-sensor circuits

When an ordinary NPN silicon transistor is connected as shown in Figure 22a and driven from a constant-current source, it generates an output voltage that varies in direct proportion to the transistor temperature. This voltage has a negative temperature coefficient of about −2 mV/°C and typically varies from about 600 mV at 0°C to 400 mV at 100°C, as shown in the idealised graph of Figure 22b.

In practice, the 'straight line' of the Figure 22b graph is linear within 1 mV or so over the 200 mV '0°C to 100°C' temperature variation range, but the precise voltage generated at any given temperature depends on the individual transistor and its operating current. If operating currents are kept below 100 uA, errors due to self-heating are negligible. Figure 22c shows the measured variation in voltage at 25°C of a small sample of transistors at currents ranging from 10 to 40 uA.

Figure 23 shows the basic method of connecting the idealised transistor sensor of Figure 22b to a DVM module so that the meter gives a direct readout of temperature in °C. The output of the sensor is fed directly to the module's IN LO terminal and a 600 mV offset voltage (equal to the sensor voltage at 0°C) is fed to IN HI. The module actually responds to the *differential* value (IN HI minus IN LO) of the input, so under this condition it sees an input of 600 mV − 600 mV = 0 mV, and gives a reading of '00.0'.

At 100°C the module sees an input of 600 mV − 400 mV = 200 mV. Since a reference voltage of 200 mV (equal to the difference in voltage between 0°C and 100°C) is fed to RFH, the meter gives a reading of '100.0' under this condition.

Figures 24 and 25 show two practical examples of digital thermometers. The Figure 24 circuit is virtually the 'standard' one published in many magazine articles and application sheets and has a typical linear accuracy of 1.5°C over the 0°C to 100°C temperature range. A stable 2V8 is generated between V_{DD} and COM of the DVM module, so R1 drives the sensor with a current of about 22 uA at 0°C, rising to about 24 uA at 100°C. This current variation, combined with the basic linear error of the transistor, causes the 1.5°C linear error of the circuit.

The 'CAL 0°C' voltage feeding IN HI is variable from zero to 875 mV via RV1, and the 'CAL 100°C' voltage feeding RFH is variable from zero to 255 mV via RV2. These two controls are for the calibration of the meter, using the technique to be described shortly. ▶

MODE (SW1)	RANGE (SW2) A	B	C	D	E
DCV	199.9 mV	1.999 V	19.99 V	199.9 V	1.999 kV (700V max)
ACV	199.9 mV	1.999 V	19.99 V	199.9 V	1.999 kV (450 V max)
DCI	199.9 μA	1.999 mA	19.99 mA	199.9 mA	1.999 A
ACI	199.9 μA	1.999 mA	19.99 mA	199.9 mA	1.999 A
R	1.999 k Ω	19.99 k Ω	199.9 k Ω	1.999 M Ω	19.99 M Ω

Table 3. Ranges and functions of the Figure 21 multimeter circuit.

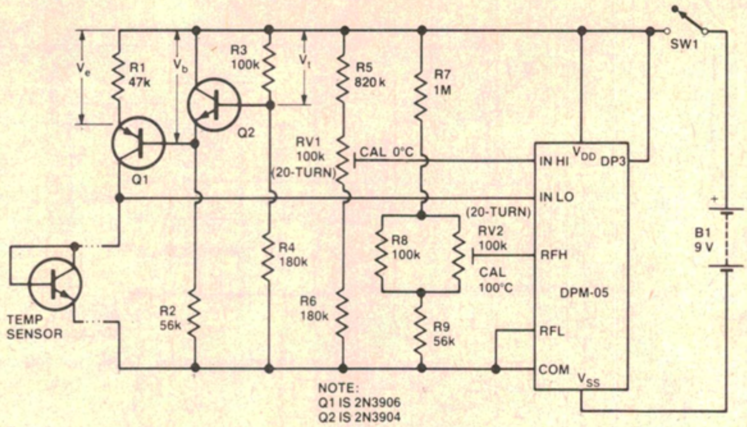


Figure 25. Precision digital thermometer using a transistor sensor. Linear accuracy is 0.5°C.

Figure 25 shows a precision version of the digital thermometer, giving a linear accuracy of about 0.5°C. In this case the transistor sensor is energised at about 20 uA via constant-current generator Q1 which is temperature compensated by Q2. This section of the circuit works as follows.

Potential divider R3-R4 is wired between V_{DD} and COM and generates voltage V_t (about one volt) across R3. This voltage is 'followed' by NPN transistor Q2, causing $V_t + V_{be}2$ to appear on Q1 base; let's call this voltage V_b. The voltage V_e appearing on the emitter of PNP transistor Q1 is equal to $V_e - V_{be}1$ and it is the product of V_e and R1 that determines the magnitude of the constant-current output of Q1. Note, however, that V_e is, in fact, equal to $V_t + V_{be}2 - V_{be}1$ and that since Q1 and Q2 operate at virtually identical temperatures and at similar current levels, the $V_{be}1$ and $V_{be}2$ values automatically cancel out at all temperatures and V_e thus equals V_t. The output current of Q1 is thus independent of ambient temperature.

Other points to note about the precision circuit of Figure 25 are that the 'CAL 0°C' control, RV1, is adjustable over the limited range of 460 mV to 710 mV. Also, the 'CAL 100°C' control, RV2, is adjustable over the limited range 140 mV to 260 mV, thus giving very fine adjustment of each calibration point.

Calibration procedure

The procedure for calibrating the Figures 24 and 25 circuits is as follows. First, solder the base and collector leads of the sensor transistor together. Then solder the sensor to a pair of flexible leads and connect it to the meter circuit. Paint all visible transistor leads and solder joints with insulating varnish (Humbrol clear varnish No 35 is excellent). Next, set RV1 and RV2 at mid value, mix a quantity of crushed ice and cold water in a tumbler (to act as a '0°C' standard) and immerse the sensor in the tumbler. Now adjust RV1 to give a reading of '00.0' on the meter. Finally, remove the sensor from the tumbler and immerse it in gently boiling water (to act as a '100°C' standard), then adjust RV2 to give a meter reading of '100.0'. Basic calibration is then complete.

If the meter is to be used mainly around some mid-scale value, such as 25°C etc, RV1 can (after initial calibration) be used to set the meter 'spot on' at that value by immersing the probe and a standard thermometer in a liquid that is raised to the desired temperature.

An IC-sensor circuit

Intersil make a special two-terminal IC for use as a temperature sensor in digital thermometers. The device is the AD590 and gives an output current of 1 uA/°K which, when fed through a 1k resistor, gives a voltage of 1 mV/°K. Uncalibrated accuracy of the device varies from 0.5°C to 10°C. Linearity error varies from 0.3°C to 1.5°C, depending on the grade of the device (indicated by a suffix number). Figure 26 shows how an AD590 can be used with a DVM module.

The AD590 needs a supply voltage of at least four volts and this is obtained by wiring the IC between V_{DD} and TEST (which is internally biased at about five volts below V_{DD}) via D1. The COM terminal is biased about 600 mV above TEST via D1. R1 is wired in series with the AD590 and generates approximately 1 mV/°K (= 273.2 mV at 0°C, 373.2 mV at 100°C). This voltage is fed to the IN HI terminal. Bandgap reference IC2 generates a temperature-stable 1.2 V via R2 and this voltage is divided down via R3-RV1-R4 to give a 'SET 0°C' offset voltage of 273.2 mV nominal at IN LO. The bandgap reference voltage is also divided down by R5-RV2-R6 to provide a 'SET 100°C' scaling voltage of 100 mV nominal at RFH. The circuit must be calibrated in the way already described for the Figures 24 and 25 circuits.

Digital capacitance meter basics

A DVM module can be made to read capacitance values by connecting the unknown capacitance to the module via a linear capacitance-to-voltage converter. The easiest way to make such a converter is to use the technique shown in Figure 27. Here, the unknown capacitor and a standard resistor are used as the timing elements in a precision monostable which produces an output pulse with a width, W, that is directly proportional to the C-R product. The monostable is triggered at a fixed frequency via a clock generator and the output of the monostable is converted to a mean dc value by a simple C-R integrator.

The mean dc value of the monostable output equals the peak pulse amplitude multiplied by W/P, where W and P are the width and the period of the pulse respectively. Thus, since R_x and P are fixed, the mean dc voltage out-

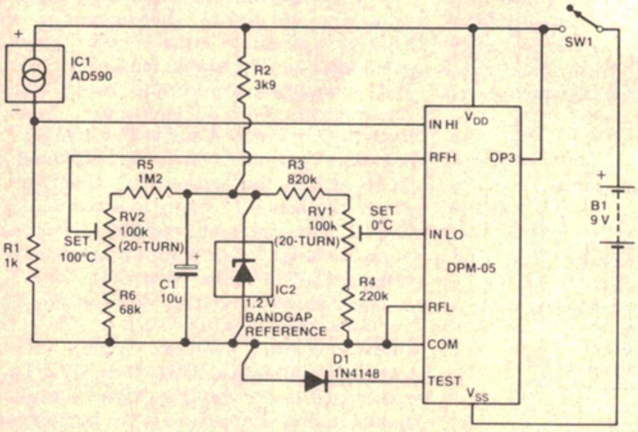


Figure 26. Digital thermometer based on the AD590 temperature-sensor IC.

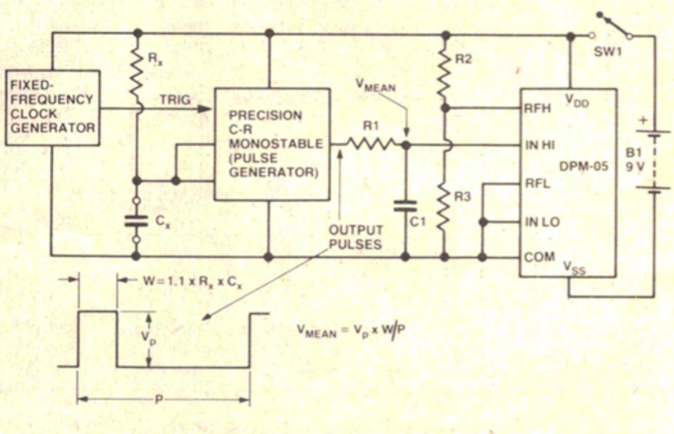
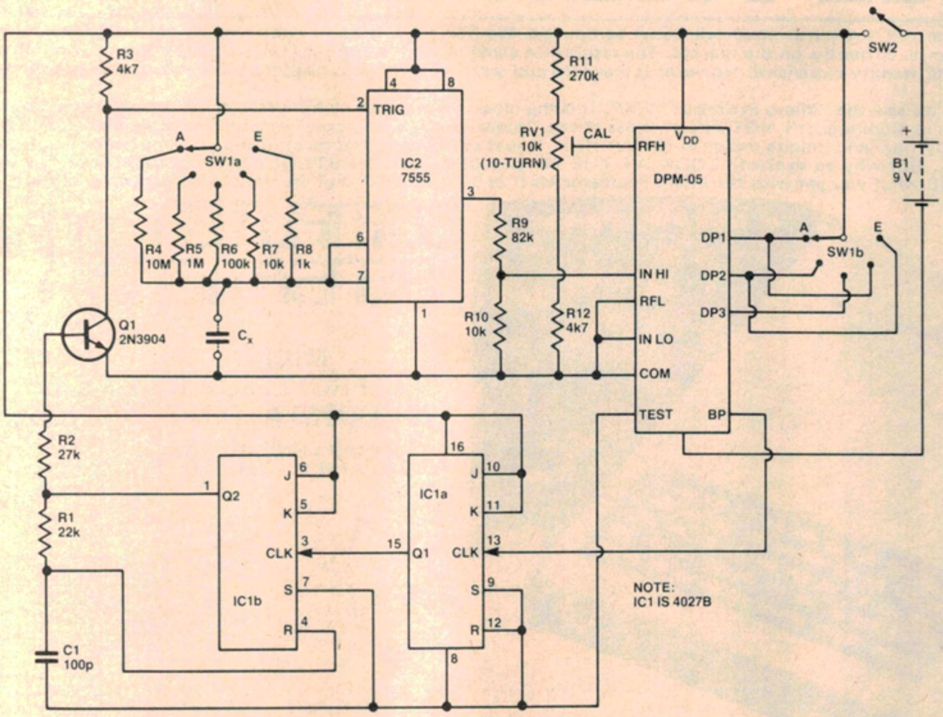


Figure 27. Basic operating principle and circuit of a digital capacitance meter.



RANGE	fsd
A	1.999 nF
B	19.99 nF
C	199.9 nF
D	1.999 µF
E	19.99 µF

Figure 28. Digital capacitance meter.

put is directly proportional to C_x and when this voltage is fed to the DVM module, the module acts as a digital capacitance meter.

In Figure 27, the reference (RFH) voltage of the module is derived from the mono's supply rail via potential divider R2-R3. Since the meter reads the *ratio* of the input and reference voltages, the calibration of the unit is independent of variations in supply rail voltage, but can be varied by altering the R2-R3 ratio. The circuit can be made to read different capacitance ranges by switching R_x in decade multiples.

Practical capacitance meters

The basic Figure 27 circuit is quite easy to implement and gives very accurate results. Figures 28 and 29 show two practical versions of the circuit. Both of these designs use a 7555 timer IC (a CMOS version of the 555 timer) as the precision monostable element, and use decade values (1k to 10M) of R_x for range selection.

The 7555 monostable generates a pulse with a width of 1.1 x C x R, giving a full-scale pulse width (at '1999' on the DVM module) of 22 ms with C and R values of 1999 pF and 10M, or 19.99 uF and 1k etc. To give the 7555 adequate recovery time between pulses, the clock period must be at least 50% longer than the maximum pulse width and must have a period of at least 33 ms.

The 7555 mono is triggered by pulling pin 2 of the IC low. If the pin is not returned high again by the time the output pulse ends naturally, the trigger pulse extends the output pulse artifically. The trigger pulse must thus be shorter than the minimum output pulse. In our application, the shortest pulse width that can be indicated by the DVM module is 22 ms/1000 = 11 us. So in the circuits of Figures 28 and 29 it is a design requirement that the 7555 must be triggered by negative-going pulses with widths less than 11 us and periods greater than 33 ms. In Figure 28 these requirements are met as follows.

In the DVM module, the TEST terminal is internally biased at about 5 V below V_{DD} and the BP (backplane) terminal switches between TEST and V_{DD} at about 50 Hz (= clock frequency divided by 800), giving a period of 20 ms. In Figure 28 IC1 is powered via the TEST terminal and the BP signal is divided-by-2 by flip-flop IC1a. The resulting 25 Hz (40 ms) signal is used to clock IC1b, which is configured as a monostable and generates positive-going output pulses with widths of 2 us via R1 and C1. These pulses are level-shifted and inverted via R2-Q1-R3 to produce negative-going 2 us trigger pulses with periods of 40 ms on the pin-2 TRIG terminal of IC2, the 7555 monostable generator.

The pulse width of the 7555 is controlled by C_x and precision range resistors R4 to R8. The 7555's output is attenuated by R9-R10 to give a mean value of about 100 mV at the midscale ('1000') setting of the DVM module. The resulting signal is fed to the module's IN HI terminal where it is integrated by the internal 10M — 10 nF filter. Divider R11-RV1-R12 feeds 100 mV nominal to the RFH terminal of the module and RV1 is used to adjust the precise calibration of the capacitance meter.

Accuracy of the Figure 28 meter is determined mainly by the precision of the R4 to R8 range resistors, which should be 1% or better hi-stab types. To calibrate the meter, simply connect a precision capacitor (say 100 nF) in place of C_x, switch to the appropriate range and adjust RV1 to give the appropriate meter reading. Calibration is then valid on all ranges.

The Figure 28 circuit has two minor defects. First, the clock signals of the 7555 are derived (via BP) from the clock signals of the DVM module. These signals are not highly frequency-stable and the calibration of the circuit may thus shift by up to 0.5% or so over the normal range of operating temperatures and supply voltages. If precise accuracy is needed, calibration should be checked before use.

The second snag is that the circuit reads *all* capacitance, including residuals, appearing between the C_x terminals. These residuals include stray capacitance and the internal capacitance of IC2 between pins 6/7 and 1, and typically total 32 pF. With no external capacitance connected, the meter thus gives a typical reading of '.032' on range A and '0.03' on range B. These residuals are too small to give readings on the remaining ranges of the meter, but must be subtracted from all readings obtained on ranges A and B.

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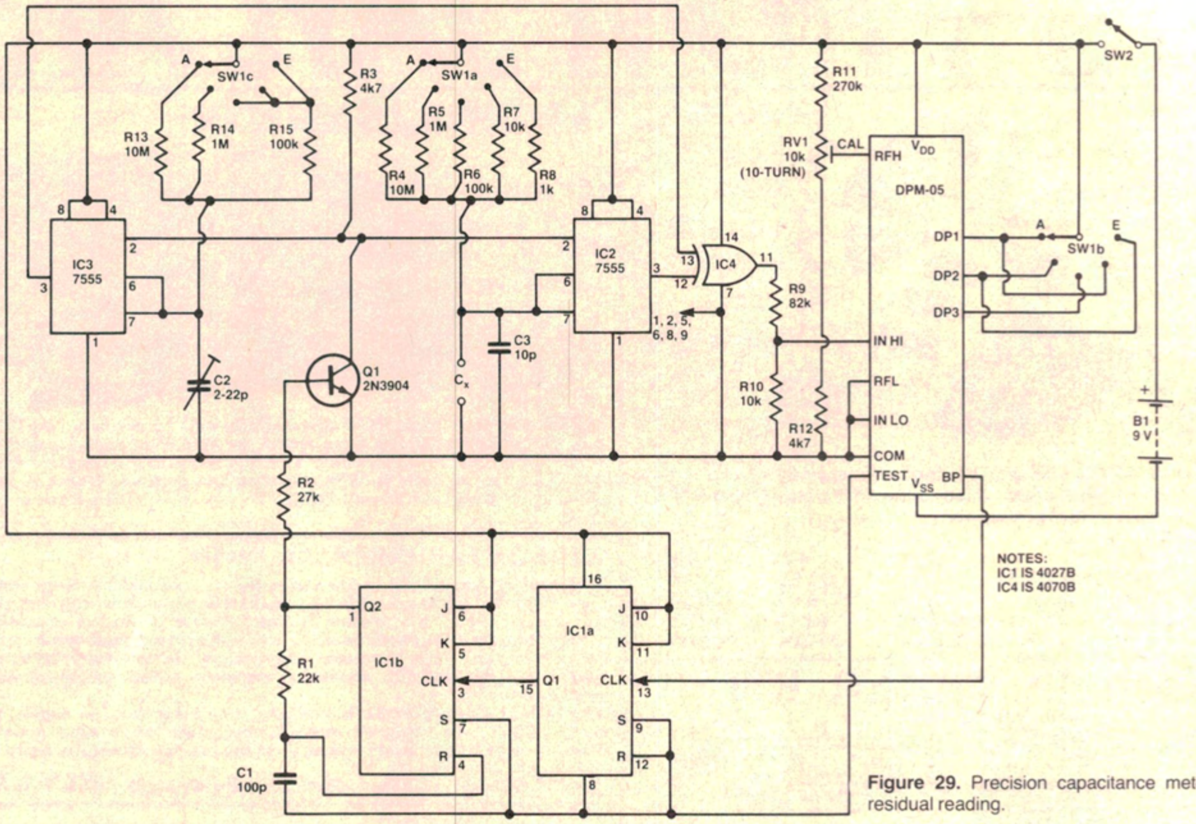


Figure 29. Precision capacitance meter with zero residual reading.

Figure 29 shows how the circuit can be modified so that residual capacitance is effectively cancelled and the meter gives a zero reading on all ranges when no external capacitance is connected to the C_x terminals. In this case the BP-derived signal is used to synchronously trigger *two* 7555 monostables. Their outputs are EX-ORed via IC4 to give a pulse with a width equal to the *difference* between the pulse widths (and thus the residual capacitances) of the two monostables. This pulse is fed to the IN HI terminal of the DVM module via R9-R10. Thus, if the monostables have identical residuals, the EX-OR pulse width is zero and the meter gives a zero reading with zero external C_x applied.

In Figure 29 monostable IC2 is connected to the C_x terminals and functions in the same way as in Figure 28, except that an additional 10 pF is permanently wired across the terminals. The IC3 monostable, however, has C2 wired across its input terminals and the value of C2 can be adjusted to equal (and thus cancel) the residual of the input of IC2. IC3 is range-switched in parallel with IC2 via SW1c. Precise ganging is provided on ranges A, B and C only and on all other ranges the residuals are too small to influence the meter readings.

Frequency measurement

A DVM module can be made to read frequency by connecting the unknown frequency to the module's input via a f-to-V converter. A suitable converter can easily be made by using a 7555 monostable; Figure 30 illustrates the principle. The input signal is first fed to an input conditioner and trigger-pulse generator which triggers a fixed-period 7555 monostable on the arrival of each new input cycle. The output pulses of the mono are converted to mean dc values by integrator R2-C2 and fed to the input of the DVM module which is scaled via R3-R4.

The mean dc value of the 7555 output pulses equals V_p (the peak amplitude of the pulses) multiplied by W/P, where W and P are the width and period of the pulses respectively. V_p and W are, however, fixed. Only the pulse period is variable and this is inversely proportional to the input frequency, f, so the mean output voltage is equal to V_p x W x f and is thus directly proportional to f. Therefore, when the DVM module is suitably scaled via R3-R4 it gives a direct reading of input frequency.

In practice, the lowest convenient full scale frequency range of a DVM-based 3½-digit frequency meter is 1.999 kHz. In this case, the 7555 pulse has a period of 500 us at full scale. For maximum accuracy the pulse width must be as large as possible but must not be greater than two thirds of P. A pulse width of about 300 us is necessary and this can be obtained from the 7555 by choosing values for R1 and C1 of 27k and 10 nF respectively.

Figure 31 shows how the basic Figure 30 circuit can be modified to act as a multi-range frequency meter. In this case the input signal is fed to an input conditioner and Schmitt trigger and the Schmitt output is used to ripple-clock four decade dividers. The 7555 300 us monostable is provided with a trigger generator than can be fed from the output of the Schmitt or from any of the dividers. Thus, when the 7555 is triggered directly from the Schmitt the meter reads 1.999 kHz full scale and when fed from the

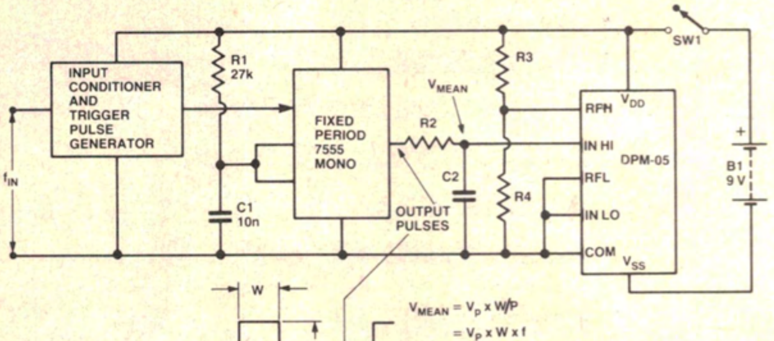


Figure 30. Basic method of using a DVM module as a frequency meter.

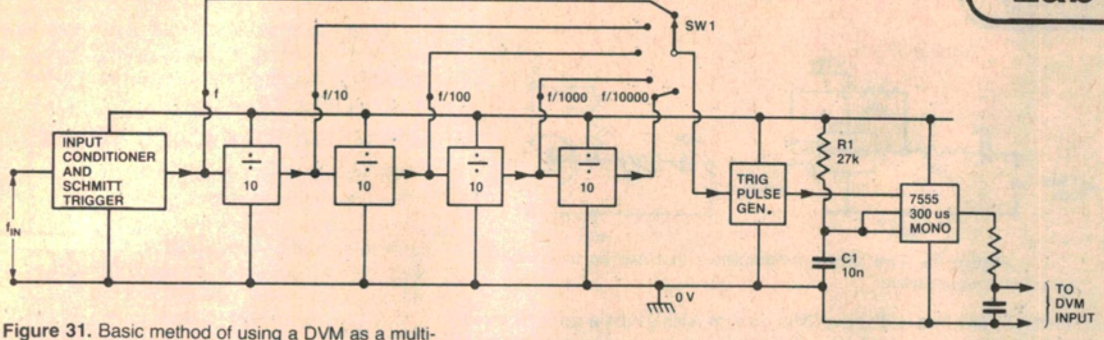


Figure 31. Basic method of using a DVM as a multi-range frequency meter.

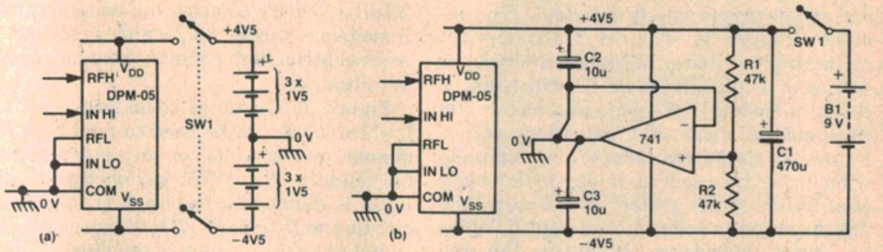


Figure 32. A DVM frequency meter needs split supplies. These can be obtained from either a stack of 1V5 cells (a), or from a single 9 V battery and an op-amp supply-splitter (b).

output of the last divider stage reads 19.99 MHz full scale.

Practical frequency meters

The 7555 IC can operate from supplies as low as 2 V. Standard CMOS counter ICs, however, need supplies of at least 3 V. Consequently, if a DVM module is to be used as a frequency meter sharing supplies that are common with those of the CMOS divider stages, the DVM module must be used in the 'split-supply' mode with its COM terminal pulled below the normal 'V_{DD} — 2V8' value by external circuitry.

In other words, COM must operate at '0 volts' and V_{DD} and V_{SS} at nominal values of +4V5 and −4V5 respectively. Figure 12 in Part 1 showed how these supplies can be obtained if the module is built into existing equipment that has split supplies. Alternatively, Figure 32a shows how the supplies can be obtained from a stack of six 1V5 cells. Figure 32b shows how the supplies can be obtained from a single 9 V battery via an op-amp supply-splitter. The supply-splitter of Figure 32b adds a quiescent current consumption of about 2 mA to the DVM circuit, but can supply additional supply currents of tens of milliamps to circuitry connected between +4V5 and 0 V.

Figure 33 shows the practical circuit of a DVM-based digital frequency meter that reads up to 19.99 MHz full scale in five decade ranges. When used with the Figure 32b power supply, the circuit consumes about 3 mA quiescent from the 9 V battery, rising to 4 mA at 1 MHz, and (when calibrated) has a reading accuracy of +/− one digit. The circuit accepts input signals in the range 200 mV to 5 V RMS and operates as follows.

Input signals are fed, via C1-R1, directly to the input of IC1a, a very fast Schmitt trigger, which is biased as half-supply volts via R2-R3. The Schmitt output is used to ripple-clock four decade-divider stages. Ordinary CMOS dividers typically operate at maximum speeds of only 800 kHz or so when powered from 4V5 supplies. To give the required fast operating speeds the very latest 'HC' types of silicon-gate CMOS counters are used in the first two (IC2 and IC3) counter positions. On the prototype unit they clock at frequencies up to about 18 MHz.

The output of the IC1a Schmitt and of the four divider stages are fed to range-selector switch SW1a. The output of SW1a is fed to 4 us trigger-pulse generator C4-R4-IC1b-IC1c which triggers the 7555 monostable via Q1. The output of the 7555 is fed to IN HI of the module via R8-R9, and a calibration 'reference' voltage is fed to RFH via RV1. The circuit is calibrated by feeding in a signal of known frequency, switching to the approriate range and trimming RV1 for the appropriate reading on the DVM module.

Once RV1 has been initially calibrated, calibration is influenced only by variations in the pulse width of the 7555 and these may be caused by thermal variations in the values of R7 and C5. For optimum calibration stability R7 should be a metal-glaze resistor and C5 should be a polycarbonate capacitor. ▶

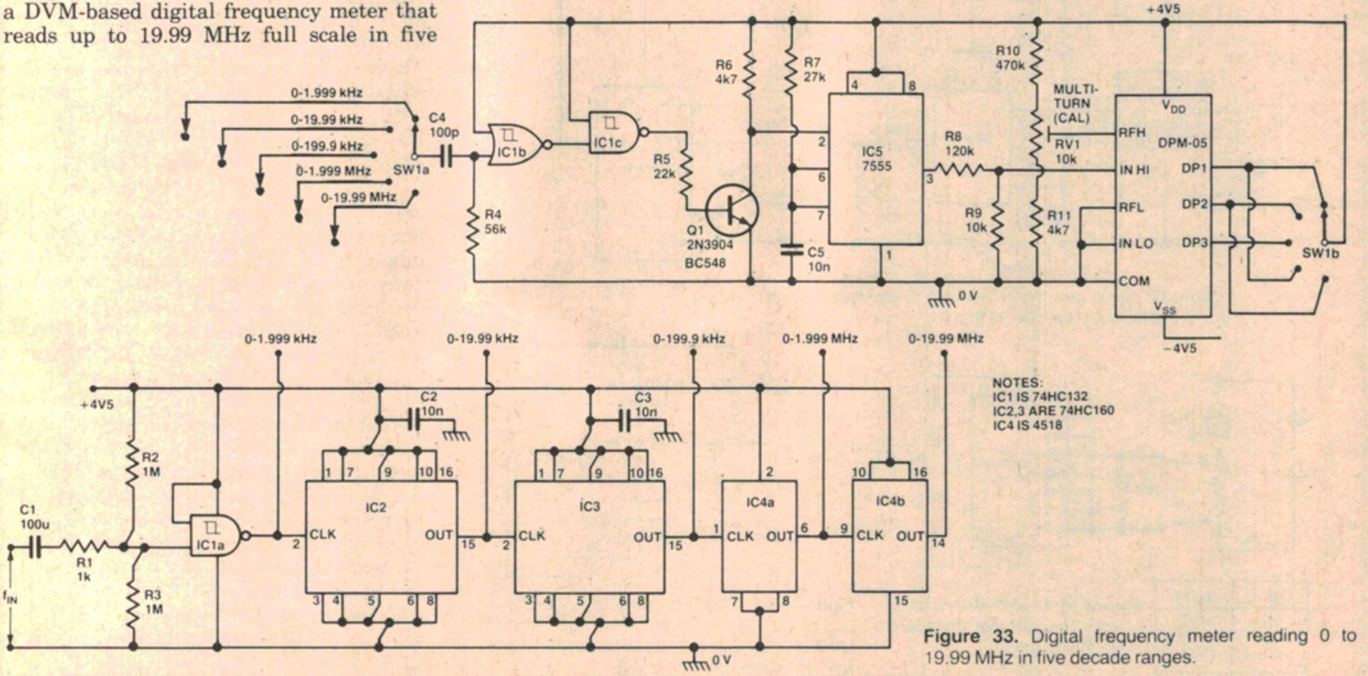


Figure 33. Digital frequency meter reading 0 to 19.99 MHz in five decade ranges.

Lab Notes

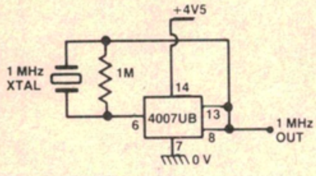


Figure 34. This 1 MHz crystal calibration oscillator can easily be added to Figure 33 circuit.

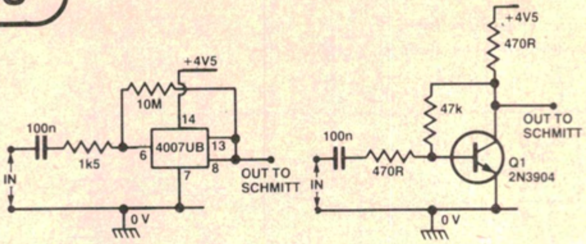


Figure 35. Two simple preamplifiers that can be used with the frequency meter.

The Figure 33 circuit can be modified in a variety of ways to satisfy individual requirements. Figure 34 shows a 1 MHz crystal calibration oscillator, designed around one section of a 4007UB CMOS IC, which can be easily added to the frequency meter and consumes a mere 300 uA when active. Figure 35 shows two simple preamplifiers which can be used to improve the basic sensitivity of the meter. The Figure 35a design, based on one section of a 4007UB, has an input impedance of about 1M and improves sensitivity by about 20 dB (to 20 mV RMS) at audio frequencies, but is useful to only a few hundred kHz. The simple Figure 35b design also gives a gain of about 20 dB at low frequencies, but has a low input impedance (about 2k2) and is useful to several MHz. Both circuits consume a couple of milliamps.

Figure 36 shows, in basic form, how the DVM module can be used to read both frequency and ac volts (or any other desired parameter). With SW1 switched to 'f', the input is switched to the input of the f-meter circuit and IN HI and RFH of the module are switched to the outputs of the circuit. When SW1 is switched to 'Vac', the input is switched to the input of the frequency-compensated attenuator, which has its output fed to IN HI via SW2 and a precision ac/dc converter (see Figure 19 in Part 1). RFH is switched to a 100 mV standard voltage derived from a bandgap reference.

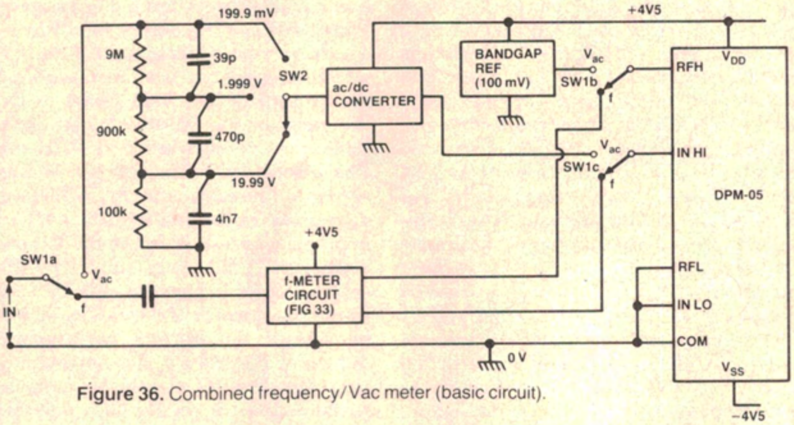


Figure 36. Combined frequency/Vac meter (basic circuit).

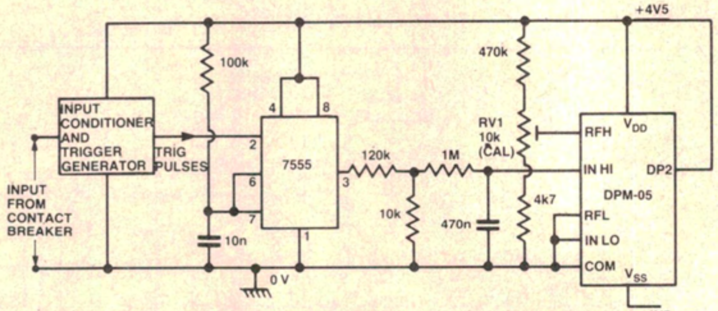
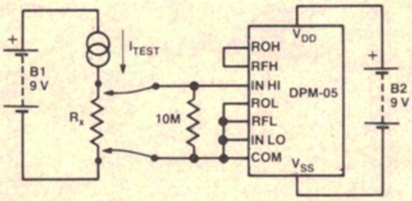


Figure 37. Basic rpm meter reading 19 990 rpm full-scale from a four-cylinder four-stroke petrol engine.



I_{test}	R_x fsd
1 mA	199.9Ω
10 mA	19.99Ω
100 mA	1.999Ω

Figure 38. Basic milli-ohmmeter using four-terminal measurement technique.

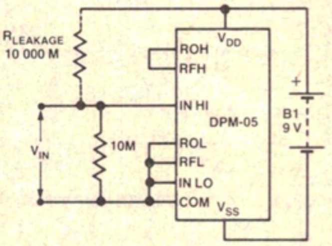


Figure 39. In this 199.9 mV dc voltmeter circuit, pc board or module leakage resistance causes the meter to indicate 28.0 mV with no external input applied.

Miscellaneous applications

DVM modules can be used to indicate the value of any parameter than can be converted into a predictable (linear or log) voltage, current or resistance. Linear transducers are readily available for measuring values of pH, light intensity, and radiation etc.

Cyclic parameters such as rpm and heartbeat rate etc, can be measured by adapting the frequency meter technique already described. The rpm of a petrol engine, for example, is directly proportional to contact-breaker (CB) frequency, f. On a four-stroke engine, f = N x rpm/120, where N is the number of cylinders. Thus, on a single-cylinder engine 10 000 rpm gives a CB frequency of 83.3 Hz, and on a four-cylinder engine a frequency of 333.3 Hz. Figure 37 shows the basic circuit of a digital rpm meter designed to read 19 990 rpm full scale (10 000 rpm at mid scale) on a four-cylinder four-stroke engine. The 7555 monostable gives an output pulse width of about 1 ms.

When measuring low values of resistance care must be taken in circuit design to ensure that the resistive effects of range switches, fuses and terminals etc, are excluded from the measurement results. The only way of achieving this is to use the four-terminal measurement technique shown in Figure 38, in which two independent circuits are used. Here, the unknown resistor is connected between the R terminals and fed with a constant current from B1. The volt drop *directly across* R_x is measured via a 199.9 mV full scale dc voltmeter powered from B2. Thus, when 10 mA is passed through R_x, the voltmeter indicates 19.99 ohms at full scale.

Constructional notes

When using DVM modules two vital usage points must be noted. The first of these arises from the high sensitivity of the module and is illustrated in Figure 39, where the module is wired as a 199.9 mV full scale dc voltmeter with a 10M input resistance. Thus, if a leakage resistance of 10 000 megohms appears between V_{DD} and IN HI, the meter will read 28.0 mV with no external input applied. Leakage resistances of this magnitude (and lower) can be caused by minute amounts of moisture or dirt appearing between the terminals of the module or the tracks of a pc board to which it is connected. To eliminate the possibility of this effect, the entire module and pc board must be cleaned and dried after project construction is complete. Then both must be thoroughly coated with insulation varnish. Humbrol clear varnish No 35 (available from model and art shops) is excellent for this purpose.

The final usage point concerns external components. General-purpose resistors and capacitors have very poor thermal stability. Consequently, in all practical DVM-based designs great care must be taken to ensure that all critical resistors are metal-glaze or similar hi-stab types, and all critical capacitors are polycarbonate types. ●