The PM 2517 automatic digital multimeter

M. P. van Alphen, R. E. J. van de Grift, J. M. Pieper and R. J. van de Plassche

Digital multimeters have been on the market for a long time, and are not in themselves particularly newsworthy. However, the recently introduced Philips PM 2517 multimeter deserves our special attention because it contains a number of interesting and original circuits. Besides an extremely accurate analog/digital converter, these include various other analog circuits, such as an accurate, programmable current generator for resistance measurements and a circuit that determines the r.m.s. value of rectified alternating-current quantities. These circuits, all of them ICs, were designed right from the start for automatic selection of the measurement ranges; the switching required can often be performed in the IC itself. The multimeter is the result of close cooperation between Philips Research Laboratories, the Scientific and Industrial Equipment Division and the Solid-state Special Products Group of the Elcoma Division.

An integrated multimeter

For many years the customary central element in a multimeter has been a moving-coil meter. This is surrounded by various circuits that reduce the measurement of voltages and resistances to the measurement of a current. In addition to this ‘analog’ multimeter digital multimeters are now available, and these have a number of advantages. The recently introduced Philips PM 2517 automatic digital multimeter is such an instrument; it is portable and gives a reading to four decimal places. Fig. 1 shows the two versions available, one with light-emitting diodes and the other with a liquid-crystal display.

In the conventional multimeter the force experienced by the moving coil in the magnetic field balances the opposing force of a spring. The magnetic field and the spring constant can be considered here as the reference quantities. In a digital multimeter the reference quantity is necessarily of an electrical nature and not mechanical. In the PM 2517 an accurately constant reference current is used. This is balanced against an input current derived from the test signal. The currents are balanced by applying each to one of the plates of a capacitor; when the currents are equal the voltage across the capacitor is zero. The number of pulses of the reference current required to produce a balance gives the desired information in digital form. The stability and accuracy of the circuit are high; the deviations from linearity are less than \( \pm 10^{-5} \) of the full-scale reading.

In moving-coil instruments there is usually a selector switch for setting to the various measurement ranges. As might be expected with the shift from mechanical to electrical functions that is characteristic of digital instruments, this switching is also electronic. The analog/digital converter of the PM 2517 is designed for compatibility with electronic switching; it has two states that differ in sensitivity by a factor of ten, and a choice between them can be made electronically. With this arrangement it is only necessary to switch the voltage-divider resistances once, which can be done with simple electronic circuits.

The digital indication of resistance values is a significant improvement over the hyperbolic resistance scale usually found in moving-coil meters. A voltage is generally used in these meters as the reference quantity, and the meter — which measures current — then indicates the reciprocal of the resistance from \( I = V/R \).
The development of a current generator that can be accurately set to various values has enabled us to use a current as reference in the PM 2517, so that the resistance measurement can be reduced to a simple voltage measurement.

The situation is rather similar for the root-mean-square (r.m.s.) value of alternating voltages and currents. Moving-coil meters react to the mean value of the rectified current; they usually have a separate scale, calibrated as the r.m.s. value for sinusoidal alternating currents. This scale reads incorrectly for other waveforms. The PM 2517 includes a circuit that calculates the true r.m.s. value independently of the waveform. This calculation is made by analog methods.

It is only because of the use of integrated circuits that there is room for the many operations that are performed in the multimeter. Six special ICs have been developed for the PM 2517, four of them analog and two digital. A bipolar technology has been used in the four analog ICs; the two digital ICs have been made in LOCMOS (Local Oxide separating Complementary MOS transistors). The analog ICs in particular contain new circuits, which have been specially designed to meet the requirements for high accuracy. Some unconventional solutions have been found; we shall discuss the more important of these circuits below.

A number of discrete components have been added to the ICs, such as voltage dividers for the various measurement ranges, shunt resistors for current measurement and variable resistors for various adjustments (see fig. 2). Discrete components are also included for instrument protection, an important aspect we have not as yet mentioned. When it is switched on an automatic multimeter sets itself to the most sensitive range position: for voltage measurement this is the 1 V range, for current measurement the 100 mA range. If the mains voltage should now be applied, for example, this must not damage the instrument. Many precautions have been taken to prevent such damage. These are so effective that no damage results even if the EHT voltage of a television receiver is accidentally applied. We shall return to instrument protection later.

However, most of the rest of this article will be a description of some of the interesting new circuits in the multimeter. To show clearly the place of these circuits in the complete instrument we shall first explain the general arrangement of the multimeter with the aid of a block diagram.
Fig. 2. The interior of the PM 2517. The large panel contains all the measurement circuits. The small panel on the left is included with the LED version (PM 2517E), and the one on the right is included with the LCD version (PM 2517X). Six ICs can be seen on the large panel; all of them were specially developed for the multimeter. Three connector sockets can be seen on the left; the folded metal strip connecting the two outer sockets is a 10 A shunt of 12 mΩ. To the right of this shunt there are two (light blue) resistors, which together form the 9 MΩ series resistance for the voltage measurement; the (red-painted) cylindrical component next to them is a PTC resistor, which provides protection from overload. The segments of the function-selector switch are printed on the panel. The oscillator coil of the d.c. inverter can be seen right at the top.

General description of the PM 2517

A block diagram of the PM 2517 digital multimeter is shown in fig. 3. The six integrated circuits in the blue boxes include the measurement and control functions. Between the input terminals and these ICs there is a greatly simplified representation of a number of voltage dividers, shunts, etc., which are in discrete-component form in the PM 2517. There is an optional choice between two displays; these are shown at the right. The upper one is the LED (light-emitting diode) display of the PM 2517E, the one below is the liquid-crystal display (LCD) of the PM 2517X. The heart of the instrument is the analog/digital converter \( A/D \) (in IC 2) and the voltage/current converter \( V/I \) (in IC 1) that precedes it. Direct voltages are converted here into a current that charges the capacitor \( C_1 \), which is also discharged again by digitally counted pulses of accurately known magnitude. The accuracy of the instrument is largely determined here. All the other quantities — alternating voltages, direct and alternating currents, resistances — are first reduced to a direct voltage, and the actual measurement is then made in this part of the instrument.

The digital information provided by the analog/digital converter is accumulated in the control unit \( CU \) (IC 5) and processed to form a control signal for the display. If the test signal is too large for the range selected, the control unit gives a command (via the red lines) to reset the voltage dividers etc. and shift the decimal point.

All measurements start at the lowest range. For voltage measurements, where the lowest range goes to 1 V, a voltage divider that reduces the voltage to a tenth is included even in the lowest range. This gives the instrument an input resistance of 10 MΩ, high enough to have an insignificant effect on most of the
circuits on which measurements will be made. The voltage divider also gives some instrument protection.

The range-selection process depends on a combination of two methods. In addition to the 10:1 voltage divider there is another one with a ratio of 1000:1.

As we said earlier, alternating voltages are reduced to the measurement of direct voltages; this takes place in several steps. After an isolating capacitor $C_2$ there

![Fig. 3. Simplified circuit diagram of the PM 2517 multimeter. On the left is the large panel with the ICs 1 to 6 (in the blue boxes), on the right the two options for the display panels, with LEDs for the PM 2517E and LCD for the PM 2517X. IC 1 contains a voltage/current converter $V/I$ and an accurate reference-current generator $(I_{ref})$, IC 2 a clock generator $Cl$ and an analog/digital converter $A/D$; the digital output signals go to the control unit $CU$ (IC 5). This supplies binary-coded decimal (BCD) digits to the display; a signal on the lines $DS$ makes clear which digit is intended. The group of outputs $Rng$ (red) gives the automatic selection of the correct range. Alternating voltages are processed in IC 3; after conversion to current and rectification the r.m.s. value is determined $(RMS)$. IC 4 contains a current-generator circuit for resistance measurements. IC 6 $(DC)$ controls the placing of the decimal point and the indications for polarity and unit of measurement on the display.

The step between the two, a factor of 100, is too large, but an intermediate step of 10 times is provided in the voltage/current converter $V/I$ by switching over to a conversion resistance $R_{conv}$ that is 10 times larger; this reduces the sensitivity by a factor of 10. Ranges of 1 V, 10 V, 100 V or 1000 V can thus be selected for voltage measurement. (The maximum readings remain just below these limits because of the four-digit indica-

is again a voltage divider with a ratio of 10:1, but now with a total resistance of 2 MΩ. This is followed by a voltage/current converter $V/I$ (in IC 3), similar to the one for the direct-voltage measurements. A choice can again be made between two conversion resistances that differ in magnitude by a factor of 10; with a second voltage divider (1000:1) a choice can once more be made from four voltage ranges.
The alternating current from the voltage/current converter is rectified in a full-wave rectifier. The r.m.s. value of the resulting pulsating direct current is then calculated in the circuit \( RMS \); the calculation does not depend on the waveform. The logarithmic relation between the voltage across a diode and the current through it is used for this calculation; we shall return to the details later. The r.m.s. value of the alternating voltage is eventually represented by the magnitude of a direct current. This passes through a resistor and the voltage across the resistor is directly applied to the input of the direct-voltage measurement circuit.

There are two ranges for the measurement of direct and alternating currents: 100 mA and 10 A. The input socket for the 100 mA range is the same as for voltage measurements. The current flows to the instrument chassis through a shunt resistor. The voltage across the shunt resistor is measured as described earlier. For measurements in the 10 A range there is a separate input socket, which is connected to the chassis by a shunt resistance of 12 mΩ. This is formed by the folded metal strip that can be seen in fig. 2.

The measurement of resistances is reduced to a voltage measurement by passing an accurately known current through the resistance. There are five ranges, from 1 kΩ to 10 MΩ. The current originates from a current-generator circuit that is included, with a current multiplier, in IC 4, and can be set between 1 mA and 100 nA in five steps of a decade. More will be said about this circuit later. The current of 1 mA gives a voltage of 1 V across a resistance of 1 kΩ; since the resistance to be measured is connected to the same input socket as for voltage measurement, the 'voltage' indication now refers to a resistance value. The symbol Ω appears on the display instead of the symbol mV. If the voltage rises above 1 V, then at a command from the control unit CU the current is automatically reduced by a factor of 10 and the decimal point displaced.

The measurement of the forward and reverse voltages of semiconductor diodes is closely related to resistance measurement. In this test a current of 1 mA is supplied from the input socket; the voltage produced across the diode is indicated in mV. If the diode is in the forward direction the voltage will be a few hundred mV; if it is in the reverse direction the voltage will exceed the upper limit of the range and this will be indicated by a special code in the display.

Finally, the PM 2517 can also be used to measure temperatures between -60 °C and +200 °C. This measurement is made with a temperature probe. The probe is connected to a separate input and contains a thermistor that forms one of the arms of a Wheatstone bridge in the instrument. The indication is given in °C. The bridge is supplied by a current of 1 mA from IC 4.

After this description of the input circuits we shall now say a few words about the control of the display. The four digits that indicate the measured result are provided by the control unit CU in binary-coded decimal (BCD) form. This information is supplied on 4 parallel lines, which means that only one digit can be transmitted at a time. A code signal on two separate lines (DS, digit selection) makes clear which of the four digits is intended.

The control of the segments of the four 7-segment digits is not the same in the liquid-crystal display as in the LED display. The digits in the LED display are illuminated one at a time in rapid succession, largely to limit the number of lines. The anodes of the corresponding segments of the four digits are connected together and receive their control from a logic circuit to which the binary code for the four digits is applied. The cathodes are connected 'per digit', however, and are only energized when the code on the two DS lines calls for this.

With the liquid crystals the four digits are shown simultaneously. Since only one digit is transmitted at a time, four circuits — one for each digit — are included to act as a buffer memory and hold the control signals for the seven segments. In both versions there is also a decoder circuit DC (IC 6), which derives the correct decimal point and unit symbol from information about the nature of the test quantity and the range selected.

The power for the PM 2517 is supplied either from four 1.5 V batteries or from a mains adaptor. To eliminate the effects of falling battery voltage, the batteries drive a d.c. inverter. This contains an oscillator, which produces an alternating voltage at a frequency of 200 kHz. The alternating voltage is rectified to give two stabilized direct voltages of ± 8.5 V, which supply all the circuits. The inverter has an efficiency of about 60%.

The analog/digital converter

In the design of an integrated analog/digital converter we had to bear in mind that many analog functions could be accurately and adequately performed in a bipolar technology, whereas although the MOS technology was very suitable for digital circuits, there were problems in the design of the accurate analog input circuit and current generator. An optimum analog/digital converter has been obtained by using a bipolar technology for all the analog functions where accuracy is important, and a digital MOS circuit for counting and control. Efforts were made to find a

principle of operation that could readily be applied in an integrated circuit. Such a principle has been found and has been called sigma-delta modulation [2]. The analog signal processing takes place in two bipolar ICs, and will be described in more detail below; the digital shift registers and counter circuits required are included in the digital IC (in LOC-MOS technology) shown as the control unit $CU$ in fig. 3.

Sigma-delta modulation

The basis of the analog/digital conversion is the well-known principle of delta modulation [3]: changes in the signal are followed as closely as possible by steps of the same magnitude, and a binary code indicates whether the step goes up or down. However, in an instrument we are not as interested in the changes in the signal as in its magnitude, which may not change for some time. Delta modulation, which in fact yields the time derivative of the signal, is therefore applied not to the test signal itself, but to its time integral: the voltage $V_c$ across capacitor $C$ (fig. 4a) is the integral of the current to be measured $I_x$. We call this 'sigma-delta modulation'.

One advantage of taking an integral is that interference from the mains is greatly reduced. This is because the integration includes many cycles of the mains; the integration time in the PM 2517 is 250 ms.

The delta modulation is produced with the aid of a circuit that measures $V_c$ and tries to keep it at zero. This is done by charging or discharging $C$, depending on the position of switch $S$, with a reference current $I_{ref}$ at the same time as the test current $I_x$ (fig. 4a) is being applied. The switch $S$ is operated in synchronism with the clock pulses from the clock generator $Cl$ by a bistable circuit $BC$, which puts $S$ into position 1 or 2 depending on whether the comparator circuit $Comp$ finds a negative or a positive voltage across $C$.  

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig4}
\caption{Fig. 4. Principle of the 'sigma-delta modulator'. \textit{a}) Block diagram. The current $I_x$ to be measured charges the capacitor $C$. The circuit is designed so that it keeps the voltage $V_c$ across $C$ to zero by carefully regulating the discharge pulses. This regulation is provided by switch $S$, which supplies a charging or discharging reference current as required. $S$ is controlled through the intervention of a bistable circuit $BC$ by a comparator $Comp$, which monitors the voltage across the capacitor. The control action takes place in synchronism with the clock pulses originating from clock generator $Cl$. The output signal $V_0$ is a digital representation of the magnitude of $I_x$. \textit{b}) When $I_x = 0$, $V_c$ alternates about the zero.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig5}
\caption{Fig. 5. The capacitor voltage $V_c$ and the output voltage $V_0$ of the sigma-delta modulator as a function of time. \textit{a}) The current $I_x$ to be measured is small with respect to the reference current $I_{ref} = \frac{1}{2}I_{ref}$. After every 32 clock pulses one extra discharge pulse is necessary to compensate $I_x$. \textit{b}) $I_x = \frac{1}{2}I_{ref}$. After each charging pulse there are two discharge pulses. This would bring the circuit to equilibrium if $I_x$ was accurately equal to $\frac{1}{2}I_{ref}$. However, $I_x$ is a little larger; after every 18 pulses one extra discharge pulse is required.}
\end{figure}
The sequence of control pulses originating from $BC$ contains the desired information about the magnitude of $I_x$ in digital form. If $I_x = 0$, $C$ is alternately charged and discharged, and the output from $BC$ is an alternating train of 'ones' and 'zeros'. The voltage $V_C$ then changes periodically about the zero (fig. 4b). If $I_x$ is slightly different from zero, an extra discharge pulse will be necessary now and again to bring $V_C$ back to zero; see fig. 5a, where 1 extra discharge pulse appears after every 32 clock pulses; $I_x$ has $1/32$ of the full-scale value here. In fig. 5b there is one extra discharge pulse after every 18 clock pulses; here $I_x$ is $2/18$ $I_{ref}$, so that for each charging pulse there are usually two discharge pulses. The upper limit of the range has been reached when only discharge pulses appear; $I_x$ is then equal to $I_{ref}$.

The 'ones' and 'zeros' that form the output signal $V_o$ in fig. 4a are applied to an up-down counter, which takes a step upwards at a '1' and a step downwards at a '0'; the up-down counter is located in the control unit ($CU$ in fig. 3). The virtue of the procedure used is that speed of measurement and accuracy can be traded against one another; the number of numerical values that can be distinguished increases with the time of counting. In the PM 2517 a total of 25 000 pulses are counted; the resolution is then $I_{ref}/25 000$. The clock rate is slightly higher than 100 kHz, and one 'measurement cycle' lasts about 250 ms, as mentioned above.

**Conversion of voltage to current**

The measurement circuit described is based on an input current $I_x$. This does not mean that it is suitable in this form for current measurements, because the currents to be measured in a circuit will not in general be supplied from a current generator (with an infinitely high output impedance), like $I_x$ in fig. 4a. In addition it must also be possible to measure voltages. A voltage/current converter is therefore included in front of the analog/digital converter. Fig. 6 shows a simplified general picture. The voltage to be measured $V_x$ is applied to the bases of the transistors $T_1$ and $T_2$ and appears across the conversion resistor $R_{conv}$, producing a current $I_x/R_{conv}$ in it. This current is in fact the difference between the collector currents of $T_1$ and $T_2$ and charges the capacitor $C$. The switch $S$ in fig. 4a is replaced here by two transistors $T_3$ and $T_4$, which pass the current $I_{ref}$ alternately to one electrode of the capacitor and then the other.

The voltage across the capacitor $C$ is kept to zero in this way. The voltage between $C$ and earth, however, is not defined, and nor therefore are the collector voltages of the four transistors. This is provided for by a control loop, which includes an operational amplifier that measures the voltage from $C$ to earth and adjusts the bias currents of $T_1$ and $T_2$ so that the capacitor is approximately at earth potential, i.e. half-way between the positive and negative supplies.

In practice the conversion of voltage to current is much more complicated than fig. 6 would suggest. The output impedance of the emitters of $T_1$ and $T_2$ is not low enough in proportion to $R_{conv}$, so that the full value of $V_x$ does not appear across $R_{conv}$. To make this output impedance practically zero it is necessary to apply negative feedback. The feedback arrangement is shown in fig. 7. The complete circuit consists of four 'current mirrors' (called 'controlled current sources' elsewhere [1]). The combination $T_5, T_4, T_6$ forms such a current mirror as does $T_9, T_{10}, T_{11}$. These current mirrors contain the necessary powerful feedback to ensure that independently of the external load and

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Fig. 6. Simplified circuit of the voltage/current converter $V/I$ and the analog/digital converter $A/D$. The function of the switch $S$ in fig. 4 is taken over by the transistors $T_3, T_4$. The current in the conversion resistor $R_{conv}$ is $V_x/R_{conv}$.

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independently of \( V_x \) the same current \( I_0 \) always flows in each of the vertical branches. The operating point of the transistors therefore does not change if \( V_x \) varies; the source of \( T_1 \) therefore follows the voltage fluctuations of the gate and since the base-emitter voltage of \( T_3 \) is constant these fluctuations are passed on undiminished to \( R_{\text{conv}} \); this is also true for the right-hand side.

Reference-current generator

We now come to the reference-current generator, which is really the corner-stone of the measurement accuracy, since it delivers the current with which the measured quantity is compared. The reference current must be accurate in value and it must also remain constant in practical use if the supply voltage and temperature vary.

\[ \text{Fig. 7. A more complete circuit diagram of the voltage/current converter. The input transistors } T_1, T_2 \text{ are junction field-effect transistors, which give a high input resistance. The circuit is built up from 'current mirrors', which ensure that a current } I_0 \text{ flows through each of the six vertical branches. Since the operating point of the transistors cannot then change, the potential difference between the two input terminals is transferred unchanged to the conversion resistance } R_{\text{conv}}. \text{ The current in this resistor leaves the circuit as a difference between the collector currents of } T_5 \text{ and } T_6. \]

'Auto-zero' circuit

The PM 2517 indicates either negative or positive voltages; the zero is effectively 'in the centre of the scale'. Stability of the zero and the absence of drift are important requirements for an accurate indication of small direct voltages. These features are ensured by including a circuit that automatically corrects deviations in the zero; we call this an 'auto-zero' circuit. The circuit is shown in fig. 8. In the figure any unbalance is represented by the voltage generator \( V_{\text{offset}} \) on one side in front of the analog/digital converter A/D. The symmetrical voltage input is connected to the A/D converter via a reversing switch. The reversing switch is operated by auto-zero pulses, which reverse it at exactly half the measurement time. This means that the voltage supplied to \( A/D \) is \( V_x - V_{\text{offset}} \) during the first half and \( -V_x - V_{\text{offset}} \) during the second half; \( V_{\text{offset}} \) is eliminated by subtracting one from the other. The subtraction is carried out by reversing the output in synchronism with the auto-zero pulses between the direct and inverted output signals from the A/D converter.

These objectives are attained by arranging that the current is defined by a geometrical property of the integrated circuit — the ratio \( p \) of the emitter areas of the transistors \( T_1 \) and \( T_2 \) in fig. 9. Imagine first of all that the resistance \( R_2 \) is removed from the circuit. We then have two dissimilar transistors that both carry the same current; the current is kept the same by a control system consisting of the two resistors \( R \) and the operational amplifier \( OA \). We thus have \( I_s = I_0 \); see the straight line in fig. 10.

\[ \text{Fig. 8. The 'auto-zero' circuit. Drift and unbalance in the input circuit, represented here by a voltage } V_{\text{offset}}, \text{ are eliminated by periodically reversing the polarity of the input voltage } V_x. \text{ At the same time the digital output signal is inverted.} \]
There is however another relation between $I_1$ and $I_2$. The sum of the base-emitter voltage of transistor $T_1$ and the voltage drop across $R_1$ is equal to the base-emitter voltage of $T_2$. This is true for the whole of the curved line in fig 10. It is clear from the figure that there is only one point (besides the origin) for which both conditions are satisfied, and the current generator automatically takes up this value.

The relation between the base-emitter voltage $V_{BE}$ and the emitter current $I$ is given by the well-known diode equation

$$I = I_B \exp \left( \frac{V_{BE}}{kT} - 1 \right). \tag{1}$$

In addition to the constants $e$ (electronic charge) and $k$ (Boltzmann's constant) the equation contains the absolute temperature $T$ and the reverse current $I_R$. The reverse current is proportional to the emitter area. For somewhat larger currents (1) can be approximated by

$$I = I_B \exp \left( \frac{V_{BE}}{kT} \right). \tag{2}$$

The two conditions shown graphically in fig. 10 are:

$$I_1 = I_2, \tag{3}$$

$$I_1 R_1 + \frac{kT}{e} \ln \frac{I_1}{I_B} = kT \ln \frac{I_2}{I_B}. \tag{4}$$

For small currents the term $I_1 R_1$ in (4) can be neglected; the equation then simplifies to $I_1 = \mu I_3$, which determines the slope at the origin of the curved line in fig. 10. At higher currents, however, the term $I_1 R_1$ predominates over the logarithmic term and the slope of the curve is determined by the magnitude of $R_1$.

The current that automatically sets itself in this way is not independent of the temperature; it increases with increasing temperature. Compensation can be provided by supplying an additional current that decreases with increasing temperature. This is the current $I_3$ in fig. 9. The current $I_3$ is equal to the base-emitter voltage of $T_2$ divided by $R_2$. Now for a transistor with the operating point determined as above the base-emitter voltage decreases by about 2 mV per °C, and $I_3$ therefore decreases in proportion. $R_1$ and $R_2$ are chosen so that the two opposing temperature effects cancel one another in the output current $I_{ref}$; the two resistors are not integrated but mounted externally.

**Rectification and determination of the r.m.s. value**

To measure alternating voltages it is necessary to rectify the voltage and determine the r.m.s. value. Because it was desired to extend the bandwidth of the instrument to rather high frequencies, these operations could not be performed digitally, since the signal-sampling rate in the PM 2517 is much too low for this. Analog methods therefore have to be used.

The r.m.s. value is not determined by approximating the alternating voltage by a sine function, but the true r.m.s. value is calculated for any waveform by using logarithms. The voltage across a semiconductor diode is proportional to the logarithm of the current in it. The alternating voltage is therefore first put into the form of a rectified alternating current. This is done in the current rectifier.
The current rectifier

The current rectifier is preceded by a voltage/current converter as shown in fig. 7. The currents supplied by the converter are \( I + \Delta I \) and \( I - \Delta I \), where \( \Delta I \) is the alternating-current component to be measured. Both currents are supplied to the current rectifier, shown in simplified form in the circuit of fig. 11.

Starting at the bottom, we see that this circuit contains two transistors \( T_1 \) and \( T_2 \) used as rectifying elements and two special current mirrors \( T_3, T_5 \) and \( T_4, T_6 \). These current mirrors ensure that equal currents \( I + \Delta I \) flow on either side. Since a current of only \( I - \Delta I \) is taken off at one side, the difference \( 2\Delta I \) must find its way to a third output via one of the transistors. In the figure it flows through \( T_1 \); when this is conducting \( T_2 \) is non-conducting, since the sum of the base-emitter voltages of the two transistors is zero at all times. A half-cycle later the roles of the two transistors are reversed.

A small direct-current unbalance can arise between the two halves of the circuit. To detect this unbalance, the collectors of \( T_1 \) and \( T_2 \) are not connected together directly, but a capacitor is connected between them, while each collector is connected to the output through a resistor (fig. 12). Differences in the direct-current component of the two collector currents cause a direct voltage to appear across the capacitor, and this voltage also appears across the input of the differential amplifier \( T_7, T_8 \), which then provides compensation by taking unequal currents at the two inputs from the current rectifier.

Determination of the r.m.s. value

The r.m.s. value of an alternating current is the value of the direct current that gives the same mean power dissipation in a resistor. The arithmetical operations follow from this definition: since the power is proportional to the square of the current, the squaring must be performed first; a mean must then be taken over at least one cycle and finally the square root is taken.

Fig. 13 gives the essential features of the circuit that carries out these operations. The rectifier current \( I_1 \) is passed through a series circuit of two transistors \( T_9 \) and \( T_{10} \) connected as diodes; the resulting voltage \( V_1 \) across the transistors is proportional to twice the logarithm of the current, and hence to the logarithm of the square of the current.

In transistor \( T_{11} \) the logarithm of the current \( I_0 \) is subtracted from this; \( I_0 \) is the current that expresses the final result of the calculation, and is delivered to \( T_{11} \) by the current mirror \( T_{13}, T_{14} \). \( V_2 \) is therefore proportional to the logarithm of the ratio \( I_0^2/I_0 \).

The reverse conversion from logarithms to ordinary quantities is made in transistor \( T_{12} \), whose collector...
current is $I_1^2/I_0$. It now only remains to take the mean with the aid of an RC filter; a current $I_0 = \langle I_1^2 \rangle / I_0$ is obtained. From this it follows that $I_0 = \sqrt{\langle I_1^2 \rangle}$, where $I_0$ is the desired r.m.s. value of the current $I_1$. The total circuit supplies a current of $2I_0$; a correction for the factor of 2 is made later in the measurement circuit. Our requirements cannot be met unless special precautions are taken.

To obtain the desired accuracy we have made use of a principle that has been called ‘dynamic element matching’ elsewhere. This can be explained with the help of fig. 14, where the principle is applied for divid-

![Fig. 13. Analog circuit for calculating the r.m.s. value of a rectified alternating current $I_1$. In the multimeter this is the current $2I_1$ (fig. 12). The direct current $I_0$ has the same r.m.s. value as $I_1$.](image)

In fact, of course, we cannot speak of ‘the logarithm of the current’, as has been done here for simplicity. The logarithmic relation between $V_1$ and $I_1$ follows from the earlier equation (2):

$$V_1 = \frac{2kT}{e}\ln \frac{I_1}{I_{\text{R}}} = \frac{kT}{e}\ln \left(\frac{I_1}{I_{\text{R}}}\right)^2.$$

The logarithm is taken of the ratio of $I_1$ and the reverse current $I_{\text{R}}$ of the transistors $T_a$ and $T_{\text{R}}$.

Similarly the expression for $V_2$ is

$$V_2 = \frac{kT}{e}\{\ln \left(\frac{I_a}{I_{\text{R}}}\right)^2 - \ln \frac{I_{\text{R}}}{I_{\text{R}}}\} = \frac{kT}{e}\ln \frac{I_a^2}{I_{\text{R}}I_{\text{R}}}.$$

The programmable direct-current generator for resistance measurements

The direct current that we require for the conversion of a resistance measurement to a voltage measurement has to be accurately set to the correct value. In fact, it has to be accurately set to a number of different values, for the different measurement ranges. The accuracy required is $10^{-3}$ to $10^{-4}$. Now since the resistances in an IC only have an accuracy of a few per cent at best, our requirements cannot be met unless special precautions are taken.

The same principle can be applied even if the ratio of the output currents is not 1:1. Let us take a ratio of 10:1 as an example, since this represents the basic operation in the multimeter. Eleven similar current generators are then used, connected to a switching net-

work with two outputs. One output carries a single current, while the other carries the sum of ten currents. The switching network is controlled by a shift register with eleven stages. A single 'one' and ten 'zeros' circulate in the shift register. It is always a different current generator that provides the single current. The ratio of the mean values of the output currents is kept accurately at 1:10; there is a ripple on the currents but this is removed by a lowpass filter.

There are two such current multipliers in the PM 2517 (CM₁ and CM₂ in fig. 15). The current ratios for each can be adjusted by changing the content of the associated shift registers. The two multipliers are connected by the current mirror CMᵢ, which is in fact a current multiplier of ratio 1:1 here. The circuit CMᵢ contains a control loop that sets its current generator to the desired value. In the same way the eleven current generators in CM₁ and CM₂ are set to the same value as the reference current. By using different combinations of the transfer ratios of CM₁ and CM₂, five different values of current varying from 100 nA to 1 mA can be derived from the reference current of 10 μA. These currents correspond to resistance ranges from 10 MΩ to 1 kΩ. The complete unit is contained in a single IC, shown in fig. 16.

A fraction of the test current does not flow through the resistance to be measured, but through the input resistance (10 MΩ) of the voltage-measurement circuit. This introduces an error, which is largest for the 10 MΩ range. Compensation is necessary, and is obtained by using an operational amplifier that always supplies a current equal to that lost in the input resistance of the voltmeter (fig. 17). The voltage $V_x$ across the resistance to be measured is always applied to the input of the operational amplifier. This has negative feedback via a voltage divider consisting of two equal resistances arranged in such a way that it amplifies twice, and gives a voltage $2V_x$ at the output. Across the 10 MΩ resistor, connected between output and input, there is therefore a voltage $V_x$; the current $V_x/10$ MΩ produced in this resistance exactly compensates for the current lost in the input resistance of the voltage meter. The operational amplifier is included in the IC, but the voltage divider and the 10 MΩ resistor are external.

**Instrument protection**

A frequently occurring type of overload from which the multimeter must be protected is the accidental application of the mains voltage to the input terminals. Another dangerous hazard is the accidental application of the EHT voltage of a television receiver. The PM 2517 remains undamaged by either of these overloads, even in its most sensitive range.
Fig. 16. Photomicrograph of the IC containing the programmable direct-current generator. The dimensions of the IC are $3.2 \times 2.6$ mm. The two identical patterns appearing at the centre are the two current multipliers. The closely-packed areas are the shift registers in digital $1^\text{st}$L; on their right can be seen the eleven current generators.
The measurement circuit for direct and alternating voltage is protected from overload by the voltage dividers, which have a high resistance and always give a reduction of ten times even in the most sensitive range. In addition, a voltage limiter that limits the voltage to ±2.5 V is connected across the input to the integrated circuit; under normal conditions the voltage at the input is no higher than ±1 V.

To prevent flashover and leakage currents in the input circuit the printed wiring on the panel is arranged to make the leakage paths as long as possible, and the panel is lacquered. The length of the leakage paths was increased by making holes at suitable places in the panel between the segments of the switch, which are printed on the panel.

In the 'current measurement' position the multimeter is protected by the quick-acting 315 mA fuse shown in fig. 3. The wire-wound 1.8 Ω shunt resistor can withstand a brief overload until the fuse melts. No fuse is provided for the '10 A' input socket; the 12 mΩ shunt resistor connected to it is rugged and can be considered as an almost complete short-circuit to the chassis.

The current-generator circuit for the resistance measurement is connected to the input circuit through a 100 Ω PTC resistor (the red component to the left of the switch in fig. 2). In parallel with the current generator there is a diode circuit that ensures that the voltage across the output of the current generator does not exceed four times the diode voltage. This diode circuit only has to carry a large current for a short time in an emergency, because the PTC resistance heats up and reduces the current.

Summary. The Philips PM 2517 digital multimeter contains six ICs specially developed for the instrument; four of these are bipolar and contain new analog circuits of high accuracy. A 'sigma-delta modulator' functions as an A/D converter. A very stable current generator in the modulator provides a current of constant magnitude, which acts as a reference. For measuring alternating voltages there is a full-wave rectifier, followed by a compact analog circuit for the determination of the r.m.s. value. The test currents for resistance measurements are supplied by an accurate and programmable direct-current generator, adjustable in five steps from 100 nA to 1 mA. The measurement ranges are selected automatically by an internal control unit, and the indication is displayed to four decimals (to 9999) by light-emitting diodes (PM 2517E) or liquid crystals (PM 2517X).