Low-resistance measurement

Attention to the nulling of lead resistances enables measurement down to 100 micro-ohms.

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Low-ohms meters have many uses in varied fields such as reliability testing of switches and relays, measurement of the diameter of fine wire, and testing electrical installations. This article describes an instrument suitable for these and many other applications where an accurate reading of low resistance is required.

Measurement of low resistance requires a special technique to null test lead and contact resistances. This technique entails the use of two pairs of test leads, called force and sense leads. One pair is used to apply a stimulus to the resistor under test in the form of a current, and the other pair to sense the voltage across the resistor (see Fig. 1). If the current in the sense leads is kept small, so that the voltage dropped across the contact and lead resistances is small compared with that across the resistor under test, then a measurement of V will give an accurate value for R_x by ohms law

$$R_X = \frac{V.}{I_F}$$

Conventional low-ohms meters use this technique, but usually suffer from one or two drawbacks. One is the joining of force and sense leads before they make contact with the resistance under test (see Fig. 2), which will eliminate the resistance of the leads, but not that of the test probes, or their contacts with the resistor under test. The use of four completely independent test leads easily solves this problem. A second drawback of conventional meters is that measurement is often performed with a direct current, and amplification of the sensed voltage is at d.c.. Amplifier offset voltage then puts a limitation on the measurement, and a zero control must be provided and frequently adjusted.

The meter described in this article does not suffer from either of these limitations. Four test leads are provided, and the measurement is made at a.c.. A block diagram of the meter is shown in Fig. 3.

R_X is supplied by a current from the a.c. current generator and the voltage across R_X is sensed by the differential amplifier. A differential amplifier was used to ensure attenuation of any common-mode signal due to lead and contact resistances of the force leads. The resulting single-ended signal is amplified by a factor of 10, and any out-of-band noise eliminated by a band-pass filter. The signal is then amplified further by a switched-gain amplifier, which sets the full scale reading of the meter. A synchronous detector is then used to mix the signal to d.c. so that a moving-coil meter can be driven. Each component of the block diagram is described in more detail below.

A.C. CURRENT GENERATOR

The a.c. current generator applies a square-wave variation in current to the resistor under test of between 0 and 100 mA. A circuit diagram is shown in Fig. 4.

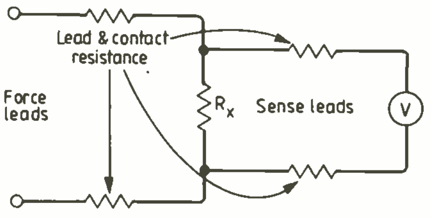

Fig.1. Conventional arrangement of test leads for low-R measurement.

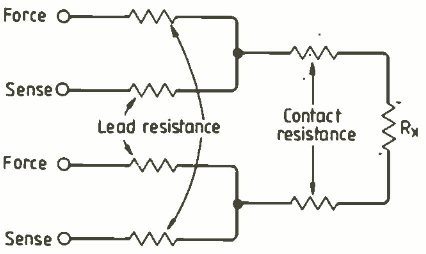

Fig.2. Arrangement of Fig.1 does not eliminate resistance of contacts to unknown R.

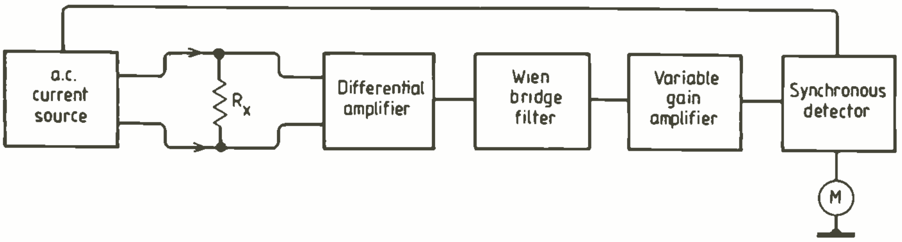

Fig.3. Block diagram of the low-ohms meter, in which four separate leads are used.

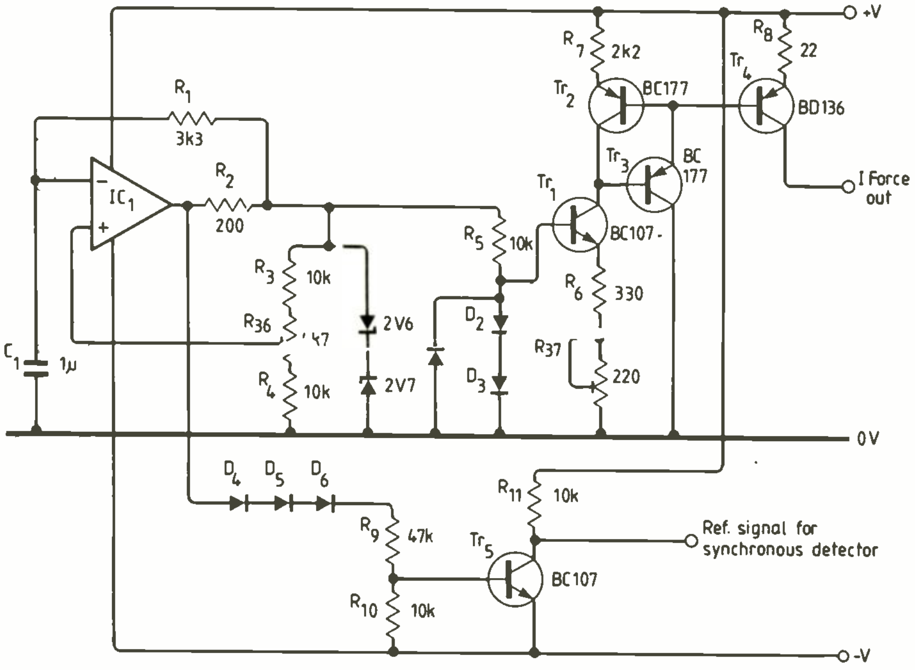

Fig.4. Alternating current force generator, providing a square-wave output, and a reference waveform for the synchronous detector.

IC_1 is configured as a square-wave generator with its frequency (approximately 130Hz) set by R_{36}. The square-wave generator drives Tr_1 via R_5, D_2 and D_3. The high-level collector current of Tr_1 is set by its emitter resistance, and low-level collector current is zero, as the base emitter junction of Tr_1 is reverse biassed. Diode D_1 prevents breakdown of this junction. Transistors Tr_2, Tr_3 and Tr_4 are configured as a current mirror with a ratio of 1:100, R_{37} being used to adjust the high-level I_{out} to about 100mA. Transistor Tr_5 provides a reference signal for the synchronous detector.

If the resistance under test is grounded at one end, the resistance of the ground lead will produce a common-mode signal which must be rejected by the differential amplifier (see Fig. 5). To avoid the use of an unduly complicated differential amplifier, the circuit shown in Fig. 6 is employed. This circuit reduces the common-mode signal due to the lead resistances by a factor of the open-loop gain of IC_2, at the frequency of I_{FORCE}. The voltage at A is adjusted so that the instantaneous voltage across R_X is centred about ground potential. Thus, the voltage across R_x is put into the differential mode, although some common-mode signal will persist due to mismatching of R_{13} and R_{14}. It is important that the ground reference required by IC_2 is taken at the differential amplifier to prevent errors due to ground track resistances.

DIFFERENTIAL AMPLIFIER

The next part of the circuit is a differential amplifier, which eliminates any remaining common-mode signal and transforms the voltage across R_X to a single-ended signal referred to ground. The circuit is shown in Fig. 7, in which the differential amplifier is the standard, single operational amplifier configuration, with unity gain and a common-mode rejection ratio limited by the matching of the ratios Rw_{15}/R_{16} and R_{17}/R_{18}.

BANDPASS FILTER

This is simply a Wien-bridge oscillator with its loop gain set to less than that needed for oscillation. The circuit is shown in Fig. 8. Centre frequency is set to 130Hz to ensure rejection of mains harmonics, whilst keeping the signal well within the bandwidth of the following amplifiers. The bandpass filter serves three functions: it attenuates harmonics of the signal so that the switched-gain amplifier is not required to amplify signals outside its bandwidth; it attenuates most of the noise so that the switched-gain amplifier is not saturated at high gains; and it acts as a preamplification stage.

SWITCHED-GAIN AMPLIFIER

Following the bandpass filter is a cascaded pair of non-inverting operational amplifiers forming a switched-gain amplifier, the circuit being shown in Fig. 9. The amplifier provides switched gains from 1 to 10000 in decade steps. At the frequency of 130Hz, the amplifiers have ample open-loop gain to perform their required function. The amplifier is arranged to give full-scale readings of 1Ω, 100mΩ, 10mΩ, 1mΩ and 100μΩ.

SYNCHRONOUS DETECTOR

The final stage of the circuit is the synchronous detector — a solution which was considered preferable to simple rectification, since a rectifier would produce erroneous results if the noise level were comparable to the signal level. The circuit for the synchronous detector is shown in Fig. 10, and works by multiplying the signal alternately by +1 and −1 at the signal frequency. This gives a d.c. component exclusively to the required signal, so that low pass filtering of the output will remove almost all undesirable effects, such as noise and mains hum. Operation of the circuit is simple: when the analogue switch is closed the amplifier is in the inverting configuration with a gain of −1, and when the switch is open the inverting gain is −1 and the non-inverting gain is +2. This results in an overall gain of 2−1=+1. The output of IC_5 drives a moving coil meter via R_m, which should be calculated to give a full-scale deflection of 0·5V. The mechanical damping of the meter gives adequate low pass filtering.

POWER-SUPPLY CONSIDERATIONS

The instrument requires a split supply of about ±6V, a mains supply being used in the prototype to avoid frequent battery replacement. If it is desired to use batteries, it would be wise to reduce the maximum force current to 10mA, and employ a test switch so that the meter is only on when a measurement is required. The complete circuit diagram shows a suitable modification to reduce the maximum force current to 10mA. With battery operation the range of full scale measurement is 1mΩ to 10Ω.

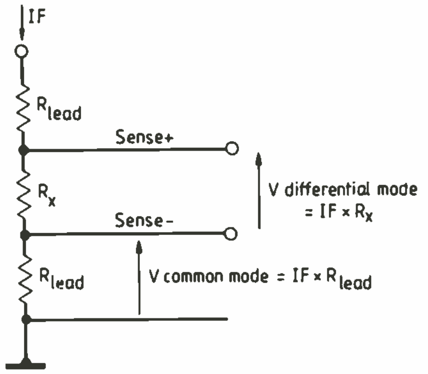

Fig.5. Grounding one end of R_X results in a common-mode voltage.

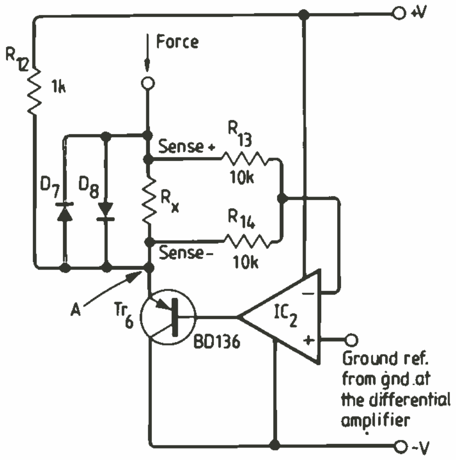

Fig.6. To reduce the common-mode voltage, R_X is connected in a feedback loop, centering the voltage about ground and rendering it a differential-mode signal.

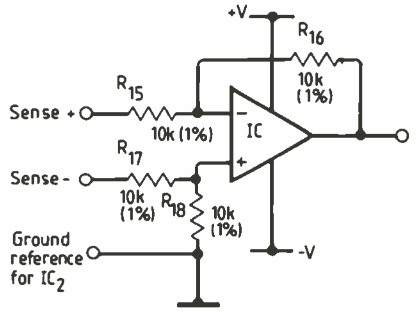

Fig.7. Differential amplifier.

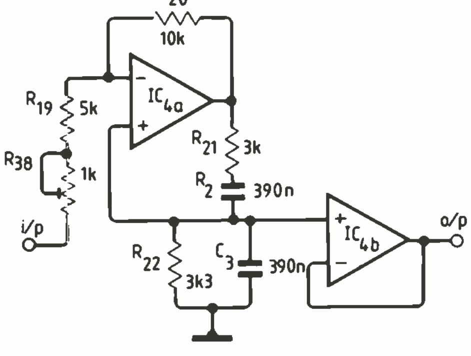

Fig.8. Bandpass filter, using Wien-bridge circuit with feedback less than that for oscillation.

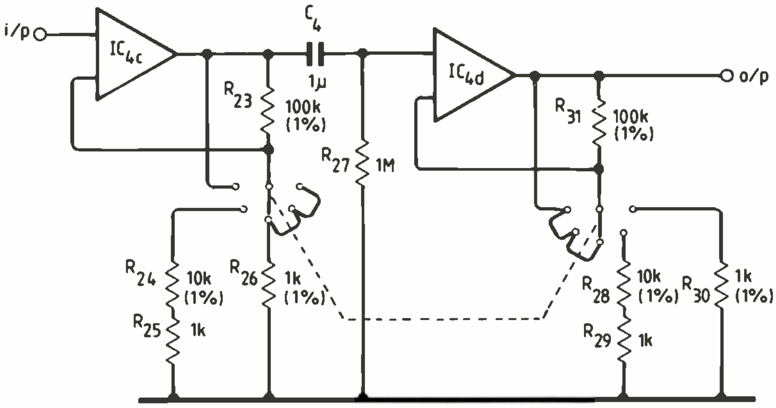

Fig.9. Switched-gain amplifier.

CONSTRUCTION

Figure 12. shows the complete circuit diagram. The prototype was built on unclad Veroboard, and connections were made on the underside of the board with fine, single-strand copper-wire. This method of construction was found to be quite satisfactory, and there is no advantage in using a printed-circuit board, though anyone wishing to do so should find that the layout is non critical except for the following:

- separate boards, or sections of a single board, should be used for the force and sense circuitry, to minimize pickup;
- the ground reference voltage for IC_2 should be taken directly from the ground connection of R_{18};
- current in the ground leads of the sense circuitry, and particularly at R_{18} should be minimized;
- the leads to and from the switch must be screened.

SETTING UP

Setting up the low ohms meter is not difficult. A 22Ω resistor should be obtained, and the instrument wired up to measure it. The range switch should be set to minimum sensitivity, and the power switched on. The voltage across R_8 should be measured to give a d.c. reading of 1V. R_{38} is then adjusted to its maximum value to ensure that the Wien-bridge filter does not oscillate. R_{36} can then be adjusted to give a maximum output, using the range switch to give a sensible reading. The 22Ω resistor is then exchanged for a 1Ω, 1% resistor, and R_{38} adjusted for full-scale deflection, with the range switch set to minimum sensitivity. If the battery option is used, a 10Ω resistor must be used instead of 1Ω.

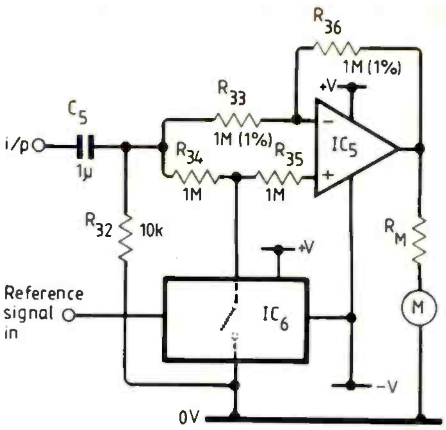

Fig.10. Synchronous detector and meter driver.

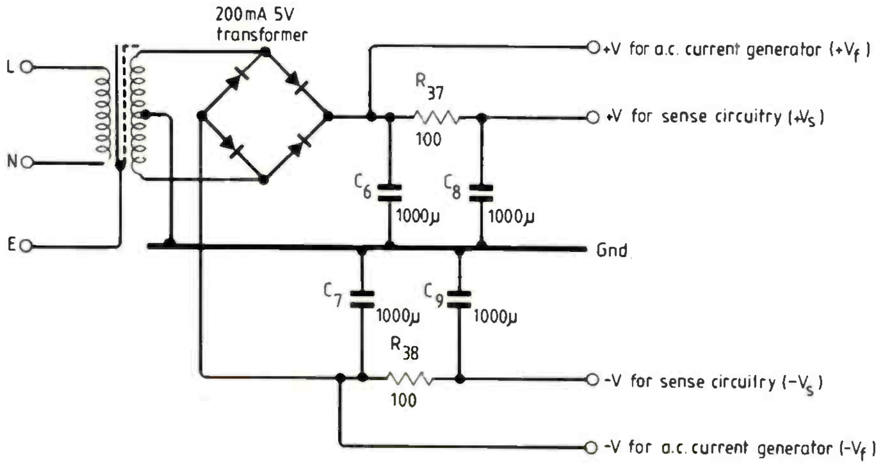

Fig.11. Mains power supply.

Fig.12. Complete circuit diagram.