Electronics for Scientists

Principles and Experiments for Those Who Use Instruments

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ELECTRONICS FOR SCIENTISTS
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Preface

This book is a practical book for scientists and science students. It is written expressly for *chemists*, *physicists*, *engineers*, *medical researchers*, *biologists*, and other science students and research workers who have little or no background in electronics but who need to gain a working knowledge of electronic devices and circuits. The text begins with *electronic principles*, *basic circuits*, and *components*. It leads systematically into *servo systems*, *operational amplifiers*, *feedback control*, *digital circuits*, and other devices used in current laboratory research and engineering control problems. The liberal use of diagrams attests to the authors' belief that a picture can speak louder than a thousand words.

The order of presentation is laboratory-centered. There is a natural progression from the basic measurement techniques necessary to start experimentation toward the complete instruments and systems. Specific components are usually introduced in the chapter where the most common or important applications are first described. Circuits with *new and special devices* are presented as well as the widespread *transistor and vacuum-tube circuits*. Most circuit diagrams contain actual component values so that they can be used as working drawings. A selected list of references with specific comments concerning the nature of the contents is included at the end of each chapter.

The three supplements at the end of the book serve several functions. Supplement 1 introduces and gives specifications on the universal experimental system used to perform the experiments in the book, and the pictures acquaint the reader with the individual components. Supplements 2 and 3 serve primarily as review of and reference to the *basic laws* and *component characteristics* which are usually introduced in basic courses of college physics. For scientists who do not remember or have had little exposure to these basic relationships, Supplements 2 and 3 are a good starting point.

This book should be especially useful as a text for a one-semester course at the junior-senior level in various physics, chemistry, or engineering college curricula, or as a self-teaching text for scientists on the job. For those who already have a good basic training in electronics, the chapters on comparison measurements, operational amplifiers, feedback control, servo systems, and digital circuits should provide both new information and reference material, because all these topics are presented in a way that the authors believe to be unique. As explained in the introduction, the authors have also found the material in this book to provide a practical working background in electronics for both graduate and postdoctoral students, especially if combined with thorough discussions of specific systems related to individual disciplines.

There have been many people influential in the start, preparation, and completion of this book. Professor H. A. Laitinen encouraged us from the beginning, both in support of the course from which this book developed and by his enthusiasm for the experimental system that we originated. The staff of the Heath Company (Benton Harbor, Michigan), especially W. Kooy, E. B. Mullings, and A. Robertson, was responsible for taking our original system and ideas and developing them into the completely integrated system of components and laboratory instruments now available for performing the experiments. Several valuable discussions took place with Professors Harry Pardue and Robert Kerr concerning portions of the manuscript. Great appreciation goes to Professor D. Lazarus of the University of Illinois Physics Department. He read all the chapters and made many important suggestions that greatly influenced our presentation of several topics. Mr. Verle Walters contributed in many ways to the construction of the original experimental system. Julia Zvilius, Frances Watson, and Linda Leahy were all very helpful in typing and assembling various parts of the manuscript. We are especially grateful for the help and encouragement of our wives, Gay Malmstadt and Mary Enke.

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taken to be sure that accuracy is maintained when an a-c voltmeter is used to measure frequencies over 1 kc.

1-5 The Ohmmeter

A series-type ohmmeter circuit is shown in Fig. 1-10. With the test prods short-circuited ($R_u = 0$), the "ohms adjust" control is turned so that the current I_1 through the total circuit resistance $R_m + R_f + R_a$ deflects the meter exactly full scale. Now, by connecting the test prods across the unknown resistance R_u, the current is decreased to a value I_2 which depends on the value of R_u. The 1.5-volt battery is across the total resistance in the two cases; so

$$I_1(R_m + R_f + R_a) = 1.5 \text{ volts}$$

and

$$I_2(R_m + R_f + R_a) + I_2R_u = 1.5 \text{ volts}$$

from which it follows that

$$R_u = \left(\frac{I_1}{I_2} - 1\right)(R_m + R_f + R_a) \tag{1-2}$$

Since a 1-ma meter movement is used and the battery is 1.5 volts, the total resistance $R_m + R_f + R_a$ will have to be set to 1500 ohms for full-scale deflection; so, from Eq. (1-2),

$$R_u = \left(\frac{I_1}{I_2} - 1\right)1500$$

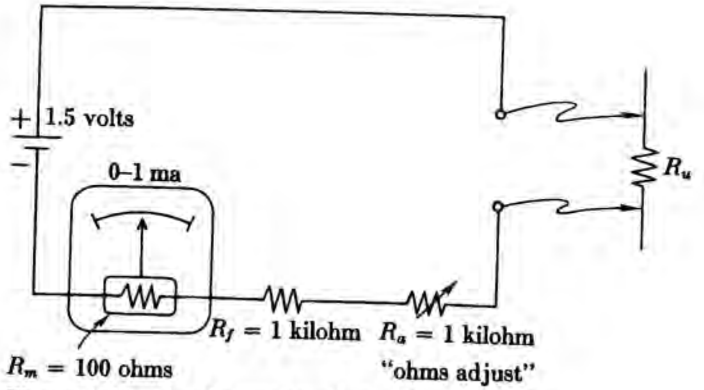

Figure 1-10 *An ohmmeter of simple series type.*

With $I_2 = \frac{1}{2}I_1$ (midscale deflection), the unknown resistance $R_u = 1500$ ohms; with $I_2 = \frac{1}{3}I_1$, $R_u = 3000$ ohms, etc. It is apparent that the scale is nonlinear. Values of R_u much higher than 1500 ohms become crowded on the "infinite ohms" end of the scale, and values much lower become indistinguishable from zero. The resistance at midscale could be decreased tenfold to 150 ohms by shunting the meter to make it 10 ma full scale and decreasing the series resistance (with test prods short-circuited) to 150 ohms. The resistance at midscale could be increased to 15 kilohms by increasing the supply voltage to 15 volts and the circuit resistance $R_m + R_f + R_a$ to 15,000 ohms. This system of changing ranges is, of course, rather cumbersome and is not too suitable for a practical multirange ohmmeter. It has the serious disadvantage of not maintaining a constant zero adjustment when switching ranges.

The principle of operation for a practical multirange ohmmeter is illustrated in Fig. 1-11. This ohmmeter is referred to as the "voltmeter type" or "potentiometer type" because the voltage is measured across a resistance that is in series with the unknown resistance R_u. The voltmeter branch has a total resistance R_v that is in parallel with R_s, so as to give an effective resistance $R_p = R_sR_v/(R_s + R_v)$, which is in series with R_r and any unknown resistance R_u. When the test leads are short-circuited, a current I_1 flows through the series circuit of $R_p + R_r$. This resistance is across a battery of E volts. When the unknown resistance R_u is connected into the circuit by the test leads, the current is reduced to a value I_2. In

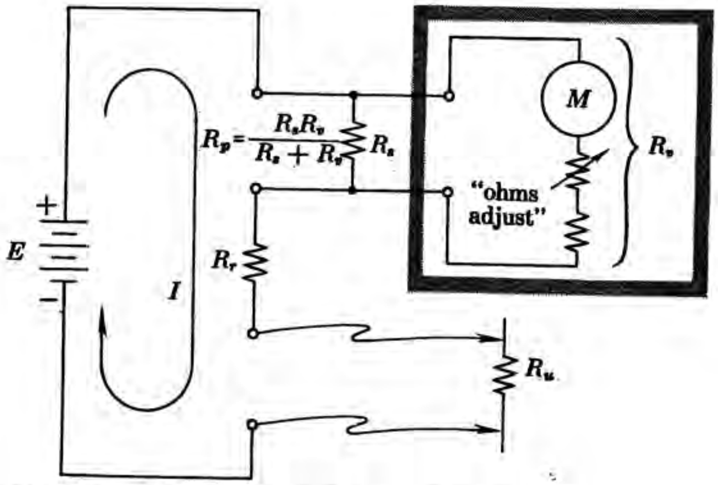

Figure 1-11 An ohmmeter of voltmeter type.

each case the sum of the voltage drops in the circuit is equal to the supply voltage, so that

$$I_1R_p + I_1R_r = E$$

$$I_2R_u + I_2R_p + I_2R_r = E$$

and solving these two equations for R_u, one obtains,

$$R_u = (R_p + R_r)\left(\frac{I_1}{I_2} - 1\right) \tag{1-3}$$

Note that the currents in the meter path will be proportional to the circuit currents I_1 and I_2. If the "ohms adjust" resistance is varied until the meter reads full scale with the test leads short-circuited, the meter will have a midscale reading ($I_2 = I_1/2$) when $R_u = R_p + R_r$, a one-third full-scale reading when $R_u = 2(R_p + R_r)$, etc.

If $R_p = 11.5$ ohms and $R_r = 1.0$ ohm, then $R_u = 12.5$ ohms for a midscale meter reading. The meter would be calibrated to read ohms directly. If $R_p + R_r$ is increased to 1250 ohms, the ohms value will equal the meter reading × 100. In this case, $R_u = 1250$ ohms for a midscale reading if the "ohms adjust" was previously varied so that the meter current was full scale (zero ohms) with the test leads short-circuited.

As the circuit resistance $R_p + R_r$ is increased for measuring larger values of R_u, the circuit current decreases. Consequently, the fraction of circuit current sent through the meter branch must be increased in order for it to read full scale. The range switch, therefore, not only switches the absolute value of $R_p + R_r$ to the desired resistance but also changes relative values of R_s and R_v; and for the very high resistance range it switches in a higher battery voltage, in order to get sufficient current through the meter. A complete circuit of this type is described in Sec. 1-6 for the multimeter.

An ohmmeter is never used while the circuit is in operation, and thus there is no circuit distortion introduced by the measurement. For resistances that depend on circuit conditions, the only solution is to establish normal operating conditions, measure the voltage across the resistance, measure the current through the resistance, and calculate.

The resistance of devices that might be damaged by moderate currents cannot be measured with an ordinary ohmmeter. Such devices include meter movements and some fuses, lights, relays, tube filaments, diodes, etc. When the danger of damage exists, some other means must be devised to make the measurement.