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LABORATORY MANUAL, ELECTRICAL ENGINEERING 24.

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Part of a series of materials in the electrical engineering sequence developed under contract with the United States Office of Education, this laboratory manual provides 10 projects dealing with basic electrical instrumentation and measurement that would be appropriate for a first course. Exercises include activities involving (1) voltmeters, ammeters, (2) calibration, (3) electrical characteristics of resistive elements, (4) wheatstone bridge and resistance strain gauge, (5) the oscilloscope, (6) diodes, (7) introduction to digital computers, (8) A.C. bridge circuits, and (9) series and parallel resonance. Several appendixes contain additional information on such diverse aspects of electrical engineering as wire size, resistance color code, standard resistor values, limiting errors, AC voltmeters, resistance boxes, and safety measures. (DH)

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PH 24

EE 28

EE 24 Laboratory Manual

Electrical Engineering Department
Syracuse University

Contract No. OE 4-10-102
U.S. Office of Education

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EE24

INTRODUCTION

The purpose of this introduction is to outline the general operating policy for the EE 24 Laboratory course. However each instructor will modify or interpret this policy as he sees fit and he will give specific instructions to his class.

LABORATORY PROCEDURE

Students will work in two-man groups. There will be sufficient equipment for everyone to perform the same project at the same time. For the first half of the semester, at least, it is planned that each project will require one laboratory period. The laboratory will be open on Tuesday and Thursday evenings to permit students to spend additional time there if they so desire. Preparation prior to the laboratory class is essential if time is to be spent profitably in class. Usually this preparation will consist of becoming familiar with the problem involved and outlining a plan of attack. Students are encouraged to discuss their plans for a project with their instructors before the laboratory period.

WRITTEN WORK

All students will use a bound laboratory notebook. Students should develop and practice good laboratory habits. All entries in the notebook should be dated and initialed. All experimental results should be included. Apparatus and equipment should be identified sufficiently to allow checking any data at a later date if desired. You should include also any preliminary plans, calculations, analysis, and conclusions or observations concerning the results obtained. Data should be entered directly into the notebook. It should not be recorded on scrap paper first and then transcribed. You may line neatly through any material which you wish to be disregarded. Graph paper should be glued or stapled into the notebook when needed. In short, the material in your notebook should be presented in such a way that it would be meaningful to a knowledgeable electrical engineer.

Your notebook will be examined throughout the semester by your instructor. Also, he will ask you to submit some formal reports covering some projects.

LABORATORY EQUIPMENT

Much of the laboratory equipment includes precision components. Many of these can be damaged. Damaging equipment will result in impeding laboratory work and will cause unnecessary expense. Everyone should take precautions in his planning to assure that he does not overload and damage equipment. Again, the instructor should be consulted.

SAFETY

Serious accidents can occur while using electricity although the rate of incidents is very low. Appendix 1 by Dr. E. J. Kletsky discusses safety in the laboratory.

REFERENCES

The following texts are available in the instrument room for use in the laboratory:

Reference Data for Radio Engineers (ITT);

Electronic Instrumentation, Prensky.

The above texts plus other handbooks and Basic Electrical Measurements by Stout are available in the Engineering library.

Also your text book for EE 20 is a useful reference.

Finally, all students are encouraged to discuss any questions regarding the laboratory with their instructors.

B. Silverman
9-11-63

Project 1

VOLTMETERS AND AMMETERS

A wide variety of commercial test instruments is available which use one meter movement to measure current in several ranges, e.g. 0-1.5, 0-15 amps and voltage in several ranges e.g. 0-3, 0-150, 0-300 volts. Some of these instruments use switches to change ranges while others have no switch but instead the different ranges are obtained by plugging the instrument leads into different jacks on the instrument. This first laboratory project is an investigation of the second kind of circuit.

It is proposed that an instrument connected as shown in Fig. 1 can be used as a 0-2 volt d-c voltmeter and a 0-1 amp. d-c ammeter. The meter movement is a 0-1 ma. d-c ammeter. Your problem is to design and construct

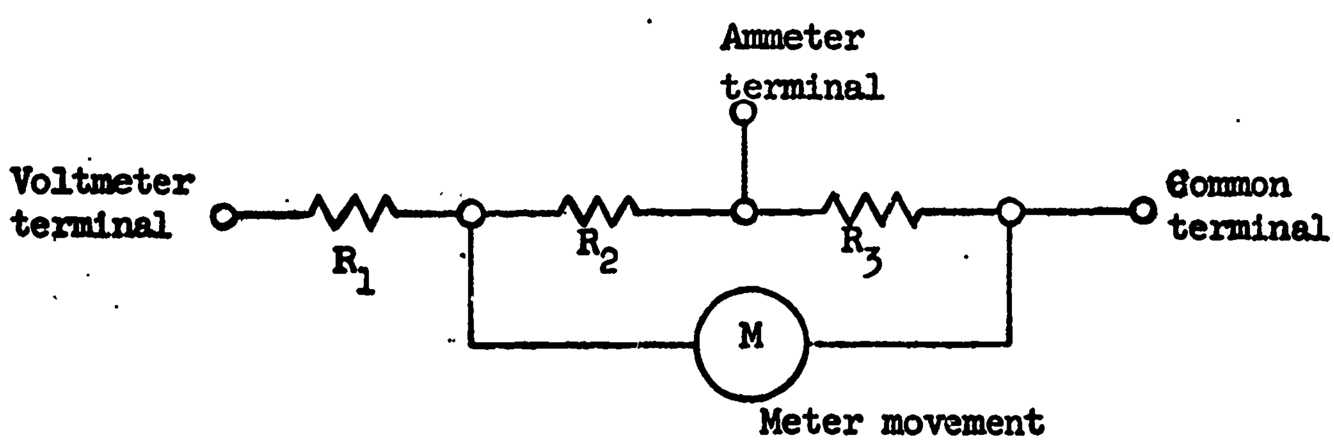


Fig. 1 Ammeter-Voltmeter Circuit

the circuit so that the voltmeter sensitivity is at least 500 ohms per volt and the voltage drop across the ammeter does not exceed 0.3 volts at full-scale current. As a reasonable objective you should try to achieve agreement within 2 per cent between your instrument and the instruments with which you compare your meter.

To facilitate the investigation we have had our shop make up mechanical assemblies as shown in Fig. 2. Each laboratory party will have one such assembly which can be plugged into one of the 0-1 ma meters from the instrument room.

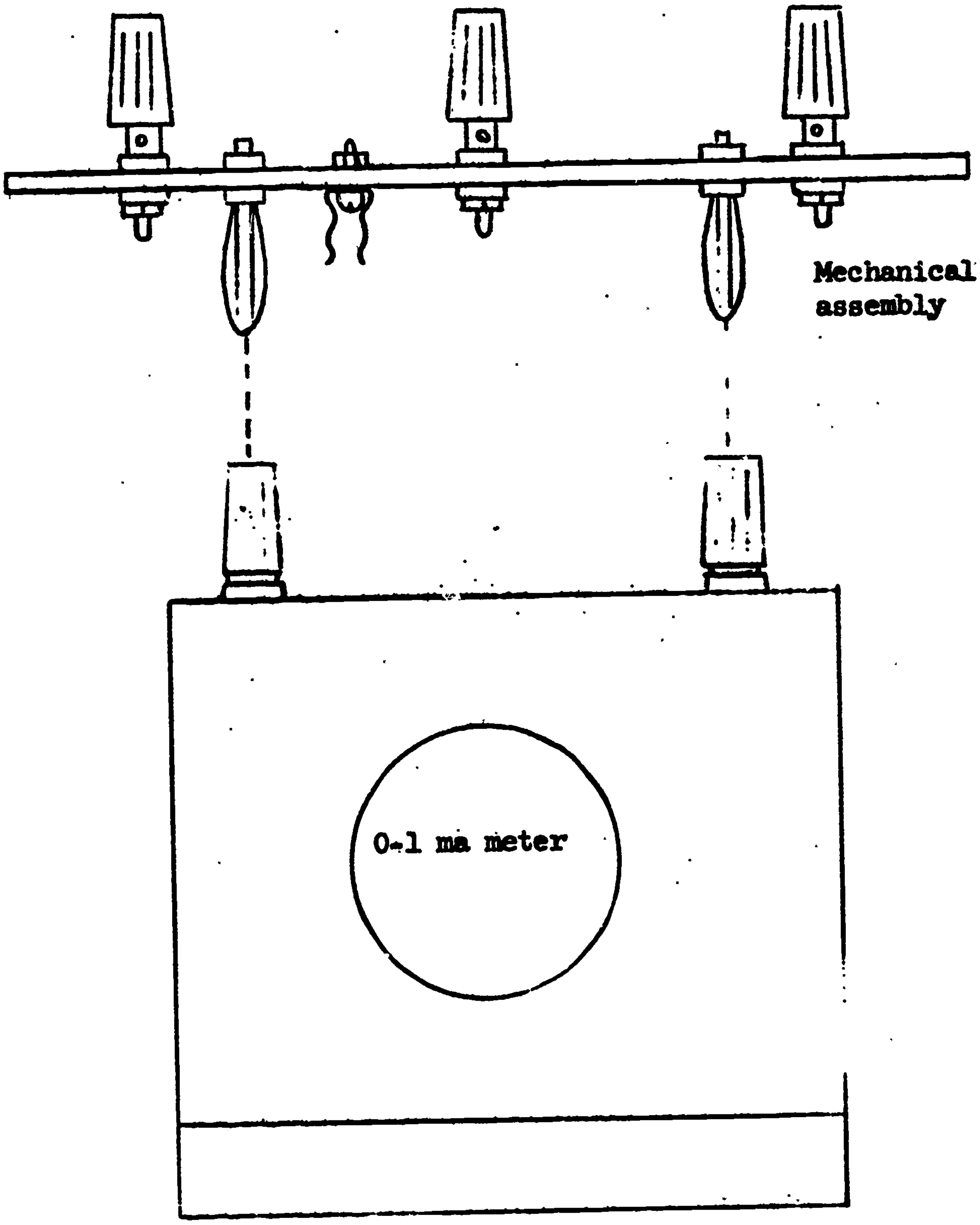


Fig. 2 The mechanical assembly is designed to plug into a 0-1 ma meter

This project is a game. The rules of the game are that only those instruments and items of material listed below can be employed to build the instrument. For example, if you need the resistance of the meter movement you should devise a way of measuring it using the available instruments and apparatus. A further rule of the game is that the available resistances have ± 10 per cent tolerance and you are expected to proceed to the finished instrument without trial and error.

In later projects you will investigate the precision and accuracy of your instrument and also use the instrument to perform engineering evaluations of other components. Hence it will be worth the effort to do careful work on this project.

Instruments and material available for this project

1 - Mechanical assembly as shown in Fig. 2

1 - Meter movement 0-1 ma.

1 - Decade resistance box 0-99,999 ohms (EICO or HEATH). See APPENDIX II for current ratings.

1 - Voltmeter 0-5 volts d-c with accuracy of about ± 3 per cent.

1 - Ammeter 0-3 amperes d-c with accuracy of about ± 3 per cent.

1 - Storage battery 6 volts.

1 - Slide-wire power resistor capable of carrying one ampere or more.

Miscellaneous carbon resistors in RMA nominal sizes (see APPENDICES III and IV) ± 10 percent tolerance.

Resistance wire (Nichrome) capable of carrying one ampere and having about 1/2 ohm per foot.

Precautions

The decade resistance boxes have current ratings that must be observed. Thus if an attempt is made to use the decade resistance to carry (say) the one ampere necessary for the ammeter the resistance box will be damaged. For the HEATH and EICO boxes, mistakes cost about $5.00 each, considering labor and components.

References

1. Stout, M. B. Basic Electrical Measurements, New York: Prentice-Hall, 1950, Chapter 17.

2. Harris, F. K. Electrical Measurements, New York: John Wiley, 1952, Chapter 5.

Project 2

VOLTMETER AND AMMETER CALIBRATION

In this project you are to prepare calibration curves for the voltmeter-ammeter constructed in Project 1, and measure the instrument resistance as a voltmeter and as an ammeter. That is, you should not make further adjustments on your instrument at this stage, but measure its characteristics.

One way of calibrating you instrument is to compare the indication of your meter with that of better-quality calibrated meters. For this purpose, several ammeters and voltmeters are available which have been calibrated by precision methods. The calibration curves for these meters are included with these instructions (see below) or supplied by your instructor. You should prepare similar calibration curves for your instrument. You will need these correction curves for some of the subsequent projects.

The voltmeter resistance is conveniently measured by a half-deflection method, e.g., using the circuit in Fig. 1. To what accuracy are you able to determine the voltmeter resistance?

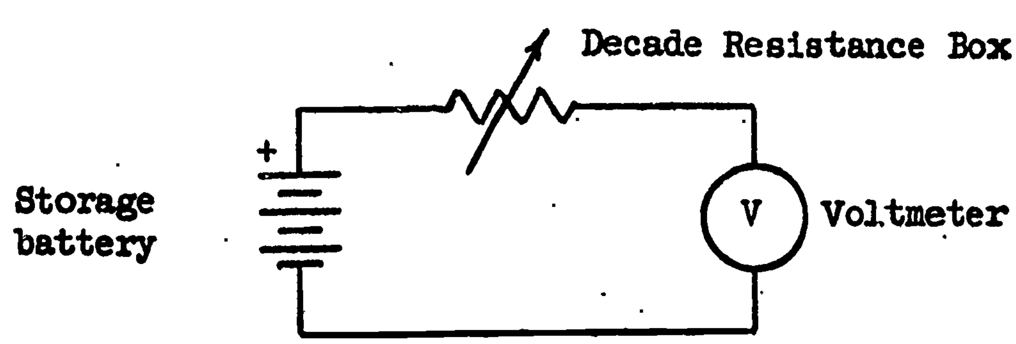


Fig. 1 Circuit for measuring voltmeter resistance

The ammeter resistance can be calculated from the voltage drop across the ammeter, as measured with the calibrated voltmeter, for full-scale ammeter deflection. What is the accuracy of your value of ammeter resistance?

Instruments and Material Available for this Project

1 - Voltmeter-ammeter built in Project 1.

1 - Precision decade resistance box 0-11,110 ohms (General Radio). See APPENDIX II for current ratings.

1 - Calibrated voltmeter with correction curve.

1 - Calibrated ammeter with correction curve.

1 - Storage battery.

1 - Slide-wire power resistor.

References

1. Stout, M. B., Basic Electrical Measurements, New York: Prentice-Hall, 1950, Pages 35-36.
2. Harris, F. K., Electrical Measurements, New York: John Wiley, 1952, Pages 6-7.

Precautions

The precision decade resistance boxes have current ratings that must be observed. Do not use a precision decade resistance box for any task where its properties are not required. For example, do not use a precision decade resistance box as a current adjuster. For the General Radio decade boxes, mistakes cost about $25 each considering labor and parts. Moreover, the inconvenience caused by a damaged decade resistor is very costly and frustrating.

VOLTMETER AND AMMETER CORRECTION CURVES

Instruments Calibrated

The following Weston type 430 instruments were specially calibrated for Project 2:

(i) D-C Voltmeters serial numbers 27388, 27396, 27397, and 27398 Correction curves for the 3-volt ranges for the four meters are shown in Fig. 1.

(ii) D-C Ammeters serial numbers 3643, 17723, and 17730. These instruments are millivoltmeters and they were calibrated with individual 3-ampere 50-millivolt shunts and individual sets of millivoltmeter leads. The same combination of millivoltmeter, standard leads and shunt should be used when making measurements. The 3-ampere ranges, from 0 to 1 ampere only, have been calibrated and the correction curves are shown in Fig. 2.

(iii) D-C Ammeter serial number 27009. This instrument has internal shunts and three ranges; however, only the 2.5-ampere range from 0 to 1 ampere and the 0.5-ampere range have been calibrated. The correction curves are shown in Fig. 2.

Voltmeter Calibration

The voltmeters of item (i) were calibrated by a conventional potentiometer method* using the following apparatus: Leeds and Northrup type K-2 potentiometer number 1 163 023; Rubicon volt box number 25307; Eppley standard cell number 604 216.

*Stout op cit p. 168.

From the correction curves of Fig. 1 it is seen that the accuracy of all the voltmeters on the 3-volt range is better than ± 0.5 per cent of full scale.

The precision of voltage measurements is limited, apparently, primarily by the user's ability to determine the position of the pointer on the scale. Without using a magnifying glass, the indication probably can be read to ± 0.005 volt or ± 1/6 per cent.

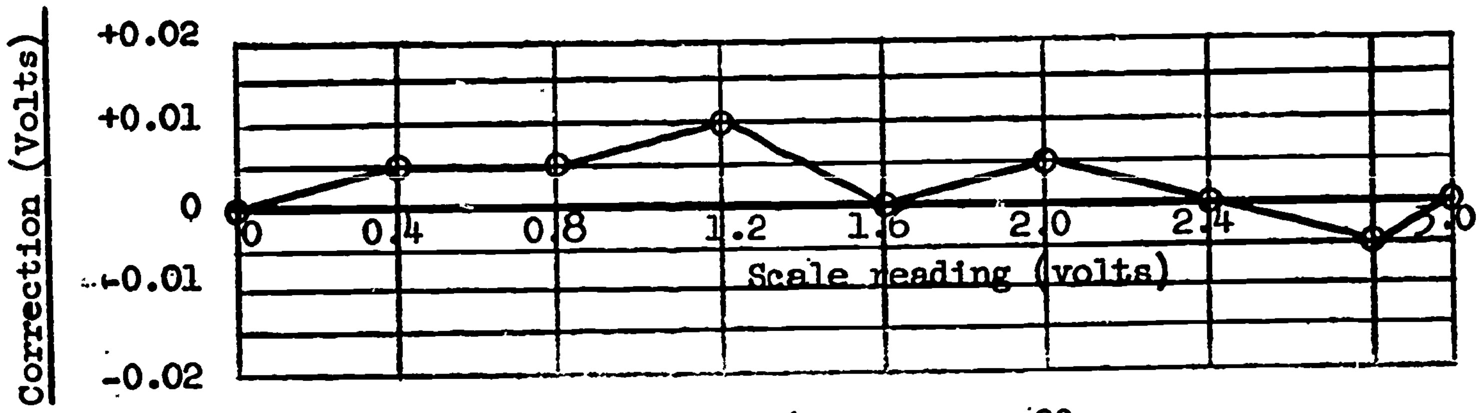
<u>Ammeter Calibration</u>

The ammeters were calibrated against the RFL set (Radio Frequency Laboratories AC-DC Instrument Calibration Standard model 829) in the Electrical Engineering Department instrument room. The RFL set readings are guaranteed to be accurate within ± 1 per cent of full scale on any range.

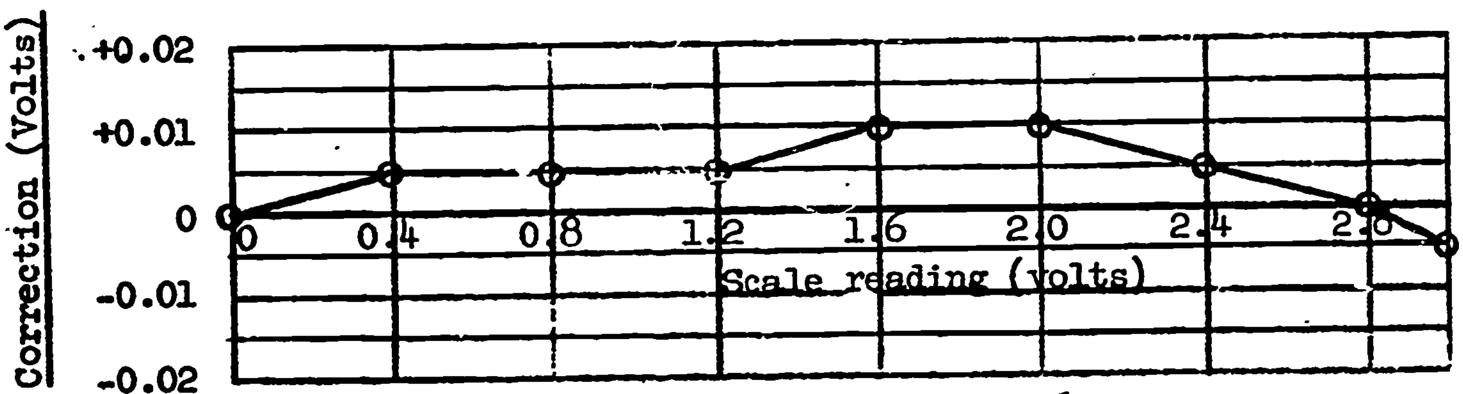
By using the 0 to 1-ampere range of the RFL set, the 0 to 1-ampere part of the 0 to 3-ampere ranges of the ammeters of item (ii) were calibrated to within ± 0.01 amperes which corresponds to ± 1/3 per cent of full scale.

The 0.5-ampere range of instrument number 270009 item (iii) was calibrated against the 0.5-ampere range of the RFL set and agreement was found to be within ± 1 per cent of full scale throughout the range, consequently no correction curve is warranted. The 0 to 1-ampere part of the 0 to 2.5-ampere range of this instrument was calibrated against the 0 to 1-ampere range of the RFL set, hence the readings are accurate to within ± 0.01 ampere or ± 0.4 per cent of full scale.

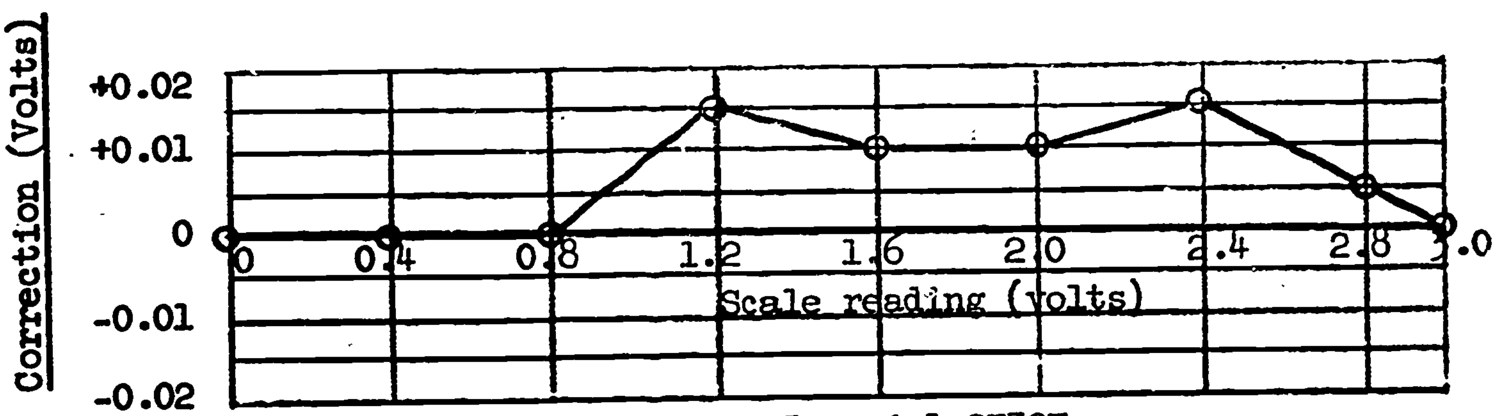
Similar limitations on precision apply to the ammeters as were mentioned above for the voltmeters.



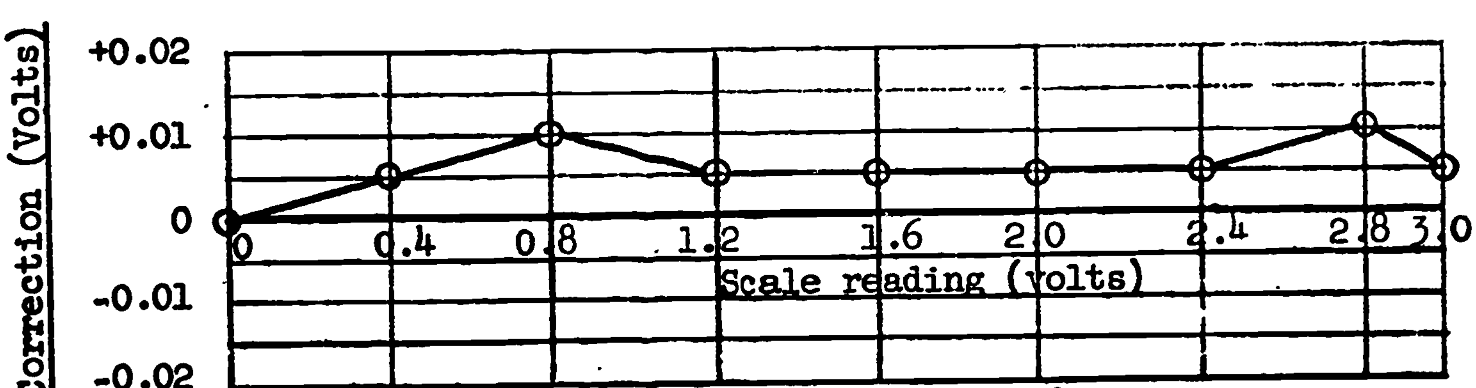
Voltmeter VD4 serial 27388



Voltmeter VD1 serial 27396

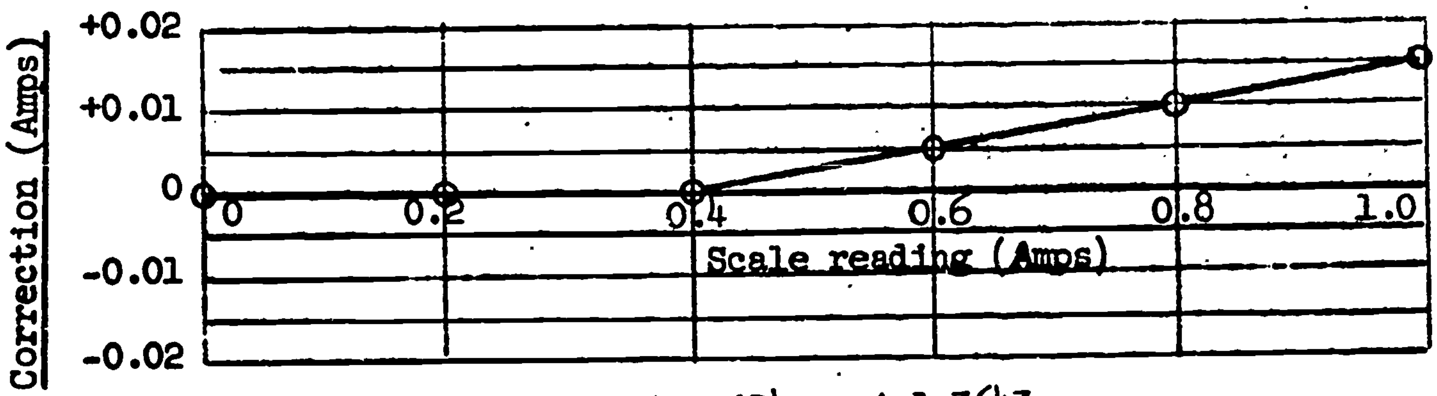


Voltmeter VD3 serial 27397

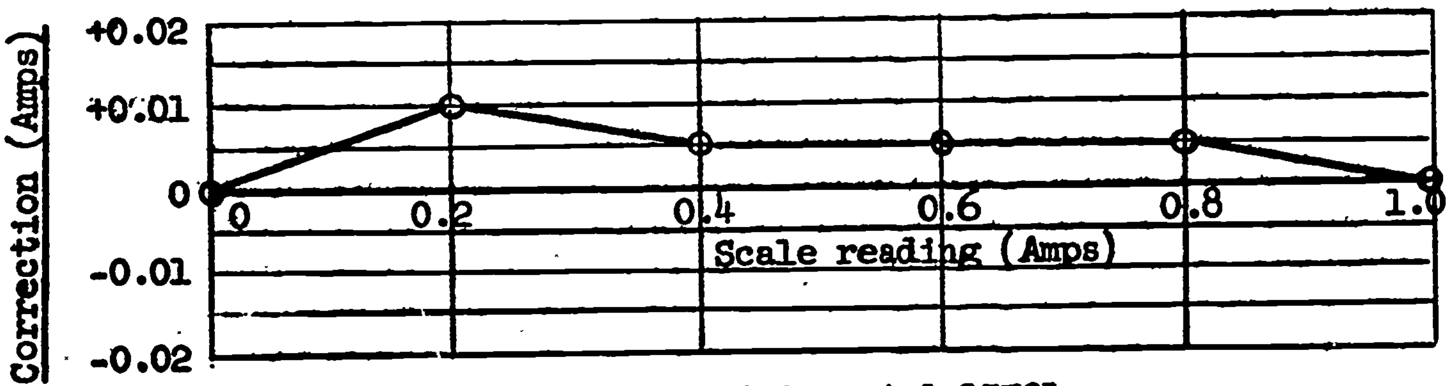


Voltmeter VD2 serial 27398

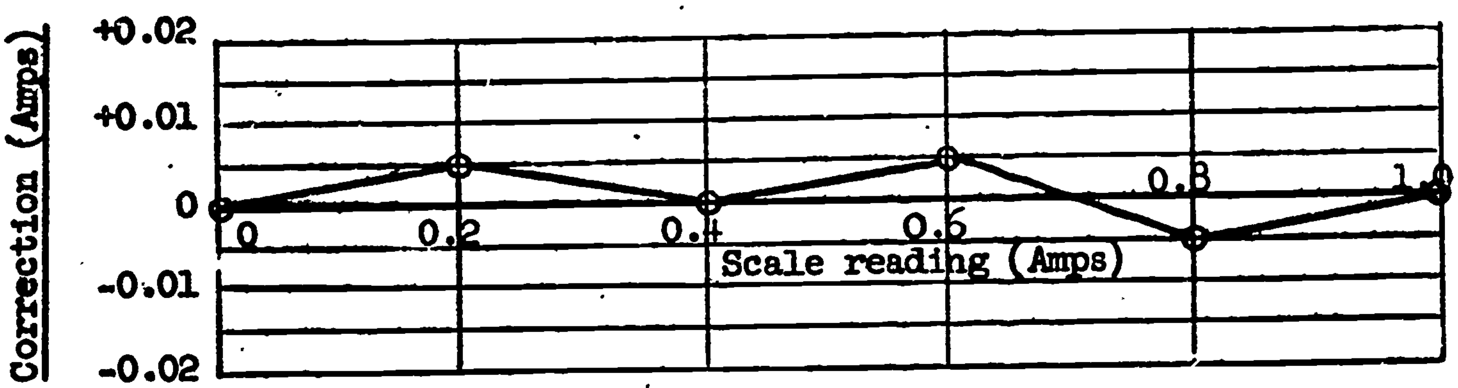
Fig. 1 Voltmeter correction curves



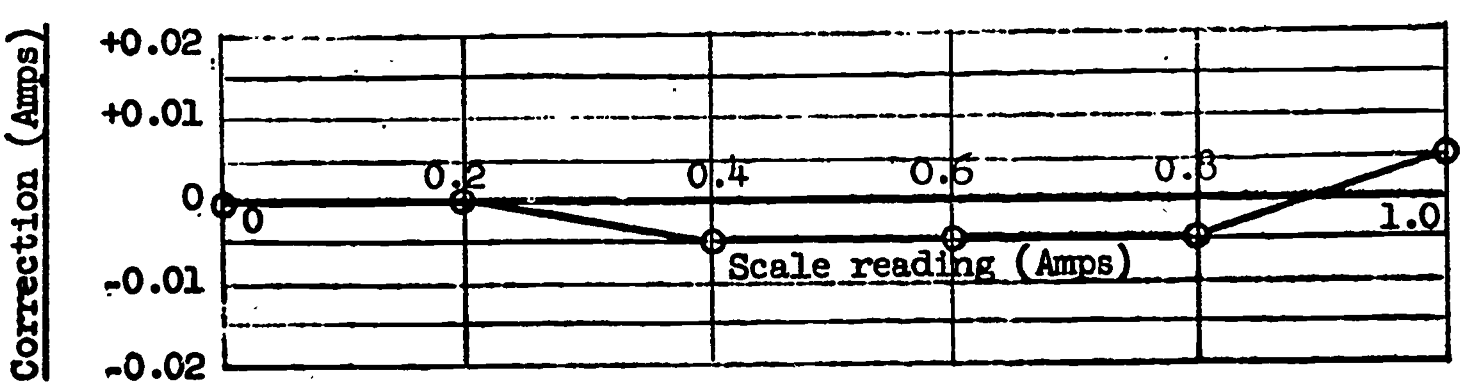
Ammeter AD4 serial 3643



Ammeter AD2 serial 17723



Ammeter AD25 serial 17730



Ammeter AD3 serial 27009

Fig. 2 Ammeter correction curves

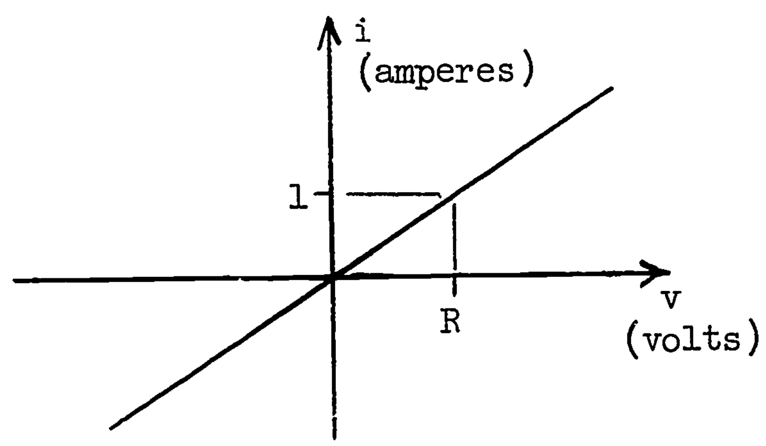
Project 3

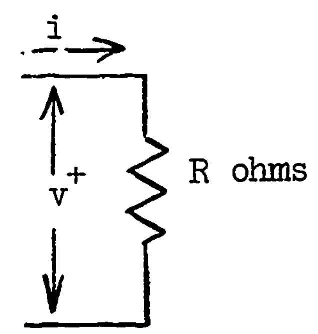
THE CURRENT-VOLTAGE CHARACTERISTICS OF SOME RESISTIVE ELEMENTS

INTRODUCTION

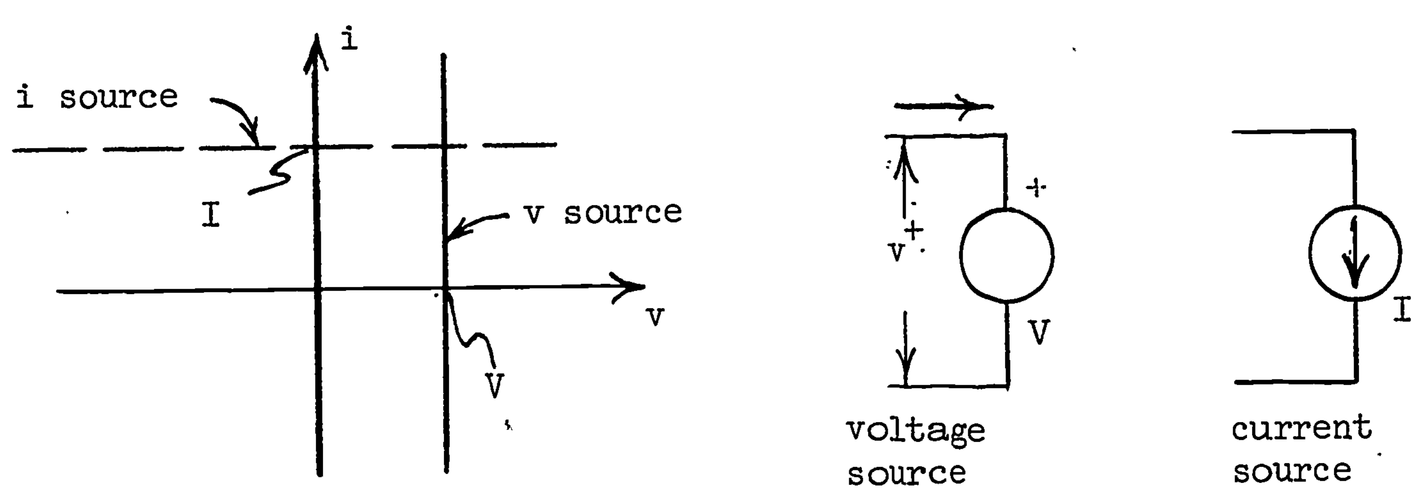
In this project you will study the relation between the current and terminal voltage (the i-v characteristic) for certain common electrical circuit elements. There will be three primary goals: 1) to practice taking accurate electrical measurements and presenting the data obtained graphically, 2) to interpret the data, wherever possible, in terms of the physical properties of the materials, measurement errors, etc. (including the identification of phenomena of unknown origin), and 3) to fit the data with linear functions and to show how closely the elements can be represented by idealized linear resistance elements, ideal voltage or current sources, and ideal diodes.

An ideal (linear) resistance is a hypothetical device having an i-v characteristic:

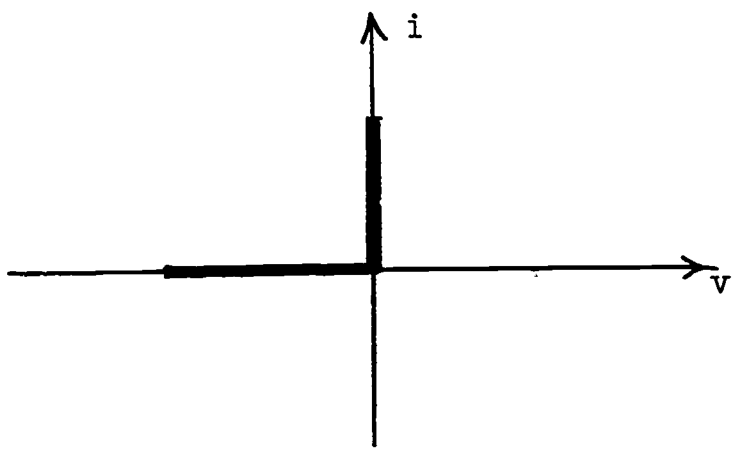


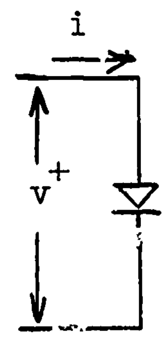


An ideal voltage [current] source has an i-v characteristic:



An ideal diode is a hypothetical circuit element that passes current freely in one direction, but not at all in the other. The i-v characteristic looks like:

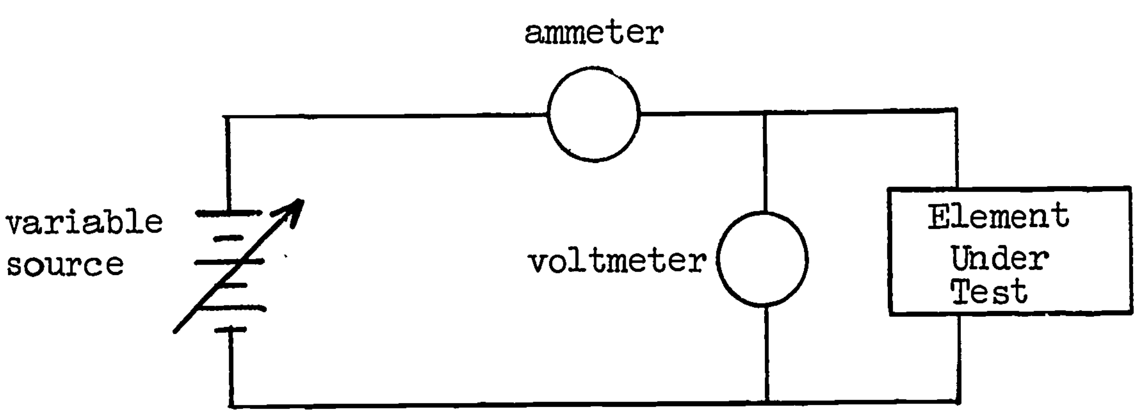


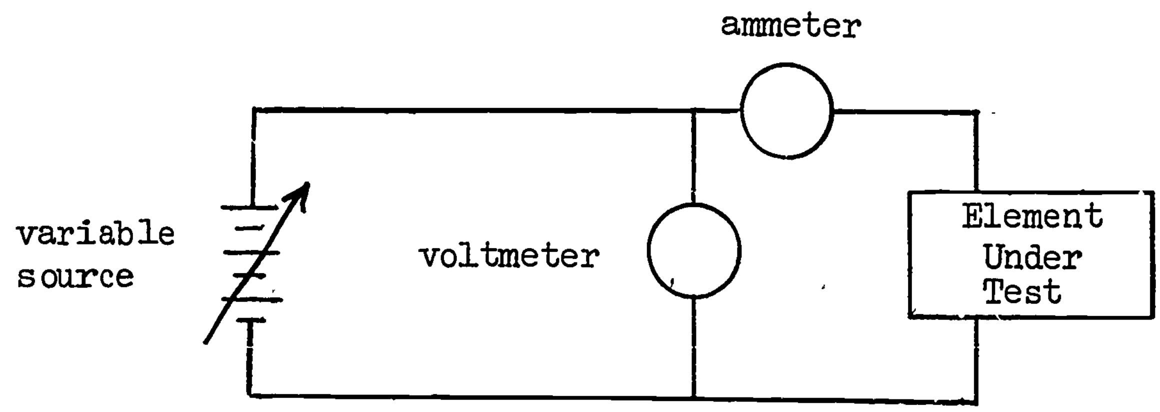


METHOD

For each element to be tested, the (dc) terminal voltage and current are to be measured simultaneously at a number of values. Unless limited by the voltage source, cover the range of voltage and current that the element can withstand without damage. You will find this range indicated on each element. (However, some groups may be asked to test certain of the elements beyond the rated dissipation). Before disconnecting each element, make a rough plot of the data (to be subsequently discarded) to make sure you have sufficient points in regions where there the plot is non-linear.

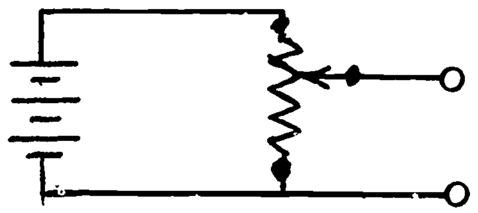
The current and voltage can be measured simultaneously by either of the following two methods:





The first method introduces an error in the current reading (due to the current through the voltmeter), and in the second method the voltage measurement is in error (due to the voltage across the ammeter). For each element, after the first reading it would be a good idea to check whether the error thus introduced is significant, and if so, whether it can be reduced by the alternate circuit.

The variable source of electrical energy can be a 6 volt storage battery and potentiometer:



However, your instructor may suggest other alternatives.

The elements to be studied will consist of:

1 composition resistor

1 incandescent lamp filament

1 dry cell

1 semiconductor diode

1 vacuum tube diode (filament power needed)

Be sure to record the identification letters of the elements actually used, and any ratings, etc., that are visible.

TO BE TURNED IN

Each student should turn in: 1) A brief description of the methodology, including circuit diagrams and identification of the instruments used. 2) i-v plots for each of the elements. For uniformity, plot v horizontally. Each plot should show both a curve fitting the data and a best-fit linear approximation. Also, for the diodes, show an expanded plot of the section of the graph where the characteristic "bends". This could be shown as an "insert" on the graph of the entire characteristic. 3) A statement of the combination of ideal elements that could be used to represent each element. 4) A discussion of any other aspects of the results that seem of interest.

Also, for at least one measurement show a computation of the percentage error due to the simultaneous connection of the voltmeter and ammeter (see above). (You must know the internal resistance of one of the meters for this.)

The Wheatstone Bridge and the Resistance Strain Gage

Objective

In this project we wish to study the Wheatstone Bridge and one of its many applications. This application is the determination of the resistance change of a resistance strain gage (RSG) which, in turn, is related to a mechanical strain.

The Resistance Strain Gage

It is convenient frequently to use electrical instrumentation to measure non-electrical physical parameters. This is possible because of the availability of suitable transducers. A transducer is a device which converts energy from one physical form to another. One of the simplest of such devices is the resistance strain gage (RSG).

Recall that the resistance of an electrical conductor is given by: $R = \rho \frac{L}{A}$.

If the conductor is strained, the resistivity, ρ, the length, L, and the cross-sectional area, A, change.

Also recall that:

$$\text{Mechanical strain} = s = \frac{\text{change in length}}{\text{total length}} = \frac{\Delta L}{L}.$$

Consequently, if a RSG is secured to a mechanical specimen which is strained, the resistance of the RSG changes. Frequently, it is more convenient to detect this change in resistance than to measure the mechanical strain directly.

If the unstrained resistance of the strain gage is R and there is a change in resistance ΔR for a strain, s, the gage factor or sensitivity, λ, is defined as:

$$\lambda = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{s}.$$

The Wheatstone Bridge

Admittedly, this change in resistance is small (perhaps of the order of one per cent). One method of determining this small change in resistance is that of comparing it with known resistances. This can be done in a Wheatstone Bridge. Such a circuit is shown in Figure 1.

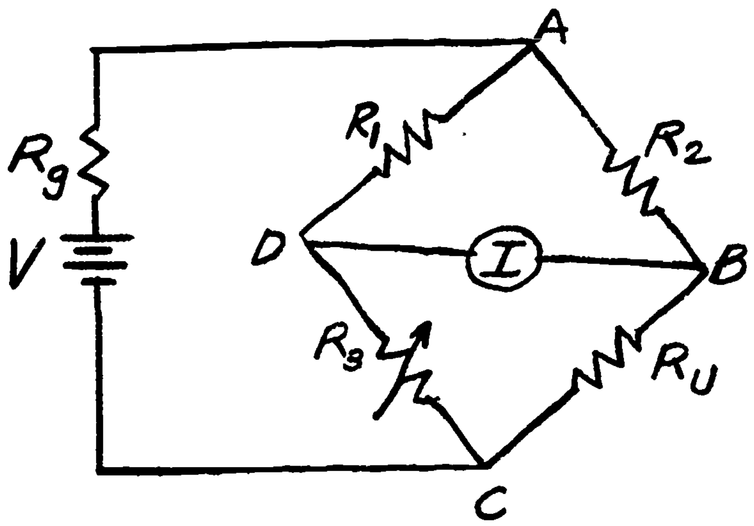


Figure 1 Wheatstone Bridge

Here the unknown resistance R_u is connected with known resistors R_1, R_2, R_3 as shown. At least one of the known resistors must be variable. If a source is connected between terminals A and C, in general, a potential difference, V_{DB}, exists between terminals D and B. Under this condition if a detector I (such as a voltmeter or ammeter) is connected between D and B, it gives an indication of this potential difference.

By adjusting the relative values of the resistors, V_{DB} can be reduced to zero. This is called the balance condition and under this condition:

$$R_1 R_u = R_2 R_3$$

or

$$R_u = \frac{R_2 R_3}{R_1}.$$

Application

1) Examine samples of some of the resistance strain gages.

2) Estimate the strain applied to the sample per revolution of the C-clamp jaw in the mechanical jig available in the laboratory.

3) Determine λ, the gage factor, for the RSG bonded to the metal sample. Do this by setting up the bridge circuit shown in Figure 1. In this circuit, let:

   V be a 6-volt dry cell;

   R_1 and R_2 are known resistors;

   R_3 is a decade resistance box;

   R_u is the RSG,

   I is a microammeter or null detector.

4) Show that when the bridge is balanced that:

$$R_1 R_u = R_2 R_3.$$

Additonal Study

5) Repeat 3) above but let V be a sinusoidal signal and I be the oscilloscope.

6) There are many practical considerations required to obtain an accurate determination of strain using strain gage measurements. For instance, part of the change of the resistance of the RSG may occur because of a change in its temperature and not because of strain. Effects of ambient changes in temperature can be eliminated by using a dummy unstrained RSG similar to the one under test as one of the other arms in the bridge. Such a circuit is shown in Figure 2.

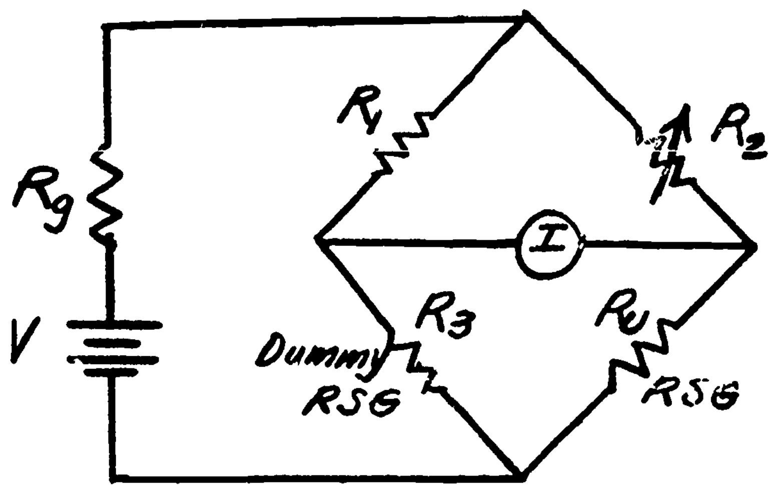


Figure 2 Temperature Compensated Strain Gage

Let R_2 correspond to the bridge balance when R_u is unstrained; and R_2' corresponds to the bridge balance when R_u' is the strained value of resistance. Show that:

$$\frac{\Delta R_u}{R_u} = \frac{R_u' - R_u}{R_u} = \lambda s = \frac{(R_2' - R_2)}{R_1} \quad \frac{R_3}{R_u}.$$

Explain why the above equation indicates that this circuit gives temperature compensation.

Using the circuit of Figure 2, determine λ again for your RSG.

7) In Figure 1 it is useful to know how V_{DB} varies as R_u deviates from the value required for bridge balance. Such an expression gives a measure of the sensitivity of the bridge.

Suppose the bridge in Figure 1 is balanced by making $R_1 = R_2 = R_3 = R_4 = R$. Also let $R_g = 0$.

Now let R_u be changed to $R_u' = (R + \Delta R)$ where $\Delta R/R \ll 1$.

Show that for this condition of unbalance, the open-circuit voltage

$$V_{DB} = V \frac{(\Delta R)}{4R}.$$

References

Stout, M.B., Basic Electrical Measurements, pages 64-80.

Prensky, S.D., Electronic Instrumentation, pages 58-67; 201-204.

Baldwain-Lima-Hamilton, Strain Gage Handbook

Project 3

CHARACTERISTICS OF LABORATORY INSTRUMENTS

I. In this laboratory period we wish to ascertain the characteristics of some of the frequently used laboratory instruments; we wish to find out about their applications, their capabilities and limitations (with regard to such things as frequency and amplitude of signals, etc.)

The equipment which we will examine includes:

1. Oscilloscopes (Tektronix, Type 503)
2. Signal Generators (Hewlett-Packard, Type 200 and others)
3. Multimeters (RCA Voltohmyst)

II. Check the accuracy of the oscilloscope sweep time scale and the horizontal and vertical input sensitivity scales.

Compare the gain and phase shift of the horizontal and vertical amplifiers. When is it important that they be matched?

Note: The frequency of the 60 cps power line voltage is maintained to within ± 0.1 cps in 60 cycles per second. This can be used as a frequency or a time standard.

The calibration voltage source available at the front panel of the oscilloscope may be used as a voltage amplitude reference.

Determine the useful frequency range of the oscilloscope.

III. Determine an equivalent circuit for the audio oscillator, H.P. 200. Calibrate its frequency and amplitude scales.

IV. Arrange two decade resistance boxes as a voltage divider at the output of a signal generator. Check the appropriateness of this arrangement for different settings of resistances and for different frequency settings of the signal generator (say 1000 cps and one megacycle). Use both the oscilloscope and the voltohmyst to measure the voltages.

V. Determine the characteristics of diodes 1N 2070. If time permits, examine the wave forms and voltage magnitudes present in the circuit used to ascertain the diode characteristics.

References: Electrical Engineering Science, Clement and Johnson, pg. 219, pp. 362-366.

Electrical Instrumentation, Prensky, Chap. 10; Appendix A, pg. 511.

EE 24 Lab Notes, Appendix VII, pg. 95,

Various Instrument Instruction Manuals

Equipment List:

Filament Transformer

Oscilloscope

Voltohmyst

Audio Oscillator

Decade Resistance Boxes (2)

Resistors, diodes, capacitors

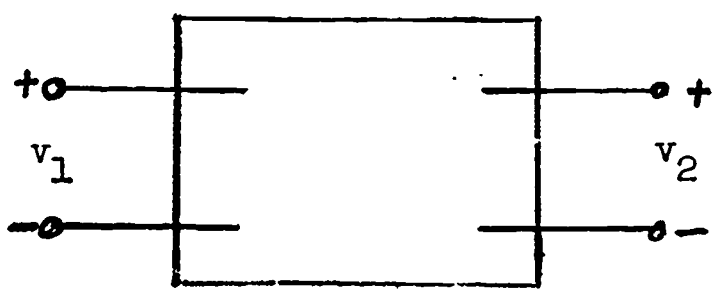
Instruction Books for various laboratory instruments

Some Circuit Properties of Diodes

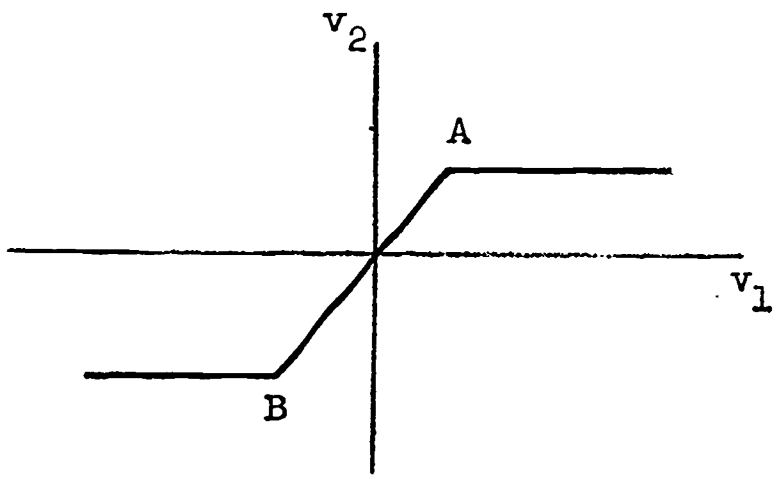
Introduction

The proper performance of an electrical system may depend on the ability of that system to constrain the amplitude of a voltage or voltages somewhere in the system to within prescribed bounds.

For instance, suppose Fig. 1,b represents the **desired transfer characteristic of the network** shown in Fig. 1,a.

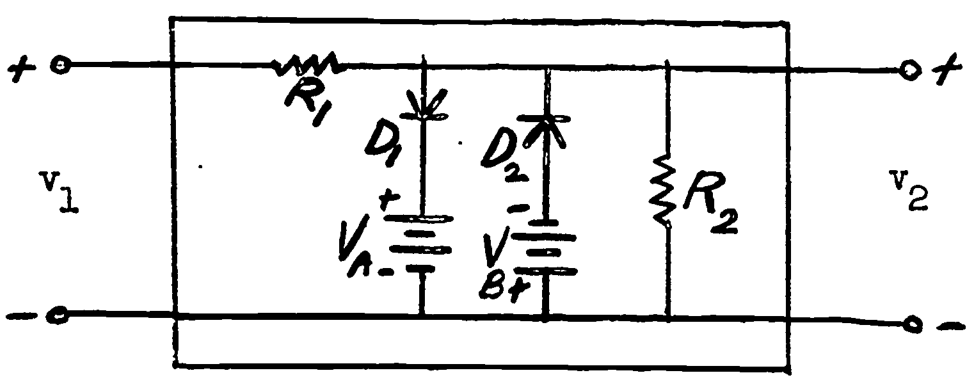


Voltage Limiter Circuit
Fig. 1,a.



Transfer characteristic
Fig. 1,b.

A network configuration capable of realizing the transfer characteristic of Fig. 1,b is shown in Fig. 2.



Voltage Limiter Circuit
Fig. 2

Problem 1.

A. Design, assemble, and evaluate the performance of the voltage limiter circuit shown in Fig. 2 having the following characteristics:

$$v_2 = 1/4\ v_1\ ; \quad |v_1| < 6 \text{ volts}$$

$$|v_2| = 1.5 \text{ volts}; \quad |v_1| \geq 6 \text{ volts}.$$

B. Suggested Procedure

1.) Analyze the circuit of Fig. 2 assuming that the diodes are ideal. This analysis should yield:

a) The breakpoints of Fig. 1,b; i.e., v_1 and v_2 at points A and B as functions of the parameters in circuit of Fig. 2.

b) The slope of the transfer characteristic between points A and B in Fig. 1,b as a function of the parameters in Fig. 2.

2.) a) Obtain the i vs. v characteristic of the diodes. (Do this by displaying this characteristic dynamically on the oscilloscope.)

b) How should R_1 and R_2 be chosen to make the transfer characteristic of Fig. 1,b. best approximate a horizontal line for $|v_1| \geq 6$ volts.

3.) a) Assemble the circuit of Fig. 2 having the specifications given in part A, above.

b) Obtain its transfer characteristic, v_2 vs v_1.

c) Also, observe $v_1(t)$ and $v_2(t)$ for $|v_1| < 6$ volts and $|v_1| > 6$ volts.

d) Compare this circuit performance with the theoretical curve of Fig. 1,b.

4.) How does the differences between the characterisitics of the physical and ideal diodes affect circuit performance.

Replace one of the diodes in your circuit with an IN 48 or equivalent. Observe the performance of this new circuit. Modify your circuit, if possible, to compensate for the non-ideal behavior of the diodes in order that specifications of part A. may be met more accurately.

Problem 2. To Be Turned In

You are employed by a manufacturer of diodes whose characteristics are equivalent to the IN 2070.

You are required to prepare an instruction sheet to explain to customers how to design a voltage limiter circuit of Fig. 2 using IN 2070's. Include design criteria to obtain any desired slope and breakpoints A and B in the transfer characteristic of Fig. 1,b.

Also, if the diode i vs. v characteristics are within ± 1% of those you measured, what accuracy can you guarantee in the transfer characteristic of the assembled voltage limiter circuit.

Instruments and Materials Available for the Project

2 Diodes, **type** IN 2070

1 Diode, type IN 48

2 Dry Cells, 1.5 volts

2 Decade Resistance Boxes

2 Potentiometers, 1000 ohms (approx.)

1 Signal Generator

1 Oscilloscope

EE 25 Project VI

AN INTRODUCTION TO THE DIGITAL COMPUTER

I. Introduction

Electronic digital computers are becoming increasingly available in all facets of modern society and, consequently, its behooves us all to learn, at least to use these computers as a computational tool. Furthermore, to the engineer, the computer offers exciting, fertile areas of research, development, and design; and lucrative opportunities in manufacturing and sales.

There are many levels of understanding which one may attain concerning computers.

First of all, one may learn to operate the computer without regard for its inner workings. This activity is called programming. It requires a knowledge of the vocabulary of the computer and (in general) of numerical analysis.

In addition, one may become familiar with the broad, general organization of the computer, often called the system design. The system design includes the specifications of the performance of the machine, i.e., capacity, speed, etc.

The logical design gives a wiring diagram of logic blocks which implement the system design.

Finally, one may study in detail the various circuits and components which perform the logic operations and meet the specifications of performance in the system design.

The engineer is in the enviable position because of his knowledge of mathematics, physics, and technology, of being able to work on all these aspects of digital computers. However, in this introductory project we shall concern ourselves with learning to use the computer as a computational tool. We shall program and solve elementary problems on the LGP-30, a desk-size, general-purpose, digital computer.

Attached is a list of programming instructions and a detailed list of operations required to use the LGP-30. Before proceeding with these, there will be a brief discussion of the general organization of a general purpose digital computer.

II. General Description

A digital computer may be defined as a device that is capable of automatically carrying out a sequence of operations on data expressed in discrete or digital (numerical) form. In what follows, computer will infer general-purpose, digital computer.

Note that the computer can handle only the numerical analyses of large classes of problems. For instance: the differential equation describing an electrical current decaying in an inductance-resistance network is:

$$L \frac{di}{dt} + Ri = 0; \qquad i = I_o \text{ at } t = 0. \tag{1}$$

Its solution is:

$$i = I_o \epsilon^{-R/L\ t} \tag{2}$$

This general functional relation shown in (2) cannot be obtained with a digital computer. However, a program can be written for the computer such that for given values of I_o and R/L the numerical values of i can be computed (and quickly!) for all specified values of t. [i.e., i(0); i(1); i(2); . . .]

Consequently, the programmed must formulate the problems to be solved in numerical form. He must know that the approximate numerical methods give solutions which converge to the exact solution. We shall not concern ourselves with these important problems at this time.

Most computers can be represented by the diagram shown in Fig. 1. The arrows indicate flow of information.

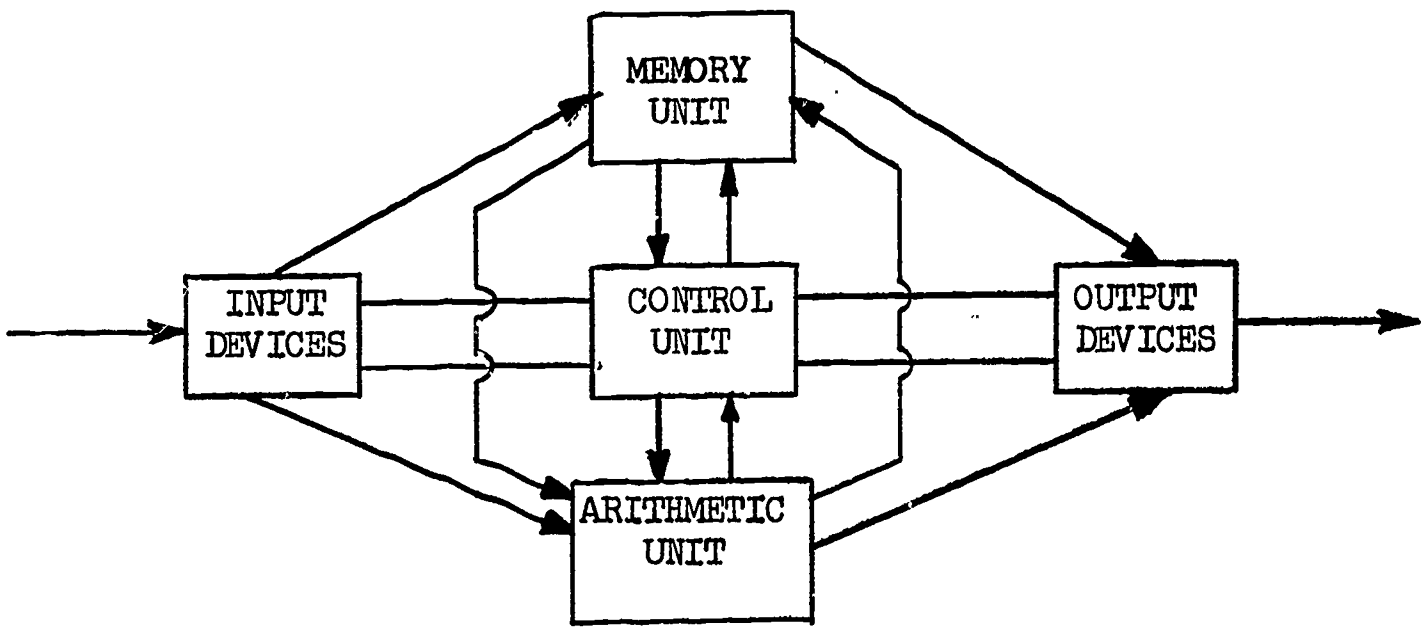


Figure 1. Block Diagram.

A. Input-Output Units

One communicates with a computer through input and output devices. In the LGP information is fed into the computer by: 1) tapes fed into a high-speed photoelectric tape reader; 2) tapes fed into the flexowriter tape reader; or 3) manually on the flexowriter.

We shall enter information by first preparing a punched tape of our program using an auxiliary flexowriter and then applying this to the tape reader.

The output will be a print-out on the typewriter. This will be controlled automatically by the program entered at the input and stored in the memory.

Precisely what can be used in a vocabulary in the program is listed following page 10 of the attached instructions. This vocabulary or list of instructions (called the G. E. Interpretive Routine) has been used to write a program for multiplying two vectors in example 1 of page 2 of the attached instructions.

Notice that the machine has no initiative, i.e., it cannot make decisions. It will do only what is included in the program. Any problem to be solved must be formulated using only the list of instructions included in the G. E. Interpretive Routine.

B. Memory Unit

These instructions plus the data are entered through one of the input devices and stored in the memory. In the LGP-30 the memory is a rotating magnetic drum. The memory has a capacity of 4096 words; each work position contains 30 binary bits plus a sign bit and a spacer bit. Each word location is identified by an address. The address and the word (or information) stored at that address should not be confused. Data are entered in floating decimal point form (see page 5 of attached instructions).

C. Arithmetic Unit

Referring still to Fig. 1, the computation is done in the arithmetic unit. In the LGP-30 this is called the accumulator or accumulator register. Actually it is a portion of the same magnetic drum which provides the memory. Data stored in the memory are brought to the accumulator as ordered by the program (stored in another portion of the memory). The data are manipulated and disposed of as ordered by the program. The results may be stored in other locations in the memory and/or printed out by the typewriter.

D. Control Unit

The control unit in Figure 1 includes the components and necessary logic circuitry (such as timing, gating, and synchronizing equipment) required to permit the computer to function properly.

III. The Problem

A. Study the attached instructions: Short Course on Use of LGP-30.

B. 1. Write a program for one of the problems in each of the two categories below. (If you have another problem of interest and it is not too complicated, you may use it.)

2. Have your instructor check your programs.

3. Run these programs on the LGP-30.

4. Check your results.

Category I

a) Given $Z = R + jX$,

Determine

$$Y = \frac{1}{R + jX} = G + jB$$

for five assumed values of R and X.

b) Given $Z = R + jX$

In the expression

$$Z = |Z|\epsilon^{j\theta}$$

Determine $|Z|$ and θ for five assumed values of R and X.

c) Given: $y = a_o + a_1X + a_2X^2 + a_3X^3$

$$= 10 + X + 2.5X^2 - 5X^3$$

Determine y when X = -1/2, 1/2, 5, 10.

Category II

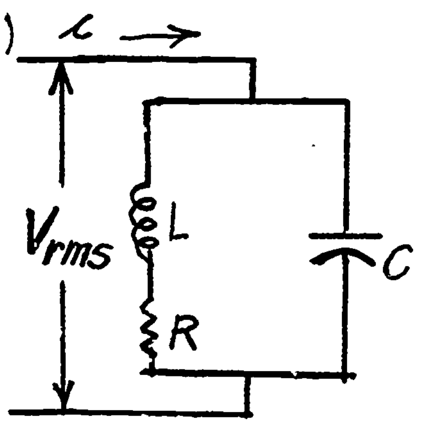
a) Given:

$$ax + by = f$$
$$cx + dy = g$$

Assume values for a, b, c, d, f, g.

Determine x.

b)



$i = 1 \sin \omega t$

$L = (10)^{-2}$ henrys

$C = (10)^{-6}$ farads

R = 5 ohms

Determine and plot V_{rms} for the following values of $\omega = 2\pi f$: 100; 1000; 5000; 7000; 9000; 10,000; 11,000; 15,000; 20,000.

B. Silverman
4/2/64

SHORT COURSE ON USE OF LGP-30

INTRODUCTION

Why you wish to join us in this venture into the workings of this small sized digital machine is unknown but, intuition says it may either be curiosity or that you have a mathematical problem that requires turning the crank far too many hours to suit your impetuous nature. Be our guest please. If you have never programmed before, you will first have to learn the rudiments of this activity before joining up with the others to find out which buttons on the computer to push and when; and if nothing happens what to do next. In fairness to all, it will be assumed that ignorance prevails but conciseness is desired.

PROGRAMMING

The LGP-30 is a digital machine that for our purposes understands commands associated with what is known as the G.E. Interpretive Routine. Suffice it to say that this method of programming simplifies the procedure for setting up a step by step program to solve a mathematical problem. The basic computational element in the computer for this routine is probably the accumulator. This is nothing more than a storage location where, for example, you can place a number you wish to add another number to or multiply by another number etc.. Numbers come to the accumulator from a magnetic drum memory. This memory is split into three useable sections: 1) Storage space for the G.E. Routine, 2) 1000 storage locations (numbered 000 - 999) for instructions in your program, and 3) 1000 storage locations (again 000 - 999) for your data. Access to the memory is provided by a typewriter (called flexowriter for some esthetic reason) and the photo reader. Other units of use to you are the counters or index registers used primarily for address modification and also an address register that holds just one address. A quick check of the programming instructions shows a typical program instruction bf 110 to have an operation bf (bring from) and an address 110. We shall shortly see why we wish to be able to modify this address.

For your ready use, the basic programming instructions are appended to this report and it is suggested that you now become familiar with them.---------So now that we are all familiar with the program instructions, let us write two short programs.

Example (1): (Simple)

Compute the Dot product of two vectors $\bar{A}$ and $\bar{B}$.

$$\bar{A} = 10.10\hat{x} - 5.00\hat{y} + 6.50\hat{z}$$

$$\bar{B} = -2.10\hat{x} + 3.10\hat{y} + .08\hat{z}$$

The program would look as follows:

```
000 bf 001
001 mb 004
002 hi 007
003 bf 002
004 mb 005
005 ad 007
006 hi 007
007 bf 003
008 mb 006
009 ad 007
010 hi 007
011 pt 007
012 ht 000
```

Here the program instructions are to be placed in instruction memory locations 000-012 and data will be placed in data memory locations 001-006 i.e. A_x in 001, A_y in 002, etc..

Notice that data location 007 is used as an auxiliary storage place in the computer.

This program is self explanatory.

Example (2): (More complicated)

This program evaluates $\sum_{n=1}^{6} n^2$

```
100 cc 000
101 bf 100
102 hi 105
103 bf 101
104 hi 102
105 bf 102
106 mb 102
107 ad 105
108 hi 105
109 bf 102
110 ad 101
111 hi 102
112 lc 005
113 tt 105
114 pr 105
115 ht 100
```

In this program the instructions are stored in memory locations 100-115.

Data is stored in locations 100 and 101 where a zero is in 100 and a one in 101.

A short explanation goes as follows: The first five instructions "initialize" the machine by clearing the counters, starting the summation at the right place, and placing a zero in the storage space of the sum. Instructions 105-108 do the squaring and the summation. 109-111 form the new "n" (that is n = n + 1). The next two instructions count the number of times the calculation has been performed, and returns the machine to 105 if it has not completed the summation. When the summation has been completed 114 prints the number and 115 halts the machine.

Suppose we take the 1st of these programs and put it on the computer. It's very simple. The G.E. codes tell the computer where to put the program and the data in memory and we're in business. So what are the G.E. codes?

G.E. CODES

There are five basic codes associated with the G.E. routine. These permit us to place or retrieve information, and to start computations.

Code	Description
1'xxxyyy'	The 1 code is used to place instructions in the machine. The xxx is the first location of the instruction and yyy the last.
2'xxxyyy'	The 2 code is used to place data in the machine. The xxx is the first location and the yyy the last.
3'xxxyyy'	This code, 3, is used to determine the contents of instruction locations xxx thru yyy.
4'xxxyyy'	This code, 4, is used to determine the contents of data locations xxx thru yyy.
5'xxx	The computer will perform the instruction in xxx and all the following instructions sequentially. At this point we could actually turn on the machine and type in our program manually but let's go for broke and make a tape.

Taping A Program

A spare typewriter is available in the LGP-30 room and can be used as follows:

1. Throw power toggle switch to on.
2. Depress Punch On lever on the typewriter.
3. Depress Tape Feed lever and allow six inches or so of tape to run out.
4. Begin to type the following

```
1'000012'
  bf001'
  mb004'
  hi007'
  bf002'
  mb005'
  ad007'
  hi007'
  bf003'
  mb006'
  ad007'
  hi007'
  pt007'
  ht000'

2'001006'
  1000000'02'
 -5000000'01'
  6500000'01'
 -2100000'01'
  3100000'01'
  8000000'-01'
```

a) All hyphens (actually a stop code to the computer) <u>must</u> be typed.

b) When an error is made, back off your tape manually one space, press <u>delete</u> lever, retype the correct symbol and continue. If the error goes unnoticed for a few symbols you must delete all symbols back to and including the error.

c) The data words are seven digit words in floating point format i.e. $N = \pm F \times 10^{\pm E}$

$$N = xxxxxxx \pm yy$$

$$xxxxxxx = F$$

$$yy = E$$

The + sign does not have to be typed.

5. A carriage return on the typewriter may be pushed at any time after completion of the stop code at the end of the instruction or data word.

6. <u>Caution</u>: Do not use the space bar between an <u>operation</u> and an address. Use a <u>zero</u> and not an "Oh" = O. A <u>one</u> is a small "ℓ".

7. When finished push tape feed, let a few inches run out and then tear off. You are now ready to fire up the computer.

A. <u>Readying the Computer</u> (If the computer is on, proceed to B)

   1. <u>Typewriter</u> - throw the power toggle switch to <u>on</u>.

   2. <u>Photo Reader</u> - push <u>Reader Power</u> button.

   3. <u>Computer Console</u> - depress sequentially <u>One Operation</u> button, <u>Manual Input</u> button, <u>Operate</u> button and <u>Power On</u> button.

When this is done, wait for several minutes until the lights on the console buttons <u>Standby</u> and <u>Standby to Operate</u> go out and then proceed.

B. Insertion of the G.E. Routine

1. Photo Reader - turn Input Switch to typewriter.

2. Computer Console - depress Manual Input button.

3. Typewriter - turn connect switch to off and make sure that all eight control levers are up.

4. Typewriter - Insert GE 10-4 Bootstrap in the front tape feed off the typewriter (printing up).

5. Typewriter - push Start Read lever.
(word manual is typed)

6. Typewriter - push Start Read lever again.

7. Computer Console - depress Fill Instruction button.

8. Typewriter - push Start Read lever.

9. Computer Console - depress sequentially One Operation, Execute Instruction and Manual Input.

10. Repeat steps 6, 7, 8 and 9 until word Normal is typed (about six repetitions).

11. Typewriter - turn connect switch to on and push Manual Input lever.

12. Computer Console - Make sure Breakpoint 32 is down (Light on) (other breakpoints immaterial).

13. Photo Reader - load G.E. Interpretive routine (printing down). Turn input switch to Reader.

14. Computer Console - depress sequentially One Operation, Normal and Start.

15. If the tape does not go in - repeat from step 1.

16. When tape is in, computer is ready for your program.

17. Depress breakpoints 4, 8 and 16 and let breakpoint 32 come up.

C. Insertion of Program

The program may be loaded through the photo reader or through the typewriter. For simplicity we will insert the program through the typewriter.

1. Typewriter - connect switch is on and the Manual Input lever is the only lever depressed.

2. Load program in front feed.

3. Computer Console - depress sequentially One Operation, Clear, Counter, Normal and Start.

4. Typewriter - raise Manual Input lever and the program will be read in. Depress the Manual Input lever at the end of the tape. Do not let the tail end pass through the reader.

Initiating Computation

At this stage you are ready to make the computer compute. This is done as follows:

1. Typewriter - depress Manual Input lever.

2. Computer Console - Do the "four button sequence" One Operation, Clear Counter, Normal, Start.

3. Light will come on on the typewriter.

4. Type in the code 5 xxx. Depress the Start Compute lever wherever a "stop code" belongs. xxx is the first location of the program, e.g. in the example 000.

5. Sit back and pray until your answers come out.

TROUBLE SHOOTING

A program may not always run the first time it is tried. Many times this may be due to an incorrect operation, which will be signaled by the computer printing an error code, or a programming error. One very effective method of determining the cause of errors is to trace the program through step by step. If the transfer control button on the computer console is depressed and the program started using the "5" code, the computer will type out the operations step by step. The transfer control button may be depressed any time in the operation, thus if an error occurs late in the operation we may let the program run for several minutes at high speed and then depress the transfer control. In this mode of operation, the computer will print out the location of the instruction, the instruction, the result of the instruction, (the number now in the accumulator), and the number used to perform the operation.

Another aid is "breakpoint 4". This will perform one operation every time the start compute button is depressed. This may be used in conjunction with the transfer control button to enable the operator to analize the results of the print out.

A wrong instruction may be corrected by; 1) going through the four button sequence, 2) typing 1'xxx', xxx the location of the wrong instruction, 3) typing the corrected instruction. If this [illegible] program performs correctly, it may be punched out to use later by using the instructions on "Tape Readout from Memory".

Tape Readout From Memory

Information stored on the drum may be punched out on tape to be used later as the input. Either the flexowriter or the high speed punch may be used to produce the tape. The input selector must be on the typewriter; the output selector on either typewriter or punch, depending on which one you prefer to use; and the transfer control button on the console must be depressed. If the flexowriter is used the punch switch should be depressed. A leader of a least one foot should be allowed, by pressing the tape feed on the appropriate device, before punching begins.

To punch instructions, a (3) should be typed followed by depressing the typewriter start compute lever. A (3), a space, then a (1′) will be punched. The first and last address must be typed followed by depressing the start compute lever. To punch out data stored on the drum a (4) is typed instead of a (3). The operation is the same. When finished the operator should allow for about another foot of tape.

Making a Tape From A Tape

If you have a taped program that you wish to reproduce, use the spare typewriter as follows:

1. Depress Punch On and Conditional Stop levers (If conditional stop is up only one instruction will be read at a time).

2. Load the tape to be copied in the front feed.

3. Press Tape Feed lever and allow about one foot of tape to come out.

4. Push carriage return on the typewriter.

5. Push Start Read lever and wait for the copy to be made.

6. When finished push Stop Read lever (do so before the tail end of the tape to be copied runs out).

7. Press Tape Feed lever and let a few inches run out before tearing off.

Robert Herman and James Rudolph

III. PROGRAMMING INSTRUCTIONS

This section contains a detailed description of the programming instructions for this routine. Frequently, a small illustrative program will follow these descriptions. For each instruction, the following information will be given:

1) The code for the operation

2) The address portion:

Either a) ppp - 3-digit instruction location

b) ddd - 3-digit data location

c) 000 - Operation does not utilize a memory location.

d) 00n - A numerical value, n.

Later, a concise summary of all operational codes will be given.

OPERATION	ADDRESS	INTERPRETATION
A. Arithmetic Instructions		
ad	ddd	Add. Adds the number in data location ddd to the number in the accumulator and places their sum in the accumulator.
st	ddd	Subtract. Subtracts the number in data location ddd from the number in the accumulator and places their difference in the accumulator.
mb	ddd	Multiply By. Multiplies the number in data location ddd by the number in the accumulator and places their product in the accumulator.
db	ddd	Divide By. Divides the number in the accumulator by the number in data location ddd and places their quotient in the accumulator.
B. Function Evaluation Instructions		
ab	ddd	Absolute Value. Replaces the number in the accumulator by the absolute value of the

		number in data location ddd. The sign of the number in ddd remains unaltered.
nv	ddd	Negative Value. Replaces the number in the accumulator by the negative of the absolute value of the number in data location ddd. The sign of the number in ddd remains unaltered.
as	ddd	Alter Sign. Replaces the number in the accumulator by the negative of the number in data location ddd. The sign of the number in ddd remains unaltered.
sr	ddd	Square Root. Replaces the number in the accumulator with the square root of the number in data location ddd.
sn	ddd	Sine (Radian). Replaces the number in the accumulator with the sine of the number in data location ddd. The number in ddd must be expressed in radians.
di	ddd	Sine (Degree). Replaces the number in the accumulator with the sine of the number in data location ddd. The number in ddd must be expressed in degrees*.
cn	ddd	Cosine (Radian). Replaces the number in the accumulator with the cosine of the number in data location ddd. The number in ddd must be expressed in radians.
do	ddd	Cosine (Degree). Replaces the number in the accumulator with the cosine of the number in data location ddd. The number in ddd must be expressed in degrees*.
at	ddd	Arc Tangent (Radian). Replaces the number in the accumulator with the angle whose tangent is in data location ddd. The angle is expressed in radians.
ez	ddd	Arc Tangent (Degree). Replaces the number in the accumulator with the angle whose tangent is in data location ddd. The angle is expressed in degrees*.
ln	ddd	Natural Log. Replaces the number in the accumulator with the logarithm to the base e of the number in data location ddd.

*Fractions of a degree are expressed decimally, not in minutes and seconds.

lz	ddd	Log (Base 10). Replaces the number in the accumulator with the logarithm to the base 10 of the number in data location ddd.
ex	ddd	Exponent (Base e). Replaces the number in the accumulator with e^x, where x is the number in data location ddd.
zx	ddd	Exponent (Base 10). Replaces the number in the accumulator with 10^x, where x is the number in data location ddd.
vf	ddd	Replaces the number in the accumulator with the fractional part of the number in ddd. The fractional part of a number is defined as the difference between that number and the next smallest integer. Thus, the fractional part is always positive. (i.e., the fractional part of 8.7 is 0.7 and the fractional part of -8.7 is 0.3)

Notes:

1. Execution of the instructions listed above leaves the number in data location ddd unaltered.

2. The address portion of the arithmetic and the functio uation instructions may also read "acc" (the accumulator), in which case the rd "accumulator" replaces the words "data location ddd" in the interpretation.

C. Moving Instructions

bf	ddd	Bring From. Replaces the number in the accumulator with the number in data location ddd. The number in ddd remains unaltered.
hi	ddd	Hold In. Stores the number in the accumulator in data location ddd. The number in the accumulator remains unaltered.

EXAMPLE I

Consider a program to determine y where $y = \frac{\sin x}{1 + \cos x}$. Assume that "x" in degrees is stored in data location 101 and "1" is in location 103. The result is stored in data location 200. The instructions are stored sequentially, starting in instruction location 300.

300	do101	Replace the number in the accumulator by the cosine of "x."
301	ad103	"1" is added to cosine x. "1 + cos x" in accumulator.
302	hi104	"1 + cos x" in data location 104.
303	di101	Replace the number in the accumulator by the sine of "x."
304	db104	Divide "sin x" by "1 + cos x" which is stored in memory location 104.
305	hi200	HOLD y in memory location 200.

a. Logical Instructions

This interpretive routine executes instructions sequentially in the instruction memory. For example, once the execution of the instruction in location 300 has been completed, execution of the instruction in location 301 will be initiated; then 302, etc. In many cases, this feature is undesirable. To repeat the same sequence of steps over and over would often be very lengthy and could exceed the capacity of the instruction memory. Also, a problem might be divided into two or more parts and the programs for these parts stored in different places in the instruction memory. Sequential operation alone is not adequate to fill these and other needs. Thus, logical instructions have been included.

There are two unconditional transfer instructions. Explanation of the instruction "transfer to control" has been deferred until later. (See page 30.)

The instruction "ttppp" transfers operation to instruction location ppp, executes the instruction stored there, and continues sequentially; (ppp + 1), (ppp + 2), etc.

Transfer instructions may also be used to vary the sequence of executing a program, depending on the numerical value of the quantity in the accumulator. These instructions are referred to as conditional transfers.

tn	ppp	Transfer on Negative. Executes the instruction in instruction location ppp if the number in the accumulator is negative. A positive number in the accumulator causes the next consecutive instruction to be executed.
tz	ppp	Transfer on Zero. Executes the instruction in instruction location ppp if the number in the accumulator is zero. A nonzero number in the accumulator causes the next consecutive instruction to be executed.
xn	ppp	Transfer on Negative Exponent. Executes the instruction in location ppp if the exponent of the number in the accumulator is negative. A positive exponent causes the next consecutive instruction to be executed.

b. Miscellaneous Instructions

ht	000	Halt. Computation halts. If the "start button" on the console is depressed, computation begins with the instruction immediately following the halt order.
no	000	No Operation. Control proceeds to the instruction in the next instruction location. This operation is likely to occur when a superfluous instruction has been deleted from a program.

EXAMPLE II.

Again, consider the program to determine y where $y = \frac{\sin x}{1 + \cos x}$. If x (angle in degrees) in equal to 180, the above equation cannot be solved. Therefore, a test is necessary to determine when the denominator is equal to zero. As before, "x" is stored in data location 101 and "1" in location 103. The result is stored in data location 200. The instructions are stored sequentially, starting in instruction location 300.

300	do101	Replace the number in the accumulator by the cosine of x.
301	ad103	"1" is added to cosine x. "1 + cos x" in accumulator.
302	tz307	If $1 + \cos x = 0$, transfer to instruction location 307, where computation halts. If $1 + \cos x \neq 0$, the next instruction is executed.
303	hi104	"1 + cos x" in data location 104.
304	di101	Replace the number in the accumulator by the sine of x.
305	db104	Divide "sine x" by "1 + cos x" which is stored in memory location 104.
306	hi200	Hold y in memory location 200.
307	ht000	Computation halts.

D. Address Modification

Repetition is a characteristic of most problems handled on automatic computers. In some instances, a repetitive process is easily programmed using only conditional transfer instructions. More often, some of the instructions to be repeated require slight modification each time they are executed. To facilitate programming of this nature, two types of address modification are available, effective and actual modification. It is this phase of programming which utilizes the address register an the nine counter registers.

1. Effective Modification

The introduction states "all instructions are composed of at least two parts, an operation and an address." One way to modify the address of any instruction is to add a third part to the instruction, namely, a counter register number. Nine registers are available. If an instruction is preceded by a register number (1 to 9), the address used for execution is the sum of the address of the instruction and the contents of the indicated counter register. If counter register three, for example, contains the number 7, the instruction 3bf120, when executed, brings the number in data location 127 into the accumulator. The address is modified only for execution purposes. In memory, it remains 3bf120.

An instruction can include as many as three counter register numbers preceding the operation. A number in the first position to the left of the operation code adds the number in that counter register to the address. A number in the second position to the left adds to the address ten times the number in that counter register. A number in the third position adds one hundred times the number in the register to the address. This augmented address must, of course, always be less than one thousand.

For example, suppose:

Counter register one contains a 3

Counter register two contains a 4

Counter register three contains a 2

1. 123bf100 would bring into the accumulator the number in data location 442.

Address	100
Register 3	2
10 times register 2	40
100 times register 1	300
	442

2. 33bf100 would bring into the accumulator the number in data location 122.

Address	100
Register 3	2
10 times register 3	20
	122

3. 200bf300 would bring into the accumulator the number in data location 700.

Address	300
100 times register 2	400
	700

There are three instructions which modify the contents of a counter register.

cc	000	Clear Counters. Clears all counter registers to zero.
ha	00n	Hold Address Register. Replaces the contents of the counter register "n" with the address stored in the address register. The address remains unaltered in the address register.
nc	xxx	Compare Counters. Compares the number in counter register "n" to the number xxx. If the number in register "n" is less than xxx, one is added to the number in counter register "n" and the first successive instruction is executed. If the number in "n" is equal to or greater than xxx, then register "n" is reset to zero and the second successive instruction is executed.

Consider three instructions in locations 100, 101, 102.

100	3c007
101	tt050
102	ht000

In executing the instruction in location 100, the number in counter register three is compared to the number 7. If it is less than 7, one is added to the number in register three and control is transferred to the instruction in location 050. If the number in register three equals or is greater than 7, then register three is reset to zero and computation halts.

Counter registers are also useful when a process is to be repeated a definite number of times. Initially, the counter register is set to zero, not one. Therefore, to repeat a sequence of instructions y times, the address portion of nc xxx instruction should be set to (y - 1).

When counter registers are used in a program, the cc000 instruction should always appear at the beginning of the program.

The advantages of this method of address modification are simplicity of use and the fact that the instructions remain unchanged in memory.

2. Actual Address Modification

Utilization of the address register is necessary to actually change the address portion of an instruction in the instruction memory. This register might well be called an address accumulator. It is the computational element where an address can be stored, incremented, or compared to another address.

The following instructions utilize this register.

fr	ppp	Fill Register. Replaces the contents of the address register with the address portion of the instruction stored in ppp. The address of the instruction in ppp remains unaltered.
fa	00n	Fill Address Register. Replaces the contents of the address register with the contents of counter register "n". The number in "n" remains unaltered.
ha	00n	See page 11.
hr	ppp	Hold Register. Replaces the address portion of the instruction in location ppp with the contents of the address register. The contents of the address register remain unaltered.
ir	00n	Increase Register. Adds the number "n" to the contents of the address register and places the sum in the register. ($0 < n \leq 999$)
rr	00n	Reduce Register. Subtracts the number "n" from the contents of the address register and places the difference in the address register. ($0 < n \leq 999$)

rv	00n	Compare Register Value. Compare the number "n" to the contents of the address register. If the contents of the register are less than "n", the first successive instruction is executed. If the contents of the register are equal to or greater than "n" the second successive instruction is executed.

There is one other instruction that results in actual address modification. This instruction, however, does not use the address register.

sa	ppp	Set Address. Adds two to the location of the instruction being executed and places this number in the address portion of the instruction in ppp.

This instruction is used in setting a subroutine exit.

The program for a problem involving the repetition of a process should consist of four parts.

1. Initialization
   - a. Counter registers are set to zero.
   - b. Any addresses which will actually be modified are set to the initial value.

   [It is important that all initializing be done by the program and not solely by loading.]
2. Execution

   The actual mathematical operations are performed.
3. Modification

   Address modification, whether actual or effective, is performed.
4. Test

   Determine whether the process has been executed the desired number of times. If not, control is transferred back to 2 above.

Three Input-Output Instructions Are Available:

id	ddd	<u>Input Data</u> - Enters one floating point number through the Flexowriter into the accumulator and replaces the contents of the accumulator and data location ddd with this number.
pt	ddd	<u>Print and Tab</u> - The contents of the accumulator are replaced by the number in data location ddd, the number is printed and the carriage moves to the right on column. The number remains in both the accumulator and location ddd.
pr	ddd	<u>Print and Return</u> - The same as print and tab, except that after the number is printed, the carriage returns to column one and up spaces.
cr	oon	<u>Carriage Return</u> - Returns the carriage to the left-hand column and up spaces "n" times. cr001' up spaces once.
ct	oon	<u>Carriage Tab</u> - Tabulates the carriage "n" times. ct002 tabs twice.

Electrical Engineering Department

EE-24

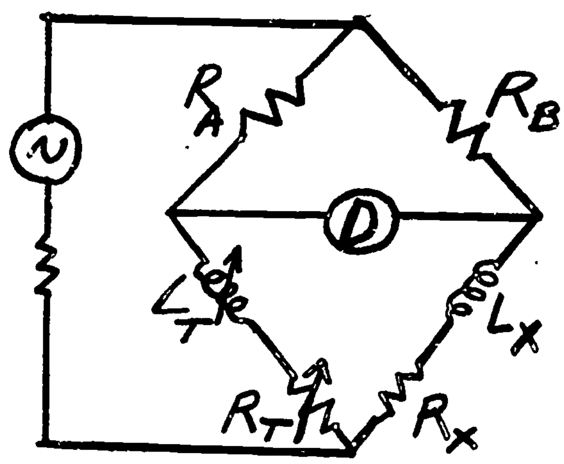
Project 7

A. C. Bridge Circuits

I. Bridge circuits give useful methods for determining values of circuit components. In such a measurement the precision and accuracy are limited by the precision and accuracy of the bridge components.

II. Assemble the bridge circuit shown in Fig. 1 and determine the value of L_x and R_x for the linear inductor furnished by the Instructor.

III. Using the same components as those of Fig. 1 for known elements, determine the value of the capacitor furnished by the Instructor.



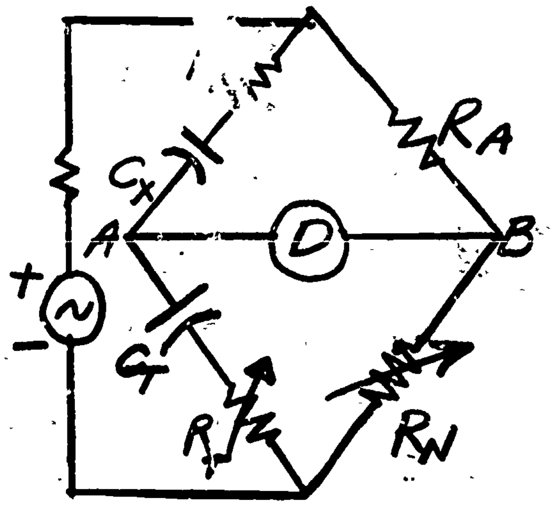
R_A and R_B are fixed resistors.
R_T is a decade resistance box.
L_T is a decade inductance box.

Fig. 1

IV. The bridge configuration shown in Fig. 1 is a straightforward extension of the d.c. Wheatstone Bridge used in Project 5.

It is natural to ask if there are other parameter arrangements which also permit a balance; and if so, what are the advantages and disadvantages of a particular arrangement. For instance: 1) Can an a c bridge be built whose balance is independent of frequency? 2) Can inductor and capacitor values both be determined with a bridge composed of only capacitors and resistors? 3) What limits the magnitude of the impedance which can be measured, etc.

For example, consider the bridge circuits shown in Figs. 2 and 3. Note that the circuit of Fig. 3 (except for the unknown) is obtained by rearranging (switching) the elements of the circuit in Fig. 2.



$v = V \sin \omega t$; ω is variable.

R_A and C_T are fixed.

R_N and R_T are known variable resistors.

R_x and C_x are unknown to be determined.

Fig. 2

The balance condition is $V_{AB} = 0$.

A.) Determine C_x and R_x as a function of the bridge parameter at balance. <u>This should be done prior to coming to class</u>.

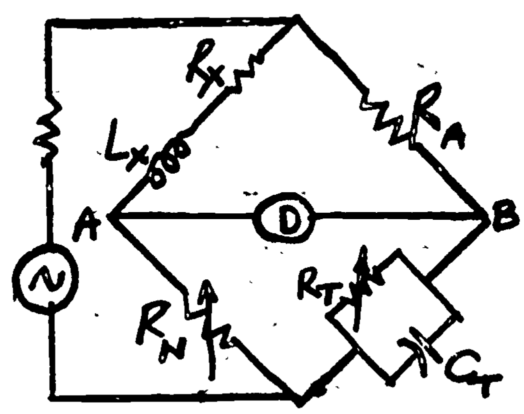


Fig. 3

B.) In Fig. 3, determine L_x and R_x in terms of the known parameter at balance; i.e., when $V_{AB} = 0$. <u>This should be done prior to coming to class</u>.

In both circuits note that:

1.) No inductors are used.

2.) Only resistors, R_N and R_T, are varied.

3.) The balance is independent of frequency. (Is this true in practice?)

V. Determine the range of R, L, and C which can be measured by the General Radio 1650 Impedance bridge.

VI. Sketch the circuit arrangements for G. R. 1650 when it measures R, L-R and C-R.

VII. Derive the expression for the unknown for each circuit arrangement in VI.

VIII. Connect in series the inductor and capacitor which have been used as unknowns. Determine the impedance of this arrangement as a function of frequency. Include its resonant frequency. Use the G. R. 1650 and check several points using your assembled bridge. Plot $|z|$ versus frequency.

IX. Compare the performance of the G. R. 1650 Impedance Bridge with that of the Wheatstone Bridge used in Project 5 and with the performance of the circuit shown in Fig. 1.

X. Equipment List:

- Fixed 1% Resistors
- Decade Resistance Box
- Decade Inductance Box
- Signal Generator
- Oscilloscope
- General Radio Bridge 1650-A and instruction book.
- Fixed Inductor (Molybdenum Permalloy core)
- Fixed Capacitor

XI. References: See Project 5, The Wheatstone Bridge.

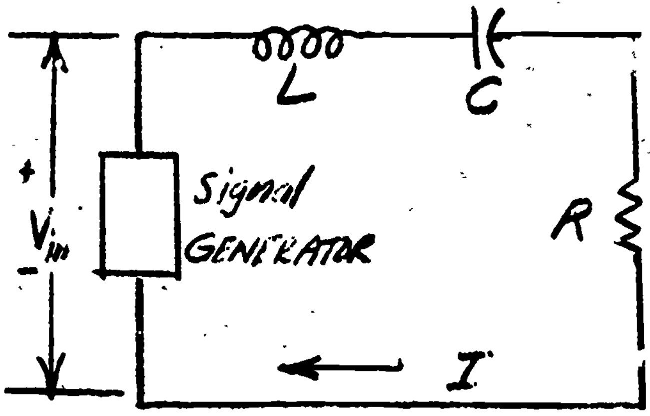
EE 25

Project I-1

Series and Parallel Resonance

The subject of resonance is so important that we wish to verify experimentally some of the well-known analytical results describing this phenomenon.

I. Series Resonance



R = 50 ohms (includes resistance of inductor)

$C = (10)^{-8}$ farads

$\omega_o^2 = \frac{1}{LC} = (10)^{10}$

$Q_o = 20$

Fig. 1

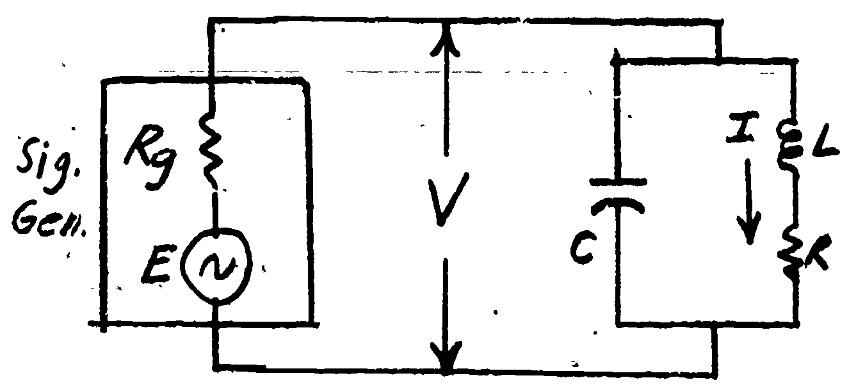
In fig. 1, L must be chosen so that $Q_o = 20$ when $\omega_o = (10)^5$.

1. Obtain a response curve; i.e., I (rms value of the current) vs. ω holding the amplitude of the input voltage constant. Include the point $\omega = (10)^5$.

2. Obtain a phasor diagram for the circuit of fig. 1 at the resonant frequency, the upper, and the lower-half power points. Include V_{in}, V_L, V_c, V_R and I.

3. Plot the results of (1) and (2). Discuss the significant characteristics of these plots.

II. Parallel Resonance



R = 25 ohms

$\frac{1}{\sqrt{LC}} = 5(10)^4$

Fig. 2

In Fig. 2, it required that maximum power be dissipated in R at $\omega_o = 5(10)^4$ for a fixed value of E.

1. Plot V and I/rms vs ω for a fixed value of E. Include $\omega = 5(10)^4$.

2. Compare this result with that obtained for series resonance.

APPENDIX I

ELECTRONS ARE FASTER

E. J. Kletsky

I. Introduction

Electricity is potentially the most dangerous commodity in general use by the public today. In spite of this, less than 1 per cent of the 100,000 accidental deaths which occur annually in the United States are directly attributable to electrocution. Considering the ever-increasing use of electricity in the home and industry, we, as electrical engineers, should be alert to protect and better this excellent safety record.

An understanding of the effects of electric shock, high-frequency heating, and other electrically produced physiological phenomena on the human body should be part of basic knowledge. The purpose of this paper is to present a brief survey of these topics in the hope that the reader will become aware of the very real dangers inherent in the application of electrical phenomena. We shall consider these dangers in each frequency band of the electromagnetic spectrum-from the power frequencies to cosmic rays.

II. The Power Frequencies

1. Electric Shock

The ratio of fatalities to injuries for electric shock accidents is very high in comparison to the corresponding figure for all other accidents. Death due to electric shock is fast and permanent. - Thus, the title of this paper.

2. Shock Sensitivity

Because of man's highly developed nervous system, he is sensitive to very small currents. For example, the tongue will give a sensation of taste at currents as low as 45 microamperes. The threshold of feeling on the hand is found to be on the order of 5 ma. DC and 1 ma. at 60 cps. The shocks due to currents at this threshold are usually considered annoying rather than dangerous. However, they are startling when not anticipated, and may cause involuntary movement which sometimes results in serious injury.

As the value of current increases above the threshold, one becomes aware of sensations of heat and contraction of the muscles. Sensations of pain develop and voluntary control of the muscles in the path of the current becomes increasingly difficult. Finally a value of current is reached where the victim "freezes" to the circuit. The value of current at which a victim can just release the electrode is referred to as "let-go" current. The average let-go current for healthy males is about 16 ma. rms. (60~). It is important to note let-go currents of as low as 5 ma. have been measured. Experience has shown that an individual can withstand with no ill after effects, except for possible sore muscles, repeated exposure to his let-go current for at least the time required for him to release the conductor.

3. Effect of Frequency and Waveform

Gradually increasing direct current produces sensations of internal heating. Sudden changes of current however, produce powerful muscular contractions, and interruption of the current causes very severe shocks. Experiments at 10 kc indicate that the let-go current is approximately 3 times the 60 cycle value. For non-sinusoidal waveforms, the peak value seems to be the critical factor in muscular stimulation.

4. Nature of Bodily Damage

As far as gross electrical effects are concerned, the body can be represented by the equivalent circuit shown in Fig. 1

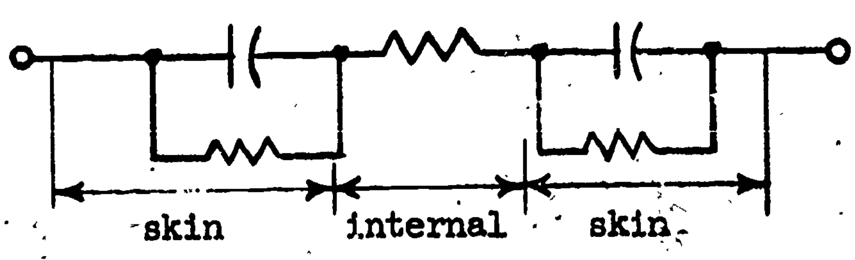


Fig. 1 Equivalent circuit for body

The outer skin (epidermis) is roughly 0.1 mm. thick and has a resistance of the order of 10^5 ohms per cm^2 when dry. The inner skin (dermis) and the internal organs are of relatively low resistance because of their high salinity. It is generally believed that the effects of electric shock are due to the current actually flowing through the body.

Electrical burns are a result of I^2R heating of the skin. The immediate formation of blisters at the point of contact causes the skin to lose its protective resistance and hence more serious damage may occur. Burns of this nature penetrate quite deeply and, while they seldom become infected, heal very slowly.

Electrical current is most dangerous when vital organs are in its path through the body. Current may cause stoppage of breathing due to excessive contraction of the chest muscles. Temporary paralysis of respiration may also occur if the current produces a block in the nervous system which prevents signals from reaching the lungs. In either case, it is imperative that an approved form of artificial respiration be applied immediately and continued without interruption until competent medical examination has been made.

5. Ventricular Fibrillation

Passage of electrical current through the heart is considered particularly dangerous. The heart exerts its pumping action as a result of complex rhythmic motion controlled by periodic electrical impulses to the muscle tissue. The regularity of this motion assures proper blood circulation. Electric current passing through the heart completely upsets this rhythmic motion and results in random muscular contractions. The heart no longer effectively pumps, but quivers like so much "Jell-O." This condition is known as ventricular fibrillation and is nearly always fatal. It has been found that energy of the impulse of current is responsible for this hazard and an estimate of the danger threshold for fibrillation is 13.5 watt-seconds.

III. The Radio Frequencies

At frequencies above the power range the primary bodily damage results from dielectric heating. Heating also occurs from both conduction current and radiation.

The temperature of the human body is maintained remarkably constant by very complex temperature regulating mechanisms. These mechanisms, coordinated by the brain, control temperature by regulating the production and loss of heat. Circulation of bodily fluids contributes to the distribution of the heat. The change in diameter of the blood vessels, for example, regulates the volume and velocity of flow. However, not all areas are equally well regulated and it is possible for local heating to occur. Such local heating is apt to be dangerous, particularly if vital organs are involved. A differential of $5^{\circ}C$ maintained for a sufficient time may be injurious or even lethal. Testes, for example, undergo degenerate changes with temperature rises as low $1^{\circ}C$.

The amount of bodily tempe. ure rise depends on the specific area exposed and its efficiency of heat elimination. Other factors contributing to temperature rise are intensity, and the duration of exposure. At frequencies below the microwave region ($f \gg 1000$ mc.) about 40 per cent of the incident energy is absorbed. These frequencies cause deep (internal) heating and are very dangerous since such heating is not well indicated by sensory elements of the skin. A tolerance figure of 0.001 watt/cm^2 for long term exposures has been consiered adequate.

Surface burns resulting from R.F. currents are similar to those encountered with the lower frequencies.

IV. The Microwave Frequencies

The effects of the lower microwave frequencies are similar to those of radio frequencies and a comparable tolerance figure for exposure should not be exceeded.

As the frequency increases ($f > 3000$ mc.), the incident energy is absorbed by the skin with an efficiency of 40 to 50 per cent.

The effects of such radiation are much the same as is encountered with infrared and sunlight.

The possibility of the formation of eye cataracts must be considered at microwave frequencies. These cataracts result in impairment of vision or even blindness as a result of the formation of a white cloud in the normally transparent cornea of the eye. Cataracts are thought to occur in a manner analogous to the formation of the "white" of an egg upon heating. Experiments with rabbits have indicated that cataracts have formed in 3 to 9 days following a single 15 minute exposure to a 100 watt source of

12 cm waves at a distance of 5 cm. While the exposure indicated here is probably extreme, care should be taken when working with high-powered radar sets.

V. Infra-Red, Visible Light, and Ultraviolet Frequencies

The immediate effects of this band of frequencies are popularly known as sunburn. The eye, however, is particularly susceptible to excess exposure at these frequencies. Such exposure can easily occur when observing an electric arc without protection. This may result in hemorrhages of the choroid (the outer lining of the retina) and actual destruction of portions of the retina itself. In addition, actual immediate pain may be encountered because of violent contractions induced in the iris. Photophthalmia (temporary snow-blindness) is due to ultra violet radiation following undue exposure to sunlight, an electric arc, or a sunlamp.

VI. X-Rays and Nuclear Radiation

The effects of this portion of the electromagnetic spectrum of the human body are still being studied. It has been found that the amount of energy absorbed by the tissue during exposure is the most important consideration. Damage to the reproductive organs has been found to be the most sensitive indication of excessive exposure.

Controlled experiments with mice exposed to fast neutron radiation from an atomic reactor indicate the type of damage sustained by living animals. During the first 9 months of continuous exposure, no visible differences were noted. The mice then began to lose weight and gradually lose hair. Eye cataracts developed after a year and death followed. Limited exposure to nuclear radiation resulted in a shortened life span.

We have yet to completely determine the consequences of the atomic bombs of World War II in terms of its biological effects. For this reason, plus the fact that the latent period between exposure and detection of damage may run into months and years, it behooves us to take all precautions against X-Ray and nuclear radiation.

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SUGGESTIONS FOR SAFETY IN LABORATORIES

A person's reputation may be seriously injured if his lack of foresight results in accidents to himself or others.

NEVER HURRY. Haste causes many accidents.

CONNECT to the SOURCE of power LAST.

DISCONNECT the SOURCE of power FIRST.

Always ASSUME that circuit SOURCES are ALIVE. Remember that any laboratory circuit may be energized at any time.

When WORKING on ENERGIZED EQUIPMENT have an ASSISTANT WITHIN SIGHT.

When WORKING on ENERGIZED EQUIPMENT, use only ONE HAND as far as practicable.

WORK DELIBERATELY and CAREFULLY as you proceed.

VERIFY you CONNECTIONS and be sure that they have been made secure.

AVOID PLACING ANY PART OF YOUR BODY IN THE CIRCUIT, either to ground or across terminals.

NEVER CLOSE A CIRCUIT UNTIL INDIVIDUALS ARE CLEAR of mechanical equipment and circuit breakers.

KEEP the FACE away FROM CIRCUIT BREAKERS.

AVOID the possibility of EXPOSING your EYES TO ELECTRIC ARCS.

NEVER CLOSE A SWITCH SLOWLY OR HESITATINGLY.

CLOSE AND OPEN CIRCUITS WITH SUITABLE APPARATUS.

CHECK the supply circuit VOLTAGE to see that it is what you expect BEFORE CLOSING CIRCUITS.

AVOID running WIRES OVER or UNDER A BELT.

NEVER STEP OVER A BELT while it is in motion.

Continued

SUGGESTIONS FOR SAFETY IN LABORATORIES (Continued)

KEEP WATCH CHAINS, FINGER RINGS, WRIST WATCHES, metallic pencils, etc., OUT OF CONTACT WITH LIVE PARTS when working around electrical apparatus.

KEEP NECKTIES and loose clothing AWAY FROM ROTATING MACHINERY.

DISCHARGE ALL CAPACITORS before working on associated circuits.

USE EXTREME CARE IN BREAKING AN INDUCTIVE CIRCUIT.

DO NOT LIFT BRUSHES from a commutator or slip ring while machines are in operation.

DO NOT USE VOLTMETERS UNTIL the ends of the two LEADS are FASTENED FIRMLY to suitable posts ON THE INSTRUMENT.

DO NOT, UNDER ANY CIRCUMSTANCES, open the secondary of a current transformer while it is carrying current.

DO NOT TAKE CHANCES. If in doubt ASK for instructions.

APPENDIX II

DECADE RESISTANCE BOX CURRENT AND ACCURACY RATINGS

MANUFACTURER	HEATH	SUPERIOR	EICO	GENERAL RADIO	GENERAL RADIO
Models	DRI	5A	1171	602J 602K 1432K	620F
<u>Max. Current</u>					
Tenths	-	-	-	1.6 amp.	1.6 amp.
Units	500 ma.	500 ma.	350 ma.	800 ma.	500 ma.
Tens	150 ma.	150 ma.	120 ma	250 ma	160 ma
Hundred	50 ma	50 ma	35 ma	80 ma	-
Thousands	15 ma	15 ma	12 ma	23 ma	-
Ten thousands	5 ma	5 ma	2.5 ma	7 ma	-

The Heath and EICO decade resistance boxes employ ± 1/2 per cent resistor and thus should be accurate to ± 1/2 per cent of the indication. The Superior decade resistance boxes have about one per cent accuracy.

New General Radio decade resistance boxes have accuries as follows:

Tenth ohm steps	± 0.5 per cent
One " "	± 0.15 " "
Ten " "	± 0.05 " "

Hundred ohm steps	± 0.05 per cent
Thousand " "	± 0.05 " "
Ten thousand " "	± 0.05 " "

Older boxes may have lower accuracy if they have not been calibrated recently.

APPENDIX III

RETMA STANDARD RESISTOR VALUES

Tolerance	5 Per cent	10 Per cent
Sizes (significant figures)	10	10
	11	-
	12	12
	13	-
	15	15
	16	-
	18	18
	20	-
	22	22
	24	-
	27	27
	30	-
	33	33
	36	-
	39	39
	43	-
	47	47
	51	-
	56	56
	62	-
	68	68

5 Per cent	10 Per cent
75	
82	82
91	-
100	100

Resistors are supplied with these significant figures times various powers of ten. The usual ranges of avialable sizes in 5 per cent and 10 per cent tolerances are as follows:

Type	Power	Min. Res.	Max. Res.
Fixed Composition	1/2 watt	10 ohms	22 meg.
	1 "	10 "	22 "
	2 "	10 "	22 "
Wire Wound (5 per cent)	1/2 watt	0.24 ohms	820 ohms
	1 "	0.47 "	5100 "
	2 "	1.0 ohms	8200 ohms

It is interesting to observe that resistor values follow approximately a geometric series. Thus each size bares to the preceding size almost the same ratio. This is important for at least two reasons: A designer can always choose a nominal 10 per cent resistor nominal size within about 10 per cent of a desired value and can thus get a resistor which is within 21 per cent of the desired value. Moreover, a manufacturer can always find a nominal size to designate any resistor that he manufactures.

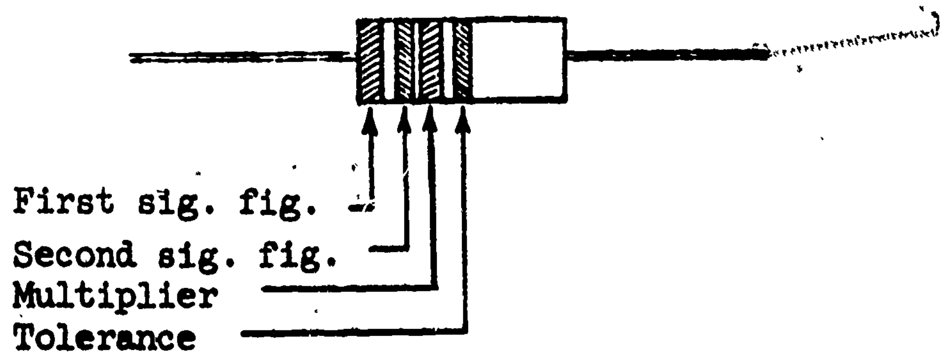
It is suggested that the reader prepare a geometric progression of sizes between 10 and 100 containing 13 terms (including both 10 and 100) and compare sizes with the nominal values. Suggest an explanation for any discrepancies. In the same way, find a suitable series for the 5 per cent tolerance resistors. Suggest an explanation for any discrepancies. Decide whether you would have used the same or different sequences of nominal resistance sizes if you had been asked by the RETMA to decide upon a set of nominal sizes.

Problem: Choose a sequence of nominal resistance sizes for ± 15 per cent tolerance resistors.

APPENDIX IV

RESISTOR COLOR CODE

Color	Significant Figure	Multiplier
Silver	0	0.01
Gold	1	0.1
Black	0	1
Brown	1	10
Red	2	10^2
Orange	3	10^3
Yellow	4	10^4
Green	5	10^5
Blue	6	10^6
Violet	7	10^7
Gray	8	10^8
White	9	10^9



Tolerances

Gold	± 5 per cent
Silver	± 10 per cent
No color	± 20 per cent

APPENDIX V

ON THE MATHEMATICS OF WIRE SIZES

Suppose you were on a desert island with no handbooks. You are asked to find the diameter of (say) No. 20 wire. Could you do it? Well, of course, in the usual desert island story you would not be worried about handbooks and wire tables, but it is interesting that with the aid of a log log sliderule, one can compute any wire size, given two key sizes and the mathematical law.

American Wire Gauge (Brown and Sharpe) wire sizes are arranged in a geometric progression. Thus

Size	Diameter (inches)	Term in Series
36	$D_{36} = 0.005$ inches	0
35	$D_{35} = r\,D_{36} = 0.005\,r$	1
34	$D_{34} = r\,D35 = r^2 D_{36} = 0.005r^2$	2
	. . . .	
1	$D_1 = r\,D_2 = r^{35} D_{36} = 0.005r^{35}$	35
0	$D_0 = r\,D_1 = r^{36} D_{36} = 0.005r^{36}$	36
00	$D_{2/0} = r\,D_0 = r^{37} D_{36} = 0.005r^{37}$	37
000	$D_{3/0} = r\,D_{2/0} = r^{38} D_{36} = 0.005\,r^{38}$	38
0000	$D_{4/0} = r\,D_{3/0} = r^{39} D_{36} = 0.005r^{39} = 0.460$	39

From this

$$0.005\,r^{39} = 0.460$$

$$r = \sqrt[39]{\frac{.460}{.005}} = \sqrt[39]{92}$$

Now you can solve the desert-island problem. From the series, we see that

$$D_{20} = r^{16} D_{36} = \left[\sqrt[39]{92}\right]^{16} 0.005 = 0.032 \text{ inches}$$

You might expect there is some reason behind the use of a geometric progression for wire sizes. In fact there is. Fine wire is made by drawing coarse wire through dies of progressively smaller size. (The wire is annealed between drawings). It is possible to reduce wire by about the same ratio in diameter at each drawing. Thus we could imagine each drawing increasing the size number by one digit.

It is left to the reader to work out further useful properties of wire sizes. Some properties are the following.

1. Number 10 wire is about 1/10 inch diameter.
2. Decreasing wire size by 3 numbers doubles the cross section area, hence halves the resistance per unit length.
3. Decreasing the wire size by six numbers doubles diameter.

APPENDIX VI

COMPUTATION WITH LIMITING ERRORS

Guarantees, Tolerances and Limiting Errors

In electrical engineering, a commonly occuring problem is the calculation of some quantity from the results of measurements of known accuracy, or using components of known tolerance. For example, when two resistors with different tolerances are connected in series, what is the tolerance of the combination? Or, if voltage, current and power are measured with instruments of known accuracy, then what is the accuracy of the calculated power factor? Error calculations such as these are known as Limiting Error calculations.

In many scientific measurements there is a certain amount of "randomness" or chance associated with the measurements. That is, the same quantity measured many times gives many different numerical results, but the results are, perhaps, clustered about a "mean" value. Statistical techniques have been highly developed to handle measurement situations of this sort, and to predict the "probable errors" in the results.

In the majority of electrical measurements, however, the randomness of the measurement due to the instrument is small compared with the tolerances on the instrument. In these cases "possible error" or limiting error is usually calculated. Essentially, "limiting error" means the largest error that can arise in view of the guarantees and tolerances on the instruments and components used.

These notes give examples showing how limiting errors in measurements, or tolerances on component values, affect the result of computations. Examples of addition, subtraction, multiplication-division, and more general computations are chosen from the field of electrical measurements. Finally, a general approach in terms of differentials is presented.

In Summation, Errors Add

Consider three resistors having known tolerances connected in series; the problem is to find the limiting error of the combination. The resistors are 1000 ohms ± 10 per cent, 3300 ohms ± 5 per cent and 500 ohms ± 1 per cent.

TABLE I

Nominal Value (Ohms)	Tolerance		Limiting Values	
			Low	High
	(per cent)	(ohms)	(Ohms)	(Ohms)
1000	10	100	900	1100
3300	5	165	3135	3465
500	1	5	495	505
4800		270	4530	5070

From TABLE I it is easy to see that the series combination has resistance between 4530 ohms and 5070 ohms, and that this is 4800 ohms ± 270 ohms, which in turn is 4800 ohms ± 5.63 per cent, or (say) 4800 ohms ± 6 per cent.

The general conclusion to be drawn from this example is that when numbers having independent tolerances, or guaranteed errors, are added, then the limiting error of the sum is the sum of the limiting errors.

In addition, it is observed that the limiting per cent error of the sum is somewhere between the largest and smallest per cent errors of the terms in the summation.

Small Differences May Have Large Per Cent Errors

In the circuit of Fig. 1 the two voltmeters have 0 to 10-volt ranges and have guaranteed accuracies of ± 0.5 per cent (of full scale). The problem is to find the voltage V_3, the limiting error in V_3, and the limiting per cent error in V_3.

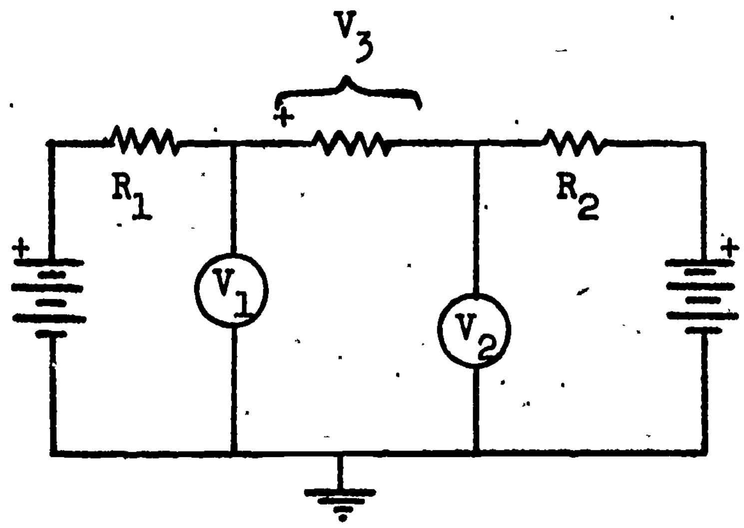


Fig. 1

TABLE II shows that the limiting error magnitude in the calculated value of V_3 is the sum of the limiting errors of V_1 and V_2 , i.e., V_3 = 0.24 volts ± 0.10 volts. The limiting per cent error in V_3 is however quite large, i.e., V_3 = 0.24 volts ± 42 per cent.

TABLE II

Quantity	Nominal Value	Limiting Error	Limiting Values	
			Low	High
	(volts	(volts)	(volts)	(volts)
V_1	6.12	0.05	6.07	6.17
V_2	5.88	0.05	5.83	5.93
V_3	0.24	0.10	0.34	0.14

The reader may suggest that, obviously, one should not attempt to determine V_3 in the manner suggested by Fig. 1; and that, at least, one should use the same voltmeter to measure V_1 and V_2. However, sometimes experimental constraints force just this sort of situation. If calculations using the small difference of measurements must be made, then these calculated values should be treated with caution.

In Multiplication and Division Per Cent Errors Add

Consider, for example, the bridge circuit shown in Fig. 2 where, at balance, the usual equation holds:

$$R_x = \frac{R_a}{R_b} R_s$$

Suppose R_a, R_b and R_s have known tolerances, then what is the limiting error in R_x?

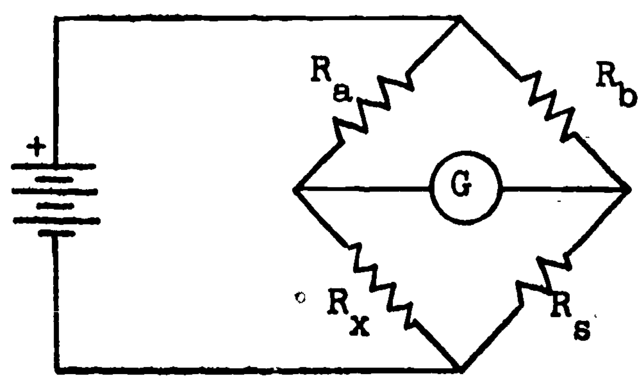


Fig. 2

One obvious approach is to calculate the nominal value, and the lower and upper limits on R_x. Observe, of course, that the upper limiting value of R_x results when R_a and R_s each have their upper limiting values, and R_b has its lower limiting value, and conversely for the lower limit. The calculations summarized in TABLE III, show that R_x = 536.2 ohms ± 2.2 ohms or R_x : 536.2 ohms ± 0.4 per cent

TABLE III

Quantity	Nominal Value	Tolerance		Limiting Values	
				Low	High
	(Ohms)	(per cent	(Ohms)	(Ohms)	(Ohms)
R_a	100	0.1	0.1	99.9	100.1
R_b	1000	0.1	1	999	1001
R_s	5362	0.2	10.7	5351	5373
R_x	536.2			534.0	538.4

The calculation of limiting errors by the method used in TABLE III is often tedious. Moreover, when the per cent errors in the factors are small, an approximate method, is entirely adequate and usually used. It is observed that in the example, the per cent error in the result is merely the sum of the percent errors in the factors. Justification for this follows.

Let R_{an}, R_{bn} and R_{sn} be the nominal values of R_a, R_b and R_s respectively. Also let the fractional limiting errors in R_a, R_b and R_s be δ_a, δ_b and δ_s. The per cent limiting error in R_a is 100 δ_a, etc. Thus, in the bridge example.

$$R_a = R_{an}(1 \pm \delta_a) = 100\ (1 \pm 0.001) \text{ ohms} \qquad (1)$$

$$R_b = R_{bn}\ (1 \pm \delta_b) = 1000\ (1 \pm 0.001) \text{ ohms} \qquad (2)$$

$$R_s = R_{sn}\ (1 \pm \delta_s) = 5362\ (1 \pm 0.002) \text{ Ohms} \qquad (3)$$

Now, let δ_x be the as-yet-unknown fractional error in R_x; and let R_{xn} be the nominal value of R_x. Thus

$$R_{xn} = \frac{R_{an}}{R_{bn}} R_{sn} \qquad (4)$$

and

$$R_x = R_{xn} (1 \pm \delta_x) \qquad (5)$$

Having defined all the necessary terms, it remains to find δ_x in terms of δ_a, δ_b and δ_s. First, note that

$$R_x = \frac{R_a}{R_b} R_s \qquad (6)$$

Substitution of Equations (1), (2), (3) and (5) into Equations (6) and division by Equation (4) yields

$$1 \pm \delta_x = \frac{(1 \pm \delta_a)}{(1 \pm \delta_b)} (1 \pm \delta_s) \qquad (7)$$

Observe that, provided $\delta_b \ll 1$, then

$$\frac{1}{1 \pm \delta_b} \doteq 1 \mp \delta_b$$

consequently

$$1 \pm \delta_x \doteq (1 \pm \delta_a)(1 \pm \delta_b)(1 \mp \delta_s) \qquad (8)$$

Recalling that the errors in R_a, R_b and R_s are not dependent upon each other, and that the limiting error in R_x results from the worst combination, it is reasoned that the signs go together, thus

$$1 + \delta_x \doteq (1 + \delta_a)(1 + \delta_b)(1 + \delta_s) \qquad (9)$$

$$1 - \delta_x \doteq (1 - \delta_a)(1 - \delta_b)(1 - \delta_s)$$

Since δ_a, δ_b and δ_x are each $\ll 1$, Equation (9) reduces to (neglecting all δ products)

$$1 + \delta_x \doteq 1 + (\delta_a + \delta_b + \delta_s)$$

$$\delta_x \doteq \delta_a + \delta_b + \delta_s \qquad (10)$$

Of course, this conclusion is easily extended to products and quotients having more factors: For products and quotients, the per cent limiting error of the result is the sum of the per cent limiting errors of all the factors.

Consider once again the bridge problem and apply the results just derived.

R_a = 100 ohms $\pm$ 0.1 per cent

R_b = 1000 ohms $\pm$ 0.1 per cent

R_s = 5362 ohms $\pm$ 0.2 per cent

$R_x = (R_a/R_b)\, R_s$

= 536.2 ohms $\pm$ 0.4 per cent

= 536.2 ohms $\pm$ 2.1 ohms

As a second example of product-quotient limiting error calculations, consider the determination of phase angle from voltmeter, ammeter and wattmeter readings using the relation

$$\theta = \cos^{-1}\left(\frac{P}{VI}\right)$$

$$\cos\theta = \frac{P}{VI}$$

The calculations of the limiting error in cos θ are shown in TABLE IV. From the guaranteed accuracy of each instrument and its full-scale units the limiting error in each reading is obtained, and then the per cent limiting error in each reading is calculated. Thus

$$\cos\theta = 0.912 \pm 2.42 \text{ per cent}$$

$$\cos^{-1} 0.912 = 24.2 \text{ deg.}$$

$$\cos^{-1} (0.912 + 2.42 \text{ per cent}) = \cos^{-1}(0.934) = 20.9 \text{ deg.}$$

$$\cos^{-1} (0.912 - 2.42 \text{ per cent}) = \cos^{-1}(0.890) = 27.1 \text{ deg.}$$

Finally

$$\theta = 24.2 \text{ deg} \begin{matrix} + 2.9 \text{ deg.} \\ - 3.3 \text{ deg.} \end{matrix}$$

TABLE IV

Quantity	Nominal Readings	Limiting Error Calculation			
		Instrument Full scale guarantee		Reading Limiting Error	
			(per cent)		(per cent)
P	467 watts	750 watts	0.75	5.6 watts	1.20
V	114.2 volts	150 volts	0.5	0.75 volts	0.66
I	4.48 amps	5 amps	0.5	0.025 amps	0.56
cos θ	0.912				2.42

Worthwhile savings in computation are obtained if it is recognized that if an indicating instrument deflection is the fraction α of full scale, then the limiting error in a reading is the guaranteed error divided by α. For example, a reading of 467 watts on a 750-watt scale of a 0.75 per cent accuracy watt meter has a limiting per cent error

$$\left(\frac{750}{467}\right)(0.75) = 1.20 \text{ per cent}$$

Limiting Errors and Differentials

One might ask at this point if there exists any unifying principle, or general method, for which all the examples presented up to now have been special cases. In fact, the total differential of calculus provides just such a general approach. Moreover, the total differential approach provides a powerful tool for calculating the limiting error when more complicated expressions are encountered.

Consider a quantity R which is given as a function of several variables $x_1, x_2, \ldots x_n$

$$R = f(x_1, x_2, \ldots x_n) \qquad (11)$$

The independent variables x_i are numerical measurements with known limiting errors, or parameter values with known tolerances. The total differential of R is

$$dR = \frac{\partial f}{\partial x_1} dx_1 + \frac{\partial f}{\partial x_2} dx_2 + \ldots + \frac{\partial f}{\partial x_n} dx_n$$

Provided that the partial derivatives are continuous and do not change too rapidly, the following approximation can be written

$$\delta R \doteq \frac{\partial f}{\partial x_1} \delta x_1 + \frac{\partial f}{\partial x_2} \delta x_2 + \ldots + \frac{\partial f}{\partial x_n} \delta x_n \qquad (12)$$

By interpreting $\delta x_1, \delta x_2, \ldots \delta x_n$ as limiting error magnitudes, this expression gives the limiting error in R. For example, if

$$R = R_1 + R_2 + R_3$$

direct application of (11) gives

$$\delta R = \delta R_1 + \delta R_2 + \delta R_3$$

which agrees with the earlier discussion about the limiting error for resistors in series, i.e. the limiting error of the sum is the sum of the limiting errors.

If Equation (12) is divided by Equation (11) then

$$\frac{\delta R}{R} = \frac{1}{f} \frac{\partial f}{\partial x_1} \delta x_1 + \frac{1}{f} \frac{\partial f}{\partial x_2} \delta x_2 + \ldots + \frac{1}{f} \frac{\partial f}{\partial x_n} \delta x_n \qquad (13)$$

which can be interpreted as an expression relating fractional errors or per cent errors. As an example consider the bridge equation

$$R_x = \frac{R_a}{R_b} R_s = f(R_a, R_b, R_s)$$

Direct application of (13) gives

$$\frac{\delta R_x}{R_x} = \frac{R_b}{R_a R_s} \left[\frac{R_s}{R_b} \delta R_a - \frac{R_a R_s}{R_b^2} \delta R_b + \frac{R_a}{R_b} \delta R_s \right]$$

$$= \frac{\delta R_a}{R_a} - \frac{\delta R_b}{R_b} + \frac{\delta R_s}{R_s}$$

Remembering that the worst combination occurs when the denominator is low (high) and the two numerator factors are high (low), and also using the nomenclature developed before gives

$$\delta_x = \delta_a + \delta_b + \delta_s$$

which is entirely in agreement with the product-quotient rule developed earlier, i.e. the per cent limiting error of the product-quotient is the sum of the per cent limiting errors of all the factors.

As a final example consider the problem of measuring the resistance R_m of a voltmeter by a half-deflection method using the circuit shown in Fig.3. The resistance R is assumed to be calibrated and adjustable in order to be able to set the voltmeter to full-scale and half-scale deflection. The meter has an accuracy of $\pm$ e of full scale.

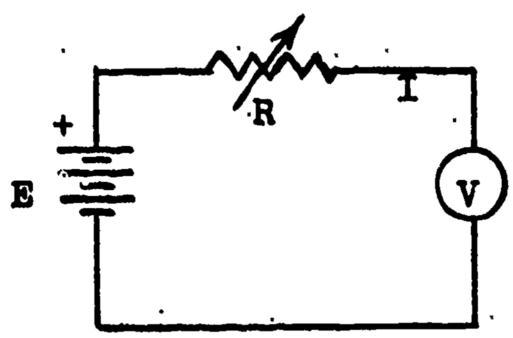


Fig. 3

When the meter reads full scale the current is I_1 and $R = R_1$. When the meter reads half scale the current is I_2 and $R = R_2$. Analysis shows that

$$R_m = \frac{\alpha R_2 - R_1}{1 - \alpha} \tag{14}$$

where $\alpha = I_2/I_1$. Ideally $\alpha = \frac{1}{2}$ and

$$R_m = \frac{\frac{1}{2} R_2 - R_1}{\frac{1}{2}}$$

$$= R_2 - 2R_1 \qquad (15)$$

Since the meter has limiting error $\pm$ e therefore α may be different from 1/2. In fact, assuming the meter current is high at half scale, and low at full scale

$$\alpha + \delta\alpha = \frac{\frac{1}{2} + e}{1 - e} \doteq \frac{1}{2}(1 + 2e)(1 + e) \doteq \frac{1}{2}(1 + 3e)$$

But

$$\alpha + \delta\alpha = \frac{1}{2} + \delta\alpha$$

$$\delta a = \frac{3}{2} e \qquad (16)$$

If it is assumed that R has negligible error, then

$$\delta R_m = \frac{\partial}{\partial\alpha} \left[\frac{\alpha R_2 - R_1}{1 - \alpha}\right] \delta\alpha$$

$$= \frac{R_2 - R_1}{(1 - \alpha)^2} \delta\alpha = 4(R_2 - R_1) \delta\alpha$$

also

$$\frac{\delta R_m}{R_m} = \frac{4(R_2 - R_1)}{R_2 - 2R_1} \delta\alpha$$

For example, if R_1 = 2000 ohms R_2 = 5000 ohms and e = 0.005, then

$$\frac{\delta R_m}{R_m} = \frac{4(5000 - 2000)}{5000 - 4000} \left(\frac{3}{2}\right)(0.005) = 0.09$$

The limiting error in the measurement of R_m by this method, and with these parameter values is $\pm$ 9 per cent.

APPENDIX VII

PROPERTIES OF A-C VOLTMETERS

A-C Voltmeter Application Problems

There are at least five problems that arise when an a-c voltmeter is chosen for a particular measurement task. First, the input impedance of the instrument must be considered, for if it is not large enough to be neglected, then the quantity being measured and even the whole operation of the circuit may be disturbed by the voltmeter. Second, if the waveform of the measured voltage is not sinusoidal, then the voltmeter indication must be correctly interpreted. Third, the voltmeter should be capable of responding satisfactorily at the frequency of the input voltage. Fourth, the voltmeter must have suitable ranges for the expected value of unknown voltage. Fifth, the voltmeter must have an accuracy satisfactory for the requirements.

Primarily, these notes are concerned with the second-mentioned problem, that of the waveform-response properties of a-c voltmeters. Almost all commercially available a-c voltmeters are designed to indicate the rms value of a sine wave. That is, almost all a-c voltmeters will read the same when they are connected in parallel to the same sine-wave voltage source, and the indicated value is the rms value of the sine wave. However, when the different kinds of voltmeters are connected to sources having nonsinusoidal voltage waveforms, then in general, the scale indications are not the true rms values of the voltages. These notes are intended to show how these differences arise, and what property of an arbitrary waveform is measured by the principal types of voltmeters.

Now, one should observe some caution in applying the mathematical niceties developed here. In general, vacuum-tube a-c voltmeters have accuracies of from ± 2 to ± 5 per cent. Thus inaccuracies often are more significant than the differences of waveform response. Also, one generally chooses an a-c voltmeter on the basis of input impedance, frequency response, range, and accuracy; the waveform-response property is in general an incidental characteristic, tolerated rather than employed as a basis for choice. Modern electrical engineering laboratory practice seems to be tending toward the use of good-quality calibrated oscilloscopes for the measurement of most nonsinusoidal waves.

There are, however, several cases where the peculiar waveform-response properties of different kinds of a-c voltmeters can be used to advantage. Project 12 gives one such example.

In the following sections, a-c voltmeters are grouped into three main categories according to their waveform-response characteristics. Comments on input impedances and frequency response are included. Finally, several properties of various commercial meters are tabulated for comparison.

I. "TRUE" RMS - TYPE INSTRUMENTS

I-1. Dynamometer Instruments

Probably the best all-round a-c instrument for low-frequency work is the dynamometer, shown schematically in Fig. 1. One way of explaining its behavior is to consider that the field coils produce a magnetic flux density proportional to the current i, and the moving coil, carrying the same current i, has a torque exerted upon it proportional to the coil current and the field flux density. Thus the instantaneous torque depends upon i^2, and consequently, the average torque and meter indication depend upon the average of i^2, which is easily shown to be related to the rms value of i(t), regardless of its waveform. A voltmeter is easily made by employing a series resistance multiplier - just as in a d-c instrument.

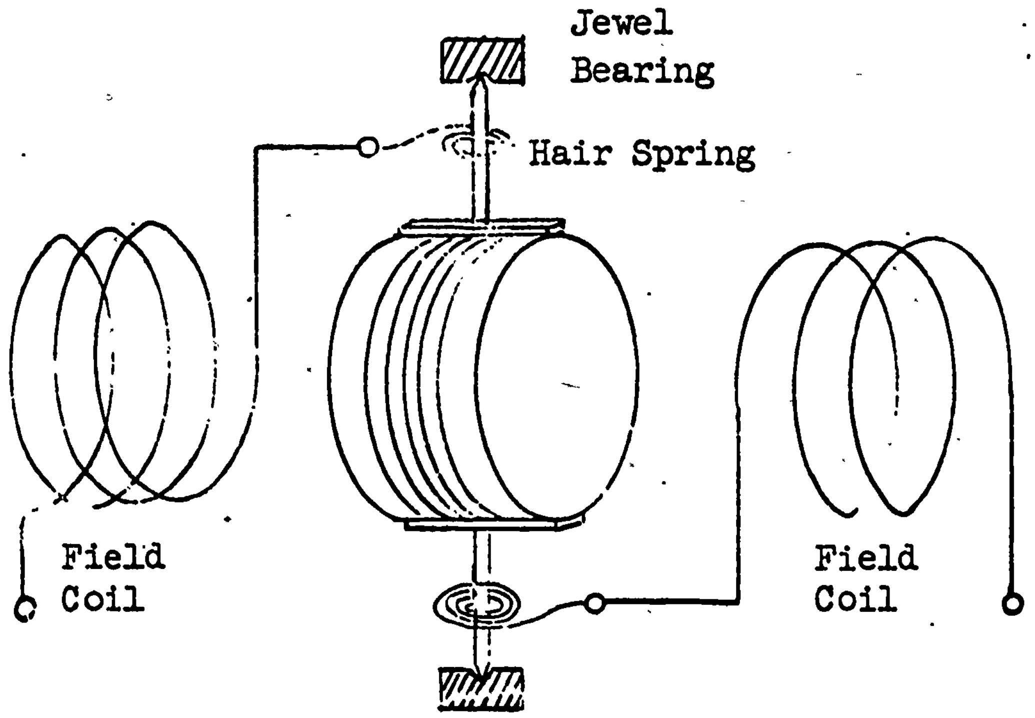


Fig. 1 Dynamometer movement

As a result of this operation, it is easy to show that all the voltage waveforms of Fig. 2 ideally give the same indication A. Since Fig. 2 (a) shows a direct voltage, the dynamometer is a suitable transfer instrument; that is, it can be calibrated on d-c and used on a-c.

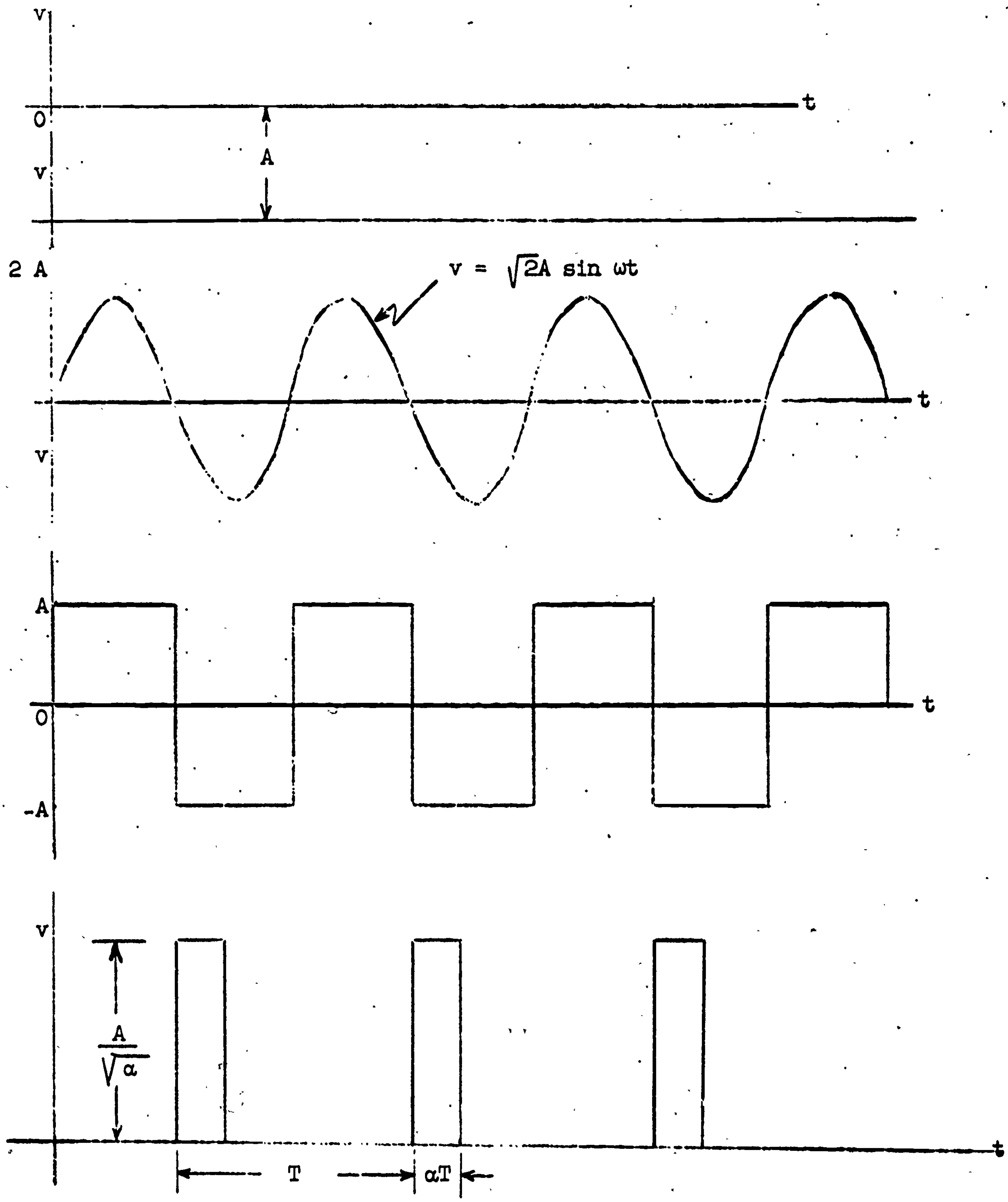


Fig. 2 True rms reading meters will give the same indication of A volts for each of the drive-voltage waveforms shown.

I-2. Iron-Vane Instruments

A voltmeter construction which is mechanically somewhat simpler than that of the dynamometer is the iron-vane movement, shown diagrammatically in Fig. 3.

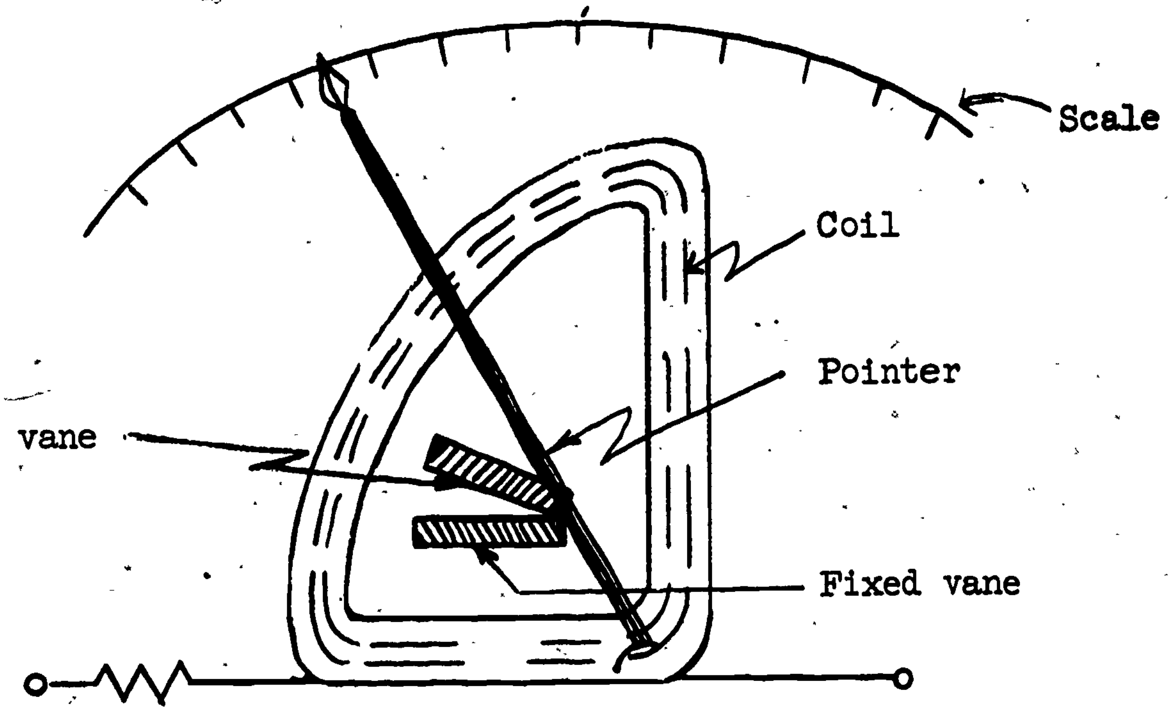


Fig. 3 Iron-vane-type movement

The operation of this device is usually explained as follows: Current in the coil produces a magnetic field which in turn magnetizes the iron vanes. Since the vanes have like poles adjacent, they repel each other. The average repulsive force is argued to be related to the average of the instantaneous coil current squared; hence, the response is essentially the same as that of the dynamometer. The iron-vane meter is basically a true rms meter, so the responses to the waveforms shown in Fig. 2 are ideally the same.

I-3. Thermocouple Instruments

For some kinds of measurements a thermocouple voltmeter is appropriate. The arrangement of a thermocouple voltmeter is shown in Fig. 4. If the heater resistance were constant, then the power dissipated in the heater would be proportional to the rms value of the current i. Consequently, the temperature rise and the d-c meter deflection would also depend on the rms meter current or voltage. Hence the thermocouple voltmeter also gives a true rms reading

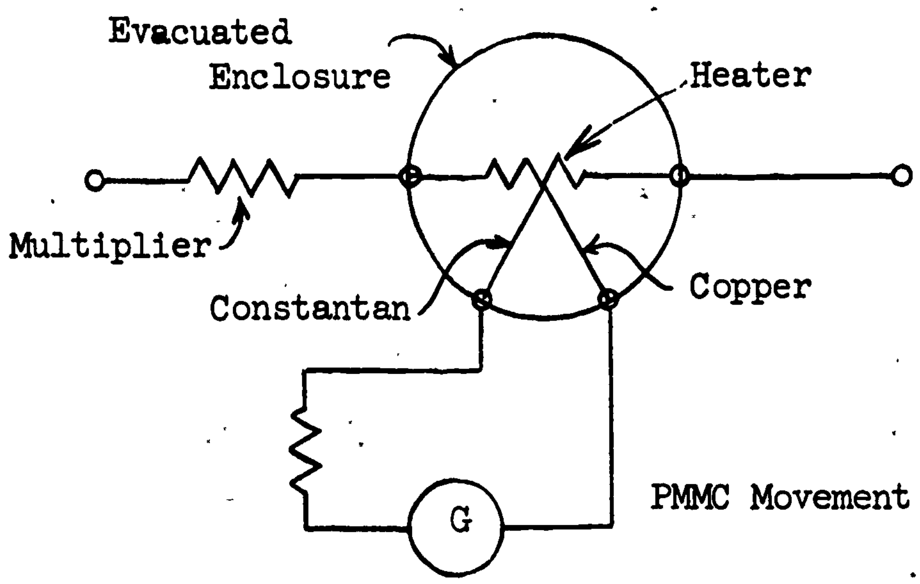


Fig. 4 Thermocouple voltmeter

I-4. Electrostatic Voltmeter

Basically, the electrostatic voltmeter consists of a parallel-plate structure similar to that of a radio-type variable capacitor, except that the rotor is mounted on jewel bearings and is fitted with a pointer. The force of attraction between the rotor plates and stator plates varies as the voltage squared; consequently the indication can be made proportional to the rms voltage.

I-5. Frequency Response and Loading

Iron-vane and dynamometer voltmeters are widely used at power frequencies because relatively accurate and rugged instruments can be built using these principles. Neither is very suitable for very low frequencies (0-10 cps) because the pointer oscillates at double frequency unless additional mechanical damping is provided. At higher-than-rated frequencies (125-1000 cycles) these meters cannot be relied upon because (a) the large reactance of the coils reduces meter-movement current (b) eddy currents in the iron parts reduce the effective flux. Even when the fundamental frequency is within the range of the meter, the higher harmonics may not be measured correctly. These meters characteristically have low sensitivity (low impedance) and the lowest ranges are the order of ten volts. Accuracies of one half per cent (or even one tenth per cent with the dynamometer) can be achieved.

The thermocouple meter is often employed at radio frequencies. The typical accuracies of one per cent are usually better than those of other high-frequency meters. There are however three main disadvantages: (1) Thermocouple meters are expensive. (2) They impose a relatively heavy load on a circuit (i.e. they have low input impedance). (3) They are delicate. Much to the chagrin of many users, a thermocouple meter can be burned out without even getting the indication up to full scale.

Electrostatic meters have close to ideal properties: No power is taken from the circuit, and the input impedance - perhaps a few hundred picofarad is very high. Unfortunately, a low-range meter (lower than a few hundred volts) is prohibitively delicate mechanically. Consequently, electrostatic voltmeters are relatively rarely employed except for high-voltage work.

II. RECTIFIER AND AVERAGING TYPE METERS

II-1. Amplifier-Rectifier A-C Vacuum-Tube Voltmeter

Several instrument manufacturers produce voltmeters which are designed to operate as follows:

1. Take the alternative component of the input waveform.
2. Attenuate this voltage, depending on the range-switch position to a usable range, (say) less than 1 millivolt.

3. Amplify - both voltage and power.

4. Rectify and average.

5. Give a meter indication proportional to this average value.

Response (meter deflection) is thus proportional to the average of the full-wave rectified a-c component at the input. In order to indicate the rms value of a sine wave, the scale reading is $\pi/(2\sqrt{2})$ times this full-wave rectified and averaged value. A functional block diagram for such a meter is shown in Fig. 5, and typical waveform responses in Fig. 6.

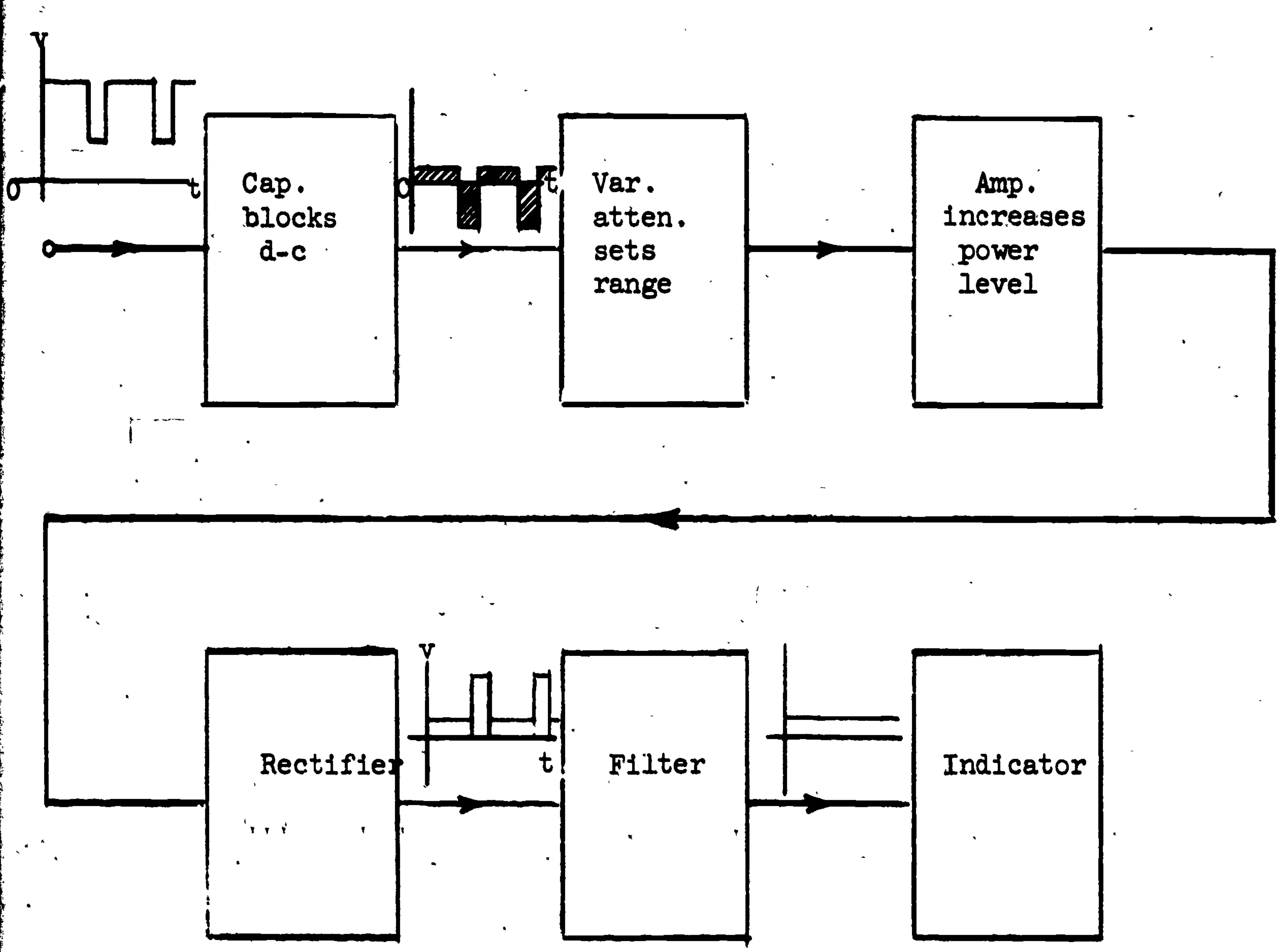


Fig. 5 Functional block diagram of amplifier-rectifier-type a-c voltmeter

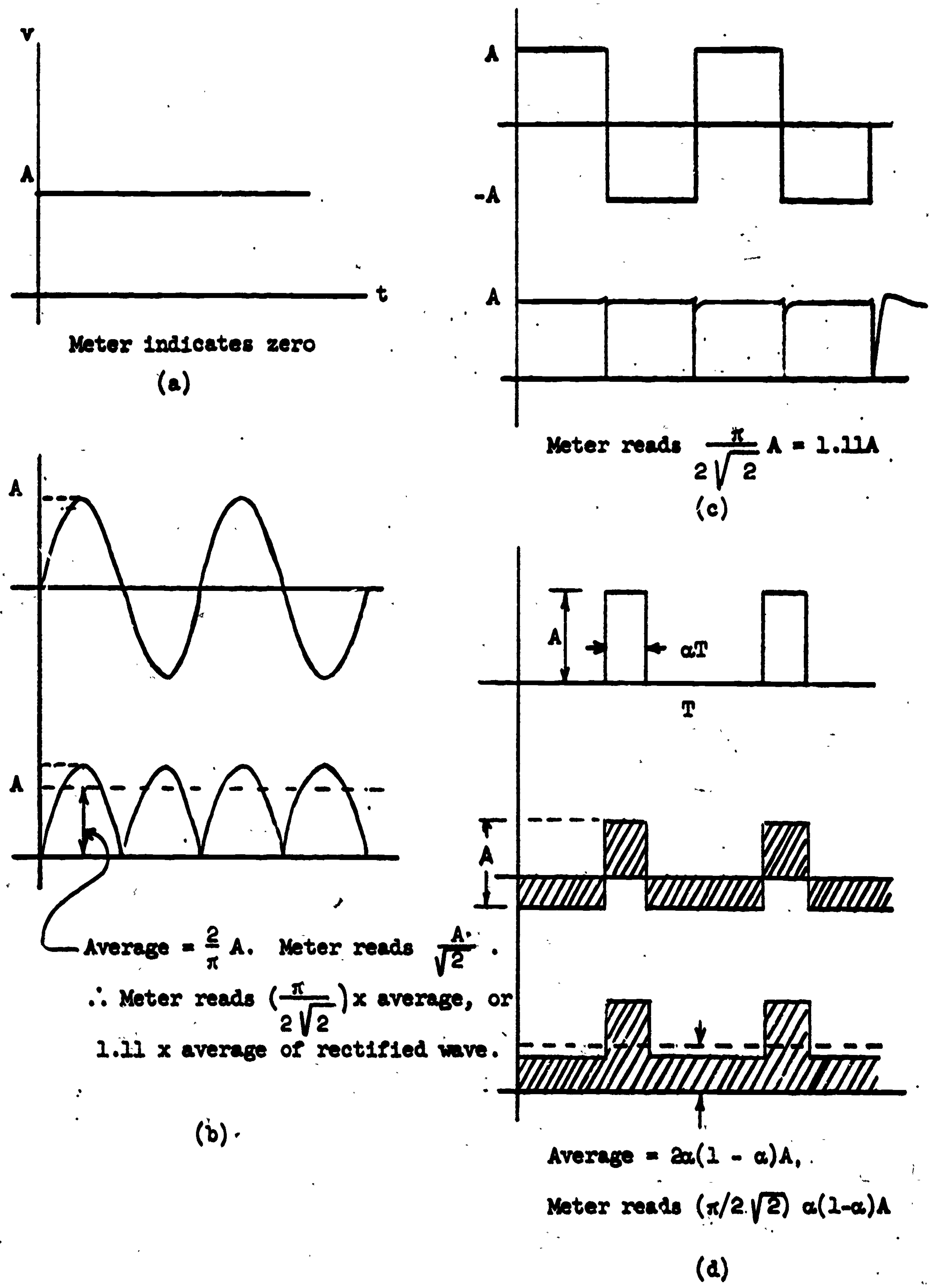


Fig. 6 Typical waveform responses for amplifier-rectifier-type meter

There appear to be several reasons for the series-blocking capacitor. One reason is that in many practical measuring tasks only the alternating component is of interest. Another reason is that a-c amplifiers are easier to design and cheaper to build than d-c amplifiers.

II-2. Rectifier-Type A-C Voltmeters

A great many a-c voltmeters for use at power and audio frequencies do not use vacuum-tube amplifiers. In general there are two sub-types depending on whether they employ a full-wave or half-wave rectifiers. A functional block diagram and typical wave forms for a half-wave rectifier meter are shown in Fig. 7 and for a full-wave-rectifier type in Fig. 8.

In operation, as shown in Fig. 7, the half-wave rectifier type responds in proportion to the average of the positive (or negative) voltage. Thus, if the rectifiers are ideal, for a sine-wave input the average meter voltage is $\sqrt{2}/\pi$ times the rms value of the sinewave; consequently, if an ordinary d'Arsonval volt meter were to be recalibrated for this application the scale designations would have to be increased by $\pi/\sqrt{2} = 2.22$. By the same reasoning, the full-wave rectifier type meter responds according the average of the rectified input and an ordinary d'Arsonval voltmeter would have to have its scale designation increased by $\pi/(2\sqrt{2}) = 1.11$.

Sometimes a series capacitor is employed to block the d-c component of the input wave. This connection or switch position is usually labeled OUT-PUT. When this arrangement is employed, the response reverts to that discussed in Section II-1 and shown in Fig. 6.

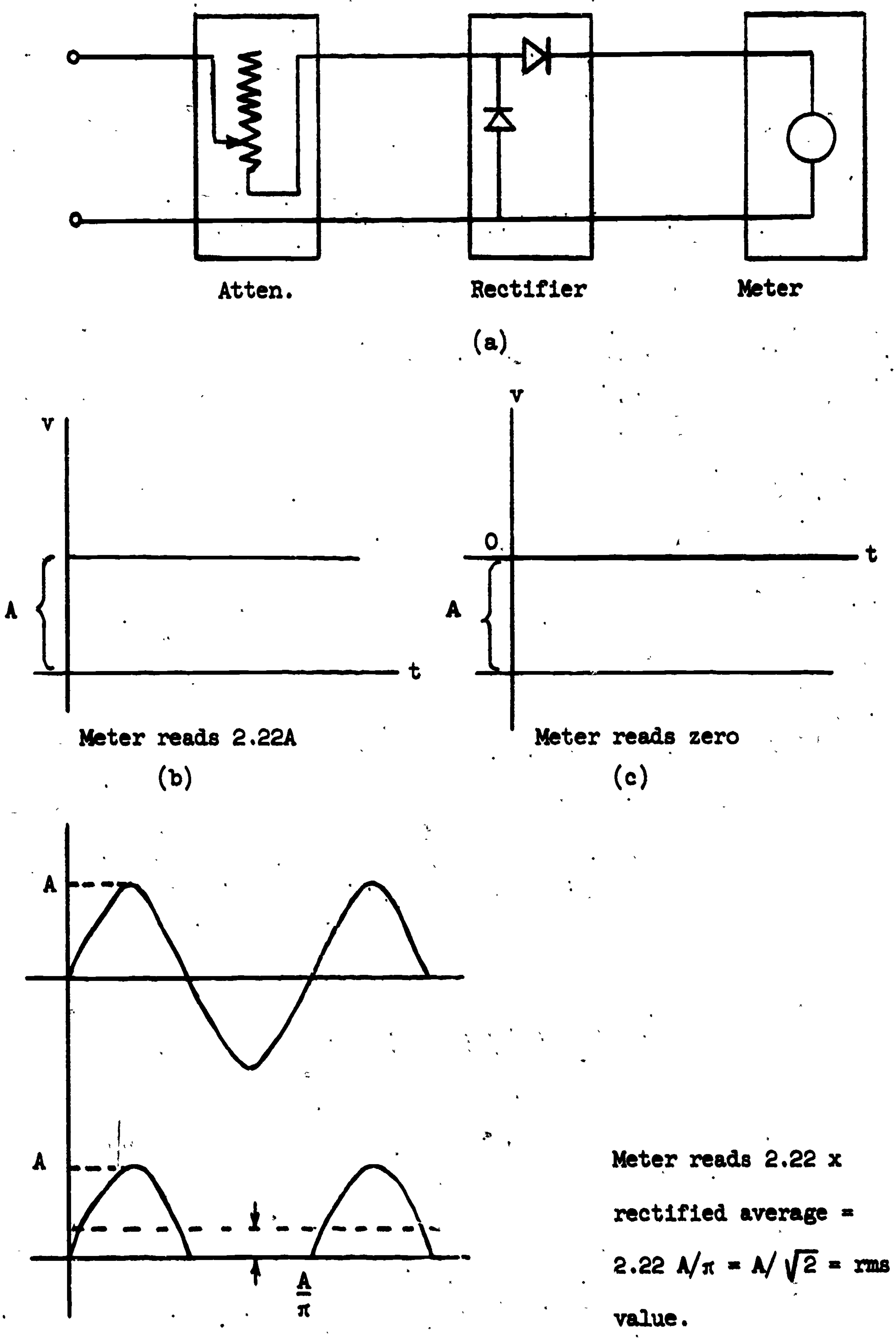


Fig. 7 Half-wave rectifier meter: (a) block diagram; (b), (c), and (d) waveform response examples

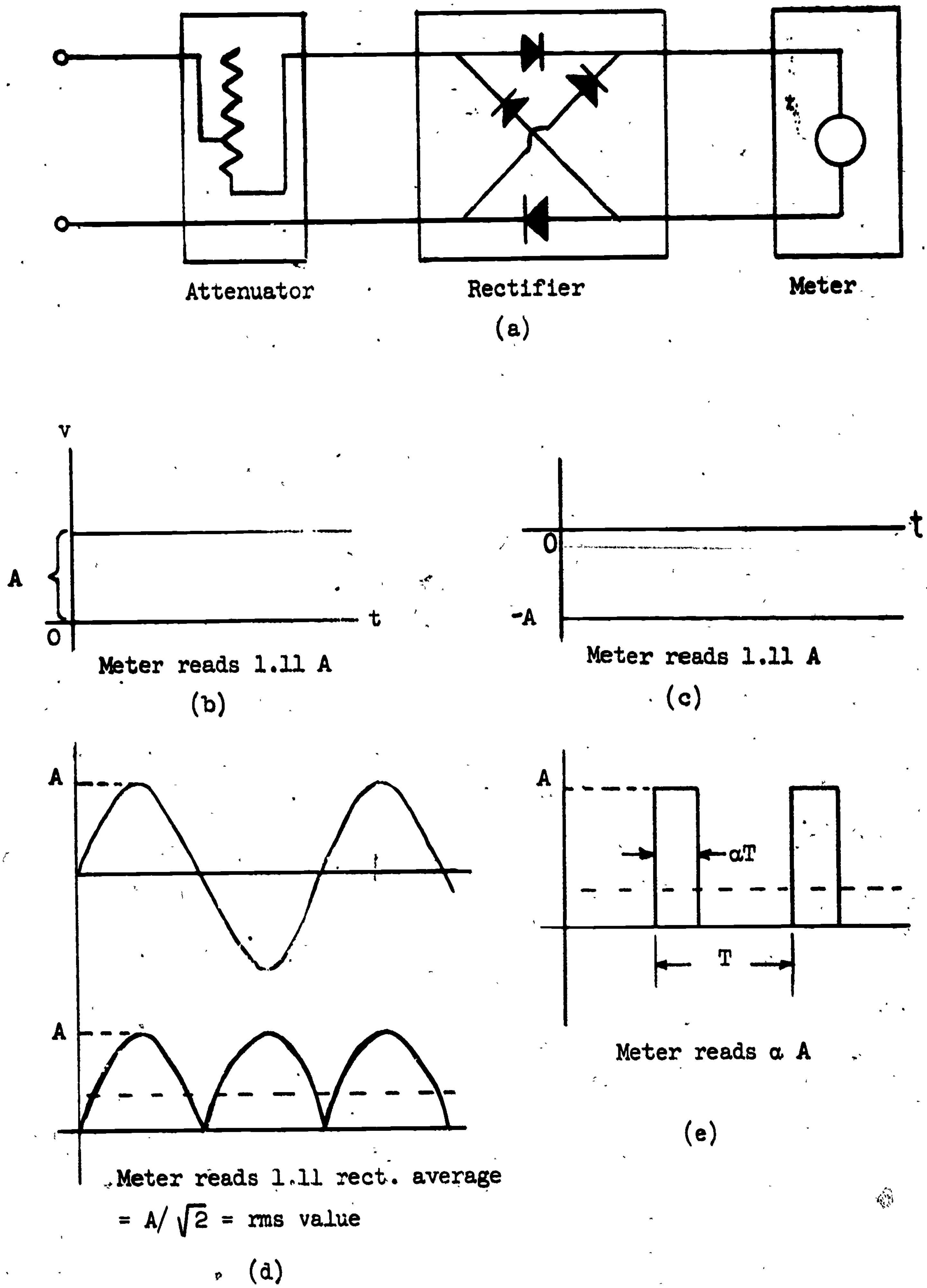


Fig. 8 Full-wave rectifier meter: (a) block diagram; (b), (c), (d) and (e) waveform response examples

II-3 Frequency Ranges and Loading

The typical amplifier-rectifier meters respond to a sine wave within their accuracy guaranties of to five per cent over a wide frequency range from say 5 cps to perhaps one to four mc depending on the meter.

If harmonies are present which are above the frequency limit, then measurements become unreliable. If the waveform being measured is very "peaked", response may be inaccurate because the peaks will overdrive the amplifiers, even though the indication is much less than full scale. Measurements of "noise", especially, become doubtful.

One important advantage of the amplifier-rectifier meter over all the other types descussed here is the practicability of low-voltage ranges. Some amplifier-rectifier meters have full-scale deflection as low as 0.0001 volts while the other types of meters usually have a smallest full-scale voltage of the order of 1/2 to 2-1/2 volts.

The amplifier-rectifier type meters usually have a constant input impedance of the order of 1 megohm, while the rectifier types usually have a constant sensitivity on all ranges of the order of 500 to 5000 ohms per volt.

The rectifier-type meters have some unusual waveform response properties at frequencies where the meter-movement inductance becomes important. These questions are not considered here.

III. PEAK READING AND PEAK-TO-PEAK READING INSTRUMENTS

III-1. Clamper-Amplifier Voltmeter

In the vacuum-tube voltmeters intended for use at the highest possible frequencies, a detector-amplifier or clamper-amplifier circuit is usually employed. This circuit is designed to perform the following operations on a waveform:

1. Take the alternating component, i.e. block the d-c component.
2. Measure the positive (or negative) peaks of the a-c component, and give an indication proportional to this quantity.

Thus to indicate the rms value of a sine-wave the meter should be calibrated to read $1/\sqrt{2} = 0.707$ of the peak value. Fig. 9 shows a functional block diagram and typical waveform responses.

In using such VTVM's precautions about waveform are important. Small "parasitic" oscillation or "spikes" may not be noticed even with an oscilloscope, but they may put high peaks on a waveform, that are unsuspected. Thus the indication will be too high.

On the other hand, these VTVM's are not satisfactory for measuring pulse voltages if the pulse width is a small fraction, say 0.1 or less of a period. This shortcoming is due primarily to the necessity of employing non-ideal diodes.

Clamper-amplifier-type meters may be good up to several hundred megacycles. Ranges usually extend from about 0.5 volts minimum full scale to several hundred volts maximum full scale. The input impedance is usually high enough so that the nonlinearity of the input circuit does not distort the wave being measured, but this possibility cannot be neglected. The impedance is usually a capacitance of a few picofarads shunted by an "effective" resistance of a few megohms.

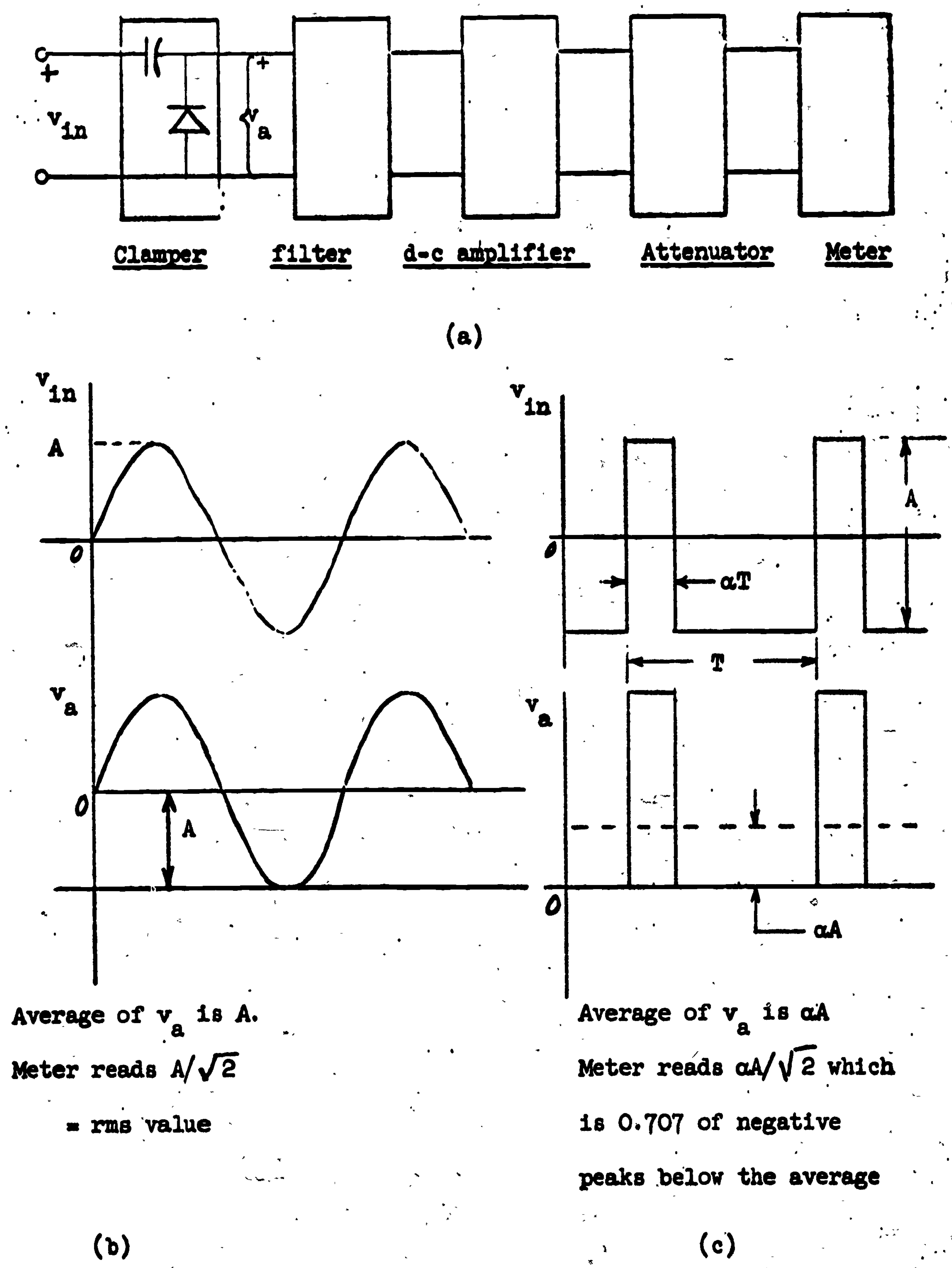


Fig. 9 Clamper-amplifier vacuum-tube voltmeter and typical responses.

III-2. Peak-to-Peak Voltmeters

Many of the same remarks apply to peak-to-peak voltmeters as have been mentioned above either in connection with the amplifier-rectifier meter or the clamper-amplifier meter. The reader is left to work out for himself the waveform-response and other implications.

Conclusions

The actual circuits details of various a-c vacuum-tube voltmeters can usually be obtained from the manufacturer's instructions and are often fairly complicated.

In choosing a voltmeter to measure nonsinusoidal waves, a rectifier-type meter often give a fairly good approximation to the rms value, and is almost always used without correction. In communication and control type circuits, rms values have little special virtue: Other measures of a voltage such as peaks and average are often more significant; nevertheless, by convenient convention nearly all meters read the rms value of a sine wave. In power work, however, rms values of nonsinusoidal waves often are the significant measures, because they provide measures of power transferred and power lost.

Table I tabulates for comparison some of the significant properties of a number of commercial instruments.

TABLE I

Properties of A-C Voltmeters

Manufacturer Model Number	G. R. 726A	G. R. 1800	G. R. 1803-B
Circuit type	Clamper Amplifier	Clamper Amplifier	Clamper Amplifier
Sensitivity Ω/V	- - -	- - -	- - -
Input Impedance	- - -	10K - 25 Meg. 3.1 pf	10-12 pf 7.7 Meg.
Frequency Range	- - -	d-c up to 100-200 Mc.	~ 100 Mc.
Voltage Ranges:			
Min. f.s. volts	1.5	0.5	1.5
Max. f. s. volts	150	150	150
Accuracy	- - -	± 2%	± 3%
Amplifier Output: Max. Volts Internal Imp.	None	None	None
Remarks:	Has terminals or probe input	Has terminals or probe input. Also d-c	Has terminals or probe input. Also d-c

Manufacturer	H. P.	H. P.	H. P.	H. P.
Model Number	400A	400C	400D	410B
Circuit type	Amplifier Rectifier	Amplifier Rectifier	Amplifier Rectifier	Clamper Amplifier
Sensitivity	- - -	- - -	- - -	- - -
Input Impedance	15 pf	15-24 pf	14-24 pf	1.5 pf
	1.0 to 2.4 Meg.	10 Meg.	10 Meg.	10 Meg. or lower
Frequency Range	10 cps to 1 Mc.	20 cps to 2 Mc.	10 cps. to 4 Mc.	20 cps to 700 Mc.
Voltage Ranges:				
Min. f.s. Volts	0.03	.001	.001	1
Max. f.s. Volts	300	300	300	300
Accuracy	± 3% 10 cps-100 KC ± 5% to 1 Mc.	± 3% 20 cps-100 KC ± 5% to 2 Mc.	2% 20cps to 1Mc 3% 20cps to 2Mc 4% 10cps to 4Mc.	3%
Amplifier Output	None			None
Max. Voltage		0.5 Volts	0.15 Volts	
Internal Impedance		1000 Ohms	50 Ohms	

Manufacturer	Ballantine	RCA	RCA	Simpson
Model Number	314	WV-97A	WV-98A	260
Circuit type	Amplifier Rectifier	peak to peak	peak to peak	fullwave rectifier
Sensitivity	- - -	- - -	- - -	Ω/Volt
Input Impedance	7.5 pf 11-0.8 Meg.	60-70 pf 0.83 to 1.5 Meg.	60-70 pf 0.83 to 1.5 Meg.	- - -
Frequency Range	15 cps to 6 Mc.	30 cps to 80-3000 Kc.	30 cps to 80-3000 Kc	20 cps to 30 Kc.
Voltage Ranges:				
Min. f.s. Volts	.01	1.5	1.5	2.5
Max. f. s. volts	1000	1500	1500	1000
Accuracy	3% 15 cps-3Mc 5% to 6 Mc.	5%	3%	3%
Amplifier Output		None	None	None
Max. Volts	1.0 volts	- - -	- - -	- - -
Internal Impedance	500 Ohms	- - -	- - -	- - -
Remarks		d-c; ohms also	d-c; ohms also	d-c; ohms also