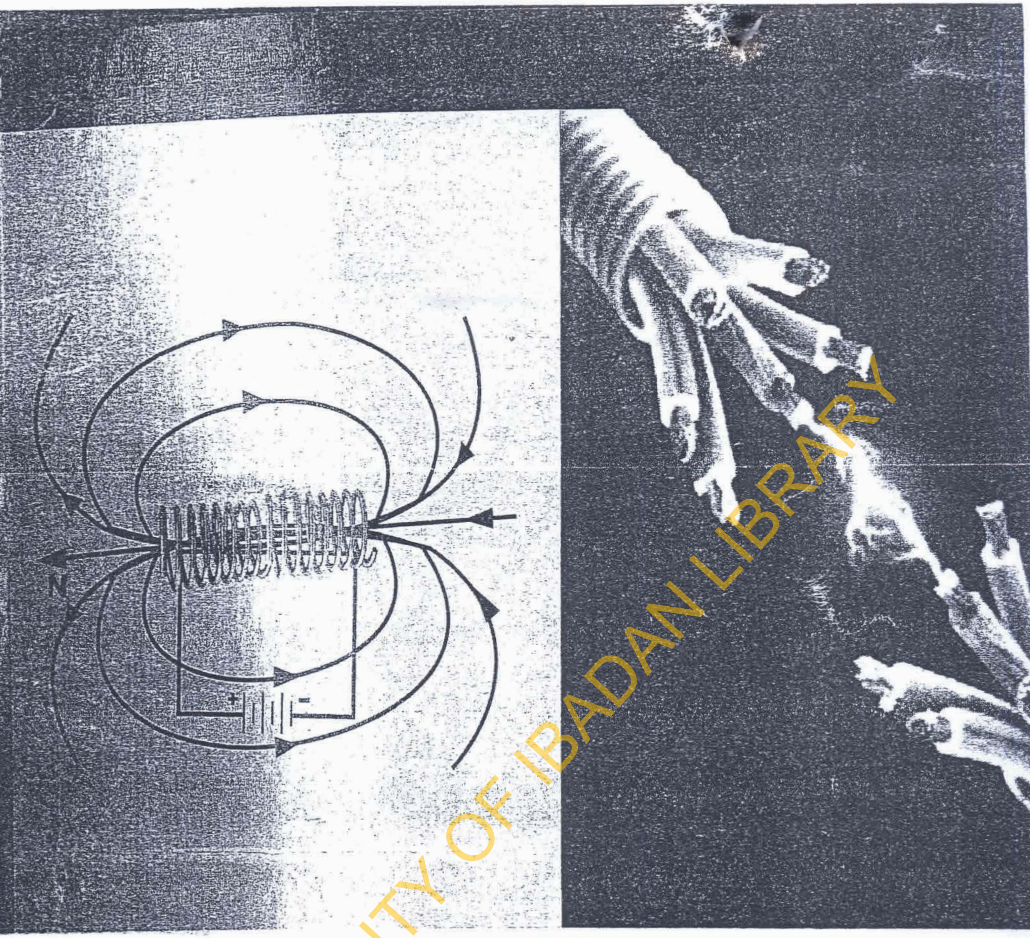

FUNDAMENTALS OF ELECTRICITY AND MAGNETISM

A Festschrift for Professor A. I. Babalola

Edited by
Idowu P. Farai
Olatunde M. Oni

Fundamentals of Electricity and Magnetism

A Festschrift for Professor Ayodele I. Babalola

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Foreword

I am honoured to be invited by serving members of our Department—The Department of Physics of the University of Ibadan—to write a ***Foreword*** to this ***Festschrift*** for Professor Israel Ayo Babalola who retired from the Department about eight (8) years ago.

Having obtained his first degree from the Department in June 1968, Ayo went on to obtain his Ph.D in the Department in February 1972 in the area of Experimental High Energy Nuclear Physics, the first doctoral research activity in this field in Nigeria.

On account of our inadequate resources to work meaningfully in this field, I encouraged Ayo, as Head of Department at that time, to move into another new area, that of Applied Experimental Solid State Physics. Thereafter, he spent a year's study leave at the Solid State Electronics Laboratory of the Electrical Engineering Department of Stanford University, California, USA. Because of Ayo's background and versatility, he was able to add this new load to his academic luggage and to initiate new research efforts in the area in the Department. He subsequently visited the Stanford Laboratory because of the good impression he made at his first visit. In 1982, Ayo was appointed an Associate of the International Centre for Theoretical Physics in Trieste, Italy.

During my tenure as Head of Department, Professor Babalola was appointed the Technical Director of the Federal Radiation Protection Service, supervised by the Department of Physics, and for which the Department was responsible to the Federal Ministry of Health of the Government of Nigeria. He filled the position with dedication and distinction. Ayo was an efficient and devoted teacher at the undergraduate and postgraduate levels, and he taught broadly through the syllabuses at both levels.

This ***Festschrift*** at the introductory level of Electricity and Magnetism is a tribute to Professor Babalola's contributions in teaching the subject as one of the basic foundations for Physics at the elementary level. It is hoped that it will improve the teaching of the subject at this level.

Olumuyiwa Awe
Emeritus Professor of Physics
University of Ibadan, Ibadan, Nigeria

Preface

The physical universe is sustained by interactions between matter and energy, every interaction process being governed by laws. Physics is the study of these laws, often through empirical measurements and/or with the language of Mathematics. The results of the study are the technological innovations that continue to affect the quality of all facets of our lives.

The traditional approach to the study of physics is to divide the subject into different areas according to the dominant forms of energy with which matter is known to interact in each area. There are usually six areas: Mechanics, Heat and Thermodynamics, Waves (optics and sound), Electricity and Magnetism, Atomic and Nuclear Physics and Modern Physics. This book, *Fundamentals of Electricity and Magnetism,* is on the ground rules of Electricity and Magnetism—two branches of Physics that are inseparable. The book is a joint effort of the entire teaching staff of Physics Department, University of Ibadan to tackle the national problem of paucity of books that are written by the teachers of the subject. The experience gathered over decades of teaching PHY 112, a second semester course on the subject, has been lucidly displayed in every chapter.

Starting with properties of the stationary electric charge and a description of the static electric field surrounding it from the very elementary level, the book covers in detail, current electricity and circuits of different kinds, magnetic fields, electromagnetic induction and their applications without assuming any serious previous knowledge of the subject. With clear and unambiguous expressions, illustrative diagrams and worked examples, the book has been simplified but, without diluting the subject matter. It is simple enough for private studies but it is intended to complement and not to substitute class notes.

I am satisfied and proud of its quality as a very useful book for 100-level and 200-level Science, Engineering and Medical students in tertiary institutions.

Idowu P. Farai
Professor and Head
Department of Physics
University of Ibadan, Ibadan, Nigeria

Contributors

Adedeji A. Adetoyinbo, Ph.D, is a lecturer in Department of Physics, University of Ibadan

Anthony O. Alabi, a former lecturer in Department of Physics, University of Ibadan and now relocated to the United States of America.

Emmanuel F. Nymphas, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Emmanuel O. Joshua, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Folorunso O. Ogundare, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Idowu P. Farai, Ph.D, is a Professor in the Department of Physics, University of Ibadan.

Ismaila A. Ojoawo, Ph.D, is a lecturer in the Department of Physics, University of Ibadan.

James A. Adegoke, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Janet A. Ademola, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Mojisola O. Adeniyi, Ph.D, a Senior Lecturer in the Department of Physics, University of Ibadan.

Muritala A. Ayoola, Ph.D, a former lecturer in Physics, University of Ibadan and now at the Department of Physics, Obafemi Awolowo University.

Nnamdi N. Jibiri, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Olatunde I. Popoola, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Olukorede O. Adewole, a former lecturer in Physics, University of Ibadan and now a lecturer in the Department of Physics, Ajayi Crowther University, Oyo.

Oluseyi E. Awe, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Rachel I. Obed, Ph.D, is a Senior Lecturer in the Department of Physics, University of Ibadan.

Taofeek A. Otunla, Ph.D, is a lecturer in the Department of Physics, University of Ibadan.

9

THE POTENTIOMETER AND ITS APPLICATIONS

J.A. Adegoke

9.1 The Potentiometer

A potentiometer is an instrument for measuring the potential (voltage) in a circuit. Before the introduction of the moving coil and digital volt meters, potentiometers were used in measuring voltage, hence the 'meter' part of their name. In this arrangement, a fraction of a known voltage from a resistive slide wire is compared with an unknown voltage by means of a galvanometer. The sliding contact or wiper of the potentiometer is adjusted and the galvanometer briefly connected between the sliding contact and the unknown voltage. The deflection of the galvanometer is observed and the sliding tap adjusted until the galvanometer no longer deflects from zero. At that point the galvanometer draws no current from the unknown source, and the magnitude of voltage can be calculated from the position of the sliding contact. This null balance measuring method is still important in electrical metrology, calibrations and is also used in other areas of electronics.

The present day potentiometer can be used as a potential divider (or voltage divider) to obtain a manually adjustable output voltage at the slider (wiper) from a fixed input voltage applied across the two ends of the potentiometer.

9.2 Potentiometer as a Measuring Instrument

The original potentiometer is a type of bridge circuit for measuring voltages by comparison between a small fraction of the voltage which could be precisely measured, then balancing the two circuits to get null current flow which could be precisely measured.

9.3 The Potential Divider

Two resistances in series can be arranged so as to provide a fraction of a given potential difference. The arrangement is known as a potential divider (fig. 9.1).

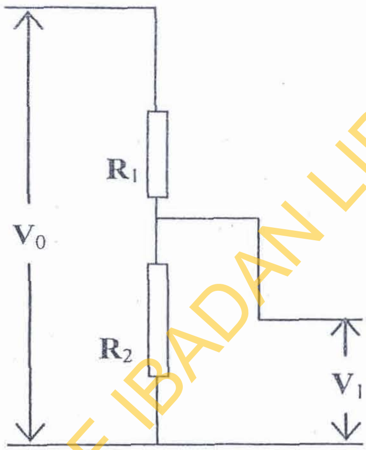

Fig. 9.1: A potential divider with resistances R_1 and R_2 across a p.d. V_0.

Let the current flowing be I,

Then $I = \dfrac{V_0}{R_1 + R_2}$

$$V_1 = IR_1 = \frac{R_1}{R_1 + R_2} . V_0$$

The fraction of V_0 obtained across R_1 is $\dfrac{R_1}{R_1 + R_2}$. If $R_1 = 20\Omega$ and R_2 is 1000Ω, then

$$V_1 = \frac{20}{20 + 1000} . V_0$$

$$= \frac{20}{1020} . V_0 \quad = \quad \frac{1}{51} . V_0$$

A resistor with a sliding contact or simply put, a solid long/continuous resistor can similarly be used, as in figure 9.2 to provide a continuous variable potential difference V_1 from zero to the full supply value V_0. This provides a convenient way of controlling the voltage applied to a load such as a lamp.

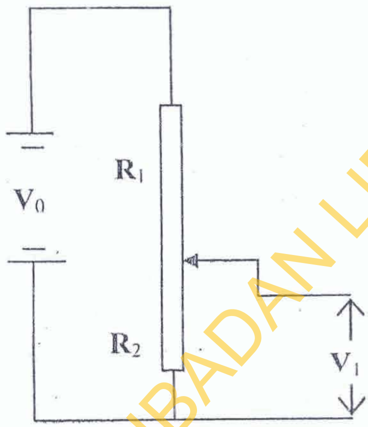

Fig. 9.2: A potential divider with a long variable resistor R_1 and R_2 across a p.d. V_0.

Worked Example

Suppose in figure 9.2, $R_1 = 1\Omega$, and $R_2 = 3\Omega$. Since the same current I flows through (series connection) the resistors, then

$$V = IR$$

and $$V \alpha R$$

It means that the potential difference across each resistor is in proportion to its resistance value. The ratio of the p.d. across R_1 and $R_2 = 1:3$. The p.d. across both resistors is V_0.

So p.d. across R_1 is $\frac{1}{1+3} V_0 = \frac{1}{4} V_0$

p.d. across R_2 is $\frac{3}{1+3} V_0 = \frac{3}{4} V_0$

9.4 The Slide-Wire Potentiometer

This is used for measuring voltages below 1.5 volts. In this circuit (as illustrated in figure 9.3), the unknown voltage is connected across a section of resistance wire typically 1m in length, the ends of which are connected to a standard electrochemical cell E_0 that provides a constant current through the wire. The unknown emf E_1, in series with a galvanometer, is then connected across a variable-length section of the resistance wire *AB*, using a sliding contact. The sliding contact is moved until no current flows into or out of the standard cell, as indicated by a galvanometer in series with the unknown emf. The voltage across the selected section of wire is then equal to the unknown voltage. The unknown voltage E_1 can be calculated from the current and the fraction of the length of the resistance wire that was connected to the unknown emf. The galvanometer does not need to be calibrated, as its only function is to read zero. When the galvanometer reads zero, no current is drawn from the unknown electromotive force and so the reading is independent of the source's internal resistance.

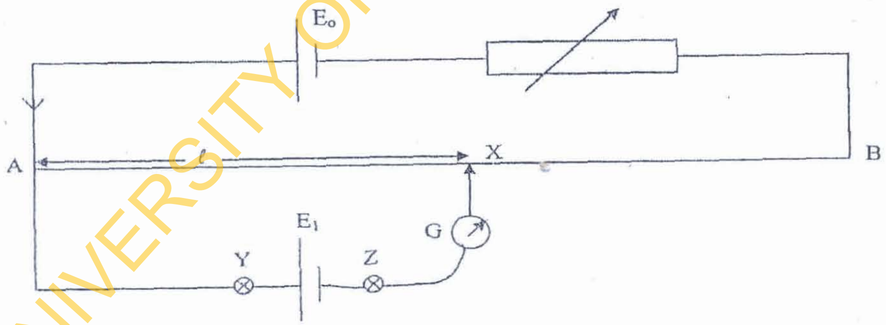

Fig. 9.3: Basic arrangement for the measurement of an e.m.f

E_0 = Source e.m.f.
E_1 = Unknown e. m.f
l = distance AX
YZ = terminals
AB = Uniform resistance wire
G = galvanometer

AB is exactly *1.0m* and *l* is the distance between *A* and *X*, is the sliding contact. At point *X*, the galvanometer indicates no current; *l* is therefore a measure of the e.m.f. *E*.

At balance point, $V_Y = V_A$

This is because there is no current along *AY*.

Also, $V_Y - V_Z = E = V_A - V_x$

Let *r* represents resistance per unit length of potentiometer wire *AB* and if *I* is current flowing in the circuit,

Then $V_A - V_x = Irl$
$E = Irl = Kl$

where *K* is constant if the current is constant. Subsequently, E_3 and E_4 can be obtained and the corresponding balance lengths l_3 and l_4, when E_3 and E_4 are put in place of E_2 in turn.

Then $\frac{E_3}{E_4} = \frac{Kl_3}{Kl_4} = \frac{l_3}{l_4}$

if E_3 is known then E_4 can be determined.

Example: If a balance point AX (=50.3cm) is obtained in an experiment to determine an unknown value of the e.m.f of a cell, and after a replacement with another cell AX is obtained to be 72.3cm. Then

$$\frac{E_1}{E_2} = \frac{50.3}{72.3} = 0.696$$

$$E_1 = 0.696E_2$$

If E_1 is known then E_2 can be calculated.

Measurement potentiometers are divided into four main classes:

(A) Constant Current Potentiometer

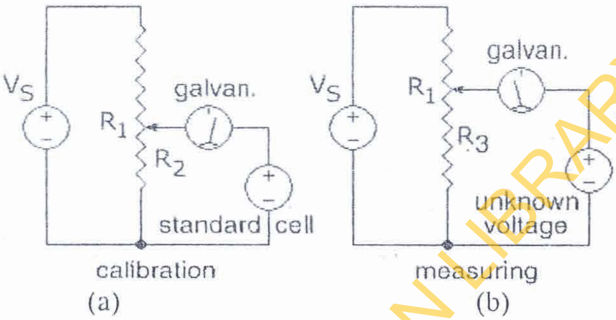

Fig. 9.4: A potentiometer, (a) being calibrated and, (b) measuring an unknown voltage. (R_1 is the resistance of the entire resistance wire. The arrow head represents the moving wiper/sliding contact).

In this circuit (fig. 9.4), the ends of a uniform resistance wire R_1 are connected to a regulated DC supply V_S for use as a voltage divider. The potentiometer is first calibrated by positioning the jockey/sliding contact at the spot on the R_1 wire that corresponds to the voltage of a standard cell so that

$$\frac{R_2}{R_1} = \frac{cellvoltage}{V_S}$$

A standard electrochemical cell is used whose emf is known.

The supply voltage V_S is then adjusted until the galvanometer shows zero, indicating the voltage on R_2 is equal to the standard cell voltage.

An unknown DC voltage, in series with the galvanometer, is then connected to the sliding jockey, across a variable-length section R_3 of the resistance wire. The wiper/jockey is moved until no current flows into or out of the source of unknown voltage, as indicated by the galvanometer in series with the unknown voltage. The voltage across the selected R_3 section of wire is then equal to the unknown voltage. All that remains is to calculate the unknown voltage from the fraction of the length of the resistance wire that was connected to the unknown voltage.

Again, the galvanometer does not need to be calibrated, as its only function is to read zero or not zero. When measuring an unknown voltage and the galvanometer reads zero, no current is drawn from the unknown voltage and so the reading is independent of the source's internal resistance, as if by a voltmeter of infinite resistance.

Because the resistance wire can be made very uniform in cross-section and resistivity, and the position of the wiper can be measured easily, this method can be used to measure unknown DC voltages greater than or less than a calibration voltage produced by a standard cell without drawing any current from the standard cell.

If the potentiometer is attached to a constant voltage DC supply such as a lead–acid battery, then a second variable resistor (not shown) can be used to calibrate the potentiometer by varying the current through the R_1 resistance wire.

If the length of the R_1 resistance wire is AB, where A is the (-) end and B is the (+) end, and the movable wiper is at point X at a distance AX on the R_3 portion of the resistance wire when the galvanometer gives a zero reading for an unknown voltage, the distance AX is measured or read from a preprinted scale next to the resistance wire. The unknown voltage can then be calculated:

$$V_U = V_S \frac{AX}{AB}$$

Constant Resistance Potentiometer

The constant resistance potentiometer is a variation of the basic idea in which a variable current is fed through a fixed resistor. These are used primarily for measurements in the millivolt and microvolt range.

Microvolt Potentiometer

This is a form of the constant resistance potentiometer described above but designed to minimize the effects of contact resistance and thermal emf. This equipment is satisfactorily used down to readings of 1 μV.

(D) Thermocouple Potentiometer

Another development of the standard types was the 'thermocouple potentiometer' especially adapted for temperature measurements with thermocouples. Potentiometers for use with thermocouples also measure the temperature at which the thermocouple wires are connected, so that cold-junction compensation may be applied to correct the apparent measured emf to the standard cold-junction temperature of 0°C.

Summary

(1) A potentiometer is an instrument for measuring the potential (voltage) in a circuit.

(2) Two resistances in series can be arranged so as to provide a fraction of a given potential difference. The arrangement is known as a potential divider.

(3) Measurement potentiometers can be divided into four main classes which are:

- (a) Constant current potentiometer
- (b) Constant resistance potentiometer
- (c) Microvolt potentiometer
- (d) Thermocouple potentiometer

EXERCISE

A load of 2000 Ω is connected, through a potential divider of resistance 4000 Ω, to a 10V supply (fig. 9.5). What is the potential difference across the load when the slider is

- (a) over a quarter,
- (b) half-way up the divider

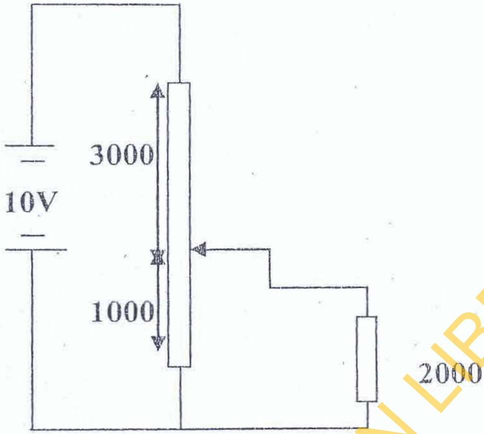

Figure 9.5