ELECTRICITY IN AGRICULTURAL ENGINEERING

THE FERGUSON FOUNDATION
AGRICULTURAL ENGINEERING SERIES

ELECTRICITY IN AGRICULTURAL ENGINEERING

Truman E. Hienton
DIRECTOR FARM ELECTRIFICATION
RESEARCH LABORATORY USDA

Dennis E. Wiant
PROFESSOR OF AGRICULTURAL ENGINEERING
MICHIGAN STATE UNIVERSITY

Oral A. Brown
CONSULTANT TO AGRICULTURAL
ENGINEERING RESEARCH DIVISION USDA

1958

JOHN WILEY & SONS, INC., NEW YORK
CHAPMAN & HALL, LTD., LONDON

Library of Congress Catalog Card Number: 58-6075

PRINTED IN THE UNITED STATES OF AMERICA

Preface

This book is concerned with fundamentals of electric energy and their applications to agricultural practices. It was prepared as a textbook for teaching courses in rural electrification to agricultural engineering students. We believe that rural electrification engineers also will find it helpful as a reference text and aid in solving technical engineering problems in farm applications of electric energy.

Results of numerous, varied experiments on farm applications of electric lighting and other radiation, electric motor operation of farm machines, and electric heating for biological and farm processing purposes have been published in this country and abroad. Engineering information on appropriate investigations has been summarized and presented in this textbook together with fundamentals of design of the electric equipment involved. This method of presentation has been employed to enable the agricultural engineer to utilize not only known methods and equipment but also to develop new or improve existing methods and equipment for farm applications of electric energy.

The textbook has been prepared on the assumption that students will have had a course in engineering physics which included the principles of electricity and magnetism and at least one general single-semester course in electrical engineering. The first five chapters have been included to review and further establish a good understanding of the fundamentals and laws of electricity. Limited attention has been devoted to generation, transmission, and distribution of electric energy.

The electric motor has been given extensive treatment because of its increasing importance as a farm power unit. Choice of the proper type of motor for a specific machine must be based on the power requirement of that machine and design of the motor. Additional knowledge of motor wiring requirements, motor controls, and protective devices is essential to insure proper installation and operation of motors for driving farm machines.

Electromagnetic radiation has also been treated extensively because of the accelerated recognition of its potentially wider application in agricultural practice. The visible, ultraviolet, and infrared portions of the electromagnetic spectrum are covered in greatest detail because of wide agricultural engineering interest in solar radiation as well as in electrical sources of such radiation. Radiation in other regions of the spectrum have been included particularly in the radio-frequency range.

Preparation of this book has been made possible through financial support of the Ferguson Foundation, Detroit, Michigan, and personal advice and support of Mr. Harold Pinches of the Foundation. It would have been impossible to undertake preparation of the book without this support. Our appreciation is gratefully acknowledged for the material furnished by many persons and organizations. Manufacturers of electric equipment have been very generous in supplying illustrative material.

The preliminary, off-set edition was used for instruction purposes at the Universities of Idaho and Illinois, and at Michigan State and Purdue Universities. Recommendations from instructors using this material and other university and industrial representatives who reviewed it have contributed to the accuracy and modernism of the book. Their help has been valuable to us and and is sincerely appreciated. Messrs. A. V. Krewatch and I. J. Pflug assisted in the preparation of material included in two chapters and we are particularly grateful for their contributions.

Hyattsville, Md.
April, 1958

T. E. Hienton
D. E. Wiant
O. A. Brown

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CHAPTER 1

Electricity and Its Relations to Materials

1.1. Introduction. Electricity as a means of supplying energy has come into general farm use. There are many reasons for the great increase of electric energy for performing agricultural operations. A few may be listed to show its importance to agriculture.

Electric energy is generated in large, efficient generating plants and distributed over great areas by transmission lines which serve individual farms. The electric energy generated by steam or hydraulic turbines of large capacity can be used by small units to supply the farm with energy. This energy is available at any time. Electric energy can be converted by rather simple machines to heat, light, sound, and mechanical energy or to chemical reaction to perform tasks and produce results not possible in any other way.

The agricultural engineer can increase the usefulness of electricity to agriculture if he understands the characteristics of the equipment that must be used to transfer and convert electric energy to perform the work that is essential to mechanical farming. The fundamental truths of electric circuits and the facilities for converting electric energy to other forms of energy are better understood than any other means of energy transmission and conversion. However, a good understanding of the fundamentals and laws of electricity are necessary if the most is to be obtained from electric equipment. It is not a subject to be treated lightly if it is to be useful.

There are three ways in which electric energy is made manifest. These are electron displacement, electron movement, and molecular excitation. Insofar as the engineer is concerned, the laws which show the relations among these three are well understood.

The combinations and effects of the three electric characteristics with respect to materials may be rather complex but are limited only by the extent of man's ingenuity. The progress that has been made in the commercial world by intense studies and careful observations has brought us to the electrical age; it has made electricity a household word and a farm necessity. It furnishes light, heat, power, and entertainment; it puts the farmer in touch with the world; it gives him the latest market news and informs him about the most recent practices of his profession; it makes possible at the farm, refrigerators, water systems, irrigation, spraying, hotbeds, storage houses either heated or cooled, and laundry systems. Electricity sweeps floors, cooks food, controls the temperature in winter and summer, milks cows, separates milk, churns butter, regulates the ventilation, kills insects, and can even remove the dust particles from the air. It is truly remarkable what has been accomplished to make electric energy the servant of the farmer. The progress and extension of electric power is in the hands of those associated with farm problems. What can be accomplished with it depends upon the ingenuity of the engineer and his ability to build machines.

1.2. Electric Potential. The meanings of electric potential can best be understood by studying the diagram in Fig. 1.1.

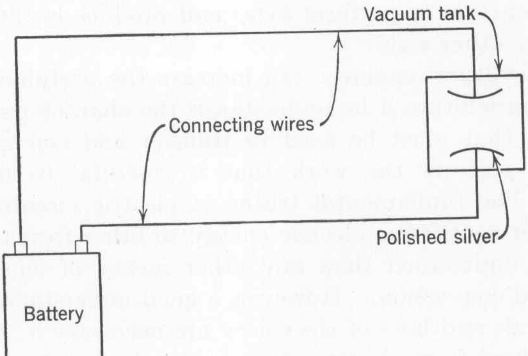

Fig. 1.1. An electric circuit with battery.

The battery is a machine so designed that it will convert chemical energy to electric energy.

The result of the electrons being displaced by the chemical reaction within the battery is an electric potential between the terminals of the battery, and there exists a condition in the space surrounding the battery terminals that did not exist before the battery was placed in the space. The condition in the space is described as an electrostatic field. The strength of the field and the electric potential are the same thing, except as they may be affected by materials of different dielectric properties.

1.3. Electric Current. When the battery is connected by small wires to the silver plates in the vacuum tank, there is an electron movement from the normal orbits of the molecules as well as a molecular excitation in the wires, and energy is transferred from the battery to the plates. Since energy is required to excite the molecules, all of the energy that leaves the battery will not reach the plates. Part of it will be changed to radiation and will be radiated from the conductor.

The electrons, which are made to move because of the electric (electrostatic) field of the battery and the nature of the materials of the circuit, create a condition around the wires described as an electromagnetic field. Since this condition is related to the electron movement in the wire, it is said that a current flows in the wire and that an electric potential exists between the wires. The magnetic field and current are functions of each other, just as the electric field and electric potential are functions of each other.

1.4. Contact Potentials. In the early part of the 19th century, Volta showed that when disks of two metals were brought in contact, insulated, and separated, each had acquired an electric charge of opposite sign. He also constructed the first galvanic pile (battery) by separating alternate layers of copper and zinc by moistened paper.

Now it is known that the electron emission of perfectly pure metals in a very good vacuum is a definite quantity—an intrinsic property of the metal. The rate of emission of electrons, n, from a pure metal can be represented by the relation

$$n = AT^2e - \rho/kT \tag{1.1}$$

A is a constant which is characteristic of the metal, the emitter; k is the universal Boltzmann gas constant (1.3708×10^{-16}); ρ is the thermionic work function of the metal surface; and T is absolute temperature.

The ability of a metal to emit electrons is responsible for the contact potentials between different metals and for the potential developed by a battery.

Irving Langmuir pointed out in 1916 that large potential differences that are of the same order of magnitude as the electromotive force of the cell exist at the metal junctions in a galvanic cell.

Any operation that causes electrons to be displaced from a neutral atom will generate an electric potential. The potential is represented by the amount of free energy (the energy not converted to heat) required to remove the electron from the atom. In addition to the energy of an electron in free space there are energy levels represented by the electrons associated with metal atoms, i.e., electron orbitals. Each energy level can accommodate two electrons.

In terms of quantum mechanics there are n^2 orbitals in the shell with a total quantum number n, the number of electrons occupying a completed shell being $2n^2$. In the hydrogen atom there is only one electron in the k shell. The Pauli exclusion principle requires that no more than two electrons occupy a single orbit, and that the two electrons in the same orbit have opposite spins. The spins of the electrons are associated with the magnetic field.

1.5. Photoelectric Effects. Electrons may be emitted by a metal when light falls on the surface. Light of shorter wavelengths causes higher energy electron emission than light of longer wavelengths. Einstein first put the relation in the form of an equation

$$\tfrac{1}{2}mv^2 = h\nu - \rho \tag{1.2}$$

In this equation h is Planck's constant ($6.547 \pm 0.008 \times 10^{-27}$ erg sec), ν is the frequency of the incident light, and $h\nu$ is the quantum of energy provided by the incident light. In escaping from the metal, the electron loses at least the energy ρ (the work function) and emerges with a kinetic energy of $\frac{1}{2}mv^2$. At the frequency that gives the electron no velocity at the surface,

$$\tfrac{1}{2}mv^2 = 0$$

and

$$\rho = h\nu\theta \tag{1.3}$$

At frequencies lower than $\nu\theta$ no electrons will be emitted from the metal surface.

The relations expressed in equations 1.1 and 1.2 show that if two metal plates be placed in a vacuum and insulated from each other, electrons may be forced from one plate to the other by: (1) one plate's being heated to a temperature high enough above that of the other to give the electrons enough kinetic energy to reach the second plate; or (2) incident light falling on one plate with a frequency high enough to give the electrons emitted from the plate (on which the light falls) sufficient energy to reach the other plate.

In either case an electric potential will be built up on the non-emitting plate with respect to the emitting plate. The potential will continue to build up until the kinetic energy of the electron

$$\tfrac{1}{2}mv^2 = eE \tag{1.4}$$

where e is the charge on the electron and E is the potential between the plates.

1.6. Electromagnetic Induction. A very important method of generating an electric potential is the one of changing the magnetic flux linkage of a circuit. If a closed loop of wire, a circuit, has the magnetic linkage changed by any means whatsoever, an electric potential will be generated in the circuit. The generated potential will be in a direction to produce a current that will oppose the change of magnetic flux linkage. Faraday discovered this important relation and expressed it quantitatively in the following equation:

$$e = N\frac{d\varphi}{dt} \tag{1.5}$$

The potential induced is independent of any other condition of the circuit. It may add to or subtract from any other potential. The equation relates the magnetic field to the electric potential of a circuit. It expresses a quantitative relation that is useful as an engineering tool for developing modern generating equipment and electric distribution systems.

The origin of magnetism has been the subject of many investigations. It is attributed to the spin of the electrons and is an inherent property of the electron. If the electron is caused to move from its normal place in the atom, as is the case when a current flows in a conductor, a quantity of energy is manifest in a magnetic field. The exact nature of the movement of electrons in conductors is not understood. It is not necessary for the engineer to have a knowledge of the nature of the excited electrons to make use of electric circuits. The statistical results of excited molecules, which are termed the electric and the magnetic fields, are bases for the theory of electric circuits.

The methods that have been discussed for developing electric potential differences are only part of a great number of ways by which such differences may be produced. Actually, potential differences are the rule rather than the exception. The engineer, however, is especially interested in methods that will produce and control electric potentials and electric circuits for useful purposes. Thermal and photoelectric methods produce only low electric energy levels whereas electromagnetic induction may be used to produce very great potential differences and large energy displacement.

The many terms associated with the transfer of electric energy may become confusing unless one sees clearly the electric circuit relations.

1.7. The Electron. Much has already been said about the part the electron plays in the transfer of electric energy. Its properties have been measured and are reasonably well known. It has a rest mass of approximately (0.911) (10^{-27}) g and has a negative electric charge. Its mass changes with speed according to the equation

$$m = \frac{m_r}{\sqrt{1 - v^2/c^2}} \tag{1.6}$$

where m_r is the rest mass in grams; c is the speed of light; and v is the speed of the electron.

Electrons in their normal states occupy energy levels around a positively charged nucleus. If all of the energy levels are filled, as in the noble gases, the atom becomes very stable. The numbers of electrons in each of these filled shells are: helium 2, neon 10, argon 18, krypton 36, xenon 54, and radion 86. This sequence of closed shells gives 2 electrons for the first, 8 for the second, 8 for the third, 18 for the fourth, 18 for the fifth, and 32 for the sixth shell. On the other hand, metallic conductors such as silver and copper have unfilled shells with electrons that are easily removed from the atom under the condition of electric excitation. The electrons in the outer shells of the metals make the metals useful for electric circuits.

1.8. The Positron. The positron has exactly the same characteristics as the electron but with a positive instead of a negative charge. In contrast to the long period of time for which an electron may exist as a particle separated from the atom, the positron has a very short life, and the part it plays in the transfer of electric energy is considered negligible.

1.9. The Hole. The flow of electrons may be used to account for both alternating and direct current in metallic conductors. However, the nature of potentials and currents in semiconductors such as transistors cannot be explained on the basis of negatively charged electrons. The theory of transistor operation requires that an energy carrier with the same characteristics of a positron be used to explain the operation in a semiconductor. If an electron be forced out of an atom of a semiconductor, the place left by the electron is termed a hole. The hole has all the electrical characteristics of the electron but has a positive charge.

1.10. Ions. Ions are atoms that have electric charges. If the atom has lost one or more electrons, it is a positive ion. Salts in solution are broken up into ions. The negative ions are anions because they migrate to the anode, and the positive ions are cations because they migrate to the cathode. The term ion is sometimes applied to a metallic molecule that has lost an electron. For example, the plate shown in Fig. 1.1 may have electrons (negative charge) on one plate and ions (positive charge) on the other.

1.11. The Nature of Electrons. There are two theories about the nature of the electron, and each has experimental results to support its validity. One theory is that the electron is a solid particle with a negative electric charge which always occurs in integral multiples of unit amounts. This theory has its foundation in Milliken's experiments made with small charged oil droplets in an electric field and by the experiments by Wilson in his cloud chamber.

The cathode-ray tube, which is familiar to everyone in the form of picture tubes in television sets, is an example of one theory. A hot filament, cathode, emits electrons that strike a fluorescent screen, and by their bombardment they create a light spot that is caused to sweep across the screen to produce a picture.

The other theory is that the electron is an energy front or packet that oscillates at a definite frequency but has no tangible existence as a particle. This theory has its basis in the mathematical prediction of de Broglie that electrons could be diffracted as light waves are diffracted when they pass through fine slits. De Broglie's predictions were found to be correct, and many diffraction patterns have been obtained by passing electrons through crystals.

Since the electron exhibits both corpuscular and wave properties, it may be thought of as a wave packet of energy of which the electron is the locus.

From the point of view of the engineer the electric units for most work are statistical in nature and are measured by external effects. These will be discussed more in detail after some attention is given to the nature of electric current.

CHAPTER 2

Energy Transfer

2.1. Energy Transfer. The transfer of energy from the battery to the plates through wires excites the molecules in the wires in such a way that the molecules give off radiation as heat. The rate at which electric energy is changed to radiation in the molecules of the conductor is a function of the magnetic field around the conductor, which makes it a function of the current I in the conductor, and of the potential drop along the conductor, or Ir drop. The changes in the magnetic field and the molecular excitation are influenced by the transfer of energy from the

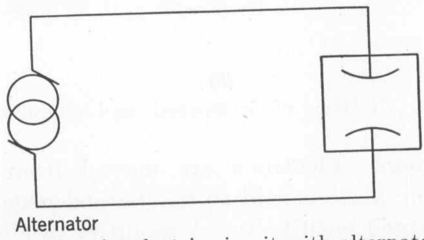

Fig. 2.1. An electric circuit with alternator.

battery to the plates. If the battery is left connected to the plates for a sufficient period of time, the strength of the electric field (the difference of potential) between the wires and between the plates will become equal to the electric field across the terminals of the battery. At the steady-state condition of Fig. 1.1 the magnetic field will disappear, there will be no current in the wires, and the molecules of the wires will no longer be excited to radiate energy. The plates will be electrically charged.

If an alternator is placed in the circuit, Fig. 2.1, there will be a continuous changing of the electric potential, the current in the circuit will alternate, and the plates will charge and discharge. Energy will be transmitted from the alternator to the plates and returned again to the alternator. The only energy required to keep the circuit oscillating will be the energy which is changed to heat in the circuit. The frequency of oscillation will be determined by the characteristics of the circuit.

The factors involved in the transfer of electric energy in a mechanism as shown in Figs. 1.1 and 2.1 are electric potential, electric current, and the electric parameters of the circuit. In the circuit energy was transferred from the battery or alternator to the plates, and a condition of equilibrium was established. The charged plates, however, are different when they are connected to the battery or alternator. There is an electric field

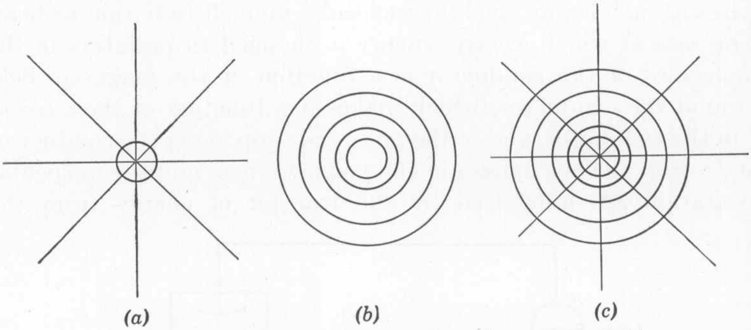

Fig. 2.2. Relation of electrostatic and magnetic fields.

surrounding them. Electrons are moved from one plate to another, and one plate is said to be charged negatively and the other to be charged positively. A quantity of electric energy is stored on the plates and in the space between them, except when the electric potential is zero.

The effects of the electromagnetic (electrostatic and magnetic) field extend in space from the conductor. The electrostatic field of an isolated conductor is assumed to extend radial lines, Fig. 2.2(*a*), and the magnetic field to go out as concentric circles, Fig. 2.2(*b*). If one is superimposed upon the other, Fig. 2.2(*c*), they are at all times at right angles to each other. The energy of the fields is $\frac{1}{2}CV^2$ and $\frac{1}{2}LI^2$, where C and L are parameters of the circuit, V the voltage, and I the current.

It is the electromagnetic field which forms a connecting link from one circuit to another and is responsible for transmitting energy through space by radio. The characteristics of the electromagnetic waves are affected by frequency. As the frequency increases, they approach the characteristics of light. The importance of electromagnetic waves in agriculture is just beginning to be investigated. The energy transmitted by them can be used to destroy insects and bacteria, and to dry farm products. What their effects may be on animal and plant life is an unknown factor. A weak electrostatic field with a strong magnetic field for inducing heat into metal parts for hardening, brazing, annealing, and soldering is finding greater application to many products. Its use on farms can be greatly extended.

2.2. The Parameters of an Electric Circuit. The parameters of an electric circuit are made up of three circuit components: (1) The *resistance* of the circuit is determined by the properties of the conductors of the circuit. It is not necessary that the circuit be made of segments of equal resistance. (2) The amount of magnetic linkage (the number of magnetic flux tubes linking the circuit) per unit current is a measure of the *inductance* of the circuit. (3) If conductors be connected to metal plates, shown in Fig. 2.1, which are separated by a vacuum or an insulator, an electric potential will be built up between the metal plates. Electric flux tubes will extend from one plate to the other. The intensity of the electric field per unit potential is a measure of the *capacitance* of the circuit. The three electric parameters of the circuit, r (resistance), L (inductance), and C (capacitance) determine the circuit characteristics.

The purpose of any circuit is to transfer electric energy from an electric generator, battery, or alternator, shown in Figs. 2.1, and 4.1 to some other point in the circuit, where the electric energy is converted to some other form of energy, such as heat, sound, or mechanical energy. It should be understood that energy is transmitted only when both the electric and magnetic fields exist around the conductor. The amount of energy transfer depends on the intensities of the electric and magnetic fields. The conductor is the electric axis of the fields, as is shown in Fig. 2.2(*c*). However, because of fields from other conductors and electrically charged particles or materials of different electric properties, electromagnetic fields are usually distorted from a uniform pattern and are not true circles or radial lines, as they are in the diagram.

Metallic conductors are used to make an electric circuit which