ELECTRICAL ENGINEERING

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Contents

Summary: Electricity, a Prime Force for Advancement

Electrical engineering is the study and profession of generation and utilization of electricity. It is a discipline of engineering built upon the knowledge of electricity, magnetism and materials. Through this knowledge, electromechanical and electromagnetic devices and electrical systems can be built. Circuit laws and theorems are utilized to design and analyze these devices and systems. Signal processing, control

theories, and measurement and instrumentation techniques are applied to achieving the control and monitoring of these devices and systems.

This article reviews the development of electrical engineering starting from the time of ancient Greeks, and gives an introduction to the principal ingredients in electrical engineering mentioned above. The review covers the events and topics significant to electrical engineering. Centuries of observation went into laying the foundations for the explosion of knowledge and practical inventions that followed the establishment of electromagnetic theory in the nineteenth century. In a quick succession of inventions and theoretical research, the use of electricity was taken from a brief burst of current prior to 1800 to the remote generation and long distance transmission of alternating currents for powering motors, lighting, and household appliances by 1900. Throughout the twentieth century new uses of electricity, including communications, computers, and automated control, continued to spring from the growing body of electrical engineering knowledge.

This article also describes new developments in the electricity supply industry that provide opportunities for non-conventional and clean power gen-eration technologies to be developed. Some new power generation technologies are also described. A summary of the chapters under the theme of electrical engineering is also presented.

1. Introduction: Live Power

Electricity is an integral part of life in modern society. Throughout the world electricity is used to light homes and streets, cook meals, power computers, and run industrial plants. Electricity is so integrated with our way of living that electricity consumption per person is used to measure the levels of economic development of countries. What is electricity; where does it come from; and was it always there?

Electricity is one form of energy. Energy can be defined as the capacity to do work, and it exists in many forms. All forms of energy seek equilibrium and will flow from a place of higher energy to places of lower energy if in the same system. The energy will flow as long as there is a path available and until energy is equal at all points.

The different points are referred to as having potential energy, because energy can only be harnessed if it is being transferred, and it will only transfer if it has another place to go to. Once a path linking two points in a system is removed, the points of potential separate and become two separate systems, each with its own equilibrium.

In electrical systems, the energy is carried by charged particles flowing through conductors. The system contains a source of potential electrical energy, a battery or a generator. The energy from the source flows to a point of lower potential, the load, where it is used. But how does this flow of charged particles light a house, create a breeze, or cook a meal? The answer is that electricity does not.

Energy cannot be expended or destroyed, only transformed to another type of energy. Electricity can be transported efficiently and converted into other forms. Here follow a few examples. In cooking, current through a resistor gives thermal energy for an oven.

In the case of lighting, current through a filament, which is a form of resistor, provides light and heat. In cooling, a current inducing a magnetic field and motion in a motor transforms electrical energy to mechanical energy. The rotational motion of the fan moves air to aid convection.

All of the above examples of using energy can be met by means other than electrical appliances, but they would require local energy sources and different fuels. Electrical energy can be generated remotely, then contained in media and transported over long distances, as well as being capable of being directly converted to all other forms of energy. The non-electric equivalents of the above examples are compared below.

A wood-fire stove is used to heat a hotplate for cooking. The fire has to be built up first. While the fire is going, a chimney is needed to duct away smoke. After cooking, the fire has to be put out or contained and the ash removed. On the other hand, an electric oven only requires the heat setting dial to be turned and it creates no smoke or ash. After cooking, further heating of the filament or element is stopped by turning the dial off.

Kerosene lamps can light open spaces. The fuel reservoir has to be refilled between uses. When the lamp is being lit the mantle can get damaged, and if it is knocked over, a fire can be started. Alternatively, an electric light bulb only requires a flick of a switch to light. It can be replaced quickly when it burns out and does not require attention during use.

To manually create a breeze on a hot, still day requires someone to provide motion for a fan, with that someone getting sweatier in the process. The electric fan allows the air to be moved without causing discomfort to anyone.

Household electrical appliances can be used at the flick of a switch, representing a great saving in labor compared to many non-electric counterparts. When a switch is closed, a path is also closed between the point of lower potential, where the appliance is, and a point of higher electrical potential, where the source of electrical energy is.

Electrical engineering is the profession and study of generating, transmitting, controlling, and using electrical energy. Electrical energy has always been a part of life on earth, from the minute signals carried in nerves through to sky-splitting lightning strikes, but the controlled generation and useful application of electricity as we know it has only been possible since the late 1800s.

2. Pre-1800: Charged Times

Centuries before the time of Christ, human beings were aware of magnetism. They were able to change the state of amber by charging amber manually. However, the understanding and use of electricity and magnetism have only occurred in the last 200 years. The most significant discoveries were made in the period 1819 to 1875.

The ancient Greeks observed as early as 600 B.C. that when amber is rubbed vigorously against cloth or wool it becomes charged, attracting other particular materials. This is drawn from secondhand accounts of the writings of the mathematician and natural philosopher Thales of Miletus (c. 630–c. 550 B.C.). Unfortunately none of his works survive. The charging of amber had to wait around 2,200 years before receiving its common name: electricity, a derivation of the Greek word for amber, electron. In 1600, William Gilbert (1544–1603) published his treatise on magnetism, *De Magnete* (On the Magnet). For this work, he investigated other materials that could be charged in the same manner as amber. To describe this effect, he coined the term electric, meaning "like amber."

In the 150 years following Gilbert's investigation, although a series of important inventions and observations were made, little progress was made toward understanding the nature of electricity. In 1661 Otto von Guericke (1602–1686) developed a method of mechanically and efficiently producing significant amounts of static electricity. Around 1675 the chemist Robert Boyle (1627–1691) observed that electric force would travel through a vacuum, and the repulsion and attraction of charged objects. In 1733, Charles Francois de Cisternay du Fay (1698–1739) stated that there were "two types of electricity."

At this stage, the understanding of electricity was still restricted to charged objects repelling and attracting other objects. This changed in 1729, when Stephen Gray (1666–1736) discovered that electric charge could travel, or be conducted, through certain materials. Materials could now be classified as being either conductive (conductors) or non-conductive (insulators). The next advance took place in 1745 at the University of Leyden. Pieter van Musschenbroek (1692–1761) developed a device that would allow electrostatic charges to be stored and then discharged. This became known as the Leyden jar, and is what is now known as a capacitor, or condenser. Circuit theory began in 1747 when William Watson (1715–1787) discharged a Leyden jar through a circuit of a conductive material (wet thread), and introduced the concept of current. Research continued into dielectric materials for greater charge storage in capacitors.

The first of the great catalysts for the evolution of electromagnetic theory came between 1751 and 1754. In this period Benjamin Franklin (1706–1790) published his book *Experiments and Observations on Electricity,* in three volumes. This publication contained the first adequate explanation of how the Leyden jar worked, and introduced his theory of an "electrical fluid" to explain currents in circuits. Though his theory was deficient in some respects, it was robust enough to allow other scientists to make great discoveries in the following century. Many of the terms Franklin introduced in his theory have remained in use.

One of Franklin's collaborators, Ebenezer Kinnersley (1711–1778), dubbed Du Fay's two types of electricity as positive and negative charges. Kinnersley also pointed out that the electric fluid theory did not account for repulsion between similarly charged bodies.

In 1777, Charles Augustin de Coulomb (1736– 1806) invented the torsion balance, a device capable of quantifying the attractive force of electric charges and magnets. Using this device, he published his findings in 1785, explaining the principle that governs the attraction and repulsion between negative and positive electrical charges. This principle was later named Coulomb’s Law and the unit of charge, the Coulomb, was named in his honor.

The electrical fluid theory could not be fully investigated, as the only available charge sources, or batteries as Franklin coined them, were Leyden jars, and they discharged all stored energy in instantaneous bursts. What was needed was a longer lasting, controllable current that would allow a more in depth study. Surprisingly this advance would come from a rather implausible theory presented by the anatomist Luigi Galvani (1737–1798). In 1791 Galvani stated, as a conclusion of his study during the 1780s, that frogs’ legs which had been preserved in salt water were a source of “animal electricity,” a new type of electrical fluid.

The physicist Alessandro Volta (1745–1827), through his friendship with Galvani, was aware of the animal electricity theory prior to its publication, and started replicating the dissimilar metals experiments with thread wetted in salt water instead of frogs’ legs in the late 1780s. Volta tried to dissuade Galvani from publishing his theory, stating it was the deceased frog’s nerves reacting to the current that caused the twitching. His advice having been ignored, Volta set himself to categorically disproving Galvani.

In 1796, Volta proved his theory correct with an experiment. A current was carried through a wet thread between two cups of salt water, with different types of metals in each. By late 1800, he had developed the first practical battery, consisting of a vertical stack of couples of copper and zinc disks separated by disks of cloth moistened in salt water. The design is known as the voltaic pile.

Publicly demonstrated in 1801, the voltaic pile did not build up as much charge as some Leyden jars, but it could release the charge in a controlled continuous current instead of a single burst. The controllable current was the catalyst for electromagnets and the great advances in electromagnetic theory during the nineteenth century. The electric potential unit, the Volt (V), is named after Volta, as is the instrument for measuring electric potential, the voltmeter.

c. 600 B.C.	First known accounts of the charging of amber
A.D. 1600	Amber like material dubbed “electric”
1661	Mechanical means of inducing charge
1675	Electrostatic repulsion and attraction observed
1729	Conduction of electric charge
1733	Two types of electricity defined
1745	Leyden jars allow charge storage
1746	Circuits and currents defined
1751–4	Benjamin Franklin published theory of electric fluid
1785	Electrostatic repulsion of positive and negative charges defined
1800	Voltaic pile allows controlled discharge of charge particles, superseding electric fluid theory

Table 1. “Charged times”

3. Electricity as a Science: Electromagnetism and Circuit Theory

Until 1820, the only sources of magnetic fields were lodestones, magnets that occur naturally, or iron that had had a magnetic field induced by a lodestone. The link between magnetic fields and electricity had been established for a long time (Gilbert’s De Magnete, Coulomb’s Law, etc.), but the actual relationship was not known. The voltaic pile allowed prolonged and controlled experimentation with electric currents which started a series of breakthroughs in understanding the nature of electricity.

In 1819, Hans Christian Oersted (1777–1851) discovered the relationship between electric currents and magnetic fields. The English scientist Michael Faraday (1791–1867) began the first systematic experimentation and study of electromagnetism shortly after Oersted published his findings. By 1820, Faraday had demonstrated how currents and magnetic fields could be used to create motion.

Andre-Marie Ampère (1775–1836) formulated the mathematical relationship between magnetic flux and currents, known as Ampère’s Law. It was published in his 1826 book *Theorie des Phenomènes Electrodynamiques* (Theory of Electrodynamic Phenomena). Ampère also showed that parallel conductors will either attract or repel each other depending on the direction of current flows, and invented the static needle and the galvanometer, the device that measures current. The unit of current, the ampere (A), is named after him, as the galvanometer recognizes Galvani’s contribution to the understanding of currents.

In 1827, the physicist and mathematician Georg Simon Ohm (1789–1854) published his book *Die galvanishe Kette, mathematisch bearbeiter* (roughly, The Mathematical Workings of the Galvanized Chain), which included his complete theory of electricity. Ohm's Law, relating voltage, current, to the impedance of a circuit, was contained in this publication. The unit of impedance (or resistance), the ohm (Ω), is named after Ohm. For a long time the unit of conductance (or admittance), the inverse impedance, was known as the mho, ohm reversed.

In 1825, William Sturgeon (1783–1850) showed that winding a current-carrying wire around an iron bar concentrated the magnetic field. Electromagnets allowed the induction of magnetic fields that were much stronger than those occurring naturally in lodestones. Joseph Henry (1797–1878) continued to experiment with electromagnets and discovered the self-induction of circuits around 1830. Self-inductance explains the operation of the inductor circuit element. The unit of inductance, the Henry (H), was named after him.

Henry also observed mutual induction, one circuit inducing a magnetic field in another, during 1830, but did not publish his findings or apply them to practical use. In 1831, Faraday publicly demonstrated mutual electromagnetic induction, now referred to as Faraday's Law of Induction. Faraday also showed how it could be used to generate current. Even though his major discoveries were not concerned with capacitance, the unit of capacitance, the Farad (F), was named in honor of Faraday. One of Faraday's experimental collaborators, Heinrich Lenz (1804–1865) is remembered by Lenz's Law, which covers the conservation of energy in electromagnetic induction of motion.

Carl Friedrich Gauss (1777–1855) contributed to many fields of mathematics and physics. Of importance to electricity, he presented the mathematical relationship between magnetic and electric flux through surfaces and sources of charge. The relationship is known as Gauss's Law. In recognition of his work the unit of magnetic induction, the Gauss, is named after him. Gauss's Law was later found to hold for gravitational flux too.

Gauss collaborated with Wilhelm Eduard Weber (1804–1891) during the 1830s for a series of electrical experiments. Weber's biggest contribution to the study of electricity was his work toward establishing universal units. He originally had the electrical energy unit named after him, but afterwards it was renamed the Coulomb. The Weber (Wb) now refers to magnetic flux.

James Prescott Joule (1818–1889) stated in 1840 that heat is produced in an electrical conductor; all types of electric heaters are based on this. This was later named Joule's Law, and the unit of energy, the Joule (J), was also named after him. Joule also contributed greatly to the formalization of the law of conservation of energy, which states that energy cannot be destroyed.

Gustav Robert Kirchoff (1824–1887) is remembered for his research on electrical current and the discovery and theoretical analysis of electromagnetic radiation. In 1857, he published his work on the propagation of electric currents in conductors. As an undergraduate student in 1845 he published Kirchoff's Voltage Law and Kirchoff's

Current Law, the cornerstones of electrical network analysis, as extensions of Ohm’s work. In the 1850s he and Robert Bunsen developed spectrum analysis to categorize the chemical elements.

Kirchoff was not the first person to discover the laws named after him. Henry Cavendish (1731–1810) used electric currents from Leyden jars, and relative pain he felt due to electric shocks, to determine the conductivity of many materials. He observed Kirchoff’s and Coulomb’s Laws during the 1770s, and made many other discoveries concerning electrical principles. However, Cavendish was an eccentric recluse and published few papers on electricity during his lifetime. It was not until the 1870s when James Clerk Maxwell was editing a volume of Cavendish’s unpublished notes that his observations were discovered.

In a paper published in 1853, Hermann von Helmholtz (1821–1894) showed that complex circuits could be represented by a voltage source in series with a single element of impedance equivalent to the impedance of the entire circuit. In this form, the simplified equivalent circuit could easily be analyzed with Ohm’s and Kirchoff’s Laws. In 1883 the French telegraph engineer M. L. Thevenin (1857-1926) rediscovered Helmholtz’s idea. The theorem is now known as Thevenin’s Theorem, or Thevenin’s Equivalent Circuit. In 1926 E. L. Norton, an engineer at Bell Labs in the United States, rearranged Thevenin’s theorem to substitute a voltage source with an equivalent current source in parallel with a a single element of impedance. This is known as Norton’s Theorem, or Norton’s Equivalent Circuit.

James Clerk Maxwell’s (1831–1879) mathematical ability contributed greatly to physics and chemistry. Apart from being the first to determine that light is an electromagnetic phenomenon, he expanded upon Faraday’s Law and published the four partial differential equations known as Maxwell’s Equations in 1873 in his book Electricity and Magnetism.

Heinrich Rudolf Hertz (1857–1894) experimentally proved Maxwell’s theory about light as electromagnetic waves to be correct. His further experimental work in this field laid the foundations for wireless communication. The unit of frequency of waveforms, including electricity transmission, is named the Hertz (Hz) in his honor.

Nikola Tesla (1856–1943) started working for the European branch of Thomas Edison’s electric lighting company in 1883. He was trying to raise funds to prototype the poly-phase alternating current power system he had designed conceptually. He moved to New York in 1884 to meet Edison himself, but it was not until 1887 that he found serious supporters for his ideas and the first patent for his system was lodged. He used money raised from selling the alternating current (AC) patents to fund groundbreaking research into high frequency energy transmission applications during the 1890s, including early radio transmission. The unit of magnetic flux density (Wb/m^2), the Tesla (T), is named after him. A secretive and eccentric genius, many of Tesla’s experiments have not been possible to replicate.

Table 2 gives the timeline of the events described in this section

1819	Link between currents and magnetic fields observed
1820	Currents and magnetic fields used to create motion
1825	Electromagnets developed, allowing stronger magnetic fields to be used
1826	Ampere’s Law defines relationship between magnetic flux and current
1827	Ohm’s law introduces concepts of impedance and admittance in circuits
1830	Henry explains self inductance of circuits
1831	Faraday’s Law explains mutual inductance between circuits, Lenz’s Law explains electromagnetic induction of motion
1835	Gauss’s Law describes magnetic and electric flux, later holds for gravitational flux
1840	Joule’s Law explains resistive heating by currents and contributes to the Law of Conservation of Energy
1845	Kirchoff’s Voltage and Current Laws aid circuit analysis
1853	Helmholtz publishes circuit reduction theorem, resurfacing later as Norton’s and Thevenin’s Equivalent Circuit Theorems
1873	Electromagnetic theory condensed into Maxwell’s Equations, which predict the electromagnetic nature of light
1883	Tesla’s first attempt to sell poly-phase alternating current idea
1887	Hertz confirms that light is an electromagnetic waveform

Table 2. Electricity as a science

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Biographical Sketch

Professor Wong Kit Po is Professor of Electrical Engineering of the School of Electrical and Electronic Engineering, University of Western Australia and, concurrently from August 2002, Chair Professor and Head of Department of Electrical Engineering of HongKong Polytechnic University. He obtained his M.Sc. and Ph.D. in 1971 and 1974 respectively from the University of Manchester Institute of Science and Technology (UMIST), UK. In 2001, Professor Wong was awarded the D.Eng. degree from UMIST. In 2000, he was appointed Honorary Professor of Tsinghua University, China. He has published many research papers on power system stability, protection, planning, electromagnetic transient evaluations, and the applications of artificial intelligence, computational intelligence, and Wavelet transform to the power system planning, operation, and power markets. In 1981, 1982, and 1987 he was awarded the Sir John Madsen medals of the Institution of Engineers, Australia, for his contributions to electrical engineering. Professor Wong was the general chairperson of the IEEE/CSEE PowerCon2000 conference. He is a Fellow of HKIE, Fellow of IEEE, Fellow of IEE, and Fellow of IE Australia. From 1999–2000, Professor Wong was the Chairperson of IEEE Western Australia Section. He founded the IEEE PES Chapter in Western Australia and was the Chairperson of the Chapter from 1996 to 1998. He was awarded the 1999 Outstanding Engineer Award from the Chapter. He was a recipient of an IEEE Third Millennium Award in 2000.