

SECTION 6, CHAPTER 3

PRODUCTION OF ELECTROMOTIVE FORCE AND INDUCTANCE

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PRODUCTION OF ELECTROMOTIVE FORCE

Introduction

1. The existence of an electric current in a circuit means that energy in some form has been changed into electrical energy. The other forms of energy are heat, chemical and movement (or mechanical) energy; all three are capable of conversion into electrical energy, just as electrical energy can be converted into any of these other forms.

2. The presence of an electric current implies the presence of an electrical pressure or electromotive force, since a current will flow only when maintained by such a pressure. It follows, therefore, that the first step in converting one of the other forms of energy into electrical energy lies in the production of an electromotive force. This can be produced by thermal (heat), chemical or mechanical methods, and each method has features which make it particularly suitable for given purposes.

Production of E.M.F. by Thermo-Couple

3. When two wires of certain dissimilar metals are joined together an e.m.f. is developed across the junction. This is assumed to be due to the different concentration of "free" electrons in the two metals, which tries to equalize itself across the

junction. If the other ends of the wires are also joined (so that a complete circuit is formed), an equal e.m.f. will be developed at the second junction. The two e.m.f.s. are, however, in opposite directions round the circuit; there will be no resultant e.m.f. since both are equal, and consequently no current will flow in the circuit.

4. The degree of freedom of electrons is closely related to temperature, and it has been observed that if two junctions are kept at different temperatures the e.m.f. developed across the hotter junction is greater than that developed across the other junction. A resultant e.m.f. is therefore set up, and current flows round the circuit. This is called the "Seebeck Effect", after its discoverer. The resultant e.m.f. obtained in this manner is extremely small, e.g., a copper/iron couple whose junctions are at 0 deg.C. and 100 deg.C. respectively will develop an e.m.f. of 1,307 microvolts (0.001307 volt).

5. The resultant e.m.f. of a thermo-couple is not affected by including a wire of some third metal as part of the circuit, but the current in the circuit will naturally be reduced because of the increased resistance. A low-resistance measuring instrument can therefore be incorporated with a thermo-couple as shown in Fig. 1. Since the e.m.f. is directly related to the difference in temperature

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ature between the two junctions, such an instrument could be calibrated to read the actual temperature of the hot junction, and such arrangements, using couples of alumel and chromel (special alloys), are in fact used for indicating temperature in the jet pipes of turbine aircraft.

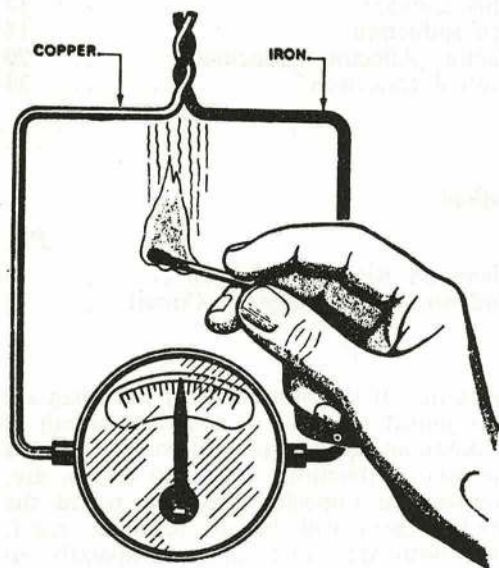


Fig. 1. PRINCIPLE OF THERMO-COUPLE.

Chemical Production of E.M.F.

6. When certain chemical substances are dissolved the solution has electrical conducting properties, although the conductivity is less than that of a metallic conductor. Such solutions are called **electrolytes**. If two plates of dissimilar metals are partly immersed in an electrolyte, but do not touch, an electromotive force is found to exist between the exposed portions of the plates. Such an arrangement, using plates of copper and zinc in an electrolyte of dilute sulphuric acid, is called a Simple Voltaic Cell, and it will produce an e.m.f. of approximately one volt.

7. When the plates are connected externally by a conductor (Fig. 2) the e.m.f. will cause a current to flow through the conductor, the plates and the electrolyte. During this process the plates and the electrolyte undergo chemical decomposition, i.e. chemical energy is being transformed into electrical energy. This action will continue until all the chemical

energy available in the electrolyte and the plates has been expended; the e.m.f. available will decline steadily, and will eventually cease to exist when—

- (a) one plate is totally consumed, or
- (b) both plates become chemically similar. (Not applicable in the case of the voltaic cell), or
- (c) the electrolyte becomes chemically inactive.

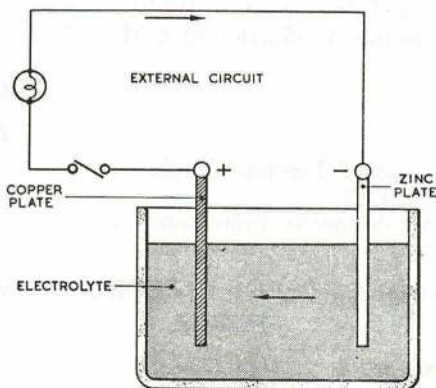


Fig. 2. SIMPLE CELL.

8. The e.m.f. of a cell depends only on the chemical nature of the plates and electrolyte, and not at all on their size or quantity. The resistance of the electrolyte, like that of a metallic conductor, varies directly as its length and inversely as its area; thus the larger the surface of the plates and the less their distance apart the smaller will be the internal resistance of the cell, enabling a larger current to flow in an external circuit of given resistance. An increase in the size of cell therefore will not increase its e.m.f., but it will increase its external circuit current and also lengthen its useful life, since a greater quantity of chemicals, and therefore of chemical energy, is available.

Mechanical Production of E.M.F.

9. When a conductor is moved in a magnetic field in such a direction that it moves at an angle to the lines of force, an e.m.f. is produced in the conductor. Such an e.m.f. is said to be "dynamically induced", i.e. it is induced by movement. Conversely if the conductor remains stationary and the magnetic field is moved in a comparable manner the same result will be obtained.

10. The production of such an e.m.f. can be demonstrated by lowering a permanent magnet into an air-cored solenoid, the ends of which are connected to a galvanometer (Fig. 3). The pointer of the galvanometer will be deflected to one side while the magnet is being lowered, indicating that a current is flowing in the circuit and therefore that an e.m.f. to support that current is being produced. The same result will be obtained if the magnet is held stationary and the solenoid is raised to cover it.

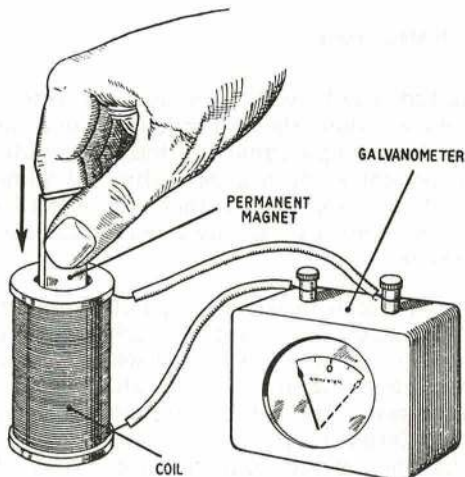


Fig. 3. ELECTRO-MAGNETIC INDUCTION.

11. When relative motion between the magnet and the solenoid ceases the pointer of the galvanometer will return to zero, although the conductor (i.e., the loops of the solenoid) is still in a magnetic field. This is clear proof that the e.m.f. is induced only when the lines of force affecting the conductor are changing. Furthermore, if the magnet is lowered into the solenoid several times at different speeds it will be observed that the deflection of the pointer increases as the speed of movement of the magnet increases. The magnitude of the e.m.f. is therefore related to the *rate of change* of flux affecting the conductor.

12. When the magnet is withdrawn the pointer of the galvanometer is again deflected, but this time in the opposite direction, indicating that the current in the circuit, and hence the induced e.m.f., has been reversed. The direction of relative movement between field and conductor must therefore

decide the direction of current and of the e.m.f. in the circuit.

13. By disconnecting the galvanometer and joining the ends of the solenoid together the resistance of the circuit will be reduced to a minimum; consequently for a given induced e.m.f. in the circuit a greater current will flow. It will now be noticed that the magnet appears to become lighter when it is being lowered into the solenoid, and heavier during the process of withdrawal. This apparent change of weight in the magnet is of course illusory, and is the result of a force exerted between the field of the magnet and the field of the current in the solenoid. This force tends to oppose the motion which is producing the e.m.f., i.e., it opposes gravity when the magnet is being lowered into the solenoid, but assists gravity when the magnet is being withdrawn.

14. The principles of electromagnetic induction are summarized by two laws:—

(a) **Faraday's Law**, which states that whenever the flux associated or linked with a circuit is changed an e.m.f. is induced in the circuit, the value of the induced e.m.f. being proportional to the rate of change of flux-linkage.

(b) **Lenz's Law**, which states that dynamically induced currents in a circuit have such a direction that their reaction opposes the motion producing them.

15. **Fleming's Right Hand Rule**. If a straight conductor is moved across the lines of force of a magnetic field (Fig. 4), an e.m.f. will be induced in it. When the ends of the conductor are connected together by an external circuit which is outside the influence of the magnetic field a current will flow through the complete circuit. The direction of the induced current can be found by the application of *Fleming's Right Hand Rule*. If the first finger of the right hand is pointed in the direction of the magnetic field, and the thumb in the direction of movement of the conductor relative to the magnetic field, then the middle finger, held at right angles to both thumb and first finger, indicates the direction of current due to the induced e.m.f.

16. The conductor shown in Fig. 4 is a current-carrying conductor in a magnetic field, therefore *Fleming's Left Hand Rule* can

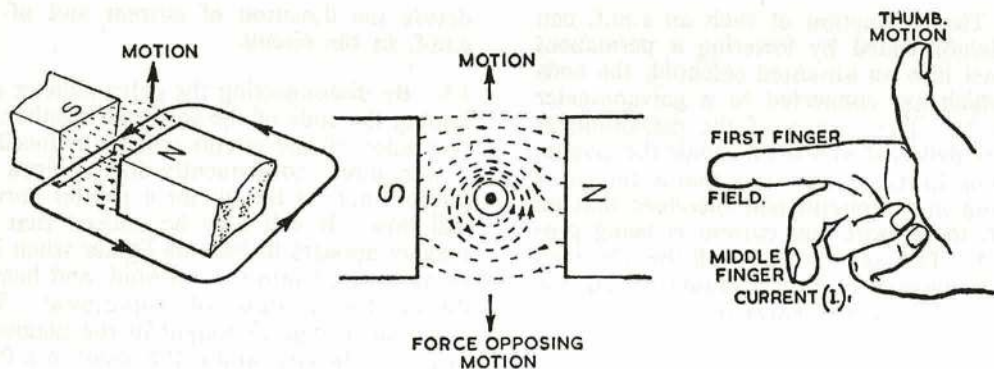


Fig. 4. FLEMING'S RIGHT HAND RULE.

also be applied to it. This shows that the force due to interaction between the field of the conductor and the field of the magnet is exerted in a *downward* direction, i.e., it opposes the motion which produces the induced current; Lenz's Law is thus confirmed. This reactionary force can never equal the force which is moving the conductor; such a state of affairs would lead to cessation of motion and hence of induced e.m.f. and current therefore of the reactionary force itself.

INDUCTANCE

Flux Linkage

17. The magnetic field of a current-carrying coil consists of lines of force, or flux lines, which form complete loops through the coil. These lines are said to be "linked" with the coil, and if their number is multiplied by the number of turns in the coil a value known as the "flux-linkage" of the coil is obtained. In an air-cored coil the total flux is directly proportional to the current in the coil, therefore the flux-linkage of the coil is likewise directly proportional to the current flowing.

Self Induction

18. According to Faraday's Law an e.m.f. is induced in a circuit when the flux linked with the circuit is changing. A change of current in a coil, by changing the flux-linkage of the coil, will therefore induce an e.m.f. known as the **self-induced e.m.f.** or **e.m.f. of self-induction** in the coil. In accordance with Lenz's Law this e.m.f. will oppose the force producing it, i.e., it opposes the *change* of current in the coil. Thus if the current is increasing the self-

induced e.m.f. will slow up the rate of increase, while the self-induced e.m.f. due to a decreasing current will tend to maintain the current at its original value. It should be clearly understood that the effects of self-induction are felt only when the current is *changing*.

19. A circuit in which an e.m.f. is induced by a change of current through the circuit is said to have the property of **self-inductance**, although the term is usually abbreviated to **inductance**. The unit of inductance is the **henry (symbol H)**, and a circuit has an inductance of one henry if an e.m.f. of one volt is induced when the current changes at the rate of one ampere per second.

Factors Affecting Inductance

20. When the core of a coil is of air or other non-magnetic material, the flux, and thus the flux-linkage, will consequently decrease *by the same amount* when the current is reduced from three to two amperes and when it is reduced from ten to nine amperes. If the current reduction is made at the same rate (e.g., one second in each case), the induced e.m.f. in the coil will be the same. The inductance of such a coil is therefore constant for all values of current.

21. In an iron-cored coil the flux at first increases rapidly as the coil current is raised from zero, but the rate of increase of flux falls off as the saturation-point of the core is approached. Beyond this point no change of flux is caused by increase of current. A change of current when the core is saturated will produce no change of flux-linkage, and no e.m.f. will be induced; the inductance of the coil in this particular circumstance is

therefore zero. A slight variation of current when the core is well below saturation point will, however, result in a relatively large change of flux and flux-linkage; a considerable e.m.f. will be induced and, in this circumstance, the inductance of the coil will be high. The inductance of an iron-cored coil is therefore variable and is influenced by the current flowing in the coil.

22. The inductance of a circuit is influenced by the form or shape it takes:—

(a) A current in a straight wire sets up a field concentric with the wire along its length, but the field is relatively weak and the flux-linkage of the wire is thus small. Such a circuit is therefore slightly inductive.

(b) If a straight wire is bent back on itself the field due to current flowing in one direction annuls that due to current flowing in the opposite direction. There is thus no flux-linkage and such a circuit is consequently non-inductive.

(c) A straight wire re-formed into a coil will produce a greater total flux for a given current, its flux-linkage will be increased, hence inductance is correspondingly increased. The use of an iron core, by increasing the total flux, will likewise increase the inductance, provided the core is not in a state of magnetic saturation.

(d) If the coil is contra-wound (i.e., one half of the turns are left-hand, the other half right-hand), the field due to one half of the coil annuls that due to the other half. The flux-linkage of such a coil is consequently zero, and the coil is non-inductive.

(e) A coil which is wound on a closed magnetic circuit as shown in Fig. 5 is very highly inductive when compared with a similar coil wound on a normal cylindrical core. The decreased reluctance of such a magnetic circuit permits a much greater

total flux for a given coil current, the flux-linkage of the coil is thus increased with a corresponding increase in inductance.

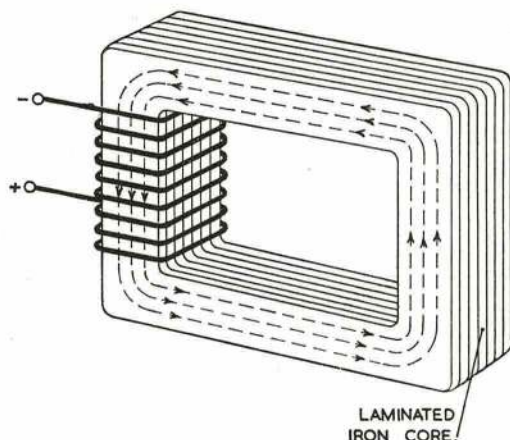


Fig. 5. COIL ON CLOSED MAGNETIC CIRCUIT.

Mutual Inductance

23. Consider now a second coil wound on the iron core shown in Fig. 5, e.g., on the opposite side to that carrying the existing coil. The same magnetic flux produced by current in the first (or primary) coil will also link with the second (or secondary) coil causing a flux-linkage in the secondary. An e.m.f. is therefore also induced in the secondary; this is known as a **mutually induced e.m.f.**, and the two coils are said to have the property of **mutual inductance**.

24. The unit of mutual inductance like that of self inductance is the henry. Two coils are said to have a mutual inductance of one henry when current changing at the rate of one ampere per second in one coil induces an e.m.f. of one volt in the other coil. The principle of mutual inductance is used in transformers, ignition coils, magnetos and similar apparatus.

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