THEORETICAL ELEMENTS OF ELECTRO-DYNAMIC MACHINERY, VOL. I

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OF

ELECTRO-DYNAMIC MACHINERY.

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PREFACE.

THIS volume is a collection of a series of articles recently published in the "Electrical Engineer" of New York.

The writer's desire and intention has been to develop for students of electrical engineering the applied or arithmetical theory of electro-magnetism, as distinguished from the purely mathematical theory of this great and important subject. The groundwork only can be said to have been completed within the limits of these covers.

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CHAPTER I.

Magnetic Flux.

MAGNETISM is the science that deals with a series of phenomena whose ultimate nature is unknown, but which result from, or are at least accompanied by, a particular kind of stress. This stress may reside in matter or in the air-pump vacuum. The magnetic metals, iron, nickel, and cobalt, when submitted to this stress, not only intensify it in their own substances, but are strained in such a manner as to sustain the stress independently to a greater or less degree after the existing cause has been withdrawn. In other words they become magnetic and remain magnetized.

The only known sources of magnetic action are three, viz., electric currents, electrical charges in translatory motion, and magnets.

Any magnetized space, or region pervaded by magnetic stress is a "magnetic field," but the term is commonly applied to the space which separates the poles of an electromagnet. The existence of stress in the field is evidenced in several ways :

1. By the magnetic attraction or repulsion of magnetized substances introduced within the field.

2. By the influence exerted on the molecular structure or molecular motion of a number of transparent substances whereby the plane of propagation of luminous waves is rotated in traversing them.

3. By the electromagnetic energy which is found to be absorbed by the medium during the establishment of a magnetic field, stored there while the field is maintained, and released at its subsidence.

4. By the electromotive forces that are found to be generated in matter moved through the field.

These experimental evidences point to the action of magnetic stress pervading the magnetized medium. Moreover the stress never terminates at an intersecting boundary, but follows closed paths. A line of stress is a closed loop like an endless chain. If a small compass-needle were introduced into a magnetic field, and kept advancing from point to point in the direction it assumed at each instant, it would finally return to the position from which it started. This can only be shown in the case of fields established by electric currents in wires, or coils of wire, as the needle could not complete its circuit through the mass of an iron magnet. The circuital distribution of the stress indicates its appurtenance to the category of fluxes. That is to say, in any magnet, or magnetized region, there is a distribution of influence analogous to the flow of current in an electric circuit, or the flow of water in a closed pipe or re-entering channel. The marked distinction, however, between the flow of magnetism, and the flow of electricity or of fluid material, lies in the fact that no work is done and no energy exchanged in the passage of the magnetic current. The electric current and the moving liquid encounter resistance and develop heat in moving against that resistance, but the magnetic flux acts as electrical currents or material currents might act, if unchecked by resistance but regulated in quantity by other limitations; and if water were itself frictionless, and were set circulating in a closed frictionless pipe, it would necessarily continue in perpetual motion. It of course by no means follows that any circulating motion of matter, or of ether, actually takes place in a magnetic circuit. That there is a possibility of such motion is a consideration left to the theory of the ultimate and fundamental nature and origin of magnetism. All that is essential to the conception of a magnetic flux is a continuous stress acting along a closed path or circuit, such that a single magnetic pole (if such could exist alone, or let us say as the nearest representation in fact, one pole of a long bar magnet) were introduced into this path it would be continually urged round the circuit.

Flux in a magnetic circuit, just as in a hydrostatic, or electric circuit, possesses at each point intensity as well as direction, and can therefore be completely specified by a vector. According to the conventions established in the absolute C. G. S. system, a field of unit intensity will exert unit pull or one dyne, upon an isolated unit magnetic pole introduced therein. The intensity of the earth's magnetic flux is approximately 0.6 unit in the open country around

New York, and consequently, a single north-seeking or unit pole suspended in that neighborhood would be drawn downwards in the direction of the dipping needle with a force of 0.6 dyne, which would represent the weight of nearly 0.6 milligramme (a dyne being about 2 per cent. greater than the earth's gravitation pull on a milligramme of matter). Practically it is impossible to obtain an isolated unit pole, but it is quite possible to measure the pull exerted by a magnetic field upon some definite system of electric currents or magnets, and to deduce what the corresponding pull would be on a unit magnetic pole. This would be the numerical intensity of the flux in the neighborhood of the point considered. Flux intensity is denoted by the symbol B, and is, strictly speaking, a vector denoting direction as well as magnitude.

The direction of a magnetic flux is the direction in which it would move or tend to move a free north-seeking pole. The north or blue end of a small compass needle points in the direction of the field surrounding it. According to this convention it follows that the earth's flux is from the geographical south towards the geographical north pole. Also,

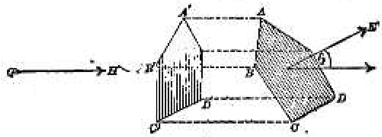

FIG. 1.

to follow the direction of a flux, is to move along it in a positive direction, while to oppose it is to move negatively.

The total quantity of flux that will pass through a given normal plane area, is the product of that area and the intensity when the latter is uniform. For example, a plane area of say 150 sq. cms. held near New York perpendicularly to the direction of the dipping needle will contain 150 x 0.6, or 90 units of flux. In ordinary language, it will contain 90 lines of force or of induction. The word induction, however, from frequent misapplication is apt to be so ambiguous that it is advantageous to dispense with it in this sense.

If the intensity varies from point to point, the total flux will be the average intensity over the surface, multiplied into the area. If the plane area does not intersect the flux at right angles the flux enclosed will be the average intensity, multiplied by the area of the boundary as projected on a plane intersecting perpendicularly, which might be termed the equivalent normal area. This is shown in Fig. 1 where A B C D represents an arbitrary boundary drawn on a plane surface whose normal E makes an angle θ with the vector G H, and this vector represents the uniform flux intensity in direction and magnitude. The total flux enclosed by A B C D will be the product of the length G H into the area A' B' C' D' which is the projection of A B C D on a plane normal to G H. Calling the area A B C D a, φ the total flux, and B the intensity, it is evident that

$$\varphi = a\ B \cos \theta$$

Finally if B, instead of being uniform throughout the space covered by the area, varies from point to point, the total flux could be found by dividing the areas into a sufficiently large number of small portions, determining the values of θ and B for each. By taking the area small enough, θ and B would be more and more nearly uniform within the limits of each, and the flux through each could then be determined separately. The sum of these fluxes would be the total flux enclosed by the whole boundary area. In other words the total flux would be the surface integral of the normal intensity all over the area as expressed by the equation

$$\varphi = -\int S.\ Bn\ ds.$$

This general result is independent of the form of the surface round which the boundary is described. This surface may be plane, warped, or convoluted.

As an example, consider the spherical surface represented in Fig. 2. Let this surface be definitely located in any permanent field—in a flux that does not vary with time—but which may be quite irregular in intensity. We may assume that the vector B is known or can be determined for every point. Draw any closed line C D E G round the sphere. Then if this sphere does not enclose any source of magnetism—current or magnet—we may follow out the plan above indicated and take the surface integral of flux: (1) over the lesser spherical area C D E G H; (2) over the greater spherical area C D E G K; (3) over a surface stretched tightly across the boundary; or (4) over any conceivable surface into which the diaphragm C D E G could be expanded. The result will in each case be the same total flux, if due precaution be taken to attach + signs to emerging + flux, and — to an entering + flux. Any element of flux not passing through the boundary must then