THE HISTORICAL DEVELOPMENT OF THE INDUCTION COIL AND TRANSFORMER.

BY DR. J. A. FLEMING, M.A.

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§ 13. **Ruhmkorff's Induction Coils.**—In 1851, M. Ruhmkorff, a skilful mechanician in Paris, profiting by the experiments of Masson and Breguet, and probably not aware of the researches of Callan and Page, addressed himself to the problem of increasing the spark-producing power of the induction coil, with the object of exalting the electrostatic effects which Masson and Breguet had produced. He paid the greatest attention to the insulation of the secondary coil, insulating the covered wire by passing it through melted shellac, and separating each layer of wire from the next by means of varnished silk or shellaced paper. He greatly lengthened the secondary circuit, employing in some coils five or six miles of secondary wire, and he insulated with care the primary from the secondary circuit by employing a glass tube on which to wind the secondary circuit, and glass cheeks to preserve the wire in place at the ends. He also supported the ends of the secondary wire on glass pillars. He provided, also, a simple form of current-reverser to change the direction of the primary circuit, and greatly improved the action of the vibrating hammer interrupter. The greatest service was, however, rendered by Fizeau by his application of the condenser (*Comptes Rendus*, 1853, Vol. XXXVI., p. 418), and Ruhmkorff carefully studied the appropriate dimensions of the condenser. This condenser he made at first of a sheet of oiled silk, covered on both sides with tinfoil; later he employed sheets of well-selected paper, carefully varnished, and coated with tinfoil on each side. This condenser was placed in the base of the induction coil, and the two terminals of the condenser connected to the two opposite sides of the "break" points. The condenser was made by varnishing close-grained but thin paper with shellac varnish. Each sheet was then examined for defects. A number of sheets of tinfoil were cut, each somewhat less in size than the sheets of varnished paper. A pile was made by building up alternate sheets of paper and tinfoil, placing each alternate sheet of tinfoil so as to protrude from the paper pile on opposite sides. The pile was then compressed, and all the tinfoil sheets on one side connected together, and also those on the other. Hence the arrangement formed a compact kind of Leyden jar, of which one set of tinfoil sheets formed the "outside" and the other set the inside surfaces, the varnished paper being the dielectric.* In the larger sized coils Ruhmkorff found it convenient to revert to the mercury-break of Page, and this was modified and re-invented by Foucault, who again suggested the advantages of making a break by withdrawing a steel or platinum point from a mercury surface, covered with alcohol or oil. Aided thus by Fizeau and Foucault, Ruhmkorff produced induction coils which enabled him to obtain secondary sparks several centimetres in length. It was, however, found that the tendency to internal sparking, and to rupture of the insulation of the secondary circuit, became very great when the coils were enlarged beyond a moderate size. In his later coils, after 1855, Ruhmkorff adopted a mode of construction which was suggested by Poggendorff, Stöhrer, and l'Abbé de la Borde, about 1854, viz., to wind the coil in sections so that no two portions of the wire which are closely adjacent are at very different potentials. When a coil is built up by winding layer over layer in the ordinary manner, the ends of the layers of wire, and particularly the similar ends of the first and last layers, are at very different potentials, and there is a great tendency for the discharge to pass between these points. In fact the sparking distance of the coil is limited by the distance of these portions of the wire. Under these conditions internal sparks were found to pass and to break down the insulation of the secondary circuit. The suggestion to wind the wire in separate partitions originally came from the English electricians, Edward and Charles Bright, who, in a patent taken out in 1852,* describe a method of thus winding electro-magnets, and in their fourteenth clause say, "The manner in which our fourteenth improvement may be carried into effect is as follows:—It is well known that the ordinary mode of winding the wire on coils is to wind it backwards and forwards upon the core. Our improved plan is to divide the core lengthways into compartments, by means of separating pieces fastened to the body of the coil, before winding and dividing the coil into compartments. In winding the wire, one end compartment is filled, and then the next, and so on." In adopting this method of winding, the flat coils of wire can be wound independently, and are then so joined up that the outside end of the wire on one coil is joined to the outside end of the wire of the next compartment, and yet the winding follows the same direction in each bobbin or separate flat coil. Hence no two portions of the wire at very different potentials are very close to each other, or, if they are, they are well insulated.

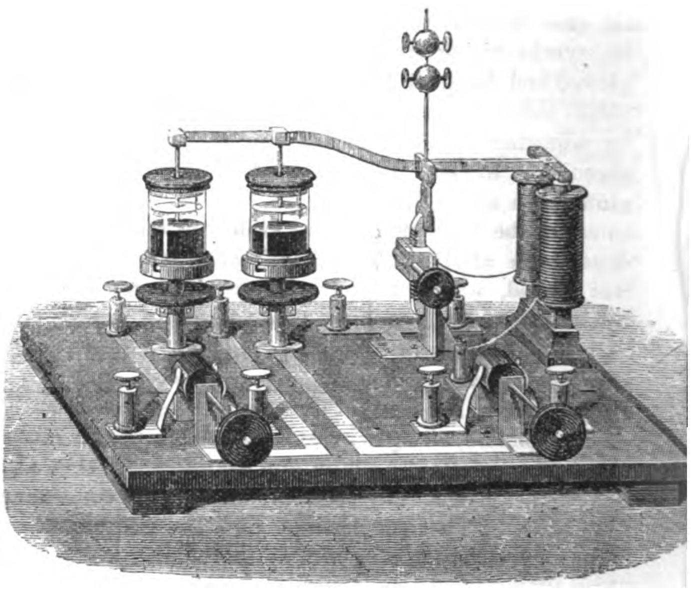

FIG. 22.—Ruhmkorff's Mercurial Break.

One of Ruhmkorff's largest coils made about 1867 was 52 centimetres in length, and the secondary circuit was divided into 80 flat coils or partitions, each compartment being occupied with five or six spirals—that is, being of a width equal to five or six times the diameter of the covered wire. The secondary circuit consisted of copper wire one-tenth of a millimetre in diameter, and 100,000 metres, or 62 miles, in length. The different compartments of the secondary circuit were insulated from one another with shellaced paper or varnished silk, and the different layers of wire in each compartment also insulated with shellac. The secondary circuit was wound upon a tube of glass as a support. The condenser employed with this coil was formed of 100 sheets of tin of a length of 50 centimetres and a breadth of 25 centimetres, insulated with paper covered with shellac, and formed a condenser having a total surface of about 12 square metres. The primary wire in this coil had a thickness of about three millimetres. This coil could give sparks 40 centimetres in length between the ends of the secondary circuit. The coil was usually worked by the current from six large Bunsen cells. For such large coils Ruhmkorff and Foucault found the

* The theory of the action of the condenser has been discussed in Vol. I. *Alternate Current Transformer*, § 7, Chap. V. When the contact breaker is provided with a condenser whose opposite surfaces are connected to the two sides of the break points, there are two distinct kinds of sparks observable at the break. There is first the spark at "break," due to the self-induction of the primary circuit, and there is the spark at "make," due to the discharge of the condenser. Rijke made the observation that the condenser is more effective in lengthening the secondary spark of the coil when the break points, or points of contact, are of gold, copper, or silver, than if they are of platinum. The discharge spark of the condenser, when a too small condenser is employed, is very bright and hot, and sometimes welds together the platinum contact points. The remedy for this accident when it occurs is to employ a condenser of larger capacity. Callan (*Phil. Mag.* [4] Vol. XIV., p. 337, 1857) suggested the employment of amalgamated copper contacts for the break, working in or smeared with oil to prevent oxidation and increase the suddenness of the break.

* British Specification, No. 14,331, of 1852.

hammer-break with platinum contacts quite unsuitable, since the contact points are rapidly burnt away by the spark at "break," due to the self-induction of the primary circuit, and by the additional spark at "make" of the contact, due to the discharge of the condenser. Hence they revived and improved the mercury break, covering the surface of the mercury with alcohol, and breaking the primary circuit (*see* Fig. 22) by a platinum point automatically lifted out of the mercury.*

§ **13a. Improvements on Ruhmkorff's Coils.**—Ruhmkorff succeeded in producing induction coils capable of giving very long sparks from the secondary circuit, but the insulation of these coils was not always found to be permanent. Du Moncel tells us that Fizeau, in endeavouring to join up several Ruhmkorff coils with the secondary circuits in series, felt severely the need for better insulation, and that M. Jean, a simple amateur mechanician in Paris, solved the problem, in 1854, by plunging the whole coil beneath the surface of a liquid insulator, viz., oil of turpentine; and by constructing coils in this manner, insulated with a fluid insulation, Jean succeeded in getting sparks of 30 centimetres in length at a time when no one, at least in France, had approached this length.† Du Moncel says that these experiments of Jean were neglected or lost sight of, and that Ruhmkorff finally succeeded in obtaining sparks of 60 centimetres in length by building up the coil in sections. Jean's coils were built up as follows: The primary wire consisted of four layers of wire and the secondary circuit of 50 layers. The primary wire had a thickness of 1½ millimetres and the secondary ·25 millimetre. The different layers of the primary and secondary were separated from each other by well-dried blotting paper. The whole coil was placed in a glass vase and filled up with oil of turpentine. The ends of the secondary wire where they emerged from the liquid were passed through glass tubes. The whole coil was baked and dried to eradicate moisture previous to immersion in the insulating liquid. M. Jean even performed this desiccation in a vacuum, and, by taking the greatest pains to avoid contact of air after and during this drying process previous to placing it in the liquid, he obtained very extraordinary insulation. There can be little question that M. Jean was here on the right track, and that this liquid insulation had many important advantages.

§ **14. Poggendorff's Researches on Induction Apparatus.**—In the *Philosophical Magazine* for July, 1855, is to be found a long Paper by Poggendorff, giving an account of his researches and suggestions with regard to the induction apparatus of Ruhmkorff. He begins by criticising the construction adopted by Ruhmkorff, as illustrated by one of his coils in the physical laboratory of the University of Berlin, and points out in the first place the defect we have already referred to in the original manner of winding the coil, and the advantages to be derived from winding the secondary coil in sections. With respect to the insulation of the wire, he advises, instead of shellac dissolved in alcohol, the use of an easily fusible insulator, such as spermaceti, or a mixture of wax and oil, or paraffin wax, or, better still, the use of a *fluid* insulator, such as vegetable oil, or oil of turpentine, so that permanent defects of insulation could not occur. He also proposed insulating the silk-covered wire by first boiling it in spermaceti to get rid of moisture and air. Poggendorff experimentally examined the construction of each element of the coil, with the object of ascertaining the best arrangement and proportions of each part. With respect to the condenser, he adopted a suggestion which apparently emanated from Halske—viz., to use mica for the dielectric, and he convinced himself of the great superiority of mica over oiled silk in this portion of the apparatus. Owing to the expense of procuring large sheets of mica, he also used very thin paper, varnished with amber varnish, as a substitute. Also he used thin gutta-percha sheet for the same purpose. Poggendorff made many experiments with the object of ascertaining the exact influence of the dimensions of the condenser upon the spark-producing power of given coils. He came to the conclusion that the stronger the primary current and the longer the primary circuit, the greater must be the capacity of the condenser in order to obtain the maximum possible secondary spark. Poggendorff established the following facts, some of which had previously been arrived at by Masson and Breguet:—

(i.) When the terminals of the secondary circuit are joined by a metallic wire, or other good conductor, induced currents at "break" and "make" of the primary circuit, which are in opposite directions, circulate in the secondary. These currents are equal in quantity, but different in electromotive force.

(ii.) If a good conducting electrolyte, such as dilute sulphuric acid, is introduced into the secondary circuit, oxygen and hydrogen are liberated at both poles of the voltameter.

(iii.) If the circuit of the secondary coil is interrupted by a thin stratum of air or gas so that the secondary circuit is not complete, then only one of the secondary currents passes, viz., that produced at the break of the primary circuit. Hence we have, then, phenomena of tension at the ends of the secondary circuit. If an electroscope is touched for a moment against one of the terminals of the secondary it will become charged, but the sign of that charge will be a matter of chance, depending on the instant when it was so touched. If, however, a spark is passed across an air-gap into the electroscope from either terminal of the secondary it will always give one kind of charge, viz., that due to the state of the secondary pole when the primary current is interrupted. The action of the condenser in strengthening the secondary current produced at the "break" of the primary is only seen when the circuit of the secondary circuit is interrupted by an air-gap or circuit of high resistance. When the secondary circuit is completed by a better conducting medium, such as a partially exhausted tube, the action of the condenser is much less apparent. Poggendorff also examined the phenomena presented when the currents from the secondary coil are employed to charge a Leyden jar. He noted the effects, independently observed by Sir W. Grove, and published by him in the *Philosophical Magazine* for January, 1855, which attend the secondary discharges when a discharging path is opened across the terminals of the condenser thus applied. Poggendorff states that, in December, 1854, he communicated to the Berlin Academy the observation that if a Leyden jar has its internal and external coatings connected respectively to the two terminals of the secondary coil, and if wires are also brought from the terminals of the secondary coil to within a short distance of each other, snapping, bright intermittent sparks will be obtained, quite different in appearance from the thin, bluish continuous sparks of the ordinary secondary discharge. *Cœteris paribus*, these discharge sparks are, according to Poggendorff, stronger the more powerful the battery, and the smaller the charged surfaces.

Grove discovered, quite independently of Poggendorff,* the effect produced by a Leyden jar connected across the secondary terminals, but he examined at much greater length the whole phenomenon. Briefly, he found it to be as follows:—If a Leyden jar has its outside coating connected to the inner end of the secondary circuit of an induction coil, and its inner coating to the outer end of that circuit, and if a pair of discharging points are connected across between the two coatings of the jar, then when the coil is set in action and the discharge points adjusted to a proper distance, loud, brilliant intermittent sparks jump across. These sparks are much more brilliant and solid than the ordinary discharge of the secondary circuit, and take place at a slightly less distance. If, now, the battery power or number of cells operating the coil is increased the effect is only to increase the sparks at the primary contact

* Foucault, *Comptes Rendus*, Vol. XLIII., p. 44, 1856.

† Jean's experiments are recorded in the *Comptes Rendus*, Vol. XLVI., p. 186, 1858. It is curious to observe that Du Moncel naturally claims priority for his countryman Jean with respect to this suggestion, to immerse the whole induction coil in oil or insulating fluid to obtain higher insulation, whilst Wiedemann (see *Galvanismus*, § 911) claims for Poggendorff the origination of the idea. Modern inventors have again become alive to the value of this suggestion, and patents have been taken out for immersing alternate current transformers in oil as a means of increasing the insulation. Mr. Brooks of late years has especially drawn attention to the use of certain oils as insulators and to the practical employment of them in cables for high pressure currents.

* See *Phil. Mag.*, Vol. IX., Series 4, 1885, p. 1.

breaker, but not much to increase the secondary discharges. When, however, a larger Leyden jar, or another Leyden jar joined in parallel with the first, is taken and connected to the secondary the effect is immediately to decrease the primary spark and to increase the secondary spark. Hence Grove found that he could apparently go on adding cells to the battery producing this primary current, or increase the primary electromotive force and Leyden jars to the secondary circuit, or increase the capacity of the secondary circuit, over wide limits, and with each such addition the brilliancy and length of the discharges from the secondary terminal were increased. In seeking for an explanation of this effect we have to bear in mind that the Leyden jar or condenser which is joined across the secondary terminals acts as a conductor of electricity *during* the time in which the induced electromotive force in the secondary circuit is increasing in amount. Also, the capacity of the condenser reacts with the self-induction of the secondary circuit to increase the maximum potential difference at the terminals of the secondary coil in a manner to be discussed more fully later on. During the period of time in which the secondary inverse induced current is flowing into the condenser it is being charged. At the instant when the secondary induced electromotive force becomes zero the condenser begins to discharge. Owing, however, to the great self-induction of the secondary circuit of the coil the charge of this condenser does not flow back through the secondary coil, but springs across the parallel air gap, making a spark. The greater brilliancy and noise of this spark, as compared with the ordinary discharge of the secondary circuit, is due to the greater quantity of electricity which passes at each discharge. Poggendorff made some very instructive experiments with two or more induction coils,* which if they had been carefully studied by subsequent inventors might have done much to prevent misconception and error. Poggendorff took two similar induction coils, which we will call A and B, and arranged them with their primary coils *in series*. A was allowed to give sparks from its secondary circuit whilst the secondary circuit of B remained open and having its soft iron core removed. The introduction of the soft iron core into the primary coil of B at once weakened the sparks from the secondary circuit of A. Hence, says Poggendorff, it follows that "two complete instruments combined one after the other mutually disturb one another, and the total effect is not equal to the sum of the effects which each would produce with the same intensity of galvanic current."

He then modified the experiment by placing the coils A and B *alongside* of one another, so that the primary circuits were joined in parallel, and he found that the insertion of the soft iron core into B *increased* the sparks given by A. He found that in the first case, when the primaries were in series, the closing of the secondary circuit of B again reproduced the sparks at their former intensity at the secondary circuit of A; whilst, in the second case, when the primary circuits of the coils were in parallel, the subsequent closing of the secondary circuit of B destroyed the augmentation of the sparks at the secondary circuit of A. The explanation of these effects is obvious in the light of what is now known as to the effect of the closed secondary circuit upon the impedance of the primary circuit. When the primary coils were in series, the introduction of the iron core into B increased the impedance of the whole circuit, and hence decreased the primary current and the secondary sparks of A, but the subsequent closing of the secondary circuit of B partly annulled the impedance of the primary circuit, and hence reaugmented the secondary sparks of A. Similar explanations apply to the case of the coils with primaries in parallel. If these experiments had been carefully considered by subsequent inventors it would have been seen that induction coils with their primaries in series are not independent of each other, and that the strength of the primary current is affected by the opening or closing of the secondary circuit of any one of them. Poggendorff examined very carefully the action of the contact breaker, both when operating in air, as well as when immersed in various liquids, and also when in a good vacuum. He found that, when the contact points of the contact breaker were immersed in pure distilled water or alcohol, the length of the secondary spark was augmented, when compared with its length, when the contact breaker operated in air. He made also the curious observation that when the contact breaker on the primary circuit operated in a good vacuum its action in lengthening the secondary spark was so much increased that it produced very nearly the same effects when acting without a condenser as did a contact breaker provided with a condenser when acting in air.

* See *Phil. Mag.*, Vol. X., 4th series, 1855, p. 137.

(*To be continued.*)

NOTE ON THE DECREMENT OF ELECTRIC OSCILLATIONS.*

BY M. V. BJERKNESS.

The law of damping, governing the oscillations of electricity in a Hertz vibrator, can be determined in a simple manner when the two following suppositions are made:—

1. The movement of electricity in the resonator is of a simple harmonic character, like that of the bob of a pendulum when under the action of a periodic force.

2. The decrement of the oscillations in the vibrator is considerably greater than that in the resonator.

On these assumptions, the intensity of the oscillations in the resonator can be calculated as a function of the ratio of the periods of the vibrator and resonator. Sufficient indication of the method of calculation will be found in Note 5 of the recent work of M. Poincaré, entitled "Electricité et Optique." In the formula there exists only one unknown quantity—the decrement of the oscillations aroused by the vibrator—and this constant has been determined by M. Bjerkness with the aid of a series of nine resonators, whose periods varied between 0·87 and 1·13 times the period of the vibrator.

The chief result of the research is as follows:—A vibrator producing oscillations having a wave length of 4·5 metres had a logarithmic decrement equal to 0·26, so that the ratio of the amplitudes of two successive elongations in the positive direction was equal to 0·77. After twenty oscillations the electrical movements were thus negligibly small, and the phenomena could not last longer than about a millionth of a second. The spark gap was from 1 to 2 mm. in length. If it was increased the decrement was found to increase, and analogous effects could be obtained experimentally by various arrangements of the apparatus, so that the decrement could not be regarded as a constant quantity.

The value found for the logarithmic decrement of the resonator was 0·002. This number must only be regarded as a rough approximation, as the properties of the secondary spark are not well enough known for accurate calculation. A comparison of this quantity, with the corresponding number found for the vibrator, affords, however, a satisfactory confirmation of supposition (2.) given above.

The decrement of the oscillations emitted by the vibrator is so rapid that some important conclusions necessarily follow. If the waves are reflected perpendicularly at a surface, so as to retrace their former course, the interference which takes place will be the result of superposing a weak wave on a more powerful one. There will not be nodes and loops in the ordinary sense, and at a distance of some wave lengths from the mirror the differences between the maxima and minima become insensible.

Elementary reasoning shows that a resonator, placed in the field of the interfering waves, is submitted to the action of oscillating forces whose amplitude varies periodically with the distance from the mirror. In the mathematical expression for the amplitude of the oscillations set up in the resonator two wave lengths will appear, the first corresponding with the waves emitted by the exciter, and the second with the waves, which correspond with the oscillations to which the resonator naturally gives rise. If the values just given for the logarithmic decrement are approximately correct, the first set of maxima

* *Comptes Rendus*, June 22 1891.