THE HISTORICAL DEVELOPMENT OF THE INDUCTION COIL AND TRANSFORMER.

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(Concluded from page 361.)

§ 20. **Sir. W. Grove's Employment of Alternating Currents with an Induction Coil.**—Shortly after the publication of the description of Wilde's magneto-electric generator, Sir W. Grove had the idea of exciting an induction coil with an alternating current. He accordingly applied an ordinary medical magneto-electric machine to the primary of a Ruhmkorff coil, first screwing up the contact breaker of the coil, so as to close the primary circuit, and cut out the condenser. He found to his surprise that he could get no secondary discharge at all. When, however, he opened the contact breaker, so as to place the condenser in series with the primary coil and the magneto-electric machine armature, he got sparks of about one-third of an inch in length between the ends of the secondary coil. Not being able himself to see fully the reason for this he appears to have shown or described the experiment to Clerk-Maxwell, who sent him the explanation of it. (See *Phil. Mag.*, Vol. XXXV., 5th series, 1868, p. 360.)

Maxwell pointed out that the reason why he obtained no sparks from the secondary circuit, when the condenser was short-circuited, and the magneto-electric machine was applied directly to the primary of the coil, was because the self-induction of the primary coil prevented the alternating electromotive force of the generator from developing any but a very small current in the primary coil. When, however, the condenser was thrown into series with the primary coil by opening wide the contact points, the capacity of the condenser annulled a great part of this self-induction of the primary circuit, and hence permitted the alternating E.M.F. of the generator to send a much larger current through the primary coil, and this was able to generate a very considerable secondary current and secondary electromotive force. The condenser neutralised in part the impedance of the primary circuit. In this same Paper, Clerk-Maxwell sketched out the mathematical theory of the shunted condenser in series with an inductive circuit as follows:—Let V_0 be the maximum value of the periodic electromotive force of the generator, and let R and L be the resistance and inductance of the primary circuit of the coil, and C the capacity of the condenser shunted by a non-inductive resistance, r, arranged as in Fig. 26. Then the following relations hold good:—Let v_1 be the potential difference of the condenser-plates at any instant, and let i_1 be the current through the primary coil, and i_2 the current through the condenser shunt. Also let I_1 be the maximum value of the current in the primary coil. If v_0 is the E.M.F. of the generator, then we may write

$$v_0 = V_0 \cos p t$$

as the expression for this instantaneous value of the E.M.F. in terms of its maximum value, where p stands for 2π times the frequency of the alternating current or electromotive force; also we can write

$$i_1 = I_1 \cos (p t + a),$$

and

$$v_1 = r\, i_2.$$

Hence we have

$$C \frac{d v_1}{d t} = i_1 - i_2,$$

and

$$V_0 \cos p t + R\, i_1 + L \frac{d i_1}{d t} + v_1 = 0,$$

as equations true at any instant, and it is easy to deduce that the maximum value I_1 of the current in the primary is given by

$$I_1^2 = \frac{V_0^2 (1 + C^2 r^2 p^2)}{r^2 \{(1 - L C p^2)^2 + C^2 R^2 p^2\} + 2 R r + R^2 + L^2 p^2}.$$

If $r = 0$, that is, if the condenser is short-circuited, this reduces to

$$I_1^2 = \frac{V_0^2}{R^2 + L^2 p^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If $r = \infty$, that is, if the shunt is removed, it reduces to

$$I_1^2 = \frac{V_0^2}{R^2 + \left(L p - \frac{1}{C p}\right)^2} \quad . \quad . \quad . \quad . \quad (2)$$

In the case when $2 C L p^2$ is greater than unity, the value of I_1 given by (2) is greater than the value given by (1). Hence the primary current is *increased* by throwing into circuit a suitable condenser. If $C L p^2 = 1$ the expression for the current is reduced to

$$I_1 = \frac{V}{R},$$

or the current has the greatest value it can have, and the inductance of the primary circuit is entirely annulled by the condenser.

Maxwell thus pointed out the condition for obtaining the maximum primary current and the reasons why the interposition of a condenser of suitable capacity increases the primary current, and hence increases the secondary electromotive force to the point of creating very considerable sparks between the secondary terminals.

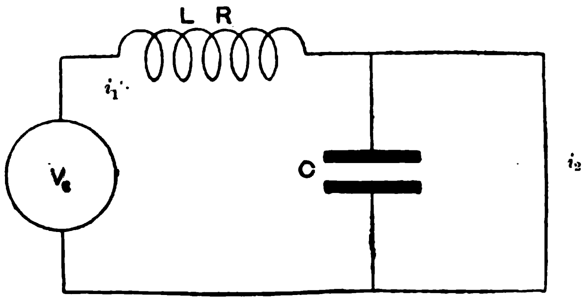

FIG. 26.

§ 21. **Mr. Apps' Large Induction Coils, the Polytechnic Coil, and Mr. Spottiswoode's Great Coil.**—In the years since 1867, Mr. A. Apps has devoted great attention to the production of large induction coils, and has been the designer and constructor of some of the most powerful coils in existence. Mr. Apps began by making coils of single flat spirals of wire insulated by discs of insulating material, but finding this construction too expensive, he adopted a modified form of the sectional winding. In 1869 he built the large Polytechnic coil, sometime exhibited and used at the old Polytechnic Institution of London. The secondary wire of this coil was 150 miles in length. The diameter of the wire was ·014 of an inch, and it was silk-covered. This secondary wire was wound in grooves about ⅛ of an inch in width and 200 in number. The iron core was a bundle of soft iron wire, 4in. in diameter, weighing 123lbs., and about 5ft. in length. The primary bobbin weighed 145lbs., and consisted of 6,000 turns of covered copper wire ·095 of an inch in diameter and 3,770 yards in length. The secondary bobbin when complete had an external diameter of 2ft. and a length of 4ft. 10in. The primary coil was insulated from the secondary coil by an ebonite tube. Excited by the current from 40 large Bunsen cells, this coil would give secondary sparks 29in. in length, and could in a few seconds charge 66 Leyden jars, each having 11 square feet of internal coated surface. The secondary discharge could pierce blocks of glass 5in. in thickness. The secondary sparks were of considerable thickness and apparent volume, and accompanied by a kind of flame. The next coil of any importance was an 18in. spark coil made for the late Mr. Spottiswoode, which was made on the same general lines as the Polytechnic coil. After introducing many improvements, Mr. Apps began, in 1876, to construct his most important induction coil, viz., the colossal induction coil built for the late Mr. Spottiswoode, which is described as follows in the *Philosophical Magazine* for January, 1877, p. 30, and which was used by Mr. Spottiswoode in many of his researches. It is thus described in the above-mentioned periodical by Mr. Spottiswoode himself:—

"The general appearance of the instrument is represented in Fig. 27, by which it is seen that the coil is supported by two massive pillars of wood, sheathed with gutta-percha, and filled in towards their upper extremities with paraffin wax. Besides these two main supports, a third, capable of being raised or lowered by means of a screw, is placed in the centre, in order to prevent any bending of the great superincumbent mass. The whole stands on a mahogany frame resting on castors.

"The coil is furnished with two primaries, either of which may be used at pleasure. Either may be replaced by the other by two men in the course of a few minutes. The one to be used for long sparks, and indeed for most experiments, has a core consisting of a bundle of iron wires, each ·032in. thick, and forming together a solid cylinder 44in. in length and 3·5625in. in diameter. Its weight is 67lbs. The copper wire used in this primary is 660 yards in length, ·096in. in diameter, has a conductivity of 93 per cent., and offers a total resistance of 2·3 ohms. It contains 1,344 turns wound singly in 6 layers, has a total length of 42in., with an internal diameter of 3·75in. and an external of 4·75in. The total weight of this wire is 55lbs.

"The other primary, which is intended to be used with batteries of greater surface, *e.g.*, for the production of short thick sparks, or for spectroscopic purposes, has a core of iron wires ·032in. thick, forming a solid cylinder 44in. long and 3·8125 in diameter. The weight of this core is 92lbs. The copper wire is similar to that in the primary first described, but it consists of 504 yards wound in double strand forming three pairs of layers, whose resistances are ·181, ·211, ·231 ohm respectively. Its length is 42in., its external diameter 5·5in., and its internal 4in. Its weight is 84lb. By a somewhat novel arrangement, these three layers may be used either in series as a wire of ·192in. thickness, or coupled together in threes as one of ·576in. thickness. It should, however, be added that, owing to the enormous strength of current which this is capable of carrying, and to the highly insulated secondary coil being possibly overcharged so as to fuse the wire, this larger primary is best adapted for use with secondary condensers of large surface, for spectrum-analysis, and for experiments with vacuum tubes in which it is desirable to produce a great volume of light of high intensity, as well as of long duration at a single discharge. The alternate discharges and flaming sparks can also be best produced by this primary. It has been used for high-tension sparks to 34in. in air, the battery being 10 cells of Grove's with platinum plates 6¼in. × 3in. Great facilities for the use of different sets of batteries are afforded by the division of this primary into three separate circuits, to be used together or separately; and by a suitable arrangement of automatic contact breakers, the primary currents may be made to follow in a certain order as to time, duration, and strength, with effects which, when observed in the revolving mirror, will doubtless lead to important results in the study of striæ in vacuum tubes.

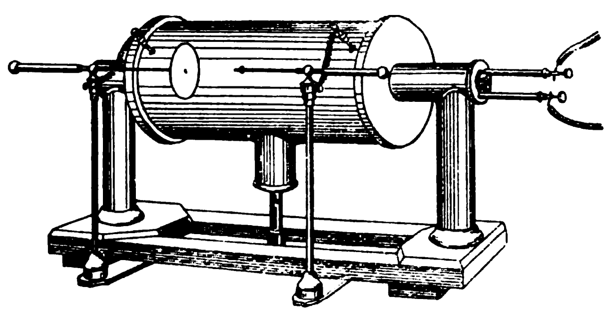

FIG. 27.—Mr. Spottiswoode's Great Induction Coil, made by Mr. Apps (1876).

"The secondary consists of no less than 280 miles of wire, forming a cylinder 37·5in. in length, 20in. in external and 9·5in. in internal diameter. Its conductivity is 94 per cent., and its total resistance is equal to 110,200 ohms. The whole is wound in four sections, the diameter of the wire used for the two central sections being ·0095in., and those of the two external being ·0115in. and ·0110in. respectively. The object of the increased thickness towards the extremities of the coil was to provide for the accumulated charge which that portion of the wire has to carry.

"Each of these sections was wound in flat discs; and the average number of layers in each disc is about 200, varying, however, with the different sizes of wire, &c. The total number of turns in the secondary is 341,850.

"The great length of the wire necessary can be easily understood from the fact that near the exterior diameter of the coil a single turn exceeds 5ft. in length. The spark, it is believed, is due to the number of turns of wire, rather than to its length, suitable insulation being preserved throughout the entire length. In order to ensure success, the layers were carefully tested separately and then in sets, and the results noted for comparison. In this way it was hoped that step by step safe progress would be made. As an extreme test, as many as 70 cells of Grove's have been used, with no damage whatever to the insulation.

"The condenser required for this coil proved to be much smaller than might at first have been expected. After a variety of experiments, it appeared that the most suitable size is that usually employed, by the same maker, with a 10-inch-spark coil—viz., 126 sheets of tinfoil 18in. × 8·25in. in surface, separated by two thicknesses of varnished paper, the two thicknesses measuring ·011in. The whole contains 252 sheets of paper 19in. × 9in. in surface.

"Using the smaller primary, this coil gave with five quart cells of Grove, a spark of 28in., with 10 similar cells one of 35in., and with 30 such cells one of 37·5in. and subsequently one of 42in. As these sparks were obtained without difficulty, it appears not improbable that, if the insulation of the ends of the secondary were carried further than at present, a still longer spark might be obtained. But special adaptations would be required for such an experiment, the spark of 42in. already so much exceeding the length of the secondary coil.

"When the discharging points are placed about an inch apart, a flowing discharge is obtained both at making and at breaking the primary circuit. The sound which accompanies this discharge implies that it is intermittent, the time and current spaces of which have not as yet been determined.

"With a 28in. spark, produced by five quart cells, a block of flint glass 3in. in thickness was in some instances pierced, in others both pierced and fractured, the fractured pieces being invariably flint glass. If we may estimate from this result, the 42in. spark would be capable of piercing a block 6in. in thickness.

"When used for vacuum tubes this coil gives illumination of extreme brilliancy and very long duration: with 20 to 30 cells and a slow-working mercury break, giving, say, 80 sparks per minute, the striæ last long enough for their forward and backward motion to be perceived directly by the unassisted eye, The appearance of the striæ when observed in a revolving mirror (as described in the *Proceedings of the Royal Society*, Vol. XXV, p. 73) was unprecedentedly vivid, and this even when only two or three cells were employed.

"Further experiments have shown that with such large coils only the newly discovered effects of very high temperature-combustion or volatilisation can be produced. On exciting the primary of the coil with a suitable dynamo-electric machine, or battery, and using a large Leyden jar in the secondary circuit (according to Sir William Grove's experiment), the electrical discharge passing between electrodes placed before the slit of the spectroscope lines and bands may be observed to advance and recede according to the variations made in the magnitude of the exciting discharges. As the atmospheric pressure may be assumed to remain constant, these effects are probably due to differences of temperature arising from the action of a greater or smaller extent of electrical effects on the electrodes in a given time."

Following on this great coil Mr. Apps has made many others, such as the 20in. spark coil made for the Framjee Kawasjee Institute of Bombay, and by certain devices of insulation has increased the length of the secondary spark beyond the length of the bobbin, thus making a bobbin of 8½in. in length give an 11in. spark. As an illustration of this fact Mr. Apps has, by permission, furnished the author with the details of six coils made for Lord Armstrong, the measurements of which are as follows:—

The secondary circuit consists of 8 miles 25 yards of silk-covered copper wire, ·0064in. in diameter. It makes 41,425 turns, and weighs in all 7lbs. 1oz. 7drs. The secondary circuit resistance is 12,500 ohms. The interior diameter of the secondary bobbin is $3\frac{5}{16}$in., the exterior $5\frac{7}{16}$in., and the length $8\frac{5}{8}$in. The secondary spark is from $10\frac{1}{4}$in. to 11in. in length. The primary coils consist of square copper wire, No. 14 B.W.G., the length of wire on each bobbin being 51 yards, laid on in four layers of 366 turns. The primary coil resistance is ·32 ohm. The length of the primary coil is 9·1in.; the outside diameter of the bobbin is 2in., and the

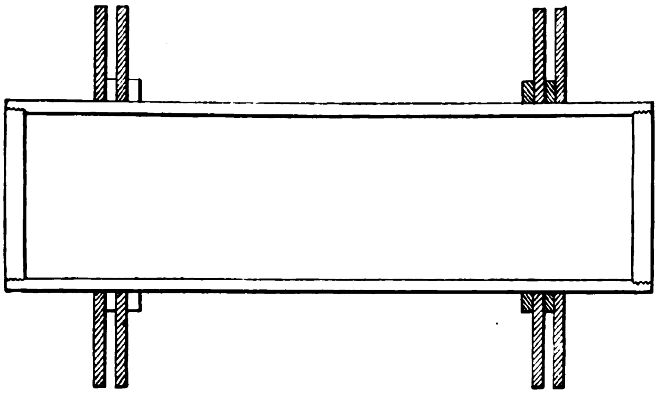

FIG. 28.—Apps's Method of Insulating the Secondary Coil.

inside diameter 1·6in. The most effective primary current is a current of 12 amperes and 10 volts. Each coil is fitted with a condenser divided into six parts. The details of the processes by which these remarkable achievements in insulation are produced are of the nature of trade secrets, but generally it may be said that the greatest precautions have to be taken to secure the result. Mr. Apps has obtained a high reputation by the excellent performance of many of his coils.

Some of Mr. Apps's improvements in induction coils are described in his British Specification, No. 177, of January 24, 1867. In this he gives the details of improvements in

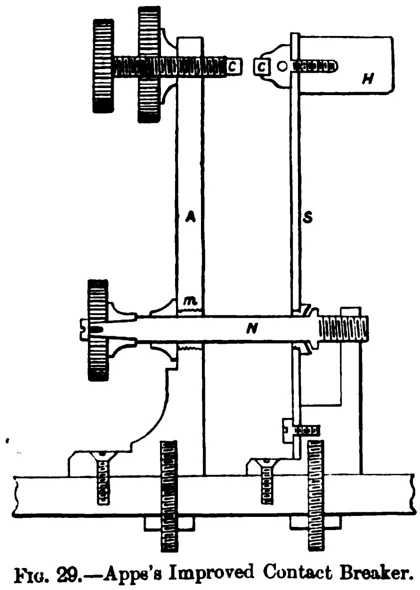

FIG. 29.—Apps's Improved Contact Breaker.

the mode of insulating the secondary coil, and in the construction of the contact breaker. His method of obtaining high insulation between the primary and secondary coil is as follows:—The primary coil is wholly enclosed in an ebonite tube (*see* Fig. 28), which projects beyond the secondary coil for some distance. On this ebonite tube are slipped, alternately, a series of ebonite discs and ebonite rings, which act as distance pieces separating the discs, and thus form a series of narrow grooves or compartments in which the secondary coil is wound. The secondary coil is then laid in these grooves, each section being carefully insulated and tested, and the several sections joined up so that no two portions of the wire which come very near to each other are at very different potentials. Besides greatly improving this groove mode of winding, Mr. Apps devoted attention to the contact breaker. He gave it the form shown in Fig. 29. In this figure S is the spring which carries the hammer head H. The pillar A is perforated and bushed at *m* with an insulating collar, and a tightening screw, N, serves to press back the hammer spring, if desired, so that the platinum contacts, *c*, *c*, are pressed more tightly in contact, and the time of vibration of the spring, S, is increased. This enables the rate of break to be altered even during the working of the coil. Mr. Apps has devised a form of multiple contact break which renders it possible to divide the break spark between several points.

It cannot be said that any subsequent improvements have been made which have altered for the better the mode of construction adopted by Mr. Apps for the construction of the induction coil since his chief large coils have been made. Other makers have introduced little changes of arrangement, but the essential features in all good coils remain the same, and even the general form of the coil is not much varied. Some changes of manufacture have been introduced, such as that in Pyke and Barnett's induction coil (*see* Fig. 30). In this coil the hammer break is erected on the top of a vertically placed coil. The hammer is mounted on a short thick spring and is

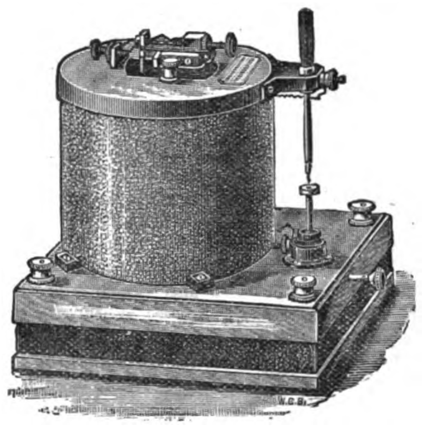

FIG. 30.—Pyke and Barnett's Induction Coil.

rapidly vibrated by an auxiliary electro-magnet, the exciting coils of which are in a shunt circuit to the main primary coil. The main coil contacts are so mounted that their normal position is in contact, one of them being carried on a spring. The vibrating hammer in its excursion strikes against one of these contacts and separates them slightly and instantaneously, thus interrupting the circuit of the primary coil.

The whole of the parts are arranged for ready and rapid adjustment. The discharging terminals of the secondary circuit are arranged at the side of the coil in a convenient manner.

A California Mining Plant.—The Dalmatia Mine is situated in the California Mountains, 1,500ft. above the sea, and nearly 60 miles from Sacramento. Fuel being dear, the question of obtaining power for operating the mine was a serious one. After deliberation it was decided to install an electric plant. The nearest water is Rock Creek, a stream running into the American River. The creek was tapped about two miles above the point where it empties into the river, and the water was then led through ditches dug and blasted through the rock to a point about 100ft. above the river. The power station is placed close to the river, and the water is led into it through a 28in. iron pipe. At the power-house is installed a large Pelton waterwheel, driving a jack shaft, to which is belted a Brush compound generator, giving 1,800 volts and 40 amperes. The current is taken by an overhead copper wire over the mountains to the mine, one and a-half miles distant, where the motor equipment is situated, driving the stamps and other mining machinery.