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The Three Hundred and Fifty-Second Ordinary General Meeting of the Institution was held at the Institution of Mechanical Engineers, Storey's Gate, Westminster, on Thursday evening, November 29th, 1900—Professor JOHN PERRY, F.R.S., President, in the Chair.

The minutes of the Ordinary General Meeting held on November 22nd, 1900, were read and confirmed.

The names of new candidates for election into the Institution were announced, and it was ordered that these names should be suspended.

The following transfers were announced as having been approved by the Council :—

From the class of Associates to that of Associate Members—

Thomas Ernest Herbert.

From the class of Students to that of Associates—

John Frank Auguste Margetts.

Messrs. J. H. Johnson and S. J. Clay were appointed scrutineers of the ballot for the election of new members.

A donation to the Library was announced as having been received since the last meeting from Société Anonyme John Cockerill, and to the *Building Fund* from Mr. James Kynoch, to whom the thanks of the meeting were duly accorded.

The PRESIDENT : I have to announce that on the 18th of December a Reception will be held at the Covent Garden Opera House, which has been most kindly lent for the

The Three Hundred and Fifty-Fourth Ordinary General Meeting of the Institution was held at the Institution of Civil Engineers, 25, Great George Street, Westminster, on Thursday evening, December 13th, 1900, Professor JOHN PERRY, F.R.S., President, in the Chair.

The minutes of the Ordinary General Meeting held on December 6th were read and confirmed.

The names of new candidates for election into the Institution were announced, and it was ordered that they should be suspended.

The following transfers were announced as having been approved by the Council, viz. :—

From the class of Associates to that of Members—

Harold William Couzens.

From the class of Members, Northern Society of Electrical Engineers, to that of Members, Institution of Electrical Engineers—

Llewellyn Andrew.

A donation to the Benevolent Fund was announced as having been received since the last meeting from Mr. Augustus Stroh, to whom a vote of thanks was unanimously accorded.

ON RAPID VARIATIONS IN THE CURRENT THROUGH THE DIRECT-CURRENT ARC.

By W. DUDDELL, Wh. Sc., Associate.

It may be thought by some that the title of this paper is rather contradictory in that there should not be any variation in the current through a direct-current arc. I will therefore explain at once that I simply use the term "direct current" as implying that the current is supplied by cells or by a direct-current dynamo, and not as implying that the current is necessarily constant in value. It may also be as well to state that by *Arc* I do *not* mean *Arc Lamp*, as all the effects to be described are quite apart from those produced by regulating mechanisms.

The effect of varying the current through the direct-current arc very slowly, so slowly in fact that the carbons have time to burn into shape corresponding to each value of the current, has been investigated by many experimenters, but it is to Mrs. Ayrton[1] that the honour belongs of giving a complete investigation of all that occurs when any of the variables in the direct-current arc are changed in any way. The other extreme, namely, very sudden changes in the current, has also been investigated by Mrs. Ayrton,[2] thus leaving a gap in the experimental evidence as to what occurs between very slow variations and isolated sudden changes in the current.

The present paper is an attempt partly to fill this gap by giving an account of what occurs when the current is periodically varied more or less rapidly over a range which is very small compared with the mean value of the direct current.

The current through a direct-current arc supplied with power from any circuit may vary either owing to changes taking place in the circuit, such as variations in E.M.F. or resistance, or owing to effects in the arc itself, such as hissing, humming. Although any variation in the current naturally entails a corresponding change in the arc itself, it will, I think, be found convenient to classify the observed effects according to whether the primary cause of the variation is in the arc or in the circuit which supplies it.

PART I.

CAUSE OF THE VARIATION OF THE CURRENT IN THE CIRCUIT SUPPLYING THE ARC.

The effects of varying the current may be divided under four heads, viz., the effect on the P.D. between the terminals of the arc, on the light emitted, on the shape of the craters, and on the vapour column. These will be considered in order. I shall assume in all cases in Part I. that the amplitude of variation of the current from the mean is small, generally much less than 10 per cent., and that the arc experimented on is neither hissing nor humming.

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[1] *The Electrician*, vols. xxxiv., xxxv., and xxxvi.

[2] *The Electrician*, 1895, vol. xxxiv., pp. 471, 541.

EFFECT ON THE POTENTIAL DIFFERENCE PRODUCED BY VARIATIONS OF THE CURRENT.

If the current varies very slowly, then the relation between the P.D. current and length is that given by Mrs. Ayrton's curves. Directly the rate of variation is increased so that the carbons have not time to burn into shape, corresponding with the instantaneous values of the current, the relation will be changed, and it is conceivable that *if* the rate of variation were high enough and the amplitude small enough, the conditions of the arc would in no way be changed, so that the ratio of the change in P.D. to the corresponding change in current, would be a constant and equal to the true resistance of the arc. I shall show later that this assumption, which is the basis of several experiments on the resistance of the arc, notably those by Messrs. Frith and Rodgers,[1] requires a much higher rate of variation of current than they employed.

One of Mrs. Ayrton's curves, contained in a letter by Prof. Ayrton to *The Electrician*,[2] illustrates very well how the connection between the P.D. and current depends on the rate of variation of the latter. This curve shows that the *first* effect of *suddenly increasing the current* through a cored-solid arc [3] is to cause a *transient rise in the P.D.* between the terminals; the effect of a *slow increase of current* being, as is well known, to produce a *decrease in the P.D.* This first transient rise in the P.D. which was obtained with a cored-solid arc, was also, I believe, obtained with a cored arc, but I am unaware of its having been observed for a solid arc.

Thinking that this might be due, as pointed out by Prof. Ayrton, to the extreme quickness of the phenomenon when *both* carbons were solid, I tried to record the transient rise in P.D. for the solid arc by means of an oscillograph, the sudden increase of the current being obtained by discharging a condenser through the arc. This experiment was successful, and a transient rise in P.D. was observed, *the P.D. and current increasing together, but only for about*

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[1] *Proceedings of the Physical Society*, 1896, vol. xiv., p. 307.

[2] *The Electrician*, 1896, vol. xxxvii., p. 321.

[3] "Solid," "solid-cored" and "cored" arc mean, respectively, arc between two solid carbons, between one solid and cored, and between two cored carbons; the top or + electrode being always placed first.

$\frac{1}{5000}$ *second.* At the end of this very short time the P.D. decreased with an increase of current in the ordinary way.

If it can be assumed that during this first $\frac{1}{5000}$ second the conditions of the arc are not changed, then the solid arc has a positive resistance, contrary to the results obtained by Messrs. Frith and Rodgers, and it is at any rate evident that, had the frequency of their superimposed alternating current been 5,000 ∿ per sec. instead of 250 ∿ per sec., the sign of the resistance as obtained by them would have changed, though I do not say that even at that frequency its true value would have been obtained. In any method for measuring the resistance of the solid arc which depends on the change in the P.D. produced by a change of current, these changes must, therefore, take place in less than $\frac{1}{5000}$ sec. in order not to allow the arc conditions to change; results to be described later indicate a still shorter time.

I will not, however, pursue this subject any further, as it would unduly extend the length of this paper to include a description of a complete series of experiments on the resistance of the arc which I have recently completed.

Effect on the Light Emitted produced by Variations of the Current.

It is well known that the light of the arc varies when the current is changed, though how small and rapid the variation in current may be and yet produce a perceptible change in the light does not seem to have been investigated. Professor Fleming and Mr. Petavel[1] and Mr. Burnie[2] have determined the instantaneous values of the light and current in the case of alternate-current arcs, and have found that the variation in light roughly follows the variation of the current; the maximum luminous intensity occurring about $\frac{1}{1000}$ sec. later than the maximum current. Herr Görges[3] has also noticed that the variations in the current due to the teeth on the armature of a dynamo produced an appreciable variation in the light at the rate of 300 per second.

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[1] *Proceedings of the Physical Society*, 1896, vol. xiv., p. 115.

[2] *The Electrician*, 1897, vol. xxxix., p. 849.

[3] *Electrotechnische Zeitschrift*, 1895, vol. xvi., p. 548.

In order to test how rapid and how small a variation of the current from the mean could be detected in the light of the direct-current arc, I arranged an arc so that its image as seen through a central slit parallel to the carbons was projected on to a rapidly falling photographic plate, the instantaneous value of the current being recorded simultaneously on the same plate by means of an oscillograph. The small quick variations of the current through the arc were produced by passing the oscillatory discharge of a condenser in series with a self-induction through it, so that the arc current consisted of a large constant part on which was superimposed a small ripple which died away after a few oscillations.

By this method I find that in an 8-ampere solid arc a *distinct variation is produced in the light emitted by both the + crater and the vapour column when the amplitude of the variation of the current from the mean is only* 3 *per cent. and the frequency of these superimposed variations is as large as* 4,300 ∿ *per sec.* At this frequency the variation in light became indistinguishable when the amplitude of the variation of the direct current was reduced to 2 per cent.

Owing to the difficulty in estimating the points of maximum density in the band on the plate which represents the light emitted in consequence of the smallness of the variation of the current and therefore of the light, I was unable to be certain whether the maximum light lags behind the maximum current; but if it does, the lag is very slight, not exceeding $\frac{1}{10000}$ sec. for an 8-ampere solid arc.

It must be remembered that the above variations of light are those of the actinic rays which affect the photographic plate; the visual rays will probably vary in a similar manner, though possibly not to the same extent.

EFFECT ON THE CRATERS PRODUCED BY VARIATIONS OF THE CURRENT.

Mrs. Ayrton tells me that she noticed that the variations in the current used by Messrs. Frith and Rodgers, who superimposed an alternating current of 0·5 to 1·0 ampere R.M.S. value, at frequency of 100 ∿ per sec. on a 10-ampere direct-current arc, so altered the shape of the ends of the carbons that she could easily distinguish them from normal carbons formed without any variation in the current. I find that if the superimposed alternating current be reduced to 0·1 ampere under the same conditions, the ends of the carbons appear unaffected.

EFFECT ON THE VAPOUR COLUMN PRODUCED BY VARIATIONS OF THE CURRENT.

SOUNDS.

Corresponding with each value of the current through the arc there is probably a definite cross-section of the vapour column, so that if the current varies rapidly through an arc of fixed length, the volume of the vapour will also vary and sound-waves will be given out. This, I believe, is the generally accepted explanation of the humming of the alternate-current arc.

In the case of the direct-current arc, sounds are also emitted even when the variations in the current are very slight. For example, the variation of current caused by the commutator segments of a direct-current dynamo passing under the brushes can be heard in the arc. This variation of the current caused by the commutator segments, even when in good condition, was found by Messrs. Frith and Rodgers [1] in the case of a 5 k.w. two-pole machine to vary between 2.5 and 9 per cent. of the mean current according to the position of the brushes.

Another striking example of how sensitive the arc is to small variations in the current is furnished by the fact that a Wehnelt interrupter, working an induction coil on the direct-current street mains, will cause any arc supplied by the same mains to give out the same noise as the interrupter itself, even when a considerable distance intervenes between the place where the arc is connected with the mains, and where the interrupter and coil are joined on, as observed by Herr Simon,[2] Mrs. Ayrton, and Mr. Jervis Smith.[3]

It must be clearly understood that the arcs here referred to are normal silent arcs; that is, if they were supplied with

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[1] *Proceedings of the Physical Society*, 1896, vol. xiv., p. 307.
[2] *Annalen der Physik und der Chemie*, 1898, vol. lxiv., p. 233.
[3] *The Electrician*, 1899, vol. xliv., p. 16.

a really steady current they would have been practically silent.[1]

In order to determine what variation in the current was necessary to cause the arc to emit a clearly audible note, the current from a high-frequency alternator, kindly lent by Sir D. Salomons, was superimposed on the direct current by the method shown in Fig. 1. The current from the alternator passes through a condenser F, a dynamometer D, and the arc in series; and it is practically prevented from flowing through the cells which supply the arc by the self-induction L. The direct current is prevented from flowing through the alternator by the condenser F.

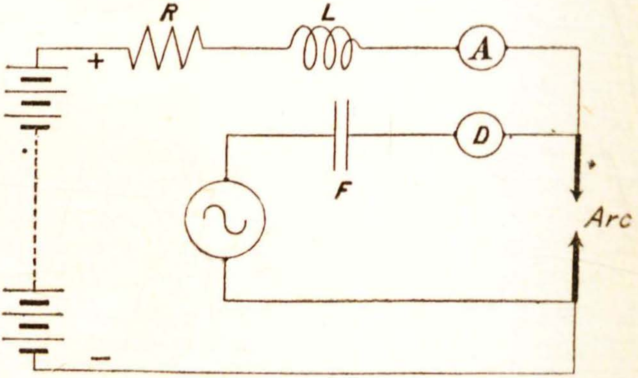

FIG. 1.

It was found by this means that a 10-ampere direct current, solid or cored arc, length 3 to 5 mm., would produce a distinct note even if as small a R.M.S. current as $\frac{1}{1000}$ ampere, as measured by D, was superimposed on the direct current for frequencies of the added current from a few hundred up to 8,000 ∿ per second. Thus *a variation of the order of 1 part in 10,000 from the mean current will alter the vapour column sufficiently to produce sound-waves.*

Further experiments with another alternator and R.M.S. superimposed currents of $\frac{1}{20}$ to $\frac{1}{10}$ ampere on a 10-ampere solid arc, proved that the sounds only became inaudible at frequencies approaching 30,000 ∿ per second.

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[1] Absolute silence is almost impossible, as the least want of homogeneity, or impurity in the electrodes, causes small spits and sounds.

At these frequencies I am uncertain whether the arc had really ceased to give a note, as the ear fails to detect sounds of so high a pitch.

This sensibility of the arc for very small changes in its current explains the fact that not only can rapid variations of current in any circuit supplied from the same generator as the arc be heard in the arc, but also variations of current which occur in a totally independent circuit supplied by a separate generator can be detected in the arc due to mutual induction between the two circuits.

ARC AS A TELEPHONE RECEIVER.

The fact that the arc is sensitive to such small variations in the current and over such a wide range of frequency, at once suggests that the direct-current arc might be used as a telephone receiver. This suggestion, which was made in a leader of *The Electrician* in 1899, had already been carried out by H. Simon [1] in 1898.

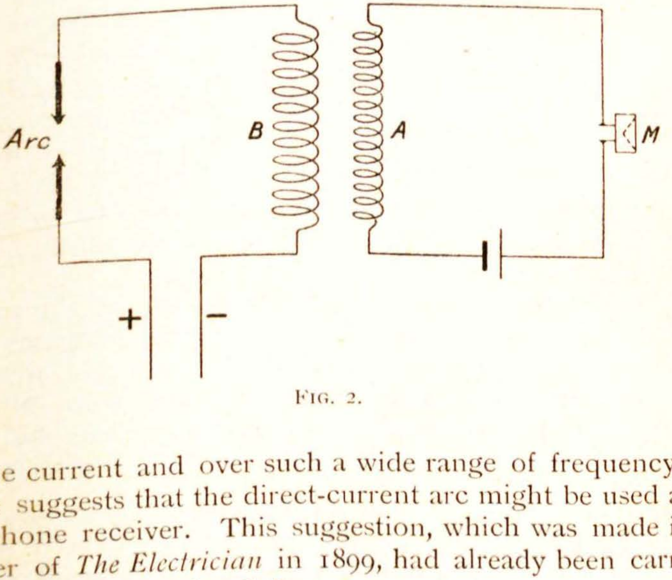

FIG. 2.

The method used by H. Simon for superimposing a microphone current on the main arc current is shown in Fig. 2, in which A and B are two coils having mutual induction, and M the microphone. The current through A varies when M is spoken into and induces E.M.F.'s in B, which vary the current through the arc in such a way that it reproduces sounds and even speech distinctly.

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[1] *Annalen der Physik und der Chemie*, 1898, vol. lxiv., p. 233.

The variation of the current through the arc obtained by this method is not as large as it might be, as the E.M.F.'s induced in B have to send currents round the whole arc circuit, including any steadying resistances, and also through the self-induction in the armature, if a dynamo is used, instead of only through the arc where the varying currents are actually required. I have obtained a better result by replacing the alternator of Fig. 1 with a microphone and mutual induction as shown in Fig. 3. A and B are the two coils of a mutual induction, F a condenser of about two or three microfarads, and L a high self-induction, the object of the self-induction being to prevent the microphone currents flowing round the cells instead of through the arc.

With this arrangement and suitable arc conditions, to be explained later, *the arc will speak sufficiently loudly and clearly to be heard at a distance of* 10 *to* 12 *feet in a quiet room.* [Experiment.][1] The sound-waves given out by the arc are, therefore, of such an intensity that when the energy is spread over a spherical surface of 20 feet diameter, the ear placed at any point can hear speech distinctly. It seems probable that if all the energy available could be collected and concentrated on the ear, very powerful sound-sensations might be produced.

The loudness of the sounds given out by the arc is increased by lengthening the arc, as this increases the volume of the vapour column which emits the sounds. It would also seem as if increasing the main current which increases the cross-section of the arc should also be beneficial, but experimentally I have not found

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[1] NOTE (*added February 1st,* 1901).—As I have had several inquiries from experimenters wishing to repeat this experiment, I append some data of the apparatus actually used at the meeting.

The microphone M was supplied by the National Telephone Company and intended for long-distance transmission, two accumulators being used in series with it. The mutual induction A : B consisted of a solenoid 30 cms. long wound with about 1,200 turns of No. 18 D.S.C. wire in six sections having an iron wire core about 15 mm. diameter. Diameter of solenoid over winding = 54 mm. For the experiments 3 sections = 600 turns were used for A, and two sections = 400 turns for B.

Resistance of A = 1·52, of B = 1·53 ohms. Mutual induction $25{\cdot}3 \times 10^{-3}$ henrys. Cored carbons were used in the arc, the other data being those given above.

If a suitable mutual induction A : B is not available a self-induction may be used, by connecting the leads from the microphone and cells to the terminals of B instead of those of A, B being now simply a coil having high self-induction and low resistance, any appreciable gain. The best results have generally been obtained with a current of 10 to 12 amperes, carbons 11 to 13 mm., and an arc length of 20 to 30 mm.

To obtain these long lengths with ease, it is necessary to use cored carbons or some other means of introducing foreign bodies, such as salts of potassium and sodium, into the arc, for there is not much doubt that the stability of the arc between ordinary cored carbons is due to the presence of potassium silicate in the core.[1] (See also Appendix I.) These salts may be introduced either by soaking the carbons in their solutions, or by using them as cores. Mr. Jervis Smith has recommended the insulator glass as a core, which I find works well.

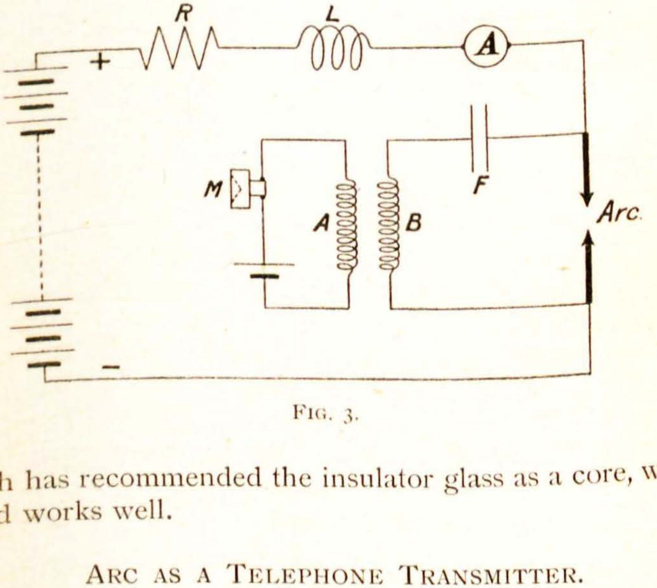

FIG. 3.

ARC AS A TELEPHONE TRANSMITTER.

Before leaving the subject of the use of the arc as a telephone, it will be convenient to consider its use as a telephone *transmitter*, though this subject strictly belongs to Part II. of this paper.

H. Simon found that if he replaced his microphone in Fig. 2 by a telephone receiver, *any sounds made near the arc were heard in the receiver*. In this case, as before, I find

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[1] See Duddell and Marchant, *Proceedings of the Institution of Electrical Engineers*, 1899, vol. xxviii., p. 66; Blondel, *International Congress of Electricity*, Paris, 1900.

it preferable to modify his method by connecting the receiver in series with a condenser between the terminals of the arc, as in Fig. 4.

A sound-wave striking the arc may affect it in two ways, either by vibrating the arc as a whole and varying its length, or the waves of condensation and rarefaction may alter the cross-section of the arc: both of these effects will tend to alter the apparent resistance of the arc, and hence vary the current through it.

The sounds obtained in the telephone receiver when using the direct-current arc as a transmitter are not generally very satisfactory, as, besides not being very loud, they are obscured by the extraneous sounds due to the small spits and hisses which occur in the arc each time the air gets to the + crater due to any slight defect in the carbons. If a common pair of carbons be used containing cracks and impurities, the noise in the receiver is sometimes unbearable, although there is no outside source of disturbance of the current through the circuit.

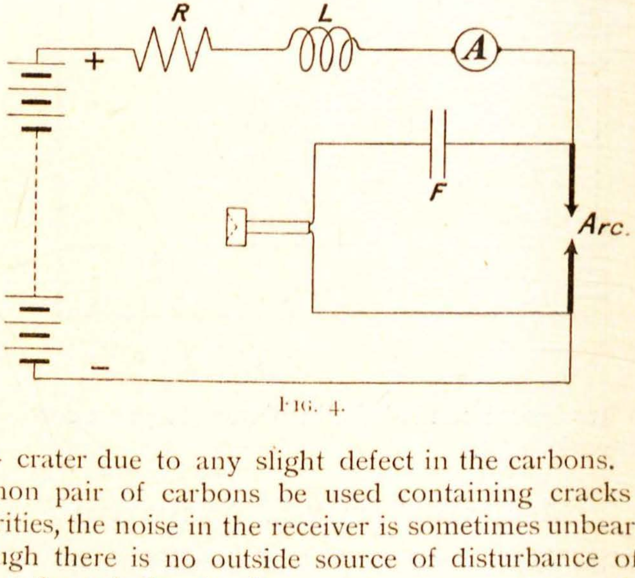

FIG. 4.

In all experiments on the arc as a telephone transmitter or receiver, it is essential that the current generator should be free from rapid variations, or extraneous sounds will be produced. If a dynamo has to be used, then the variations of the current produced by the commutator segments may be minimised by inserting a large self-induction in series with the arc, as in Figs. 1, 3, and 4. This self-induction serves the double purpose of keeping extraneous variations

HUMMING ARC.

CARBONS: + 11 and − 9 mm. Solid "Apostle." Mean P.D. = 50·5 volts. Mean Current = 15·2 amperes.

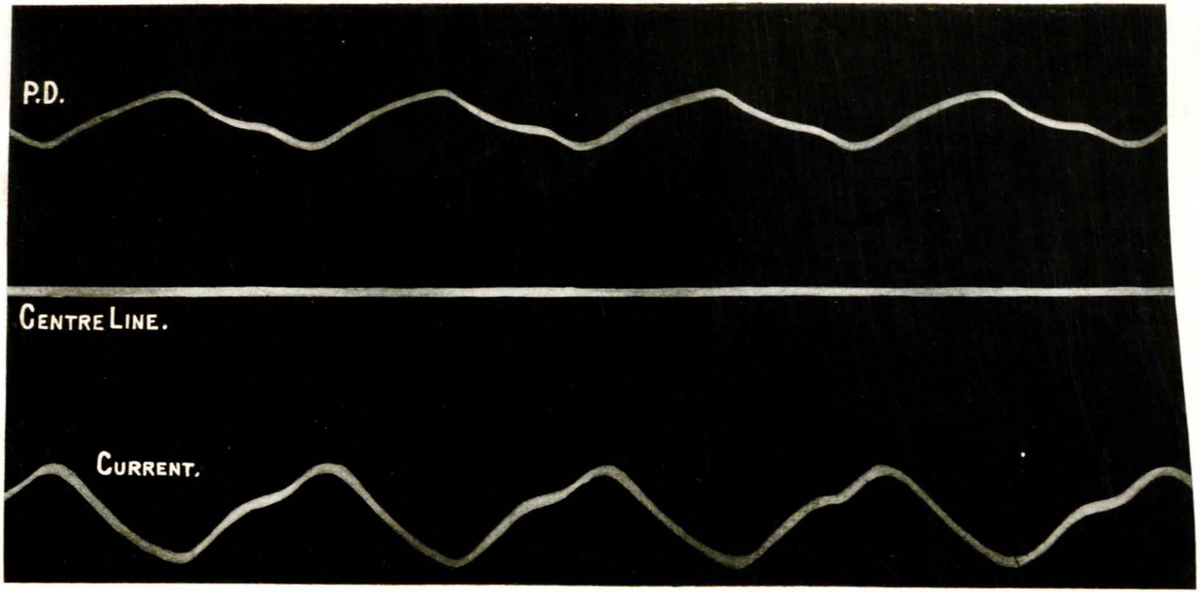

FIG. 5.

Scales:—1 mm. = 0·5 volt = 0·186 ampere = $\frac{1}{6400}$ second. Centre Line = 40 volts = 20 amperes.

HISSING ARC.

Carbons: + 11 and − 9 mm. Solid "Apostle." Mean P.D. = 38 volts. Mean Current = 22·3 amperes.

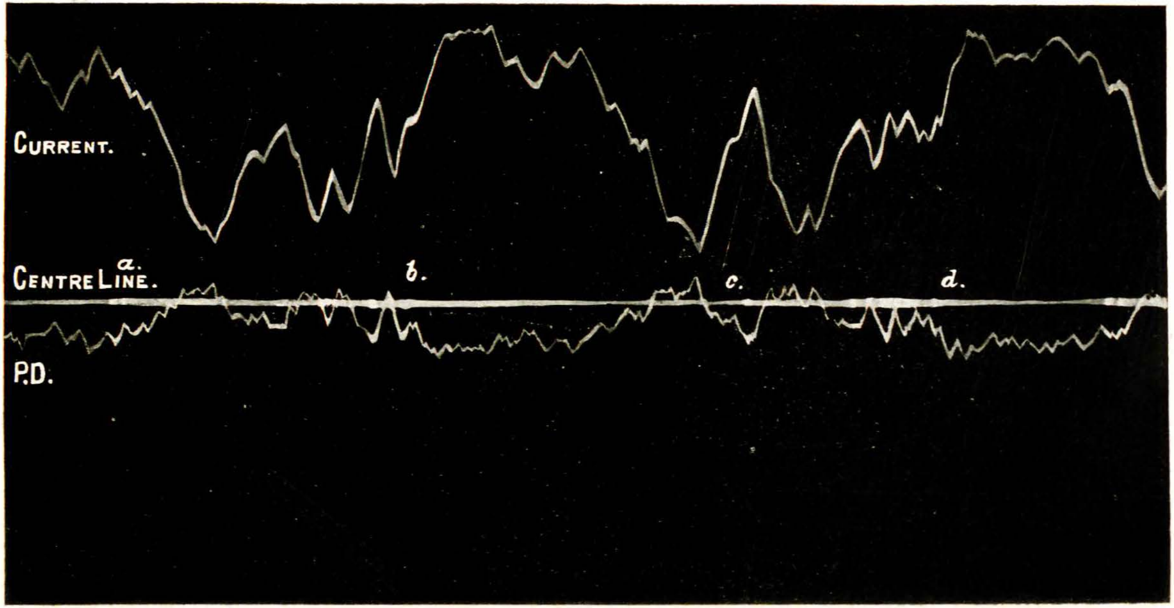

Fig. 6.

Scales:—1 mm. = 0·5 volt = 0·1 ampere = $\frac{1}{6400}$ second. Centre Line = 40 volts = 20 amperes.

HISSING ARC.

CARBONS: + 11 and − 9 mm. Solid "Apostle." Mean P.D. = 45.5 volts. Mean Current = 19·5 amperes.

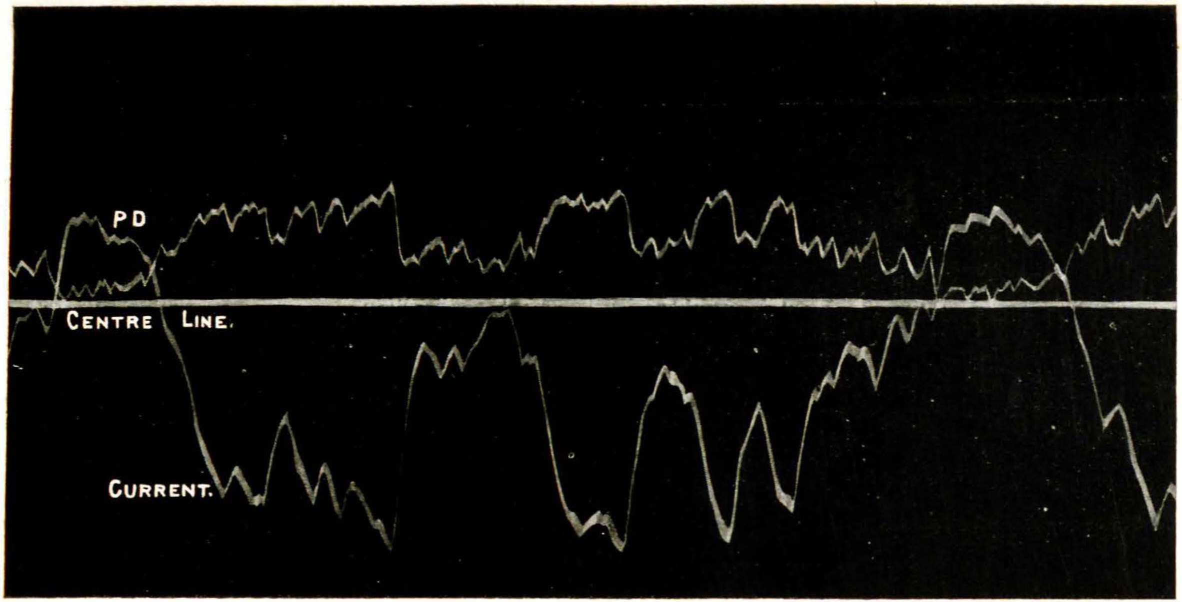

FIG. 7.

Scales :—1 mm. = 0·5 volt = 0·1 ampere = $\frac{1}{6400}$ second. Centre Line = 40 volts = 20 amperes.

VERY SHORT HISSING ARC.

CARBONS : + 11 mm. Cored "Apostle" ; − 9 mm. Solid "Apostle."

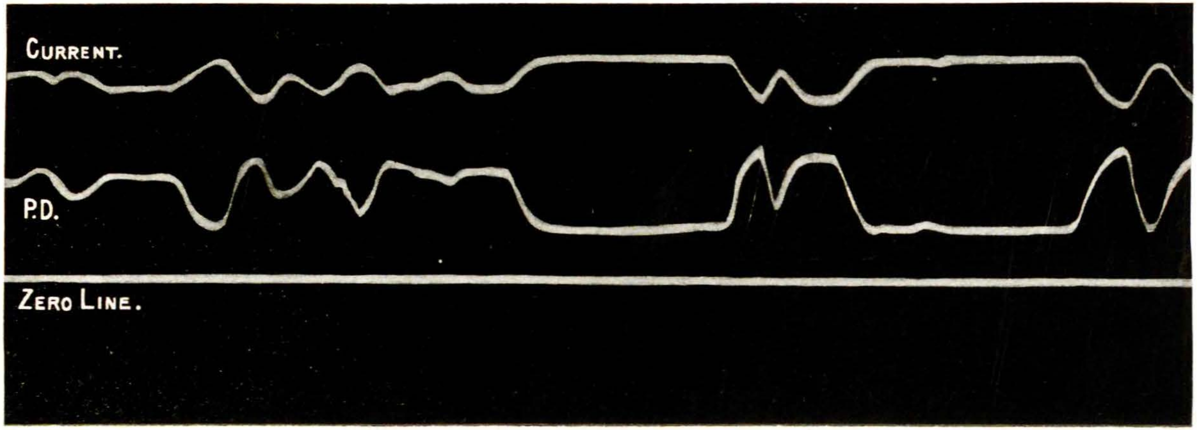

FIG. 8.

Scales :—1 mm. = 1·5 volt = 1·0 ampere = $\frac{1}{6400}$ second.

of the current out of the arc, and of preventing the variations we desire to observe from being dissipated in the source of supply.

Thus we see that *the direct-current arc is not only extremely sensitive to small variations in its current of almost any frequency, but also that it is affected by such small changes of outside conditions as sound-waves produce.* Whether this sensibility can be turned to useful account in telegraphy or telephony remains for future experiment to decide.

PART II.

CURRENT CAUSED TO VARY BY THE ARC.

HUMMING.

Mr. Trotter[1] discovered that the direct-current humming arc rotates, including a coma-like appearance at the + crater, and he also found that the current through the arc varied periodically, the frequency of these variations being the same as the pitch of the humming sound produced, and as the speed of rotation of the arc.

In order further to investigate the connection between the variation of the light P.D. and the current, I have recorded the P.D. and current by means of an oscillograph, the humming arc experimented on being used as the source of light to illuminate the oscillograph mirrors. The arc was so inclined that only the light from the + crater and a small part of the vapour column reached the mirrors. So that the density at any point of the lines represents the photographic intensity of the light emitted at that instant in the direction of the mirrors by the + crater and part of the vapour column, and the distance of the point from this zero line measures the P.D. or the current as the case may be.[2]

A typical example of the variations observed in the humming arc is given in Fig. 5, from which it will be seen that the P.D. current and light emitted in a fixed direction vary in a regular periodic manner with the same frequency.

The variation of the current, which is about 6 per cent.

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[1] *The Electrician*, 1894, vol. xxxiii., p. 298.

[2] In Figs. 5, 6, and 7, the centre line is not the zero line, but represents 20 amperes and 40 volts.

from the mean, is not sufficient to account for the large variation in the light emitted in the direction of the mirrors. This periodic variation of the light is most probably due to the fact that the arc rotates so that the + crater alternately either supplies light to the oscillograph mirrors, or is prevented from doing so by being on the other side of the + carbon. The periodic time of the variations of the light will, of course, be unaffected by a change in the position from which the arc is observed, but the times at which the light maxima occur relatively to the times at which the current is a maximum will depend on this position.

Thus besides the rotation of the humming arc and the variation of the current observed by Mr. Trotter, I find that the light and P.D. vary with the same frequency, so that in the humming arc the frequencies of the rotation of the arc, and of the variations in the P.D. current, and light emitted in a given direction, are identical with the pitch of the note given out.

HISSING.

It has been shown by Messrs. Frith and Rodgers[1] and by Messrs. Duddell and Marchant,[2] that when a direct-current arc supplied from a constant source hisses, the current through it and the P.D. between its terminals vary rapidly; and M. Blondel[3] and Mr. Brown[4] have also found that the light emitted varies.

If the current through the humming arc be increased until the arc hisses, the variations in P.D., current, and light change, I find, in a most striking manner from the regular periodic variations of Fig. 5 to the very irregular variations shown in Figs. 6 and 7.

In spite of the very irregular nature of the variations, which irregularity is not surprising in view of Mrs. Ayrton's explanation of the cause of hissing given before this Institution last year, I think that they can be separated into two kinds, a large comparatively slow variation, and a rapid superimposed one. The light given out is alternately bright, with rapid variations in intensity, *a* to *b* Fig. 6, and dull with hardly any variations, *b* to *c*; the slow varia-

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[1] *Proceedings of the Physical Society*, 1896, vol. xiv., p. 320.

[2] *Journal of the Institution of Electrical Engineers*, 1899, vol. xxviii., p. 86.

[3] *La Lumière Electrique*, 1892, vol. xliii., p. 54.

[4] *Physical Review*, 1898, vol. vii., p 210.

tion of the light corresponding with the larger variation of the current : the maximum light and current do not, however, occur simultaneously.

In view of the explanation given in the case of the humming arc that the large variations of the light is due to its rotation, and in view of the fact that the hissing arc is also probably rotating, as pointed out by Mrs. Ayrton, I think that the larger variations of P.D., current, and light in the hissing arc must also be due to the rotation of the arc. If this is the case, then the brighter parts of the curves are produced by light from the + crater and the rapid variations of density chiefly present in these parts of the lines are due to the rapid variation of this light from the + crater. [Experiment.]

Now these rapid variations in the light correspond with the small rapid changes in the current and the P.D., so that *the rapid variations of P.D. and current correspond with the variations of the light emitted by the + crater, and the large slow variations with the rotation of the arc as a whole.*

Considering one of the larger light maxima, say from *a* to *b*, or *c* to *d*, Fig. 6, during which the oscillograph mirrors receive the light from the + crater without being obstructed by the carbon, it will be seen that in many cases the maximum light and minimum P.D. occur practically at the same instant, whilst the *maximum current occurs later than the light maximum.* This is the opposite to what occurs when the current through the arc is varied by any *change in the circuit,* for in this latter case *the maximum current occurs before the light maximum.*

The periodically recurring sequence of events in the hissing arc is thus probably as follows, putting aside the rotation of the arc as a whole. Owing to the crater becoming too large for the end of the + carbon, the air obtains access to the crater surface as found by Mrs. Ayrton, the oxygen of the air there combines with the carbon, causing a rise of temperature, an increase of brilliancy, a drop in the P.D., followed very slightly later by a rise in the current.

I think that the above observations on hissing and humming are explained by, and confirm, the fundamental nature of Mrs. Ayrton's discovery of the cause of the hissing of the arc.

SOUNDS EMITTED BY VERY SHORT ARCS.

A very short hissing arc, so short that practically no light can get out from between the carbons, sometimes produces a shrill whistling sound, accompanied by a small tongue of green flame. The variation of P.D. and current for such an arc are given in Fig. 8, in which the current and P.D. have varied between two limits, viz., 22·5 amperes at 24 volts and 28 amperes at 9·5 volts, the former of which would produce a hissing arc, while the later values of the current and P.D. can only be explained on the assumption that the arc is short-circuited by a bad contact, such as a loose piece of carbon. The whistling sound is probably due to the periodical short-circuiting and relighting of the arc.

SOUNDS EMITTED BY VERY LONG ARCS.

The frying sounds emitted by very long arcs, noticed by Mrs. Ayrton,[1] are probably due to the fact that long arcs are very sensitive as telephone receivers, as mentioned in Part I., so that very slight variations in the current will cause them to give out sounds. In confirmation of this it may be mentioned that a *very long silent* arc can be obtained if the arc is supplied with current from *accumulators* which are *not* in use for *any other* purpose, and if the arc circuit be so arranged that *no* variations of the current can be induced, or produced, in it by causes outside the arc.

If, on the other hand, the direct-current arc be supplied by a dynamo, or if the arc circuit be placed so that there is mutual induction between it and leads carrying a dynamo current, then the long arc will give out a sound corresponding with rate at which the dynamo segments pass the brushes. This explanation was, I believe, first suggested by Professor Ayrton and Mr. Mather.

INTERMITTENT ARCS.

If a direct- or alternate-current arc be blown out by means of a jet of air or CO_2, or by means of a transverse magnetic field, it will, under suitable conditions, relight

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[1] *The Electrician*, vol. xxxiv., p. 338.

itself; and if the blowing be continued, the arc will be extinguished and relight itself again and again with great rapidity, giving out a harsh sound. The rapidity of these intermittances may be very great; M. Blondel [1] has found them to be as high as 3,000 to 4,000 per second in the case of the alternate-current arc, and M. Abraham [2] has obtained 100,000 per second in the case of the flame discharge.

It was suggested by Professor Fitzgerald that this intermittance of the arc might be used to produce some high-frequency alternating current which I required. I therefore tried rendering a direct-current carbon arc in series, with a self-induction intermittent by means of a magnet. With this arrangement the rate of intermittance was irregular and not very high, probably owing to the E.M.F. of my source of supply being too low, although E.M.F.'s up to 300 volts were employed.

In order to try and overcome this irregularity, I connected a condenser (about 5 mf.) between the terminals of the arc, when to my surprise I found that the direct-current arc was intermittent even when *not* blown in any apparent way either by a stream of gas or by a magnetic field, and further that no self-induction in series with the arc was necessary.

Here then was a puzzle—a direct-current solid arc burning under ordinary conditions with resistance in series, and supplied with current from accumulators, became intermittent and gave out a musical note on simply shunting the arc with a condenser.

Leads were, of course, employed to connect the condenser as a shunt to the arc, and on twisting these leads together so as to destroy the small amount of self-induction which they possessed, I found that the musical note stopped, to be started again on separating the leads; and on interposing in the condenser circuit a loose coil of wire, the sound was greatly magnified. Hence the true statement of the facts is that given below.[3]

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[1] *La Lumière Électrique*, 1893, vol. xliii., p. 54.

[2] *Société Française de Physique*, "Séances," 1899, ii. p. 70.

[3] NOTE (*added February 1st*, 1901).—Since writing the above Professor Elihu Thomson has written to me and to *The Electrician* pointing out that he carried out practically identical experiments as early as 1892, and patented this method for producing Alternating Currents. I regret that I was unaware of these experiments at the time of writing the paper, and so omitted to give Professor Thomson credit for them. Professor Thomson's letter, an editorial note on his patent specification, and a reply from me, appear in *The Electrician* for January 18th, 1901, vol. xlvi., p. 477.

MUSICAL ARC.

A direct-current arc of suitable length and current, between solid carbons, will give out a musical note if it be shunted with a condenser in series with a self-induction, as in Fig. 9, even though the source of supply of the current be perfectly constant and the arc be protected as far as possible from any outside cause of disturbance. [Experiment.]

I find that the musical note is produced by oscillatory currents flowing in the circuit composed of the condenser F, the self-induction L, and the arc, Fig. 9, and its pitch is determined by the periodic time of this circuit—that is, on the relation between the capacity, self-induction, and effective resistance of the circuit. Neglecting the resistance, which it will be shown later must be small, the periodic time of the circuit $\tau = 2\,\pi\,\sqrt{\text{L.F.}}$, and this has been found, by judging the pitch of the note by ear, to be approximately correct, so that for lecture purposes Kelvin's law can by this means be easily demonstrated. (See Appendix III.)

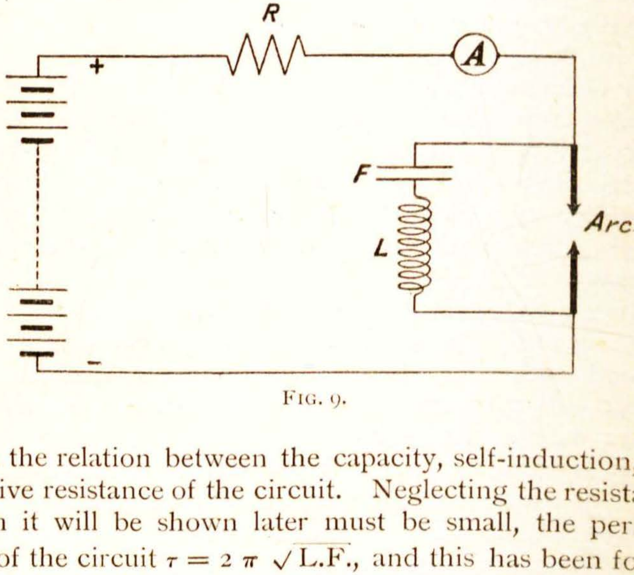

FIG. 9.

It must be remembered that although we have an alternate current through the condenser and self-induction, the source of supply is not an alternating one, and that *it is the arc itself which is acting as a converter and transforming a part of the direct current into alternating, the frequency of which can be varied between very wide limits by altering the self-induction and capacity.* The upper limit I find to be about

10,000 ∿ per second, and the lower limit, if such exists, is well below 500 ∿ per second.

It has long been known that a train of oscillations of almost any frequency can be obtained on discharging a condenser through a suitable inductive resistance, but of course these oscillations have a rapidly decreasing amplitude ; and the means of supplying energy to such a circuit so as to maintain *the amplitude of the swings constant*, other than by means of a varying source of power having the same periodic time as the circuit, has been wanting. It is, therefore, necessary to inquire under what conditions it is possible for the arc to cause the source of direct current to supply the energy necessary to maintain the oscillations in the condenser circuit when once they have been started.

If the resistance in the main circuit in series with the arc is large, and if δV be a small instantaneous change in the P.D. between the terminals of the arc, δA the corresponding small change in the current through it, and r the resistance of the condenser circuit, not including the condenser ; then, during the time this small change lasts, sufficient energy may be supplied to the condenser circuit to make up for the energy dissipated there, in ohmic losses, if the following conditions are fulfilled (see Appendix II.) :—

1. $\frac{\delta V}{\delta A}$, negative.
2. $\frac{\delta V}{\delta A}$, numerically greater than r.

The question is, can the arc fulfil these two conditions? Messrs. Frith and Rodgers[1] have experimentally determined the value of $\frac{\delta V}{\delta A}$, which they call the resistance of the arc, for various arcs, and they found that while $\frac{\delta V}{\delta A}$ was always + when *both* carbons were cored, it was, on the contrary, always − when *both* carbons were solid ; and that it was as small as −2 ohms for a 4-ampere solid arc. Now the resistance of the condenser circuit, r, external to the condenser, can easily be made less than 2 ohms, so that the arc can fulfil both the necessary conditions.

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[1] *Proceedings of the Physical Society*, 1896, vol. xiv., p. 307.

I will now describe some observations on the musical arc which tend to confirm the above conclusions.

Arcs between solid carbons for which $\frac{\delta V}{\delta A}$ is always negative *work well*, while those between *cored* carbons for which $\frac{\delta V}{\delta A}$ is positive I find *will not work* under any conditions. [Experiment.]

The largest negative value of $\frac{\delta V}{\delta A}$ given by Messrs. Frith and Rodgers is 2 ohms for a 4-ampere solid arc, and it is probable that it did not exceed 2·5 ohms. for the smaller currents, viz., 3 to 3·5 amperes, which I used. According to the above conditions, 2·5 ohms should be the limiting resistance of the condenser circuit; by experiment it was found that when the resistance of this circuit was increased to 2·4 ohms the oscillations stopped and could not be restarted. [Experiment.]

It is evident that besides the resistance there are other causes, such as hysteresis, which tend to dissipate the energy in the condenser circuit and stop the arc giving its note. The hysteresis in an iron-wire core introduced into the self-induction will instantly stop the note. [Experiment.] Any complete circuit such as a ring of wire placed near the self-induction has the same effect. [Experiment.]

On several occasions before the importance of these causes of the dissipation of the energy were realised, considerable trouble was experienced in tracing the reason of the arc failing to give its note. As examples, in one case it was traced to an ammeter and in another to the tinfoil in the condenser which were acting as short-circuited secondaries to the self-induction coil, which had been placed too near them. [Experiment.]

The relation between the self-induction, capacity, and frequency can be very easily demonstrated by playing a tune on the arc by varying either the capacity or the self-induction by means of a key-board. [Experiment.] (See Appendix III.) Another method of varying the self-induction is by separating or bringing closer together the turns of the coil, as if playing on a concertina, the relative positions of the turns determining the self-induction and the pitch of the note. The musical arc can be used as a means of comparing self-inductions or capacities by comparing the pitch of the notes produced.

The "enclosed arc" will work equally as well as the open arc, though the note given out is not so audible owing to the globe; but it can easily be made so by taking advantage of some of the telephoning effects mentioned in Part I.

The alternating current through the condenser circuit may be as large as from 3 to 5 amperes R.M.S. value, and the direct current in the main circuit also varies considerably depending on the amount of resistance in the circuit. This condenser current is sufficient to show experiments with alternating currents which do not require much power, and is very convenient in many cases for lecture purposes as the frequency, and any changes in it, are at once evident from the pitch of the note given out by the arc. Magnetic space telegraphy can easily be demonstrated on a small scale by using the self-induction coil as the transmitting circuit. [Experiment.] Several arcs can be used in series when more power is required in the condenser circuit than can be obtained from one arc alone.

TABLE OF DATA OF MUSICAL ARCS.

	Open Arc.	Enclosed Arc.
Carbons both solid.	*Conradty.*	*Electra.*
Diameter	9 mm.	13 mm.
Arc Length	1·5 mm.	1·0 mm.
,, Current	3·5 amps.	5 amps.
Resistance in Series R. ...	42 ohms.	about 28 ohms.
Self Induction of L.	$5{\cdot}3 \times 10^{-3}$ h.	$5{\cdot}3 \times 10^{-3}$ h.
Resistance of L. and Leads ...	0·41 ohms.	0·41 ohms.
Capacity of Condenser F. ...	1·1 to 5·4 mf.	1·1 to 5·4 mf.
R.M.S. Current through Condenser when Capacity = 5·4 mf.	3 amps.	4·5 amps.

For the convenience of those who may wish to repeat these experiments, I have inserted a table of good working conditions for open and enclosed arcs. The exact figures need not be strictly adhered to, as the musical arc will work over a wide range of conditions. It may perhaps be well to mention that only condensers suitable for high voltages should be used, as although the P.D. arc is only 50 volts, the P.D. condenser rises to several hundred volts.

METAL ELECTRODES SWITCH CONTACTS.

In connection with the above experiments the attempt was made to replace the carbons by metal electrodes, when I found that on trying to shunt the metal arc with a condenser it went out, no self-induction except that of the leads being used. [Experiment.] Of course, whether the arc is extinguished or not depends on the capacity used to shunt it and on the other conditions of the circuit; thus in the present case, with a 3-ampere arc between 6 mm. diameter copper electrodes and a resistance in series of from 50 to 60 ohms, supply voltage 200, it was found that the arc was always extinguished when shunted with a condenser having a capacity from 0·6 to 5·4 mf., though with the smaller condenser, 0·6 mf., and longer arc lengths the extinguishing was not quite so certain. Condensers larger than 5·4 mf. were not tried, though I have no doubt that they would prove even more effective.

This experiment is very instructive as showing how very soon the metal arc becomes practically non-conducting after the current through it is interrupted, for if we consider that the current through the arc is reduced to zero at the instant of first connecting the condenser, and remains zero unless the arc relights, then the time required for the 0·6 mf. condenser to charge up to $(1 - \frac{1}{\varepsilon})$, or 63 per cent. of the supply voltage, *i.e.*, 126 volts, is about $\frac{1}{27000}$th of a second. So that we may consider that if the current through the metal arc is interrupted for about one twenty-seven thousandth of a second, even applying about three to four times the normal voltage,[1] will not cause it to relight. This is very different from the case of the arc between cored carbons, for it is well known that the current through a 10-ampere cored arc may

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[1] Direct-current metal arcs as above usually require a P.D. roughly about 30 volts.

be interrupted by opening a switch in series with it for, say, a quarter-second, and yet the arc will relight on closing the switch again, owing to the high conductivity of the vapour left, when the arc is extinguished. The comparison is, however, not quite a fair one, as it might be expected that with the larger current, viz., 10 amperes used with the cored arc, more conducting vapour would exist than with the 3 amperes used for the metal arc, and that it would therefore take longer for the vapour column of a 10-ampere arc to cool down and attain a high resistance than that of a 3-ampere arc.

In order to make a fair comparison, the metal electrodes were replaced by cored carbons and a 3-ampere arc obtained under as nearly as possible the same conditions as the copper arc. This cored carbon arc could not be extinguished even on shunting it with the largest condenser, viz., 5·4 mf. [Experiment], and it was found necessary, in order to make the cored arc go out on shunting, to reduce the current through it to below 1 ampere; but with such a small current the arc is rather unstable and liable to go out even when not disturbed in any way. Two solid carbons were also tried, and the effects were found to be intermediate between the cored arc and the metal arc, as a 2-ampere solid arc could just be put out by shunting with the 5·4 mf. condenser, whereas the 3-ampere metal arc always went out on being shunted with a condenser of as small a capacity as 0·6 mf., as already stated.

The correct method of finding out whether the arc will relight in any given case after it has been extinguished on suddenly reducing the current through it, is the following:— Let A, Fig. 10, be a curve which might be drawn between the P.D. which will have to be set up between the electrodes to relight the arc, and the time that has elapsed since the arc was extinguished; and B the curve that connects the actual rise in P.D. between the electrodes (*i.e.*, between the condenser terminals) and the same time. Then the condition for the arc to relight is that the curve B touches or cuts the curve A.

Unfortunately we do not know much about the curve A between P.D. required to relight the arc and time except that it starts from the P.D. at which the arc was burning at the instant it was extinguished, and attains a final constant value equal to the P.D. required to spark across between the electrodes. We can, however, form some idea of the steepness of the curve A at the commencement, for we know that, if the arc fails to relight, the curve A lies between the ordinate at the time of connecting the condenser and the curve B, that is the ordinate at time nought. The shape of this latter curve, which represents the P.D. between the terminals of the condenser during charge, can be calculated from the known data of the circuit; thus with the copper arc mentioned above, which is just extinguished by shunting with a condenser of 0·6 mf. capacity, E.M.F. in circuit being 200 volts, resistance 56 ohms, and self-induction of leads neglected, the curve B will start with an initial steepness of about 6 × 10^6 volts per second. In spite of this very rapid rise of curve B, it will generally fail to intersect the curve A for the 3-ampere copper arc, so that the apparent resistance of the copper arc seems to increase at a very high rate after the current through it is stopped.

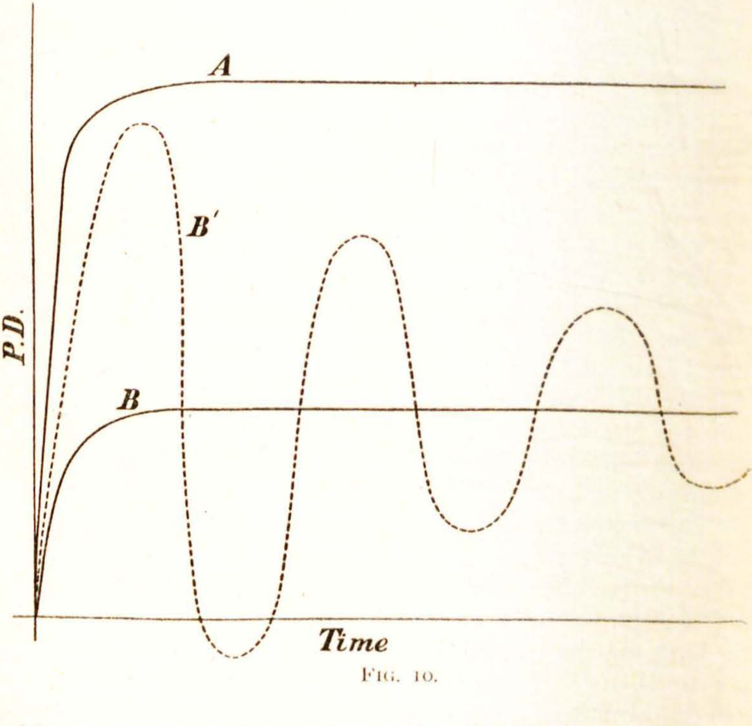

FIG. 10.

With cored carbon electrodes the arc under similar conditions could not be extinguished by shunting with 5·4 mf., so that since the initial steepness of the curve B was $\frac{1}{9}$th, or about 7×10^5 volts per second, this curve always intersected the curve A for cored carbons. Further, I think that the curves would still intersect, that is the cored arc would relight, if the initial steepness of B had been even many times smaller, so that the rate of increase of apparent resistance of the cored arc after interruption of the current is many times smaller than with the copper arc. In what has been said above, I have neglected the unknown self-induction of the leads, so that the figures given must be considered as only rough approximations.

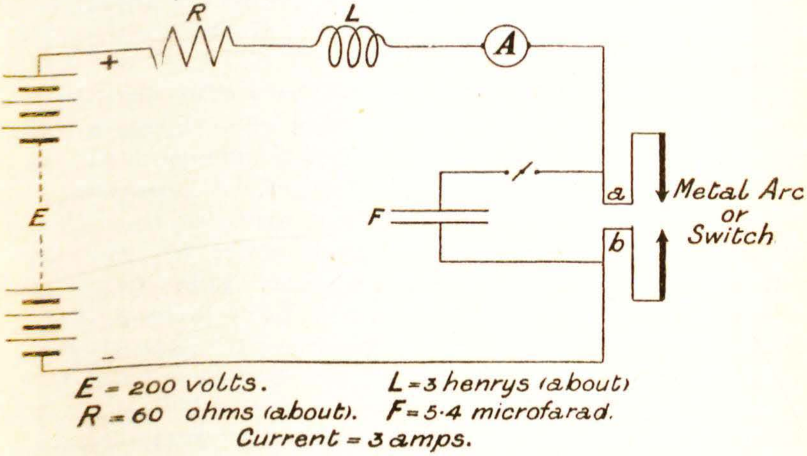

FIG. 11.

The extreme rapidity with which it is necessary to increase the P.D. between the terminals of the metal arc in order that it may relight again after the current through it has been stopped, explains the fact that it seems impossible to maintain an *alternate* current arc between *metal* electrodes at ordinary frequencies and P.D.s of even several hundred volts; and that it requires a P.D as high as 2,000 volts to maintain a metal arc as found by Herr Arons.[1]

If the non-inductive resistance in series with the arc be replaced by a highly inductive one as shown in Fig. 11, the

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[1] *Wiedemann's Annalen*, vol. lvii., p. 185.

curve B will be altered in shape, and with the conditions inserted under Fig. 11 the charge of the condenser will be oscillatory as shown by B′ Fig. 10, the maximum P.D. attained if the arc fails to relight at all being many times as high as the E.M.F. of the source of supply. Although the arc is put out on shunting with a condenser, it does not follow that it may not have really relit and gone out again several times corresponding with each swing of the condenser, before it is finally left extinguished owing to the dying away of the oscillations; and this is probably what occurs when the curve A is not very steep, as in the case of cored carbons. In this case the maximum rise in P.D. will be limited by the shape of the curve A and by the amplitude of the oscillations being rapidly damped, due to conduction through the arc.

This high rise in P.D.—caused by the sudden annulling of the current through the self-induction when the metal arc is extinguished on shunting it with a condenser—is very serious, as the following experiment shows. A 3-ampere arc between two copper electrodes 6 mm. diameter, the conditions of the circuit being those given under Fig. 11, was shunted with a condenser 5·4 mf. capacity. This caused the arc to go out and so high a rise in P.D. to be produced that the insulation of the leads broke down, a spark passing from *a* to *b*, accompanied by a report. [Experiment.] When, however, I substituted carbons for the copper electrodes, no report was heard, nor was any serious rise in P.D. noticed. [Experiment.]

The next experiment tried was to connect the condenser permanently as a shunt to the metal electrodes, and then to attempt to strike the arc, the circuit being arranged as in Fig. 11. I found that it was impossible to strike an arc between metal (Cu, Fe, Al, and Brass) electrodes if the capacity of the condenser F, Fig. 11, exceeded 0·1 mf.—even although an E.M.F. of 200 volts was used—and that on separating the electrodes the sudden interruption of the current through the self-induction set up oscillations in the circuit and a high rise in P.D. between the terminals of the condenser similar to that produced when the metal arc was extinguished by shunting with a condenser as explained above. The condition that determines the possibility of striking the arc is similar to the condition that governs the relighting of the arc after the current through it has been reduced to zero as explained above. For corresponding with each position of the electrodes as they separate there is a certain P.D. required to start the arc, and if the relation between the position of the electrodes and time be known, then a curve between P.D. required to start the arc and time can be plotted similar to curve A, Fig. 10 above, and the intersection or otherwise of this curve with the curve B′ determines whether the arc will strike or not.

The practical interest in this subject of the striking of the arc lies in the fact that when the attempt is made to interrupt a steady direct current flowing through an inductive circuit by means of a switch with metal contacts, an attempt is really made, at the first instant, to strike a metal arc between the contacts, and if these contacts be shunted by a condenser which prevents the arc from forming, a high rise in P.D. will occur. If, however, the arc was allowed to form, the time during which the break takes place would be lengthened, and no such great rise of P.D. would be produced. This rise in P.D. has been mathematically investigated by Mr. Johnson[1] on the assumption that the arc does not form, and putting the data given under Fig. 11 into his equation, I find that the rise in P.D. is just over 2,000 volts as compared with 200 volts the E.M.F. in the circuit. It is, therefore, of importance when it is required to prevent these rises in P.D., on breaking the circuit to so choose the substance of the switch contacts that the arc shall not be prevented from forming or be suddenly extinguished by the action of the condenser, that is to say *that arcing at the switch contacts should rather be encouraged than otherwise*, of course always supposing that no special method such as a non-inductive resistance shunting the switch be provided to dissipate the energy stored in the self-induction.

The following experiments illustrate the importance of the nature of the switch contacts and of the condenser which shunts them. The circuit used was that shown in Fig. 11, the arc being replaced by a switch with brass contacts, and the data of the circuit being those given below the figure. When the condenser F was disconnected, and the insulation between *a* and *b* was made to consist of a single thickness of paper, I found that the circuit might be

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[1] *The Electrician*, 1900, vol. xlv., p. 281.

made and broken by means of the switch, either quickly or slowly, without the paper between *a* and *b* being pierced. [Experiment.] After reconnecting the condenser F, however, every time the switch was opened the paper was pierced, and even three thicknesses of the paper could not withstand the rise in P.D. that occurred. [Experiment.] The steady P.D. required to pierce one thickness of the paper was found by a separate experiment to be about 550 volts, and that required to pierce three thicknesses about 1,500 volts, so that without the condenser shunting the switch the rise in P.D. on breaking the inductive circuit was under 500 volts, but with the condenser as a shunt to the switch was over 1,500 volts, showing that the metal arc must have been almost completely suppressed, as the maximum value of the P.D. calculated above on the assumption of no arc forming at all was only just over 2,000 volts.

The influence of the nature of the contacts of the switch on the rise in P.D. which occurs when the switch is shunted by a condenser is very marked; thus with the metals, copper and brass, serious rises in P.D. were always found to occur, with solid carbons as contacts the rise was much less, and with cored carbon contacts was inappreciable. [Experiment.]

Breaking the circuit between metal contacts under tap-water, or shunting the metal contacts while in air by wires dipping into water, also prevented any serious rise in P.D.

It was also found that resistance or self-induction introduced into the connections between the condenser and the contacts greatly reduced the rise in P.D. on opening the switch.

I attempted to use an electrostatic voltmeter to measure the rise in P.D. instead of the rough method of the piercing of paper, but although the voltmeter was sufficiently sensitive to read steady P.D.s much below that required to pierce the paper, it failed to indicate the rises in P.D. This is probably due to the short time the rise in P.D. lasts.

There are two practical cases in which capacity shunts the switch contacts to which I will refer.

The first is the ordinary induction coil in which the circuit is the same as Fig. 11, the switch being replaced by the contact maker. In this case a high rise in P.D. is required so that the nature of the contact points should be such that the arc can be completely extinguished by as small a condenser as possible; for the rise in P.D., if the arc is completely extinguished, will be the higher the smaller the capacity of the condenser. (See also Appendix IV.) It is evident, therefore, that carbon would be very unsuitable for the contacts of an induction coil. This has lately been shown to be the case by the experiments of Mr. Beattie,[1] who finds that with a slow break the maximum length of spark obtainable between the terminals of the secondary, using *platinum contacts*, is nearly 2½ times that obtainable when *carbon contacts* are used, the current interrupted at the break being the same in both cases. I think that if *cored carbons* had been used, a much greater disparity in the spark length would have been found. [Experiment.]

The second case is that of a switch or circuit breaker connected with a concentric cable so that the capacity shunting the contacts is supplied by the distributed capacity of the cable. Whether this distributed capacity in practical cases will have the same effect as a condenser shunting the contacts, as suggested by Mr. Johnson, is, I think, a matter for further experiment. If it has, then serious rises in P.D. are to be apprehended on interrupting a *direct* current, though an inductive circuit, by means of metal contacts, the capacity of the cable forming a shunt to the contacts.

Assuming this to be true for *direct* currents, may not some of the breakdowns of concentric cables supplying power by means of *alternating* current be also due to the sudden quenching of the arc at metal contacts, and not to the fact that the current is an alternating one? I suppose, of course, that the attempt to interrupt the current is made at some point in the period when the current is large.

Before concluding this paper, I wish to express my indebtedness to Professor Ayrton and Mr. Mather, of the Central Technical College, not only for allowing me to carry out the experiments in the laboratories of the College, but also for the valuable assistance and advice they have given me during the course of the experiments. I also wish to express my thanks to the many students who have helped me from time to time, and especially to Messrs. Brown, Watson, and Fithian.

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[1] *Phil. Mag.*, 1900, vol. l., p. 146.

CONCLUSIONS.

If the current be suddenly increased through a direct-current arc between two solid carbons, the P.D. and current increase together for less than about $\frac{1}{5000}$ second, and at the end of this very short time the P.D. decreases with an increase of current in the ordinary way.

If the current through a direct-current arc varies by as little as 3 per cent. from the mean, and if the frequency of these superimposed variations is even as high as 4,300 ∿ per second, a variation in the light emitted by both the + crater and the vapour column can be detected.

A rapid periodic variation of the order of one part in 10,000 from the mean current will alter the vapour column of the arc sufficiently to produce sound-waves; and a variation of one part in 100 will produce sound-waves even at frequencies as high as 30,000 ∿ per second.

The arc is affected by such small changes of outside conditions as sound-waves produce.

The direct-current arc can be used both as a telephone receiver and transmitter.

In the direct-current humming arc the P.D. current and light emitted vary periodically, the frequency of these variations being the same as that of the rotation of the arc as a whole, and of the pitch of the sound emitted.

In the direct-current hissing arc the P.D. current and light emitted vary very irregularly, the larger and slower variations corresponding with a rotation of the arc as a whole and the smaller and more rapid to the hissing proper, *i.e.*, the oxygen of the air obtaining access to the crater surface as demonstrated by Mrs. Ayrton.

Under certain conditions the direct-current solid arc will emit a musical note when shunted by a self-induction in series with a condenser.

When emitting the musical note, the direct-current arc transforms direct-current energy into alternate-current energy, the frequency of the latter being determined by the self-induction, capacity, and effective resistance of the oscillating circuit. The pitch of the note emitted may be used as a means of comparing self-inductions and capacities.

If a direct-current arc be shunted with a condenser of several microfarads capacity, the arc will generally be extinguished if the electrodes are of metal, and not if they are of cored carbon, the resistance in series with the arc being non-inductive.

If the resistance in series with the arc be highly inductive, then, when the metal arc is extinguished by shunting it with a condenser, a violent rise in P.D. occurs between the terminals of the arc.

The rise in P.D. that occurs when an inductive circuit is broken by means of a switch, the contacts of which are shunted by a condenser, is much higher if their contacts are of metal than if they are of cored carbons, owing to the condenser extinguishing the metal arc formed at the contacts more suddenly than the arc formed when carbon contacts are separated.

APPENDIX I.

ON THE RESISTANCE OF THE CORES OF CORED CARBONS.

I do not remember having seen it pointed out that the much greater stability of arcs between cored carbons than of those between solid carbons can not be very well due to the high conductivity of the material of the core, while in place in the carbon, for the cores have generally a higher specific resistance than the solid carbon which surrounds them, as the following experiment shows:—

Three carbons were taken—two cored and one solid—of the same nominal diameter (11 mm.), and a current of 9·9 amperes was passed through them. The drop of volts was measured along a length of 20 cms. of each after they had attained a steady temperature.

Each of the three carbons then had a hole 3·16 mm. diameter drilled through it so as to completely remove the cores of the cored carbons and the centre of the solid carbon, and the drop of volts was remeasured as before. The results are given in the table below, from which it appears that drilling a hole in the solid carbon increased its resistance 7·8 per cent., whereas drilling the same sized hole (which removed the core and a small amount of the solid carbon) in a cored carbon of the same make only increased its resistance by 2·1 per cent.

Allowing for the fact that a small quantity of solid carbon was removed along with the core in drilling, *the specific resistance of the core, of one make of cored carbon, was about sixteen times that of the surrounding solid carbon, and in the other the specific resistance of the core was practically infinite.*

Make of Carbons	"Apostle" *Solid.*	"Apostle" *Cored.*	"Brush" *Cored.*
	mm.	mm.	mm.
Mean diameter	10·97	10·95	10·70
Mean diameter of core	—	2·84	2·82
Drop of volts along 20 cms. *before* drilling ...	1·71	1·74	1·52
Drop of volts along 20 cms. *after* drilling ...	1·84	1·77	1·56
Per cent. increase of resistance due to drilling..	7·8	2·1	2·4
Ratio $\frac{\text{Specific resistance of core}}{\text{Specific resistance of surrounding solid carbon}}$ about		∞	16

APPENDIX II.

ON THE CONDITIONS WHICH GOVERN THE CONVERSION OF DIRECT CURRENT INTO ALTERNATING CURRENT IN THE MUSICAL ARC.

(See Fig. 9.)

Let E and C be the E.M.F. and current through the cells, when there is no oscillatory current through the condenser circuit.

Let V and A be the P.D. and current through the arc under the same conditions.

Let R be the resistance in series with the arc, including that of the cells.

Let r be the resistance of the condenser circuit.

Let δV be a small change in the P.D. arc which produces a current δi through the condenser circuit for a time δt, and let δV and consequently δi be assumed to change sign at the end of each interval of time δt.

Let δA and δC be the corresponding changes in A and C; E being assumed constant.

The energy supplied to the condenser circuit—

during one interval $\delta t = (V + \delta V)(+\delta i)\,\delta t$

" next " $\delta t = (V - \delta V)(-\delta i)\,\delta t$

Total during one complete period $2\,\delta t = 2\,\delta i\;\delta V\;\delta t$

Energy dissipated in ohmic losses during $2\,\delta t = r(\delta i)^2\,2\,\delta t$

In order that, during each complete period $2\,\delta t$, energy may be supplied to the condenser circuit, we must have

$\delta i\;\delta V$ positive.

And in order that this supply shall make up for the ohmic losses we must have

$$\delta i\;\delta V \geqq r(\delta\, i)^2$$

Now

$$\delta C = \delta A + \delta i$$

$$\text{and } C = \frac{E - V}{R}$$

$$\therefore \delta C = \frac{-\delta V}{R}$$

$$\text{and } \delta i = -\frac{\delta V}{R} - \delta A = -\left(\frac{1}{R} + \frac{\delta A}{\delta V}\right)\delta V$$

$$\delta i\,\delta V = -\left(\frac{1}{R} + \frac{\delta A}{\delta V}\right)\left(\delta V\right)^2$$

$\therefore$ for a supply of energy to condenser circuit $\frac{\delta V}{\delta A}$ must be negative and numerically less than R.

Supposing $\frac{\delta V}{\delta A}$ negative, then in practice the second condition is always fulfilled, or $\frac{\delta V}{\delta A} + R$ would be negative and the whole circuit unstable.

Next the condition that sufficient energy be supplied to make up for the ohmic losses gives

$$\delta i\,\delta V \geqq r(\delta i)^2$$

and as $\delta i\,\delta V$ is positive,

$$r\,\frac{\delta i}{\delta V} \leqslant 1$$

$$-r\left(\frac{1}{R} + \frac{\delta A}{\delta V}\right) \leqslant 1$$

$\therefore$ to obtain best supply of energy to condenser circuit we require R very large and r very small.

Suppose $\frac{1}{R}$ may be neglected, compared with $\frac{\delta A}{\delta V}$ then condition becomes

$$-\frac{\delta V}{\delta A} \geqq r$$

Thus it is possible if $\frac{\delta V}{\delta A}$ is negative and numerically greater than r, for the condenser circuit to receive sufficient energy during each very small complete oscillation to compensate for the energy dissipated in ohmic losses during the oscillation. For larger oscillations, similar but more complicated expressions will probably be required.

APPENDIX III

On the Relation between the Pitch of the Note and the Capacity and Self-Induction Shunting the Musical Arc

In order to demonstrate that the pitch of the note emitted by the musical arc is determined by the capacity and self-induction of the circuit shunting it, and is given by the formula frequency of note emitted $= \frac{1}{2\pi\sqrt{L F}}$, when the resistance of the circuit is negligible, a series of capacities was calculated by means of this formula, to give one octave of the diatonic scale, on the assumption of a constant self-induction L. A fairly close approximation to this series of capacities was obtained by combining in parallel condensers chosen from a set of eight Swinburne condensers, the capacities of which are given below. A keyboard was constructed which made the necessary connections. The condensers used in parallel and their actual capacities are tabulated against the notes on the keyboard they were respectively intended to produce. This arrangement of condensers and keyboard, arrived at entirely by calculation, was that used to play tunes on at the meeting.

The self-induction L consisted of a coil of about 40 lbs. of No. 10 D.C.C. copper wire coiled into a coil of about 18 inches diameter, having a resistance of about 0·44 ohm and a self-induction of 14·75 henrys.

The frequency of each of the notes emitted by the arc was determined for me by Mr. G. Wall and Mr. L. Murphy by comparing, by means of a monochord, each note with a standard tuning-fork giving 512 complete vibrations per second. The frequencies so determined are tabulated below along with the frequencies calculated by means of the formula from the known self-induction and the capacity in each case. The agreement between the two demonstrates, I think, fairly conclusively that the pitch of the note is determined by the periodic time of the circuit shunting the arc. It will be noticed that the calculated frequency is in most cases about 1 per cent. higher than the observed; this is probably due to the fact that in calculating the frequencies no account has been taken of the resistance of the circuit in which the oscillating currents are flowing, as this resistance should include that of the arc. This is borne out by the fact that the note depends to a slight extent on the length of the arc and on the current through it. Another possible cause of the difference may be that the capacities of the condensers used may not be quite the same at these high frequencies, 550 to 1,100 ∿ per second, as at 100 ∿ per second, the frequency at which they were determined.

List of Swinburne Condensers.

Called.	Capacity in Mfs.	Called.	Capacity in Mfs.
a	2·515	*e*	0·307
b	1·142	*f*	0·119
c	1·146	*g*	0·130
d	0·612	*h*	0·057

DATA OF CONDENSERS FOR MUSICAL ARC.

Note on Keyboard.	Condensers Used in Parallel.	Capacity in Mfs.	Frequency ∿ per Second.	
			Calculated.	Observed.
C	*a*, *b*, *c*, *d*, *g*	$5{\cdot}54_5$	558	545
D	*a*, *b*, *d*, *g*	$4{\cdot}39_9$	624	618
E	*a*, *d*, *e*, *f*	$3{\cdot}55_3$	695	688
F	*a*, *d*	$3{\cdot}12_7$	740	735
G	*b*, *c*, *g*, *h*	$2{\cdot}47_5$	832	822
A	*b*, *d*, *f*, *g*	$2{\cdot}00_3$	926	915
B	*b*, *e*, *g*	$1{\cdot}57_9$	1042	1045
C	*b*, *f*, *g*	$1{\cdot}39_1$	1110	1101

To increase the alternating current in the condenser circuit and the loudness of the notes emitted, it is necessary to increase the number of solid arcs used in series. With the ordinary 200-volt supply only three solid arcs can be run in series, and even this number gives trouble owing to want of sufficient stability. In order to overcome this difficulty I employed the arrangement shown in Fig. 12, by means of which all the advantages in stability of having only two arcs in series are secured at the same time that, as far as the condenser circuit is concerned, we have four arcs in series and the consequent increase in the alternating current and the loudness of the notes emitted. As used at the meeting the data were as follows: Pressure of supply 200-

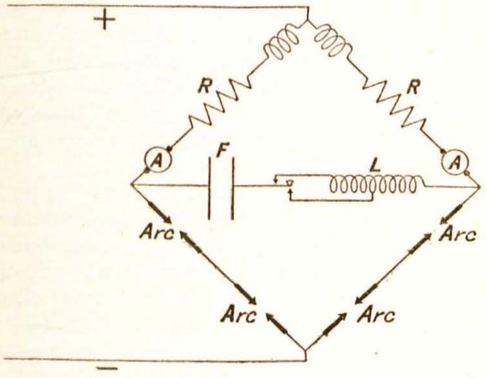

FIG. 12.

volts current through each arc 5 amperes. Carbons + 11 and — 9 mm. solid "Apostle." Arc length about 1 mm. F condenser and keyboard described above. L self-induction described above, with an extra point brought out so as to reduce its value to ¼ and give a second octave.

APPENDIX IV.

(*Communicated February* 22, 1901.)

During the experiments on the shunting of a metal arc with a condenser, I noticed that the rise in P.D. which occurs between the terminals of the arc when the circuit is inductive always seemed to be greater when the condenser was applied as a shunt to an arc after striking the same than when the electrodes were first shunted with a condenser and afterwards the attempt was made to strike the arc. Prof. Fitzgerald suggested to me, quite independent of the above observation, that in the case of an ordinary induction coil an increase of spark length might be obtained if instead of connecting the condenser, as is usual, permanently as a shunt to the contact points the condenser was disconnected during the time the contact points separate to a small distance, and was then connected as a shunt to them so as to suddenly extinguish the small arc or spark that had formed between them.

In order to carry out this suggestion a contact maker driven by a motor was constructed by means of which the condenser could be connected as a shunt to the contacts, which acted as the interrupter for the primary current of the induction coil either before their separation (ordinary method) or at any desired time interval after the separation of the contacts and the formation of the arc between them (new method).

With this apparatus, using a six-inch spark "Apps" induction coil the primary current being supplied by three accumulators and regulated by means of a carbon resistance, and using the condenser belonging to the coil, I found that if the primary current was adjusted to give the maximum length of secondary spark, first with the condenser applied before the separation of the contacts, second with the condenser applied a certain time after their separation, then the spark length in the latter case (new method) was from two-and-a-half to three times as great as in the former or ordinary way. Again, if, when the spark length was adjusted to its maximum value with the new method, the condenser was applied in the ordinary way without changing the current or the speed of the contact maker, then the secondary spark was reduced to about one-sixth or one-seventh the length, so that the new method of applying the condenser to the induction coil gives in both cases a considerable increase of spark length over the old.

An observation was made whilst working with this contact maker on the curious way in which a trace of oil on the contacts affects the secondary spark length. If, with the condenser connected in the ordinary way, the current through the contacts was so small that practically no arc formed between them, then a trace of paraffin oil on the contacts *increased* the secondary spark length. If, on the other hand, the current was so large that appreciable arcing was taking place, then the oil on the contacts *reduced* the spark length, apparently due to the oil being decomposed, and introducing carbon vapour into the arc between the contact points, thus reducing the suddenness of the interruption of the primary current.

The President.

The PRESIDENT: It is quite evident we have not time for much discussion, and I am sorry to say the discussion on this paper cannot be adjourned. I think, however, we ought to call upon Professor Ayrton to say how it bears upon that negative resistance of his which was so much maligned some time ago.

Professor Ayrton.

Professor W. E. AYRTON: The paper which we have just heard read has given me exquisite pleasure: not because I have any claim to be its author, although I felt as pleased while I heard it read as if I had been the writer; nor is it merely because I feel convinced that these experiments of to-night will assist in the development of the electrical industry of to-morrow: it is rather because it so rejoices the hearts alike of professional men—yea, and of professors—to find a student who so resembles a solid carbon arc that he is ever on the alert to catch at and magnify any hint which may come from Nature or man. From Mr. Duddell's papers of two years ago, and of to-night, we learn much; among other things this second one has taught us how valuable was that research made some five years ago by Messrs. Frith and Rodgers. For what did that investigation really show us? It brought out an absolutely new fact. Supposing this is an alternating-current circuit (Fig. A), the alternator running at a given frequency and supplied with a given exciting current, the alternating current in the circuit being measured by an accurately graduated alternate-current ammeter, and that this is a wholly separate circuit—a direct-current circuit supplied by accumulators—and sending a direct current through a solid carbon arc. Then what they showed was this, that if you make a break in this alternate circuit and insert the solid carbon arc (Fig. B) without making any change in the resistance, speed, or excitation of the alternator, etc., you increase the alternate current, not merely the current when flowing in one direction—for the condenser stops any direct current—but you increase the current in *both* directions; that is, the alternate-current ammeter reads higher after the arc has been inserted than it did before, and higher than it will if the arc be short-circuited. Now that investigation was undertaken by these gentlemen because certain theoretical considerations led me to suggest that if the method that had been employed by various experimenters to measure the resistance of the arc—a method employed without comment or adverse criticism as long as a positive answer was obtained—was applied in a certain case to an arc a negative answer for the resistance of the arc would be found: that the method, in fact, which up to that period had been used successfully to give the resistance of the arc, and which had always given a positive value, I pointed out would give under certain conditions, a negative answer. Certain preliminary experiments

Professor Ayrton.

having been made by Mr. Mather which confirmed my idea, a long investigation was carried out by Messrs. Frith and Rodgers. And they found that whenever the arc was formed between *solid* carbons, the ratio of an instantaneous change of P.D. to the corresponding instantaneous change of current was *negative*, whereas if the carbons were *both cored* it was always *positive*.

A howl of indignant criticism followed. Had Messrs. Frith and Rodgers and I lived in the Middle Ages we should undoubtedly have been burned in the solid carbon arc. But there were three distinguished investigators who had the insight, who had the courage, not to be drawn into this net of conventional antagonism, and these were Professor Gray, then of Bangor, now Lord Kelvin's successor at Glasgow, Mr. Oliver Heaviside, and last but by no means least, the Chairman of your Dublin local section, Professor Fitzgerald, to whom we, like so many experimenters, are indebted for the many suggestions which he has made. And I, even I, ventured to suggest that progress would be more expedited, I thought, if the critics, instead of merely cavilling at the anatomy of the sugar figure on the cake, would cut it open, and see whether there were really any plums inside. It has remained, however, for Mr. Duddell to be the real Jack Horner to put in his thumb and pull out the plum, and modestly leave you and me to finish the rhyme and add "what a good boy he is."

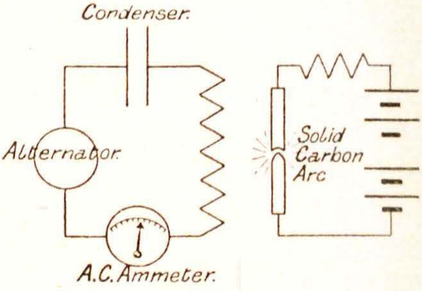

FIG. A.

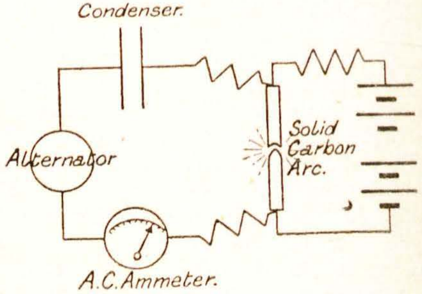

FIG. B.

Professor Ayrton.

I do not propose this evening to consider whether or not what Messrs. Frith and Rodgers measured was the true resistance of the arc, because opportunity, I hope, we shall soon have of going fully into the subject; but in justice to Messrs. Frith and Rodgers, and in virtue of the far-reaching principle that they really brought to light, I desire to emphasise what they really obtained. Mr. Duddell has taught us what was the real significance of their work. Our lost friend Professor Hopkinson, following Mr. Wilde, proved several years ago that two alternators could not be run in series. Thus, for example, if an alternator with a certain exciting current supplied to it, and driven with a steam engine, or an electric motor, or whatever it might be, were coupled mechanically to another similar alternator, driven by an independent steam engine, and speed were got up so that the two machines were going exactly in step and then were joined in series with some outside circuit, he proved to us that the moment this mechanical coupling was severed the two alternators would get out of step. So, as is well known, two alternators cannot run in series. And he might have added—if there had been the slightest necessity for him to do so—that if two alternators cannot continue running in series even if they have been started with the same frequency and exactly in step, still more impossible must it be for one alternator, driven by its own steam engine, to run in series with another independently driven when the frequency of the second is being altered within wide limits. Nevertheless, gentlemen, that is exactly what the arc does. For in Fig. B we have one alternator running in series, with a second alternator, viz., the solid carbon arc, supplying alternating current to the circuit—because the arc transforms direct-current energy into alternate-current energy—and does it in such a way that whether the frequency of this alternator be as Messrs. Frith and Rodgers found, seven periods per second, or 70, or 170, or 250, which was the highest limit which could be obtained in my laboratory at that time, and whatever the current might be, within the limits they tried, this gallant little alternator—the solid carbon arc—helps the other, and supplies current sufficiently in phase as to make the alternate current greater when it, the arc, is inserted than when it is taken away or short-circuited.

Mr. Duddell has not only pointed out the importance of that result, the novelty of that result, but he has pointed out something even further. He has shown us that an ordinary so-called perfectly silent arc supplied with current from accumulators is, if the carbons be solid, like the mouthpiece of a flageolet or flute, not blown. The application of a shunt to that arc, consisting of a capacity in series with a self-induction, performs two operations. It starts vibrations in the arc, just as blowing a flute gives rise to vibrations of many different rates. Just as one of those rates of vibration is picked out and reinforced in the case of a flute or flageolet by the form of the resonance chamber dependent on the position of your fingers or keys, so in this musical arc the particular one of the many vibrations that is probably started which is picked out and reinforced depends on the capacity of the condenser and the value of the self-induction which is in series with it.

Professor Ayrton.

Already he has shown you a practical result that has followed from this. I do not mean merely those illustrations which he has given of magnetic space telegraphy, and by means of which he has shown how it has become possible to easily and experimentally demonstrate that the E.M.F. of the current induced in the distant secondary coil is proportional to the frequency of the alternating current in the primary, which will be of marked value to teachers; but beyond that he has shown us how to much improve a well-known instrument. The other day he demonstrated in my laboratory that, adding to the ordinary circuit of that very induction-coil, joined up as usual, his little motor so as to put the condenser across the break *just after* the break was made, a spark was obtained from five to seven times as long as was obtained with the coil in the ordinary way. Even if you try to make the comparison absolutely fair, and try to arrange the very best conditions in each case for the old method and for the new method, you still find a great advantage. Let somebody take, for example, an induction coil and arrange the battery-circuit, contact-breaker, etc., in the old way as well as he can, and let Mr. Duddell use the same induction-coil, battery, condenser, etc., and deal with it as well as he can, then the spark produced in the latter case will be from 2½ to 3 times as long as in the former.

There is one other point which has come out in connection with these experiments of a rather different kind. Some ten or more years ago a paper was read by Dr. Sumpner and myself before the Royal Society, pointing out what was then new, that in the case of an alternating-current arc, if we used solid carbons, the true power given to the arc, that is the power measured by some accurate method, was considerably less in some cases than the current measured by a good current ammeter multiplied by the pressure measured by an alternate-current voltmeter. Subsequently to that, in making experiments I was pretty convinced that under certain circumstances a direct-current arc behaved in the same way. I was pretty certain, in the case of a direct-current arc, especially when solid carbons were used and the arc was hissing, that the power-factor was no longer unity, but not sufficiently sure of the fact to publish it, especially in view of the way in which that other paper which I have just referred to was received at the Royal Society, and the scepticism which was raised when Dr. Sumpner and I pointed out how far from unity we found the power-factor was with certain alternate-current arcs. But now I am sure, from results of experiments which have been recently made in my laboratory, that with an arc supplied with accumulators, a so-called steady direct-current arc, if the carbons be solid and there is hissing, the power-factor may be several per cent. different from unity—that is, the true power as measured by a true instrument, for example a good wattmeter, may be several per cent. less than the product of the voltmeter reading into the ammeter reading.

When I read this paper of Mr. Duddell's, I thought he had proved that a solid carbon direct-current arc was the most sympathetic soul I had ever met, but you have convinced us that that is not quite the case, for you have shown Mr. Duddell this evening that the sympathy of his arc is even exceeded by the sympathy of his audience.

Dr. Fleming.

Dr. J. A. **Fleming**: It is very difficult to decide who ought to be congratulated the more heartily this evening; the members of this Institution for having had an opportunity of hearing such a delightful paper from Mr. Duddell, or Mr. Duddell himself for having completed such an excellent piece of scientific work. It is a paper which I am sure must especially gladden the heart of our President, for if I mistake not it will have important practical results in connection with electrical engineering, and it will perhaps assist in showing that science sometimes does go before practice, and not follow it.

The matter that has most interested me has been the experiments with the continuous-current arc setting up oscillations in a circuit containing a condenser short-circuited on the arc, because I have been attempting something in that direction lately, only unfortunately I have concentrated all my attention on the alternating-current arc between metallic electrodes, whereas I ought to have directed attention to carbon electrodes. I am afraid it will be a matter of regret to me that I made that choice. It is, of course, a well-known fact that if an alternate-current arc between metallic balls is used, strong oscillations can be set up in a condenser circuit shunting the balls, especially if the arc is blown upon by a well-regulated current of air. But the effect with the continuous-current arc is exceedingly interesting, because it seems to depend on certain critical conditions as to the state of affairs when the arc is extinguished. If I mistake not, a rough explanation of it is something in this direction. Imagine the condenser and inductive circuit to be placed across the carbons when the arc is in operation. Then at that moment the arc is robbed of its current, and is extinguished. Then the potential rises, the condenser becomes charged, and it discharges itself through what remains of the conducting vapour, and then re-establishes the arc, and so sets up a periodic state of affairs —a sort of flutter is created in the arc which expresses itself in a musical note. But, as Mr. Duddell points out, it will not take place if cored carbons are used, and it will not take place if metallic electrodes are used. It seems to be perfectly clear from his experiments that the reason why it will not take place with a metallic electrode is because the arc vanishes too quickly. Perhaps the reason why it will not take place with the cored carbons is that the conducting vapour remains too long. In that case I should like to know whether the sound will be produced by cored carbons if blown upon by a gentle current of air.

Certainly one of the most practically important parts of Mr. Duddell's paper is the final section, in which he deals with the question of switch contacts, and, if I mistake not, that will cause some heart-searching to those who have been responsible for the manufacture of high-tension switches. Hitherto the idea has been in the minds of every one of us that what a high-tension switch ought to do is to have jaws which fly apart as quickly as possible, and break the arc as rapidly as possible. That, according to these experiments, is exactly what it ought not to do. I lately came across, in a technical journal, an elaborate description of a switch for high-tension purposes. It was to be made of non-arcing metals. I suppose Mr. Duddell will tell us that that is exactly how not to do it, and that what we want to do in constructing a switch of that

Dr. Fleming. kind is not to destroy the arc, but to encourage the arc, only it must be an arc which is under perfect control, and which you can whittle away by degrees, having it under perfect control until it is finally extinguished.

I recollect trying many experiments with carbon poles underneath the surface of water drawn apart in the endeavour to combat some of those very difficulties which Mr. Duddell alludes to at the end of his paper, when he speaks about the risks and dangers of interrupting alternating currents in concentric cables. I suppose there is no question that some of those effects have been due to the very things he has explained to us to-night.

There is one other point I should like to notice, viz., experiments with the induction coil. It is well known to every one who handles induction coils that although a coil will work well with a certain number of cells, taking, we will suppose, five amperes and working with ten volts, yet if you try to work that coil upon a 100-volt circuit, and put in a resistance to keep the current down to five amperes, it will not work at all. You get a very reduced secondary spark out of it. And the explanation is clear. When you have the higher voltage, as the contact points separate the arc is drawn out, and the decay of the magnetism of the core is therefore hindered, which is exactly what you do not want. Therefore the moral of these things is, that in the contact of an induction coil you must do exactly the opposite to that which ought to be done when constructing high-tension switches. I am sure all this portion of Mr. Duddell's paper will have valuable consequences in directing those responsible for the design of large switches to consider their ways and be wise.

Mr. Trotter. Mr. A. P. TROTTER (*communicated*) : The fact that I have published so little about my researches on the rotatory phenomena of the direct-current arc, makes me reluctant to criticise those parts of Mr. Duddell's paper which cover the same ground, and if I did differ with him on a few isolated points, I do so without diminishing my esteem for the paper as it appears in print, and my admiration for the experiments with which it was so brilliantly illustrated.

The sensitiveness of the arc to small variations of the current was brought to my attention by the clicks which corresponded to the commutator sections of a little motor which I used to drive my stroboscopic discs. The motor was in shunt to part of an iron-wire resistance in series with the arc. I used about 20 amperes on a 100-volt circuit. The motor took about one ampere ; I substituted an induction coil for the motor, and the hum or squeak of the contact maker was clearly reproduced by the arc. In both of these cases the main current was not interrupted, but a small change was made in a shunt. I used to work late at night, and did not attempt serious work until I knew by the sound that the Kensington Court dynamos had shut down, and that the supply was derived from the batteries.

I do not think that the model exhibited to show the rotation of the arc gave a good idea of the actual conditions. The crater is horizontal, with a good arc between vertical carbons. With a silent, fairly short arc the cupped surface appears to be uniformly luminous, but on gradually

Mr. Trotter.

increasing the current, and before the hum begins, photometrical examination shows the rotatory phenomenon. The bright spot is the "head" of the comma-like patch of luminosity. This spins round, but always within the crater, and it can never be "on the other side of the + carbon" as Mr. Duddell suggests, unless the arc be very long, and the + carbon rounded instead of being flat or cupped, and the arc very irregular. I think Mr. Duddell has rather exaggerated the extent of the rotation, perhaps by way of making the point more clear. But I agree with him generally that the periodic variation of the light is most probably due to the fact that any one portion of the crater supplies at one time a brilliant and at another time a less brilliant light to the oscillograph mirrors. Unless the whole of the light can be collected and dealt with, I do not think that the author is justified in saying that "the light" varies with the frequency of the hum. It is not unlikely, however, that the total light *does* vary; but this, on account of the variation of current rather than on the strength of the author's photographs.

In 1894 I observed the variation of the current by means of a telephone wound with thick wire carrying the whole current of 20 amperes. I made some attempt to measure the variation, as an alternating current, but I had not the means for doing so: this was one of the matters which I wished to investigate before publishing anything more. Other matters which I have regarded as indispensable features of an account of the humming arc are a set of photographs of the "white spot," the "comma," and the "butterfly," and an investigation of the relation between periodicity, of hum, current, and length of arc. The variation of current has been admirably measured by Mr. Duddell, but he has not, I think, thrown any light on the cause of the variation. We merely have his statement, that with a humming arc the current and the volts and the light vary with the frequency of the hum. I see no likelihood of being able to continue my research at present, and I should be glad to see Mr. Duddell or some equally competent investigator take it up where I left off. I think that I can account for the rotation, but I am quite unable to understand the variation of the current.

After a long study of enlarged images of silent, humming, and hissing arcs, the author's diagrams, Figs. 6 and 7, do not convince me that Mrs. Ayrton is justified in suggesting that "the hissing arc is also probably rotating." Examination of the images of hissing arcs with various kinds of stroboscopic discs has not disclosed either rotation or periodicity. The diagrams show exactly what might be expected from a phonograph reproduction of a hiss. The image of the crater of a hissing arc shows a patch or patches of brilliant luminosity jumping about: I can find no better expression. They may flicker with more or less regularity for a second or two, but with an ordinary hissing arc the behaviour is erratic and capricious. Fig. 6 shows three waves having a periodicity of about one hundredth of a second; if this were continued for an appreciable period it would give a hum, sounding the lower G of the bass clef, and in so far as any periodicity exists, the arc is a humming arc as well as a hissing arc. As in the case of the humming arc, the record of the oscillograph cannot be accepted as

Mr. Trotter. indicating the variation of the whole light unless the whole light is dealt with.

Of the remainder of the paper I will say nothing but to repeat my admiration, and of the parts to which I have referred I would say, without disparagement, that they serve to fill up chinks between the classical paper on the Hissing Arc and one on the Humming Arc, which has not yet been written. He who has time and opportunities for writing the latter has some fascinating work to do.

Mr. O'Gorman. Mr. M. O'GORMAN (*communicated*): Mr. Duddell, with admirable self-restraint, puts the suggestion of damage to concentric cables from the sudden interruption of an arc between metal contacts in the shape of a question. His suggestion is very probably right in certain cases, but I think these cases are at present rare, for several reasons.

1. The capacity needed to extinguish suddenly a metallic arc when the voltage was 200 was shown by his experiments to be considerable —as cable capacities go. (The entire eleven miles of the Ferranti Deptford main has only a capacity of 3·8 microfarads, and Mr. Duddell used 5 mfd.).

2. That capacity must be, so to speak, immediately available, not separated from the arc to which it is a shunt by either self-inductions or a resistance, one or both of which are almost always present in the armature of the dynamo, motor, &c., if not in the mains, through which the cable capacity acts on the arc of a switch.

3. The capacity is almost invariably shunted in low-tension systems by the non-inductive filaments of the lights which are not extinguished at the time of the operation of the switch under consideration, for the load on a central station of any magnitude such as would have a large capacity on its mains never falls to zero.

4. The leakage from main to main is almost invariably sufficient to allow a normal current of a few amperes to flow; thus the capacity shunting the arc is itself shunted by a small resistance, say 100 ohms, even supposing the arc to be struck when there are no non-inductive filaments connected.

5. It was proved by Northrup and Pierce (*Electrical World*, Nov. 6, 1897), in a paper quoted by Steinmetz, that the disruptive effect of high-frequency oscillations from a condenser and self-induction, or the peaky volt surgings from an induction coil, is much less than that of a sinusoid alternating voltage, on heavy insulating oils (which are the basis of the bulk of modern concentric cables). Hence 2,000 volts does not of itself always mean a very heavy puncturing effect applied to a cable, though it may mean a great deal with a piece of dry paper, the path across which is practically an air-gap.

On high-tension mains in ordinary practice we are far from getting the short snappy, almost explosive extinction of the spark which Mr. Duddell got on each occasion signalised by the paper puncturing, and I have been unable to speak to any one who has seen such a sudden interruption of the arc in practice on the mains. This is due to two facts. First, that a D.P. switch is always used which disconnects the condenser from the circuit while breaking it; and secondly, if one limb of the switch operates before the other has begun to arc, as is frequent, Mr. O'Gorman.

or if a single-pole switch is used, the condenser is not directly in shunt across the metal arc between the contacts, but is across them, *in series with the self-inductions of the line and some part of the load in parallel with the alternator.* Whether alternating generators having small self-induction are for this reason to be preferred, is a question which is probably settled by the fact that all alternators now made have such resistance and self-induction that sparks are not usually swamped with this dangerous suddenness.

Every one who heard Mr. Duddell's paper must agree that he may justly feel proud of his brilliant success, both in research work and in demonstration.

Dr. Marchant.

Dr. E. W. MARCHANT (*communicated*): There is a question which is of some interest in connection with one of the experiments Mr. Duddell showed at the demonstration on December 13th. I refer to that in which the music of the arc was first changed in note, then stopped altogether by the introduction of an iron-wire core into the self-induction he was using.

Apart altogether from phenomena produced by energy absorption, the increased self-induction of the coil produces an increased impedance of the circuit, and a consequently decreased alternating current in the circuit, the impressed P.D. remaining constant. This reduced current gives rise to a diminished expansion and contraction of the vapour column, and consequently a note of less intensity is heard. At the same time, the absorption of energy in the core prevents the amplitude of the oscillations in the circuit increasing beyond a certain limit; they are damped out too quickly. I wish to draw attention more particularly to the causes of the energy absorption. Mr. Duddell describes the effect as being due to hysteresis, but I think he should describe it as an effect partly due to hysteresis and partly to eddy current loss. It does not seem to be generally recognised that the eddy current loss in iron is always very much greater than in any other metal, copper for instance. In several instances descriptions of effects produced by iron wires that are not produced by copper wires have been published, and the cause of the difference in behaviour of the two metals at once put down to hysteresis without taking account of eddy currents, quite forgetful, apparently, of the fact that eddy-current loss in iron wires at ordinary induction densities, is many thousands of times greater than in copper, in spite of the relatively great conductivity of copper. For example with No. 28 soft iron wires, with an induction density of about 15,000 lines per sq. cm. and a frequency of 1,000, the eddy-current loss is double that which is due to hysteresis. It would seem, therefore, in this experiment that eddy currents are at least as potent as hysteresis.

The very interesting experiment shown by Mr. Duddell with an induction coil, in which the spark length from the secondary was increased by connecting the condenser the instant after the spark was formed at the contact breaker, is capable, I think, of a comparatively simple explanation. The experiments preceding this proved that the P.D. induced between metal electrodes is higher when the condenser is suddenly switched on with the arc burning, than when the

Dr. Marchant.

current is suddenly switched on, the condenser being always in connection.

When a condenser is switched on between the terminals of a spark-gap, oscillations are set up in the condenser circuit (the frequency of the oscillations depending on the conditions of the circuit) which may enable the arc to restrike. If, however, the time at which the condenser is switched on be so regulated that the arc will just not restrike, the current through the coil is annulled with great suddenness, at a rate calculable from the conditions of the circuit. If, on the other hand, the condenser be applied from the beginning of the break, the arc will be able to restrike, and rapidly alternating currents will traverse the metal arc until the distance between the contact points has so far increased as to prevent this. In other words, the cause of the phenomenon is the fact that the rate of flow of current into a condenser, and the consequent rate of extinction of the current through the induction coil, has its maximum value when the condenser is first connected, a fact known from the solution of the equations determining the charge of a condenser.

I can only add my congratulations to Mr. Duddell on his admirable paper, and still more admirable experiments.

Mr. Russell.

Mr. ALEXANDER RUSSELL (*communicated*): For his wonderful discovery of a simple method of obtaining alternating currents of high frequency from the direct-current mains, Mr. Duddell deserves the grateful thanks of all electricians. In case any of those who did not hear Mr. Duddell may think that the method requires elaborate apparatus or careful tuning, the following account of a rough experiment with an ordinary direct-current arc lamp may prove instructive. The lamp was run direct from the hundred-volt street mains through a resistance, and had the ordinary shunt and series regulating coils. A coil of 110 yards of 7/15 cable about 2 feet in diameter, wrapped up as it came from the makers, was put in series with a condenser, and the two were placed as a shunt between the carbons. The condenser was a very roughly made one of about 1·9 microfarad capacity, and was similar to those used with ordinary induction coils. On switching on the current, which was about twelve amperes, a high musical note could be heard very occasionally, but on reducing the current the note became continuous. Placing another coil of cable in the neighbourhood of the first coil, it was easy to feel and easy to see by the sparking on breaking the circuit that powerful induction effects were taking place between the two coils. The induced E.M.F. could also be read on a hot-wire voltmeter up to a distance of two or three feet between the coils.

A Siemens' electro-dynamometer placed in the main circuit read 3 amperes (C), and another in the condenser circuit read 2·1 amperes (I). The resistance of the coil of cable and of the dynamometer and leads was about 0·25 ohms (R), and the musical note given out by the arc showed that the frequency of the alternating current was about two or three thousand per second. The P.D. between the carbons was 48 volts, and the current in the main circuit did not appreciably alter when the condenser circuit was switched on and off.

Mr. Russell.

The power-factors of the arc and the condenser circuit can be easily found. Let $V + e$ be the P.D. between the carbons where V is a constant and e varies, then, as is well known, the effective P.D. will be $\sqrt{V^2 + v^2}$, where v is the effective value of e. Let also R be the resistance of the condenser circuit, shunting the arc when the condenser is short-circited, and let I be the effective value of the instantaneous current in this circuit, then the power expended in it will be $R\,I^2 + H$, where H represents the power expended in the condenser and in neighbouring metallic circuits. When we can neglect H, the power-factor of the condenser circuit

$$= \frac{\text{true watts}}{\text{apparent watts}}$$

$$= \frac{R\,I^2}{\sqrt{V^2 + v^2}\,I}$$

$$= \frac{R\,I}{\sqrt{V^2 + v^2}}$$

$$= 0{\cdot}011.$$

[On switching off the condenser circuit the P.D. fell from 48 to 40. Hence $\sqrt{V^2 + v^2} = 48$, $V = 40$

$$\therefore v = 27$$

In practice v and I do not remain steady for more than a few seconds at a time, and vary between wide limits.]

If C be the current in the main circuit, then the alternating component in C is very small, and so we can consider C as constant.

$$\left.\begin{array}{r}\text{The instantaneous power}\\ \text{expended in the arc}\end{array}\right\} \begin{array}{l}= (V + v)(C - i)\\ = V\,C - v\,i + v\,C - V\,i.\end{array}$$

Now the mean value of the last two terms for a complete period is zero, and the mean value of $-v\,i$ is $-R\,I^2$.

$$\therefore \text{Power expended in arc} = V\,C - R\,I^2$$

$$\therefore \text{Power-factor of the arc} = \frac{V\,C - R\,I^2}{\sqrt{V^2 + v^2}\,\sqrt{I^2 + C^2}}$$

$$= 0{\cdot}68.$$

The current through the arc is of course $\sqrt{I^2 + C^2}$, *i.e.*, 3·66 amperes. The power-factor of both arc and condenser circuit taken together

$$= \frac{V\,C - R\,I^2 + R\,I^2}{C\,\sqrt{V^2 + v^2}}$$

$$= \frac{V}{\sqrt{V^2 + v^2}}.$$

Hence, as Professor Ayrton pointed out, we have part of a direct-current circuit with a power-factor less than unity. The determination

Mr. Russell.

of v is not very easy when v is small, as V and $\sqrt{V^2 + v^2}$ are nearly equal to one another. For example, if V is 48 and v is 6, then the difference between V and $\sqrt{V^2 + v^2}$ is only 0·37 of a volt.

Mr. Duddell mentions that for a very rapid rise of i, v shows an initial rapid rise, and hence v and i will have the same sign. This seems to indicate that when the frequency of the natural vibration of the condenser circuit is greater than 10,000 it may be impossible for its current to absorb sufficient energy from the arc to keep up the vibrations, and hence the phenomenon would cease. As Mr. Duddell has not yet published his experiments on the resistance of the electric arc, it perhaps would be hardly fair to ask him to elucidate more fully some of the results in connection with it he has mentioned. So far as interest and importance are concerned, the paper by Messrs. Duddell and Marchant on alternate current arcs was hard to beat, but I think Mr. Duddell has done it.

Mr. Clinton.

Mr. W. C. CLINTON (*communicated*): The extinction of the metal arc when shunted by a condenser is probably materially assisted by the superior conductivity of metal electrodes. In confirmation of this it may be noted that extinction under given conditions is certain with copper poles, less certain with zinc, and does not take place with carbon. It would be interesting to know whether extinction is accomplished with the same certainty using copper after the arc had been running for, say, an hour, and everything was thoroughly hot.

Mr. Duddell.

Mr. W. DUDDELL (in reply) [*communicated February* 22, 1901]: To the interesting remarks made by Professor Ayrton on the connection between my experiments and those of Messrs. Frith and Rodgers, and on the bearing of these experiments on the value of the resistance of the arc, I will make no reply, as I hope at an early date to enter very fully into this subject.

The fact that the power factor of a direct current hissing arc is less than unity is evident from Figs. 6 and 7, and its value could be calculated from them. Mr. Alexander Russell justly points out that the power factor of the Musical Arc is also less than unity; in fact, if an arc, or any other conductor which has a resistance or an E.M.F. depending on the strength of the current, forms part of a circuit through which a varying current flows, so that the instantaneous values of the P.D. and current do not have a constant ratio, then the power factor of that circuit will be less than unity.

Dr. Fleming, in his explanation of the phenomena of the Musical Arc, assumes that the arc is extinguished at each oscillation; but this is not necessarily the case, as by changing the conditions of the arc, the current can be caused, either to vary over a very limited range without at any instant becoming very small, or it may be caused to vary over such a large range that actual reversal of the direction of the current through the arc takes place, the arc current becoming practically an unsymmetrical alternating current.

Dr. Fleming also asks whether cored carbons can be used if the arc be blown upon by a gentle current of air. Intermittent arcs can certainly be obtained between cored carbons by this means; in fact, so far as I have tried, *intermittent* arcs can be produced between any elec-

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trodes with suitable circuit conditions and blowing either by means of a magnet or a current of air. This latter phenomenon, where the arc is, so to say, mechanically extinguished and relights, must not be confounded with the Musical Arc, which depends for its action on a certain specific property of the arc considered simply as an electrical conductor, no actual extinctions or intermittances of the arc being necessary for the phenomena to maintain themselves continuously.

Dr. Marchant raises the question of the connection between the value of the alternating current in the condenser circuit shunting the arc, and the frequency. I have measured this current, and I find it very little affected by change in frequency; this is probably due to the fact that the periodic time of the current is always the same as the periodic time of the circuit, so that it is the resistance of the shunt circuit which determines the flow of the current and not its self-induction or capacity. Dr. Marchant says that "eddy current loss in iron is many thousand times greater, at ordinary induction densities, than in copper," but is this a fact? If the *induction* is the same, then the loss in copper, other things being equal, is greater than in iron. Does not Dr. Marchant mean for the same *magnetising force?* Taking the case of the experiment shown at the meeting of an iron wire core introduced into the self-induction coil stopping the note. The coil used consisted of 98 turns of No. 12 D.C.C. wire, mean diameter 35 cms. Self-induction without core $5{\cdot}3 \times 10^{-3}$ henry. The core used consisted of a bundle 3 cms. diameter of No. 26 iron wires 54 cms. long. Weight 1·9 kilogrammes. The frequency was about 950 ∿ per second without the core and was reduced by its introduction, the arc just failing to emit its note when the core was central in the coil. It is improbable that the induction in the core attained 1,000 lines per cm.^2 so that although the eddy current loss is considerable, I still think that the cessation of the note was mainly due to hysterises, though whether it was due to hysterises or eddy current losses does not affect the object of the experiment, viz., to show that causes which tend to dissipate the energy in the condenser circuit may stop the arc giving its note.

Mr. Clinton asks whether the extinction of the metal arc when shunted by a condenser will take place with the same certainty after the arc has been running for, say, an hour.

I have no experience of metal arcs which have been running for such a long time; after a few minutes the arc is burning between globules of molten metal, and in this condition the extinction still takes place. Any further burning will not, I think, materially affect the conditions, as the molten metal then drops off as it is formed. I am of the opinion that the suddenness does depend on the quickness with which the vapour condenses under the given conditions; thus, if the whole space in which the arc was burning was at a higher temperature than the temperature of volatilisation of the metal, I should expect that extinction would not be produced.

In connection with the subject of the dangers of capacity shunting the switch contacts in inductive circuits, Mr. O'Gorman advances several reasons for thinking that at present such dangers are rare. I am not, however, inclined to agree with him, and if I were re-writing

Mr. Duddell. my paper at the present time, I should no longer use such self-restraint as to put the suggestion of damage to concentric cables in the form of a question. I will consider the reasons he gives as far as possible in order.

1. There are in use at the present time, and their number is rapidly increasing, a considerable number of concentric cables having two or more microfarads capacity, and these capacities would be sufficient to produce the sudden extinction of the arc between the switch contacts under my conditions. It must also not be forgotten that the smaller the capacity, other things being equal, the higher will be the rise of P.D. between the terminals of the switch, supposing the arc is extinguished.

2 and 3. Mr. O'Gorman is quite correct that the capacity must directly shunt the switch contacts and not be separated from them by any considerable self-induction or resistance. This actually occurs in practice in several cases. I will take as an example the ordinary case of switching off a high tension concentric cable from the buss bars, to which several such feeders are connected, as shown in Fig. C. The outers are all assumed connected together and to earth. The capacity of the inner of, say, cable *a* to the inners of cables *b*, *c*, &c., will be due to the capacity of *a* in series with the joint capacities of *b*, *c*, &c., and will have a value which will range between one half, in the case of two identical cables, and equal, in the case of a large number of cables, the capacity of the inner to the outer of each cable. This capacity of the inner of *a* to the inners of *b*, *c*, &c., *directly shunts the contacts of the switch* in the inner of *a*, so that if an inductive load be connected to the cable, we have all the necessary conditions for a serious rise in P.D. between the switch contacts and consequent danger to the cables.

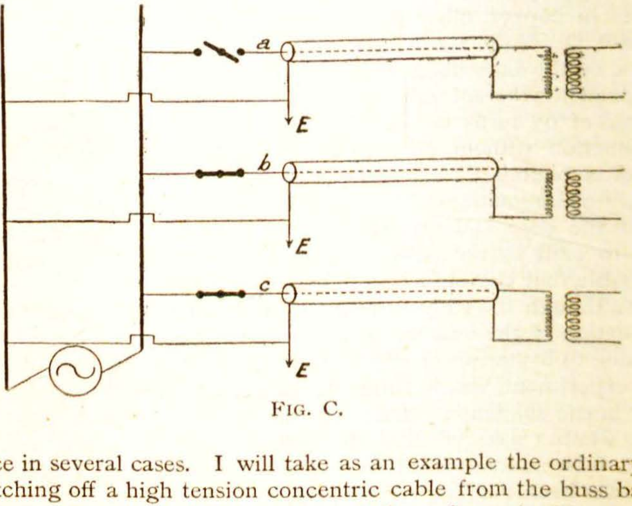

FIG. C.

In spite of Mr. O'Gorman's statement at the end of his remarks "that a D.P. switch is always used which disconnects the condenser from the circuit while breaking it," I think it is more usual in the case of high tension feeders to employ single-pole switches (Ferranti switch

Mr. Duddell.

gear), though even when D.P. switches are used it can easily be seen that they would not prevent some considerable capacity from still *directly shunting the switch contacts*. Another case in which capacity directly shunts the contacts is that of a switch in a substation which joins the inners of two concentric cables. The insulation resistance of high tension cables will in general be several megohms, so that there will not be sufficient leakage to reduce the danger.

In low tension networks the dangers are much less; probably the worst are those due to a short circuit or to a large motor failing to start up, resulting in the action of some automatic cut-out or fuse whose contacts, or those of the short circuit itself, are practically directly shunted by part of the capacity of the system. If the capacity is shunted by a non-inductive resistance as low as 100 ohms I should certainly expect the danger to be very small.

5. Without further experiment I am unable to say what is the puncturing effect of the rises in P.D. I have observed, as I have always had to be most careful to keep the rises well under control to avoid breaking down the condensers. One thing is, however, quite certain, and that is that even with experiments on such a small scale as those described in the paper the puncturing effect is considerable.

There is one other point which I have not yet alluded to, and that is the question as to whether a distributed capacity such as that of a concentric cable will behave the same as a condenser. It was this doubt which led me to put my suggestion of the possible danger to cables in the form of a question. Owing to the courtesy of Mr. Minshall I have been able to test this point experimentally with an actual cable under more nearly practical conditions, and I find that the rises in P.D. do take place when using the distributed capacity of a concentric cable.

Mr. Trotter alludes to the extreme sensibility of the arc to small variations in the current through it. Since writing the paper I have heard of another rather interesting example of this sensibility. Whilst I was making experiments on the Musical Arc at the Central Technical College, obtaining my current from the street mains, Mr. W. Bradfield noticed that an arc, with which he was working in Sir W. de W. Abney's laboratory, and which was also supplied by the street mains, was playing a tune.

Thus this latter arc, which was burning under ordinary conditions and was not adjusted in any way to make it sensitive, detected the effect, on the distributing network of a large supply station, produced by my Musical Arc taking a current which was varying by about half an ampere from the mean, although the two arcs were in totally distinct buildings, at a distance, in a straight line, of about 400 yards from one another, and at a considerably greater distance if measured along the street mains.

Mr. Trotter is quite correct that the model of the humming arc shown at the meeting was greatly exaggerated, but this was necessary to make the effect visible to those at the back of the lecture hall. When I said that the light varies, I thought that I had made it clear that the light to which I referred was that given out in the direction of my lens, Mr. Duddell. as I use at the end of my section on the humming arc the expression "the light emitted in a given direction." In order to make this quite clear I have inserted the words "in a given direction" into my conclusions at the end of the paper.

It is admitted, I think, that the humming arc rotates. Suppose it is once started in rotation, it cannot continue so without some force or forces are acting on it tending to maintain the rotation. The question is, what is the nature of these forces? At first sight there are two possible causes outside the arc itself which may tend to maintain the rotation and humming. I refer to convection currents of air and to the effect of a magnetic field. The first of these does not seem to be the true explanation, as the arc will hum in any position even with the carbons horizontal; the second, the magnetic field, is also for a similar reason excluded; in fact, the arc will still hum even if deflected to one side of the crater and kept there by means of a magnet. So that neither of these causes seems able to supply a satisfactory explanation of the rotation of the arc observed when humming.

Within the arc itself there is a possible cause for the rotation, viz., if the arc is burning between any two points, and there exist contiguous to them any two other points between which the current would do less work in maintaining the arc, then the arc will tend to move from between the former to between the latter points—that is, under ordinary conditions the arc will tend to move to between those points requiring the lower P.D. Suppose the arc is rotating, I will call the side of the spot where the current passes from the carbon to the gas, which *leads* in the direction of rotation, and which is constantly moving to points on the end of the carbon through which no current was passing, the *leading side*. In order that the arc may continue to rotate, it is necessary that the leading side should be moving into successive positions which require less P.D. to maintain the arc than do the other sides. There are three possible causes of such an effect. (1) The ends of the carbons may be nearer together at the leading side than elsewhere. (2) The oxygen of the air may obtain better access to the leading side, either directly or by being absorbed in the carbons. (3) The temperature gradient at the leading side may be different to elsewhere. Of these (1) does not seem to be the true cause of the rotation, as the arc will often move from burning between points at a shorter distance apart to between those at a longer; though a variation in distance in conjunction with the rotation of the arc may well be the cause of the observed variation in P.D. and current. (2) The direct access of the oxygen of the air to the hot carbon and its combination with it would seem to tend to stop the rotation, as it would be less likely to combine with the cooler carbon at the leading side and produce a drop in P.D. there, such as Mrs. Ayrton discovered in her experiments on hissing, than to combine with hotter carbon at the other sides. It is difficult to say whether the oxygen absorbed in the carbon would behave in the same way. (3) The possible less temperature gradient at the leading side seems to me one of the most probable causes of the rotation, though considerably more experimental evidence as to its effect on the P.D. required to maintain the arc is necessary before any very definite opinion can be expressed. If the opportunity offers I hope to continue my experiments on humming along this line. Mr. Duddell.

In conclusion, I wish to express my thanks to the members of the Institution for the very kind way in which they received my paper. I wish also to thank Messrs. G. Wall, L. Murphy, R. M. Moberly, and J. F. Hunt for the untiring way in which they helped me to prepare and carry out the experiments shown at the meeting.

The President. The PRESIDENT: I will now ask you to give a vote of thanks to Mr. Duddell for his paper. I really do think we have had the most extraordinary luck this session with regard to having good papers, and I think this is one of the best.

The vote was carried with acclamation.