THE PRODUCTION OF HIGH FREQUENCY OSCILLATIONS FROM THE ELECTRIC ARC.

By L. W. Austin.

The first experiments for the production of electrical oscillations from direct currents appear to have been made by Prof. Elihu Thomson,¹ who in 1892 proposed the following method for transforming continuous currents into continuous trains of high frequency oscillations. A source of direct current at 500 volts was connected through high inductive resistances to a spark gap, which was shunted by a condenser and inductance. An air blast or magnet was used to blow out the continuous current arc.

Mr. W. Duddell² in 1900 described experiments showing that when a suitable inductance and capacity are placed in shunt around an ordinary direct current arc a musical tone is given out. According to Duddell the following conditions must be fulfilled in order that the oscillations be satisfactorily produced. The carbons must be solid, not cored; the arc must be of suitable length (1–2 mm); and the current must be of suitable strength (3–5 amp.). In addition, a high resistance must be placed in the main arc circuit and the ohmic resistance of the shunt circuit around the arc should be in general less than 2 ohms. About 5 millihenrys and from 1 to 5 microfarads form a suitable shunt circuit.

The cause of this phenomenon has not been made entirely clear; but according to Duddell's theory, the production of oscillations requires that the V, I curve of the arc should have a falling characteristic; that is, that dV/dI should have a negative value and be greater numerically than r ; V represents the potential difference

¹ U. S. Patent No. 500630; July 4, 1892.

² W. Duddell, Journ. Inst. Elec. Eng., **30**, p. 232; 1900.

across the arc, I the direct current, and r the resistance in the shunt circuit around the arc. The simple explanation of the formation of the oscillations according to this theory is as follows. When the shunt is closed on such a circuit as has been described, a part of the current flows into the condenser, thus robbing the arc of a part of its current; but since V increases as the current in the arc decreases, this really increases the potential difference, and the condenser continues to charge. When in turn it discharges through the arc it increases the arc current, and thus decreases the potential difference until entirely discharged. The process then repeats itself.

According to Duddell the frequency of the oscillations in the singing arc depends only on the inductance and capacity in the shunt circuit except as it is modified by the damping, and the frequency is limited by the fact that dV/dI ceases to be negative at a moderately high frequency. Good results may, however, be obtained between 500 and 10,000 per second by a proper adjustment of inductance and capacity.

This theory has been treated mathematically by P. Janet,³ who has arrived at conclusions agreeing with those of Duddell. A second theory of the phenomenon has been advanced by Maisel,⁴ who claims that the sign of dV/dI in the arc is of no importance, but that the occurrence of oscillations depends only on the temperature of the negative electrode. He holds that as the current is withdrawn from the arc by the charging of the condenser the temperature of the electrode falls until the arc is extinguished, being relighted again by the backward surge of the charge from the condenser the next instant, provided the temperature has not fallen too low. He contends that, according to his own observations and those of Corbino,⁵ the current in the shunt circuit is not sinusoidal, and that the frequency can not be determined simply by the formula $1/n = 2\pi\sqrt{CL}$, and also that it has been shown by Salomonson⁶ that a frequency as high as 400,000 may be produced.

³ P. Janet, *Comptes Rendus*, **134**, p. 821; 1902.

⁴ S. Maisel, *Physikal. Zs.*, **5**, p. 550; 1904.

⁵ M. Corbino, *Atti dell' Assoc. Elettr. Ital.*, **7**, p. 369, also p. 597; 1903.

⁶ Wertheim Salomonson, *Konink. Akad. Wetensch. Amsterdam, Versl.*, p. 381; 1902-3.

In 1902 Prof. R. A. Fessenden⁷ proposed a spark gap or arc fed by continuous current as a source of radiation for wireless telegraphy and afterwards developed the idea, calling attention to the advantages of using high potential and forming the arc under pressure.

H. Th. Simon, and Simon and Reich⁸ have also experimented extensively on this subject, using metal electrodes as well as carbon; and more recently Simon⁹ has published a theory of the phenomenon based on his own theory of the arc. In this he agrees with Duddell and Janet as to the necessity of a falling characteristic for the arc curve, and concludes that high frequency oscillations can probably best be obtained by using high voltage and low current and electrodes, which are good conductors of heat like the metals.

Since the present work was begun, V. Poulsen¹⁰ has announced the successful production of oscillations ranging as high as one million per second and of considerable power, which have been used successfully in wireless telegraphy. In the Poulsen arc the anode is copper and the cathode carbon, while the arc is formed in an atmosphere of hydrogen which appears considerably to increase the intensity of the oscillations.

ARRANGEMENT OF APPARATUS.

During the first portion of the work the source of current was for the most part a 240-volt constant potential circuit, though at times 120 volts were substituted for this. The current was cut down by a variable resistance and the primary of a small transformer was introduced into the main circuit as a choking coil. A diagram of the connections is shown in Fig. 1. Here A is a d. c. ammeter, B a d. c. voltmeter across the arc, H a hot wire ammeter reading to 10 amp. with a resistance of about 0.3 ohm. The capacity C consisted of one or two small mica condensers of 0.04 mf capacity each. The inductance L, generally used in the oscillatory circuit, consisted of three turns of No. 16 wire wound on a battery jar. The

⁷U. S. Patents No. 706742, Aug. 12, 1902; No. 730753, June 9, 1903; No. 793649, July 4, 1905.

⁸Simon and Reich, *Physikal. Zs.*, **3**, p. 278; 1902; **4**, p. 364; 1903.

⁹H. Th. Simon, *Physikal. Zs.*, **7**, p. 433; 1906.

¹⁰V. Poulsen, *Electrotech. Zs.*, **27**, p. 1040; 1906.

inductance of this coil and the connecting wires amounted to 0.009 millihenry approximately. The frequency of the oscillations was

Fig. 1.

always measured by the resonance method in a secondary circuit so loosely coupled to the primary that the reaction between the circuits was negligible, as shown by special experiments. This secondary circuit consisted of a variable air condenser C' , a hot wire ammeter H' reading to 0.23 amp. and having a resistance of 7 ohms, a coupling inductance L' of 25 turns of No. 16 wire wound on a jar, and sometimes a variable roller inductance in addition.

EXPERIMENTS WITH THE GRAPHITE ARC.

Preliminary experiments were made, using as the electrodes of the arc solid carbon, cored carbon, copper, graphite, and copper anode with carbon cathode. It was found that with all of them oscillations with a frequency of over 100,000 could be produced. The first three gave in general only transitory high frequency oscillations, at least when the arc was

formed in air, and it was only in the case of graphite electrodes that it was found possible to get steady enough conditions so that any quantitative observations could be made.

Below are given the data of a typical experiment:

PRIMARY CIRCUIT.

Electrodes	graphite, ends flat
Diameter	12 mm
Resistance in series with arc	about 50 ohms
Arc current	4 amp.
P. D. across arc	26 volts
P. D. open circuit	242 volts
Arc length	about 0.3 mm
Inductance in shunt circuit	0.009 millihenry
Capacity	0.4 ohm
Alternating current in shunt	4.0 amp

SECONDARY CIRCUIT.

Inductance

0.168 millihenry

Capacity

variable

Resistance

7 ohms

Current

0.1-0.2 amp

Fig. 2.

It was found that under the above conditions the high frequency oscillations were readily obtained and were very constant, sometimes running for half an hour without attention before the oscillations disappeared. When the frequency was measured by the secondary

resonance circuit it was discovered that there were well-marked maxima corresponding to frequencies of 295,000, 580,000, and 910,000 per second. The lowest frequency appears to carry the largest part of the energy, while the highest was the weakest. The frequency calculated from the inductance and capacity of the primary circuit was 260,000. It seems possible that there may be other frequencies present of even shorter period and less intensity, but I was unable to detect them.

Change of Frequency.—According to Simon's results with low frequency arcs the frequency should increase with increasing cur-

Fig. 3.

rent and with decreasing arc length. These points were investigated, and the results are shown in Tables I and II and in the curves of Figs. 2 and 3. Table I and the curves *a*, *b*, *c*, Fig. 2, show the effect on the three maxima due to changing the resistance in the main circuit. It is to be noted that the lower frequency changes less than the other two, and that the three frequencies roughly approximate to the ratios 1:2:3. It was not considered possible to measure the change in arc length with any accuracy, as the total range of length over which the oscillations could be obtained was

only a few tenths of a millimeter. Table II and curve *g*, Fig. 3, therefore show only the relation between the change in frequency of the second maximum and the current change produced by changing the arc length. Curve *g* shows that the frequency increases with decreasing arc length much more rapidly than would be the case if the change were entirely due to the resulting change in current, showing that the shortening of the arc produces by itself an increase in frequency.

Experiments were also made on the effect of using the 120-volt circuit instead of the 240 volt, and also on the effect of putting two arcs in series. The capacity in the primary circuit in these experiments and in the one shown in Table II was 0.08 mf. The results are shown in Tables III, IV, V, and in the curves of Fig. 3. It is seen that the curves for one arc at 120 volts and 240 volts lie near together. The observed difference may be due to a slight difference in the adjustment of the arc length. The introduction of a second arc in series with the first produced a marked lowering in the frequency while the alternating current rose from 5 to 7 amp.

Resistance in the Shunt Circuit.—Under the conditions given on page 328, adding an ohm to the resistance of the shunt circuit destroyed the oscillations entirely, while one-fourth ohm reduced them about one-half. No change in frequency as far as could be observed attended the changes in resistance and alternating current in the shunt oscillatory circuit.

In connection with the graphite arc some experiments were made in wireless telephony. A wire was connected to the secondary oscillatory circuit and run up outside the window of the laboratory while the other side of the secondary was earthed. The current in the antenna was about 0.1 amp. A microphone was inserted in the antenna, and when this was spoken into the words could be understood in a telephone connected to an electrolytic wireless receiver attached to a similar antenna wire on a neighboring building about 50 meters distant. The articulation was loud and fairly distinct; but the hissing noises from the arc were disturbing. This arrangement was of course merely experimental. By making better use of the energy and using proper aerials and microphone a much greater distance could have been covered, probably several miles.

THE ARC IN HYDROGEN.

According to Poulsen much more powerful oscillations can be produced with the arc in hydrogen than can be obtained in air. This point was tested in a simple but effective way suggested by Poulsen by forming the arc in the interior of a gas flame. It was found at once that the high frequency oscillations formed much more readily with the carbon and carbon-copper electrodes than in air. The best results were obtained using copper anode with carbon cathode or with both electrodes of graphite.

While the pressure of the hydrogen enabled the oscillations to be produced more easily and to be maintained with greater arc length (up to about 0.8 mm in the case of graphite at 240 volts), the most remarkable effect was the increase in the energy which could be drawn from the oscillating circuit. As has been before mentioned, no resistance of more than one or two ohms could be inserted directly in the oscillatory circuit without destroying the oscillations. Large resistances can, however, be placed in the secondary coupled circuit and in this way power can be derived from the primary circuit. With the graphite arc in air at 240 volts only about six or eight watts can be absorbed in this way. With the arc in hydrogen supplied in sufficient quantities this power may amount to more than 100 watts, in one experiment bringing a 110-volt 32-cp lamp to full brightness.

Below are given the data of an experiment with the arc in hydrogen which may be compared with the data on page 327 when the arc was in air

PRIMARY CIRCUIT.

Direct current without oscillations	5 amp
Direct current with oscillations	2.5 amp
Potential difference without oscillations	40 volts
Potential difference with oscillations	90-100 volts
Potential difference, open circuit	240 volts
Alternating current in primary	9 amp
Capacity	0.08 mf

SECONDARY CIRCUIT.

Inductance	0.168 millihenry
Capacity	0.00011 mf
Resistance	110 v. 32-cp lamp
Alternating current	1 amp

The most noticeable thing in the above experiment, after the marked increase in power developed, is the marked decrease in direct current and increase in fall of potential across the arc. This depends on the amount of load in the secondary, and with the secondary removed the differences would have been less. The same changes can be noted in the graphite arc in air, but then the current drops only about 0.1 amp. and voltage increases but a few volts.

The presence of the hydrogen, at least when poured in a stream directly into the arc, as in the present case, has a very detrimental effect on the sharpness of tuning. The maxima frequently become so unsteady that it is almost impossible to determine the frequency. This may be due to the blowing about of the arc by the gas stream. Very peculiar pressure conditions certainly exist in the arc as is shown by the remarkable way in which the gas flame in which the arc is formed is blown outward when the oscillations are taking place.

The cause of the beneficial effect of hydrogen in the arc is not entirely clear. It seems certain that it is partly due to the high heat conductivity of the gas which helps to cool the electrodes between the surges of the current. According to Poulsen, in addition to the cooling effect, there is a marked influence on the electrical conductivity of the arc which he considers of great importance; but this is a question which will require further investigation before conclusions can be reached.

THE ARC IN STEAM.

Experiments were also made in which the arc was formed in steam. The graphite electrodes were used in some cases and in others the copper anode and carbon cathode. It was found possible to duplicate all of the effects observed with the arc in hydrogen. Oscillations were obtained as readily and with approximately the same power. Oscillations of great power were also observed when the arc was formed under water, where the steam was produced by the heat of the discharge. In this case frequently cooling became too rapid, so that the arc blew itself out.

THE HIGH POTENTIAL ARC IN COMPRESSED AIR.

In the following experiments I have made use of the ideas of Fessenden¹¹ and Simon¹² in putting the arc under pressure, using a high potential circuit, small current, and metallic electrodes. The source of current was a set of ten 500-volt direct current dynamos in series driven by a 2-hp motor. A fixed resistance of about 30,000 ohms was in series with the machines, and on short circuit the direct current was 0.15 amp. The voltage on open circuit, as measured on a Braun electrostatic voltmeter, was 4,500 volts.

Fig. 4.

pressed air condenser having a capacity of 0.0044 mf, L the three turn jar inductance of 0.009 millihenry and R the 30,000 ohm series resistance.

The leads W W run to the terminals of the set of small dynamos. The air chamber P is of massive iron with removable ends and with small windows of heavy glass at the front and back for observing the arc. The electrodes proper E were thin caps of metal, shaped as shown in Fig. 5, and screwed down by nuts and rubber washers to the ends of the electrode tubes T. These were hollow and arranged for water circulation. The electrode tubes were introduced into the pressure chamber through tightly fitting

In Fig. 4 the general arrangement of the circuits is shown. Here T is the compressed air arc, A a d. c. ammeter, V a Braun electrostatic voltmeter, C a Fessenden com-

Fig. 5.

¹¹ Fessenden, l. c.¹² Simon, l. c.

brass sleeves, the space between the two being filled with mutton tallow to make an air-tight joint. The sleeves were insulated from the pressure chamber by hard rubber rings. Air pressures up to about seven atmospheres were obtained by means of a double cylinder automobile pump.

The observations below give the complete data of a typical experiment:

Air pressure in arc	6.8 atm
Electrodes	silver, 0.8 mm thickness
Direct current without oscillations	0.15 amp
Direct current with oscillations	0.11 amp
Potential difference of arc without oscillations	90 volts
Potential difference of arc with oscillations	2,000 volts
Potential difference, open circuit	4,500 volts
Arc length	about 0.4 mm
Inductance in shunt circuit	about 0.009 millihenry
Capacity	0.0044 mf
Alternating current	11.5 amp
Frequency	850,000

The most noticeable thing in these observations is the remarkable rise in arc potential difference when the oscillations occur. It is evidently a more marked example of the phenomenon described above with the arc in hydrogen. It is also seen that the oscillations cause the direct current to drop in the same way that was observed in the low potential arc. It has always been found to be one of the characteristics of the singing arc, and also of the low potential, high frequency arc, that no resistance of more than an ohm or two can be introduced into the shunt oscillatory circuit without causing the oscillations to cease. In the high potential arc this is not the case. Resistances amounting to several hundred ohms may be introduced without any detrimental effect.

The question of the presence of other frequencies than the fundamental was investigated by means of the secondary resonance circuit, but none was found. Unlike the low potential arc this arc showed no change of frequency when the direct current was reduced by more than half by increasing resistance. There was also no change in frequency when the arc length was varied.

Efficiency of the Oscillations.—A 110-volt 100-cp lamp was placed in the shunt oscillatory circuit, and at a frequency of 650,000 an alternating current of 2.1 amp. was observed. By means of direct-current observations this was determined to repre-

sent a consumption of about 200 watts. As the available power, after subtracting that absorbed in the series resistance, amounted to but a little over 300 watts, the efficiency was more than 60 per cent.

Experiments were also made at higher frequencies by the same method, 180 watts being obtained at 1,500,000 and 140 watts at 3,500,000. At about 4,500,000 the oscillations became irregular and the observations were not pushed further.

Effect of Air Pressure.—Figure 6 shows the remarkable increase in the oscillations produced by the increased air pressure. Starting with the apparatus and data indicated in the typical experiment, page 328, already cited, the air pressure was gradually decreased

Fig. 6.

with the result shown in the figure. Above 5 atm. little change takes place, but below this the oscillations fall off rapidly and become much less steady. Below 2 atm. this unsteadiness becomes so great that no accurate readings can be taken.

During the work several different metals were tried as electrodes. Of these copper gave results nearly as good as silver, while zinc, aluminum, and platin-iridium (10 per cent Ir.) were all much poorer. This seems to indicate that metals with the higher heat conductivities are best suited for the purpose.

Continuity of Wave Trains.—It has been generally assumed that oscillations formed from the direct current arc are undamped, i. e.,

that the wave trains are continuous. While this is undoubtedly the case at low frequencies (singing arc), there is a point above which the arc breaks up into successive sparks, probably depending on the magnitude of the direct current. The high potential arc in compressed air is certainly not continuous. Using the circuit, the data for which are given on page 14, the damping coefficient γ , measured by Drude's method, amounted to about 0.1 per period. We have in this case simply a spark discharge with the sparks following each other very rapidly. Attempts were made to determine whether the waves were undamped in the case of the low potential graphite arc at frequencies of 300,000 and 100,000. The observations indicated that damping existed; but the constant slight shifting back and forth of the frequency due to changes in the arc might very well have stimulated this effect. Therefore, the indications can not be considered conclusive.

SUMMARY OF RESULTS.

1. The experiments show in agreement with Salomonson ⁶ *that the ordinary singing arc with carbon, or better, graphite electrodes is capable of producing oscillations of several hundred thousand per second.*

WITH THE GRAPHITE ARC.

2. The oscillations as investigated in a secondary resonance circuit show three frequencies of decreasing intensity corresponding approximately to the first three harmonics. This shows that the wave is not only not sinusoidal, but not even symmetrical.

3. The frequency increases with increasing direct current. Figs. 2 and 3.

4. The frequency increases with diminishing arc length. Fig. 3.

5. Putting arcs in series reduces the frequency. Fig. 3 (equivalent to increasing arc length).

6. The frequency does not, as far as has been observed, vary with the intensity of the oscillations.

7. No considerable resistance can be placed in the shunt oscillatory circuit without destroying the oscillations. Resistance may, however, be introduced into the secondary coupled circuit, thus giving means of obtaining power.

8. The power is much increased when the arc is formed in hydrogen or steam.

WITH HIGH VOLTAGE ARC IN COMPRESSED AIR.

9. When an arc is formed in air at a pressure of 6 atm. between silver or copper electrodes, the direct current being less than 0.2 amp. and the voltage of the circuit 4,500 volts, the arc takes on all the characteristics of a very rapid spark discharge.

a. The frequency is independent of the direct current and of arc length and depends only on the inductance and capacity of the oscillatory circuit.

b. No other frequency than the fundamental has been observed. The wave is probably sinusoidal.

11. Unlike the low potential arc, resistances of several hundred ohms may be inserted in the shunt oscillatory circuit, and thus power amounting to more than 60 per cent of that calculated to be available can be derived from the oscillations.

12. The high-voltage arc is nearly free from the hissing noises always heard at low voltages. It is therefore particularly well suited for use in wireless telephone experiments.

TABLE I (Fig. 2).

Current changed by changing resistance.

240 volt circuit. Potential difference across arc about 34 volts.

Currents		Frequency
D. C.	A. C.	n
1.0 amp.	2.2 amp.	217,000
		400,000
		705,000
2.0	3.2	263,000
		520,000
		820,000
2.5	3.5	274,000
		540,000
		820,000
3.0	3.5	289,000
		550,000
		860,000
4.0	4.0	295,000
		580,000
		910,000

TABLE II (Fig. 3, Curve G).

Direct current changed by changing arc lengths.

120-volt circuit.

D. C.	Potential difference across arc	A. C.	Frequency
			n
3.8 amp.	40 volts	1.5 amp.	368,000
3.9	34	2.3	380,000
4.1	26	4.8	394,000

TABLE III (Fig. 3, Curve E).

1 arc, 120-volt circuit.

Potential difference across arc about 30 volts.

Currents		Frequency
D. C.	A. C.	n
2.1 amp.	1.0 amp.	315,000
2.8	1.5	356,000
3.0	1.5	365,000
3.5	2.0	379,000

TABLE IV (Fig. 3, Curve D).

1 arc, 240-volt circuit.

Potential difference across arc about 34 volts.

Currents		Frequency
D. C.	A. C.	n
2.0 amp.	2.2 amp.	312,000
2.5	2.5	356,000
3.0	3.2	378,000
3.5	4.1	390,000
5.2	4.9	420,000

TABLE V (Fig. 3, Curve F).

2 arcs in series, 240-volt circuit.

Potential difference across arc about 54 volts.

Currents		Frequency
D. C.	A. C.	n
4.2 amp.	5.8 amp.	316,000
5.0	6.7	355,000
5.8	6.2	371,000

WASHINGTON, April 1, 1907.