VI

ON ELECTROMAGNETIC EFFECTS PRODUCED BY ELECTRICAL DISTURBANCES IN INSULATORS

(*Sitzungsber. d. Berl. Akadem.* Nov. 10, 1887. *Wiedemann's Ann.* **34**, p. 273.)

It is obviously a fundamental assumption in the most promising electrical theories that electrical disturbances in insulators are accompanied, not only by the electrostatic actions (which are known with certainty to exist), but also by the corresponding electromagnetic actions. All that we know about electrical phenomena has long tended to raise this assumption to a high degree of probability; but as yet it can scarcely be said to follow with certainty from any direct observations. In the following pages are described a series of researches which will, I hope, assist in filling this gap. They exhibit an electromagnetic effect which proceeds from insulators; they can be repeated with unfailing success and without extensive appliances. A magnetic effect arising out of processes in an insulator has already been exhibited in an experiment by Herr Röntgen,[1] if we assume that the final communication relating to this experiment confirms the interpretation first assigned to it.

In order to detect the electromagnetic action, I made use of the extremely rapid electric oscillations which can be excited in unclosed metallic conductors by the appropriate use of sparks.[2] The method is the following:—A primary conductor in which oscillations of the kind referred to are excited, acts inductively

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[1] W. C. Röntgen, *Sitzungsber. d. Berl. Acad.*, 1885, p. 195. Cp. also the more recent paper, *Sitzungsber. der Berl. Acad.*, 1888, p. 23.

[2] See II. and V.

upon a secondary conductor. The induced disturbance is observed by inserting a spark-gap. In order to make the observation delicate both conductors are adjusted to the same period of oscillation. The secondary conductor is now brought as near to the primary as possible, but in such a position that the forces acting upon its various parts neutralise each other, so that it remains free from sparks. If the equilibrium is now upset by bringing other conductors near, sparking commences again; the system acts as a kind of induction-balance. But it is an induction-balance which has this peculiarity, that it also indicates a change when large insulating masses are brought near it. For the oscillations are so rapid that the quantities of electricity displaced in insulators by dielectric polarisation are of the same order of magnitude as those which are set in motion by conduction in metals.

The Apparatus

Fig. 24 shows the apparatus by means of which this principle was put into practice. Only the essential parts are shown; we have to imagine them as connected by a light wooden frame. $A A'$ is the primary conductor, consisting of two square brass plates 40 cm. in the side, which are connected by a copper wire $^1/_2$ cm. thick and 70 cm. long. In the middle of the latter a spark-gap $^3/_4$ cm. is inserted; the poles consist of well-polished brass knobs. If we now conduct to the latter the most powerful discharges of a large induction-coil, the plates A and A' are first electrified in opposite senses and then, at the instant when the spark passes, discharge into one another, thereby giving rise to the oscillations which are peculiar to the conductor $A A'$, having a period which may be estimated as the hundred-millionth part of a second. The discharge of the induction-coil which immediately follows has no more effect upon the phenomena which we are here considering than has the presence of the induction-apparatus and the wires leading to it. The secondary conductor B forms an exact circle of 35 cm. radius, and is made of copper wire 2 mm. thick; it contains at f a spark-gap the length of which can be varied by a fine screw from a few millimetres down to a few hundredths of a millimetre. A circle having the above dimensions is in resonance with the primary conductor, and when it is placed in a suitable position secondary sparks 6-7 mm. long can be obtained. For the purpose of our experiment the circle is mounted so that it can rotate about an axis passing through its centre and perpendicular to its plane; when the circle is rotated thus its position is not altered, but the spark-gap rotates with it. The position of the axis is such that its direction lies in the plane of the plates *A* and *A′*, and in fact coincides with the line *m n* which is symmetrical with respect to them. If we add that the smallest distance between *A A′* and *B* is 12 cm., the description of our apparatus is complete. The phenomena which we now observe by means of it are the following:—

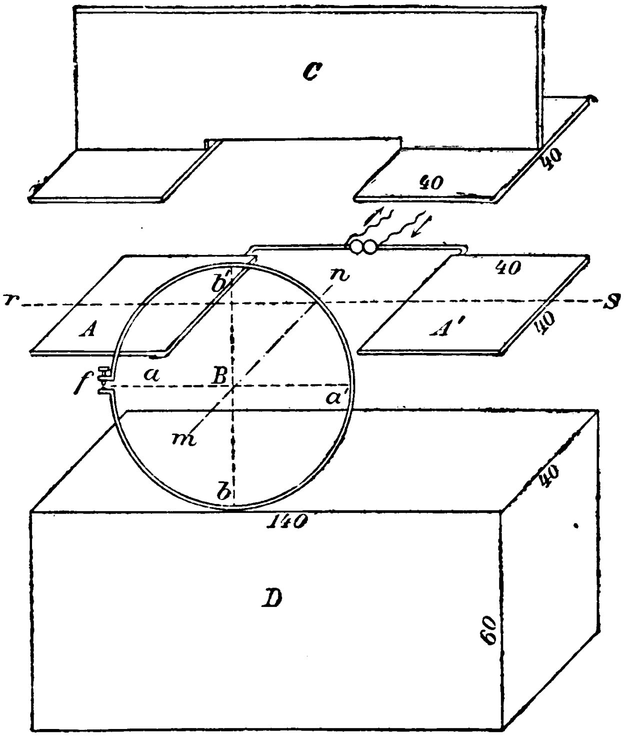

Fig. 24.

When the spark-gap *f* lies in the horizontal plane of *A A′*, *i.e.* at *a* or at *a′*, it is entirely free from sparks. When the circle is rotated a few degrees in either direction from this position, minute sparks arise. These small sparks increase in length and strength as the spark-gap is removed farther from the position of equilibrium and reach a maximum length of about 3 mm. when *f* is at the highest and lowest points, *b* and *b′* respectively, of the circle. The oscillations of the secondary conductor which are thus made manifest are always due to the forces acting upon those parts of the circle *B* which are opposite to the spark-gap. Although in form it is nearly closed, *B* must be regarded as an unclosed circuit; those parts of it which lie on either side of the spark-gap act only as capacities of the ends of the current. The effective force is the resultant of the electrostatic force and the electromagnetic force which is opposed to it; the former, being the greater of the two, determines the direction of the total force. If we regard the direction of this force and the amplitude of the oscillation excited by it as being positive when f is at the highest point of the circle, then we must regard the force and the amplitude as being negative, with reference to a fixed direction in the circle B, when f is at the lowest point. The amplitude changes sign as it passes through zero in the position of equilibrium.

It will assist us in what follows if we also consider here the phenomena which occur when we shift the circle B a little downwards, parallel to itself and without moving it out of its plane. When this is done the sparking distance increases at the highest point and diminishes at the lowest point; the points which are free from sparks—the null-points as we may call them—no longer lie on the horizontal line through the axis, but appear to be rotated downwards through a certain angle on either side. The slight displacement has changed the effect of the force of induction, although it has scarcely changed the effect of the electrostatic force, for the former, when integrated around the closed circle B, now gives an integral which is not zero; hence it gives rise to an oscillation the sign of whose amplitude is independent of the position of the spark-gap; and according to our convention this sign is positive. For the direction of the integrated force of induction is opposite to that of the electrostatic force in the upper half, but is the same as that of the electrostatic force in the lower half of the circle B, in which latter we regard the sign of the electrostatic force as being positive. Since the oscillation which is now superposed does not differ in phase from the former one, their amplitudes are simply added together. This explains the results observed.

The explanations of the phenomena which we have here given will be found more completely established in the preceding paper.[1]

Effects produced by Approach of Conductors

Hitherto it has been assumed that the conductors $A A'$ and B are set up in a large room as far away as possible from all objects which might disturb the action. Such an arrange-

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[1] See V.

ment is necessary if we wish to secure an actual disappearance of the sparks at *a* and *a'*. For we soon observe that sparks are produced when conductors are brought near, *e.g.* when long metal rods are placed on the floor underneath the apparatus. A little attention shows that even the body of the observer exerts a perceptible influence. If he places himself 1-2 metres away on the prolongation of the axis *m n* the apparatus is free from sparks; but if he approaches nearer in order to examine the sparks, he always finds them present. These very minute sparks have to be observed from a distance, and it follows as a necessary consequence that the observer must work in a dark room, and that his eyes must be rendered more sensitive by not exposing them to light beforehand.

We have now to choose a conductor which will produce a moderately large effect, and of which we may assume the oscillation period to be smaller than that of our primary oscillation. These conditions are fulfilled by the conductor made of sheet-metal, which is shown at *C* in our illustration. When it is lowered towards the primary conductor *A A'*, we observe the following effects:—The spark-length has decreased at the highest point *b*, and has increased at the lowest point *b'*; the null-points have moved upwards, *i.e.* towards the conductor *C*, whereas there now is noticeable sparking where the null-points originally were. From the last experiment in the preceding section we know what effect would be produced by shifting the conductor *A A'* upwards. The same effect—qualitatively—would be produced by introducing above *A A'* a second current having the same direction as that in *A A'*. Now our conductor *C* exerts exactly the opposite effect; and, if we assume that there exists in *C* a current which is always in the opposite direction to that in *A A'*, this effect is naturally explained as being due to an inductive action proceeding from *C*. This assumption is indeed necessary, for the preponderating electrostatic force tends to produce such a current; and, since the natural period of oscillation of the conductor is less than that of the force, the current must have the same phase as the exciting force. In order to test the correctness of this explanation I proceeded to experiment further in the following way:—I left the horizontal plates of the conductor *C* in position, but removed the vertical sheet, and in place of it introduced in succession longer and thinner wires, with a view to increasing gradually the period of oscillation of the conductor *C*. The results of this progressive change were as follows:—At first the null-points retreated farther and farther upwards, but at the same time became more and more indistinct; they were no longer points of extinction, but simply points of minimum spark-length. Hitherto the spark-length at the highest point was much smaller than at the lowest point; but after the disappearance of the zero-points it began to increase again. At a certain stage the sparks in the highest and lowest positions again became equal, but no null-points could be found anywhere in the circle; in all positions there was vigorous sparking. From here on the spark-length at the lowest point grew less, and in its neighbourhood there presently appeared two null-points, which at first were only feebly marked; these soon became more distinct, and approached towards the points *a* and *a′*, but always lay on the half of the circle remote from the conductor *C*. Finally they coincided with the points *a* and *a′*; the electrical condition was now identical with that which obtained before the conductor *C* had been brought near. The successive changes are just what might be expected according to our conception of the mode of action. For if the period of oscillation of the conductor *C* approaches that of the conductor *A A′*, the current in *C* becomes stronger, but at the same time there arises a difference of phase between the current and the inducing force. At the stage where resonance occurs the current in *C* is strongest, and the difference of phase amounts (as in every case of resonance of a moderately damped oscillation) to a quarter-period; hence there can no longer be any interference between the oscillations induced in *B* by *A A′* and by *C* respectively. This condition evidently corresponds to the stage specially referred to above. If the period of oscillation of *C* becomes much greater than that of *A A′* the amplitude of the oscillations in *C* again decreases, and the difference of phase between them and the exciting force now approaches a half-period. The current in *C* is now at every instant in the same direction as that in *A A′*; interference between the oscillations excited in *B* by these currents is again possible; but the effect produced by the conductor C must be opposite to that which it exerted in its original position.

If the conductor C is brought very close to $A\ A'$ only small sparks appear in the circle B. By bringing the conductors closer together the period of oscillation of $A\ A'$ is increased, and thus $A\ A'$ and B are no longer in resonance.

Effects produced by Approach of Non-conductors

A very rough estimate shows that if large masses of insulating substances are brought near to the apparatus, the quantities of electricity displaced by dielectric polarisation must be at least as great as those which are set in motion by conduction in thin metallic rods. The approach of the latter has been found to produce a very noticeable effect in our apparatus; if, therefore, the approach of large insulating masses produced no similar effect, we should naturally conclude that the electricity displaced by dielectric polarisation did not exert a corresponding electromagnetic action. But if the views of Faraday and Maxwell are correct, we should expect that a noticeable effect would be produced, and, further, that the approach of a non-conductor would act in the same way as that of a conductor having a very short period of oscillation. Experiment fully confirms this expectation; and the only difficulty in carrying out the experiments is that of procuring sufficiently large masses of the insulating material.

I made the first experiments with a material which lay ready to hand, namely, paper. Underneath the conductor $A\ A'$ I piled up books in the form of a parallelopiped 1·5 metre long, 0·5 m. broad, and 1 m. high, until they reached the plates A and A'. It was shown without doubt that sparks now appeared in those positions of the circle which before were free from sparks, and that in order to make the sparks disappear the spark-gap f had to be turned about 10° towards the pile of books. Encouraged by this, I had 800 kgm. of unmixed asphalt cast in the form of a block 1·4 metre long, 0·6 m. high, and 0·4 m. broad (D in Fig. 24). The apparatus was removed on to this, the plates being laid upon the block. The effect could be immediately recognised; the results obtained were as follows:—

1. The spark at the highest point of the circle was now considerably stronger than at the lowest point (that nearest the asphalt).

2. The null-points were displaced downwards, *i.e.* towards the insulator, and when the plates were laid right upon it the angle of displacement (which could be measured with fair accuracy) was 23°. But the sparking no longer ceased completely at these points. At the original zero-points there was now vigorous sparking.

3. When the plates A and A' rested upon the asphalt block the period of oscillation of $A A'$ was altered; the period of oscillation of B had to be increased at the same time in order to obtain sparks of maximum length.

4. If the apparatus was gradually removed in any direction away from the asphalt block the effect continuously diminished, without experiencing any qualitative change.

We have here all the effects of a conductor of small period of oscillation. The accordance between the mode of action of the insulator and of a conductor is further shown by the fact that the one can be compensated by the opposing action of the other. Thus, if the apparatus lay upon the asphalt, and the conductor C was brought near it from above, the null-points shifted backwards towards their original positions, and they again coincided with the points a and a' when the conductor C' was brought within about 11 cm. of the conductor $A A'$. If the upper surface of the asphalt lay 5 cm. beneath the plates A and A', compensation was attained as soon as C was brought within 17 cm. of $A A'$. The compensating action always took place when the conductor was somewhat farther off than the insulator. In a rough way these experiments show that the action of the insulator is, quantitatively as well as qualitatively, about what we should expect.

The asphalt used was an excellent insulator; it contained (as might be suspected from its high specific gravity) a large amount of mineral matter. One hundred parts (by weight) were found to give no less than 62 parts of ash, consisting of 17 parts of quartz-sand, 40 of calcium compounds, and 5 of aluminium and iron compounds.[1] It might be suspected that the action should be attributed entirely to these constituents, some of which might perhaps act as conductors. In order to remove this doubt I had a second, and exactly similar, block made of the so-called artificial pitch: this also is an excellent insulator, and gives scarcely any ash. The phenomena observed with this were the same as those above described, excepting that they were not quite so strongly marked; for example, the maximum displacement of the null-points here was only 19°. Unfortunately, however, this artificial pitch contains not only hydrocarbons but also free carbon in a very fine state of division, and it would be difficult to determine the amount of this latter. It cannot be denied that this carbon would have some conductivity, and hence the doubt in question is not entirely removed by this experiment. The expense of undertaking further investigations on the same large scale with pure substances was prohibitory. I therefore had the system of conductors A A' and B made again of exactly one-half the linear dimensions, and tried whether the phenomena could be followed with sufficient accuracy in this smaller model. The result was satisfactory, although, of course, with such exceedingly delicate sparks the strain upon the observer's attention was necessarily increased. For the purpose of demonstrating the phenomenon, or for quantitative experiments, it would be advisable to adhere to the larger dimensions. With the small apparatus I investigated altogether eight substances, which I will now mention in order:—

1. *Asphalt.*—The large block already described was used. When the plates A and A' lay upon the block, so that their front edges lay along the front edge of the block, the rotation of the null-point amounted to 31°. When the apparatus was drawn forward, so that the central line $r s$ coincided with the front edge of the block, the rotation amounted to 20°.

2. *Artificial Pitch obtained from Coal.*—Here, again, the large block was used. The rotations in the two positions referred to in (1) amounted to 21° and 13° respectively.

3. *Paper.*—When the apparatus was placed upon a block of paper 70 cm. long, 35 cm. high, and 20 cm. broad, the null-points were displaced about 8° towards the paper.

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[1] For the analysis I have to thank my colleague, Herr Hofrath Engler.

4. With a block of dense and perfectly dry wood the rotation of the null-points amounted to about 10°.

5. *Sandstone.*—When the apparatus was brought near to a sandstone pillar in the building (almost touching it), the null-points were rotated about 20° towards the sandstone. I had already observed with the large apparatus that the stone floor exercised a perceptible effect as soon as the apparatus was brought within half a metre of it.

6. *Sulphur.*—A massive block 70 cm. long, 20 cm. broad, and 35 cm. high, was cast from roll sulphur in a wooden mould, and the mould was then removed. The action of the block was very distinct; the various effects described above could be perceived, and the rotation amounted to 13-14°.

7. *Paraffin.*—The paraffin was white; it melted between 60° and 70°, giving a liquid as clear as water and free from impurities. It was melted and poured into a cardboard mould of the same dimensions, which was afterwards removed. The action was very distinct, and the rotation amounted to 7°.

8. *Petroleum.*—In order to investigate the effect of a liquid insulator, I filled an oak trough with 45 litres of pure petroleum. The internal dimensions of the trough were:—Length 70 cm., breadth 20 cm., depth 35 cm. When full it produced a rotation of about 7°, when empty about 2°. The very perceptible difference indicates the effect which would be produced by the petroleum alone.

The concordance between the observations made upon so many substances, some of which were pure, scarcely leaves any doubt that the action is a real one, and that it must be attributed to the substances themselves, and not to impurities in them. Indeed, I see only two objections which can be urged against this interpretation of the phenomena, and it will be advisable to rebut these at once. In the first place, it might be asserted that the effect is not an electromagnetic one, but that the insulator changes the distribution of the electrostatic force in its neighbourhood, and that this change in the distribution results in a change in the phenomenon. I have tried in vain to interpret, in accordance with this assumption, the various phenomena observed. But the assertion can be directly disproved. For, if the insulator fills a space which is only bounded by lines of force, and by parts of the surfaces of *A* and *A'*, it cannot give rise to any change in the electrostatic force outside its own mass. Now the vertical plane through the centre line *r s* is certainly made up of lines of force, and so also is the horizontal plane of the plates *A* and *A'* themselves. If, therefore, the insulator is bounded by these two planes, and if it extends behind the former and under the latter, as far as it can exert any influence, then every electrostatic effect outside the insulator is avoided. Now if we place our smaller apparatus with the line *r s* upon the upper front edge of one of the large blocks, the conditions referred to are sufficiently fulfilled. But when this was done the action, as already stated, did not cease, but was of similar strength to that observed under the most favourable conditions. It follows that the action did not arise from electrostatic forces.

In the second place, it may be objected that the effects should be attributed to currents arising through a residual conductivity. This objection can scarcely be urged with respect to such excellent insulators as sulphur and paraffin; nor do I believe that it is valid in the case of inferior insulators such as wood. Even assuming that such a substance insulates so badly that it allows the charged plate *A* to discharge in the ten-thousandth part of a second, but not much more rapidly, then during an oscillation of our apparatus the plate would never lose more than the ten-thousandth part of its charge. The conduction-current proper in the substance under consideration would therefore never exceed the ten-thousandth part of the primary current in *A A'*, and hence it would be quite ineffective. Hence in the case of the better insulators, at any rate, any assistance through conduction is excluded.

At present it does not appear to be possible to give any discussion of the quantitative relations of the experiments that would be of interest.

We have now seen what effect is produced upon the secondary circuit *B* by bringing a metallic conductor *C* near to the primary conductor *A A'*. If *C* was in resonance with

A A′, its action upon *B* could not interfere with the direct action of *A A′*. But at the same time, when the conditions for resonance were fulfilled, its action was fairly powerful, and could even be perceived when *C* was removed 1-1·5 metre away from *A A′*. Upon this I based experiments which should establish a finite rate of propagation of the electric forces. For if these forces require time to proceed in the first place from *A A′* to *C*, and then again from *C* back to *B*, the difference of phase between the effects of *A A′* upon *B* and of *C* upon *B* will increase when the distance between *A A′* and *C* increases; and the two effects must again become capable of producing interference if the distance between *A A′* and *C* becomes so great that the time taken by the electric force in traversing it is one-quarter of the half-period of oscillation. Hitherto these experiments have been unsuccessful, for I have not been able to detect any of the phenomena which I had expected. But since it was at best a question of observing exceedingly delicate changes, I do not consider that this negative result should weigh against the positive results which I have obtained otherwise.