Some Comments on J. Guala-Valverde's Experiments on Unipolar Induction

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J. Guala-Valverde and his colleagues have carried out a series of experiments on unipolar induction, and they present arguments to show that their results are compatible with the predictions of Weber's theory of electrodynamics, while they contradict the predictions of Maxwellian theory. The present paper argues that their results are compatible with either theory, and that the experiments do not provide a means of deciding between them.

1.Introduction

Electromagnetic Induction is a fascinating and surprisingly controversial subject. When Faraday carried out his classic experiments in the 1830's, he interpreted his results in terms of magnetic fields consisting of lines of force. His ideas were later developed by Maxwell, and expressed in the form of a mathematical field theory. Maxwell's theory was further developed by Hertz and Heaviside among others, and finally it was extended by Lorentz to provide a complete account of the interaction of charged particles with electromagnetic fields. (For the sake of conciseness the general system developed by these physicists will be described as the Maxwellian theory.) A basic tenet of this theory was that at any given time, a charged particle interacts with the field in its immediate vicinity, and that no action at a distance is involved.

The Maxwellian theory has of course gained wide acceptance. However an alternative approach was developed by Weber in the 1840's, and recently there has been a renewed interest in his ideas, due in large measure to the work of A.K.T.Assis [1],[2]. According to Weber all electromagnetic phenomena can be explained in terms of action and reaction forces between pairs of electrical point charges. These forces act instantaneously at a distance, and they lie along the line joining the two particles; their magnitudes are a function of the distance between them, and of the first and second time derivatives of this distance. One should note that Weber's main concern was with the forces between electrical charges and electrical currents, whereas the main concern of the Maxwellians was with the electromagnetic field. A principal merit of the Maxwellian scheme is that it provides a powerful entry into radiation theory, in both its classical and quantum forms; while a principal merit of Weber's scheme is that it leads to important insights into the dynamics of rotating systems and Mach's Principle.

The foundations of the two theories are clearly different. The question arises: can one design an experiment which would decide unambiguously which of the theories is to be preferred, in the field of classical electromagnetism? This is not easy, as there are many situations in which both theories predict the same results for different reasons, at least in the case of quantities that can be measured without too much difficulty. A promising area would seem to be unipolar induction, for which the theories provide explanations that definitely contradict each other. With some ingenuity one should be able to observe effects for which the theories make different predictions.

2. Unipolar Induction

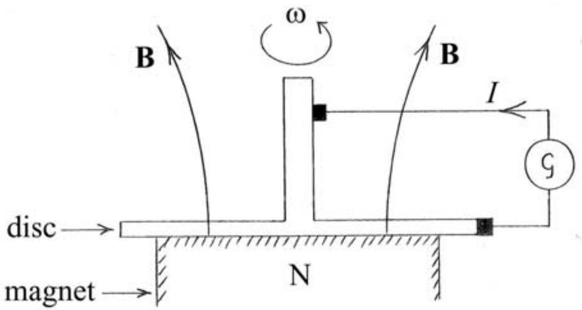

Figure 1. Faraday's Disc.

There have been a number of investigations designed to test the two theories using unipolar induction, and before we mention some of them we should recall one of Faraday's original experiments, which is shown in Figure 1 [3]. A copper disc was mounted on a metal axle and was cemented to the head of a cylindrical steel magnet, in such a way that they could be rotated together about their common axis. A galvanometer was connected between the axle and the rim of the disc by means of brush contacts, and when the magnet and disc were rotated a continuous current was observed to flow. Note that in this experiment the disc and the magnet both have cylindrical symmetry.

We will now interpret this effect according to the two theories, using the laboratory as the frame of reference. The Maxwellians would argue that the magnetic field of the magnet is symmetrical about its axis, and when the magnet rotates its field does not change in time. The conduction electrons in the disc have taken up the disc rotation, and they experience a radial magnetic force which drives them towards the axle and hence round the circuit. On the other hand the external circuit containing the galvanometer is not in motion, and its electrons do not experience a magnetic force in the direction of the circuit. The force driving the electrons round the circuit originates in the disc.

Weber's explanation is quite different. The forces on the conduction electrons depend on their motion *relative to that of the magnet* [4]. The disc is at rest relative to the magnet, and Weber would argue that the magnet exerts no net force on the disc electrons. He would also argue that because the external circuit is moving relative to the magnet, its electrons do suffer a magnetic force which drives them round the circuit. To use that much disputed phrase, the Maxwellians claim that "the seat of the EMF" lies in the disc; Weber claims that it lies in the external circuit.

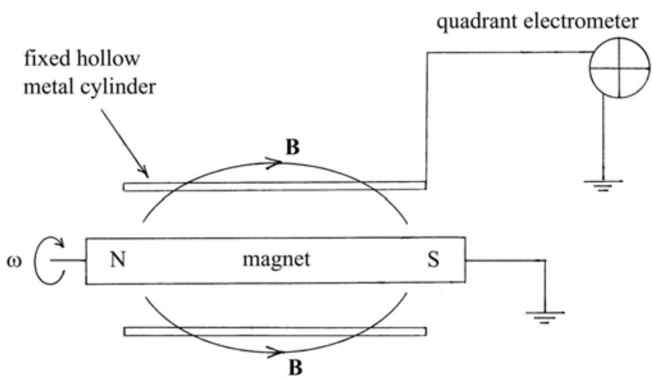

Figure 2. Kennard's Experiment.

The basic task is to modify Faraday's apparatus in such a way that the theories predict different measurable effects. In 1912 E.H.

Kennard designed the system which is shown in a very simplified form in Figure 2[5].

A cylindrical bar magnet was surrounded by a hollow metal cylinder, which was coaxial with the magnet but not in electrical contact with it. The magnet could be rotated about its axis, while the hollow cylinder was held in a stationary position, and one end was connected to a quadrant electrometer. According to Weber's theory, when the magnet rotates the electrons in the hollow cylinder experience forces similar to those postulated in the external circuit in Figure 1, and there is a displacement of charge from the centre of the cylinder towards both ends. No continuous current can flow because the system is on open circuit, but the charge displacement should produce a deflection in the electrometer. No such deflection was in fact observed when the magnet was set in rotation, in agreement with the predictions of the Maxwellian theory. In 1977 this result was confirmed by D.F.Bartlett et al., using much more sensitive equipment[6]. It is agreed generally, but by no means universally, that these experiments support the Maxwellian theory, but not that of Weber.

Recently J. Guala-Valverde and his colleagues have carried out a series of experiments using a different experimental design, which will be discussed in detail in the next section [7]-[9]. Their conclusions are diametrically opposed to those of Kennard and Bartlett, and they find that their results are compatible with Weber's theory but not with that of the Maxwellians. (They describe the Maxwellian theory as "absolutist" and the Weber theory as "relativistic", but I prefer to label them in a more neutral fashion, using the names of their authors.) The results of these experiments have led Guala-Valverde to challenge the arguments in a paper by the present author, which discusses unipolar induction in terms of the Maxwellian theory [10],[11]. I am very grateful to Prof. Guala-

Valverde for bringing the modern form of Weber's theory to my notice, but I have to take issue with his interpretation of his own experiments. I shall argue that his results are compatible with the Maxwellian theory, as well as with that of Weber. If this is correct it could remove a possible contradiction between Guala-Valverde's results and those of Kennard and Bartlett.

3. Guala-Valverde’s Experiments: Generator Mode.

The apparatus used in Guala-Valverde's first set of experiments is shown schematically in Figures 3 and 4. The magnet is made of ceramic material, and has the form of a thin annular disc with the magnetisation parallel to its axis. (The edges of the magnet are shown shaded in the diagrams.) A sector of the magnet has been cut away, and for the sake of clarity this is made much broader in the diagrams than was actually the case; in Guala-Valverde's experiments the missing sector usually subtended an angle of 12° at the centre, and smaller angles were also employed. The missing sector is described by Guala-Valverde as the *singularity*. The magnet was fixed to a turntable of insulating material, in such a way that it could be rotated about its own axis. The magnetic field $\mathbf{B}_1$ inside the magnet is directed out of the plane of the figures. Within the singularity the magnetic field $\mathbf{B}_2$ is reversed relative to $\mathbf{B}_1$, and is directed into the plane of the figures. If the positive *z* axis is directed out of the plane, then B_{1z}, the vertical component of $\mathbf{B}_1$, is positive; while B_{2z}, the vertical component of $\mathbf{B}_2$, is negative. The strengths of the fields $\mathbf{B}_1$ and $\mathbf{B}_2$ may vary considerably as a function of position.

Two concentric copper rings were attached to the turntable, the larger outside the annulus of the magnet and the smaller inside it; carbon brush contacts were connected to the rings at fixed points c and d. The brush contacts are connected to a high resistance voltmeter by means of a stationary external circuit, which is described by Guala-Valverde as the *closing circuit*. In the configuration shown in

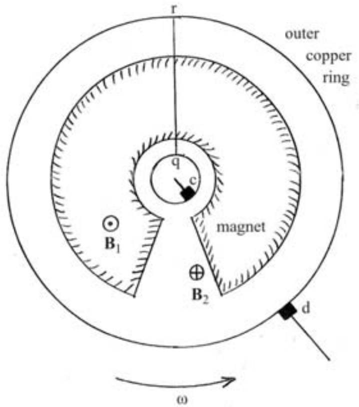

Figure 3. Generator Mode: Case A.

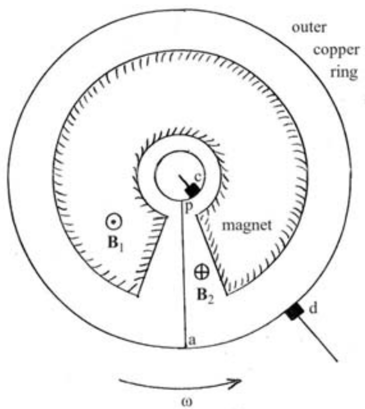

Figure 4. Generator Mode: Case B.

Figure 3, a straight piece of copper wire (described as the *probe*) is soldered to the inner ring at point q, laid radially across the magnet and soldered to the outer ring at point r. However in Figure 4 the probe is connected between points p and a, and passes through the singularity. These two configurations will be labelled Case A and Case B respectively, and in each case the probe plays the part of the disc in Figure 1. An external motor caused the turntable to rotate counter-clockwise with angular velocity ω, and the voltage between points c and d was measured.

In Case A it was found that point r was at a positive potential relative to point q, and we will now consider this result in terms of Maxwellian theory. Owing to the very high resistance of the voltmeter the current in the circuit is effectively zero, and the Lorentz force along the probe must be zero. (The Lorentz force in the copper rings is also zero, and this implies that the electric field in these rings is zero.) At a general point along the probe we have:

$$E_r = -\omega r B_z \tag{1}$$

Assume for the moment that the electric field can be described by a scalar potential $V(\mathbf{r})$. The voltage across the probe:

$$V_{rq} = V_r - V_q = +\int_q^r \omega r B_z \,\mathrm{d}r \tag{2}$$

At points on the probe which are in contact with the magnet, B_z is a positive quantity. At points on the probe lying outside the magnet B_z is negative, but it falls away to zero as one moves away from the magnet. Hence the integral in equation (2) is expected to be positive, and this is borne out by experiment.

Now consider the result to be expected for Case B according to the Maxwellian theory. Within the singularity B_z is negative, and the same is true for the parts of the probe lying outside the magnet; hence one might expect that the integral corresponding to (2) should also be negative. This would give a *negative* value for $V_{ap} = V_a - V_p$.

Experimentally, however, V_{ap} is found to be *positive*, and is equal to V_{rq} within the accuracy of the experiments. (Guala-Valverde's experiments have been repeated in another laboratory, and all his results have been confirmed [9].)

These experimental findings seem to contradict the Maxwellian theory, but not the Weber theory, in which the seat of the EMF is located in the closing circuit, and is little affected by the singularity in the magnet. However this analysis does not do justice to the Maxwellian theory.

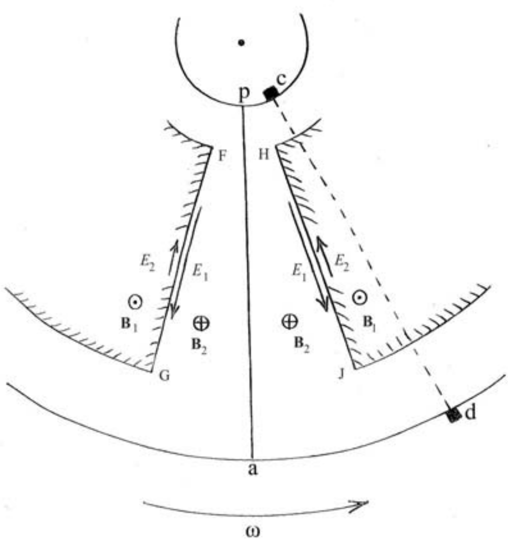

Figure 5. Induced electric fields in Case B.

The creation of the singularity in the magnet has destroyed its cylindrical symmetry, and when the magnet rotates its field becomes time-dependent. Figure 5 describes Case B, at a moment in time when the singularity is approaching the fixed line cd. The line FG is advancing to the right, and when it sweeps over a fixed point in the laboratory frame, the field at this point changes rapidly from $\mathbf{B}_2$ to $\mathbf{B}_1$. This induces a circulating electric field, according to the Maxwell equation:

$$\mathrm{curl}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

Let E_1 be the tangential component of **E** just outside the magnet, and E_2 the tangential component of **E** just inside, at a point on the line FG. From equation (3) it follows that:

$$E_1 - E_2 = \omega r\left(B_{1z} - B_{2z}\right) \tag{4}$$

A similar equation holds along the line HJ.

There is a formal analogy between equation (3) and the circuital law for the magnetic field generated by a current, and the induced electric field in the region of the singularity has a similar form to the magnetic field of a short solenoid. Inside the singularity the electric lines of force are crowded together, while outside they are widely dispersed. This makes it possible for the electric field along the probe to be directed outwards, so that it can counteract the term $\mathbf{v} \times \mathbf{B}$. The value of the EMF can be obtained from Faraday's Law of Induction:

$$\mathcal{E} = \oint\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right).\mathrm{d}\mathbf{s} = -\frac{\mathrm{d}\Phi_{\mathrm{B}}}{\mathrm{d}t} \tag{5}$$

where Φ_{B} is the total flux linking the circuit. (There has been much debate about the range of validity of Faraday's Law, particularly in the case of unipolar generators [12]. However it is generally agreed that, within the Maxwellian theory, equation (5) is uncontroversial for wire circuits such as that shown in Figure 5.) In this figure the leads from the brush contacts are assumed to rise vertically out of the page, and the dotted line is subtended between points c and d.

To determine the EMF we need to construct a surface that spans the whole circuit. It will consist of two parts; a horizontal surface bounded by the points {p,a,d,c}, and a vertical surface bounded by the closing circuit (See Figure 5). Provided that the singularity is not too close to the fixed line c-d, the magnetic field has no component normal to the vertical surface, and only the horizontal surface needs to be considered. As the line p-a moves to the right, the area inside the loop occupied by the field $\mathbf{B}_2$ remains constant, while the area occupied by the field $\mathbf{B}_1$ is diminishing. From equation (5) it follows that:

$$\mathcal{E} = -\frac{\mathrm{d}\Phi_{\mathrm{B}}}{\mathrm{d}t} = +\int_c^d \omega r B_z \mathrm{d}r \qquad (6)$$

Hence the EMF is a positive quantity, and it tends to drive current from d to c in the closing circuit. Note that Faraday's Law gives us the correct value of $\mathcal{E}$, but it does not tell us at what point in the circuit is energy being given to the electrons; i.e. the seat of the EMF.

We should trace the direction of the electric field in the various parts of the circuit. In the probe **E** is directed outwards as indicated by equation (1), and this might suggest that point d is at a lower potential than point c, giving a negative value for $\mathcal{E}$. The fallacy in this argument is to be found in equation (3); when the magnetic field is time-dependent, **E** cannot be expressed completely in terms of a scalar potential $V(\mathbf{r})$. For Case B equation (1) is valid, but equation (2) is not. In the closing circuit **E** is directed from d to c, and the voltmeter gives a positive value for V_{ap}.

The argument we have used to calculate $\mathcal{E}$ clearly needs modification when the singularity is actually passing through the fixed line c-d in Figure 5. In this situation the magnetic flux linking the vertical surface is not zero, and is not easy to calculate. Hence for

Case B the EMF is given by equation (6), except when the singularity is passing through the line cd, when it undergoes a "blip".

We now return to Case A, as shown in Figure 3. Here it is convenient to calculate the EMF using a horizontal surface {r,q,c,d}. Provided the singularity is not too close to the line c-d, the EMF is again given by equation (6), which is equivalent in this case to equation (2). When the singularity is passing through the line c-d, the EMF again suffers a blip, as in Case B. Hence according to the Maxwellians the EMF is exactly the same for Case A and Case B, and it is independent of the position of the probe.

This is precisely the result to be expected by the Weber theory, in which the EMF is generated entirely in the closing circuit, is independent of the position of the probe, and is disturbed as the singularity passes through the line c-d. Here we have a striking example of the way in which the Maxwellian and Weber theories predict the same result for the induced current, but for different reasons.

4. Guala-Valverde's Experiments: Motor Mode.

The apparatus designed by Guala-Valverde can be run backwards as an electric motor, though as he points out the technical problems are greater in this case, owing to the need to reduce friction to a minimum. Continuing our analysis of the Maxwellian theory, we now see if it can explain the action of the system in the motor mode.

We consider first the situation for Case A, as shown in Figure 6. A constant voltage power supply has been connected across points c and d, with d at the positive potential; this causes a current I to flow down the probe towards the central axis. If the magnet is uniformly magnetised its field is equivalent to that of a surface current I_m which flows round the edge of the disc, and it simplifies the argument if we represent it in this way. When the line d-c is not too close to the singularity, the magnet behaves like a symmetrical cylinder and experiences no torque. The probe experiences a force directed to the left due to the field $\mathbf{B}_1$, and this gives rise to a torque on the turntable, which causes it to rotate in a counter-clockwise sense.

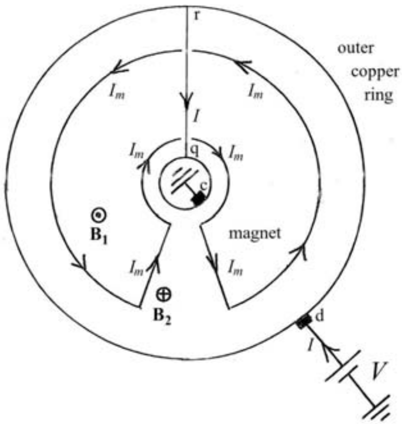

Figure 6. Motor Mode: Case A.

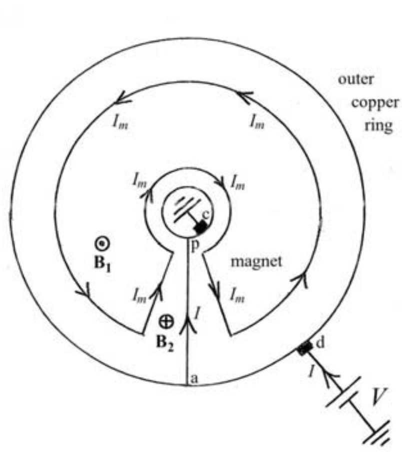

Figure 7. Motor Mode: Case B.

Now consider the situation for Case B, as shown in Figure 7. The probe experiences a force to the left due to the field $\mathbf{B}_2$, which produces a clockwise torque; this has been confirmed by Guala-Valverde by detaching the probe from the turntable. But unlike the situation in Figure 6, there *is* now a torque on the magnet. The current I in the probe attracts the current element I_m on its left, and repels the current element I_m on its right. When both probe and magnet are fixed to the turntable, the forces in the neighbourhood of the singularity tend to cancel each other, but the more distant parts of the magnet still produce a force on the probe, such that the overall torque on the turntable is counter-clockwise. This torque is equal and opposite to the torque on the closing circuit, so that it suffers a blip as the singularity passes through the line c-d, and this effect is independent of the position of the probe. All this agrees with the predictions of the

Weber theory. Note that in both Case A and Case B the turntable moves in such a way as to produce an EMF which opposes the applied voltage V.

Guala-Valverde has recently extended his experiments to study more complex systems [13]. Unfortunately his discussion is based entirely on a conviction that his earlier experiments disprove the Maxwellian theory, and I have argued that this is not the case. From a detached viewpoint it is not clear what new evidence his most recent experiments provide.

5. Conclusions

I suggest that the Maxwellian theory, *when considered on its own terms*, can explain the results of Guala-Valverde's experiments on unipolar induction. If this is the case, the interpretation of these experiments is not "indisputable" as Guala-Valverde and his colleagues have claimed [8], and both the Maxwellian and the Weber theories are able to explain them. On the other hand the Kennard-Bartlett experiments *do* distinguish between the two theories, and their results pose serious problems for the Weber theory. Taken together, the evidence from these experiments seems to favour the Maxwellians.

Acknowledgement

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