Unipolar Induction

A Messy Corner of Electromagnetism:

A Contribution for The Clean Up with Some Far-Reaching Consequences

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Abstract

In the light of own measurements on a Faraday generator, the well-known theories concerning Unipolar Induction and the Faraday paradox seem to be problematic. On the other hand, all results obtained, and all other processes described as a paradox in connection with the Faraday generator can be explained without contradiction based on the theory of Wilhelm Weber.

Keywords: Faraday generator, Unipolar induction, Ampère´s law, Weber's Fundamental Law of Electrodynamics

HISTORICAL DEVELOPMENT

In 1832 Faraday discovered that one could induce a DC voltage with a rotating magnet but realized at the same time that a rotating magnet behaves strangely in comparison to a linearly moving permanent magnet, a fact initially incomprehensible to him. It made no difference whether the permanent magnet rotates about the same axis of symmetry together with a rotating disc, or whether the magnet remains at rest. In both cases, Faraday observed an induction effect.

If one uses a magnet made of conductive material and dispenses with the possibility of letting the disc rotate independently, the independent disc can be omitted. Thus, there are the following two versions of a so-called Faraday generator (Figure 1), both used by Faraday.

There are different explanations about how this generator operates since the times of Faraday. These have been extensively reported in various publications (Müller, 2014) (Mongomery, 1999; Miller, 1981).

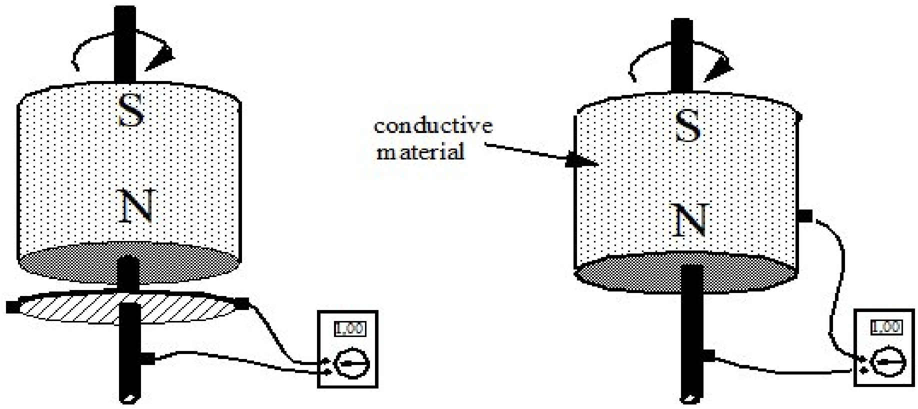


Figure 1. *Two versions of a Faraday generator*

The problem to be solved is the following: If a magnet moves relative to a conductor circuit on a straight or curved line, the occurring so-called motional induction depends only on the relative velocity between the two parts. This process is reciprocal. In a rotary movement, however, the process is not reciprocal. When the magnet is stationary, an induction voltage occurs on a rotating disc, but this is not the case with a rotating magnet and a stationary disc.

To explain this paradoxical effect, the following two contradictory theories can be found:

1. The so-called N-theory, which states, that the magnetic field remains stationary with a rotating magnet. The electrons inside the magnet and the rotating disc are rotating through this stationary magnetic field and are accelerated due to the Lorentz force either towards the edge or towards the axis of magnet or disc. The origin of the induction is inside the magnet or the disc.
2. The so-called M-theory, which states that the magnetic field co-rotates with the magnet, the induced voltage is caused by the field lines - also referred to as lines of force - cutting the conductor parts of the external circuit. The origin of the induction is inside the external circuit.

The M-theory was used by Kelly (1998) to interpret his measurements. In contrast, Chen et al. (2016) concluded, based on their measurements, the validity of the N-theory. Thus, the strange situation results that a branch of classical physics, namely Electromagnetism, despite all unsurpassed successes in theory and technology, tolerates diametrically contradictory experimental findings regarding a phenomenon discovered almost 200 years ago.

OBJECTIVE AND GENERAL RESULTS

To provide a positive contribution to clarify this predicament, the present article presents the results of some simple experiments, where the usual restriction to a region with a predominantly homogeneous magnetic field (for example, close to the front side of the magnet) has been dispensed. Instead, the resulting interactions in the surrounding of the rotating magnet are explored by using discs of different sizes and shapes.

It turns out that most of the measurements carried out can be satisfactorily explained by neither the N nor the M theory. In some cases, the measurement results are in apparent contradiction to the implications of these two theories. If, for example, a disc is chosen whose diameter is somewhat more extensive than that of the rotating magnet, the induced voltage, measured between the edge of the disk and the axis of rotation, increases significantly, compared to a disc with the same size as the magnet. For N theory, which assumes a stationary, non-rotating magnetic field, the slightly larger disc rotates in the inner and outer regions through oppositely directed magnetic fields.

For a disc with a larger diameter than that of the magnet, the induced voltage should decrease (fig.2). The opposite is the case.

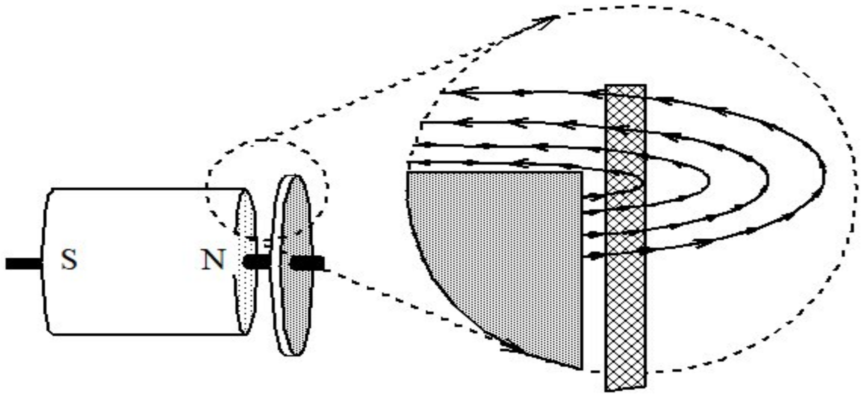


Figure 2. *Magnetic lines through an aluminum disc with a slightly larger diameter than the magnet*

For the N-theory, where the co-rotating magnetic lines intersect the external circuit and thereby cause the induced voltage, the magnetic field is usually smaller with increasing distance of the sliding contact to the magnet; it will not increase. The induced voltage should, therefore, be smaller, possibly remain the same size, never rise. That, however, is the case. In the following text, we discuss a theory that was developed by Ampère in the 1820s and was later expanded by Wilhelm Weber, who presented in 1846 his Fundamental Law of Electrodynamics. All measurements carried out here can be brought in agreement with Weber's Fundamental Law.

THE APPROACH OF WEBER AND AMPÈRE

In 1820 Oersted discovered that there is a connection between the long-known phenomenon of natural magnetism and the newly emerging phenomenon of electric currents. In addition to Faraday, the French physicist Ampère began to focus on this new field of research. In contrast to Faraday, Ampère's idea was that the interaction between electric currents causes all phenomena of magnetism. Besides, he refused to accept a force like the Lorentz force. He postulated that in nature, there could only be repulsive and attractive forces between interacting partners whose line of action coincides with the connecting line between the two partners.

In 1822, Ampère published a law - the original Ampère's Law - that allowed him to make quantitative statements about the forces between individual current elements (Assis & Chaib, 2011). This work was taken up and further developed by Wilhelm Weber in Göttingen. In 1846, Weber published his Fundamental Law of Electrodynamics and showed that both, Ampere‘s Law and Faraday‘s Flux Law could be deduced from this Fundamental Law (Weber 1846) (Assis 1994). Weber`s equation represents an extended Coulomb force, describing the interaction between two-point charges q_1 and q_2. New are two additive elements; the first contains the factor $-v^2/c^2$, the second the factor $+a/c^2$. Weber's fundamental law describes the mutual force $F_{1>2}$ (force of q_1 on q_2) and $F_{2>1}$ (force of q_2 on q_1) between two charge carriers q_1 and q_2 separated by a distance r.

The law reads as follows:

$$\vec{F}_{1>2} = \frac{q_1 q_2 r^0_{12}}{4\pi\varepsilon_0 r^2_{12}}\left(1 - \frac{v^2_{12}}{2c^2} + \frac{r_{12}a_{12}}{c^2}\right) = -\vec{F}_{2>1}$$

The terms $\boldsymbol{v}_{12}$ and a_{12} denote the relative velocity dr/dt and the relative acceleration d^2r/dt^2 between the interacting partners. The term r^0_{12} denotes a unit vector in the direction from q_1 to q_2. The constant c, first introduced by Weber, was later experimentally determined by him and Kohlrausch as matching in dimension and size the speed of light (Weber and Kohlrausch, 1893). A detailed presentation of Weber´s Electrodynamic theory can be found at Assis (1994).

THE EXPERIMENTS IN DETAIL

Preliminary Experiment

In a preliminary experiment, it was first determined that the induced voltage measured across the rim of the magnet and the rotational axis are - as required by theory - linearly dependent on the rotational speed. The dimensions of the magnet used are shown in Figure 3 (a); the measurement result is shown in figure 3 (b).

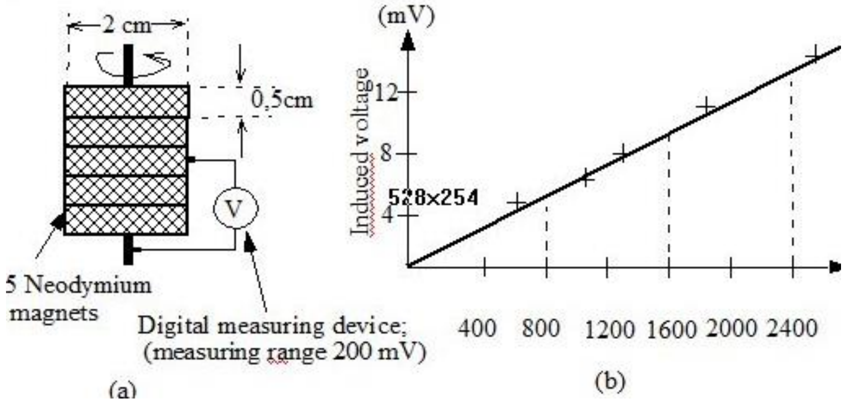


Figure 3. *(a) Used permanent magnet; (b) $V_{ind} = f(\omega)$*

The drive was a drill with a V-belt drive for setting different angular velocities. The connections between the conductors of the external circuit and the rotating parts were made employing springy wires. The use of carbon sliding contacts proved to be problematic. The contact resistance varied in time due to the abrasion of the carbon.

Measurement on Differently Sized Rotating Discs

In the main experiment, the induced voltage was measured on separate discs of different sizes rotating together with the magnet, each at the same distance from the rotating magnet and in each case as a function of the angular velocity. The result is shown in Figure 4.

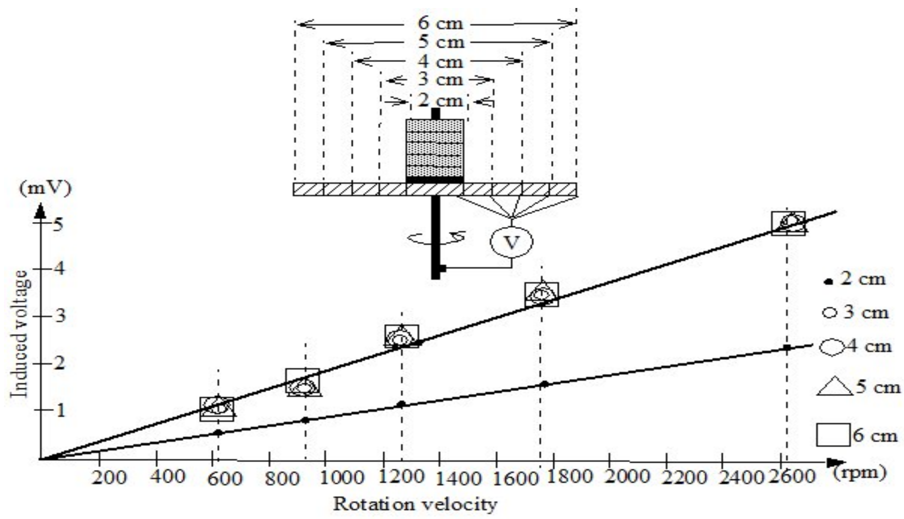
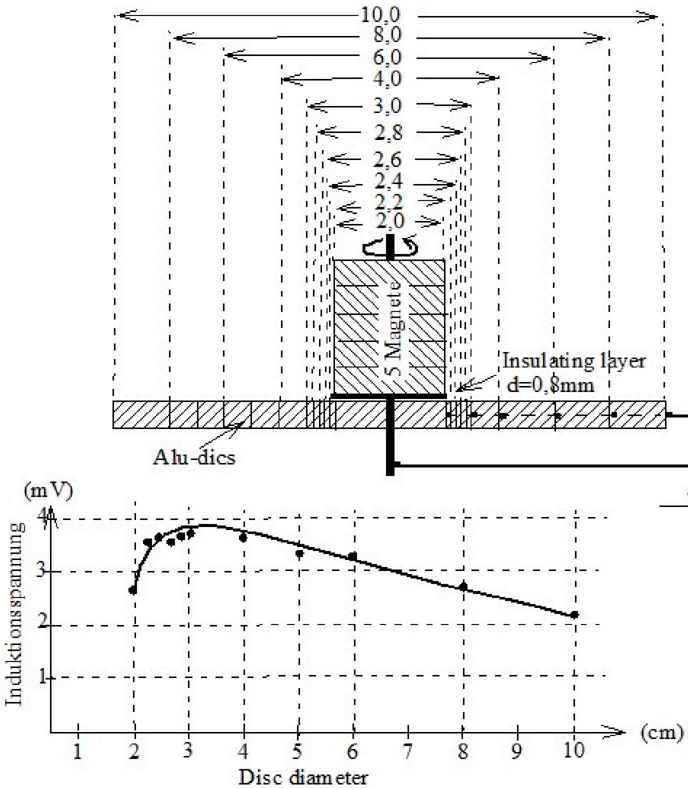


Figure 4. *Induced voltage as a function of the rotational speed for different sized discs*

Striking are two results. It shows, on the one hand, that within the scope of the measuring accuracy, the same induction voltage is measured for the disc with diameters between 3cm and 6cm. Based on both the M and N theory, a significant decrease in the induced voltage should be expected.

A second result is even more noticeable. Between the discs with 2cm and 3cm diameter, the measurements increase clearly. As already mentioned, this is in bright contrast to expectations based on both M and N theory.

To clarify the following surprising result, the relevant area (between 2cm and 3cm disc diameter) was examined in more detail by the use of appropriately graded discs. Also, discs with 8 and 10 cm diameter were used. The result is shown in Figure 5.



d(cm)	V (mV)
2,0	2,7
2,2	3,5
2,4	3,6
2,6	3,5
2,8	3,6
3,0	3,7
4,0	3,6
5,0	3,3
6,0	3,3
8,0	2,7
10,0	2,2

Figure 5. *Measurement of the induced voltage for rotating discs of different size*

Weber's law states that magnetic forces only occur between charge carriers that move or accelerate relative to one another, or, in general terms, where the mutual distance changes. When magnet and discs rotate together, there is no change in distance. Therefore, according to Weber, these parts are not subject to any interaction. Taking as a model for the magnet a current-carrying coil, causing the same field strength, the most substantial changes in distance and thus the most significant interaction forces occur at the contact point between the magnet (current-carrying coil) and the sliding contact, connected to the external circuit, or between the charge carriers at these locations. Further attraction or repulsion forces are caused by the interaction between the flowing electrons in the other extended parts of the coil and the sliding contact.

When looking from the position of a contact point, sliding at a 2cm disc (same size as the magnet), the electrons, flowing in the distant parts of the coil appear at a very unfavorable angle to contribute force components perpendicular to the disc surface in the direction of the external circuit. When using larger discs, the situation changes; the force components increase due to the changing angle (fig.6)

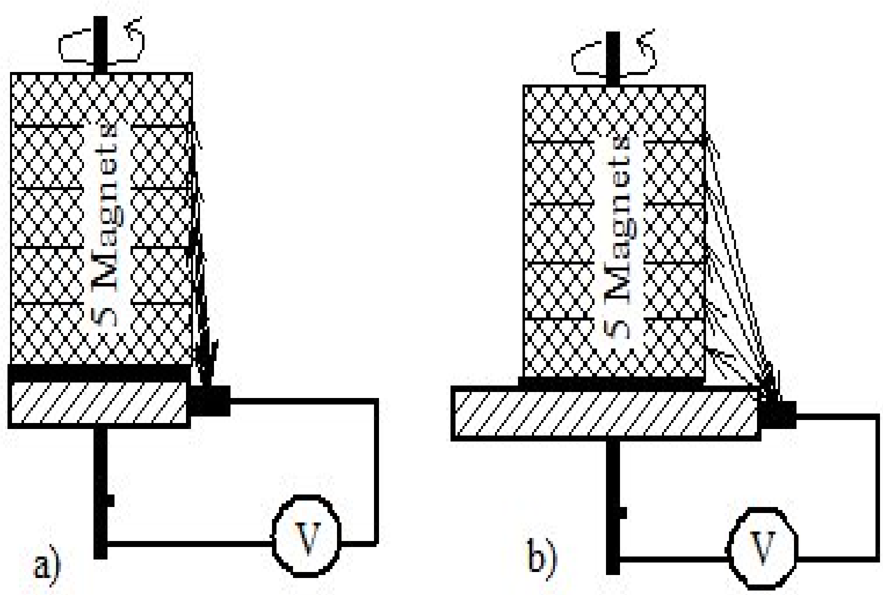


Figure 6. *Interaction between a magnet and sliding contact at different distances (see text)*

Thus, it can be supposed that the number and strength of these additional force components cause an increase in the interaction despite the greater distance and can thus explain the measured increase of the induced voltage. This assumption still requires confirmation by a corresponding calculation, which still needs to be done.

Two further experiments support this assumption. On the one hand, ring-shaped discs of different seize were placed around a single magnet. The induced voltage between the outer edge of the aluminum ring and the axis of rotation was measured at constant rotational speed (Figure 7).

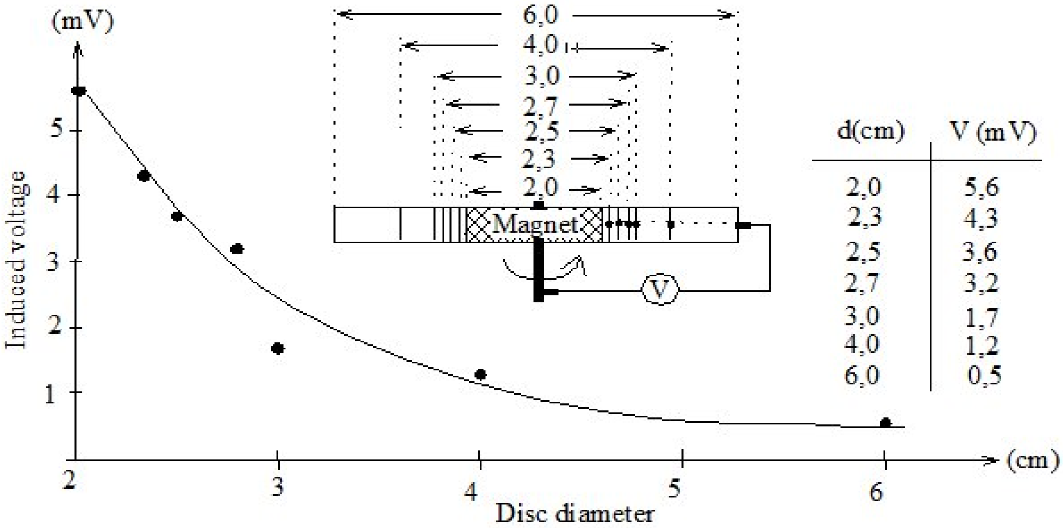


***Figure** 7. Measurement of the inductance voltage on ring-shaped aluminum discs, which rotate together with a magnet inside around a fixed axis*

The result shows, as expected, a continuous decrease in the induced voltage with increasing distance between the sliding contact and the magnet. However, when using a more extended magnet, the result changes (Figure 8).

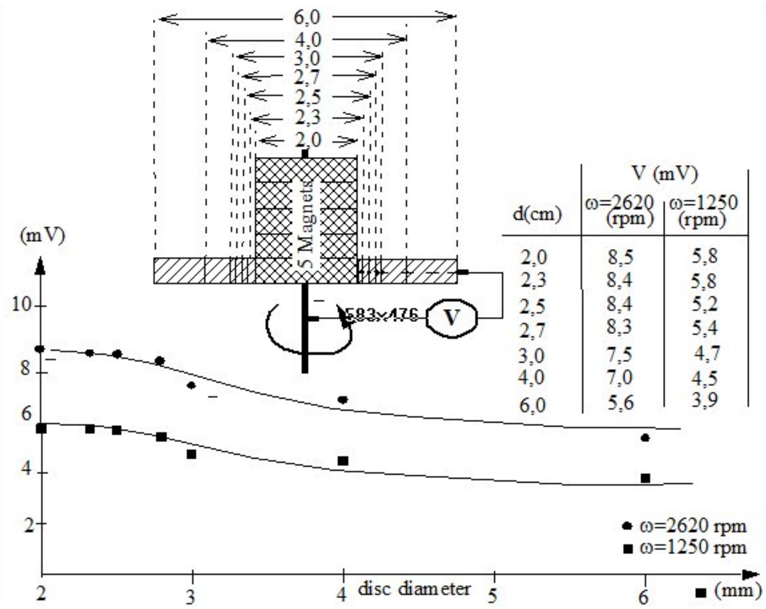


***Figure 8.** The same measurement as in Figure 6 with a more giant, more extended magnet*

Again, the measured induced voltage increases in the nearer surroundings of the magnet and also in the more distant surrounding. This result supports the above-stated assumption. With increasing distance between sliding contact and magnet, and looking from the position of the contact point, the electrons flowing in the more remote parts of the coil appear under a favorable angle to supply a force component towards the external circuit. A final experiment once again demonstrates the importance of the position of the sliding contact. Instead of a single disc, one with an extended surface was used (fig. 9).

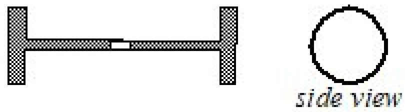


Figure 9. *Aluminum disc with an enlarged outer surface*

The setup and the measured results are shown in figure 10.

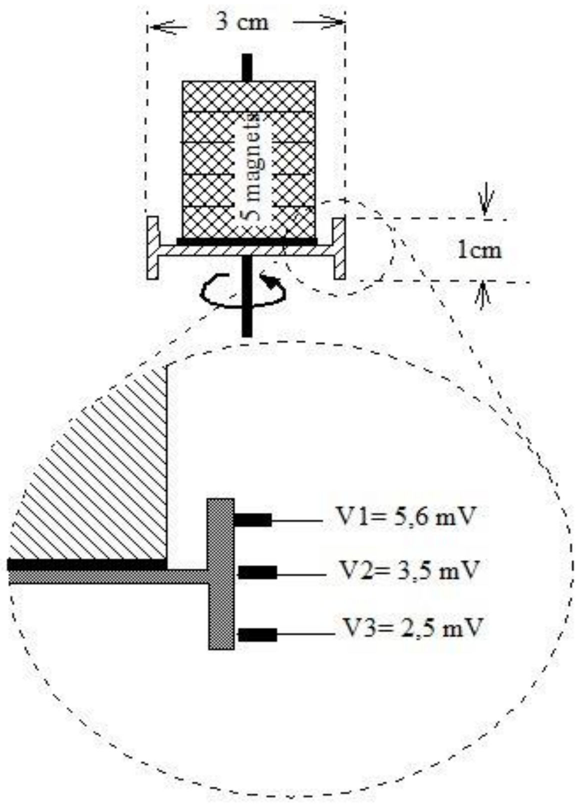


Figure 10*. Measurement of the induced voltage on a disc with an enlarged outer surface*

It turns out that not the distance between the disc and the front side of the magnet, but the position of the sliding contact is decisive. This result is consistent with Weber's theory, which implies that interaction occurs only between charge carriers moving relative to each other. It seems to be not very promising to attempt to explain this result based on Lorentz's theory.

A similar argument was published by Wesley (1990) concerning an experiment with a Z-shaped antenna, that could only be correctly predicted by Weber's theory, but not by the standard theory. In this work, the following statement is found:

The interpretation of the magnetic field by Faraday and Maxwell as physically solid rigid lines of force attached to a source is seen to be physically untenable. The B field, like the A field from which it is defined, is merely a mathematical artifact, a mathematical device, of no particular direct physical significance, used to help solve the problem of how moving point charges affect moving detector charges.

There is nothing to be added.

STILL TO BE CLARIFIED QUESTIONS

1. Why do you measure with a rotating magnet of conductive material and a stationary external circuit between the surface of the magnet and the axis of rotation an induced voltage, which is significantly higher than the induced voltage occurring between the rim of a rotating disc and the rotational axis?

2. Why does no induction voltage occur in a Faraday generator when only the magnet is rotating, but the disc and the external circuit remain stationary?

3. Why do you measure with a Faraday generator an induction voltage when the disc rotates, but the magnet and the external circuit remain stationary?

4. In cases 1 and 3, it is also necessary to clarify why the induced voltage reverses when either the axis of the magnet or the direction of rotation is reversed.

Questions 1 and 4

With a rotating current-carrying coil (as a model for a magnet) and a stationary external circuit, the latter is polarized. The free electrons of the external circuit (at rest relative to the laboratory) interact with the positive and negative charge carriers inside the rotating coil. These two parts, however, cancel each other independent of the rotation velocity except for the flowing free electrons, which are causing the magnetism. This cancellation explains why the rotation of the magnet does not influence the measurement. Only the flow rate of the free electrons in the solenoid is important. Only these free electrons and those in the external circuit exist as interacting partners. The flow rate of these free electrons is amplified by the rotation and this explains, why the induced voltage is a function of the rotation velocity ω. It also explains why the polarity of the induced voltage inverses if either the sense of the rotation is inversed, or the axis of the magnet is rotated by 180 degrees.

Question 2

If only the magnet rotates and the disc and the external circuit remain stationary, then both the disc and the external circuit, are polarized, but both in the same sense. Disc and external circuits represent a stationary closed circuit, on which the magnet applies attractive or repulsive forces, depending on the direction of rotation and the orientation of the magnet. Such forces can cause polarization of parts of this circuit but cannot cause a continuously flowing current.

Questions 3 and 4

With a rotating disc and a stationary magnet, the free electrons of the disc interact with the flowing electrons inside the stationary magnet. Depending on the orientation of the polar axis of the magnet, the latter move either in the direction of rotation or in the opposite direction. As in classical electromagnetism, it follows from Weber's equation that, in general, parallel currents attract each other, and anti-parallel currents repel each other. That makes it understandable why the reversal of the measured induced voltage occurs not only with a reversal of the direction of rotation but also with a rotation of the polar axis by 180 degrees.

DIDACTIC CONSIDERATIONS

As long as the scientific community tolerates the fact that since the beginning of research in this field, there is uncertainty about the cause of Unipolar Induction, it cannot be blamed on textbook writers nor teachers not to include this topic in the curriculum. Besides, the topic of “Electromagnetic induction” is a difficult one when it needs to be taught. As elegant as the right-hand rule and the mathematical formulations

$$F_{Lorentz} = qF + q(v \times B) \text{ and } \oint E ds = -\, d\Phi/dt$$

are, so difficult is it to illustrate the content of these equations or to make the described phenomenon understandable. How is it possible for a force to be produced perpendicular to the magnetic field (whatever that is) and perpendicular to the velocity of the charge carrier?

Once a rather young student asked:

"Do the magnetic lines buckle to the right, like rubber bands, when they push the electron to the left?"

Is there any right answer to this student?

Furthermore, which mechanism could explain why an annular electric field is induced around an area where the magnetic flux is changing?

All this remains unexplainable, and so this subject could be the occasion for many students to either find physics too difficult and incomprehensible or themselves as insufficiently gifted to succeed in this subject.

How secure, however, is the Weber/Ampère approach to connect with everyday experience, in which there are only, as in Mechanics and Electrostatics, attractive and repulsive forces.

If there were no alternatives to the current curriculum, one would have to accept the existing teaching situation. Then specific laws of nature would not be accessible to the imagination, and one would have to accept the restriction to mathematical formulations.

However, if there is an alternative that is much simpler and clearer, then from a didactic point of view, it is not responsible not to take note of this alternative and not to carefully check its correctness and applicability.

To refuse such an examination, arguing that it could not be that a severe theory was forgotten for centuries, is not rational and is risky. Historians may prove one day that also in physics, the processes are not always only based on rationality and that theories are sometimes pursued not necessarily because of their correctness but because of the fame of their inventors or suppressed for all other human reasons such as competition or ambition.

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