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New measurements on the Faraday generator and new questions about induction

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Abstract

The question of how the processes around the Faraday generator with its rotating magnet should be interpreted has been controversial since its discovery by Faraday. Does the magnetic field rotate together with the rotating magnet or does it remain stationary? Furthermore, does one only needs Faraday's flux law to interpret inductive processes or are there processes in which this law fails and a satisfactory explanation can only be found with the help of the Lorentz force? This question seemed to have been resolved recently in favour of Faraday's flux law (Zengel 2019), which has been described as a universal law that applies without exception to every conceivable case.

The measurements presented here raise doubts as to the validity of this interpretation.

Keywords: Electromagnetic induction, Faraday generator, Faraday's flux law, Lorentz force, Wilhelm Weber´s Fundamental Law of Electrodynamics

Introduction

A Faraday generator usually consists of a rotating magnet and a metallic disc (Fig.1a); the disc can either rotate independently or together with the magnet. If the magnet is made of conductive material, the metallic disc can be omitted and the form of a Faraday generator is then as shown in Figure 1b

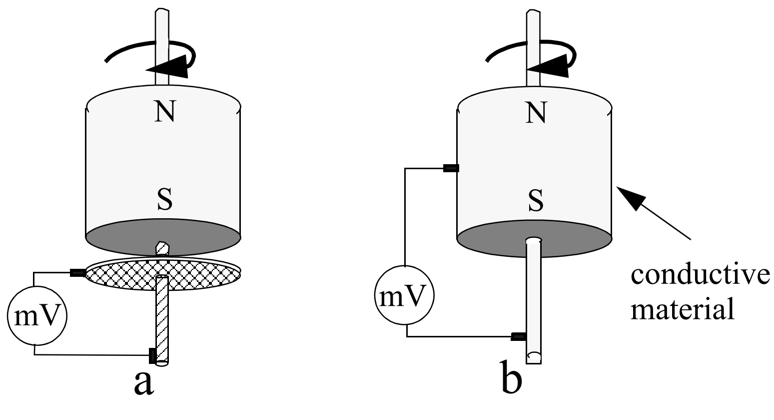

Fig. 1: Two versions of a Faraday generator

The questions that arise when operating a Faraday generator are:

Why is induction (as expected) observed with a rotating disc and a stationary magnet, but not with the reciprocal process: a rotating magnet and a stationary disc?

Why is induction observed when the magnet and disk rotate together?

These questions have prompted lengthy discussions. The story began with Faraday's discovery of the paradoxical results in a Faraday generator in 1832; discussions continues to this day. The key question has been whether Faraday's flux law is universal or whether, as Feynman [1964] claimed, there are exceptions in which only the Lorentz force can provide a meaningful explanation for the observations. Furthermore, it is disputed whether the magnetic field rotates with a rotating magnet (so-called M-theory) or whether it remains stationary despite the rotating magnet (so-called N-theory). It is undisputed that the magnitude of the magnetic field is constant in the entire surrounding of a magnet rotating around its polar axis. But does this rotation give the magnetic field a component of movement or is it indistinguishable from a stationary magnetic field?
Kelly (1998) published measurements that, he argued, confirmed the N-theory. And by contrast, Chen et. al. (2016) based on their own measurements confirmed the validity of the N-theory.
If a stationary magnetic field is assumed, the conduction electrons within the magnet and within the rotating disk move through this stationary magnetic field and are accelerated due to the Lorentz force either towards the edge of the magnet and the disk respectively, or towards the axis of rotation. The origin of the induction would then lie within the magnet or the disk.
If one assumes that the magnetic field rotates with the magnet (M-theory), then this magnetic field cuts the outer part of the circuit, at rest in the laboratory, and causes an induced current based on Faraday's flux law. The origin of the induction would lie outside the magnet or the disk.
A recent paper by Zengel (2019), in which a detailed account of this discussion can be found, culminates as follows:

> In summary, the Lorentz force law and Maxwell's version of Faraday's law describe different phenomena, and may for that reason predict different emf‘s in certain experiments, but neither law should ever predict a result that is inconsistent with the flux rule, $\varepsilon = -\frac{\mathrm{d}}{\mathrm{d}t}\iint \vec{B} \cdot d\vec{A}$.

This seemed to have finally resolved these questions, but the measurements described below cast doubt on the validity of Zengel’s statement

The measurements

A cylindrical Niodymium magnet (outer diameter. 20 mm, height = 5 mm; central bore = 4 mm) was used. A stationary drill with V-belt drive served as the drive.
The following link leads to a paper with a detailed description of the measuring device with helpful hints (http://www.astrophysik.uni-kiel.de/~hhaertel/New-Measurements/measurement-setup.htm).
A first control measurement showed - as required - a linear dependence of the meas-

ured induced voltage on the rotational speed (Fig.2).

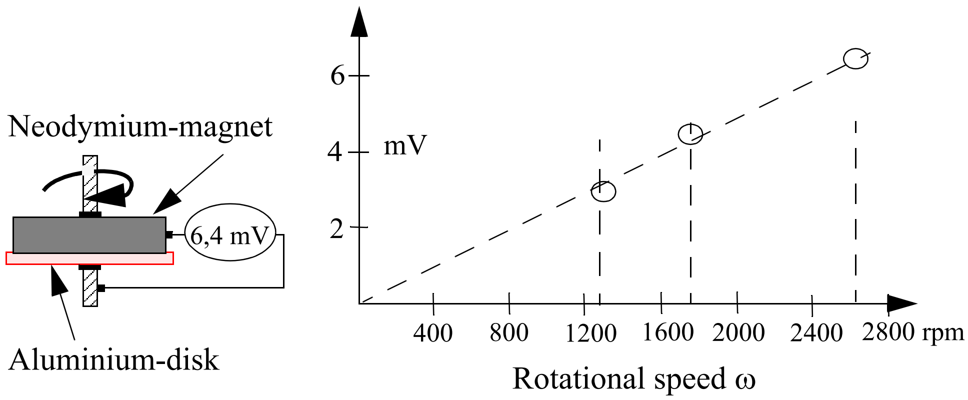

Fig. 2: Voltage proportional to rotational speed.

Figure 3a shows the magnet used together with the magnetic field, indicated as usual by lines, which are to be thought of as symmetrical around the magnet.

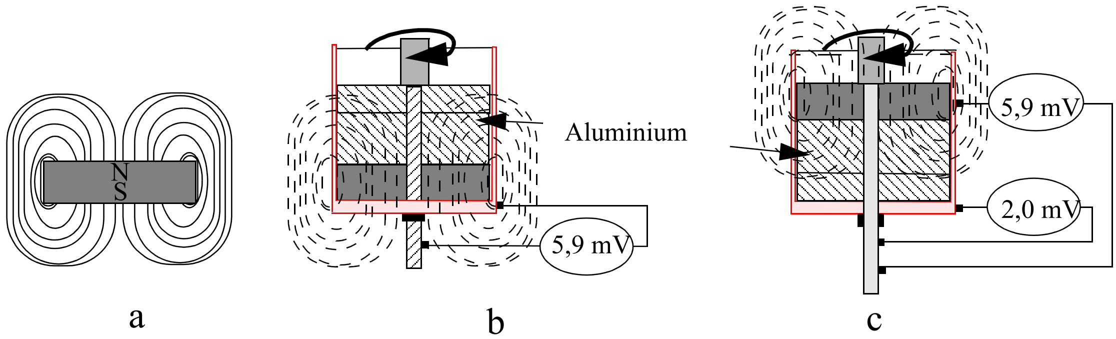

Fig. 3: Presentation of the measurements carried out (see text)

The new measurements referred to here are shown in Figures 3b and 3c. In a first step, the disk was expanded to a kind of sleeve with relatively thin side walls, the magnet was attached directly above the bottom of the sleeve, and the induced voltage was measured between the base of the rotating sleeve and the axis of rotation (Fig. 3b).

In a second step, the magnet was attached within this sleeve at a large distance from the bottom of the sleeve with the help of two spacer blocks. As expected, the measurement between the bottom of the sleeve and the axis of rotation resulted in a correspondingly smaller reading for the induced voltage because of the smaller magnetic field present there.

What effects are to be expected from the side walls of the rotating sleeve? In the vicinity of the magnet, they move mainly parallel to the magnetic lines, so there is hardly any place where magnetic lines could be cut. As a first approximation, no major influence on the measurement result should be expected.

The opposite is the case.

The readings for the induced voltage rises again at the height of the magnet to the same value as the value measured at the bottom of the sleeve as shown in Figure 3b (see Figure 3c).

How can this result be explained on the basis of Faraday's flux law or the Lorentz force?

Where is the area with an increased magnetic flux, changing in time or where is the increased number of magnetic field lines being cut by rotating parts?

These questions must be addressed with the help of Faraday's flux law, assuming that this law is a law of nature and not just a rule that applies in most cases.
If access is available to a workshop where the necessary parts of rotational symmetry can be manufactured, it would be an interesting task to repeat these experiments with a class or group of students, to check them and to try to answer these questions. An additional task would be to predict, what would be the effect of sleeves with thicker side walls and then to check the prediction by experiment.
The measured results could suggest that it is not the disk, but the distance between the sliding contact and the magnet that is important for the occurrence of an induced voltage in a Faraday generator.
This would be in accord with a theory put forward by Wilhelm Weber in the 19th century. He proposed that the Coulomb force as an interaction between two charge carriers or two groups of charge carriers is influenced if there exists a relative speed and / or a relative acceleration between the interacting partners.
But before adopting this explanation, we should first see whether a satisfactory answer to the above questions can be determined.
Further information can be found in the literature (Assis, 1994) (Härtel 2019)
It is worth adding a few words about Wilhelm Weber, who is largely unknown and whose theory is often described in a negative fashion, with the suggestion that it is only an action-at a-distance theory and not a field theory. It is true that Weber's theory is an action-at a-distance theory, just like the Coulomb law or the universal law of gravity. What is not generally known is that Weber was the first to set up the telegraph equation. In addition Weber not only theoretically predicted the possibility of a telegraph, but also realized it by stretching two wires over the roofs of Göttingen, to connect his institute with the Institute of Astronomy and via which he could send electrical pulses. There is a memorial in Göttingen that shows Gauss and Weber and commemorates the moment when the first telegraph was invented and implemented. (https://www.atlasobscura.com/places/gauss-weber-telegraph-memorial)

Literature

Assis A.K.T. (1994) Weber's Electrodynamics, Kluwer Academic Publishers, Dordrecht 055202 (10pp)

Chen K., X.-J. Li and Y.-X. Hui (2016) An Experimental Study on Unipolar Induction, Acta Physica Polonica A, Vol. 131.

Feynman, R. P., Leighton, R. B., & Sands, M. L. (1964). The Feynman Lectures on Physics: Electromagnetism and matter (Vol. 2). Addison-Wesley Publishing Company

Härtel H. (2018) Electromagnetic Induction: An Alternative for Teaching and Understanding. European Journal of Physics Education, 9, 2 p. 1-13.

Härtel H. (2018) Electromagnetic Induction from a new Perspective, European Journal of Physics Education, 9, 2 p. 29-36.

Kelly A. G. (1998) Faraday's Final Riddle; Does the Field Rotate with a Magnet? Monographs 5 & 6 of the Institution of Engineers of Ireland.

Zengel, K. (2019) The history of the Faraday paradox of the unipolar generator, Eur. J. Phys. **40** (2019, 055202 (10pp)