G Coil experiment as metamorphosis of the Faraday disk

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Abstract

A new experiment on unipolar induction has been designed and built by topologically modifying the structure of the Faraday disk. The metamorphosis consists of replacing the magnet with a solenoid, with the same axis of rotation as the disc, and connected in series with a radial conductor, which replaces the disc. This resulting shape has been called G Coil, due to the shape similar to the letter G that the device forms. This experiment demonstrates the viability of a new electrical machine that works as a motor without the need for any external magnetic field. Working at low voltages and high currents.

Keywords: Arago disk, Faraday disk, G Coil, Faraday's Paradox.

1 Introduction to the Faraday disk

In January 1832, during the *Experimental Researches in Electricity* [1], Michael Faraday unveiled the Faraday disk, which would be the simplest direct current generator ever constructed. The idea occurred to him in 1831, from a modification or metamorphosis of Arago's disk. Francesc Arago, in 1824, discovered that a copper disk, rotating on its axis of symmetry, produced magnetic effects[2]. The Faraday disk consists of a disk of copper or a conductive material, which can rotate regarding its axis of symmetry and so that it is close to one of the poles of a cylindrical magnet, see figure 1.1. A connection is made through a static electrical circuit, between the shaft and the periphery of the rotating disc, using a sliding contact. It is observed that when the disc rotates relative to the magnet, a direct current appears in the circuit and if the direction of rotation is reversed, the direction of the generated current is also reversed. The same reversal occurs if the polarity of the magnet is changed.

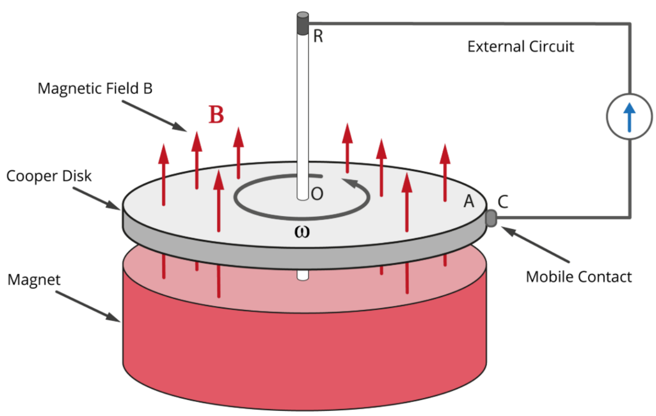


Figure1.1: Sketch of the Faraday Disk or Homopolar Generator.

It should be emphasized that all the components of this experiment rotate symmetrically around the axis of rotation of the disk. This symmetrical rotation is a fundamental detail about the relative rotational motion between the copper disc and the cylindrical magnet. This arrangement between the disc and the magnet is called a unipolar generator or homopolar generator because in this configuration the electromagnetic induction is produced through a single pole of the magnet. It is also characterized as a particular case of a direct current generator, where there is no switching or alternation of magnetic poles necessary to generate electricity.

According to the geometry between the copper disc and the magnet, there are four possibilities of relative movement between them. Faraday realized these four relative motions and designed the way to perform the various experiments, which we have listed as follows.

Experiment 1: The disk rotates while the magnet remains at rest.

Experiment 2: The disk remains at rest and the magnet rotates

Experiment 3: The disc rotates in solidarity with the magnet.

Experiment 4: Rotate only the magnet, without the disc.

The following table 1 shows the results obtained by Faraday, grouped throughout all his experiments carried out with the relative movement between the disk and the magnet. The results obtained from the relative movement between the disc and the magnet and its consequence in the generation of induced current, observed in the galvanometer, depending on the type of relative movement, are indicated.

Tabla 1: Resultados de los experimentos realizados por Michael Faraday

Experiment	Disk	Magnet	Current
1	Rotate	Static	YES
2	Static	Rotate	NO
3	Rotate	Rotate	YES
4	Without Disk	Rotate	YES

Let's look at these experiments in detail.

1) **First Experiment:** Rotation of the disc while keeping the magnet static

In this first experiment between the copper disk and the magnet, the magnet is held static while the disk rotates, as indicated in Figure 1.2. The result is a direct current that circulates in the conductor that joins the mobile contact on the copper disc and the contact in the center of the axis of rotation of the disc.

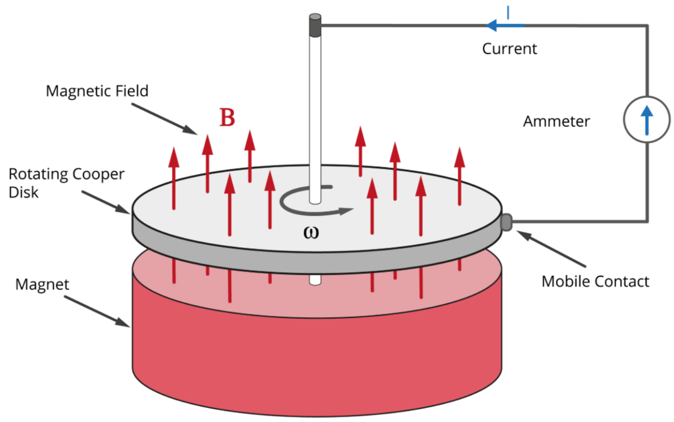


Figure 1.2: Sketch of the first experiment with the Faraday's Disk

2) **Second Experiment:** Rotation of the magnet keeping the disc static

In this second experiment, the disk is kept static while the magnet rotates, as indicated in figure 1.3. In principle, the system is equivalent to the first experiment, since a relative speed between the disk and the magnet is also obtained. However, the result is totally negative, no current is generated. Thus, this result leads us to deduce that this second experiment is not equivalent to the first. Let's find out in more detail what the difference is. It is evident that current cannot be generated in this dynamic configuration between the disc and the magnet, since the second principle of thermodynamics would not be fulfilled.

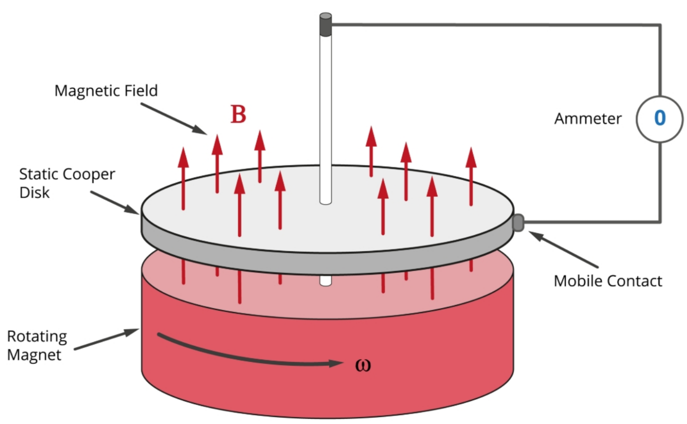


Figure1.3: Sketch of the second experiment with Faraday's Disk.

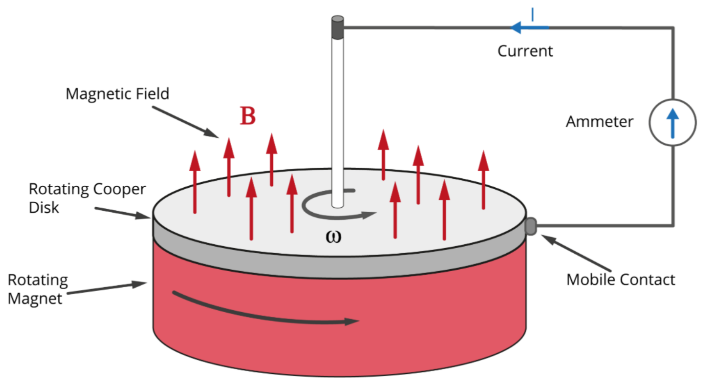
If we imagine the Faraday disk in a vacuum, where the magnet can rotate without any friction, the magnet would rotate forever from an initial impulse. In this way, energy would be generated through the circuit, in the form of electric current, without any external force applied. Let's look at an essential detail, in this second experiment the electrical contacts between the disk and the circuit are not mobile, they are static.

Another way to visualize the null result of this experiment is how Faraday tried to solve it. For him, the magnetic field lines did not rotate with the magnet, that is, the magnetic field lines remain stationary when the magnet is rotating. So, then Faraday's law on electromagnetic induction due to flux variation does not hold. In this case, there was no variation in the magnetic flux and, however, an induced current appears. This discussion is commonly referred to as Faraday's Paradox and has sparked considerable debate regarding the possibility of magnetic field lines rotating with the magnet. Richard Feynman established that unipolar induction is an exception to the law of induction, and thus calls it the flux rule[3]. The character overflow rule is widely discussed in McDonald[4].

3) **Third Experiment:** Simultaneous rotation of disc and magnet

In this third experiment, the magnet remains attached to the disk and the two rotate jointly. Since there is no relative speed between the magnet and the disk, no generation of electric current should occur. In other words, no flux variation should be seen between the disk and the magnet if the magnetic field lines are dragged by the magnet. However, contrary to expectations, a direct current is produced in the circuit, thus indicating Faraday's idea that the magnetic field lines are not dragged by the magnet.

It is necessary to realize that now the contact between the disc and the electrical circuit is once again a moving contact. A current appears again as long as the rotation movement exists in the moving contact.



Figur3 1.4: Sketch of the third experiment with Faraday's Disk..

4) **Fourth Experiment:** Rotation only of the magnet without presence of the disc

In this last experiment, the copper disc is omitted, and only the magnet is rotated in contact with the electrical circuit. In this case, an electric current also appears in the circuit through the moving contact.

It should be noted that in these four experiments, the only one in which electric current is not generated is the one in which there is no mobile contact.

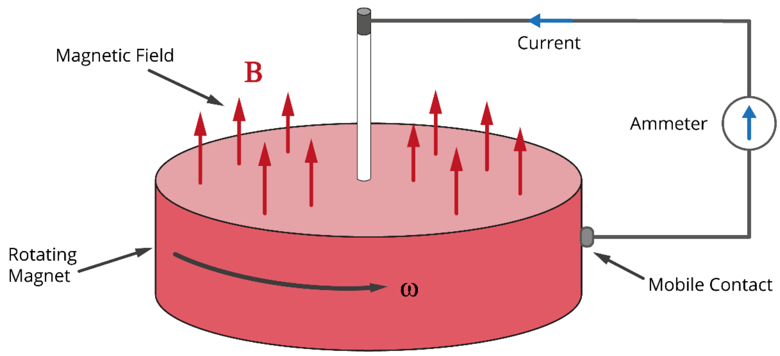


Figure 1.5: Sketch of the fourth experiment with Faraday's Disk.

2 Application of the Lorentz force to the Homopolar Generator

Let us next consider the Faraday disk, where the copper disk is rotating with an angular velocity □ within a uniform magnetic field B, see figure 2.1. In this case the system behaves as a homopolar generator and the creation of a current is observed that can be measured using an ammeter.

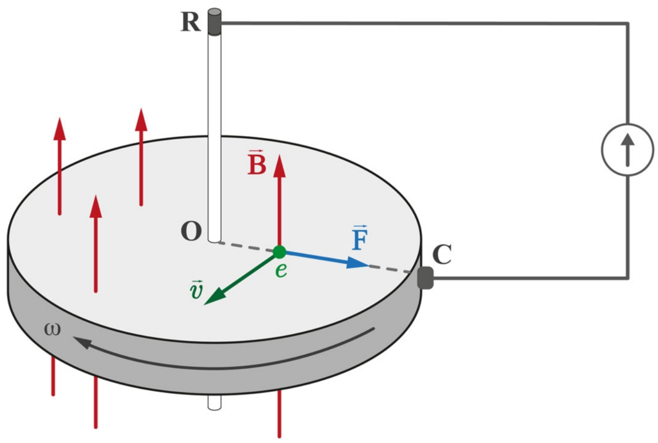


Figure 2.1: Sketch Faraday's Disc with force, velocity and magnetic field vectors .

In the laboratory reference system (Σ) the magnet is at rest. Then, from the Σ system, a homogeneous and uniform magnetic field is observed. Given this condition, there is no variation in the magnetic flux and consequently the law of electromagnetic induction indicates that an electromotive force is not produced. However, experiments indicate that this electromotive force does occur. Under these conditions, we calculate the electromotive force by directly applying the Lorentz force.

As we can see in Figure 2.1, we consider a closed circuit OCR, a circuit that is closed between O and C by the movement of the charges of the conductive disk, subjected to the Lorentz force. In this situation a polarization effect appears, where according to the direction attributed to the rotation of the disk, the Lorentz force drags the positive charges towards the center of the disk and the negative charges towards the periphery. Considering that the real movement is due to the electrons, and they have a negative charge, the direction of the force will follow the direction indicated in figure 2.1.

$$\vec{F} = q\vec{v} \times \vec{B} = -e\vec{v} \times \vec{B}$$

The polarized disk then acts as a generator. To illustrate this in more detail, we consider $d\vec{l}$ as a differential element of path length CO, thus the electromotive force ε will be indicated by the following expression

$$\varepsilon = \oint_C \left(\vec{v} \times \vec{B}\right) \cdot d\vec{l}$$

We observe that $\vec{v} \times \vec{B}$ is directed along the $d\vec{l}$, following the radial direction. Since the movement is rotation, the speed of the loads increases with the radius of gyration, $v = \omega r$. In this way we can rewrite the integral and determine the value of the electromotive force..

$$\varepsilon_F = \int_0^R Bvdr = B\omega \int_0^R rdr = \frac{1}{2}B\omega R^2$$

3 G Coil or Metamorphosis of the Faraday disk

According to the experiments carried out on the Faraday disk, we observe that an electric current is induced regardless of whether the magnet rotates regarding the disk or the disk rotates regarding the magnet, only the relative rotation speed intervenes. Which shouldn't surprise us. However, more curious is experiment number 4 where an induced current is produced on the rotating magnet itself. We can assume then that the condition of the magnet does not affect the rotation of the disk-magnet system. On the other hand, the Faraday disk contains a generator-motor symmetry. If we introduce a current into the circuit we will make the disk rotate. With this reasoning in mind, we can replace the magnet with a solenoid located on the axis of rotation of the disk, through which a current will pass that generates the same magnetic field as the magnet it replaces.

Let us now consider that the effect of rotation on the disk is generated in a radial path and, therefore, it is this linear portion of the disk that exerts the rotational moment. We can, in this way, replace the disc with a radial conductor connected in series with the solenoid. Simulating the joint rotation of the disk and the magnet in Faraday's experiment, but now forming a new homopolar set[5]. We call this new set of our invention G Coil, for simplicity, given the shape associated with the letter G of the set.

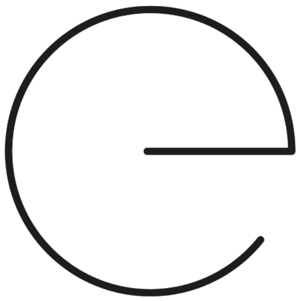


Figure 3.1: G Coil. Schematic of the coil in series with the radial part.

With the purpose of determining the behavior of the homopolar motor based on the characteristic of the G coil, we have designed and built several experiments. The first consists of demonstrating that a prototype G Coil engine can rotate as suggested by the theory proposed above. Because of the weak Lorentz force generated, two drawbacks arise in this type of experimentation. The first consists of reducing the friction force between the contacts; this is achieved by replacing solid metal contacts with mercury. The second drawback is to obtain the maximum current that can circulate; Thus, the decrease in mercury contacts also decreases the resistance, contributing to achieving the maximum possible current. Under these conditions, the Loop G circuit becomes almost a short circuit, allowing the voltage source to supply the maximum possible current. Our design and construction of the G Coil consists of a diameter of 85 mm with a diameter of 110 mm and a height of 95 mm. With these dimensions, we were able to make it rotate with a current of about 100 A during the experiment.

Figure 3.2 shows the assembly of loop G built to carry out the experiments. One mercury contact is located at the top where it will be attached to the voltage source and the other contact at the base, where the coil or loop is located and whose terminal is in contact with the mercury. Since the current that will circulate will be high, the metallic contact with the mercury both at the top and at the bottom must also be of minimum resistance.

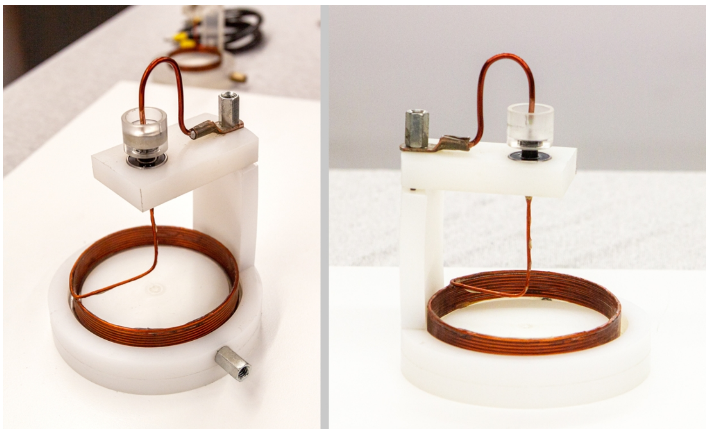


Figura 3.2: G Coil device. Coil diameter: 85 mm. Diameter of G Coil: 110 mm. Altura: 95 mm. Rotational current of about 100 A.

The union with the mercury in the upper part is achieved through a hollow cylindrical piece that will be responsible for keeping the mercury inside (figure 3.3). This is joined to the copper wire of the coil together with a bearing in its lower part. The voltage source cable is connected to the upper part of the cylindrical piece. In this way, we have managed to eliminate friction between the cables, although they are electrically connected through mercury. It should be noted that the ends of the cables in contact with the mercury must be free of resin to maintain electrical contact between the copper and the mercury.

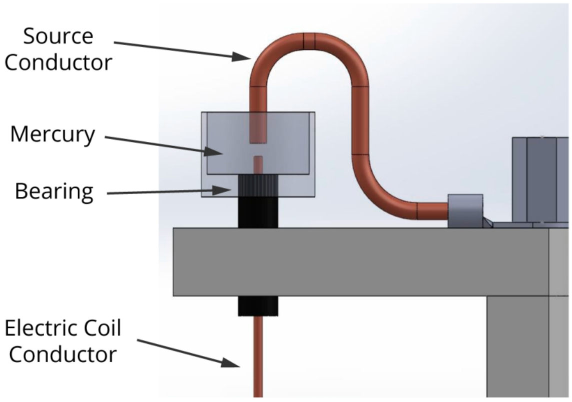


Figure 3.3: Connection with the mercury at the top of the G Coil.

Electrical contact at the bottom or base of G Coil is made by immersing one end of the coil in mercury, ensuring that it maintains contact during the rotation of G Coil. As shown in the following figure 3.4.

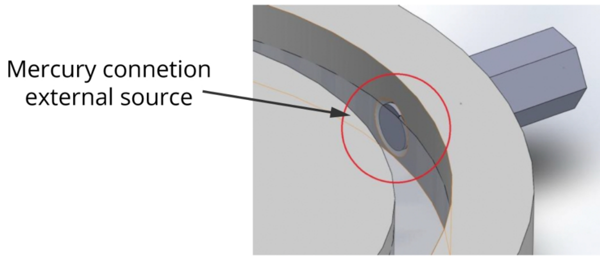


Figure 3.4: Contact between the mercury ring, contained in the annular cavity, generated for the mercury liquid contact track and the output terminal to the battery..

The schematic, in 3D representation, of the final result of the G Coil structure is shown in figure 3.5, illustrating all the essential components..

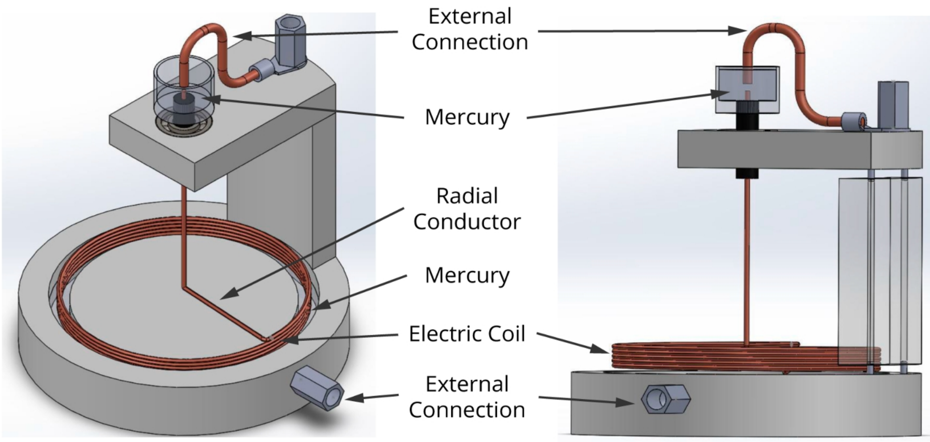


Figure 3.5: Schematic 3Dof the structure of the G Coil. The rotor is suspended and guided by the upper mercury contact, the lower part contains a peripheral contact, immersed in mercury, contained in the lower annular cavity.

4 Calculations on G Coil

Given the successful result of the experiment on the discovery and invention of G Coil, the principle underlying the origin of the rotation movement and its calculation are determined below. We start from the hypothesis that the configuration of the G loop is analogous to that of the Faraday disk (figure 4.1), so we propose the same type of interaction of the current with the magnetic field. Simplifying the calculation, since we are only interested in the fundamental principle that drives the rotation movement.

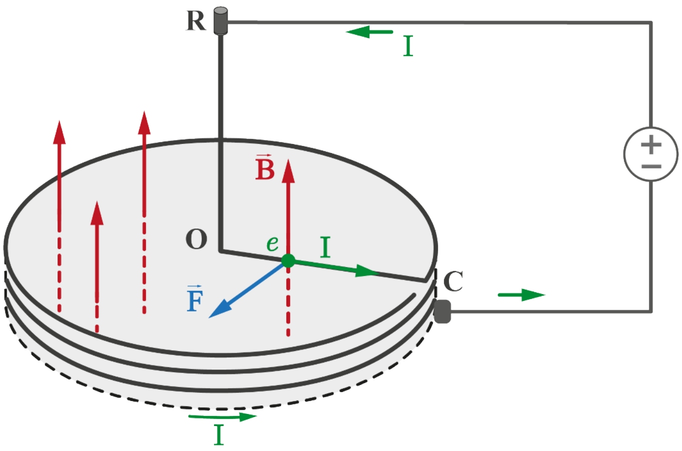


Figure 4.1: Circuit of the G Coil.

In this way, the force F acting on the radial conductor OC is given by

$$F = IBR$$

and considering that this force is applied in the center of the radial conductor, the moment N will be given by

$$N = \frac{1}{2} IBR^2$$

Intending to obtain an approximation of the movement of the circuit of coil G, we continue performing an approximate calculation considering that the coil has very few coils and its length will, therefore, be much smaller than its radius.

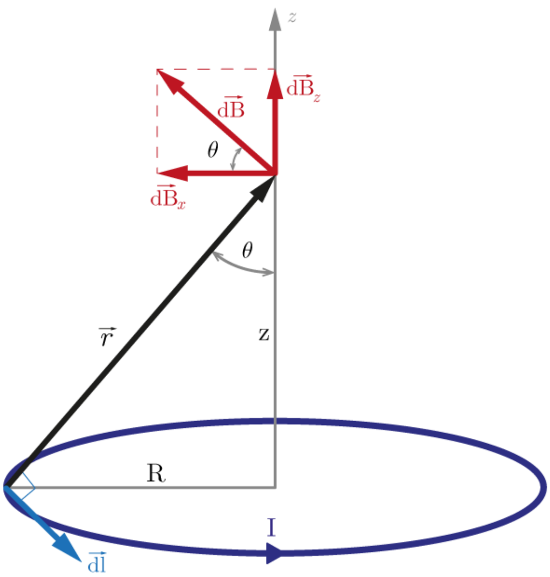


Figure 4.2: Magnetic field of a circular loop.

We determine the magnetic field using Biot and Savart's law for currents

$$d\vec{B} = \frac{\mu_0 I}{4\pi}\frac{\vec{dl} \times \vec{r}}{r^3}$$

since the vectors $\vec{dl}$ and $\vec{r}$ are perpendicular, the vector product is simplified

$$\vec{dl} \times \vec{r} = rdl \sin \pi/2 = rdl$$

being $r = \sqrt{R^2 + z^2}$ and the magnitude of the magnetic field dB

$$dB = \frac{\mu_0 I}{4\pi}\frac{rdl}{r^3} = \frac{\mu_0 I}{4\pi}\frac{dl}{r^2}$$

The component of the magnetic field dB_x is canceled when integrating throughout the entire circuit, only the component will remain dB_z,

$$dB_z = dB \sin\theta$$

where $\sin\theta = \frac{R}{r}$, obtaining

$$dB_z = \frac{\mu_0 I}{4\pi}\frac{dl}{r^2}\left(\frac{R}{r}\right) = \frac{\mu_0 IR}{4\pi}\frac{dl}{r^3}$$

the integral throughout the entire circuit C will be of the form

$$B_z = \frac{\mu_0 IR}{4\pi}\int_C \frac{dl}{r^3}$$

and since the position vector r does not depend on the circular path C, we obtain the modulus of the z component of the magnetic field along the z axis.

$$B_z = \frac{\mu_0 IR}{4\pi r^3}\int_C dl = \frac{\mu_0 IR}{4\pi r^3}(2\pi R) = \frac{\mu_0 IR^2}{2r^3} = \frac{1}{2}\mu_0 I \frac{R^2}{(R^2+z^2)^{3/2}}$$

The value of the magnetic field in the center of the coil will be given by z = 0, obtaining the next value

$$B = \frac{\mu_o I}{2R}$$

As an approximation, we consider this value as valid at the point of application of the force F, where we obtain

$$F = IBR = I\left(\frac{\mu_0 I}{2R}\right)R = \frac{1}{2}\mu_0 I^2$$

Applying the dynamic conditions, the balance of moments between the Lorentz force F, considering its application in the center of the radial conductor, and the force F_r of friction applied at the end, we obtain the following relationship.

$$F\left(\frac{1}{2}R\right) - F_r(R) = 0$$

Considering that the F_r is dynamic, we apply a friction force proportional to the tangential speed,, $F_r = bv = \omega bR$. We obtain the following relationship for the angular velocity, considering the application of the force F in the center of mass of the radial conductor.

$$\begin{aligned} F - 2F_r &= 0 \\ 2b\omega_G R &= \frac{1}{2}\mu_0 I^2 \\ \omega_G &= \frac{\mu_0}{4bR} I^2 \end{aligned}$$

We observe that the angular velocity depends on the square of the current, this means that the direction of rotation of the loop G does not depend on the direction of the current, as is proven in experimentation. In this way, it works in both direct current and alternating current. At the same time, it depends inversely on the radius of the loop, indicating that the smaller the radius, the greater the angular velocity. As is also proven in experimentation, where coils with a smaller radius rotate more easily and with greater speed.

5 Conclusions

As a result of the knowledge acquired in all the experiments carried out on the Faraday disk, a new electrical device with rotation movement has been designed and built. By verifying that the condition of the magnet does not affect the rotation of the Faraday disk, the magnet can be replaced by a solenoid, with the same axis of rotation as the disk, and connected in series with a radial conductor, which replaces the disk. The resulting shape has been called G Coil, due to the shape similar to the letter G that the device forms.

The result is a new type of set of electrical machines that rotate without the need for an external magnetic field. The difficulty of this type of machine lies, as in the Faraday disk, in the mobile electrical contact. This contact needs to act with low friction and at the same time acquire the characteristics of an excellent metallic contact. Initially, mercury was used as a low-friction contact with high electrical transmission. However, apart from the problems of toxicity and amalgams with other metals such as copper, its handling is complicated. Once these inconveniences were overcome, a device has been built with the G-spiral structure. Verifying both theoretically and experimentally that it rotates equally in direct current and in alternating current.

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