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Design, Production and Comparison with Theoretical Calculations of a Uniform Electromagnetic Field Generator with Helmholtz Coils

Ferdi AVCI*[a], Emin AĞRALİ[b], Orhan YAMAN[c] and Mehmet ÇAVAŞ[d]

[a]*Muş Alparslan University, Department of Machinery and Metal Technologies, Muş, Turkey*
[b]*Muş Alparslan, Department of Electricity and Energy, Muş, Turkey*
[c]*Firat University, Department of Digital Forensics Engineering, Elazig, Turkey*
[d]*Firat University, Department of Mechatronic Engineering, Elazig, Turkey*

* *Corresponding author: E-mail: f.avci@alparslan.edu.tr*

ABSTRACT

Helmholtz coils, which are widely used in the scientific world, are used to generate a uniform magnetic field (EMF). It is used in many test applications due to its ability to generate EMF at the desired frequency. It is easier to work with these coils at low frequencies. Since their inductance and internal resistance will be low due to the low frequency, the intended EMF can be obtained by supplying enough current to the coils. Helmholtz coils are used in many areas such as electromagnetic interference tests, biomedical experiments, physics experiments, instrument calibration. In this study, an EMF generator operating in alternative current was designed and manufactured for different EMF generation between 1 mT and 2 mT. Helmholtz coils with circular geometry were manufactured for the EMF generator. The fabricated helmholtz coils are positioned on the vertical axis. A current of 21 A will be passed through the helmholtz coil, which is the maximum value for 2 mT. 2.2 mm conductor cross-section was selected for passing 21 A current. At 21 A, it was found to operate without heating. The radius of the Helmholtz coil was preferred as 15 cm. The conductor weight used in the Helmholtz coil is 1000 g in total. The results of the theoretical calculations for the EMF generator and experimental measurements on the fabricated prototype were tabulated and graphs were obtained. They were compared graphically and the difference between their values was analyzed.

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1. INTRODUCTION

Helmholtz coils are widely preferred in different distribution and test applications due to their homogeneous magnetic field generating properties. The ability to generate an electromagnetic field (EMF) at a specific frequency makes them suitable for low frequency applications. When operating at low frequencies, the inductance and internal resistance of the coils are low; this allows sufficient current to pass through the coils to obtain the desired field regime.

The combination of electric and magnetic fields that propagate in the form of a series of waves at a certain distance and frequency from each other is called the electromagnetic field [1].

When examining the electric and magnetic fields that form the electromagnetic field, it is seen that these fields move in sinusoidal waves, in planes perpendicular to each other, and at right angles to one another.

The electric field, whose unit of measurement is Volt/meter, is created by the presence of electric charges. A plugged-in electrical appliance generates an electric field, even if it is not switched on. The electric field, which decreases in intensity as it moves away from the source, can be prevented from spreading by insulating materials.

When electrical charges on a conductor are changed, an electrical network is formed. Depending on this current, a magnetic field is formed. The unit of measurement of magnetic flux density is Tesla (T). The unit of measurement of the magnetic field is the Gauss (G) (1 T = 10,000 Gauss). Electric current and magnetic field are directly proportional. The magnetic field caused by electric current cannot be blocked by insulating objects [2].

The purpose of the Helmholtz coil is to obtain a uniform homogeneous magnetic field [3].

The structure of the Helmholtz coil consists of two coreless coils with a radius of R, connected in series and positioned parallel to each other, with a distance equal to their radius between them [4].

These systems can be positioned horizontally or vertically.

According to Biot-Savart's law, the magnitude of the magnetic field generated at a distance x from a circular wire of radius R carrying a current I is calculated using Equation 1.

$$B_{(X)} = \frac{\mu_0 . I . R^2}{2 .(R^2+X^2)^{3/2}} \quad (1)$$

For a circular coil with number of turns N, the value N must be added as a product to equation 1.

$$B_{(X)} = \frac{\mu_0 . I . R^2 . N}{2 .(R^2+X^2)^{3/2}} \quad (2)$$

In Equation 2;

B : Elektromagnetic field (T)
μ0 : Permeability of free space $(4. \pi. 10^{-7}\ Tm\ A)$,
I : Coil current (A),
R : Coil radius (m),
N : Number of turns in each coil
X : Distance of the coil from the center on the axis of symmetry (m)

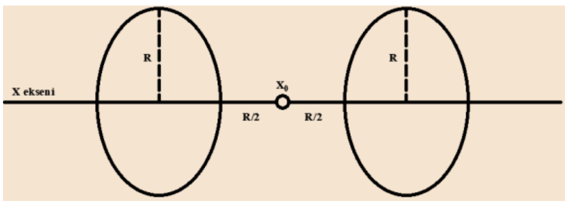

Figure 1. Schematic representation of the Helmholtz coil [5]

As seen in Figure 1, the distance from the center of a coil to the midpoint of a given point (x_0 point) is used to calculate the magnitude of the magnetic field created by the coils around this point. When the distance from the center of the first coil to the midpoint is (+R / 2), by substituting this value for X in equation 2, the magnitude of the magnetic field created by the first coil at this midpoint (B_1) is calculated as follows:

$$B_{(X)}(X = X_0) = \frac{\mu_0 . I . R^2 . N}{2 .(R^2+(R/2)^2)^{3/2}} \quad (3)$$

$$B_1(X_0) = \frac{\mu_0 . I . R^2 . N}{2 .(R^2+(R^2/4))^{3/2}} \quad (4)$$

$$B_1(X_0) = \frac{\mu_0 . I . R^2 . N}{2 .(5\sqrt{5}.R^3/8)} \quad (5)$$

$$B_1(X_0) = \frac{\mu_0 . I . R^2 . N}{2 .(5.R^2/4)^{3/2}} \quad (6)$$

$$B_1(X_0) = \frac{4}{5 .\sqrt{5}} \frac{\mu_0 . I . N}{R} \quad (7)$$

When the distance from the center of the second coil to the midpoint is (−R / 2), the magnitude of the magnetic field created by the second coil at the midpoint (B_2) can be calculated by substituting this value for X in equation 1.2. This calculation is carried out by repeating the same operations for the first coil.

$$B_{2(X= X_0)} = \frac{\mu_0 . I . R^2 . N}{2 .(R^2+(-R/2)^2)^{3/2}} \quad (8)$$

$$B_2(X_0) = \frac{\mu_0 . I . R^2 . N}{2 .(R^2+(R^2/4))^{3/2}} \quad (9)$$

$$B_2(X_0) = \frac{\mu_0 . I . R^2 . N}{2 .(5\sqrt{5}.R^3/8)} \quad (10)$$

$$B_2(X_0) = \frac{4}{5 .\sqrt{5}} \frac{\mu_0 . I . N}{R} \quad (11)$$

As given in Figure 1, the magnitude of the uniform magnetic field at the midpoint between the Helmholtz coils (Btotal); is the sum of the magnetic fields of both coils at the midpoint.

Equation 16 is used to calculate the magnetic field magnitude at this midpoint.

$$B_{total}(X_0) = B_1(X_0) + B_2(X_0) \quad (12)$$

$$B_{total}(X_0) = \frac{4}{5 .\sqrt{5}} \frac{\mu_0 . I . N}{R} + \frac{4}{5 .\sqrt{5}} \frac{\mu_0 . I . N}{R} \quad (13)$$

$$B_{total}(X_0) = \frac{8}{5 .\sqrt{5}} . \left(\frac{\mu_0 . I . N}{R}\right) \quad (14)$$

$$B_{total}(X_0) = \frac{8}{5 .\sqrt{5}} . \left(\frac{4.\pi .10^{-7} . I . N}{R}\right) \quad (15)$$

$$B_{total}(X_0) = 0.8991 \, . \, 4 . \pi \, . \, 10^{-7} . (\frac{I . N}{R}) \qquad (16)$$

If Equation 15 is arranged, the magnetic field calculation of the Helmholtz coil can be shown as in Equation 17 [5].

$$B = \frac{8}{5\sqrt{5}} \, x \, \frac{\mu_0 \, N \, I}{R} \qquad (17)$$

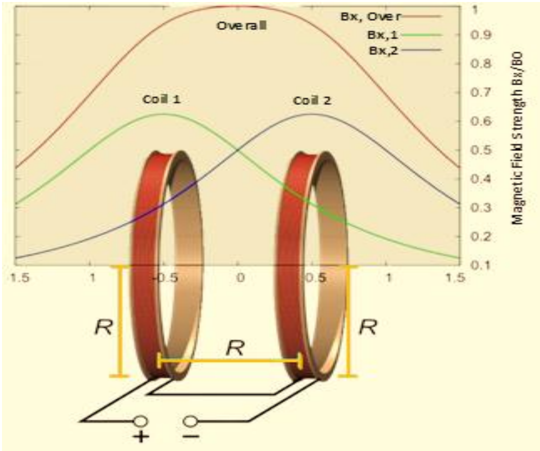

Figure 2. Helmholtz Coil [6]

Figure 2 shows the graphical variation of the Helmholtz coil.

Jankevica et al., in their study, produced a Helmholtz coil to produce a constant 50 Hz EMF. The radius of the Helmholtz coil was determined as 25 cm, the distance between the coils was 25 cm and the number of coil turns was determined as 189 turns. It was emphasized that this configuration provided a uniform magnetic field intensity at the center of the coil. It was stated that the produced magnetic field intensity was controlled by adjusting the electric current in the range of 0-725 μT. In their study, a moderately high EMF intensity of 518 μT was selected considering the current EMF intensity standards and possible health effects [7].

Maulana et al., used an EMF generator consisting of two Helmholtz coils with a diameter of 30 cm and 200 turns, placed coaxially at a distance of 15 cm, and a pulse generator. The accuracy of the magnetic field intensity generated by the Helmholtz coil was evaluated with a maximum magnetic field intensity of 2.0 mT and a repetition frequency of 15 Hz [8].

In the study conducted by Saqib et al., it was stated that the Helmholtz coil they produced had a radius of 14 cm. The structure was created using plywood material. The plywood was cut into the desired circular shape and glued. Wooden dowels and glue were used to fix the structure. The circular shaped coil has 97 splines in each ring. The coil is designed to withstand voltages up to 5 kV and temperatures of 45 ° C. The total length of the wire in each ring is 27.16 meters. The measured resistance of each coil is 1.4 ohm. In the study conducted, it was stated that the magnetic field value produced at a distance of 0.105 m from the coil center was 32 mT [9].

In their study, Sadiq et al. produced a Helmholtz coil to create the necessary magnetic field. The Helmholtz Coil consists of a 12.88 cm diameter and 550 turns of copper conductor placed on a horizontal coaxial. In Helmholtz coil experiments, it was emphasized that DC was applied in the range of 2-100 mA and as a result, a magnetic field was produced in the range of 0.4 -180 μT [10].

Alkis et al., In order to obtain very low frequency (ELF) EMF, they produced a device with two pairs of Helmholtz coils with a diameter of 30 cm and a distance between the coils of 15 cm. The EMF generator was made by winding 120 turns of 1.0 mm copper wire. The coils were placed horizontally, facing each other. In this way, the EMF was directed vertically and polarized linearly. 50 Hz alternating current generated by an AC power source was applied to the Helmholtz coils. It was stated that the EMF intensity was measured as 4 mT using a digital teslameter [11].

Nismayanti et al., in their study, aimed to obtain the correct magnetic field value by modeling the Helmholtz coil using Comsol Multiphysics. As a result of this research, it was stated that a device producing an EMF value of 1.5 mT was successfully designed when the number of turns is 150, the distance between two coils is 2.5 cm, the current value is 0.5 A and the coil diameter is 5 cm [12].

Jiang et al. proposed a new temporal wireless power transfer system based on Helmholtz coils. This study aims to reduce energy consumption and miniaturize wireless power transfer systems for implantable devices. Unlike traditional wireless power transfer systems, the transmitting coils were designed and manufactured using Helmholtz coils with a centroidal symmetric structure. A more uniform and stable magnetic field was obtained thanks to the structural improvements. In addition, the negative effects of the position changes of the receiving coil on the stability of the transmission power were also reduced [13].

In their work, Katiyar et al. designed and manufactured a Helmholtz coil consisting of a pair of coils, each with a diameter of 120 cm. Each coil, which contains 7 turns in a single layer, was positioned on the same axis with a distance of 59 cm. The coils were wound on a circular frame and supported by a wooden structure. It was emphasized that the produced Helmholtz coil produced EMF in the range of 1–30 μT according to different DA values [14].

In another study, they investigated the effects of 5 mT, 10 mT and 20 mT electromagnetic fields obtained with a Helmholtz coil on the germination percentage, pigment content and antioxidant capacity of sunflower and chickpea plants that were left for 20 minutes per day. As a result, they concluded that MF application has an effect on plant metabolism and has the potential to be used in agricultural applications [15].

Gencer et al. investigated the effects of pulsed electromagnetic field (PEMA) on blood glucose levels and weight gain. They used 23 Wistar Albino rats in the study. Groups of 8 rats were exposed to the magnetic field setup (1.5 mT- 50 Hz) created between Helmholtz coils with and without Cvit in a plexiglass (40 cm x 40 cm x 15 cm) cage for 4 hours every day between 08:00 and 12:00 for 28 days. As a result, they determined that PEMA application did not cause a significant change in blood glucose levels but made a significant difference in weight gain [16].

In this study, EMF generators were manufactured with Helmholtz coils and EMF changes were calculated according to different current values up to 2 mT. Experimental data were measured using the same values. The aim of this study is to determine the amount of error between calculation and experimental study. Many studies have been done with the Helmholtz coil in the literature. Some of these studies are given below.

2. MATERIAL AND METHOD

In this study, the experimental and computational results of the currents supplied to the EMF generator designed for different EMF generation between 1 mT and 2 mT operating in AC current are compared. Excel program was used for calculations.

Equation 18 was used for theoretical calculations.

$$B = \frac{8}{5\sqrt{5}}\ x\ \frac{\mu_0\, N\, I}{R} \quad (18)$$

$$I = \frac{B.5\sqrt{5}.R}{8.\mu_0.N} = \frac{0{,}01.5\sqrt{5}.0{,}15}{8.4.\pi 10^{-7}.16} = 10{,}4\ A \quad (19)$$

The calculation was repeated for other values.

When looking at the EMF formula; it is seen that the magnetic field depends only on the change of current since the number of turns (N), the electromagnetic permeability of the gap (μ0) and the radius of the coil (R) are constant in the experimental setup.

It is manufactured with helmholtz coils with circular geometry for EMF generator. The helmholtz coils are positioned on the vertical axis. The EMF value in the helmholtz coil manufactured is maximum 2 mT. 21 A current will be passed for this value. 2.2 mm conductor cross-section was selected for passing 21 A current. At 21 A, it was found to operate without heating. The radius of the Helmholtz coil was preferred as 15 cm. The number of turns of each coil was determined as 16 turns. The conductor weight used in the Helmholtz coil is 1000 g in total.

Here, the change between EMF and current value for the EMF generator is organized as a table. The variation of these values is graphed.

The drawings of the cabin where the Helmholtz coils will be placed were designed in the SolidWorks program.

The cabin where the Helmholtz coils will be placed basically consists of 2 different parts. These are the support and the table parts.

MDF material was used in the cabin construction to prevent the electromagnetic field from being affected. The MDF material used is 18 mm thick.

The dimensions of the support pieces are 60x150x18 mm. The appearance and technical drawing of the support piece are given in Figure 2.

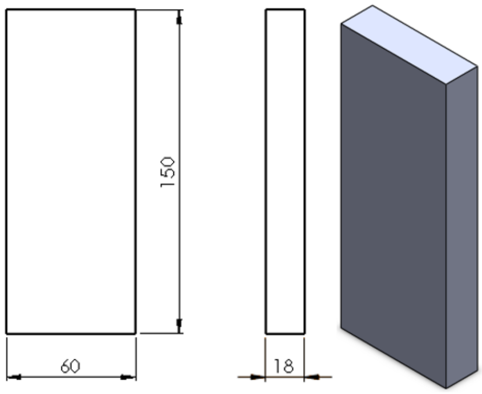

Figure 3. Technical drawing and solid model view of the support part

The dimensions of the table parts are 350x350x18 mm. The technical drawing of the table part is given in Figure 3.

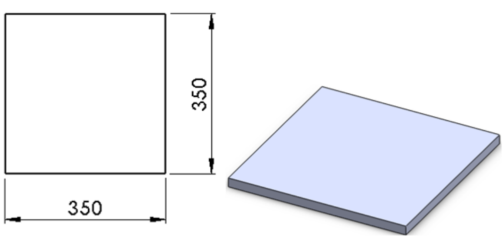

Figure 4. Technical drawing and solid model view of the table part

The assembly drawing of the created EMF cabin is given in Figure 5.

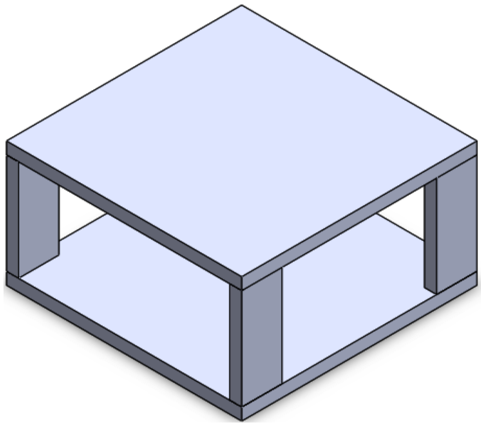

Figure 5. Solid model view of the assembly

The manufactured EMF generator is shown in Figure 6.

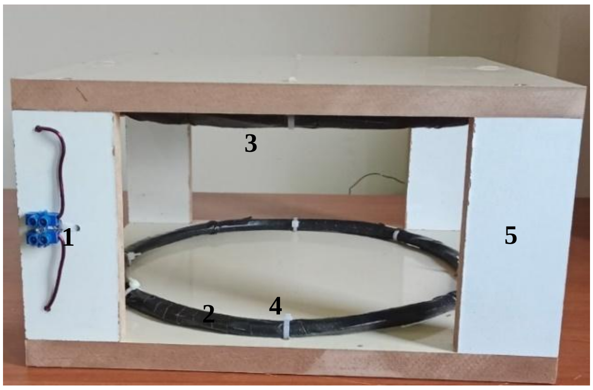

Figure 6. Manufactured EMF generator

The definitions of the numbers in the picture are given below.

1 : Power Input
2 : Helmholtz first coil
3 : Helmholtz second bobin
4 : Coil fixing clips
5 : EMF generator cabinet

3. RESULTS AND DISCUSSIONS

The results of the calculations obtained experimentally from the prepared system and for the same values are given in the table. At the same time, graphs were created with these values.

The values obtained by calculation are given in Table 1.

Table 1. Values found by calculation

Experiment Number	Current(A)	EMF(T)
1	10.4	0.001
2	11.5	0.0011
3	12.5	0.0012
4	13.6	0.0013
5	14.6	0.0014
6	15.6	0.0015
7	16.7	0.0016
8	17.7	0.0017
9	18.8	0.0018
10	19.8	0.0019
11	20.9	0.002

The graph of current and EMF values obtained as a result of the calculation is given in Figure 7.

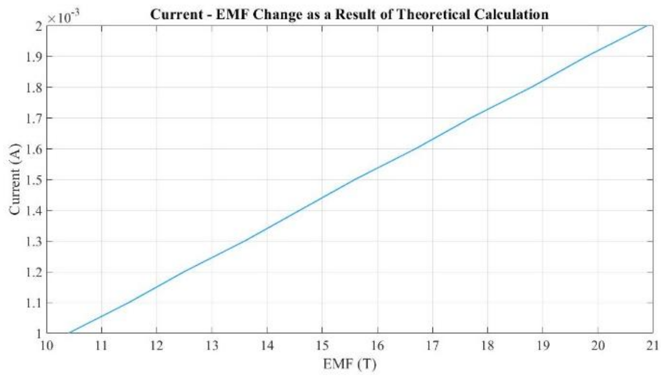

Figure 7. Current - EMF change as a result of calculation

It is seen in Figure 7 that there is a linear relationship between current and EMF depending on the formula.

It is seen in Figure 4 that the EMF value of the current increases. Therefore, there is a linear relationship between the current and the EMF.

In the experimental indications, it is seen that when the number of turns (N), the permeability in the cells (μ_0) and the radius of the coil (R) are constant, the infection with the EMF formula occurs correctly.

PCE-G28 EMF Tester was used in the experimental studies. PCE-G28 EMF Tester is given in Figure 8.

Figure 8. PCE-G28 EMF Tester

The values measured in the experimental study are given in Table 2.

Table 2. Values found by experimental measurement

Experiment Number	Current(A)	EMF(T)
1	9.8	0.001
2	10.8	0.0011
3	11.8	0.0012
4	12.8	0.0013
5	14.1	0.0014
6	15.4	0.0015
7	16.2	0.0016
8	17.5	0.0017
9	18.4	0.0018
10	19.7	0.0019
11	20.7	0.002

The graphs of current and EMF values obtained by experimental measurements are given in Figure 8.

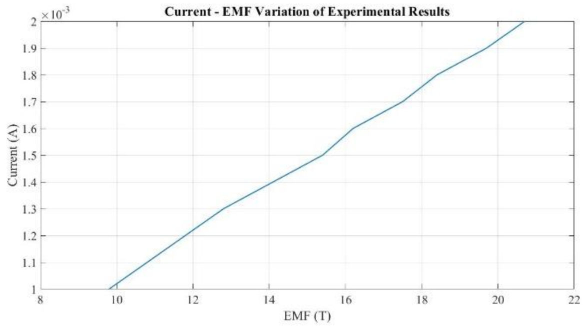

Figure 9. Current - EMF variation as a result of experimental measurements

In this study, the experimental and computational results of the currents supplied to the EMF generator designed for different EMF generation between 1 mT and 2 mT operating in AC current are compared.

The EMF current values obtained as a result of experimental and calculation results are compared and the difference between them is given in Table 3.

At the same time, the percentages of these differences according to the calculation results are calculated and given in Table 3.

Table 3. Comparison of current values of experimental and calculation results

Experiment Number	Experimental Results Current(A)	Experimental Results EMF(T)	Calculation Results Current(A)	Calculation Results EMF(T)	Amount of Error in Current(A)	Percentage of Error in Current(%)
1	9.8	0.001	10.4	0.001	0.6	5.77
2	10.8	0.0011	11.5	0.0011	0.7	6.09
3	11.8	0.0012	12.5	0.0012	0.7	5.6
4	12.8	0.0013	13.6	0.0013	0.8	5.88
5	14.1	0.0014	14.6	0.0014	0.5	3.42
6	15.4	0.0015	15.6	0.0015	0.2	1.28
7	16.2	0.0016	16.7	0.0016	0.5	2.99
8	17.5	0.0017	17.7	0.0017	0.2	1.13
9	18.4	0.0018	18.8	0.0018	0.4	2.13
10	19.7	0.0019	19.8	0.0019	0.1	0.51
11	20.7	0.002	20.9	0.002	0.2	0.96

The average of the error amounts in the current given in Table 3 is approximately 0.45 A, and the standard deviation of these values is calculated as 0.24. The average of the error percentages is approximately 3.25, and the standard deviation is 2.22.

When Table 3 is examined, it is seen that the amount of error in the current is high at low current amounts, while the amount of error in the current is low at high current amounts.

The graph comparing the EMF and current values obtained from experimental and computational results is given in Figure 9.

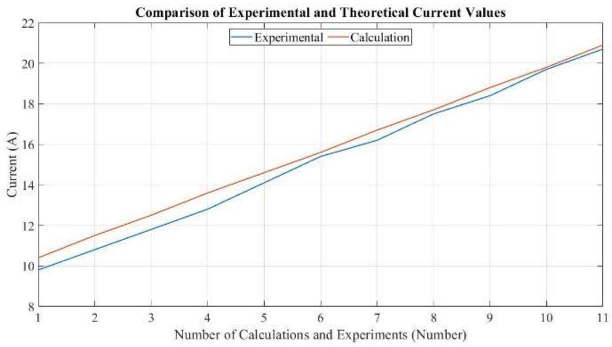

Figure 10. Comparison of theoretical and experimental data

The amount of error between the experimental results and the theoretically calculated values for the current supplied to the system was determined. These errors were found to be between 0.1 and 0.8 A. This amount of error is thought to be due to the factors affecting the measurement and the precision of the system manufacturing.

In terms of percentage, the amount of error varies between 0.51% and 6.09%. These values are acceptable for some applications.

4. DISCUSSION

A study reported that they produced an electromagnetic field generator using a Helmholtz coil with a diameter of 50 cm and a coil turn count of 189, at a fixed frequency of 50 Hz. The magnetic field strength control provided adjustment to the range of 0-725 microtesla by controlling the electric current [7].

In another way, an EMF generator resulting from two Helmholtz coils with a diameter of 200 turns and 30 cm placed coaxially and a generator pulse can be used together to obtain a maximum energy field density of 2 mT at a frequency of 15 Hz and multiplied [8].

In our study, we designed and built an EMF generator using a Helmholtz coil configuration operating at a fixed frequency of 50 Hz. Each coil has a radius of 15 cm, with a separation distance of 15 cm between the coils, and 16 turns per coil. By adjusting the electric current in the range of 10.4 to 20.9 A, we achieved a magnetic flux density ranging from 1 mT to 2 mT.

The amount of error is predicted to decrease with more precise manufacturing and as the factors affecting measurement are reduced.

Providing the current supplied to the system with a controller is also thought to contribute to the reduction of the margin of error.

While current control is provided by the controller, determining different types of controllers will also reveal another factor that will reduce the margin of error.

While providing current control with the controller, determining the controller parameters using different algorithms is thought to be another factor that will reduce the margin of error.

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