

# Simulation of leakage current measurement on medical devices using helmholtz coil configuration with different current flow

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**Abstract.** Leakage current measurement which can follow IEC standard for medical device is one of many challenges to be answered. The IEC 60601-1 has defined that the limit for a leakage current for Medical Device can be as low as 10  $\mu\text{A}$  and as high as 500  $\mu\text{A}$ , depending on which type of contact (applied part) connected to the patient. Most people are using ELCB (Earth-leakage circuit breaker) for safety purpose as this is the most common and available safety device in market. One type of ELCB devices is RCD (Residual Current Device) and this RCD type can measure the leakage current directly. This work will show the possibility on how Helmholtz Coil Configuration can be made to be like the RCD. The possibility is explored by comparing the magnetic field formula from each device, then it proceeds with a simulation using software EJS (Easy Java Simulation). The simulation will make sure the concept of magnetic field current cancellation follows the RCD concept. Finally, the possibility of increasing the measurement's sensitivity is also analyzed. The sensitivity is needed to see the possibility on reaching the minimum leakage current limit defined by IEC, 0.01mA.

## 1. Introduction

The increasing number of medical devices being used in hospitals creates several basic things to be concerned. One of them is dealing with the patient's safety. It is common to see the use of electricity for medical device's power supply, so electrical safety is a mandatory standard. One of its requirements is to measure the leakage current. It is to prevent things that endanger patient's life caused by electrical over current. It may also prevent any electrical shocks.

### 1.1. Leakage current standard

The IEC (International Electro-technical Commission) published IEC60601 document that consists of collection of technical standard for safety and efficiency for medical devices. One of the standards talks mainly about leakage current standard. According to IEC, leakage current's limit can be categorized depending on the type of applied part.

The Applied Part itself is defined as part of a medical device which has a physical contact with patient. Following the type of contact, Medical Device is categorized into three types:

- B Type: There is no electrical contact with patient,
- BF Type: There is a part connected to patient but not directly to the heart,



- CF Type: There is a part connected to the heart of patient.

Following these applied part categories (B/BF/CF), a medical device must limit its leakage current to leakage current standard. The limit according to IEC 60601-1 is shown at Table I, the leakage current limits [1]. It is shown that the minimum limit is at CF Type, for Patient Leakage Current at Normal Condition (NC), is 0.01mA or 10  $\mu$ A. The maximum limit is shown at most of categories. It is at 0.5mA or 500  $\mu$ A.

**Table 1.** Leakage Current.

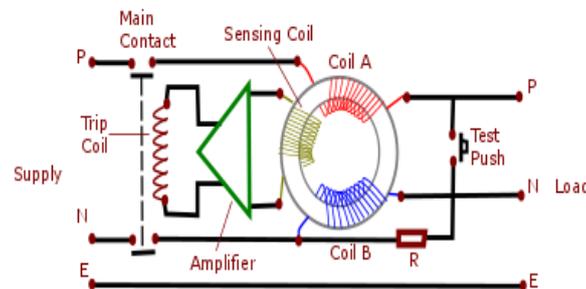
Leakage Current	<i>B-Type</i>		<i>BF-Type</i>		<i>CF-Type</i>	
	NC <sup>a</sup>	SFC <sup>b</sup>	NC <sup>a</sup>	SFC <sup>b</sup>	NC <sup>a</sup>	SFC <sup>b</sup>
<b>Earth</b>	0.5mA	1mA	0.5mA	1mA	0.5mA	1mA
<b>Enclosure</b>	0.1mA	0.5mA	0.1mA	0.5mA	0.1mA	0.5mA
<b>Patient</b>	0.1mA	0.5mA	0.1mA	0.5mA	0.01mA	0.05mA

<sup>a</sup>NC: Normal Condition.

<sup>b</sup>SFC: Single Fault Condition.

### 1.2. ELCB and RCD

ELCB (Earth-leakage circuit breaker) is a safety device which is used at electrical installation to prevent any electrical shocks. Later on, it is developed into the RCD (Residual Current Device). It improves the ELCB Voltage Based Measurement to become Current Operated Measurement. This current operated ELCB aka RCD is possible to measure leakage current directly. To understand its function and how it works, Typical RCD circuit [4] is shown at Fig. 1.



**Figure 1.** Typical RCD Circuit

The core are the toroid, two main coils (A and B), and one sensing coil. There is also circuit test to test the tripping mechanism. Lastly, there is tripping mechanism; a kind of relay, consisted of amplifier and trip coil.

Considering a possibility of leakage current, there are two paths on how the electrical current's flow through this RCD. They are:

- In normal condition the electrical current flow will be:  
Supply P (Phase)  $\rightarrow$  Toroid's Coil A  $\rightarrow$  Load P  $\rightarrow$  (Load)  $\rightarrow$  Load N  $\rightarrow$  Toroid's Coil B  $\rightarrow$  Supply N.
- When leakage current happens, the electrical current flow will be:  
Supply P (Phase)  $\rightarrow$  Toroid's Coil A  $\rightarrow$  Load P  $\rightarrow$  (Load)  $\rightarrow$  Load E (Earth)  $\rightarrow$  Supply E.

Leakage Current is returning to supply through the earth path. It is different with normal path which use Toroid's Coil B and goes back to Supply N. If it is assumed that current flows through Toroid's Coil A is  $I_1$  and the current flows through Toroid's Coil B is  $I_2$ , then the above case could be written as follow:

- In normal condition:

$$I_1 = I_2 \quad (1)$$

$$I_1 = I_2 + I_{leakage} \quad (2)$$

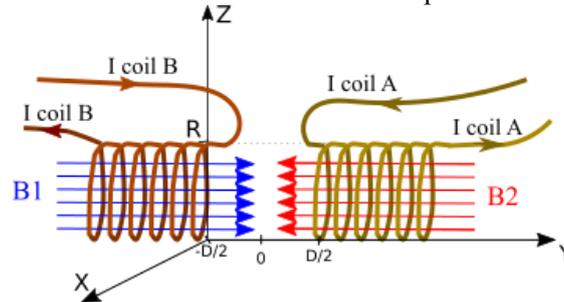
The measurement of leakage current is using the sensing coil by having induced e.m.f. During the leakage current case, ampere at Toroid's Coil A will exceed ampere at Toroid's Coil B. This leakage current will make alternating magnetic flux results in the toroid core. Then, this magnetic flux will be detected by the sensing coil, which is also wound at the toroid core.

Once there is enough induced e.m.f. (Electromagnetic Field), there will be a little current flow at sensing coil. This e.m.f. current will go through amplifier to drive trip relay coil. This is how the tripping mechanism happened. That is also how we can limit amount of leakage current before being cut off.

### 1.3. Helmholtz coil configuration with different current flow

Helmholtz Coil configuration is structured by two N-turn circular coils with radius R, each perpendicular to the y axis symmetrically, with a distance D. The original Helmholtz coil creates uniform magnetic field by having similar current flow direction on both circular coils. This will make similar magnetic field goes to the same direction. Its usage is well known for any experiments which may need to eliminate Earth Magnetic Field [2].

Here in this configuration, it has the same structure but different current flow. It is to differentiate magnetic field from those two circular coils. It is shown at Fig. 2, Helmholtz Coil with Different Current Flow. Looking at how the magnetic fields are against each other, it shows that it applies the same way like how the two main coils at toroid's RCD work. This concept can become the way to measure the leakage current after trying to explore more on theories of magnetic fields and later using simulation. There will be differences from Helmholtz Coil compared to RCD Toroid's Coil.



**Figure 2.** Helmholtz Coil with Different Current Flow

### 1.4. Helmholtz coil configuration with different current flow

Both devices, RCD and Helmholtz Coil with different current flow have main similarity on the use of magnetic field from two coils. That is why it is necessary to focus on this magnetic field measurement.

Thus, this work tries to explore more about the magnetic field and to make a model of that magnetic field. First is by using known formulas and then with making the simulation. Then it extracts the possible sensitivity measurement from the simulation.

## 2. Comparison between RCD and helmholtz coil with different current flow

The difference between existing RCD and the Helmholtz Coil Configuration is the medium for its coils or magnetic permeability. RCD is using toroid shape medium and most of used medium is a ferrite core. While Helmholtz Coil is simply free space of air. This difference has effect on the magnetic field's value and the equations.

2.1. Ampere law

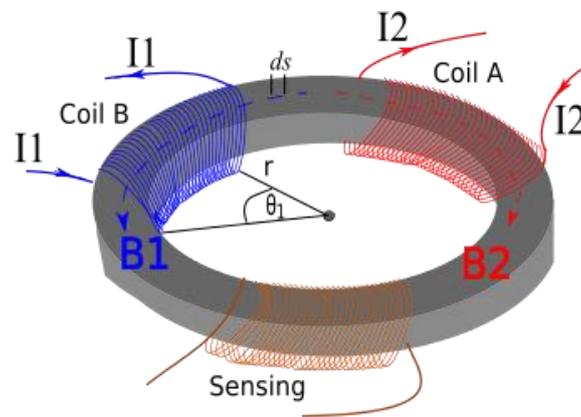


Figure 3. RCD Toroid’s magnetic field

It is necessary to have a review of the basic formula. A magnetic field formula for a symmetrical current source is best calculated using Ampere’s Law compared with Biot-Savart Law. The generalization Ampere’s Law for an enclosed loop (enc) is written as:

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{enc} \tag{3}$$

Note: to use this formula, the system must have certain symmetry [3]. For RCD, this shape requirement is shown by solenoid wounded at toroid as part of circle.

2.2. RCD current equations

RCD is designed to get the magnetic field from the incoming current (I1) and subtract it with outgoing current flow (I2). Using the Ampere’s Law for one of RCD’s coil, the magnetic field (B1) can be calculated as follow:

$$\oint \vec{B} \cdot d\vec{s} = B_1 \int_{\theta_1} ds = B_1 \theta_1 r = \mu_r I_{enc} = \mu_r N_1 I_1 \tag{4}$$

$$B_1 = \frac{\mu_r N_1 I_1}{\theta_1 r} \tag{5}$$

The magnetic field’s value depends on the toroid’s medium  $\mu_r$ , number of turns from coil B, enclosed part of circle  $ds_1$  in terms of  $\theta_1$  radian, and also the radius  $r$  as distance from center of the circle. First by assumption, there is no missing of magnetic field from the medium. Then, by having the same number of turns on Coil A and Coil B,  $N_1 = N_2 = N$ ,  $\theta_1 = \theta_2 = \theta$ , and also using (2), total magnetic field’s difference becomes:

$$\Delta B = B_1 - B_2 \cong \frac{\mu_r N}{\theta \cdot r} (I_1 - I_2) = \frac{\mu_r N}{\theta \cdot r} I_{leakage} \tag{6}$$

2.3. Biotsavart law

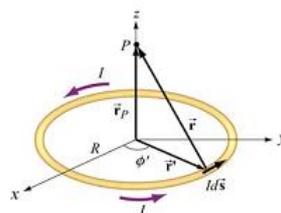


Figure 4. Point P at a distance |z| from Solenoid Coil [3]

For the Helmholtz coil configuration, the equation should be calculated using Biot-Savart Law by considering that the center point is outside the solenoid at a distance from the solenoid's coil. The Biot-Savart law expressed dB from a current source  $I_{ds}$ , as:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{s} \times \hat{r}}{r^2} \quad (7)$$

$\mu_0$  is the permeability of free space,  $4\pi \cdot 10^{-7}$  (T.m/A). Looking at Fig. 4, components from (7) can be elaborated by considering the vector of r, as follow [3]:

$$\hat{r} = \frac{\vec{r}}{r} \quad (8)$$

$$r = |\vec{r}| = \sqrt{R^2 + z^2} \quad (9)$$

$$d\vec{s} \times \vec{r} = Rd\phi' [z \cos \phi' \hat{i} + z \sin \phi' \hat{j} + R\hat{k}] \quad (10)$$

Then (7) can be rewritten as:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{s} \times \vec{r}}{r^3} = \frac{\mu_0 IR}{4\pi} \frac{z \cos \phi' \hat{i} + z \sin \phi' \hat{j} + R\hat{k}}{(R^2 + z^2)^{3/2}} \quad (11)$$

To get amount of magnetic field B, this discrete magnetic field can be Integral. The value of component at axis vector; i and j will be zero. It is as a result of integral of sin and cos function respectively. Thus total B value becomes [3]:

$$B(z) = \frac{\mu_0}{4\pi} \frac{IR^2 (2\pi)}{(R^2 + z^2)^{3/2}} = \frac{\mu_0 IR^2}{2(R^2 + z^2)^{3/2}} \quad (12)$$

#### 2.4. Helmholtz coil with different current flow equation

The purpose of using this Helmholtz coil configuration is copying the previous RCD mechanism. It is to get the difference of magnetic field value from B1 and B2. As seen from Fig. 2, the direction of the two values is against each other on the same axis, axis y. Thus the equations, one can apply superposition on (12) and multiply it with number of coil's turn  $N_A$  and  $N_B$ , as follow:

$$\Delta B = B1 - B2 = \frac{\mu_0 R^2}{2} \left[ \frac{N_B I_{CoilB}}{[(y - D/2)^2 + R^2]^{3/2}} - \frac{N_A I_{CoilA}}{[(y + D/2)^2 + R^2]^{3/2}} \right] \quad (13)$$

This equation shows that the magnetic field's value depends on its coil's radius (R), distance between the two coils (D), the coil's number of turns ( $N_A$  and  $N_B$ ), and the current value on each coil ( $I_{CoilA}$  and  $I_{CoilB}$ ).

To simplify the equation, the calculation can focus only in the middle of those two coils. This can be calculated by setting the position of the middle point on  $y=0$ . Thus both coils will have a distance equals to  $D/2$  from the middle point, assuming the number of both solenoid coils is the same,  $N_A=N_B=N$ . The (13) becomes (14).

$$\Delta B = \frac{\mu_0 NR^2}{2} \left[ \frac{I_{CoilB}}{[(D^2/4) + R^2]^{3/2}} - \frac{I_{CoilA}}{[(D^2/4) + R^2]^{3/2}} \right] \quad (14)$$

Then, if it follows the default Helmholtz Configuration, the setting is also having  $D=R$ . That will make (14) as simpler, as follow:

$$\Delta B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 N (I_{CoilB} - I_{CoilA})}{2R} \quad (15)$$

This  $\Delta B$  value is shown at the middle of Fig. 5, the magnetic field simulation with a text  $B=1.05E-24$ . Finally, it is possible to get the relation between magnetic field and  $I_{\text{leakage}}$ . It is by applying (2) into (15) for the leakage current,  $I_{\text{leakage}}$ , which is shown at (16).

$$\Delta B \cong \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 N I_{\text{leakage}}}{2R} \quad (16)$$

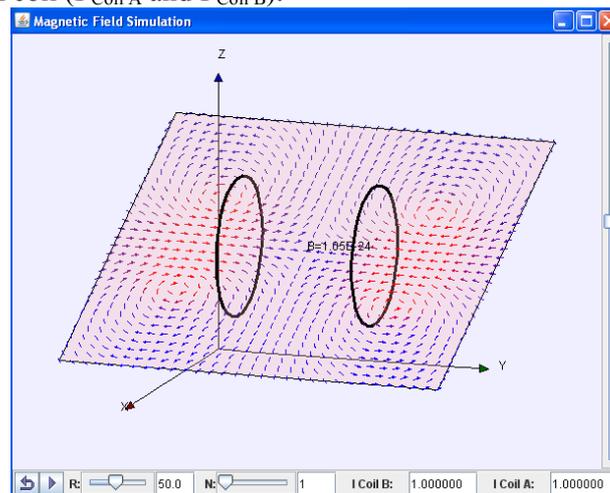
### 3. Simulation and sensitivity

Fig. 5 is made using EJS (Easy Java Simulation). Many things are also simulated using this software. Some of the examples are common tools like vernier caliper and micrometer [5]. It shows how the magnetic field will behave. It also helps us to draw the equation.

#### 3.1. Simulation

*Easy Java Simulation* or EJS is an *open source* software. It is designed to author and model science which allows user to create Java programs with minimal programming [2]. By using this tool, it is easier for us to simulate the equations. It also helps us to confirm our possible core on designing how the leakage current measurement on medical devices will be.

The designed program has four possible inputs. It is shown at Fig. 5. The inputs are the possible components which are described at (15). They are the coil's radius ( $R$ ), coil's number of turns ( $N$ ), and the current value on each coil ( $I_{\text{Coil A}}$  and  $I_{\text{Coil B}}$ ).

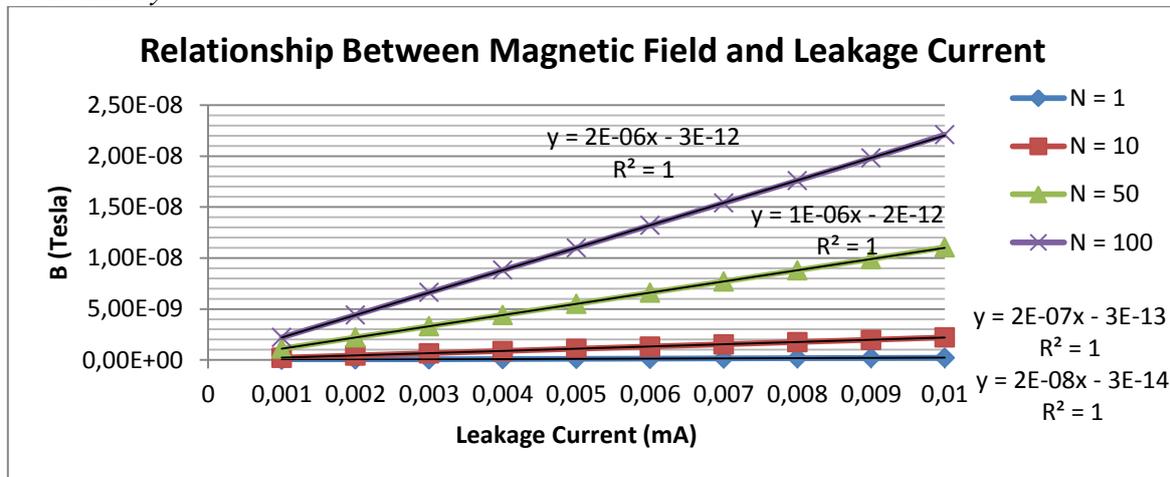


**Figure 5.** Magnetic Field Simulation

Figure 5 shows the magnetic field condition for a configuration of Helmholtz Coil with  $R=50$ ,  $N=1$ , and there is no leakage current. It is seen from the value of  $I_{\text{Coil A}}$  and  $I_{\text{Coil B}}$ . They have the same value of 1.000000 A. At this condition, the magnetic field value at middle point is  $1.05 \times 10^{-24}$ . This value shows that there is very little flux at that position. It is almost zero. This value is not zero because the calculation step on this program is using numerical method.

The program's logic is not directly using (15). It is because each coil is an individual magnetic field source and simulated as it is. That is why the calculation of the middle point's magnetic field is actually subtraction of each individual coil's magnetic field.

### 3.2. Sensitivity



**Figure 6.** Magnetic Field vs. Leakage Current

From the simulation software, it is possible for us to draw the relation between the magnetic field's value at middle of two coils,  $\Delta B$ , versus the leakage current,  $I_{\text{leakage}}$ . It is shown at Fig. 6, Magnetic field vs. leakage current.

Fig. 6 also shows possible different magnetic field value by increasing the coil's number of turns,  $N$ . It is shown at the figure as  $N=1, 10, 50$ , and  $100$ , as examples. The lines at the figure are also showing the sensitivity of the configuration. The sensitivity is the gradient value of each line. They are  $\approx 2 \times 10^{-8}$ ,  $2 \times 10^{-7}$ ,  $1 \times 10^{-6}$ , and  $2 \times 10^{-6}$  following the number of turns,  $N$  respectively. It shows that the magnetic field value is linear to coil's number of turns.

### 4. Conclusions

This work has shown the possibility of using Helmholtz coil configuration with different current flow as another form of RCD. From the explanation of this paper, some points can be listed:

- The RCD's Formula expressed at (6), and the Helmholtz Coil with Different Current Flow's Formula expressed at (16) shows similar relation between the leakage current and the resulted magnetic field with different value of  $k$  as in,
- The EJS software can be used to show the magnetic field of Helmholtz Coil with Different Current Flow. Its simulation shows how the magnetic fields from two coils are canceling each other.
- Either using resulted formula, or EJS software, it is possible to get the possible sensitivity of the magnetic field against the leakage current. That sensitivity is linear to coil's number of turns.

The future work will be investigating the sensing coil as shown at Fig. 3 RCD Toroid's Magnetic Field.

### Acknowledgment

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### References

- [1] IEC 60601-1. 1995. *Medical Electrical Equipment-Part 1: General Requirements for Safety and Essential Performance*. (Geneva: International Electrotechnical Commission)
- [2] Hwang F K, Wolfgang C, and Robert M 2014 OSP ComPADRE collection June. *Helmholtz Coils*. <http://www.compadre.org/osp/items/detail.cfm?ID=8983>
- [3] Lewin W and John B 2007 *Physics II Electricity and Magnetism* MIT Open Course Ware,

- Spring. <http://ocw.mit.edu/courses/physics/8-02-physics-ii-electricity-and-magnetism-spring-2007/index.htm>
- [4] Withfield J 2008 *The Electricians Guide Book*. EPA Press. 16th ed, <https://www.tlc-direct.co.uk/Book/5.9.2.htm>
- [5] Wee L K, Ning H 2015 Vernier caliper and micrometer computer models using Easy Java Simulation and its pedagogical design features--ideas for augmenting learning with real instruments. *Phys. Educ.* **49** issue 5
- [6] John B 2007 *A Practical guide to IEC 60601-1*. (United Kingdom: Rigel Medical). <http://www.rigelmedical.com/downloads/Rigel-Medical-A-Practical-guide-to-IEC-60601-1.pdf>