Comparative Assessment of Maxwell and Helmholtz Coils Magnetic Field for Biotechnological Applications

B. Mihailescu, I. Plotog
Center of Technological Electronics and Interconnection Techniques, Politehnica University of Bucharest
Bucharest, Romania
bogdan.mihailescu@cetti.ro

M. N. Velcea
Horticulture Faculty
USAMV
Bucharest, Romania

Abstract—The studies regarding magnetic field (MF) biotechnological applications in the range of Extremely Low Frequency (ELF: 3Hz to 300Hz, ITU Recommendation V.431-7) were generally based on Helmholtz coils (HC) systems in order to obtain a constant intensity for a determined volume. The paper presents the comparative studies of HC and Maxwell coils (MC) consisting in modelling, simulations and measurements of MF intensity. For this the geometry of the external coils of the MC system was designed identically with HC type. Based on the obtained results, there are defined the internal field intensity distribution for both coils systems used to design biotechnological applications.

Keywords—Maxwell coils, Helmholtz coils, ELF magnetic field.

1. INTRODUCTION

Life on Earth has evolved under natural and, more recently under artificial electromagnetic fields. From this point of view, the geomagnetic field (GMF), a static magnetic field (MF) type with values depending on the geographical position on Earth surface, is the most important natural electromagnetic field influence.

In the range of Extremely Low Frequency (ELF) defined according to the International Telecommunication Union (ITU) Recommendation V.431-7 the nomenclature of the frequencies and wavelength bands used in telecommunications specifies the range between 3Hz to 300Hz; under Very Low Frequency (VLF) band [1], another natural influence factor, more subtly, is the variable electromagnetic field characterized by the quasi standing waves type result of electromagnetic phenomena consequence of lightning storms occurring at any moment in the resonant cavity formed between conductive surfaces of the Earth and the ionosphere. This phenomenon, Schumann resonance (SRW), was predicted in 1952 [2]. The first measurements results were published in 1954 [3] and the subsequent experiments [4] find a fundamental value 7.83 Hz and harmonics 14, 20, 26, 33, 39 and 45 Hz. Variations of these values appear being determined by the solar cyclic activity, latitude and other phenomena that could affect the properties of Earth's electromagnetic cavity.

Some experiments, including spatial ones, demonstrate the life on earth it is in strong connection to the Schumann resonance. For example: in the absence of ELF electric and magnetic fields appear a total desynchronization of the human body clock to the outside world and introducing an artificial electric field at around 10Hz resynchronized the circadian rhythms [5, 6, 7].

The artificial electromagnetic fields having important influence in the life on Earth as consequence of their high values of intensity are result of human activity. In the ELF range they are generated by the communications networks and the most important coming from transport networks (high voltage) and the public network (low voltage) of electricity at 50 Hz in Europe, respectively 60Hz in USA. World Health Organization (1984) realizes a comprehensive study regarding environmental health criteria for ELF electromagnetic fields taking into consideration the influences of the both components, electric and magnetic, generated by electricity main network in different type of locations like hospital, factories, homes and nature, respectively biological influences aspects [8].

In order to study the influence of the MF in the ELF range over the human and plant physiology with double targets, on one side the protection aspects and on other the positive influence, there is a necessity of good references regarding the MF intensity and devices for generating under control electromagnetic fields.

The local GMF value is used as reference for defining the values of the magnetic field identified in the experiments. The following reference values relating to local MF intensity were defined [9]:

- super weak field (conditionally zero or magnetic vacuum) defines the MF having intensity under 100 nT;
- weak (low) MF is defined in the range from 100 nT to 0.5 mT but considering the GMF local value, the weak MF will be maximum ten time more this value;
- higher MF intensity relating to GMF is defined in the range from 0.5 mT to 1ST.

For Bucharest at geographical coordinates 44° 25’ 50” Latitude Nord and 26° 7’ 23” longitude East, the total local geomagnetic field value is 48.304µT (table 1), calculated using...
The most used coils systems for generating MF with specific intensity and frequency are Helmholtz type.

One example is the study of MF as influence factor with large implications on seeds germination [11], rooting [12], and growth of plants [13]. Important studies regarding biochemical changes induced by MF in the range of ELF exposure of vegetal organisms were done in Romania [14]. All these experiments emphasize the necessity of a dedicated MF generator (MFG) with capability to provide the imposed intensity and frequency with precision and stability in the ELF range. The MF intensity determined by the coils current parameters will be necessary to cover the range relating to local MF intensity [9].

The MF field uniformity for a determined volume is very important for the plant biotechnology experiments and biochemical consequences studies. This condition could be accomplished by the type of magnetic coils system used. For MF induction values measurements was used Globisens Labdisc Physio system.

**A. Magnetic Coils System Design**

For the problem of obtaining MF field uniformity for a determined volume many solutions were proposed beginning with Helmholtz coils system (1849) which becomes a classical solution and reference for numerous improvements devised in attempts to produce larger volume with increasing MF uniformity. Systems with increasing number of coils and different geometry were proposed, one of solution being the Maxwell coils with three coils, part of virtual sphere. Helmholtz coils (Fig. 1a) are two identical circular coils, L1 and L2, with radius RH distance, part of a virtual sphere of radius RSH symmetrically positioned at RH relative to center:

\[
R_H = \sqrt{\frac{4}{5}} R_{SH}
\]  

(1)

The Helmholtz coils are activated in phase (Fig. 1b) being series connected and current IH flows in the same direction [16, 17, 18, 19]. In the central point of Helmholtz coils system, with assumption of negligible coils thickness compared to their radius RH, the MF induction value, B_H: is:

\[
B_{H0} = \left(\frac{3}{2}\right) \mu_0 N I_H / R_H
\]

(2)

Where \( \mu_0 = 4\pi \times 10^{-7} \text{Tm/A} = 1.257 \times 10^{-6} \text{Tm/A} \), N = number of turns, and I_H = coils current (A).

For the experiments the Maxwell coils system was designed considering identical L1 (radius R1) and L2 (radius R2) corresponding to Helmholtz coils. The central coil L3 radius, RMS, is equal to virtual sphere radius, RSM. Relating to the Helmholtz coils geometry and referring to notations used in Fig. 1, 2, the Maxwell coils geometry is defined by relations:

\[
R_V = R_S = R_M = \frac{\sqrt{4/7}}{R_H} R_M
\]

(3)

\[
D_M = \frac{\sqrt{3}}{7} R_M
\]

(4)

\[
R_M = \sqrt{4/7} R_H
\]

(5)

The ampere-turns product, NI, is the same for L1 and L2 coils, but unlike Helmholtz type, for Maxwell coils the middle coils L3 is defined as:

\[
(NI)_{L1, L2} = 49/64 (NI)_{L3}
\]

(6)

According to relation (6), if it has kept the same value as Helmholtz coils value for current flow by L3 coils will be necessary to increase for this coil the number of turns:

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If it has kept the number of turns, it is necessary to increase the value for current flow by L3 coils:

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(I)_{L3} = 64/49 (I)_{L1, L2}
\]

(8)

The experimental Helmholtz and Maxwell coils structures were realized considering RH = 100mm, based on geometry definition formulas (1) to (5). The turns number of L3 coil was calculated using (7) formula, where N = 1000 is L1 and L2 turns number.

The constructive data is:

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<thead>
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<th>Horizontal Intensity [nT]</th>
<th>North Comp (+ N - S) [nT]</th>
<th>East Comp (+ E - W) [nT]</th>
<th>Vertical Comp (+ D - U) [nT]</th>
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**II. EXPERIMENTS DESIGN**

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</tr>
</tbody>
</table>
\[ R_1 = R_2 = R_4 = 100\text{mm} \quad (9) \]
\[ R_M = 132.3\text{mm} \quad (10) \]
\[ D_M = 86.6\text{mm} \quad (11) \]

B. Magnetic Field Generator

In order to assure the coils variable current with imposed intensity and frequency value was, designed, realized and used for experiment a dedicate MF generator (Fig. 3) as an application of 180 MHz Direct Digital Synthesis (DDS) synthesizers [21]. The DDS AD9581 type was used to realize sine wave signal generator with digital control of the output signal’s frequency and level under control of PIC18F4580 microcontroller. The frequency of the reference clock signal also determines the frequency resolution of the system [23, 24]. The coils current is obtained by conversion tension-current.

III. EXPERIMENTS RESULTS AND DISCUSSIONS

The model’s geometry and simulation was performed in Ansys Maxwell software environment. The simulation was performed for a frequency of 10Hz and 100 mA for the Helmholtz configuration. For the Maxwell configuration, the frequency remained at the same value, however the current for the middle coil, L3, larger in diameter (Fig. 2), was 130.6 mA according with the relation (8). To properly model the magnetic flux density B generated by the Helmholtz and Maxwell coils configuration, an appropriate current return path is included in the simulation. The resulting geometry is presented in Fig. 4 and Fig. 5.

The MF induction values of the HC and MC coils structures were measured at 10 Hz on the diametrical plan where they were defined measuring points starting from center to the coils internal edge with one centimeter step. The comparative measurements were done for currents from 100mA to 400mA presented in Table 1. The graphical representation of the measurements results confirm the simulation results, emphasizing a larger zone with better uniformity and higher intensity of MF generated by Maxwell coils compare to Helmholtz type with same coils geometry.

### Table II. Maxwell (MC) and Helmholtz (HC) Coils System Magnetic Field Intensity Comparative Measurements at 10Hz Frequency Value Function of Coils Current.

<table>
<thead>
<tr>
<th>No.</th>
<th>(I) [mA]</th>
<th>Type</th>
<th>(D) [cm]</th>
<th>(BM) [mT]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>MC</td>
<td>1.16</td>
<td>1.16</td>
<td>1.15</td>
<td>1.15</td>
<td>1.14</td>
<td>1.11</td>
<td>1.1</td>
<td>1.09</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>MC</td>
<td>2.23</td>
<td>2.23</td>
<td>2.21</td>
<td>2.2</td>
<td>2.19</td>
<td>2.16</td>
<td>2.12</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>MC</td>
<td>3.33</td>
<td>3.32</td>
<td>3.31</td>
<td>3.29</td>
<td>3.26</td>
<td>3.21</td>
<td>3.18</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>MC</td>
<td>4.44</td>
<td>4.43</td>
<td>4.41</td>
<td>4.38</td>
<td>4.34</td>
<td>4.27</td>
<td>4.22</td>
<td>4.17</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>HC</td>
<td>2.76</td>
<td>2.76</td>
<td>2.8</td>
<td>2.79</td>
<td>2.74</td>
<td>2.61</td>
<td>2.61</td>
<td>2.41</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>600</td>
<td>HC</td>
<td>3.68</td>
<td>3.7</td>
<td>3.71</td>
<td>3.7</td>
<td>3.64</td>
<td>3.48</td>
<td>3.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Magnetic field generator block diagram.

Fig. 4. Helmholtz coils magnetic field.

Fig. 5. Maxwell coils magnetic field.

Fig. 6. Maxwell and Helmholtz comparative induction values function of coils geometry.
IV. CONCLUSIONS

The paper presents a comparative analysis between Helmholtz and Maxwell coils as a response of necessity to increase the volume of uniform MF in the ELF range as support of seeds germination, rooting and growth of plants experiments, including the studies regarding biochemical changes induced as consequence of exposure of vegetal, animal and human organisms.

The results of HC (Fig. 4) and MC (Fig. 5) MF modelling and simulation done at 10Hz frequency and comparative induction value function of coils geometry graphically presented (Fig. 6) were confirmed by the experimental coils systems measurements for different current values at the same 10 Hz frequency graphically presented in Fig. 7., considering the distances (D) relating to the coils system midpoint (Table 1) and demonstrate the increasing MF constant volume of MC compare to HC.

The Maxwell coils magnetic system, although not usually used for biotechnological applications, looks to be a solution for generating uniform magnetic field system.

ACKNOWLEDGMENT

This paper was published under the frames of European Social Found, Human Resources Development Operational Program 2007-2013, project no. POSDRU/159/1.5/S/132765 and the “Partnerships in priority areas” (PN II) Romanian research program developed and supported by MEN-UEFISCDI, SIOPTEF project no. 121/2012, PN-II-PT-PCCA-2011-3.2-899 and partially by the BLCPL project, PN-II-PT-PCCA-2013-4-1546, no. 58/2014.

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