Original Article

An Adjustable Extremely Low Frequency Electromagnetic Field Generator

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A B S T R A C T

Purpose- The risk effect of long-term occupational exposure to extremely low-frequency electromagnetic fields (ELF-EMFs) has been studied extensively. However, due to several experimental issues such as exposure measurement error and the lack of standard ELF-EMFs exposing devices, the obtained results are controversial. The inconsistent reported results preclude clear conclusions on the evidence of an association between EMF exposure and the disorders reported. To assist with resolving these issues, a digital–low cost ELF-EMFs generator to produce EMFs with desired magnitude and frequency is proposed.

Methods- A sinusoidal waveform with adjustable amplitude and frequency controlled by a microprocessor is generated and then is applied to a coil with a U-shape core. To increase the accuracy of the instrument, three coils with 250 turns; 500 turns; and 1200 turns were designed and used in the instrument. The amplitude and frequency of the voltage delivered to each of these coil are controlled by turning off and on TRIAC transistors controlled by a microprocessor–based system.

Results- The designed instrument provided EMF with magnitude of 0.55 mTesla to 1.56 mTesla with error rate < 5.9% and frequency of 10 Hz to 50 Hz with error rate <1%. The provided EMF was sufficiently homogeneous over a given volume and was stable over time.

Conclusion- The quantitative and qualitative experimental results showed that the designed instrument is reliable and accurate to be used in research laboratories for further investigation of the health effect of long-term occupational exposure to ELF-EMFs.

1. Introduction

An electromagnetic field (EMF) is the area of energy generated by an electrically charged object. The EMF that surrounds an electrical device is in fact the mutual interaction of an electric field generated by stationary charges and a magnetic field produced by moving charges of the device. Power lines, electrical wiring, and appliances are examples of the electrical devices that produce EMF.

Several studies have been conducted to investigate the health effects of exposure to EMFs [1-4]. Most of these investigations showed that long-term occupational exposure to extremely low-frequency electromagnetic fields (ELF-EMFs) increases the risk of several diseases such as amyotrophic lateral sclerosis (ALS), Alzheimer disease, cancer,

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and the risk of arrhythmia-related heart disease. Zhou *et al* [5], showed that there is a significant relationship between exposure to ELF-EMFs and the risk of ALS. Several other epidemiological studies have also revealed the evidence of an association between occupational exposure to power frequency electromagnetic fields and ALS. A comprehensive review of these studies is provided in [6]. García *et al* [7] found that there is a correlation between occupational exposure to ELF-EMFs and Alzheimer disease. Hug *et al* [8] showed the existence of a relation between occupational magnetic field exposure and the risk of dementia. The correlation between the risk of cancer and exposure to EMFs generated mainly by high-voltage power lines are investigated and reported in [9-16].

Few studies also suggest that electric and magnetic field exposure may increase the risk of cardiovascular disorders [17-19]. A possible association between occupational magnetic fields and arrhythmia-related heart disease are reported in [19]. Exposure to power-frequency electric and magnetic fields was found to alter mean heart rate and to reversibly reduce the normal variability of the heart rate.

Although the aforementioned studies showed the risk effect of long-term occupational exposure to ELF-EMFs, the exact health effects of ELF-EMFs is still controversial. Inconsistent results reported on the evidence of an association between EMF exposure and the aforementioned disorders preclude clear conclusions. Exposure measurement error and the lack of standard ELF-EMFs exposing devices are two reasons for these inconsistent results.

In this paper, details of designing and fabricating a suitable and reliable ELF-EMF generator are presented. Using the provided instrument the magnitude of the produced ELF-EMF can be varied from 0.55 milliTesla (mT) to 1.56 mTesla. The frequency of the produced EMF can also be adjusted from 10 Hz to 50 Hz. Such an accurate instrument can be used to precisely investigate the health effect of ELF-EMF.

2. Method

Fundamentally, EMFs are made up of electric fields and magnetic fields in which electric fields are generated by electric charges and magnetic fields are produced by the flow of electrical current through wires or electrical devices. EMFs can be described mathematically using Maxwell's equations as [20]

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \qquad (1)$$

Where E is the electrical field, B is the magnetic field, μ_0 is the magnetic constant, J is the current per unit area, ε_0 is the electric constant.

Practically, EMFs are produced when a current flows through a solenoid. The magnitude field inside a solenoid with Nturns (loops) and the length of L is given by [20]

$$B = \mu \frac{NI}{L} \qquad (2)$$

where μ is the magnetic constant and I is the current flowing through the coil. As shown by this equation, the magnetic field and ultimately the EMF produced by a coil can be controlled by altering the current passing through the coil. In this work, this is implemented by controlling the power delivered to the coil. In fact the main objective here was to design an electronic circuit that based on a requested value for the magnitude of EMF automatically adjusts the power delivered to a solenoid for producing the desired EMF. The block diagram of the designed ELF-EMF generator is shown in Figure 1. Details of each block are given below.

1- Processor and Command Unit (PCU) gets the desired frequency and magnitude of the requested ELF-EMF from the keyboard and then sends appropriate commands to TRIAC switch unit to generate suitable waveform. In addition, this unit processes the feedbacks received from the voltage measurement unit and tunes the output more accurately.

2- Voltage Measurement Unit Measures the input voltage and the circuit output voltage and sends them to the PCU to find the zero crosses (half cycle beginnings) of the input voltage and tune the output.
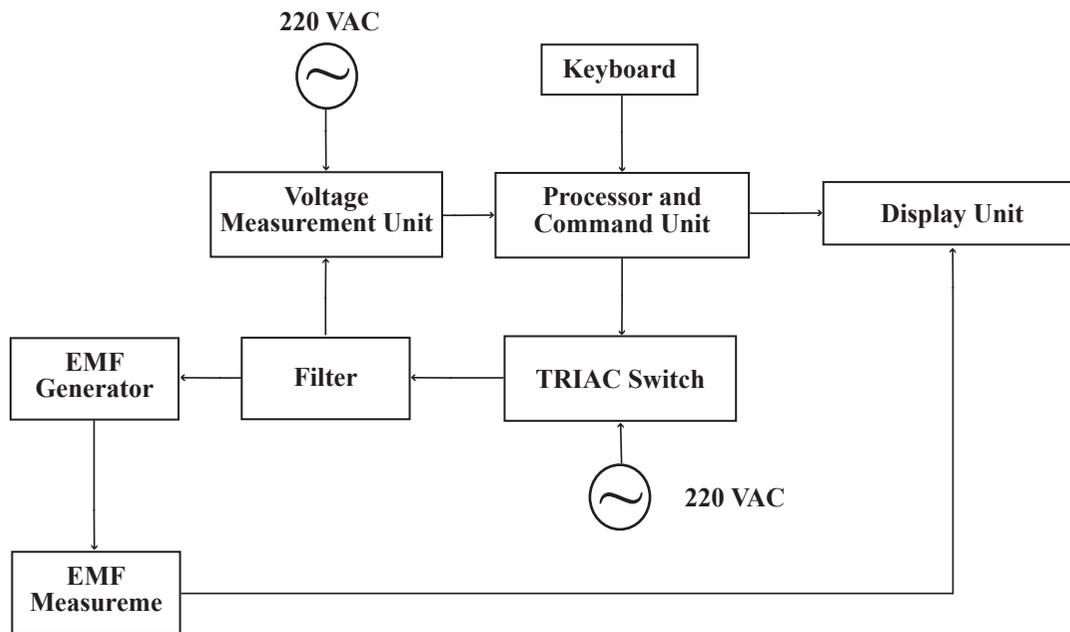
220 VAC

Figure 1. The block diagram of the designed ELF-EMF generator.

3- TRIAC Switch Unit (TSU) turns on and off the 220VAC input voltage to generate a waveform with desired amplitude and frequency. To adjust and control the magnitude of the generated EMF, a closed-loop system is employed here. The system, in fact, measures the current flowing through the coil and then sends the measured value to the PCU. The control system, to control the current of the coil, then adjusts the RMS value of the voltage across the coil by turning on and off the 220VAC input voltage. TRIAC transistors are used to switch the voltage. The TRIAC is directly driven by the PCU, which sends a pulse to the TRIAC for each firing. The output waveform, and therefore the amplitude and frequency of the generated waveform, are controlled by the phase delay of the TRIAC drive. The delay, here, is referred to the zero crossing of the input voltage (220VAC) which is detected by the PCU. Using 50 Hz-220VAC input, the frequency of output waveform can be $50/M$ Hz where M is a positive nonzero integer number; $M \in \{1,2,3,\ldots\}$. In other words, the frequency of the output waveform can be 50 Hz, 25 Hz, 16.75 Hz, 12.5 Hz, and 10 Hz. In the first M cycles the TRIAC is turned on at the positive half cycles of the input voltage and in the next M cycles the

TRIAC is turned on at the negative half cycles and so on. Two output waveforms of the TSU are shown in Figures 2 and 3.

The generated waveform in this stage (as shown in Figures 2 and 3) is not sinusoid. In fact, this complex wave consists of the harmonics of the desired frequency. Therefore, to obtain sinusoid waveform with the desired frequency the complex waveform should to be filtered.

4- **Filter band-passes** the waveform generated by the TSU to obtain a sinusoid waveform with the desired frequency. The filter used here is a second–order analogue band- pass Butterworth filter with lower 3 dB cut off frequency of f_{c1} Hz and upper 3 dB cut off frequency of f_{c2} Hz; where f_{c1} and f_{c2} should satisfy the following inequalities:

$$f_{c1} < f$$

$$f < f_{c2} < 2f$$

where f is the desired output frequency. The above inequalities guarantee that the filter keeps the desired signal with the frequency f Hz and remove

the undesired harmonics with the frequencies 2*f* Hz, 3*f* Hz, 4*f* Hz, *and so on.*

Figure 4 shows the output of the designed filter both in time domain and in frequency domain.

5- EMF Generator is a U–shaped electromagnet that consists of a coil and a U-shaped iron core (see Figure 5). The EMF generator produces the requested EMF. The frequency of the generated EMF is identical to that of the voltage applied to the coil. The magnitude of the generated EMF is proportional to current applied to the coil (as discussed in Equation 2).

To increase the accuracy of the system in generating an EMF with predefined parameters (frequency and intensity) three coils with different turns were designed and used in the presented instrument: one coil with 250 turns; the second one with 500 turns; and the third one with 1200 turns. Experimental study showed that, the coil with 500 turns can generate an EMF with 1 mT and the coil with 1200 turns can generate an EMF with 4 mT with a reasonable accuracy.

3. Results

The accuracy of the designed instrument in generating a requested EMF was evaluated experimentally. The magnitude of the generated EMF was measured using a Gauss meter and was compared with the desired value. Likewise, the frequency of the produced EMF was measured using a digital frequency counter, the unit was compared with the desired value. The measuring instruments used were calibrated and their accuracy was established first.

The experimental results of testing the designed instrument in generating EMF with the magnitude of 0.55 mT, 0.65 mT, 0.67 mT, 0.75 mT, 0.78 mT and 1.56 mT and with the frequency of 5 Hz, 10 Hz,12.5 Hz,16.67 Hz, 25 Hz, and 50 Hz showed that the designed instrument can provide the requested EMF with at most 5.9% tolerance. The error rate of the instrument was estimated to be between 2.1% (for 1.56 mT) and 5.9% (for 0.55 mT). The error rate for the desired frequency value is about 1%.
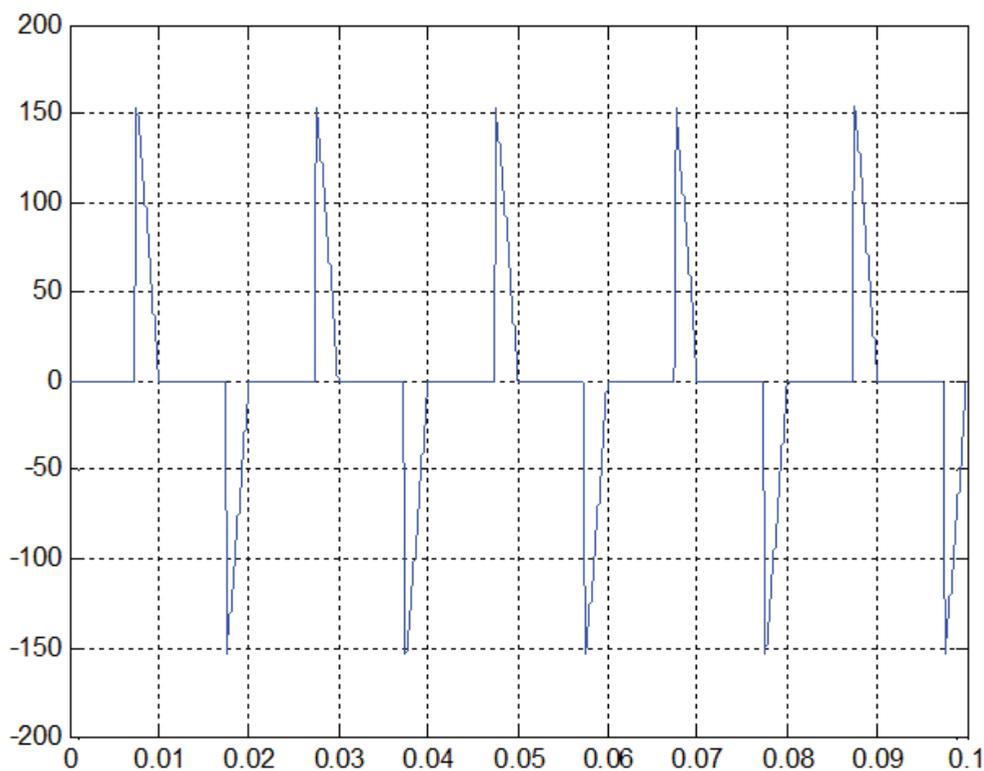

Figure 2. Typical waveform generated using a TRIAC switch for the frequency 50 Hz.
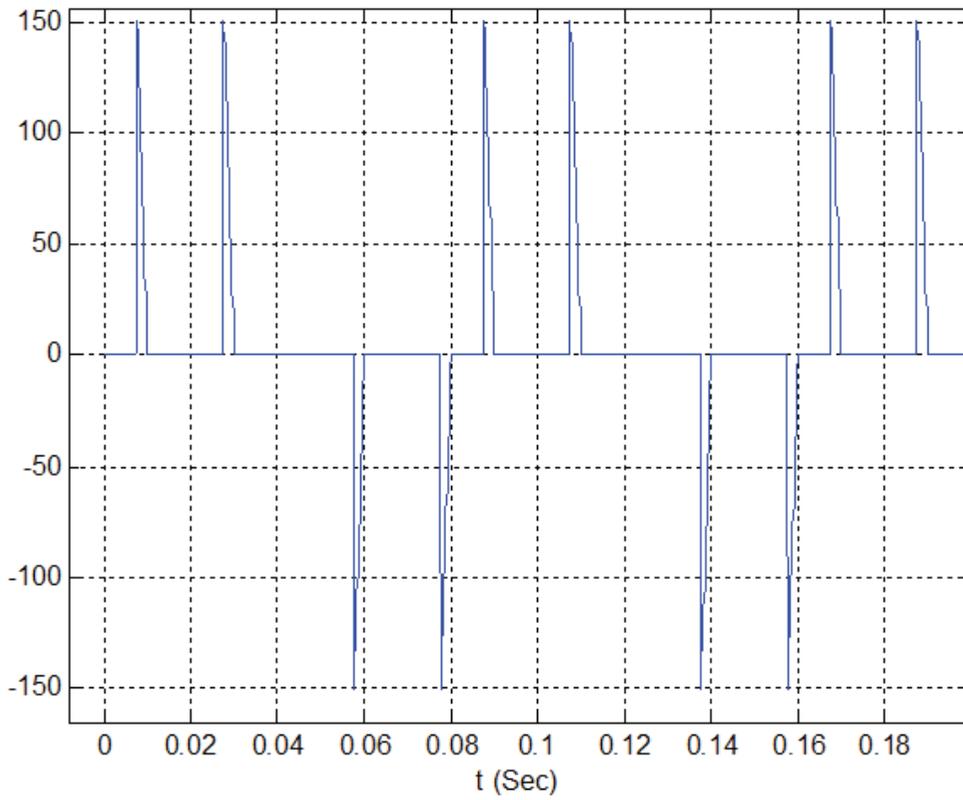
Figure 3. Typical waveform generated using a TRIAC switch for the frequency12.5 Hz (*M*=4).

(a)   (b)
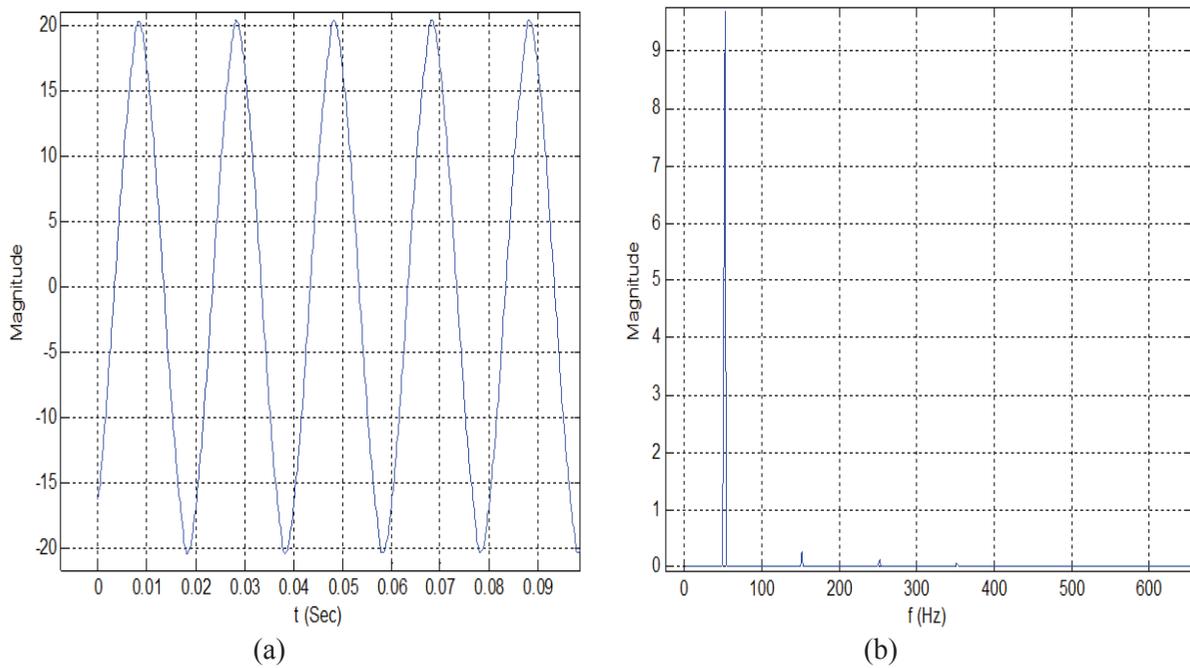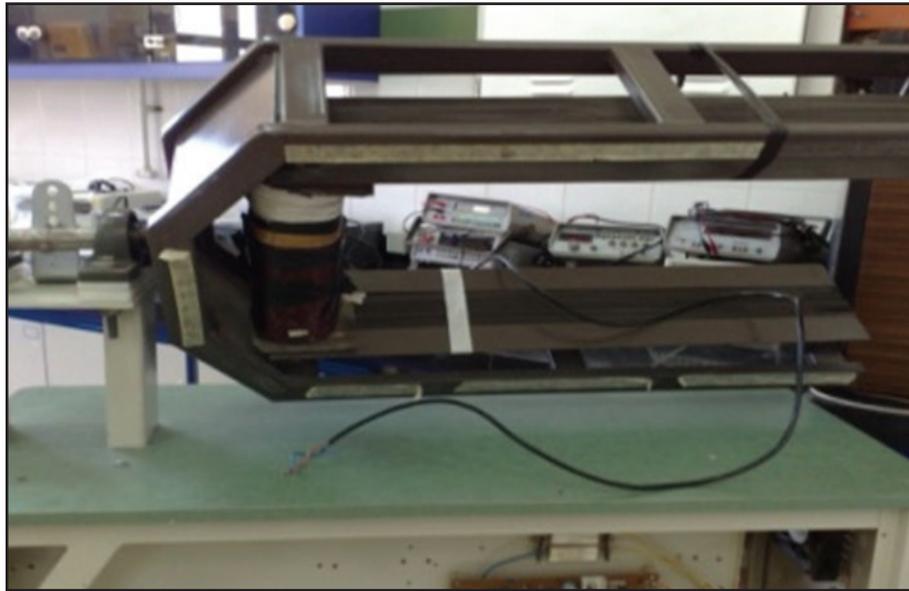
Figure 4. Filtered waveform using a second order Butterworth filter (a) in time domain (b) in Fourier domain.

Figure 5. The U–shaped electromagnet of the designed EMF generator.

4. Discussions

The association between EMF exposure and the risk of several diseases such as ALS, Alzheimer disease, cancer, and the risk of arrhythmia-related heart disease has been investigated in several studies. Most of these studies have revealed such an association, but due to some experimental issues such as exposure measurement error and the lack of standard ELF-EMFs exposing devices the exact health effects of ELF-EMFs is still controversial and some inconsistent results have been reported. To assist with resolving these issues an accurate and reliable ELF-EMF generator to produce EMFs with desired magnitude and frequency values was designed and fabricated. It is worth mentioning that, the objective of this work is designing and fabricating the reliable instrument, the biomedical application of the instrument is under study.

Quality-control measures showed that the developed instrument is sufficiently accurate to produce the EMF with the desired characteristics. The estimated error rates were 2.1% for 1.56 mT and 5.9% for 0.55 mT. The estimated error rate in generating a wave with a desired frequency is about 1%. Based on the obtained results, the error rate increases inversely related to the EMF intensity desired value (set-point). One reason for this increase in the error rate is that a small change in the current delivered to the coil cause a large error in the generated EMF. A small bias is the current of the coil is multiplied by the 1200 (number of turns of the coil used for garneting such EMF) and therefore causes a big error. Controlling the current more accurately may reduce this error, but obviously the instruments and devices required for such an accurate control may increase the cost of the instrument. Nevertheless, the present accuracy of the designed instrument is high enough to be used in research laboratories for further investigation of the health effect of long-term occupational exposure to ELF-EMFs.

The induced magnetic field inside the designed U-shaped coil is not exactly uniform. In fact, the magnitude of the EMF in the lower end of the coil is higher than that in the upper end of the coil. In addition, field lines are not exactly straight lines; they curve toward the edges of the coil. The simulation studies and the obtained Quality-control experimental results approved the simulation study. Nevertheless, the quantitative and qualitative experimental results showed that the EMF provided by the equipment was sufficiently homogeneous over a given volume (equal to the area of a mouse's cage) and was stable over time. Consequently, the presented ELF-EMF generator may assist with further investigation of the health effect of long-term occupational exposure to ELF-EMFs.

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