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Author

Lo, C.C.

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A WIDE DYNAMIC RANGE PORTABLE 60-Hz MAGNETIC
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C.C. Lo, T.Y. Fujita, A.B. Geyer,
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C.C. Lo, T.Y. Fujita, A.B. Geyer and T.S. Tenforde

Lawrence Berkeley Laboratory
Berkeley, California U.S.A. 94720

Abstract

A portable dosimeter has been developed for monitoring human exposure to power-frequency magnetic fields in residential and occupational environments. The microprocessor-controlled dosimeter has been designed to measure 60-Hz field intensities that vary from 20 μ G to 600 mG, thereby covering the broad range of field levels generally encountered in households and occupational settings. A digitized resolution of 2.5 μ G is provided in the 20 μ G to 10 mG range, and 150 μ G resolution in the 10 mG to 600 mG range. Automatic range switching is implemented for both signal processing and data acquisition.

Introduction

Several recent epidemiology surveys have indicated that a relationship may exist between cancer risk and residential or occupational exposures to power-frequency magnetic fields.¹ A major deficiency in these epidemiological studies was the failure to use quantitative dosimetry procedures for characterizing magnetic field exposure levels. A program has therefore been undertaken to develop a compact battery-operated dosimeter that can be used for extended monitoring of the power-frequency magnetic field levels encountered by individuals in both industrial and residential environments.

The 60-Hz magnetic fields that are present near the surfaces of rotating machinery and certain household appliances reach intensities greater than 1 G, but typical levels within household and businesses range from 50 μ G to 150 mG.²⁻⁵ In the vicinity of high voltage transmission lines, fields up to 330 mG are present at ground level.⁶ In order to encompass the broad range of field levels to which humans are exposed, the portable dosimeter described in this report was designed to have a wide dynamic range from 20 μ G to 600 mG. The detection circuit utilizes three orthogonal 500-turn copper loops, and provides narrow bandpass filtration of the 60-Hz signals. A phase-lock loop and synchronized detector are used for processing the signals acquired on each of the three axes. The battery-powered dosimeter is microprocessor-controlled and contains 4000 12-bit words of ROM and RAM memory. The design of the data acquisition and storage system is similar to that used in a portable dosimeter previously developed in our laboratory for measuring DC magnetic fields.⁷

Sensor Design

Both thin-film Hall generators and multiturn coils were initially considered for use as field sensing elements in the dosimeter. The Hall sensor is attractive because of its small size and insensitivity to high-intensity electric fields. However, the output sensitivity is typically 12 nV/mG, which is too low for the detection of fields in the tens of microgauss range. The use of several Hall generators in series would increase the detector sensitivity, but would lead to an unacceptable increase in both the rate of battery power consumption and the total volume occupied within the dosimeter by the magnetic field sensors. Multiturn

copper coils which provide a significantly greater signal output were therefore chosen as the detector elements for the magnetic field dosimeter.

From Faraday's law of induction, the peak voltage signal, V_p , produced by a coil positioned transverse to an incident magnetic field is

$$V_p = 2\pi fNB A$$

where N = number of turns in the coil, B = amplitude of the magnetic flux density, A = coil cross-sectional area, and f = magnetic field frequency. If $N = 500$ and $A = 5.5 \text{ cm}^2$, the r.m.s. voltage output of such a coil is 6.8 μ V/mG, which exceeds the output of a thin-film Hall generator by nearly two orders of magnitude. The coil parameters can be easily changed to obtain a desired output signal level.

In the portable dosimeter, three 500-turn coils are arranged along orthogonal axes to monitor the x, y and z components of 60-Hz ambient magnetic fields. Since the coils are also sensitive to electric fields, they are shielded within individual copper chambers. These copper shields have been found by direct measurements to have no influence on the penetration of 60-Hz magnetic fields. To avoid erroneous operation of other dosimeter components in large electric fields, the entire unit is also encased in a conductive shield.

Dosimeter Operation

Figure 1 shows a block diagram of the dosimeter, and Fig. 2 is a schematic diagram of the detector circuitry associated with each of the three orthogonal coils. The signal output from each coil is amplified by two 60-Hz bandpass preamplifiers in cascade. The first stage is a second-order multiple-feedback bandpass active filter having a gain of 40 at 60 Hz. The input signal path is AC coupled to prevent any significant amplification of very low frequency signals induced by body rotation within the earth's magnetic field. The second amplifier stage employs a twin-T bandpass active filter having a gain of 250 or 4.1 depending on whether the field being monitored is below or above 10 mG. The FET transistor in the feedback path controls the gain of the second active filter. The total maximum gain of the two active filters is set at 10,000 so that a 50 μ G field will yield a 3.4 mV signal and a 10 mG field will yield a signal of 680 mV at the output of the second active filter. When the field being monitored exceeds 10 mG, the total gain of the two active filters is automatically decreased to 165. A 20 mG field will thus yield a 22.4 mV signal and a 500 mG field will yield a 560 mV signal at the output of the second active filter.

The second active filter supplies signals to the phase-lock loop (PLL) and the synchronous detector. The PLL phase locks with the incoming signal and produces a quadrature voltage-controlled oscillator (VCO) output that is in phase with the incoming signal. The quadrature VCO output is then used as the demodulating signal for the synchronous detector. The demodulated output is passed through a low-pass filter suppressing

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Fig. 1 Block diagram of the portable 60-Hz magnetic field dosimeter.

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Fig. 2 Schematic diagram of the magnetic field detection circuitry.

all harmonics except the DC component, which is determined only by the amplitude of the incoming 60-Hz magnetic field.

The DC output of the synchronous detector is amplified to be compatible with the 0-5 V range of the analog-to-digital converter in the data acquisition section of the dosimeter. The amplified detector output is also used for automatic ranging purposes. A comparator is used to look at the amplified output of the detector, and compares this signal to a reference voltage that is derived from its own output and the +7 V bus voltage. In the high-gain operation range the reference voltage is set at +5 V. When the field being monitored exceeds 10 mG, the comparator changes state and reduces the gain of the active filters to 165. At the same time it changes the reference voltage to +70 mV which represents a 9 mG field. If the field being monitored drops below 10 mG, the comparator changes state and again the dosimeter operates with a gain of 10,000.

The output of the comparator is also buffered by two FETs to produce a TTL-compatible signal that is used to make two important decisions. Every time a transition occurs either from 0 to 1 or 1 to 0 it signals the program to hold off operation for 120 ms to allow the PLL and various filters to stabilize before digitization is carried out. The TTL "0" level also signals the program that the field being monitored is in the 20 μ G to 10 mG range, whereas the TTL "1" level indicates that the ambient field is in the 10 mG to 600 mG range.

Three analog switches are used to transfer data to the ADC. Digitization of the three orthogonal axes is done sequentially. A waiting time of 500 μ s before digitization allows the analog switches to reach a stable "on" state. A 12-bit successive approximation ADC is used to match the 12-bit architecture of the microprocessor. The ADC is used in the unipolar mode providing 2.5 μ G/bit and 150 μ G/bit in the low- and high-gain modes, respectively. A programmable interface element (PIE) interfaces the ADC and the universal asynchronous receiver-transmitter (UART) used for serial data transmission to the microprocessor.

The microprocessor memory unit consists of 1024 12-bit words of read-only memory (ROM) and 3072 12-bit words of random-access memory (RAM). The ROM contains the monitor and input-output handler. Scratch-pad memory, temporary buffers, program and data storage registers are located in RAM. The data acquisition program is initialized by a bench-mounted HP85 computer during start-up of the dosimeter. This computer also retrieves data from RAM through an RS-232-C serial interface when the field monitoring is completed.

Dosimeter Performance

Initial development and calibration tests for the dosimeter's field detection circuitry were carried out with a standard coil that provided a known magnetic flux density as a function of the applied current. The coil was placed inside a Mu-metal shield to reduce the background 60-Hz magnetic field. The lowest background field thus obtained was about 20 μ G. The current used to excite the coil was generated by a function generator, and was monitored by measuring the voltage drop across a current shunt.

Figure 3 shows the amplified detector output as a function of magnetic flux density. In the high sensitivity range, the DC output of the detector buffer amplifier ranged from 13 mV to 4.8 V, corresponding to

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Fig. 3 Plots of the amplified detector output as a function of magnetic flux density.

field levels of 20 μ G to 10 mG. From the data presented in Fig. 3, it can be seen that the controlled field was contaminated by the background field below 50 μ G. This contamination is evidenced by the deviation of the 20 μ G signal output from the otherwise linear transfer function of the detector. When the ambient field exceeds 10 mG, the DC output voltage exceeds 5 V and forces the comparator to change state and reset the dosimeter to the low sensitivity range. In this range the DC detector buffer amplifier output varied from 80 mV to 5 V, corresponding to field levels of 10 mG to 625 mG. The linearity of the detection system was observed to be within 2%.

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Fig. 4 Harmonic rejection performance of the 60-Hz magnetic field detection circuitry.

Figure 4 shows the harmonic rejection performance of the dosimeter field detection circuitry. All ambient harmonic fields are at least 45 dB below the fundamental 60-Hz field. The measurement was made by setting a fixed flux density level and monitoring the detector buffer amplifier output as the signal frequency was scanned across the range indicated in Fig. 4. Contamination of the main 60-Hz signal by internally generated harmonics is less than 1%.

Discussion

Initial performance tests have demonstrated that the 60-Hz magnetic field dosimeter's detection system is capable of monitoring the broad range of fields from 20 μ G to 600 mG. The dosimeter will therefore be suitable for detecting the extremely low-intensity fields present in households at locations away from appliances as well as the higher field levels in the vicinity of rotating machinery, numerous appliances, business machines, and high-voltage transmission lines.

Two limitations in the present design of the dosimeter are its 4K memory capacity and the anticipated 10-hr limit on continuous operation when a single set of three 3.9 V lithium batteries is used as the power source. The first of these limitations could be removed through the use of a more powerful CPU with expanded memory capacity. The second limitation is a result of the present state of battery technology, and could be overcome if higher energy density batteries become commercially available. It would also be possible to extend the continuous operating time by hybridizing the dosimeter circuits to provide more space for housing additional lithium batteries.

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