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TECHNIQUE FOR REDUCING THE AMBIENT ELECTRIC FIELD GENERATED BY INDUCTIVE VOLTAGES IN LOW FREQUENCY MAGNETIC FIELD GENERATORS

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Pensacola, Florida

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U. S. Navy interest in the physiological effects of nonionizing radiation in the extremely low-frequency (ELF) range has led to the construction of research facilities in which various life forms can be exposed and their physiological responses to these fields monitored. The magnetic component is generated by a coil system in resonance with a capacitor bank. The inductive voltage drop across the system is sufficient to generate a high electric field between the coil sections. This electric field is undesirable because it does not allow effects of the magnetic field to be separated from effects of the electric field.

The undesirable electric field component can be minimized by breaking each section at its center. These subsections can then be connected with the capacitors in such a way that the electric field generated by each coil segment is canceled by the electric field generated by another segment of the same coil. Several different arrangements will accomplish the desired cancellation. The pros and cons of each arrangement are a function of the required number of capacitors and the voltage levels on the interconnecting cables. Very large coils producing high magnetic fields can be constructed in this manner.

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SUMMARY PAGE

THE PROBLEM

U. S. Navy interest in the physiological effects of non-ionizing radiation in the extremely low-frequency (ELF) range has led to the construction of research facilities in which various life forms can be exposed and their physiological responses to these fields monitored. The magnetic component is generated by a coil system in resonance with a capacitor bank. The inductive voltage drop across the system is sufficient to generate a high electric field between the coil sections. This electric field is undesirable because it does not allow effects of the magnetic field to be separated from effects of the electric field.

FINDINGS

The undesirable electric field component can be minimized by breaking each section at its center. These subsections can then be connected with the capacitors in such a way that the electric field generated by each coil segment is canceled by the electric field generated by another segment of the same coil. Several different arrangements will accomplish the desired cancellation. The pros and cons of each arrangement are a function of the required number of capacitors and the voltage levels on the interconnecting cables. Very large coils producing high magnetic fields can be constructed in this manner.

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INTRODUCTION

U. S. Navy interest in the physiological effects of non-ionizing radiation in the extremely low-frequency (ELF) range has led to the construction of research facilities in which various life forms are exposed and their physiological responses to these fields monitored. The magnetic fields are generated by one or more coils of wire through which a current of the proper frequency is passed. The size of these coils depends on the type and number of specimen to be exposed. For example, two squirrel monkeys were exposed for extended periods within a Helmholtz pair configuration 0.6 m* in diameter (2,3). Human subjects have been exposed in a coil system 3.6 m in diameter.

The inductive reactance of this large coil is sufficient to prevent the low voltage power source from driving the coil at currents necessary to produce the desired magnetic field. This reactance can be balanced and the overall impedance reduced by placing in series with the coil a capacitive reactance numerically equal to the inductive reactance. This creates a resonant circuit and permits the coil to be driven by a low voltage power source. The resonant circuit solves the problem of generating a high magnetic field over a large volume; however, the inductive voltage drop across the coil generates an electric field within the subject area of the coil. The resulting electric field is undesirable because it does not allow physiological effects of the magnetic field to be distinguished from effects of the electric field. This report describes a technique which minimizes these electric fields.

RATIONALE

Consider coils of the Helmholtz pair configuration as shown in Figure 1. The capacitance is such that the total capacitive reactance equals the total inductive reactance. Under these tuned conditions the total voltage drop across the coils can be much higher than the voltage at the terminals of the power source. For example, with large coils generating 10^{-3}Wb/m^2, the power source could be less than 100 volts while the inductive voltage drop may be several thousand volts. The electric field at the center of the coil (point 0 in Figure 1) is the vector summation of the electric field generated by the surface charge on elemental segments of both coils L_1 and L_2. At any instant of time, the resultant electric field generated by the elemental segments of L_1 are in the same direction at point 0 as the resultant electric field generated by elemental segments of L_2. The magnitude and distribution of the electric field between these coils depends upon the diameter and spacing of the coils; for the types of coils discussed here, the magnitude could be several hundred volts per meter.

The total inductance of the coil system is equal to the self inductance of coil L_1 plus the self inductance of coil L_2 plus the mutual inductance of both coils. Since coils L_1 and L_2 are tightly wound and the diameter of the bundle is small compared to the spacing between L_1 and L_2, the mutual inductance is, for practical application, evenly distributed

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*All units and symbols in this report conform to The International System of Units (SI), NBS Special Publication 330, 1972 edition.

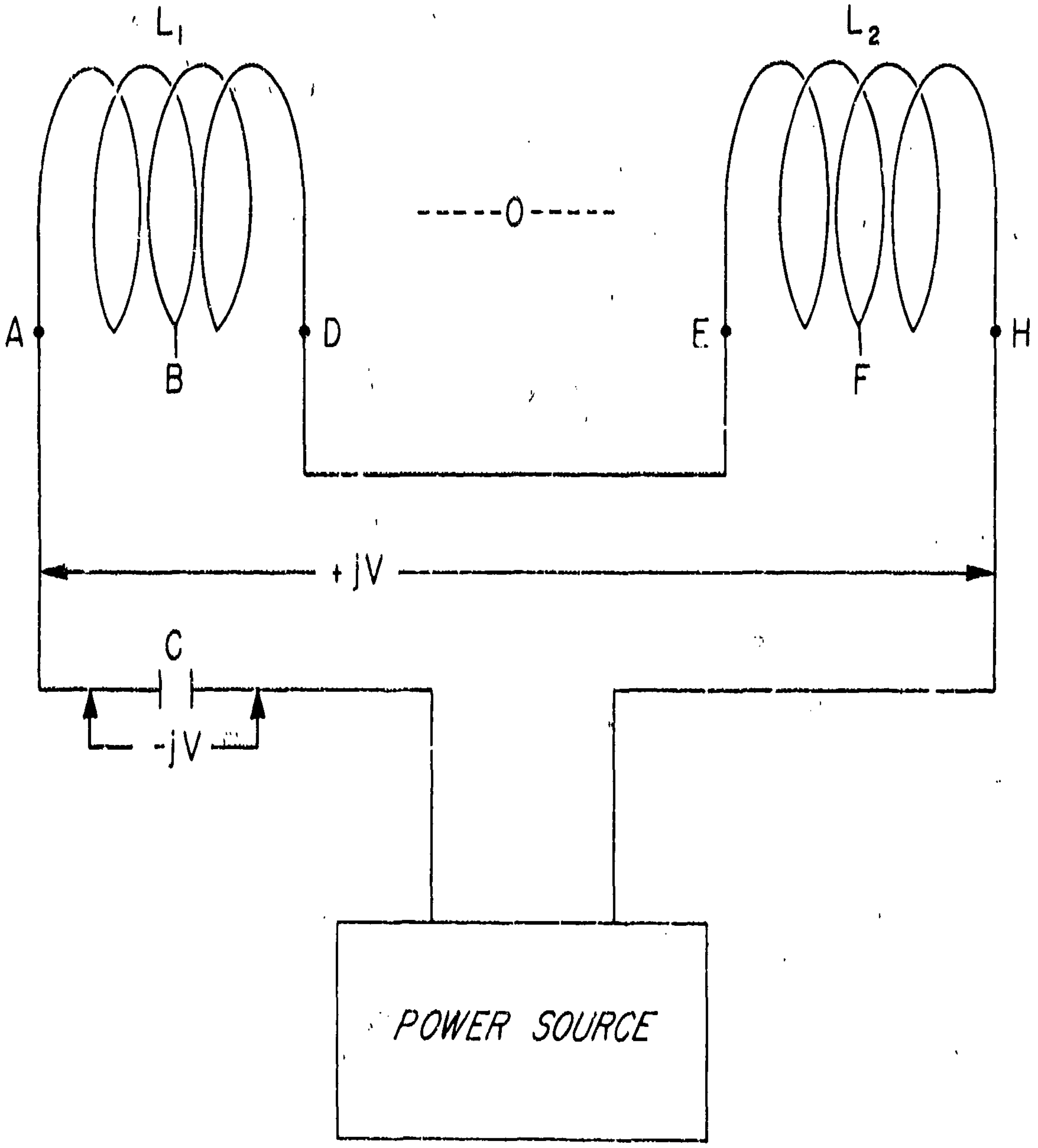

Figure 1

Electrical schematic diagram for coil system constructed in the Helmholtz pair configuration. The system is tuned with a single capacitor C. The voltage drop across the coils is high and generates a significant electric field at point 0 on the axis of the system.

throughout the system. If the coils were center taped at points B and F as in Figure 1, the voltage drop across each subsection, for example A to B, would equal one-fourth the total voltage drop or + jV/4. In Figure 2 the coils have been broken at points B and F. A series capacitor has been inserted at each of these points. The reactance of each capacitor is numerically equal to one-half the total inductive reactance of the system; therefore, the voltage drop across each capacitor is - jV/2.

In Table I the reactive voltage drops, with respect to point A in Figure 2, are shown as one moves through the system. The values are the vector sum of all values from point A; thus, point C is equal to the voltage drop from A to B (+ jV/4) plus the voltage drop from B to C (- jV/2). Every segment of coil L_1 having a voltage with vector operator + j is balanced by another segment of L_1 at the same voltage with vector operator - j. The separation between these segments would be small compared to the overall dimensions of the system; therefore, at points within the subject area, the electric field vectors produced by these segments would be essentially equal in magnitude but opposite in direction with a negligible resultant. The same is true for L_2.

Table I

Voltages of Points in Figure 2 with Point A as the Reference

Point	Voltage
A	0
B	+ jV/4
C	- jV/4
D	0
E	0
F	+ jV/4
G	- jV/4
H	0

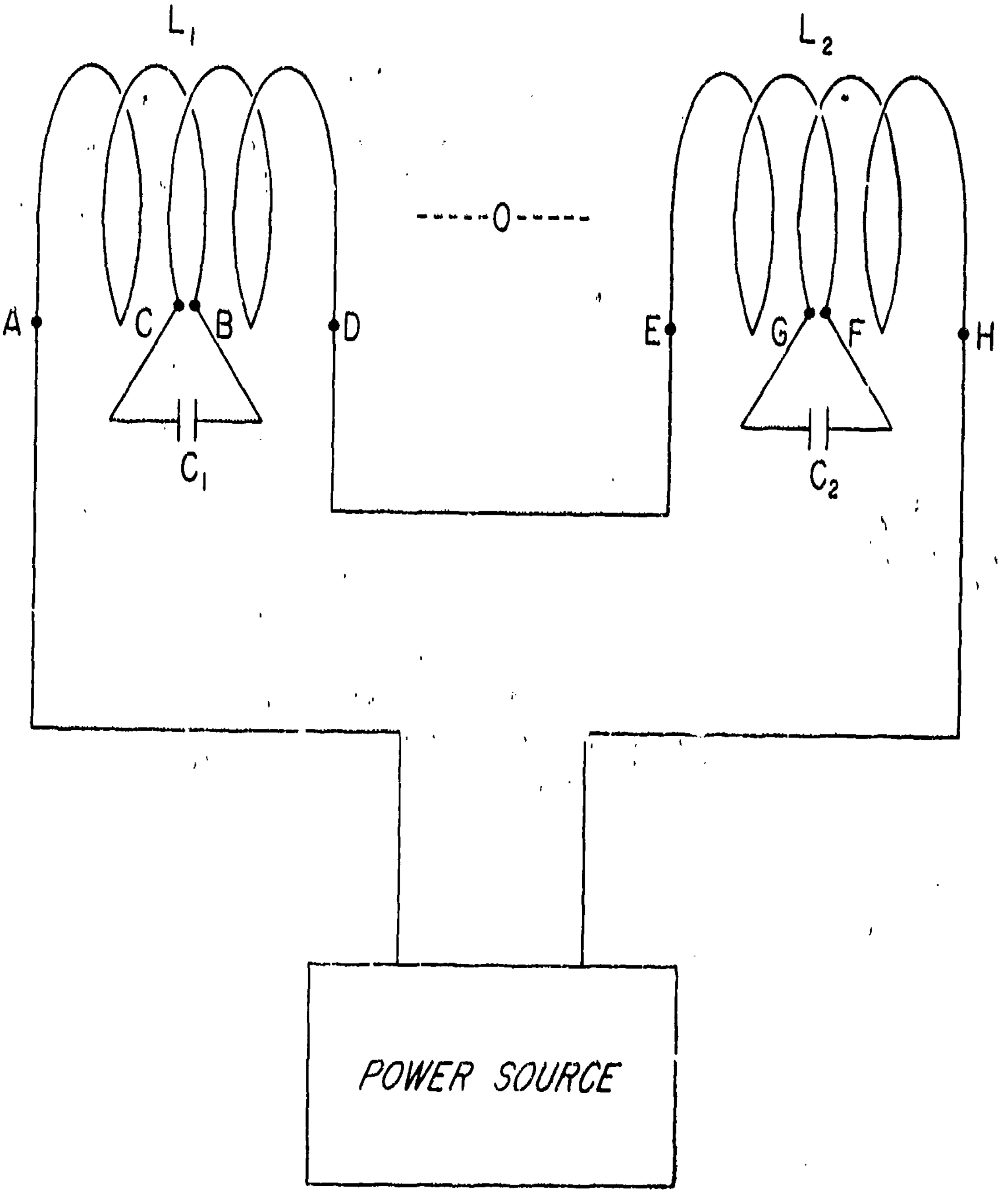

Figure 2

Electrical schematic diagram for coil system similar to the system shown in Figure 1 except that capacitors C_1 and C_2 are used. The voltage drop across the system is small and the electric field at point 0 is also small.

In addition to reducing the electric field in the subject area, the arrangement in Figure 2 also reduces the voltage level on the cables connecting the power source to the system. These voltages are now a function of the DC resistance of the coil winding and will not exceed the output voltage of the power source; therefore, the hazards associated with high voltage lines are greatly reduced.

The Helmholtz pair configuration can also be balanced using only one capacitor as illustrated in Figure 3. The voltage drop across each subsection, for example, AB, is $+jV/4$, where V is the total voltage drop across the Helmholtz pair just as if the capacitor were placed as shown in Figure 1. The voltage drop across the capacitor is $-jV$, and its reactance is numerically equal to the total inductive reactance of the system. In Table II the voltages of each point in Figure 3 are shown with respect to point A. The values are vector sums of all values from point A. The desired result has been accomplished in that every segment of L_1 and L_2 having a voltage with vector operator $+j$ is balanced by another segment within the same coil having the same voltage with vector operator $-j$.

Table II

Voltages of Points in Figure 3 with Point A as the Reference

Point	Voltage
A	0
B	$+jV/4$
C	$-jV/4$
D	0
E	$+jV/4$
F	$+jV/2$
G	$-jV/2$
H	$-jV/4$

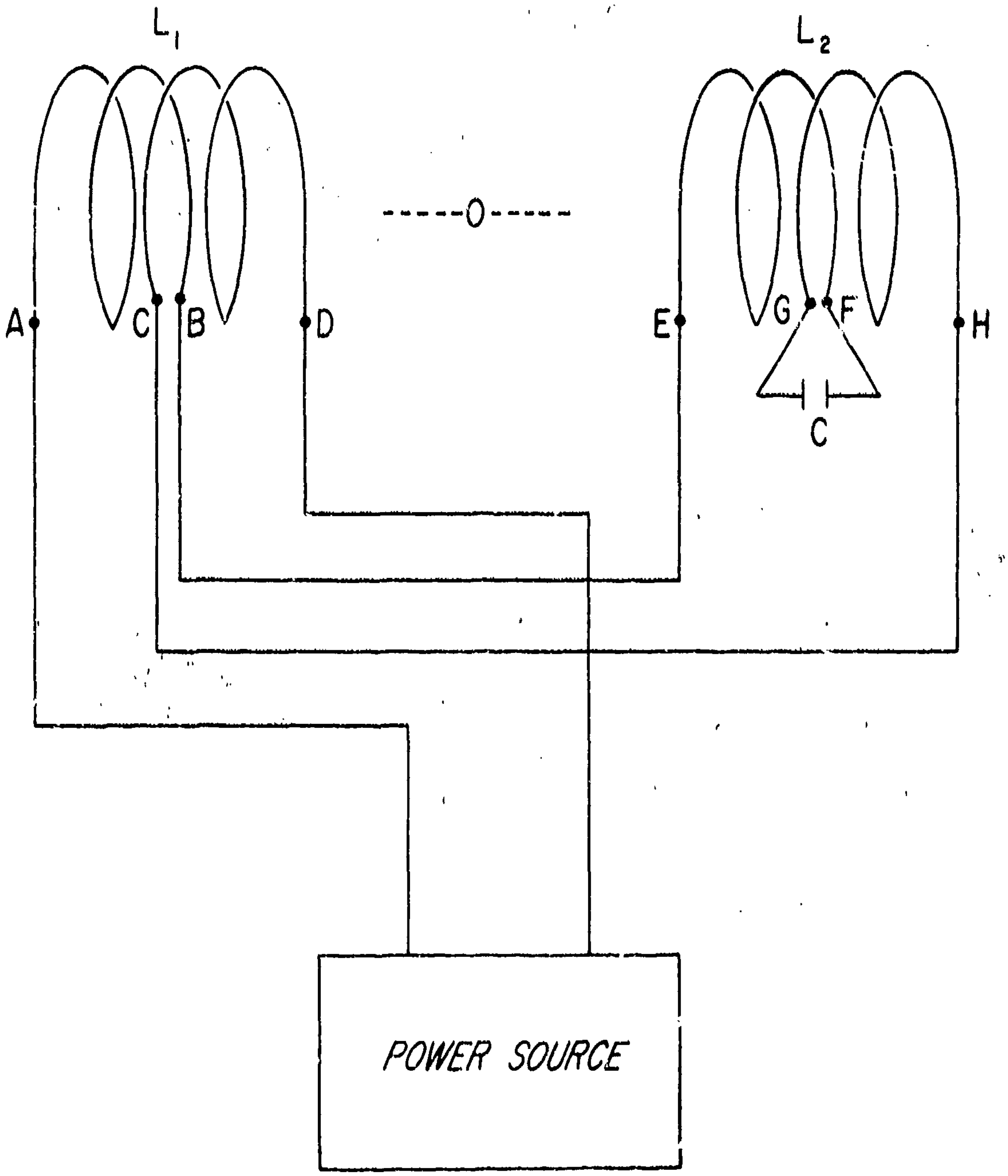

Figure 3

Electrical schematic diagram for the same type coil as shown in Figure 2 except that a single tuning capacitor is used and the subsections are connected in a different sequence. This arrangement also provides for vector cancellation of the electric field. See the text for a discussion of the relative merits of these arrangements.

The disadvantages of the arrangement in Figure 3 compared to Figure 2 are: (1) An additional cable connecting L_1 and L_2 is required, (2) both interconnecting cables are at a high voltage and may require special precautions to reduce the hazard, (3) the voltage rating on the capacitors must be twice that required for Figure 2. These disadvantages must be weighed against the one advantage that the total capacitance required is one-fourth of that required in Figure 2.

The arrangement of Figure 2 has special significance because it allows the design of large coils capable of generating magnetic fields much higher than possible with the arrangement in Figure 1. The design in Figure 1 would ultimately be limited by voltage breakdown of the coil insulation and by the availability of high voltage capacitors. Extending the basic design principle of Figure 2 allows these voltages to be kept low. Each subsection may be further divided and capacitors inserted in series with these subsections. The subsections should be of equal inductance and the capacitors should be equal. The value of the capacitors should be such that the sum of all capacitive reactance in a coil section is numerically equal to the sum of all inductive reactance in the section. Very large coils producing high magnetic fields could be constructed in this manner.

APPLICATION

These principles were applied in the construction of the coil system at the Naval Aerospace Medical Research Laboratory (Figure 4). This system was constructed in a Barker-Four configuration (1) which consists of four separate coils. The turns in the two outer coils exceed the turns in the two inner coils by a factor of 2.3. The overall length of the system is 3.6 m which is also the length of one side of the square coils. The spacing between the two inner coils is 1.8 m.

A schematic of the coils and capacitors is shown in Figure 5. The heavy vertical lines represent the four square wood structures in Figure 4. Each structure contains a coil of tightly wound wire. Each coil has been split to form two subcoils having equal turns as shown.

The total inductance of the coils between points A and H is 78.7 mH. The system is tuned at 45 Hz. The capacitance between D and E is 158.8 μF which provides a capacitive reactance equal to the total inductive reactance between A and H.

To demonstrate the theory for this specific system, the inductive reactance (X_L) of each coil is designated by a subscript numerically equal to the number of turns in the subsection. The value of the capacitor was chosen such that the capacitive reactance (X_C) is numerically equal to the sum of the inductive reactance for all subcoils between points A and F; therefore,

$$X_C = X_{L36} + X_{L16} + X_{L36} + X_{L16} = 2(X_{L36} + X_{L16})$$

The resulting reactive voltages with respect to point A are shown in Table III. The voltages at each point are the vector summation of all voltage drops from point A. Voltage

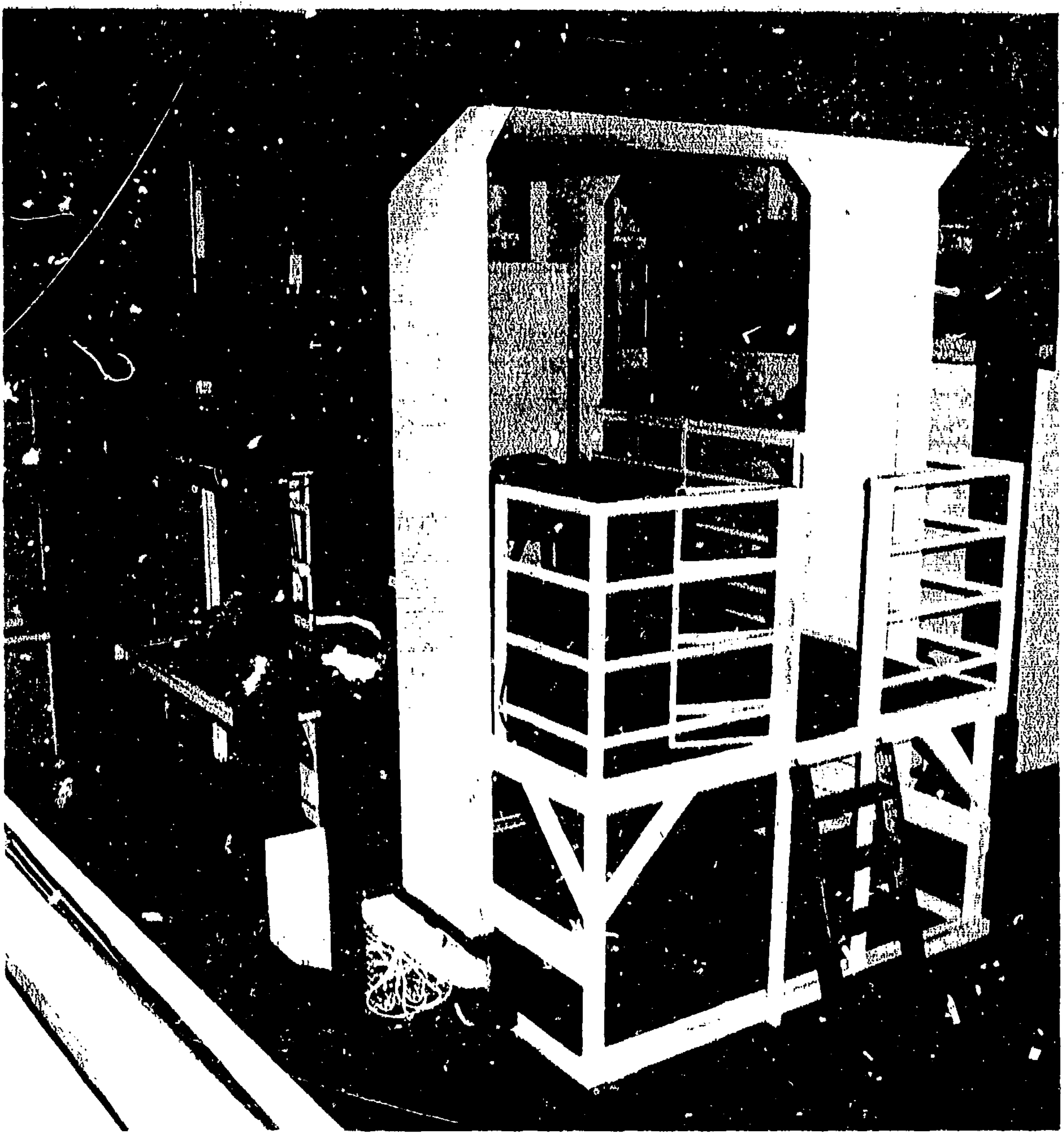

Figure 4

This coil system at the Naval Aerospace Medical Research Laboratory has four coil sections. The cover at the lower left corner of the nearest coil has been removed to expose the wire bundle. The capacitor bank for the first two sections is directly behind this open corner. The bank for the last two sections is out of view at the far right corner of the rear section. Cables leaving the top of the two inner sections are connected to a power source in the adjacent control room. The system can generate fields up to 10^{-3}Wb/m^2 rms over a test area 2.4 m x 4.8 m.

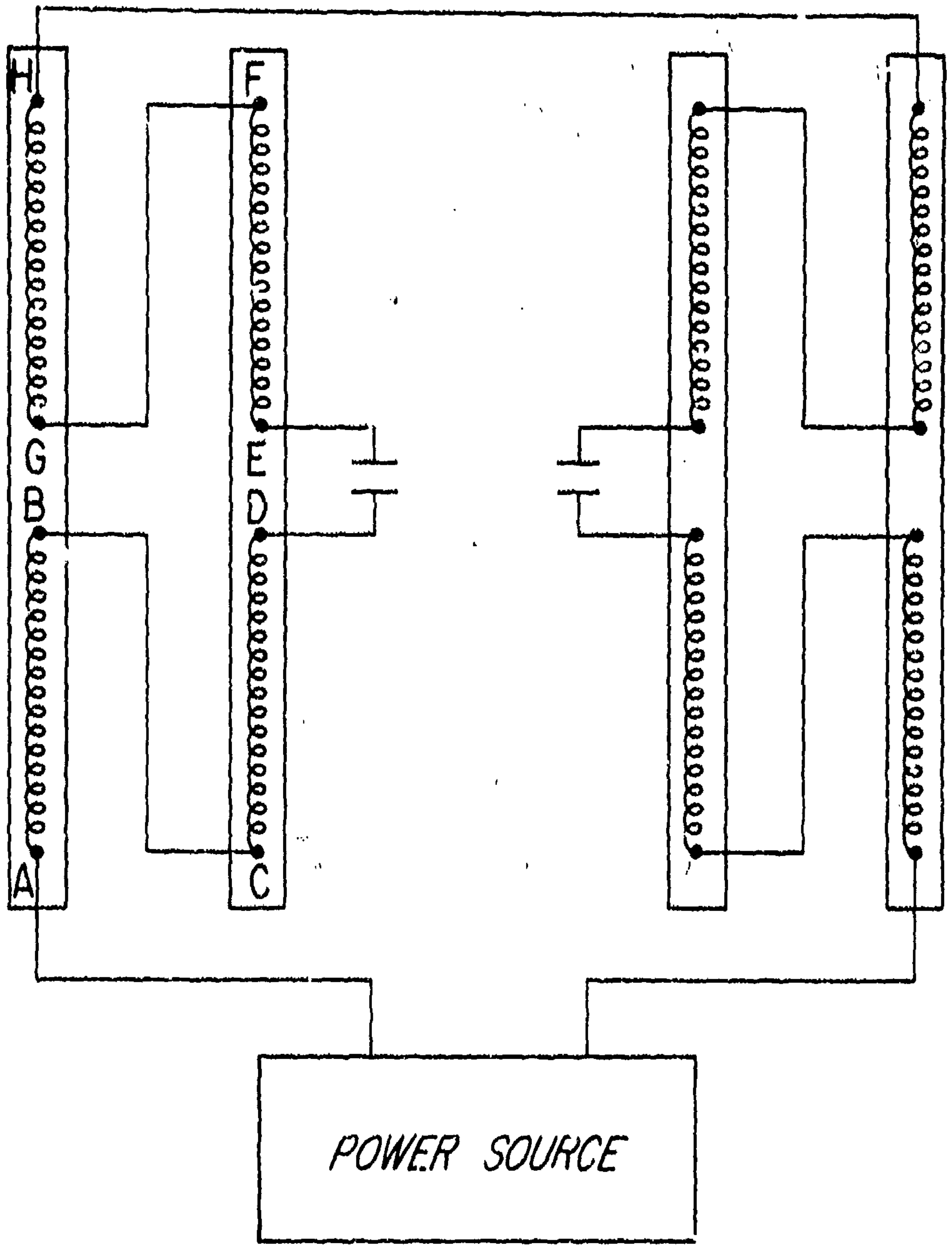

Figure 5

Electrical schematic diagram of the coil system shown in Figure 4. The four rectangles represent the four coil sections. The coils in each section are tightly wound together with an electrical discontinuity at the center. For example, A through H is a 72-turn coil with a break between the 36th and 37th turn, resulting in two 36-turn subcoils, AB and GH. The physical separation between points A and H is less than 10 cm. C through F is a 32-turn coil with a break between the 16th and 17th turn, resulting in two 16-turn subcoils, CD and EF.

drop is defined as the product of electric current, I, and the reactance. For example,

$$V_E = +jIX_{L36} + jIX_{L16} - jIX_C$$

If X_C is replaced by its numerical equivalent, $2(X_{L36} + X_{L16})$, the equation can be simplified as follows:

$$V_E = +jIX_{L36} + jIX_{L16} - j2I(X_{L36} + X_{L16}) = -jI(X_{L36} + X_{L16})$$

Note that the voltage at point E is numerically equal to the voltage at point D but 180° out of phase. A similar analysis can be made for the entire system such that every segment in a given bundle having a voltage with vector operator + j is balanced by another segment in the same bundle with vector operator – j. It should also be noted that resistive voltage drops have been neglected because they are very small compared to reactive voltages.

Table III

Voltages of Points in Figure 5 with Point A as the Reference

Point	Component Voltages	Net Voltage
A	0	0
B	$+jIX_{L36}$	$+jIX_{L36}$
C	$+jIX_{L36}$	$+jIX_{L36}$
D	$+jIX_{L36} + jIX_{L16}$	$+jIX_{L36} + jIX_{L16}$
E	$+jIX_{L36} + jIX_{L16} - jIX_C$ $(X_C = 2X_{L36} + 2X_{L16})$	$-jIX_{L36} - jIX_{L16}$
F	$-jIX_{L36} - jIX_{L16} + jIX_{L16}$	$-jIX_{L36}$
G	$-jIX_{L36} - jIX_{L16} + jIX_{L16}$	$-jIX_{L36}$
H	$-jIX_{L36} + jIX_{L36}$	0

The electric field at the center of the coil system shown in Figure 4 was measured for single-capacitor tuning and for two-capacitor tuning at 45 Hz. The configuration for a single capacitor is similar to Figure 1 with the capacitor between the power source and the coils. The configuration for two capacitors is shown in Figure 5. Results of these measurements are given in Table IV.

Table IV

Measured Electric Fields at the Center of the Coil System shown in Figure 4

Coil Current	Axial Magnetic Field	Axial Electric Field	Vertical Electric Field	Transverse Electric Field
		Single Capacitor Tuning		
3A	10^{-4}Wb/m^2	3.4 V/m	1.3 V/m	0.3 V/m
5A	1.6×10^{-4}Wb/m^2	5.4 V/m	2.1 V/m	0.6 V/m
		Two Capacitor Tuning		
3A	10^{-4}Wb/m^2	0.08 V/m	0.1 V/m	0.03 V/m
5A	1.6×10^{-4}Wb/m^2	0.1 V/m	0.2 V/m	0.05 V/m

With two-capacitor tuning the axial electric field at 3A was reduced by a factor of 32.25 as compared to the field obtained with single-capacitor tuning. At 5A it was reduced by a factor of 54. Since the coil system contributes more to the axial field than to the vertical or transverse fields, two-capacitor tuning reduces the vertical and transverse fields by smaller factors. It should be noted that the vertical field contains a significant 60 Hz ambient component which is not affected by the capacitor tuning. The reduction in the vertical field by two-capacitor tuning, therefore, is not as great as that observed in the axial or transverse fields. These measurements agree with theory and clearly show that the method provides an effective means for reducing the electric field generated by inductive voltages in resonant coil systems.

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