A Universal Systems Model Incorporating Electrical, Magnetic, and Biological Relationships

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***Abstract*— A discussion about the background of biological effects from electromagnetics is presented. A summary of the leading interactions is presented. An electrical model is presented. The model explains the biological interactions in electrical terms. Methods of mitigating the effect of power systems on biological systems are noted. An appendix provides a comprehensive mathematical development of a universal systems model.**

I. Introduction

A. Reason for Concern

THERE HAS BEEN considerable discussion in the popular press about the hazardous impact of electromagnetic fields on biological systems [1]–[4]. Much of this information has been based on confined data and speculation. There has been a limited response in the technical literature [5]–[8]. The result is a lack of rigorous information. Therefore, the technical community has often reacted negatively and defensively to the proposed biological threat of electromagnetics.

Because of all the popular press discussions, every electrical installation has become suspected of causing health hazards. The electrical engineer will ultimately be drawn into this fray by litigation or in an attempt to set safety guidelines within his organization. The lack of data at this time creates a tenuous problem for the designer.

Nevertheless, there is adequate evidence to demonstrate some effect of electric and magnetic fields on human and other biological systems. These effects are not as dramatic as some other health hazards. However, as prudent engineers, we must be prepared to defend our designs and to mitigate the effects where reasonable.

The routine use of field theory is not common for most electrical engineers. This paper will develop the theory so that the engineer will not have to reread advanced mathematics and fields texts. The mathematics relationships are shown in the Appendix for those who are interested. This field theory will be a necessary ingredient to understand why selected designs are better and to understand why biological systems are impacted by some electrical and magnetic fields under different conditions.

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B. Background

A large part of the biological suppositions has a major problem. There is a lack of correlation to conventional electrical theory. If the biological proposition can be related to electrical models, then the presentation will be more acceptable. However, if an appropriate model is not available, then the credibility of the biological impact is severely hampered.

Every physical system that has been successfully modeled fits the same mathematical structure. Biological systems are no different. However, determination of the model parameters is challenging. A major constraint is that the period of observation may be long compared with the life of the subject. Furthermore, repetitive tests on the same specimen are difficult. As a result, the absolute *cause–effect* model of classical physics may be difficult to determine.

For this reason, broad studies must be made. These look for trends and correlations. Therefore, the *spectrum-type* model used in atomic physics has more validity. As additional *spectral-study* statistics are available, the models can be refined. Then, an effective, classical cause-effect model is provided.

Engineers and physical scientists prefer to investigate data that can be precisely repeated. However, epidemiological studies, by their very nature, rely on past data. Furthermore, the sample cannot be exactly duplicated. This creates a quandary for the blending of physical and biological information. Nevertheless, by careful definition and correlation of known information from the two diverse scientific fields, a reasonable consensus can be developed.

C. Definitions

An understanding of the terminology used by the scientists can resolve much of the conflict.

Hazard: A hazard is an event that is known to cause definite damage to the object. A person touching an electrical potential of 120 V encounters a well-defined hazard. In a normal situation, the hazard results in a shock or death. Hazards are easily identified by cause and effect with known results.

Effect: An effect is the response to the stimuli of an event, but the result of the exposure is not definite. A person exposed to an electromagnetic wave in the form of a bright light encounters a definite effect. The effect is squinting. However, the long-term hazard that will result from a brief flash is not well known. Effects are identified by cause and effect with possibly unknown results.

Association: An association is an event that will stimulate a response in some cases, but the mechanism is not definite. There is an association between time spent studying for an exam and the grade on the exam. Associations are not identifiable by a cause and effect.

The following term is not scientific in its correlation of data. However, it may be the most powerful operator of all the terms.

Perception: A perception is a conceptual idea that may or may not be based on demonstrable evidence. Nevertheless, the response to the perception is as real as a verifiable event.

D. Organizational Concerns

There have been numerous media reports and some limited technical articles about the association between biological systems and electromagnetic fields. In addition, a number of organizations have become interested in the information.

The Electric Power Research Institute (EPRI) is a utility-sponsored research-development and advocacy organization. Understandably, the constituency of this group have a vested interest in the outcome of the discussions [9], [10]. This has been the major funding establishment for electromagnetic impact on biological systems.

The National Cancer Institute is a private advocacy group that investigates a variety of potential carcinogens. Because of cancer associations with electromagnetics, the organization has begun programs to promote their perspective.

The Department of Energy is the leading government organization looking into associations between electrical phenomena and biological systems. Nevertheless, a limited budget has been available. The Environmental Protection Agency has recently become the focal point.

The Institute of Electrical and Electronic Engineers is a technical affiliation of professionals working in electrical systems. Because engineers are normally the group that makes risk assessment for projects, this organization has begun work on standards and guidelines for describing the problem. A series of articles in the *IEEE Spectrum* has provided some insights to the problem [5], [7], [8].

This is a list of prestigious establishments that are investigating the biological association with electromagnetic fields. It is apparent that the association is a significant concern. The economic impact and social survival of our society's lifestyle depends on the resolution of this question.

There is no doubt but that a problem is perceived to exist. It is now the responsibility of the technical community to define the scope of the problem. Only then can logical, feasible, viable responses be addressed.

It is the responsibility of engineers, biologists, and society to determine the risk-to-benefit ratio between exposure to electromagnetic disturbance and the desire for the services and comfort provided by electrical energy.

If the problem is a serious health risk, engineers must develop techniques to mitigate the impact. If the problem is only a nuisance with occasional irritations, these must be identified and resolved. If the problem is only a perception, then we must educate those outside the technical community.

II. Biological

A. Present State of Knowledge

As with many developments in science, the observance of electromagnetic interaction with human biological problems was coincidental. Wertheimer and Leeper observed a correlation between electrical power line configuration and leukemia in children [11]. To date, the strongest link between electromagnetics and biological effects continues to be power line configuration. This Denver study published in 1979 has been the impetus for much discussion.

No body of knowledge is ever complete. However, increasing discussion and investigation tends to shed additional insight into perceived problems. The study of cancer correlations has progressed rather dramatically in the last 40 years. A greater awareness now exists about carcinogenic contributors that were previously considered benign. Nevertheless, the scientific community must be careful about creating phobias concerning every facet of our existence.

There are now numerous studies that have made or dismissed associations between electromagnetic fields and biological systems. These occur only 11 years after publication of the inaugural technical report. Only a few of these will be mentioned so that the reader will have an overview of the present state of the art. The inquisitions can be grouped in three categories: epidemiological, individual organisms, and cellular or organ level.

B. Epidemiology

Epidemiology studies correlate historical data for a large population of people. The people generally fit a particular category based on location or occupation. Any biological data is purely statistical in nature. The results can only show an association with a stimulus (electromagnetic fields for example) since there are many extraneous factors involved with each person. Risk factors greater than one indicate increasing associations.

Since applications engineers are predominantly involved with power systems, we will primarily discuss 60-Hz fields. All further synopsis in this section will deal only with low-frequency (less than 100 Hz), comparatively low-power, electric and magnetic fields.

The epidemiological studies have primarily investigated cancers such as leukemia and tumors. Six international studies, including three in the United States, have related magnetic fields in homes to cancer. One found no association [7]. The others noted increased incidence at levels as low as 0.2 μT for ac power frequencies. A Swedish study and a study by Savitz for the New York Power Lines project tend to confirm the first report by Wertheimer. The dc level of the earth's field is about 50 μT. (Note the Section IV-E for term descriptions.)

Twelve U.S. and eight international studies have investigated the effects of occupation with cancers. Only two Swedish studies have found no association. A Johns Hopkins study of 50 000 workers showed a sevenfold increase in leukemia and other cancers for telephone line splicers. A 10-yr survey of East Texas workers showed an increased risk ratio of ten for brain cancer among electric utility workers [7]. Dr. Milham of Washington has found an increased incidence of leukemia in ten out of 11 men working in close association with electric or magnetic fields [12]. Note that even these large changes still represent a very small number.

C. Individual Organisms

Fortunately, we do not purposely do damaging experiments on people in our society. Hence, experimental tests on individual organisms are conducted on animals. Dr. W. R. Adey of the UCLA Brain Research Institute has been a prolific investigator of electromagnetic phenomenon on biological systems [13], [7]. With colleagues, he has shown that monkey brain waves and behavior patterns are disturbed by low-frequency electric fields at levels as low as 1 v/m. These tests were confirmed using cats. Other tests demonstrated a delay in reaction of monkeys exposed to low-frequency fields (including 60 Hz).

The biological clock which is known as the circadian rhythm, is disturbed by low-frequency fields. This has been repeatedly demonstrated by measuring chemical secretions. Batelle Pacific Northwest Laboratories has shown a correlation with users of some types of electric blankets [7]. The New York Project showed a slowing of repetitive learning in rats [14].

Other studies have reported a variety of interactions. Arguments can always be found against any research data, especially by those affected by the information. A bibliography of 159 studies with bioelectromagnetic emphasis is listed in *Biological Effects of Power Line Fields*, which is a report of the New York State Power Lines Project [14]. The vast majority of published reports show a measurable association between biological system changes and electromagnetic fields.

D. Cells and Organs

Dr. Adey and his colleagues did the first work showing that low-frequency fields increased the release of calcium ions from nerve tissue [13]. This work has been repeated by others. The rate of DNA synthesis in some types of human cells is modified by low-level electric fields [15], [7]. Increased ODC enzyme activity is used as a cancer indicator. This activity has increased at electric field levels as low as 0.1 mv/cm.

The mechanism for these and other operations are not always apparent. Nevertheless, numerous studies have reported an interaction between the electromagnetic environment and the biological responses.

III. Model

A. Systems Description

All physical systems, whether they are biological or not, exhibit common mathematical model characteristics. To understand the potential biological impact of electromagnetics, it is first necessary to identify the model for the electrical system. The biologically defined effects are a different perspective of the electrical phenomenon.

Since a diverse group of readers are impacted by this subject, the presentation will not rely on complex mathematics. A parallel development that addresses the mathematical perspective is presented in the Appendix for those interested.

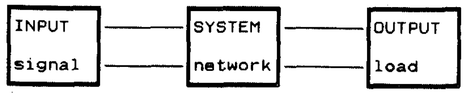

Fig. 1. System model.

A basic model can be developed using classical control systems (Fig. 1). The model is sometimes referred to as a two-port network [16], [17]. The model consists of three fundamental ingredients. These are an input or stimulus (cause) module, a system or transfer function module, and an output or effect module.

Most analyses of electrical phenomenon consider linear responses. This is not a valid assumption for the biological model. The system operates with the normal exponential response of other second-order physical systems. The response (output) of the system (transfer function) to a stimulus (input) is only valid within limits (boundary conditions). Stimuli outside the boundary will not cause proportional response. In fact, the system may overload and have no response.

Energy is the best measure to correlate various interactions. The three components of energy are as follows:

$$W_{\text{external}} + W_{\text{thermal}} + W_{\text{internal}} = 0.$$

The internal energy is a source characteristic of the system. This contains the elements of the system and the *static* fields. It is the characteristic response when there is no input function. The thermal energy contains the *conversion* between forms and the system entropy. It is the heat or loss in the system. The external energy contains the forcing function and *dynamic* fields. It is the driving force. Metric units are used for the explanations because the values can be interchanged easily. A conversion table that gives the equivalent English units will be shown later.

B. Internal

The internal energy can be described by three different components commonly called elements. For an electric circuit, the elements are a capacitor, a resistor, and an inductor. There are equivalent elements in a magnetic circuit. There are three displacements that can be used for each of the element types. Only two displacements are of interest for electromagnetic systems. These are electric charge q and magnetic pole strength p. Their orientation is perpendicular vectors. The unused third displacement is mass.

C. Capacitive-Source

Electromagnetic: The source or capacitive component provides the *potential* energy of the system. The source electric and magnetic fields are independent of each other. Two terms are used to identify the field strength. These are the density and the intensity. Density is the concentration of displacement (charge or pole strength) in a known area. Intensity is the force exerted by the displacement. The intensity is equal to the

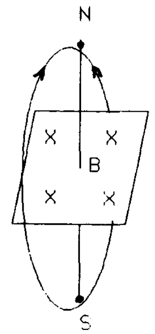

Fig. 2. Magnetic-displacement dependence.

density times the velocity. The subscripts indicate the vector directions.

Electrical density	$D(q)_y$ c/m^2
Magnetic density	$B(p)_z$ Wb/m^2
Electric intensity	$E(q)_y$ N/c
Magnetic intensity	$H(p)_z$ N/Wb.

Fig. 2 illustrates a magnetic circuit. The poles are placed perpendicular to the plane. The density is the pole strength divided by the plane area. The intensity depends on the length of the path from the pole around the plane.

Biological: The strength depends on the shape of the displacement (charge or pole) and on the reciprocal of the distance $'s'_r$ between the displacements. The field strength is defined in reference to a plane between the displacements. If the displacement is at a point (as shown in Fig. 2), then the density varies by $1/s_r^2$. If the displacement is along a line, the strength depends on $1/s_r$. If the displacement is over a plane area, half the strength is on each side of the plane.

D. Resistive Conversion

Electromagnetic: The same fundmental internal energy relationship that exists in source fields also creates real work and a resulting temperature. The temperature in turn can be used to effect a change in energy from one source to another. The change in energy over time is power.

Biological: Resistive energy has thermal radiation rather than electromagnetic. The form of heat damage to a system is very different from electromagnetic impacts. Unfortunately, this is the only effect analyzed in most studies.

E. Inductive Storage

Electromagnetic: The same fundamental internal energy relationship can be developed into a storage configuration. This is an inertia-type term. It is the *kinetic* energy of the internal system.

Biological: The controls model for the system is often described as a filter on the input. This analogy provides a rich group of performance measures. Resonance is one of these measures.

Resonance occurs when the storage (inductive) energy is equal to the source (capacitive) energy. At resonance, all the internal or characteristic energy can be converted to resistance energy and power. Resonance is defined at the natural or characteristic frequency of the system. If the frequency of an external signal matches the natural frequency, then more energy is transferred to the internal system. As a result, more internal excitation occurs.

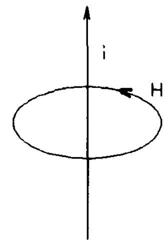

Fig. 3. Magnetic-current dependence.

Biological: This is one explanation of why cells and organisms respond to windows of frequencies. An organism may have many internal electromagnetic circuits. There will be several resonant frequencies where a pronounced response will be observed. Power line frequencies seem to be near one of these resonant frequencies. It would be expected that similar types of cells would nominally have the same electrical model. Similar cells would respond in a similar fashion, whereas different cells may not respond.

F. External

Electromagnetic: The system model is considered to be spherical in shape. The internal electromagnetic relationships are independent. On the surface of the sphere, the fields are interrelated. Furthermore, the external fields are dynamic, depending on the motion of displacements (charge or poles).

The cause of the electric field is the voltage potential. The magnetic field is dependent on the current flow as shown in Fig. 3. The intensity of the fields decreases with an increase in the length of the path around the circuit. In general, the intensity is expressed as a flow rate (Wb/s or A/s) through a distance.

Electric intensity	$E(v)_t$ V/m
Magnetic intensity	$H(i)_s$ A/m.

Since the dynamic fields are interrelated, there is a common radiation. The impact is discussed in Section IV-A. Furthermore, at very low energy levels, the quantum energy can be a factor.

Biological: There are recognized levels of electric and magnetic fields in the vicinity of power lines [8], [9]. The level of electric fields near distribution lines are 0.1 to 1 V/m. Those under a 765-kV power line are 10 000 V/m. Magnetic levels in homes are 0.01 to 5 μT. Under a 765-kV line, the levels are 1 G (10 mT).

Where rigid standards for safe exposure levels have been adopted, they are tending toward 100 V/m and 15 μT [8]. Recent Swedish efforts are moving toward 0.2 μT.

G. Thermal

The thermal equation has three components. These are entropy or loss, conduction energy, and inherent property energy. Since all three components have to do with heat, they will have an impact in the biological system.

IV. Model Application

A. Energy Concentrations

Electromagnetic: Many terms are used for concentrations of energy. These can be reduced to three basic definitions. Energy or radiation density is the amount of energy in a volume. Emittance is the energy density that exists during a period of time. Intensity is a velocity change on the energy density.

Energy density $D(W)$ J/m^3
Emittance $E(W)$ w/m^3
Energy intensity $I(W)$ w/m^2.

Although other energy sources may exist, the present discussion concern is only electromagnetic (q and p). The radiation strength depends on the shape of the energy source and on the reciprocal of the resulting volume factor. Volume is 3-D. As the shape dimension increases, the volume factor dimensions will decrease. The same amount of energy is spread over a larger surface. Therefore, the concentration will decrease at one location.

If the energy is at a point, then the density varies by $1/s_r^3$. If the energy is along a line, the strength depends on $1/s_r^2$. If the energy is over a place area, the density decreases by the distance $1/s_r$ from the plane.

Biological, Points: For biological consideration, typical point sources are motors, computer screens, and electronic devices. The radiation effect can be dramatically reduced by a slight increase in distance separation $(1/s^3)$.

Biological, Lines: For line sources, the radiation effect drops off somewhat more slowly $(1/s^2)$. Typical line sources are multiconductor cables and long wire conductors. The return path must be balanced and close to the current-carrying conductor. The closeness of the wires is compared with the distance to the specimen. Close circuit paths have a single effect on the specimen.

Biological, Planes: When the energy is distributed over a large area, the source appears to be a plane. Typical plane sources are blankets and conductors that are widely separated. The wide separation makes the conductor current appear unbalanced to the specimen. The electromagnetic field effect can be reduced by bringing the conductor and return path to close proximity.

B. Application

To mitigate the electromagnetic fields associated with power lines, restrict the use of unbalanced systems. Ground return paths should be avoided since the magnetic field is spread out. Three-phase electrical circuits should be constructed in a diamond shape to reduce the spacing and resulting dispersed field.

Fig. 4 shows a typical 12 470 V, three-wire, distribution power line and the associated electric intensity and magnetic density [24]. It can be observed that at 50 ft from the center line of the right of way that the magnetic field still exceeds the

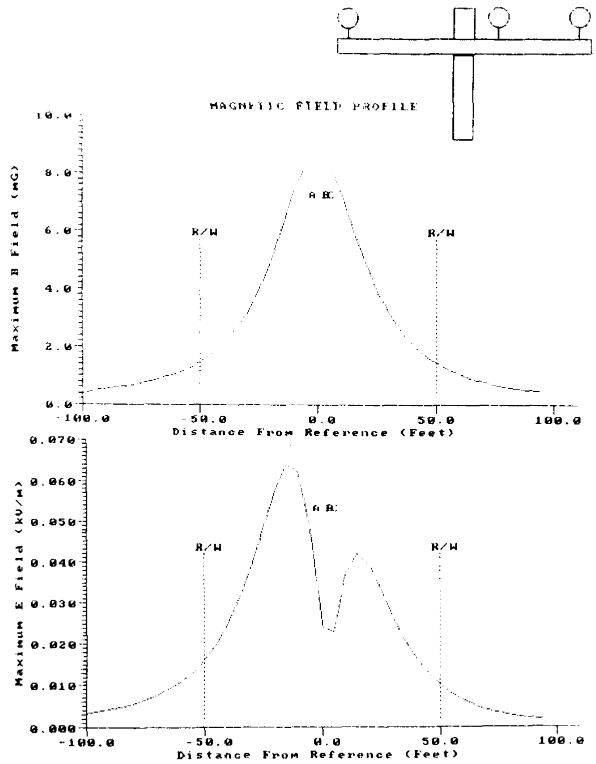

Fig. 4. 12 470 typical distribution.

0.2 μT level that has been associated with biological impact in some studies.

By making only a slight modification in the configuration, both the electric and magnetic fields can be dramatically lowered. Fig. 5 shows the changes. The magnetic field has been lowered below the 0.2-μT (2.0 mG) threshold.

Electric fields can be shielded with a variety of conducting materials. However, magnetic fields will pass through most objects including the earth. This makes magnetic mitigation more complex. Iron-based materials are the most effective shields since the materials are magnetic conductors.

C. Energy Solution and Dosage

Electromagnetic: All the energy terms are second order because of the trinity of components. Therefore, the energy at any time will follow the general solution form.

$$W(t) = W_{\text{final}} + (W_{\text{initial}} - W_{\text{final}})e^{-zt}\cos(wt + \tilde{o}).$$

A constant, steady-state term is given by W_{final}. An exponential decay term drops off with the attenuation factor 'z.' An oscillating component with phase shift is given by the cosine term.

Biologic: The energy has amplitude, frequency, and phase shift terms. This relationship is significant since most biological effects have been associated with a varying (pulsed or oscillating) field.

Energy is the common unit of conversion between forms and responses. It should be the underlying basis for any

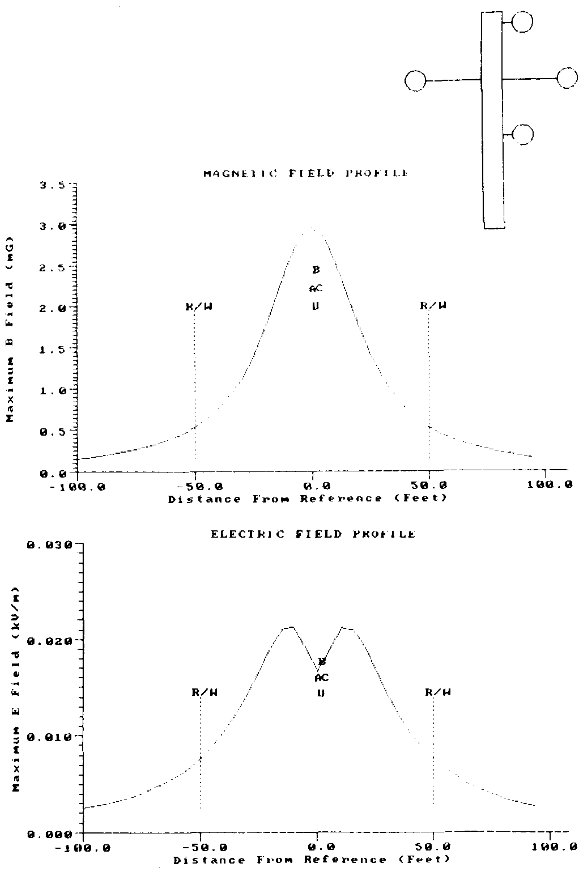

Fig. 5. Redesigned distribution system.

relationship. Dosage for a specimen is generally defined by the product of a magnitude value and a period of time. Dosage coincides with an energy definition when power is the magnitude.

$$W = \int p \, dt.$$

Incomplete Dosage: If either the magnitude of power or the time is increased, the energy will increase. However, this relationship does not provide for the complete electromagnetic energy solution. Power only exists on the resistance conversion, conservation, and thermal terms. There are other electromagnetic terms that do not have an energy-power-dosage equality.

Therefore, the simple power-dosage-type equation will not provide adequate explanation of electromagnetic influence on a system. A more complex measure must be used. The general solution form is one possibility. Alternately, a different definition of dosage relationships to energy must be developed. A component equation is proposed below.

Nonthermal Dosage: Early evaluations of electromagnetic effects on biological systems concentrated only on thermal heating [14]. This Joule heating is again a power relationship. This thermal analysis encounters the same limits on validity as discussed in the two previous paragraphs.

In addition to heat, there are several other intriguing phenomenon that influence the electromagnetic impact on systems. One procedure that has been tried is correlating a simple field strength measure. Field strength measurements are often not directly associated with the system total energy exposure. Hence, summation of field strength over time is not a valid dosage measure. Nevertheless, the field strength magnitude and time are partial indicators.

Simple Dosage: The conventional simple dosage concept assumes only an amplitude and time of exposure. However, when a varying field is applied to the system (transfer function), the response (output) will be the same frequency as the stimulus (input). Furthermore, the amplitude and phase angle will be changed.

There is an alternate energy relationship that could correlate to dosage. This is the conservation of electromagnetic energy. Dosage uses a product of time. Conservation depends on a ratio with time change.

$$dW - \frac{d_{(\mathrm{elec})}}{dt} = 0. \tag{1}$$

If the time change is short, then energy is very large. This energy definition would then be incorporated in the general solution form.

Complete Energy Dosage: By analyzing the electric and magnetic components one at a time, the electromagnetic influence on the specimen can be found. This influence is a summation of the total exposure. The components include the magnetic, thermal, and electric fields and the volume of the field at the specimen location. Note that all the terms are vectoral portions of a sphere. Hence, the orientation of the specimen must be evaluated.

The xyz subscripts indicate rectangular orientation of the sphere radius. The t subscript is tangential on the surface and perpendicular to the x and y radii. The s subscript is on the surface and perpendicular to the y and z radii The integrals are triple integrals since all the terms vary. Modified notation is used for simplicity.

$$W = \int H_s B_z V + \int P_x t + \int E_t D_y V.$$

This relationship is easiest to measure from a field perspective. Alternately, the circuit values of current and voltage can be used.

$$W = \int iBA + \int EHA \, dt + \int vDA.$$

The most basic values can be described. All three of the equations provide the same information but from different measured values.

$$W = \int ip + \int Pt + \int vq.$$

These relationships indicate the total impact is the result of current and magnetic density and electric and magnetic intensity, with voltage and electric density. Any one item may be quite small, but may still impact the total energy if its associated term is large. This complex relation assures us that there will continue to be difficulty in correlating electromagnetic field effects on biological specimens.

D. System versus Carcinogen Model

One carcinogen model assumes that there is a stimulus that initiates the cancer activity. Then, another stimulus promotes the development of the cancer. This model fits very well with the control system electromagnetic model shown in Section III.

The biological system (transfer function) can be modified by other stimuli. The initiator signal creates a new system transfer function that is the product of the system and the initiator. The electromagnetic stimulus would then act as a promoter to create a different response on the new system.

The control model would have the following forms. The first equation is the effect without an initiator in the system. The next two describe the effect after an initiator.

$$\begin{aligned}\text{First response} &= \text{System } X\text{EM (no impact)}\\ \text{New system} &= \text{System } X\text{Initiator (minor impact)}\\ \text{New response} &= \text{New system } X\text{EM promotor (impact).}\end{aligned}$$

The equations can be combined to show the composite effect.

$$\text{New response} = \text{System } X\text{Initiator } X\text{EM (impact).}$$

The system characteristics include the capacitive, resistive, and inductive elements. Hence, a frequency, damping, and phase shift are associated.

E. Unit Scaling

The electromagnetic fields that have an impact on biological systems are very small. As a result, the units are considerably different than would be experienced inside a purely electrical/magnetic device such as a motor.

Furthermore, there are several different systems of units referenced by the literature. Table I will provide some corresponding terms. The common units are Gaussian values or IEEE standard values where appropriate [18]. Type 2 component units are based on the fundamental definitions using metric values.

TABLE I

Parameter	Common	XScale =	Type 2
Magnetic pole	Mx	10^8	Wb
Magnetic density	T	1	Wb/m^2
	G	10^4	Wb/m^2
	γ	10^9	Wb/m^2
Magnetic intensity	Oe	$4\pi \times 10^{-3}$	A/m
Electric charge	C	1	C
Electric density	C/m^2	1	C/m^2
Voltage	V	1	Wb/s
Current	A	1	C/s
Energy	Ws	1	J
Power	W	1	W

V. Conclusion

A quote from the first sentence of the summary to the New York Power Line Project is appropriate [14]. "It is clear from the results of the studies sponsored by the Project, as well as from many other recent studies, that both 60-Hz electric and magnetic fields can affect certain biological systems." Numerous approaches are being considered by a number of agencies. The IEEE has at least two committees investigating possible standards. These are long-term approaches at best. In today's litigious environment, each engineer and company must make the best effort to protect their interests from spurious suits. This protection requires an understanding of the present public perception, whether it is valid or not. It further requires a detailed knowledge of the basic engineering.

Furthermore, the engineering considerations of the design, construction, and operation of electrical systems are changing. Where prudent, the system must be used in a way that will have the least impact on the public and on employees that might be exposed. The cost-benefit tradeoff necessarily includes the legal, social, and ethical responsibility. All these considerations must be made without overreaction to perceived problems. Walking this tightrope is one of the biggest challenges that has faced electrical engineers.

Appendix A
Introduction

This appendix is added for those who want to investigate the mathematics of the problem. The paper may be read completely without referring to the Appendix.

A. Background

Relationships that illustrate the fundamental nature and factors of physical systems are not generally available across scientific disciplines. As a result, much of the understanding of the underlying physics and engineering aspects of the problem has been lost. This comes from trying to manipulate the mathematics and jargon terms. This loss of general comprehension has prompted investigation of alternate ways to explain and work science and engineering problems [19].

Interdisciplinary understanding is critical to the success of most major systems analysis. If we are to achieve any hope of cross discipline interaction, relationships must be illustrated using the most basic factors.

The following equations, principles, and laws have been developed in an attempt to overcome some of the shortfalls of the traditional approach to equations for electrical and biological systems.

The concepts and laws are universal. However, only electromagnetic problems will be considered. Adding the other components to the system is beyond the scope of this paper.

The relationships are a compendium of experience, insight, and references. The technical references that have had the most impact are listed in [20]–23].

B. Energy

Although diverse systems may interact, energy can be used to equate the forms. Each of the items has three components. A principle can be stated for the energy relationships.

Principle One: Any item that can be uniquely identified can be further explained by three components. The components are source, conversion, and storage.

The composite energy equation illustrates the nature of the system.

$$W_{\text{external}} + W_{\text{thermal}} + W_{\text{internal}} = 0.$$

The internal energy is a source that is characteristic of the system. The internal characteristic is described by an inverse square law. The thermal energy describes the conversion between forms. Thermal energy contains the system entropy. The external energy represents the system storage or conservation.

The performance can be observed by the comparative position for each of the electromagnetic components of the energy system. The system may be considered to be a rotating sphere. There are internal and external positions within the sphere.

C. Dimensions

A brief explanation of the three different type dimensions is necessary. The symbol 's' represents dimensions associated with volume 'V.' The symbol 'b' represents dimensions associated with force-arm or lever distance resulting in rotational motion. The symbol 'd' represents motive distance in the direction of action.

Dynamic fields tend to be 3-D with circular surfaces. However, other measures tend to be rectangular. Therefore, a lineal representation of a spherical system will be used. The subscript 'r' represents a radial distance. The subscript 't' represents a tangential dimension on the surface. The orthogonal dimension on the surface uses the subscript 's.' The 'j' axis is the internal projection. The radial distance 'r,' as well as 'j,' are on the internal rectangular $x - y - x$ axes.

All the dimension terms are vectors. The subscript represents the vectorial direction. The product of vectors with the same subscript is the dot product. The results lie along the common axis. The product of vectors with different subscripts is the cross product. The results lie perpendicular to the axes.

A star ($*$) product will be defined as the circular product. This contains both a dot and cross product. The result is a lineal and rotational motion. The rotational motion on the t axis will track a cosine along the x axis.

APPENDIX B
INTERNAL

The internal characteristics are related by the First Law.

First Law: Displacements exist in pairs, where the value of one is determined by measurement compared with the other. The internal energy between the two is proportional to a product of their value, a field medium, a motive distance, and a lever distance and is inversely proportional to the volume of their system.

The internal energy of a system is described by three elements. The summation of the internal elements provides the characteristic equation for a system.

$$W_{\text{internal}} = W(n)_{\text{storage}} + W(n)_{\text{conversion}} + W(n)_{\text{source}}.$$

There are three displacements n in a physical system. Hence, there are three equations of this form. For electromagnetic problems, only charge and pole strength are required. The unused third displacement is mass.

A. Capacitive-Source

The source or capacitive energy may be called the potential energy. The energy equation can be written in generic form. The form is expanded to show all the factors.

$$dW_r = d\{b_{rs} * k(n)_r n_r n_o\, d_r / V_r\}$$
$$dW_r = d\{[1/C(n)_r] * n_r n_o\}.$$

When the component equation is not time constrained, it is a source. All the factors except displacement represents the capacitance of the system.

The variables may be grouped to define various terms. All the terms and values may be differential.

Term	Value	Description
n_r	basis	displacement along axis
n_o	reference	displacement reference
$k(r)$		reference field medium
$k(o)$		field medium in vacuum
$k(n)_r$	$k(r)k(o)$	field medium
A_r	$s_t X s_j$	area vector
V_r	$s_t X s_j^o s_r$	volume vector
$mf(nk)_r$	$n_o/C(n)_r$	motive force (capacitive)
$D(nk)_r$	$n_o d_r/V_r$	density–flux
$I(nk)_r$	$k(n)_r n_o d_r/V_r$	intensity
$F(nk)_r$	$k(n)_r n_r n_o d_r/V_r$	force–centripetal
$W(nk)_r$	$[1/C(n)_r] * n_r n_o$	apparent energy (capacitive).

The correspondence of the generic energy with electrical and magnetic terms are shown.

Term	Electric	Magnetic
n_r	q_y, charge	p_z, pole
$k(o)$	$1/e_o$, permittivity	$1/u_o$, permeability
$1/C(n)_r$	1/capacitance	reluctance
$mf(nk)_r$	$v(q)_y$, emf	$i(p)_z$, mmf
$D(nk)_r$	$D(q)_y$, C/m^2	$B(p)_z$, Wb/m^2
$I(nk)_r$	$E(q)_y$, nt/C	$H(p)_z$, nt/Wb.

The same terms can be identified for a mass displacement. Although Newtonian physics are not displacement related in the strict sense, this method is commonly used in physics and engineering analysis. Therefore, it also will be represented by using distance as displacement from the same capacitive-source equation.

Term	Mass	Newtonian
n_r	m_x, mass	b_r, distance
$k(o)$	G_o, gravity factor	G_o, gravity factor
$1/C(n)_r$	l/compliance	k, spring constant
$mf(nk)_r$	$v(m)_x$, gmf	F, force nt
$D(nk)_r$	$D(m)_x$, g/m^2	$D(b)_x$, nt/m^2
$I(nk)_r$	$G(m)_x$, nt/g	$G(b)_x$, 9.8 m/s^2 for m_0 = earth.

The factor d_r/V_r may be aligned to result in the area A_r. For a spherical system, the surrounding surface is a shifted Riemann sphere of area $4\pi s_r^2$. Then, the force relationship represents the familiar inverse-square law.

The potential field relationships shown are for an electric or a magnetic field. When both exist, the radiation equation for energy concentration is required. This will be developed later.

B. Resistive-Conversion

The conversion component will result in a change of energy forms. Since the physical environment is less than perfect, the energy conversion is never complete. This can be stated in the Second Law.

Second Law: Each energy conversion results in a loss in order of the system. Power is derived from the system only when there is opposition or resistance to the energy change.

When a time constraint is placed on the internal system, the field medium k is replaced by the resistivity r. The time constraint creates a velocity-type relationship. The time operation causes a rotation in motion direction.

$$dW_t = d/dt_r\{b_{rs} * r(n)_t n_r n_o\, d_t/V_t\}$$
$$dW_t = d/dt_r\{R(n)_t * n_r n_o\}.$$

All the factors except displacements represent an opposition or resistance. Again, the displacement may be charge, poles, or mass.

Term	Value	Definition
$mf(nr)_t$	$d/dt_r\{R(n)_t * n_o\}$	motive force (resistive)
$mt(nr)_t$	$d/dt_r\{n_r\}$	motive through
$\sigma + jw$	$d/dt_r\{b_{rs}/S_t\}$	lineal and rotational motion
$F(nr)_t$	$d/dt_r\{r(n)_t n_r n_o d_t/V_t\}$	force (resistive).

The definition of only a few addition terms is necessary.

Term	Electric	Magnetic
$mf(nr)_t$	$v(q)$, V	$i(p)$, A-turn
$mt(nr)_t$	$i(q)$, A	$v(p)$, V.

The mass displacement is also noted with the corresponding Newtonian relationship, which is not a true displacement but is commonly used.

Term	Mass	Newtonian
$mf(nr)_t$	gravity motive	force
$mt(nr)_t$	mass flow	velocity.

C. Inductive-Storage

With motion, storage can be translated to another form. A second-time constraint causes an acceleration-type relationship. The time impact is kept separated to defined additional terms.

The field medium k is replaced by the inertivity l. The second-time operation causes another rotation in motion direction. The subscript 'r' in this relationship is 180° from the 'r' in the potential equation.

$$dw_r = d^2/dt_r t\{b_{rs} * 1(n)_r n_r n_o\, d_r/V_r\}$$
$$dw_r = d^2/dt_r t\{L(n)_r * n_r n_o\}.$$

Only one new term is necessary.

Term	Value	Definition
$F(nl)_r$	$d^2/dt_r t\{l(n)_r n_r n_o\, d_r/V_r\}$	force–centrifugal.

Resonance occurs when source energy is equal to storage energy. Since the reciprocal of time is frequency, the characteristic frequency can be defined.

$$w(n) = 1/'\sqrt{LC}$$

D. External

The external energy contains the forcing function. By extension, it also contains the radiation if the system is not at rest.

Because the external energy will be applied to the internal energy, there is a conversion. This relationship embodies the Third Law.

Third Law: Conservation demands that nothing is created or destroyed but may change forms. The summation of the external performance minus the time constrained change on the internal characteristics must be zero. Conservation is a characteristic of energy.

In accordance with Principle One, there are three components of external energy.

$$W_{\text{external}} = W_{\text{mass-distance}} + W_{\text{electromagnetic}} + W_{\text{wave}}.$$

Only one of the components explicitly contains electromagnetics. A relationship has been developed that combines both effects [19]. The equation defines a relationship that will be called the conservation of electromagnetics.

$$dW(pq) - d/dt_r\{b_{ys} * p_z q_y\, d_t s_y/V_y\} = 0$$
$$dW(pq) - d\{k(pq)_x * p_z q_y\, d_t s_y/V_y\} = 0.$$

Several terms should be defined. Compare these kinetic terms with similar terms in the internal potential definitions.

There is a duality between electric and magnetic terms because of the product of charge and pole strength in the conservation equation.

Term	Value	Definition	Units
$v(pq)_t$	$d/dt_r\{p_z\, d_t/s_t\}$	emf	V
$i(pq)_t$	$d/dt_r\{b_{ys} * q_y/s_s\}$	mmf	A
$E(v)_t$	$d/dt_r\{p_z/s_t\}$	electric intensity	V/m
$H(i)_s$	$d/dt_r\{q_y/s_s\}$	magnetic intensity	A/m
$k(pq)_X$	$d/dt_r\{b_{ys}\}$	e-m medium	m/s
$k(pq)_x$	$1/\sqrt{[eu]_x}$	e-m medium	m/s
$U(pq)_x$	$d/dt_r\{b_{ys}\}$	e-m velocity	m/s
$F(pq)_x$	$d/dt_r\{p_z q_y\, d_t s_y/V_y\}$	force	newton.

The dynamic current circuit and the magnetic intensity circuit are orthogonal. The circles formed by the circuits are interlocking rings forming a toroid. In the limit, the summation of all the circuits results in a sphere. A second external relationship contributes to low-level energy systems. This is the quantum energy due to frequency. The conservation of wave-equation illustrates the medium effect.

$$dW(wc) - d/dt_r\{b_{xs} * h(p)w_x d_s s_e/V_x\} = 0$$
$$dW(wc) - d\{k(pq)_x * h(P)w_x\, d_s s_e/V_x\} = 0.$$

The terms are similar to other previous equations.

Term	Value	Definition	Units
$w(0)$		fundamental wave	cycle
$w(r)$		harmonic	unit
w_x	$w(r)w(0)$	medium description	cycle
f	$d/dt_r\{w_x\}$	frequency	cps
$h(P)$	6.62560^{-34}	Planck's constant	j-sec
$F(wc)_x$	$d/dt_r\{hw_x d_s s_e/V_x\}$	force	Newton.

For completeness, the conservation of mass-distance relationship is given.

$$dW(mc) - d^2/dt_r t\{b_{xs} * m_x\, d_x\} = 0$$

This equation contains Newton's force equation as well as Einstein's mass energy relationship. Angular and lineal momentum are also contained in the star product. The cross product component of the star operating on the mass is the sine of the reference angle. This is also the reciprocal of the Lorentz transform when the distances approach the wavelength.

A number of important laws are derived from the conservation of energy. These are simply special cases where part of the relationship is held constant. Using the electromagnetic term, Kirchhoff's current law arises when flux is held, and Kirchhoff's voltage law arises from holding charge constant.

From the mass-distance term, several relationships develop. The conservation of lineal and angular momentum involves the first time, mass, and distance. Force is the next time operation on the momentum. Finally, rotational energy and torque are this time operating on the lever distance and momentum.

The boundary limits applied to the conservation of energy equation provide the basis of nuclear physics. The star product provides the angle of incidence for interaction at the boundary.

E. Thermal

The three thermal equation components are property heat, conduction energy, and entropy. The entropy is the global loss. The conduction provides transfer of energy. The property heat is the inherent energy in the system. The property energy includes Nernst values for electromagnetics. The thermal equation has independently reversible relationships.

$$W_{\text{thermal}} = W_{\text{entropy}} + W_{\text{conduction}} + W_{\text{property}}.$$

The expansion of these terms adds complexity to the problem without adding to the understanding of the particular problem under discussion. However, for completeness of the universal equations, these terms are listed.

The thermal source relationship includes mass, charge-pole, and wave terms.

$$\begin{aligned} dW(nT) = {} & d\{K(R)m_x T_{xs}\} \\ & + d\{K(N)[T_x/b_{xt}]Xp_z q_y\, d_y/A_z\} \\ & + d\{h(B)w_x T_x\}. \end{aligned}$$

The thermal conversion relationship incorporates thermal conductivity when expressed in the reciprocal form.

$$dW(RT) = \{K(T)A_x T_x/b_x\}\, dt_r.$$

The thermal storage term is the global inertia and entropy. To show the independently reversible format, this is explained as a temperature.

$$dT(LT) = d^2/dt_r t\{L(T)W(LT)\} = d\{W(LT)/S(L)\}.$$

Appendix C
Energy Concentrations

Many terms are used for concentrations of energy. Energy or radiation density is a volumetric concentration. Emittance is the time-constrained density. Hence, this is a power density term. Intensity is the velocity constrained density. This is the force-arm distance on emittance. The velocity constrained term represents a flow rate and may be called flux.

Term	Value	Definition	Units
$dD(W)$	$d\{W/V\}$	energy density	J/m^3
$dE(W)$	$d/dt\{W/V\}$	emittance	W/m^3
$dI(W)$	$d/dt\{b_{rs} * W/V\}$	energy intensity	W/m^2.

Although other energy sources exist, the present discussion concern is only electric and magnetic (q and p). The radiation depends on the configuration of the energy source and the resulting volume factor.

There may be three types of energy conservation. As the distribution dimensions of the energy increase, the volume factor dimensions will decrease. The radiation strength is measured on the surface of the volume factor.

A point source has a spherical volume configuration. Then, the volume factor is 4/3 πs_r^3. When the energy is distributed along a line, the surrounding configuration is a cylindrical tube. The volume factor is the surface area. When the energy is distributed over a large area, the source appears to be a plane. Then, the volume factor is the distance to the corresponding plane.

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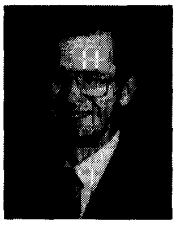

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