

What are “electromagnetic fields”?

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INTRODUCTION

We often see in the popular press, and in related technical articles, discussion of the possible adverse effects on plants, animals, or humans of the “electromagnetic fields” surrounding high-voltage transmission lines or from other sources. Engineers know of *electric fields*, and *magnetic fields*, and *electromagnetic radiation* (which involves both of those kinds of fields). But just what are “electromagnetic fields”?

This article discusses what seems to be the meaning of “electromagnetic fields” in that area of interest and also in the area of formal physics. Considerable technical background is given, but only in such detail as is needed to support the topic of the article. Almost no mathematics is involved. Appendixes cover several related matters.

The article solely covers the terminology involved and its technical underpinnings. It does not discuss any matters of the possible adverse effects of various of the phenomena on plants, animals or humans.

1 THE QUICK ANSWER (FOR THE IMPATIENT READER)

For those readers who would be tempted to go “to the back of the book” and see the answer, here it is, in simplified form. The answer might not be fully meaningful to those not familiar with the technical background involved—that’s why the rest of the article is here!

- In formal physics, “electromagnetic field” refers collectively to the AC *electric fields* and *magnetic fields* that occur as aspects of *electromagnetic radiation* (such as a radio wave), or that exist as that radiation is being formed. It does not refer to some “third kind of field”.
- As encountered in the popular press, typically in writing about concern with possible physiological effects of various phenomena, and in related technical articles, “electromagnetic fields” most often means “AC *electric fields* and/or *magnetic fields*” (which one depending on what is being written about), but may in some cases also embrace *electromagnetic radiation*.

It does not of itself refer to a specific one of those phenomena, nor does it refer to a phenomenon beyond those.

2 FIELDS

2.1 In Mathematics

In mathematics, a field is defined as a set of numbers that exhibits certain mathematical properties. Commonly-considered fields (rarely identified by that term) are the set of integers, the set of rational numbers, and so forth.

This definition does not relate at all to our topic here.

2.2 In physics

In physics, a field is defined as a physical property that has a value (scalar, vector, or tensor) at each point in space and time. While that is consistent with the usages of the term we will discuss, that is of little help.

2.3 Familiar fields

In physics and engineering, we are most often concerned with a field as a phenomenon that (at each point in space and time) exerts a force on some type of particle. Three important examples are:

- A *gravitational field* exerts a force on a particle having mass.
- An *electric field* exerts a force on a particle having an electric charge.
- A *magnetic field* exerts a force on a particle having an electric charge which is moving.

3 ELECTRIC AND MAGNETIC FIELDS

Electric and magnetic fields play major roles in this story.

3.1 Electric field

Imagine that we have two metal plates, separated (let's say in air) by a certain distance. We apply a certain electrical voltage between the two plates.

This creates between the two plates an *electric field*, the direction of which is perpendicular to the plates.

3.2 Magnetic field

Consider a straight electrical conductor carrying a certain current. At any point outside the wire, there is a *magnetic field*. Its direction is around a circle centered on the wire.

3.3 Time-varying fields

Of course the strength of an electric or magnetic field may vary over time, as a result of variation of the voltage (for the electric field) or current (for the magnetic field) that generates the field. If that voltage or current is what we consider an AC voltage or current, then we can think of the resulting field as being an “AC field”.

3.4 Those fields are stationary

It is important to note that either kind of field, of itself, whether constant or varying, is spatially stationary. That is, it does not move in space (propagate). Accordingly, the phenomenon of an electric or magnetic field, of itself, even an AC one, does not qualify for the name “radiation”.

4 ELECTROMAGNETIC RADIATION

4.1 Introduction

Electromagnetic radiation is a physical phenomenon manifested, along a certain path in its travel, as an *electromagnetic wave* (of which a *radio wave* is a well-known example).¹ In that wave we have an AC *electric field* and an AC *magnetic field*, with their spatial directions at right angles, each varying at the same frequency in synchronism with the other.

4.2 Propagation

This phenomenon propagates through space (“at the speed of light”²) and it is that property that earns this phenomenon the name “radiation”. As the radiation propagates, it transports energy. As the radiation propagates, the energy shifts back and forth between the electric and magnetic fields at the frequency of the radiation. The electric field generates the magnetic field, and the magnetic field generates the electric field. It is a wondrous “team collaboration.”

¹ For our purposes here we can consider *electromagnetic radiation* and *electromagnetic wave* to be interchangeable. For uniformity, I will mostly speak of *electromagnetic radiation*.

² Not a surprise, since light is in fact electromagnetic radiation.

One might be concerned that this sounds like some sort of perpetual motion, but it is not. The energy continuously carried outward by the wave is continually replenished by the “transmitter”.

4.3 “Radio frequency”

Electromagnetic radiation is theoretically possible at any frequency. For a certain (quite arbitrary) range of frequency, this phenomenon is spoken of as a “radio wave”, and the abbreviation “RF” (radio frequency) is often applied to such radiation or to the electrical signals that produce it.

4.4 Other forms of electromagnetic radiation

Light is the same phenomenon, albeit at a gigantically high frequency. And x-rays are the same phenomenon, at an even higher frequency.

4.5 Universal ratio between the strength of the two fields

It turns out that for any electromagnetic radiation, no matter its frequency, or its source, or how far from the antenna we are, or how “potent” the radiation is at that point, for propagation through any given medium (*e.g.*, vacuum, air), the ratio of the “strengths” of the electric and magnetic fields is always the same (as dictated by fundamental laws of physics).

4.6 Wavelength

We will encounter the concept of the *wavelength* of electromagnetic radiation at any given frequency.

Figure 1 is a plot of the value of the electrical field of an *electromagnetic wave* (that is, electromagnetic radiation considered in its travel along a certain path) **at some instant**.

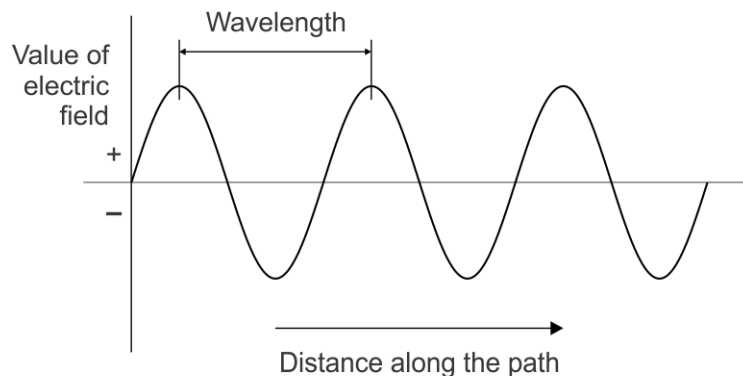


Figure 1. Electric field of an electromagnetic wave

We note that along the path of the wave the electric field has both positive and negative values (just like the voltage of an AC electrical signal).

The distance along the direction of travel of the wave, at a given instant, between two adjacent occurrences of, say, its positive maximum is defined as the *wavelength* of this wave.

The wavelength of an electromagnetic wave is proportional to the reciprocal of its frequency, thus:

$$\lambda = \frac{c_m}{f} \quad (1)$$

where λ (lower case Greek *lambda*) is the wavelength, c_m is the speed of light (in the medium of propagation involved), and f is the frequency of the wave.

For perspective, note that the wavelength of electromagnetic radiation at a frequency of 2.4 GHz (as used in, for example, Bluetooth wireless communication between electronic devices) is about 125 mm, or almost 5 inches.

But if we consider electromagnetic radiation at 60 Hz (the usual frequency of AC electrical power lines in the US), we would find that its wavelength is 5000 km, or about 3100 miles! Hold that thought.

4.7 The near and far fields, and in between

4.7.1 Introduction

We often simplistically think in terms of electromagnetic radiation being created “right there” by an antenna energized by an AC voltage at the frequency of transmission.

But if we look a little more closely, we find that immediately at the antenna that antenna has typically generated an AC electrical field and an AC magnetic field, synchronized with each other, at some frequency.

The ratio of their strengths is not (necessarily) the universal ratio between the strength of the electric and magnetic fields in electromagnetic radiation. Each is not caused by the other; they are both caused by the antenna. So we can see that, even considered together, they do not seem to constitute “electromagnetic radiation.

But most importantly, these fields themselves do not propagate through space; they are spatially “stationary” (although they vary in

time at the frequency involved). It is for that reason that, even taken together, they are not considered “radiation”.

However, as we move outward from the antenna, we find that these stationary AC fields gradually give birth to the actual *electromagnetic radiation* phenomenon, where an AC electric field and an AC magnetic field travel together, each feeding the other, and which propagates through space at the speed of light, carrying energy as it goes.

And because this phenomenon does propagate through space, it earns the name “radiation”.

As we go along some direction of the propagation of this being-born electromagnetic radiation, the strengths of the stationary electric field and the stationary magnetic field decline. They are sacrificed to the birth of the electromagnetic wave.

4.7.2 *The gradual formation of the electromagnetic radiation*

Now over what span of distance does this process of birth complete? If we look at the math involved, we find that theoretically it never completes. That is, at an arbitrary great distance from the transmitting antenna, there is still some remnant of the two stationary fields, albeit microscopic in strength.

The spatial scale of this transformation process is proportional to the wavelength of the frequency involved.

Although this process never actually “completes”, for convenience of calculation we often arbitrarily consider that at a distance of 2 times the wavelength from the antenna or more the process is so nearly complete that we consider the electromagnetic radiation to be completely formed, and the stationary fields completely gone (sacrificed to the birth of the electromagnetic wave).

We describe that as the “far field” situation.

In that same vein, over a distance from the antenna out to 1 times the wavelength we arbitrarily consider that the stationary fields are of constant strength and no electromagnetic radiation has yet been born.

We describe that as the “near field” situation.

In the intervening region of distance from the transmitter from 1 times the wavelength to 2 times the wavelength, we arbitrarily consider that there exist both the stationary fields and electromagnetic radiation, in varying proportion, as though the transformation from two stationary fields to electromagnetic radiation wholly takes place in this “no man’s

land” between the near field and far field regions. We may speak of that region as the “transition region”.

4.7.3 *The near field communication (NFC) system*

The concept of “near field” and far field” phenomena has for the most part, until recently, only been encountered by physicists and radio engineers. But in modern times many people have seen reference to the *near field communication* (NFC) system.

This is used in a wide range of very short distance communication purposes (the distance involved typically being only about one inch or so), often involving a smartphone. One example is to allow two smartphones, held back-to-back, to exchange information (perhaps contact information). Another example is to allow a smartphone application to acquire data from a continuous glucose monitor (CGM) sensor worn (on the skin) by diabetics.

The NFC system operates at a frequency of 13.56 MHz, clearly in what is considered the “radio frequency” regime. At that frequency, the wavelength is about 22 m (about 72 ft). Thus, at the typical working distance of NFC operation (one inch or so), we are clearly in the “near field” regime (thus the name).

In fact, the detection of this signal by the receiving device is wholly by detection of the magnetic field generated by the transmitting device. The electromagnetic radiation that is gradually formed by the interaction of the magnetic and electric fields generated by the transmitter as we go farther from the transmitter is not utilized³.

Essentially, the two devices are “coupled” by an air-core transformer, with the primary winding in the transmitting device and the secondary winding in the receiving device.

4.8 The effect on a charged particle

A particle having an electric charge, in a region where there is electromagnetic radiation (that is, where there is an “electromagnetic field” in the sense that term is used in physics) is subject to two forces at any point in space and time:

³ In fact, the “antenna” of the transmitting device (typically of the “loop” type) is designed to be relatively ineffectual in generating an electric field. The result is that the intensity of the electromagnetic radiation that eventually ensues is very small. This minimizes the possibility of unintended receipt of, or interference by, the NFC signal as electromagnetic radiation at any even moderately-distant point.

- A force due to the electric field, which depends on the strength of the field and the charge on the particle, and is in the direction of the field.
- If the particle is moving in an appropriate direction, a force due to the magnetic field. The magnitude of this force depends on the strength of the magnetic field, the charge on the particle, and the component of the velocity of the particle that is at right angles to the direction of the field. The direction of this force is at right angles to both the direction of the field and the component of the velocity of the particle that is at right angles to the direction of the field.

The combination of those forces causes an acceleration of the particle, which changes its velocity, which in turn changes the second component of force on it. And of course both fields continue to vary in their strength with time. So we can imagine that the path of such a particle is indeed complicated to reckon. And yjay is really of no consequence to the matter at hand here.

5 QUANTIFYING THESE PHENOMENA

The “strength” of electric fields, magnetic fields, and electromagnetic waves can be quantitatively described with various units. This is discussed in Appendix A.

6 THE “ELECTROMAGNETIC FIELD”

6.1 Introduction

Here we finally get to the actual question that is the title of this article: “what does ‘electromagnetic field’ mean?”

6.2 In physics

6.2.1 *Description*

In formal writing in the area of physics, the term “electromagnetic field” refers to, throughout the saga of the birth of electromagnetic radiation, the collective phenomena of both an AC electric field and a companion synchronized AC magnetic field, whether stationary precursors to the electromagnetic radiation, components of the actual propagating electromagnetic radiation, or a mixture of the two.

Note that here, “electromagnetic field” does not refer to some physical phenomenon different from the electric field or the magnetic field. It just embraces related instances of those two. (It’s a little like “ham and cheese”, which does not describe any new food substance.)

There are several ways to mathematically describe such an electromagnetic field. One way describes its electric field aspect as a vector quantity, and also its magnetic field aspect as another vector quantity (both functions of space and time—the “where and when”).

Another way is with a mathematical *tensor* that in effect combines both those descriptions (also a function of space and time).

6.2.2 *First usage*

It is considered that the term first appeared in the seminal 1865 paper by famed Scottish physicist James Clerk Maxwell, “A Dynamical Theory of the Electromagnetic Field”.

6.3 *Synonym for “electromagnetic radiation”*

In some “learned journal” papers on the potentially adverse physiological affects of *electromagnetic radiation*, that phenomenon is described as “electromagnetic fields” (“EMF”). The reason for this usage (which seems well-ingrained) is not apparent to me.

6.4 *In the popular press*

6.4.1 *Introduction*

In the popular press, we may find discussions of concerns that plants, animals, or humans may be physiologically damaged by extended exposure to what are almost always described as “electromagnetic fields” (often abbreviated as “EMF”), generated, for example, by high-voltage electrical transmission lines, or perhaps by cellular telephone towers, or microwave ovens. What are those “electromagnetic fields”?

6.4.2 *Electromagnetic radiation?*

We might from the term at first think that the phenomenon mentioned is actually *electromagnetic radiation*. And in fact, as mentioned above, some formal papers use “electromagnetic field” to clearly mean “electromagnetic radiation”

But a prominent subset of this area of concern relates to phenomena generated by AC power transmission lines, operating in the US at a frequency of 60 Hz. The voltages and current involved lead to the generation of both *electric* and *magnetic fields* that, at the ground level under the lines, are by no means trivial in strength..

But if we delve into the math involved, we find that even in the case of a 60 Hz transmission line operating at an extremely high voltage, and whose conductors carry immense currents, the resulting

electromagnetic radiation even on the ground directly under the transmission line is of inconsequential strength.

This is a consequence of the large wavelength of that frequency, so at such a point we are just at the very beginning of the “near field” region (as discussed in Section 4.7), in which we consider the actual electromagnetic radiation to have not yet been born to any significant degree. So it generally warrants no attention in this specific area of discussion. It can’t, in that situation, be considered as what is meant by “electromagnetic fields”.

6.4.3 *The same as used in physics?*

Or perhaps the reference is to the electromagnetic field as the term is used in physics (as discussed in Section 6.2). But no.

6.4.4 *What it does mean*

It turns out that in this area of interest, seemingly the term “electromagnetic field” usually means electric fields, or magnetic fields, or (maybe) electromagnetic radiation, whichever is of importance in a particular discussion..

6.4.5 *What it is not*

Note that here, “electromagnetic field” does not refer to some phenomenon different from the electric field, the magnetic field, or electromagnetic radiation.

6.5 In related technical articles

In technical (but not “learned journal” level) articles about this particular area of concern, “electromagnetic fields” is often used in this same way: not to describe a unique physical phenomenon, but rather to mean electric fields, or magnetic fields, or maybe electromagnetic radiation.

7 ABOUT “ELF” PHENOMENA

Often, especially in discussions of the possibility that electric and/or magnetic fields could have physiological effects, we see the abbreviation “ELF”⁴ (extremely low frequency) mentioned, sometimes even as the seeming descriptor of some particular physical phenomenon. The usage there is a bit tricky, and is discussed further in Appendix B.

⁴ Usually said “E-L-F”, not “elf”.

8 CONSUMER “EMF METERS”

There are available at the consumer level instruments that are typically described as “EMF meters”. These are suggested for use to assess the level of exposure to “electromagnetic fields” that may be found near electrical transmission lines, or (for some meters) perhaps emitted from a nearby cellular telephone base station (“cell tower”) or from such appliances as microwave ovens, or the Wi-Fi hub in a home’s computer system, or a Bluetooth earpiece, or a computer itself. They are often commonly described as also being of use in “ghost hunting”. These are discussed further in Appendix C.

9 EFFECT ON ANIMALS AND HUMANS

It is almost only in discussions of the possible adverse effect of the phenomena discussed in this paper on animals and humans that we encounter this second use of the term “electromagnetic fields”, and those matters themselves are far outside the scope of this article (and the ken of this author).

But it is of note that in writings that discuss some specific harm to animals or humans, possibly even suggesting the physiological mechanisms of that harm, almost always the phenomenon involved is actually specifically the electric field. or the magnetic field, or electromagnetic radiation.

So, while ascribing the situation of concern as exposure to “electromagnetic fields” is not false (under the meaning of that term used in this area of interest), it inaccurately suggests the existence of some phenomenon that is not an electric field, or a magnetic field, or electromagnetic radiation, but something else.

10 ELECTROMAGNETIC HYPERSENSITIVITY

This is also related to the topic of this article only by way of the use of the terminology discussed here.

Electromagnetic hypersensitivity is an malady in which an individual is said to seemingly be overly-sensitive to “electromagnetic fields”, usually in an adverse way.^{5 6} But what phenomena are considered “electromagnetic fields” in this regard?

⁵ A well-known case is that of a fictional character, Chuck McGill, in the TV series “Better Call Saul”. Chuck claimed to be severely afflicted by even the presence nearby of a flashlight battery, but that was later shown to not really be so.

It seems that the possible scope of the malady includes over-sensitivity to electric fields, and/or magnetic fields, and/or electromagnetic waves (electromagnetic radiation). That is, the meaning of “electromagnetic radiation” here is essentially the same as elsewhere in the area of concern over adverse effects of “electromagnetic fields” on animals and humans.

11 OTHER USES OF THE TERM

In some contexts, “electromagnetic fields” is used when it is in particular *electromagnetic radiation* that is of interest. While, in the usage in formal physics, “electromagnetic fields” does include (collectively) the fields that are the sole components of electromagnetic radiation, in my opinion the use of the term “electromagnetic fields” (rather than “electromagnetic radiation”) to refer to this phenomenon unduly obscures what is really meant.

We most often see this usage in publications relating to the adverse physiological effects of electromagnetic radiation.

12 THE OTHER “EMF”

One reason that electrical engineers⁷, first encountering “EMF” in the context of concern with the effects of such on animals and people, are often baffled is that “EMF” has a long history of use in the field of electrical engineering as the abbreviation for *electromotive force* (a quite different meaning). This matter is discussed in Appendix D.

13 HIGH VOLTAGE DC TRANSMISSION LINES

Most of the references to electrical transmission lines above are in the context of AC operation, as that is the most widespread. But today there is considerable and increasing use of high capacity transmission lines operating on a DC basis, with conductor voltages to ground (in the US) of up to 800 kV⁸ (soon perhaps greater), and I felt I should give that a nod here.

Although this practice requires the use of costly AC-DC and DC-AC conversion equipment at both ends of the lines (to couple them into a

⁶ One paper describes this as “idiopathic environmental intolerance to electromagnetic fields” (IEI-EMF)”, where “idiopathic” is seemingly used in its medical sense, meaning “of unknown causation”.

⁷ Myself included.

⁸ 1.6 MV conductor-to-conductor.

basically AC-based power grid), for lines of considerable length the cost of these is said to be less than the cost advantages of the transmission lines themselves (a topic that is outside the scope of this article).

These lines also exhibit significant (DC) electric and magnetic fields nearby (the generation of such fields is not solely an AC phenomenon).

There have been expressed many concerns with the implications of these fields, the specifics of which concerns are outside the scope of this article.

But much of the anecdotal information speaks not to the possibility of induced physiological effects but rather of direct “electric” effects, such as tales of sparks being emitted from umbrellas used under or nearly under such lines, or “tingling” felt in the extremities of persons under or nearly under such lines.

14 SUMMARY

- As encountered in the context of formal physics, “electromagnetic field” refers to the combination of the stationary synchronized AC *electric* and *magnetic fields* that are the precursors of electromagnetic radiation; or the combination of the fields that are the components of propagating *electromagnetic radiation* (as an electromagnetic wave); or the overall combination of the fields of both types (both stationary and propagating) that we consider to exist in the “transition region”.

Note that here, “electromagnetic field” does not refer to some field phenomenon distinct from the *electric field*, the *magnetic field* or *electromagnetic radiation*, nor does it intrinsically refer to a certain specific one of those.

- As encountered in the popular press, typically in writing about concern with possible physiological effects of various phenomena, and in related technical articles, “electromagnetic fields” most often means “*electric fields* and/or *magnetic fields*” (which one depending on what is being written about) but may in some cases also embrace *electromagnetic radiation*.

Note that here, “electromagnetic field” does not refer to some field phenomenon distinct from the *electric field*, the *magnetic field* or *electromagnetic radiation*, nor does it intrinsically refer to a certain specific one of those.

15 EDITORIAL SUGGESTIONS

I suggest that authors wishing to speak (outside the realm of formal physics) about *electric fields* and/or *magnetic fields* and/or *electromagnetic radiation* would say “electric fields” and/or “magnetic fields” and/or “electromagnetic radiation” (as is applicable) and avoid the term “electromagnetic fields”.

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Appendix A

Quantifying these phenomena

A.1 INTRODUCTION

The “strength” of electric fields, magnetic fields, and electromagnetic waves can be quantified in different ways, various units being involved. This appendix summarizes that situation. An alert: this gets a bit more “in the weeds” technically than this article in general.

In this discussion, “SI” refers to the International System of Units, the “modern metric system”, whose units are today preferred for use in scientific and engineering work.

A.2 PHENOMENA AND THEIR MEASURES

In formal technical wiring, we are careful to distinguish between *physical phenomena* and their *measures*. For example, if we write, “This causes a current, I_{e1} , to flow into the emitter of this transistor”, “current I_{e5} ” might mean either:

- The physical phenomenon of a current (named “ I_{e1} ”) flowing, or
- The measure of the “strength” of this current represented by the value “ I_{e1} ”. That is a number. even though we might not know its numerical value at some instant.

And mathematicians, in particular, would like us to be aware that these are not the same thing.

But in most work, maintaining that distinction is not of any great value—there is little chance of misunderstanding. In fact, if we speak of “current I_{e1} ”, it can usually be taken to mean both of those things.

Nonetheless, in what follows, I will try and be rigorous about the difference, which might make some of the writing seem “extra complicated”.

On the other hand, since the *measures* of these phenomena actually speak of what we reasonably think of as their “strength”, to facilitate understanding I will actually mostly use that actually-imprecise term.

A.3 ELECTRIC FIELDS

The strength of an electric field, symbolized mathematically as E , is stated in *volts per meter* (V/m), a composite SI unit. As with all SI units, the usual SI multiplier prefixes (*mili*, *kilo*, etc.) may of course be applied. That is, an electric field strength of 0.04 V/m may be stated as 40 mV/m.

In the case of an AC electric field, which varies cyclically over time, it is usually the root-mean-square (RMS) measure of the field strength that is stated.

A.4 MAGNETIC FIELDS

A.4.1 Two meanings

Here we can be confounded by the fact that, often throughout the technical literature, term “magnetic field” is used to denote two distinct but related properties of a magnetic phenomenon, each with its own measure of “strength” and symbol for that. Because of that, I will deal with magnetic phenomena in greater detail than might seem to be needed here.

A.4.2 An electrical circuit analogy

We can perhaps best grasp this matter by first looking at an electrical circuit. In Figure 2, we see a simple electrical circuit

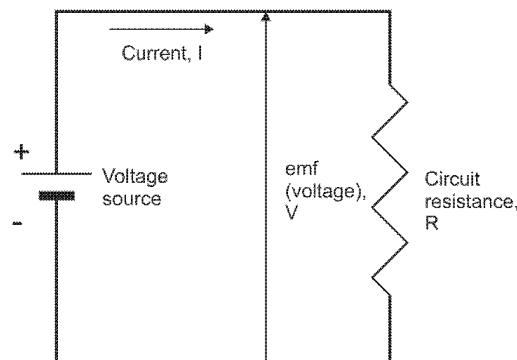


Figure 2. Electrical circuit

It comprises a source of “voltage” (the “battery” symbol), and a circuit whose resistance is “lumped” as a resistor, whose resistance value is represented by R . The “strength” of the voltage is represented by V .⁹

Note that the traditional name for what is most often today called *voltage* is *electromotive force* (emf). Hold that thought.

⁹ Note that the symbol “ V ” has a dual meaning. It represents the voltage as a physical phenomenon, and also (as a mathematical symbol) the “measure” of the “strength” of that phenomenon. A similar thing applies to the symbols “ I ” and “ R ”.

The result is that an electric current, whose strength is represented by the symbol I , is caused to flow. That is given by the infamous Ohm’s law, in this form:¹⁰

$$I = \frac{V}{R} \quad (2)$$

There is a sort of “cause and result” relationship at work here, where V is the measure of the “cause” and I is the measure of the “result”.

A.4.3 A basic magnetic circuit

Now we will move into the magnetic domain with a simple magnetic circuit, a mostly square circuit of, for example, iron, seen in Figure 3.

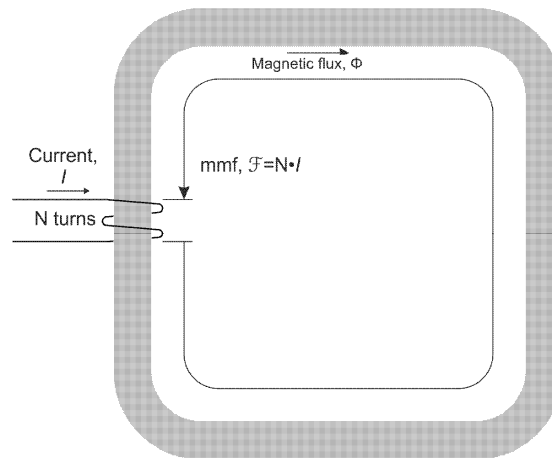


Figure 3. Magnetic circuit

The circuit is energized by a *magnetomotive force* (mmf) (note the parallel with the traditional name of an electrical phenomenon), created by an electric current in the coil we see at the left. The strength of this magnetomotive force is represented by the symbol “ $\mathcal{F}$ ”¹¹. It is the product of the current, I , in the coil and the number of turns, N , in the coil.

¹⁰ Electrical engineers often remember that relationship in the classical form $E = IR$, where “ E ” is an earlier symbol for *voltage* (derived from its formal name, *electromotive force*).

¹¹ Actually, the traditional symbol is what is often called “curly F ”, but that is sometimes problematical typographically, so I use a “script F ” from the Unicode “letter-like symbols” block (and later the same for an “ R ” symbol).

The result is that a *magnetic flux* is caused to flow¹² through the circuit. The strength (we can think, “amount”) of this flux is represented by the symbol Φ (upper case Greek “*phi*”).

The two are in fact related by what we can think of as the “Magnetic Ohm’s law”, thus:

$$\Phi = \frac{\mathcal{F}}{\mathcal{R}} \quad (3)$$

Where $\mathcal{R}$ represents the *reluctance* of the magnetic circuit (sort of the analogue of the *resistance* of an electrical circuit).

There is a sort of “cause and result” relationship at work here, where $\mathcal{F}$ is the measure of the “cause” and Φ is the measure of the “result”.

Note that these quantities apply to the magnetic circuit visualized as “one-dimensional”

A.4.4 Spatially-normalized values

But in speaking of what exists at points in the three-dimensional magnetic circuit, we call upon *spatially-normalized values*. We see this in Figure 4.

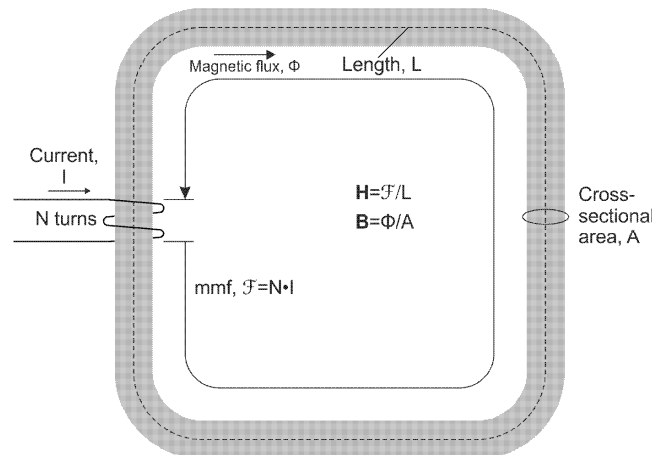


Figure 4. Magnetic circuit—spatially-normalized values

We divide the mmf, $\mathcal{F}$, by the length of the magnetic circuit, L , to get a property and quantity whose formal SI name is *magnetic field strength*, with symbol $\mathbf{H}$ (the boldface style reminds us that this is a vector quantity, that is, it has both a magnitude and a direction).

¹² *Flux* in fact means “flow”.

And we divide the magnetic flux, Φ , by the cross sectional area of the circuit, A , to get a property and quantity whose formal SI name is *magnetic flux density*, with symbol **B** (again a vector quantity).

There is a sort of “cause and result” relationship at work here, where **H** is the measure of the “cause” and **B** is the measure of the “result”.

A.4.5 An ambiguity in names

Sadly, the term “magnetic field strength” (in a quantitative sense) is often carelessly used for either the property *magnetic flux density* (**H**) or the property *magnetic field strength* **B**. This can be avoided by utilizing the official SI names of these properties.

In that vein, here, I will use the term *magnetic field strength* for **H**, and *magnetic flux density* for **B**.

I will only use “magnetic field” to speak of the overall physical phenomenon.

A.4.6 What we will mostly be concerned with

In the area of interest considered in this article, the magnetic property we will be most concerned with is **B**, the *magnetic flux density* (the “result-like” property).

As to the quantification of this property, wide use is made of two different units. The SI unit of magnetic flux density is the *tesla*¹³ (T). This unit is used today in essentially all contexts in Europe, and is often used in serious technical writing in the United States.

But still in much technical writing in the United States, and almost universally in the area of interest discussed here, the older (and non-SI) unit the gauss¹⁴ (g)¹⁵ is used. It is related to the tesla (T) thus:

$$10,000 \text{ gauss} = 1 \text{ tesla} \quad (\text{exactly})$$

¹³ Named in honor of the brilliant and decidedly eccentric pioneer in the field of electricity and its applications, Nikola Tesla.

¹⁴ Named in honor of the German mathematician and physicist Carl Friedrich Gauss, a major contributor to the scientific understanding of magnetism

¹⁵ For SI units named in honor of a person, the unit name is not capitalized (“volt”) but the abbreviation is (“V”). But the gauss is not an SI unit, so that rule does not apply, and the traditional abbreviation for that unit is “g”.

Again, in either case, the usual SI multiplier prefixes (*milli*, *kilo*, etc.) may of course be applied.

In the case of an AC magnetic field, which varies over time, as an “overall” measure, it is usually the root-mean-square (RMS) measure of the magnetic flux density that is stated.

A.5 ELECTROMAGNETIC RADIATION

A.5.1 Introduction

The strength of electromagnetic radiation at some point in its travels is commonly stated in one of two forms.

A.5.2 Areal power density

We can state the *areal*¹⁶ *power density* (usually said as just “power density”) of the radiation at the point of interest. This is the amount of power transported by the radiation per unit area of a hypothetical plane through that point, perpendicular to the direction of propagation of the radiation, through which the wave progresses..

In fact, although we often do not recognize this, that measure is a vector quality, consisting of a magnitude (defined as I just described) and a direction (the direction along which this power flows).¹⁷

In an electric circuit the power is the product of the voltage and the current.

Similarly, the areal power density of electromagnetic radiation is the product of the electric field strength (E) and the magnetic flux density (B) (times a certain constant). Its symbol is commonly **S**.

The SI unit for this property (an SI composite unit) is the *watt per square meter* (W/m^2). As always, SI multiplier prefixes may be used when appropriate.

This is the notation used in most scientific work to describe the “potency” of an electromagnetic wave at a certain point, and is also used for that in some regulatory contexts.

¹⁶ “Areal” means “pertaining to area”. It is often confused with “aerial” (which essentially means “pertaining to or in the air”). Areal densities are often called *surface densities*.

¹⁷ That vector is often called the “Poynting vector”, after John Henry Poynting, an English physicist, who first characterized this measure. This provides a wonderful pun for electrical engineering sophomores, since it is **pointing** in the direction the power flows.

In the case of an AC electromagnetic wave, where the instantaneous areal power density at a point varies over time, it is usually the time average of the areal power density that is stated.

A.5.3 Electric field strength

As discussed just above, in electromagnetic radiation the areal power density is proportional to the product of the strength of the electric field and the magnetic flux density of the magnetic field.

But, as I mentioned in Section 4, in a given medium through which electromagnetic radiation propagates (and we are most often concerned with that being air), the ratio of the strength of the electric field to the strength of the magnetic field is always the same.

Thus, the areal power density is proportional to the square of the strength of the electric field (stated on an RMS basis), a constant being involved.

Accordingly, we can describe the strength of electromagnetic radiation at a certain point just by stating the strength of its electric field. As we saw above, the basic SI composite unit for electric field strength is the volt per meter (V/m). As always, SI multiplier prefixes are used when appropriate. There is no uniform symbol for this property in this usage.

This is the notation used in much “practical” radio engineering work for describing the “potency” of an electromagnetic wave at a certain point, and is also used for that in some regulatory contexts.

Yes, alternatively we could also state the strength of the magnetic field for this purpose, But the nature of the unit of an electric field has been much more easily grasped than the nature of the unit of magnetic flux density, and so the electric field got the nod for this form of notation.

A.5.4 What about the electromagnetic field?

As I mentioned earlier, in formal physics we often encounter the notion of the “electromagnetic field”, a concept that embraces both the electric field and the magnetic field that together make up electromagnetic radiation, or the fields that are a precursor to the electromagnetic radiation as it is born.

This “electromagnetic field” is described quantitatively in one of two fairly arcane ways, which I mentioned earlier but did not discuss.. Unlike the other physical properties discussed in the article, this description does not consist of a single number (or a number plus a

direction). Thus we cannot consider it to state the “strength” of the electromagnetic field.

However, there are equations that, from the parameters of that description, can give us the “strength” of the *electromagnetic radiation* that is involved (in one of the forms mentioned just above).

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Appendix B

About “ELF” phenomena

B.1 ITU RADIO FREQUENCY BANDS

With respect to radio waves, the International Telecommunication Union (ITU) classifies the frequencies of such waves over the total range of 3 Hz-3 THz in terms of a set of named decade-wide “frequency bands”.

The lowest of those bands, spanning the frequency range 3-30 Hz, is called the “extra low frequency” (ELF) band. The next of those bands, spanning the frequency range 30-300 Hz, is called the “super low frequency” (SLF band).

A few steps higher we have the range from 30 Mhz-300 Mhz, called the “very high frequency” (VHF) band, and beyond that the range from 300 MHz-3 Ghz, called the “ultra high frequency” (UHF) band. At the top of this scheme (as so far defined) we have the range from 300 Ghz-3 THz, called the “tremendously high frequency” (THF) band.

While these frequency band designations are intended to be used to describe the frequencies of radio waves, is not unusual to use these band definitions for things that are not radio waves but are related to such (such as radio frequency electrical signals or electric or magnetic fields).

Under the ISO scheme, AC electric and magnetic fields with a frequency of 50 Hz or 60 Hz (the frequencies of most AC power lines worldwide) would be considered SLF phenomena.

However, various scientific, regulatory, and advisory bodies, and many authors, use “ELF” to designate a different frequency range, especially with respect to the matters discussed in this article. In fact, in that area of discussion, 60 Hz phenomena are typically spoken of as “ELF”¹⁸ phenomena, that frequency range usually in that case being considered to run from just above zero through perhaps 100 kHz. In other contexts, that range is considered as being from just above zero through 300 kHz. There is no “official” standardization of that usage.

And often, especially in the popular press and related technical articles, the various phenomena of the type being considered here whose frequencies fall in that range are characterized as “ELF” phenomena, without mentioning the nature of the phenomenon being mentioned.

¹⁸ Again, usually said “E-L-F”, not “elf”.

Now, from the broader context, it would seem that what is implied by, for example, “ELF fields” would include *electric fields*, *magnetic fields*, and *magnetic radiation* of frequency in that range. But as I discussed in section 6.4.2, at a frequency of 50 Hz or 60 Hz, the *electromagnetic radiation* from an AC power line would be miniscule. As a result, it is “understood” that when mention is made of “ELF fields”, that generally refers only to *electric fields* and/or *magnetic fields*. Sometimes we see mention of “ELF-EMF” phenomena, but with that same implication.

In such contexts, when actual electromagnetic radiation is to be mentioned (typically at a frequency of well above 100 kHz) it is characterized as an “RF” (radio frequency) phenomenon, since the frequencies at which is generally practical to generate a usable electromagnetic wave are typically considered “radio frequencies”.

So, to summarize, in this area of discussion:

- When we see ELF “things” mentioned, almost always the reference is to electric or magnetic fields (and at “relatively low” frequencies).
- When we see “RF” things mentioned, almost always the reference is to electromagnetic radiation (and at not “relatively low” frequencies).

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Appendix C EMF meters

C.1 INTRODUCTION

There are available at the consumer level instruments that are typically described as “EMF meters”. These are suggested for use to assess the level of exposure to “electromagnetic fields” that may be emanated by electrical power lines, or in the case of some of those meters, from a nearby cellular telephone base station (“cell tower”), or from such appliances as microwave ovens, or the Wi-Fi hub in a home’s computer system, or the computers themselves. They are often commonly described by sellers as also being of use in “ghost hunting”.¹⁹

C.2 PROPERTIES DETECTED AND MEASURED

Many of those meters are described as being able to detect and report the magnitude of *electric fields* and *magnetic fields* but not of *electromagnetic radiation*. They typically report the strength of detected electric or magnetic fields in the accepted scientific/engineering metrics and units (see Appendix A).

Some units, however, also detect *electromagnetic radiation*. This latter aspect (when present) is most commonly described for use in detecting “RF” (radio frequency) phenomena, since the range of frequencies over which they can detect electromagnetic radiation is that generally considered to be “radio frequencies”.

These devices report the strength of detected electromagnetic radiation in one of the accepted scientific/engineering metrics and units

Devices of this latter kind are often described as detecting “EF/MF/RF” (meaning electric fields, magnetic fields, and radio-frequency electromagnetic radiation).

C.3 FREQUENCY RANGES

One model with that full range of capabilities, made by a well-respected maker of electrical measuring instruments²⁰, as to the

¹⁹ A matter that is way beyond the scope of this article, and the ken of the author.

²⁰ Perhaps embarrassed by the mention, by sellers of this unit, of its use for “ghost hunting”, they do not include this item in their general catalog of measuring instruments.

detection of electric fields and magnetic fields has a stated frequency range of 30 Hz-1000 Hz, and thus would seem to be well suited for the detection and quantification of such fields generated by, for example, high voltage transmission lines.

As to the detection of electromagnetic radiation (“RF”), the unit has a stated range of 50 MHz-3.5 GHz. It would thus not be suited for the detection of electromagnetic radiation from power lines. But as we heard before, the electromagnetic radiation produced by transmission lines operating at the usual US frequency of 60 Hz would typically be miniscule, and thus does not generally warrant measurement. This aspect though would seem suited for the detection of electromagnetic radiation at the frequencies of most concern (perhaps the electromagnetic radiation emitted by a domestic microwave oven).

I have had no experience with such instruments.

Related is a class of instruments often described as “RF field strength meters”. They are intended to measure the “strength” of electromagnetic radiation, often reporting the result in terms of the electric field strength²¹ (as mentioned in Section A.5.3, thus the name.

The frequency range of such instruments varies widely over the different kinds, but might typically be 100 kHz-1 GHz.

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²¹ In many cases, since the range of possible indications is immense, a “decibel” (logarithmic) reporting scheme is often used. Generally the base of that scheme is an electric field strength of 1 μ /m (one microvolt per meter), RMS.

Appendix D

The other “EMF”

One reason that electrical engineers²², first encountering “EMF” in the context of concern with the effects of such on animals and people, are baffled is that “EMF” has a long history of use in the field of electrical engineering, as the abbreviation for *electromotive force*.

That is actually the historical formal name for the electrical property usually today described as “voltage”. The name comes from the fact that this property describes with what force (the term here being metaphorical) the electrical phenomenon of interest motivates electrons to move through a circuit (thus causing an electrical current).

As this area of study progressed, this property came to be denominated in the unit *volt*.

As a result, perhaps because the term “electromotive force” was rather clumsy, in practical work that property was usually spoken of as the “voltage” of a certain circuit. And that eventually became the official term for that property in many areas of work.²³

But there are a few situations where, for some reason, the historical term “electromotive force” continued in use (albeit often only abbreviated, as “EMF”). For example, in a certain type of electric motor, the “stator” (the stationary part) carries coils that generate a magnetic field. There are coils in the “rotor” (the rotating part) that are fed with a voltage, which causes a current to flow through them. The result is that those coils experience a physical force that leads to a torque that turns the rotor (and thus the load).

But as the rotor coils travel through the magnetic field from the stator, that generates a voltage in the rotor coils (just as would be the case of a generator). That voltage is inherently opposite in direction from the voltage applied to the rotor coils, and thus counters that voltage, leading to a lower net voltage to energize the rotor.

In fact, at a certain speed of rotation, and assuming a certain torque load on the motor at that speed, this situation reaches equilibrium, the net voltage on the rotor windings causing a current that creates a

²² Myself included

²³ You might think that for a similar reason, electrical *current*, denominated in the unit *ampere*, would have come to be called in practical work “amperage”, and while there is some history of that, it did not become the “official” practice.

torque on the rotor just matching the load on the motor, and the motor continues to turn at that equilibrium speed.

But, for whatever historical reason, that *voltage* that is generated in the rotor coils is typically called by the historical name “counter electro-motive force”, or more commonly, the “counter EMF” (often done as “counter emf”).

And of course this meaning of “EMF” has nothing to do with the other two meanings of “EMF” discussed in this article.

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