Low frequency fields

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10.1 Introduction

The word "radiation" is often taken as a synonym to electromagnetic waves. All electromagnetic waves are solutions of Maxwell's equations, but the waves have very different properties when they interact with matter, depending on the frequency (and wavelength) of the waves. In figure 1 the so-called electromagnetic spectrum is given, and we see that very high frequency electromagnetic fields appear as γ-rays (gamma radiation), X-rays and ultraviolet (UV) radiation. These examples of waves are called ionizing radiation, since such radiation may knock out electrons from atoms or molecules so that the molecule is left with an net electric charge (becomes an ion, at least for a short time) and a more or less permanent radiation damage may be created.

Waves with lower frequencies can not ionize atoms or molecules directly, and are called non-ionizing radiation. Waves with slightly lower frequencies than UV are visible light. Then follows infrared radiation, microwaves and radio waves. As one moves to even lower frequencies, the common solutions of Maxwell's equations are no longer ordinary electromagnetic waves. Thus, when we come down to e.g. 50 or 60 Hz, we rather talk about low frequency electric and magnetic *fields*, in short, electromagnetic *fields*, and they are no longer an integral part of the electromagnetic spectrum. For that reason, "power line radiation" is not a natural part of Figure 10-1, and is consequently put in a parenthesis.

When we discuss the intensity, dose and biological effects from ionizing radiation or light, it is relatively easy at least to characterize the radiation: Type of "particles", the photon frequency or particle energy spectrum, the intensity at various positions in space, and the

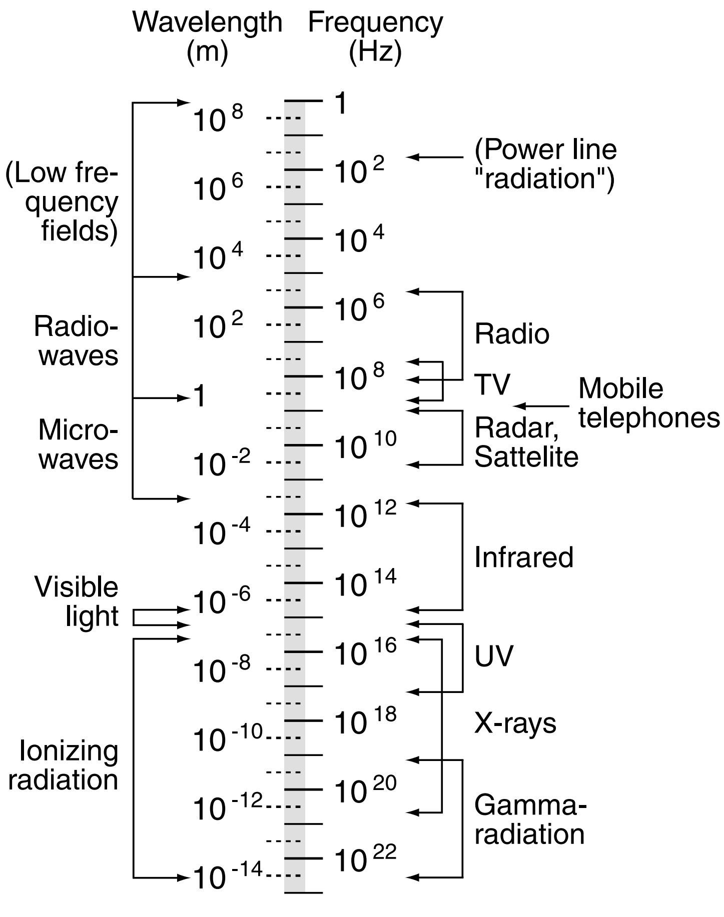

Figure 10-1. The electromagnetic spectrum with the various manifestations of electromagnetic waves, depending on their frequency. The product of frequency and wavelength is always the speed of light.

direction of the radiation are almost all you need. In order to study biological effects, one also needs to know how long time the radiation lasted and often how the radiation is absorbed in various biological tissues. For ionizing radiation and light, the wavelength is always very small compared to a living organism.

For low frequency fields the situation is quite different. Here, there is an extreme variety in the different fields produced by different sources, and a biological effect may depend on a lot more parameters than for ionizing radiation or light. This makes the low frequency field of research very challenging and complicated. When people use concepts and methods of analysis proper for ionizing radiation also when considering the low frequency conditions, they often end up with wrong conclusions. Some misconceptions still survive in some circles, even among physicists. In this chapter the first part is devoted to clearing up concepts and misconceptions. We try to build a foundation and understanding in basic physics so that it will be easier to understand e.g. the fundamental difference between what kind of biological effect one might expect for extremely low frequency fields on one hand and radio frequency fields on the other. The use of mathematical formulas has been kept to an absolute minimum.

In the second part of this chapter, various biological effects from low frequency fields are discussed, and in the last part, shielding of fields are discussed in general.

10.2 Electric fields

A brief history of fields

When one pulls an acryl pullover over one's head, the hair is often standing out for a minute or so afterwards. This effect is due to electric fields; the acrylic pullover picks up electrons from the hair and leave it with a net positive electric charge. Between charges there are forces, and the forces result in the rising hair. Forces between charges are actually by large the strongest forces we know of in nature today that can work on distances larger than an atom. Mathematically, the electric force $\boldsymbol{F}$ between two particles is given by Coulomb´s law:

$$\boldsymbol{F} = k_0\, q_1\, q_2 / r^2$$

where q_1 and q_2 are the two electric charges, k_0 Coulomb´s constant, and r the distance between the two particles. The force is directed so that two charges of the same sign repel each other, while two charges of opposite sign attract each other. Electrons have negative electric charge and protons (a main building block of the nucleus of atoms) have a positive electric charge. Charge is conserved and quantisized.

Mathematical formulas will in only be used a few times in this presentation. Readers that want a more formalistic presentation, are referred to standard textbooks in classical electromagnetism.

Coulomb´s law was formulated by Charles Coulomb (1736-1806) in the eighteenth century, and the force between the two charges was described by an «action by distance». A charge at one position led to a force on a charge at another position in space, in spite of no contact between the two charges. Michael Faraday (1791-1867) argued later that one could use a different approach and still get the same result: He suggested that the presence of e.g. the first charge *changed a property of space* everywhere, and this property was called *an electric field*. When one put another charge into space, it will *get in contact* with the electric field on this spot. The result would be a force in one particular direction. The force is equal to the charge of the last particle times the electric field at that particular point in space where the charge was placed. The electric field has a magnitude and direction that fits to the old Coulomb law description, but the big difference is that we now have switched to an «action by contact» description rather than «action by distance». The force was described by one charge and the electric field at the point in space where this charge was positioned; an electric field the charge was in contact with. The fact that the electric field itself had to be due to another charge, was more or less treated as a separate problem.

Since the days of Faraday we have used the concept of fields in physics, not only for electric fields, but also for magnetic fields. Maxwell collected and extended the present mathematical formalism of electric and magnetic fields in 1873. A set of four «Maxwell´s equations» in concert with one equation called the Lorentz force law, is now the basis of our current descriptions of electromagnetic phenomena in the frequency range we cover in this presentation.

Vector fields

It is important to remember that the electric field not only has a *magnitude*, but also a particular *direction*. The electric field is pointing radially away from a positive charge, and radially towards a negative charge.

If we place first one charge at some position in space, and then another charge at a different position, the total electric field at some arbitrary third position, will be what we call a *vector sum* of the fields due to each of the two charges. Figure 10-2 indicates how we add the electric field $\boldsymbol{E}_+$ due to a positive charge and the field $\boldsymbol{E}_-$ due to a negative charge, in order to find the total electric field $\boldsymbol{E}_{tot}$ at two different positions P_1 and P_2 in space. We see that at position P_1, the total field is larger than each of the contributions, but still, the magnitude is smaller (or equal) than the sum of the magnitudes of the constituents. At position P_2, the total electric field is smaller than at least one of the two contributions.

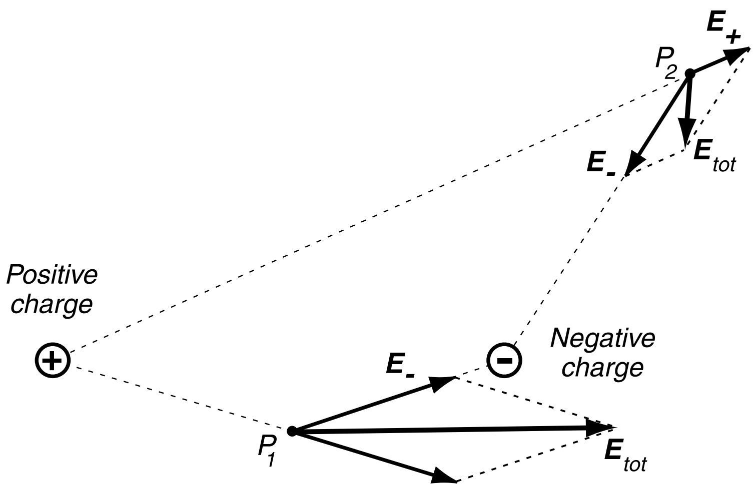

Figure 10-2. The total electric field from two charges can be determined by a vector sum of the two contributions. The magnitude of a vector sum is always somewhere between zero and the sum of the magnitude of the two contributions.

It is important to realize that the picture in Figure 10-2 is quite general and apply for the electric field from any sources. The resulting field is not found by simple summation in the same way as when one add one glass of water to another vial of water. In that case, the sum of the two vials of water always gives a total volume equal to the sum of the volumes of the two constituents. For electric (and magnetic) fields, the sum is seldom as large as the sum of the constituents (regarding magnitudes). In extreme cases the sum of two electric (or magnetic) fields may even be zero.

The picture is complicated even further if the different sources for fields have different frequencies.

Thus, if heating cables are introduced in a bathroom in a house near a power line, the magnetic field from the power line in the bathroom may either be enhanced by the field from the heating cables, or it may be reduced. In some cases one may switch between these two possibilities by simply interchanging the two leads from the heating cable when connecting them to the mains.

The characteristics of vector addition discussed, is one of the many reasons that it is complicated to do research on electric and magnetic fields and figure out what kind of effects they have on a human body in everyday life. This is in contrast to ionizing radiation where it almost without exception, is correct to sum different contributions to ionizing radiation in as simple manner as when one add several vials of water (no vector addition).

Where do we find electric fields in general

We have stated above that an electric charge creates an electric field all over the space. But even if every electron in the universe is electrically charged, we only happen to see the influence of a tiny, tiny little fractions of these. The reason is that the charge of an electron most often is matched by an equal positive charge of a proton, leaving a net zero electric field in the surroundings. However, if we create a charge *separation*, as e.g. when pulling an acrylic pullover over one's head, we do get electric fields. Another way to create charge separation is to apply a battery or connect a cable or an appliance to the mains. Do you put two (not connected) wires to each end of a battery, a few electrons will be removed from one of the wires and an equal number will be dumped on the other wire. We then have a net electric charge on each wire, and an electric field will appear. If we increase the electric potential (voltage) on the battery, the charge separation will increase in proportion with the voltage, and the electric field in the surroundings will increase.

There are a close relationship between the following parameters: Charge separation (or net electric charge on each constituent), electric potential (voltage) and electric field. In some situations it may be wise to keep focus on the relationship of potential and electric field, since one have an electric field whenever there is an electric potential between two (or more) nearby objects. However, electric potential is a rather abstract quantity, and not readily applicable for non-conductors. Therefore, in many cases it may be more fruitful to consider electric field more as a result of (unbalanced) charges rather than a result of potential differences. It is easier then to remember that one can never change an electric field without some movement of electric charges.

Regarding a power line, for example, there exist a voltage difference between the three leads, and there also are voltage differences between each of the wires and ground. In order to create the voltage difference between the wires internally and also between wires and ground, there must exist a charge separation. Thus, when considering the power line at one moment of time, there will in general be different net electric charge per unit length on each of the three wires. It is this charge that is responsible for the electric field.

By keeping the focus on charge and electric field, we understand from the example above that a power station actually has to supply the three wires with net charges in order to keep the voltage. Thus, a fraction of the current in the power line is actually not used on the other end of the line, - it is only used *along* the line in order to keep the voltage.

Keeping an eye on *charges* may be the best warranty for understanding that there e.g. will flow a current in a human being exposed to an electric field from a power line. We will return to this later.

Unit of electric fields

The most common way to create an electric field for experimental purposes, is to apply a voltage between two parallel plane metallic plates. If we apply an electric voltage of e.g. $V = 1000$ V (1000 volts) between the plates, and the distance between the plates is $d = 0.1$ m, there will be an electric field E between the plates, approximately given by:

$$E = V/d = 1000 \text{ V} / 0.1 \text{ m} = 10000 \text{ V/m (volts per meter)}$$

Note that electric field is measured in V/m (volts per meter). For larger fields (e.g. fields near power lines) we often use kV/m (kilovolts per meter). 1 kV/m = 1000 V/m.

In the description above, charges were not mentioned at all. The main reason is that for metallic objects it is often easier to measure voltage than charge. However, charge certainly play a role even here. The voltage only exists because there is a net difference in electric charge on the two plates. The larger difference in net charge, the higher is the voltage difference. In fact, the electric field just outside any metallic object is directly proportional to the density of charges (e.g. charge per square millimetre) on the metal surface, and there are no such easy relationship between voltage and electric field. So when it really counts, we can again use the picture that it is the charge that is responsible for the electric field.

10.3 Magnetic fields

While electric fields are due to charge separations (net electric charge in certain regions of space), magnetic fields are due to movement of net charges. The most common situation in our context is the existence of electric currents, e.g. in a metal cable. The simplest case is a single electric cable that is straight and long (compared to the distance of interest from the cable). Figure 10-3 indicates the direction and the magnitude of the magnetic field from such a cable. The direction is given by the so-called «right-hand-rule»: If one grab around the cable with the right hand and let the thumb go in the direction of the electric current, then the magnetic field has a direction indicated by the rotation of the four other fingers around the cable.

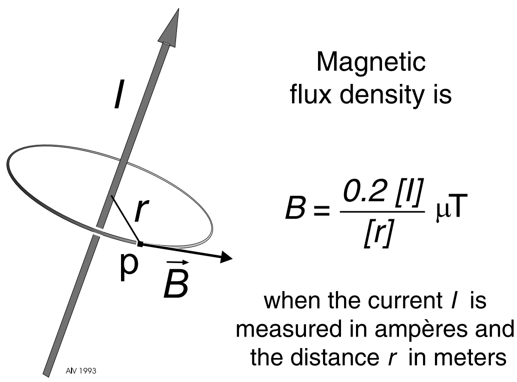

Figure 10-3. Magnetic field at a distance r from a straight wire carrying an electric current I.

"Magnetic field" is a term often used by ordinary people and even among professional physicists. However, strictly speaking "magnetic field" is either synonymous with "magnetic flux density" (identical to "magnetic induction"), symbolized by the letter *B* and measured in the unit tesla (T) or microtesla (µT), or with "magnetic field strength", symbolized by the letter *H* and measured in the unit ampère per meter (A/m). In practice most people think of *B* when they talk about "magnetic field" at power frequencies, and *H* at radio frequencies in the context of most interest in this book. In this chapter, we will use "magnetic field" in that particular way. However, in other contexts, it might be different. In air (vacuum) the connection between the two are as follows:

$$B \text{ (in µT)} = 1.257 * H \text{ (in A/m)}$$
$$H \text{ (in A/m)} = 0.796 * B \text{ (in µT)}$$

In some American literature the old unit gauss (G) or milligauss (mG) is still often used instead of tesla. The connection between these units are:

10 mG = 1 µT,   0.1 µT = 1 mG

The magnetic field is proportional with the electric current in the cable, and it is inversely proportional with the distance to the line (cable). The last property can be explained by stating that if one move from one position a distance *r* from the line, to another position at a twice that distance from the line, the magnetic field decreases to half of what it was in the first position.

Magnetic fields are vector fields, similarly as electric fields. Thus, it is not possible to add the magnetic field from one source to the field from another source without taking both the magnitude and direction of the fields into consideration.

Most often electric currents are going in closed circuits. When we send electric current to a lamp, currents at one moment of time flow towards the lamp in one lead and away from the lamp in the other lead in the cable to the lamp. The total current through a thought cross-section of the cable is always zero (or very close to zero). However, the magnetic field is not zero, since the two leads do not occupy the same positions in space.

Figure 10-4 indicates that the magnetic field between the leads is stronger than if we had only current in one lead, but outside the cable, the magnetic field is considerably lower for the two-lead case than if we had only one lead (we assume that the currents in the two-lead case goes in opposite direction and is equal of magnitude).

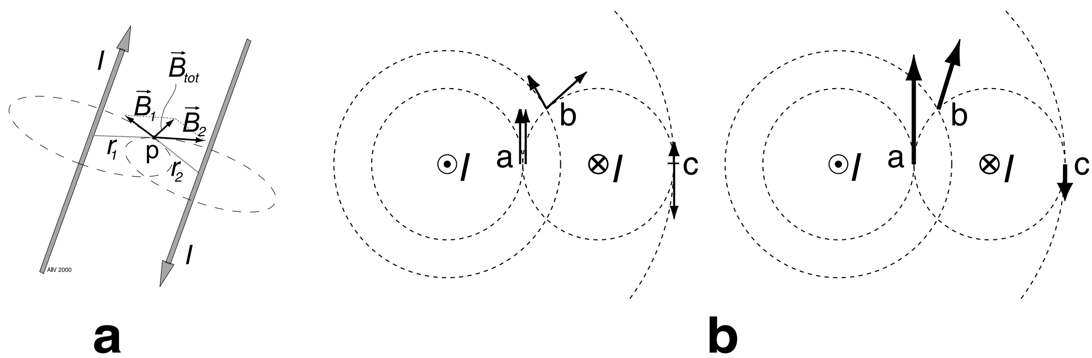

*Figure 10-4. Magnetic field from two straight wires both carrying an electric current I, but in opposite directions. In **a** the wires are drawn in perspective, in **b** the magnetic field is given in a plane perpendicular to the wires. Separate contributions from the two wires (left) and the total field (right) is drawn for three different positions. One can easily see that the magnetic field is stronger between than outside the wires.*

When we calculate the magnetic field from a parallel cable, as indicated in figure 4, one interesting result is that when one are 2-3 times the internal distance between the two leads away from the nearest conductor/line, the magnetic field, ***B***, is:

- approximately directly proportional to the internal distance, *d*, between the two leads,
- approximately inversely proportional with the *square* of the distance, *r*, to the midpoint between the leads.

Mathematically, the relationship can be written as follows:

$$B = 0.2\ [I][d]\ /\ [r^2]$$

The magnetic field is given in µT if the current *I* is measured in amperes, the distance *r* between the two leads in meters, and the distance *r* from the midpoint to the place the magnetic field is determined is also measured in meters.

This is a very important finding since it means that if we want to reduce the magnetic field from current carrying cables, we can reduce the distance between the leads, and/or we can move away from the cable: The magnetic field at a distance 2*r* is for example only 1/4 of what the field is at a distance *r*.

10.4 Characteristics of low frequency fields

Static vs. time-varying fields
So far we have not discriminated between static conditions and time-varying conditions, but that is very important when considering electric and magnetic phenomena. When we use a battery and send a current through e.g. a flashlight bulb, there will be an electric and magnetic field in and around the flashlight that do not vary with time (in the time-scale of seconds and a few minutes). On the other hand, if we plug a lamp in the mains, the electric and magnetic field will constantly change in time, but go through the same time cycle 50 (Europe) or 60 (US, Canada) times every second. We say that the voltage and current have a frequency of 50 or 60 Hz (hertz). Figure 10-5 indicates the difference between the static situation with a “direct current” (DC) for the

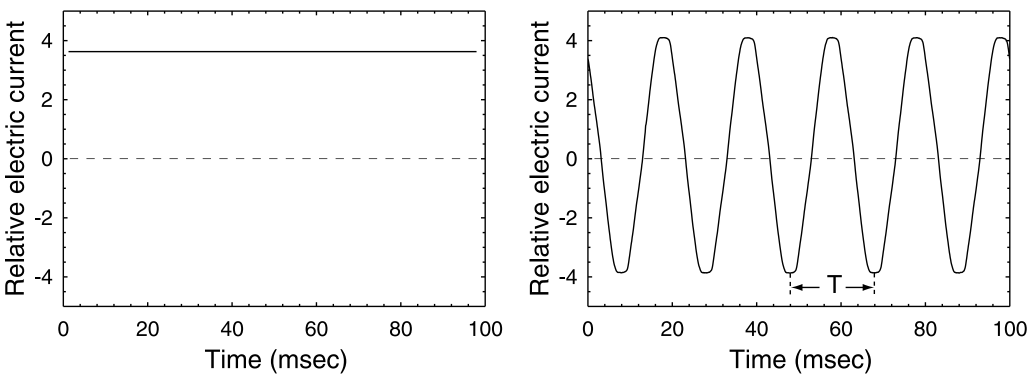

Figure 10-5. Time-variation in the current through a flashlight connected to a battery (to the left) and a lamp connected to the 50 or 60 Hz mains (to the right). The “direct current” (DC) do not change with time, while the “alternating current” (AC) have a periodic time-variation. The frequency v is always 1/T where T is the cycle time.

flashlight, and the "alternating current" (AC) for the lamp connected to the mains. In the figure only the time-variation in the current is given, but charge-separations, electric fields and magnetic fields will follow a similar time-variation.

If the electric field at one particular point in space have a given magnitude and direction at one moment of time, ten milliseconds later (for a 50 Hz AC system) the electric field will have the same magnitude but opposite direction. Ten more milliseconds later, the field will return to the starting point again. Thus, the field constantly changes in magnitude and changes from one direction to the opposite, the field at one moment of time is always identical to the field one or more complete cycles later.

Electric and magnetic fields from DC equipment are time-independent and is called static fields. Fields from AC voltages or currents are periodic time-varying fields with a characteristic frequency given in Hz. There are, however, many different kinds of time-varying fields, and we discriminate between periodic fields or not, and for periodic field we discriminate between a pure harmonic time variation (only one frequency present) and variations with several harmonics present on the same time. Figure 10-6 give one example of an almost harmonic magnetic field time-variation (from an incandescent lamp, upper part of the figure) and two examples of non-harmonic periodic time-variation of a magnetic field (from a PC power supply and a fluorescent lamp, middle and lower rows, respectively). The frequency analysis of the time variations are also given.

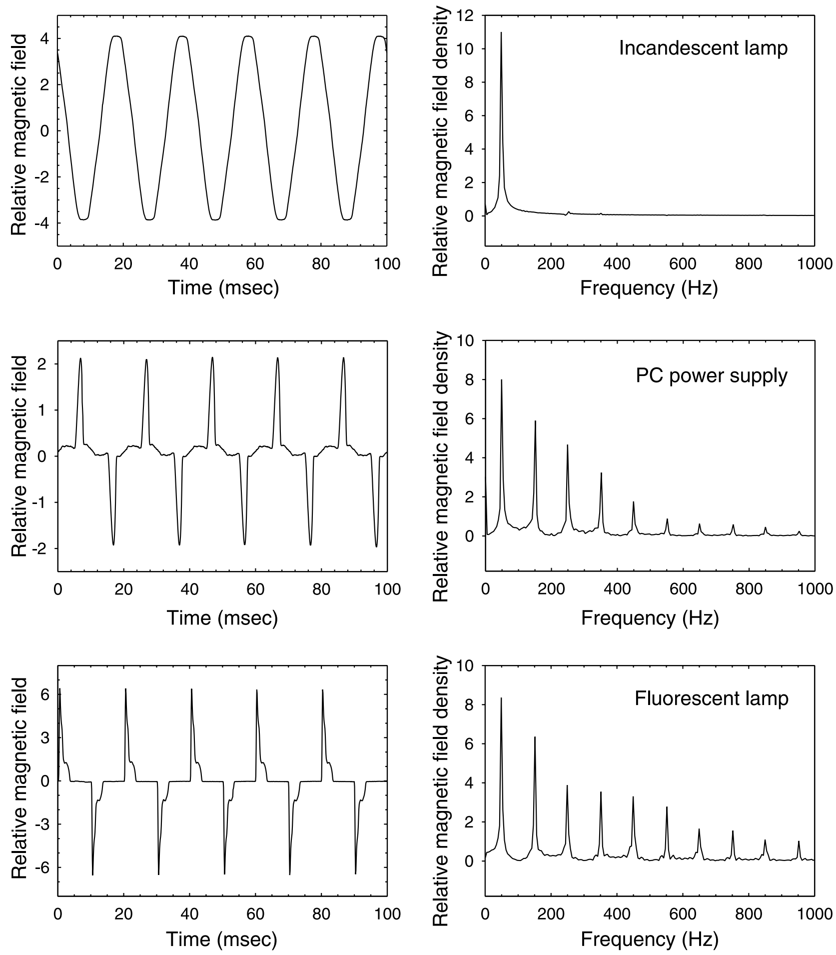

Figure 10-6. Almost harmonic and clearly non-harmonic time-variations of magnetic fields close to an incandescent, a PC power supply, and a fluorescent lamp, respectively. Frequency analysis shows that the almost harmonic signal contains almost only one frequency, while the non-harmonic signals contains many frequencies.

Electric and magnetic field from power lines and other “three-phase” sources, changes constantly direction so that all possible directions in a plane are covered during a cycle. The tip of the field vector will follow an ellipsis or a circle, and the field is said to be elliptically (or circularly) polarized. For “one-phase” sources, e.g. a lamp, the tip of the field vector only point out a straight line. The field is then said to be linearly polarized.

When an electric or magnetic field changes constantly with time, as for fields close to an AC source, the field strength may be given as the peak value during the cycle or some kind of “mean value”. The true mean value for a AC field is normally zero, so more often the so-called effective value or the root-mean-square (RMS) value is used instead. For electric or magnetic fields, the effective value and the root-mean-square value are defined in the same manner as for an electric current or voltage. Thus, for a pure harmonic time-variation, both the effective value and the root-mean-square value is equal to the peak value divided by the square root of 2. For non-harmonic time-variations only the root-mean-square value must be used.

The term “effective value” comes from the fact that: If an AC current passed e.g. an oven, and the effective value of the current was I_{eff}, then a DC current I_{DC} equal to I_{eff} (in value) would produce identical heat as the AC current.

In figure 10-7 the time-variation of two different 50 Hz magnetic fields are presented, both have a field strength of 3 µT root-mean-square. The peak values are, however, very different: Approximately 4.2 µT for the field with near harmonic variation (square root of 2 multiplied by 3 µT is 4.2 µT), but more than 21 µT for the non-harmonic field. As we shall see later on, biological response may depend on the time derivative of the magnetic field variation (how fast the magnetic field varies in time within a limited period of time). It is then clear that a magnetic field with the time-variation given at the right of Figure 10-7 in such cases may have a much higher effect than the harmonic time-variation at the left of Figure 10-7, in spite of the field value one would measure would be identical. Thus, it is by no means clear that e.g. two different magnetic fields have the same biological effect even if they have identical strengths given as root-mean-square.

The fact that very different waveforms can give identical root-mean-square values, represent a considerable problem when one would like to compare exposure with guidelines for maximum exposure. The guidelines do not provide enough information on how to deal with different waveforms (different harmonic contents) in a proper way. The reasons may partly be the complexity of the problem, and partly the lack of scientific knowledge on what parameters are important for various biological effects.

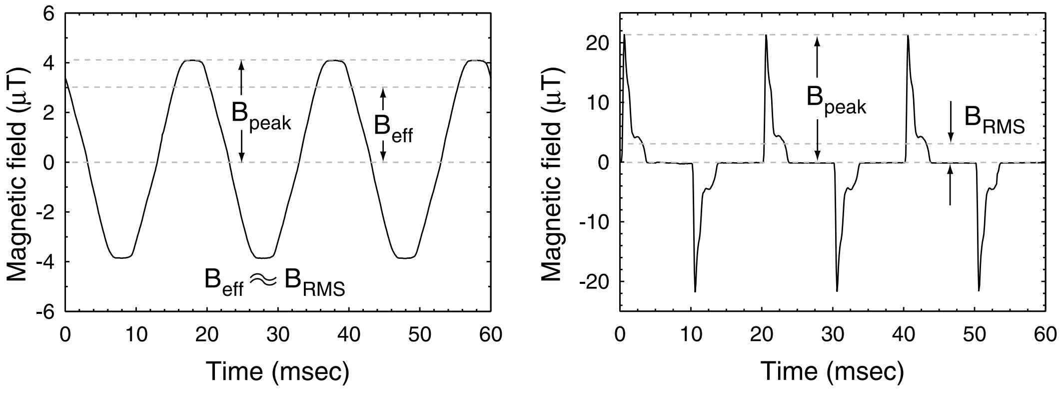

Figure 10-7. Two magnetic fields with identical root-mean-square values may have a very different peak-value for harmonic and non-harmonic time-variations.

For complicated time-variations it is often more useful to present the complete time-variation in a field instead of trying to just pick out a single number.

As pointed out in the paragraphs above, there are many details indeed to keep records of when characterizing electric and magnetic fields from low frequency sources. In some cases it is really quite an challenge to characterize the field pattern, e.g. close to a computer screen (visual display unit, VDU). Other situations are more readily characterized, e.g. the fields from a power line and cables or appliances that run on 50 or 60 Hz alternating currents, without producing extra harmonics. Hopefully, the reader of these paragraphs now understand that a characterization of a magnetic field of e.g. 10 µT (with no additional information) is about worthless. And even more details follows in the next few sub-chapters.

Near-fields vs radiating field / waves

Depending on the main frequency of the time-varying fields, it is customary to characterize fields as static, extremely low frequency, very low frequency fields, radio frequency fields and microwave fields. Higher frequencies are treated elsewhere in this book and is then regarded as electromagnetic waves ("radiation") (see figure10- 8). The definition of the different frequency bands for low frequency fields are not universally agreed upon, but one possible characterization is as follows:

Classification	*Abbreviation*	*Frequency band*
Static fields	-	0 - 3 Hz
Extreme low frequency	ELF	3 - 3000 Hz
Very low frequency	VLF	3 - 300 kHz
Radio frequency	RF	0.3 - 300 MHz
Microwaves	-	0.3 - 300 GHz

A similar characterization is used for electromagnetic *waves*, as illustrated in figure 10-1. As mentioned briefly in the start of this chapter, we discriminate between fields and waves, and we will now give grounds for this interpretation.

Electromagnetic waves are particular solutions of Maxwell´s equations, and they all have some specific properties:

- Electric and magnetic fields are always perpendicular on each other, and also perpendicular to the direction the wave is moving,
- There is a unique relationship between the magnitude of the electric and magnetic field. If one of them is known, the other one can be calculated.
- The wave carries energy away from the source (the antenna), and the energy generally speaking never returns to the source.
- There are a given relationship between frequency f and wavelength λ for electromagnetic fields: $f\lambda = c$, where c is the velocity of light (the velocity of the wave).
- At least for electromagnetic waves with a wavelength similar to visible light, the energy in the electromagnetic wave is exchanged with the surroundings by so-called «photons», each with an energy $E = hf$, where h is the so-called Planck´s constant and f the frequency of the wave.

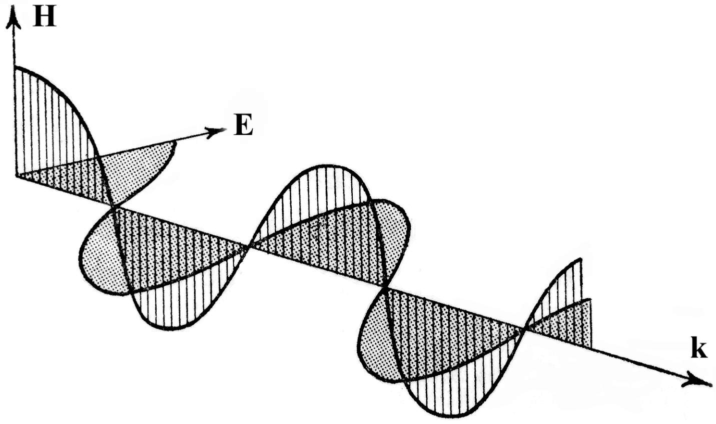

Figure 10-8. Electromagnetic waves represent particular solutions of Maxwell´s equations, but in practice they are only realized for radio and higher frequencies. Near power lines and appliances where only static or low frequency currents or voltages appear, electric and magnetic fields do not *follow the characteristics given in this figure.*

For low frequency electric and magnetic fields, *none* of the characteristics mentioned above is valid! This is an important point. The electric and magnetic field close to power lines, appliances etc. are not closely related. It is possible to find situations with strong electric fields and a very weak magnetic field, and other situations where it is the other way around. The electric and magnetic fields are not necessarily perpendicular to each other, they are not carrying away energy so that it do not return back to the source, and it is meaningless to talk about wavelengths since the fields do not show a wave behaviour. From this it also follows that it is nonsense to talk about energy per quantum, since the fields we are talking about do not show wave-characteristics, which is the underlying description of photons (a more detailed explanation why the concept of photons is useless for very low frequency fields, is given by Vistnes and Gjötterud, 2001).

One might wonder when it is correct to use the concepts and characteristics of electromagnetic waves and when not. A rule of thumb says that wave-characteristics dominate the fields only when you are more than about one calculated wavelength away from the source («antenna»). The calculated wavelength can be found by the simple relationship:

Calculated wavelength = Speed of light / Frequency

For visible light that means wave behaviour is expected at a distance larger than about 500 nm (0.0000005 m) from the source, for a mobile telephone with a frequency of about 900 MHz, the distance is 0.33 m, for a FM radio transmitter with a frequency of 100 MHz, the distance is about 3 m, but for a 50 Hz appliance or power line, the distance is 6000 km! If one stands on the Moon and pick up electric and magnetic fields from power lines here on the Earth, one may (if one are able to detect it) find that the fields follows the characteristics for electromagnetic waves. But for every practical situation here on Earth the wave part of the fields is so minuscule, that it would be impossible to detect.

When one is closer to the source («antenna») than the calculated wavelength, electric and magnetic fields might be almost independent of each other etc. as mentioned above. We use the term «near field» to characterize this situation, in contrast to the «far field» where the waves dominate.

Since energy is not transported away from the source by near fields, people working in this field of research usually do not talk about «radiation» from power lines and appliances (50 Hz). We talk only about *fields*: electric fields and magnetic fields. In situations we want to include both variants, we use the shorthand notion: Electromagnetic *fields*. This is *in contrast to* electromagnetic waves and electromagnetic radiation. However, most lay men, journalists etc. have not discovered this distinction, so in the society the most common term is still «radiation from power lines», «radiation from a computer screen» etc. Hopefully, this practice will change over time.

10.5 The human body in static and low frequency fields

What happen when a human being is exposed for a static or low frequency electric or magnetic field? We will first describe well known physical aspects, and later cover to some degree the more uncertain mechanisms that have been discussed in the literatures.

A human body consists of cells in contact with each other, and with an intercellular fluid. Each cell is separated from the surroundings with a biological membrane, which is very thin, but even so, a relatively insulating medium. Some tissue contains structures that are more effective insulators than other tissue. Fat tissue and also the myelin sheets around myelinated nerve fibres, are examples of tissue with low electric conductivity.

The aqueous part of the body, on the other hand, contains ions in large quantities, so that the electrical conductivity of the aqueous part is relatively high. Not only free ions may contribute to electrical currents in the human body. Proteins, both soluble and membrane-bound, may have a net electric charge, and move as a response to external fields.

The body is as briefly indicated above, a very complicated medium with respect to the response to electric and magnetic field. It is in fact so complicated that no one has been able to model the body anywhere close to the «true» picture. We are forced to use approximations, and the very simplest approximation we can make is a sphere or ellipsoid filled with a homogenous medium with a «mean» value for the conductivity etc. This model can be termed the «salt water bag model».

Static electric field

If we use the salt water bag model for the human being in a vertical electric field, the result is as indicated in Figure 10-9a. The original electric field result in ion movement, positive ions is moved in the direction of the field, negative ions in the opposite direction. The ions will continue to move until the accumulation of ions in each end of the body actually is producing an electric field that is opposite and equal to the external field. Then, as the electric field inside the body everywhere is zero, there will be no more movement of ions.

The picture given in Figure 10-9a is applicable when there is a good insulation between the body and the ground. In many cases the insulation is not very effective, but still the ions in the foot region may be neutralized by ions (eventually electrons) originating from the ground. In both cases the overall picture of the situation may be similar as indicated in Figure10- 9b. In this case there will both be an electric current *inside* the body a short period of time after it is exposed to the field, and a current through the interface man/ground. The last part is of particular interest, since it leave us with a possibility to measure this current. A small current that is only available inside the body is i practice very difficult to measure.

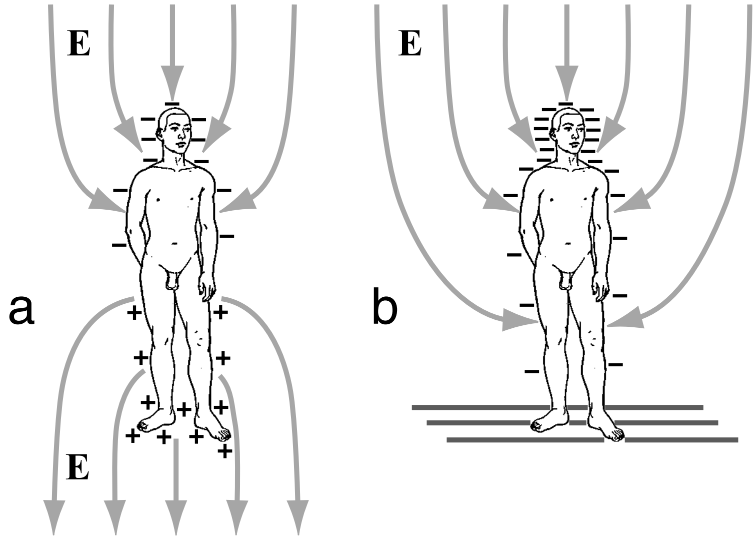

*Figure 10-9. A human body in an external electric field. In **a** the body is insulated from ground, and in **b** the body is grounded through the feet. The charges that accumulate on various parts of the body is for clarity reasons drawn just outside of the body. In reality the charges are located in a thin layer in the skin.*

What we see in Figure 10-9b is closely related to what happens when a human body moves outdoors and gets exposed to the Earths natural electric field of about 100 V/m (up to several thousand volts per meter on special occasions, e.g. under thunderstorms). There will be a movement of charges in the body a short time after the body is exposed to the Earths field, but after that nothing particular happens. The body has become polarized.

One detail should be mentioned in particular. The polarization of the body leads to zero electric field inside the body, but to an increased electric field just outside of the upper part of the body (in the head region). This field may influence the transport of dust, virus, bacteria, allergens etc. from the air. These particles often picks up some electric charge (due to naturally occurring ionization of air), and those particles that happens to be positively charged, will be attracted to the head. Some will lead to enhanced deposition of the particles to the skin, and some may lead to enhanced deposition in the nose, mouth and lungs. In cases like that, we might have a so-called «indirect effect» of the electric field.

Time varying electric field

The discussion above on what happens when a human body is exposed to a static electric field makes the foundation for understanding what happens when the body is exposed to a time varying field. The point is, that the situation that happened only once when a man is exposed to the static electric field of the Earth, will be repeated again and again for every cycle in the field variation of a time-dependent field. When a man is standing below a high tension power line, an alternating electric current will flow through the body of the man, all the time. If we allow the current to continue from man to earth, we are able to measure this current directly. Figure 10-10a shows the principle used when measuring the alternating current between man and ground, and Figure 10-10b shows a picture of an actual measurement of the current.

In principle one could use an ampere-meter directly in the measurement of the current, but the current is so small that ordinary battery driven multi-meters are not sensitive enough. Therefore, the current is determined indirectly by using Ohms law after measuring the voltage across a 1 kΩ resistor.

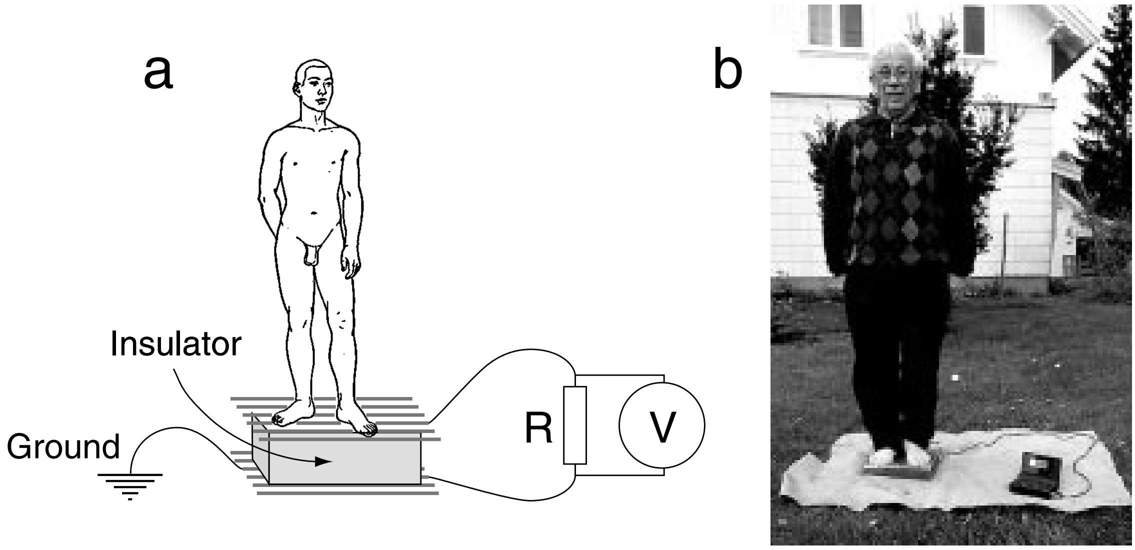

*Figure 10-10. Measurement of the alternating current flowing between a human body and ground in an external AC electric field. The principle used in the measurement is given in **a**, and in **b** an actual measurement situation is illustrated.*

As we have seen, there will be an alternating current through a man in an alternating electric field. How large is that current? When the field varies very slowly (as for power frequency fields), the *number of charges* that are needed in order to make the internal electric field in the body almost zero, is only dependent on the maximum external electric field. But electric current is the amount of charges that pass a cross section *per second.* It is not the net transport over time we are looking into, since that is zero. The alternating current is proportional to the maximum charge that passes a cross section in the body per (infinitesimal little) time during the current cycle. *Thus, the maximum current during a cycle will increase linearly with the frequency.*

The current will in principle lead to heating of the tissue. In fact, the power delivered to the tissue is proportional to the current squared. Thus, a man exposed (whole body) for a 1 kV/m 1 kHz electric field will receive a heating effect that is 400 times what he receives in a 1 kV/m 50 Hz field. (Current increases by a factor 1000/50 = 20, and the heating goes as the current squared.) This means that the heating effect becomes more and more important as the frequency increases. This fact have the following implication: At low frequencies, the heating effect due to external electric fields, is usually negligible.

When the frequency increases more and more, the conductivity in the body sooner or later is insufficient to transport ions fast enough so that the electric field inside the body is about zero. When this effect becomes important, the current no longer increases proportionally with the frequency. In fact, at about 30 MHz a standing, adult man, with good contact between ground and his feet, will have the highest possible heat absorption when the body is exposed to an electric (electromagnetic) field of a given strength. We talk about a *resonance effect*. For a man isolated from the ground, the maximum current happens at about 60 MHz. (In physics, the kind of saturation behaviour we here experience, is closely related to the frequency response of a RC-circuit.) The resonance frequency depend on the direction of the electric field relative to the standing man. The numbers given are for vertical polarization of the electric field (along the main body axis). It should be mentioned that the resonance phenomena are more complicated than we have suggested above, since at these high frequencies there are usually a mixture of so-called “near fields” and “far fields”, but we will not go into more detail here.

We have so far suggested that the electric field inside the human body is about zero for all frequencies well below the resonance frequency. Under such circumstances, there are time enough for ions to move so that they will screen out the external electric field. This picture is only partly correct. At 50 Hz, the internal field will be about 0.0000001 times the external field (Polk, 1986), but this fraction will increase steadily with frequency. It should be noted, however, that even if the internal electric field (in a salt bag model) is very small, the electric current might be worth consideration. Since the body is not a salt bag, the current will lead to local differences in electrical potential that eventually will lead to biological effects. The current through the ankles of a barefooted human being exposed to the electric field at ground below a high tension power line, is almost on the borderline of a current that can lead to spontaneous trigging of nerve fibres or muscles (more details later on).

Current vs current density

When we talk about electric current through a power line or another cable, we talk about the total charge that passes a cross section of the cable per time. The current that flows through the body will pass different cross sections in different parts of the body. If the current that passes a horizontal cross section at the hips is the same as the current that passes the ankles, it becomes clear that the electric current *seen locally* in the tissue must be very different at those two parts of the body. We therefore are more interested in *current density* (current per cross section area) than in the total current, when we judge effects on a human body. Current is measured in ampères (A) (or milliampères, mA or microampères, μA), and current density is measured in ampères per square meters (A/m^2) or milliampères per square meters (mA/m^2). An example of current densities in a human body is given in Figure 10-11.

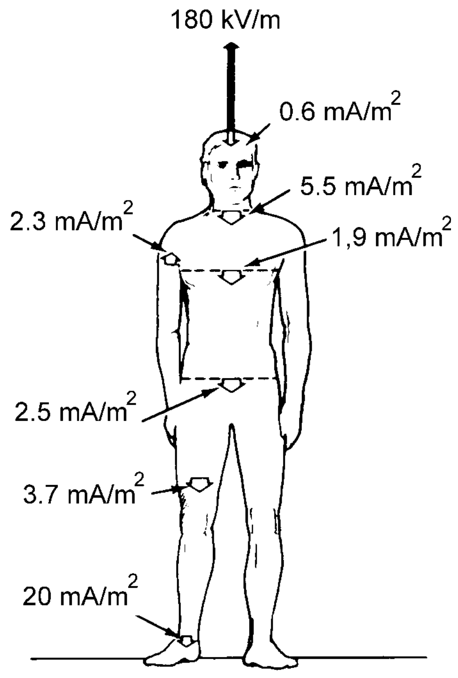

Figure 10-11. Current density in various parts of a man standing in a 60 Hz 10 kV/m vertical electric field (unperturbed field). The man is in contact with ground through his feet. The field in the head region becomes about 180 kV/m due to the charges drawn to the head region (see figure 8b and corresponding text). (Redrawn from Kaune, 1981)

The «normal» current density in the body is roughly speaking:

10^{-4} - 10^{-3} A/m^2	in the brain
10^{-3} - 10^{-2} A/m^2	near the heart

These numbers can be compared with induced current densities various places in the body when it is exposed to the following external electric or magnetic fields:

10^{-6} - 10^{-4} A/m^2	magnetic fields at ground level near power lines
10^{-4} - $2*10^{-3}$ A/m^2	electric fields at ground level near power lines

Use of current density instead of the total current is important in order to understand when an effect is likely to occur or not. However, even this parameter is a very crude one. In the body the current is distributed; some will follow muscles, some blood vessels, some the intercellular fluid, etc. The current density gives only a mean value, and at the tissue level the value may be very different. Another weakness in comparing current density from external sources to those that occur naturally, is the fact that local fields have a rather chaotic time-dependence with a broad frequency characteristic, while external fields often are dominated by only one frequency. In addition, current density created by nerve or muscle activities show little or no coherence from one spot in the body to another, located several centimetres away, while induced current density from external sources may have a much higher spatial coherence. Thus, one should be careful in drawing too heavy conclusions from comparisons between natural current densities and induced current densities.

Static magnetic field

Electric charges that have little or no movement, is not affected by a static magnetic field. Some nuclei (and other particles with unpaired spin) are affected by the field, but only in a very week manner. Thus, the human body is almost transparent to a static magnetic field. The magnetic field we have outside the body is very close to the field found inside the body.

Static magnetic field do have an effect on ions and other charged particles, but only if they are in motion. The corresponding force points in opposite direction for positive compared to negative charges. In physics, this effect is known as the Hall-effect.

In the body the Hall-effect produces a slight charge separation of ions in blood vessels, and there will be a small electric potential from one side of a blood vessel to the other. The effect can be demonstrated by electrocardiography (EKG) during examinations by magnetic resonance imageing (MRI) where the patient is exposed to very high static magnetic field. However, the effect seems to disappear as soon a the patient is removed from the strong magnetic field, and there seems to be no health effect as a result of the examination.

The Hall effect takes also place when people travel by aeroplanes in the Earths magnetic field. The ions in the body will be slightly separated, so that there will be a slight potential difference between one side of the body and the other side. However, this slight potential difference will not lead to an electric current (except for a very small current when the aeroplane changes speed or direction). The situation is very similar to what happens when a person steps out of a house and become exposed to the static electric field from the atmosphere.

A strong magnetic field may also influence on chemical reactions through a so-called radical pair reaction. When a chemical reaction takes place, a molecule is often split into two radicals, and each of the two constituents may react with other reactants, or react again with each other so that no net reaction takes place. A strong static magnetic field may influence on how easily the reaction is carried through to new products or not. In this way the magnetic field may influence on biological processes and eventually, on health effects. This “radical pair hypothesis” is interesting, but experiments have so far only been carried out on model systems and with rather strong magnetic fields. It is difficult to guess how important this mechanism is for the case when people are exposed to magnetic fields.

Time varying magnetic field

In a generator for electricity we generate electric potential and current through induction. The effect was discovered by Faraday about hundred and fifty years ago. The point is that if the magnetic field varies in time through some material where electric current can flow, there will be induced an electric current, and the current will last as long as the magnetic field changes with time.

In power lines and appliances etc., we use alternating current, and alternating magnetic field is produced. If a human body is exposed to such a magnetic field, an electric current is induced. The current will last as long as the body is exposed to the magnetic field.

The induced current from time-varying magnetic field have the same characteristics as for time-varying electric field, that it will increase linearly with the frequency. Thus, again a heating effect will be proportional with the frequency squared.

However, there are an important difference between electric and magnetic field with respect to the current they produce. We have already described how the electric current flows for electric field exposure. For a time-varying magnetic field the induced electric current will tend to follow a circular pattern in a plane perpendicular to the field. The induced current is largest at the periphery of the body and is reduced to zero somewhere in the middle. The electric current is more or less proportional to the radius in the circular path we are considering. Thus, for a vertical AC magnetic field, the induced electric currents in a standing man will follow horizontal circular patterns, and the current density will be considerably higher at the periphery of the body than along a vertical axis in the middle. The current density will also be higher in the trunk and central parts of the body than in a leg (because of the radius effect).

This radius effect is a serious complication when we want to study biological effects and use cell cultures or small animals in model systems. The induced electric current density through a mouse will be much smaller than the current density in a man for the same time-varying magnetic field. If we use cell cultures, the difference may be even more dramatic. Thus, it might be that we have to use a magnetic field thousands of times stronger when we look for an effect on cell cultures than if we use a man as a «laboratory animal». But we are not sure that an effect is due to induced currents or if it is due to the magnetic field itself. This leaves researchers in a difficult situation when they should choose magnetic field in their experiments, a difficulty known as «the scaling problem».

10-6 Biological effects

Even if for example X-rays and 50 Hz electric fields both are examples of electromagnetic phenomena, their mechanisms of interaction with biological tissue are completely different. X-rays are described by individual, tiny, more or less localized energy packets, that can ionize atoms or molecules on their way through a biological tissue, leaving behind damaged molecules including DNA. Power frequency electric and magnetic fields interact as classical fields which most importantly interact with «free» charges, e.g. ions in the intercellular fluid. In air static or low frequency electric field may accelerate ions/electrons until they reach an energy that will lead to ionization (by collision by an atom or molecule). Thus, static and low frequency fields may lead to ionization as an *secondary* effect, but nearly with no exception, static and low frequency fields can not ionize as a *primary* effect. In biological tissue, where ions or electrons collide far more frequently than in air, charged particles will gain insufficient energy between two collisions, so that ionization will not take place even as a secondary effect.

Acute effects at low frequencies

Which options are there for a static or low frequency electromagnetic field to yield a biological effect? First of all, the field may lead to an electric current, either by polarization as for an electric field, or by induction, as for a magnetic field. And the electric current may lead to potential differences across cell membranes large enough for a biological response to take place in one way or another. A well known effect is the initiation of nerve activities. Nerve fibres may be activated along neurons, and an action potential may lead to sensory stimulation (if an afferent fibre is activated), or to some muscle contraction (if an efferent fibre is activated).

There must be at least a few milliseconds after one action potential in a nerve fibre till the next one can take place. This «refractive period» is due to the time it takes to normalize ion concentrations across the membrane after each action potential has occurred. Thus, electromagnetic fields and the corresponding electric currents, is only efficient in activating nerves if the field has a frequency between a few hertz to about 1 kHz. Most efficient are frequencies between 10 and 100 Hz, thus, the power frequency of 50 or 60 Hz is about the most efficient frequency for activating nerves. This is utilized in electrotherapy of use in medicine.

Løvsund and co-workers carried out some experiments where people were exposed to a strong, time-varying magnetic field in the eye region. People left in partly darkness experienced a kind of light sensation called «magneto-phosphenes», when the magnetic field became strong enough and the frequency was in the right region. Figure 10-12 indicates the minimum magnetic field that was necessary in order to produce magneto-phosphenes. For this particular system, the optimum frequency was about 30 Hz, and the minimum magnetic field was then 20 mT (20.000 µT, about three orders of magnitude higher than what is found in houses near power lines). It has been estimated that magneto-phosphenes may occur when the current density in the eye region is above 10 mA/m^2.

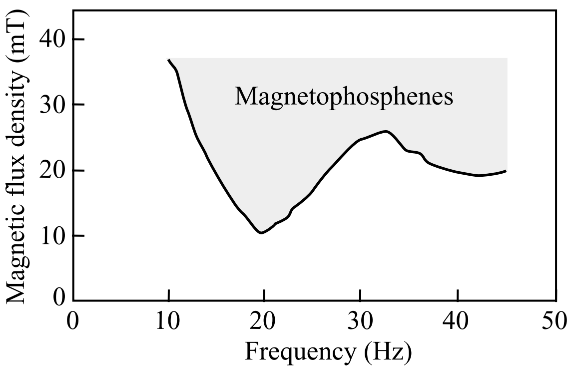

Figure 10-12. Minimum magnetic field at various frequencies necessary in order to produce light-sensation in the eye (magneto-phosphenes), according to Løvsund and co-workers (redrawn from their original paper, 1980).

We have done some preliminary experiments with 50 Hz magnetic field exposure of the lower arm of people. For sufficient high fields, one can feel some tingling sensation, and feel some increased muscle activity for a slightly weaker field than 20 mT. Thus, we think that the minimum values given by Løvsund are overestimating how strong a magnetic field must be before it can lead to trigging of nerves.

Not only harmonic (sinusoidal) time-varying fields, but also various kinds of pulsed electromagnetic fields with a repetition frequency between zero and a few hundred hertz, may lead to trigging of nerves.

Trigging of nerves are an effect that takes place immediately when the body is exposed to strong low frequency fields, and the direct effect is terminated immediately after the exposure has ceased. Such effects are called *acute effects*, and they can be demonstrated in a very reproducible way, from one laboratory to another. There are no doubts about such an effect.

In industry people are occasionally exposed to so strong electric or magnetic low frequency fields that acute effects actually take place. This may happen in areas up to one meter away from very high current cables leading to melting furnaces or other low impedance loads. Electricians and other workers in these areas have reported disturbances in their vision. One group of people in a test laboratory for transformers, even claimed that muscles were activated so that the eye apple actually moved relative to the rest of their head. This happened only in a somewhat extreme circumstance when the magnetic field exposure was very high (about 10 mT 50 or 60 Hz for all head and the upper part of the body).

We have heard from two independent laboratories that people have complained about strong headache for hours after prolonged exposure to fields that e.g. leads to magneto-phosphenes. We are unaware of any systematic, scientific study of the headache phenomena at such high fields. For ethical reasons it might even be difficult to carry out such a study. On the other hand, magnetic field stimulation is used in research in neurology, but then with pulses and shorter total exposure time. In those cases, people seems not to complain about headache.

Guidelines for exposure for low frequency fields

It is obvious that it is undesirable to let people without strict control be exposed to low frequency fields strong enough to induce acute effects. For that reasons various organizations have recommended guidelines for exposure, where the rationale behind the guidelines has been to avoid acute effects. For 50 or 60 Hz fields, the recommended limits for guidelines issued by ICNIRP (International Commission on Non-Ionizing Radiation Protection) in 1998, is:

	50 Hz	*60 Hz*	
Magnetic field (B):			
	500 µT	417 µT	occupational exposure
	100 µT	83 µT	general public
Electric field:			
	10 kV/m	8.3 kV/m	occupational exposure
	5 kV/m	4.2 kV/m	general public

It could be noted that 5 kV/m (or 4.2 kV/m) is less than the electric field at ground level below a high tension power line.

There are various different sets of guidelines for exposure, issued from various organizations. Most of them are rather similar, but they may vary considerably in the way they handle local exposure (e.g. much higher field exposure in a limb than at the main body), and in the way they handle for how long an exposure can be accepted (e.g. some guidelines accept higher exposure during a few hours a day than for the 24 h limit). We will not go into more details here.

Guidelines are nearly without exceptions based on the scope of avoiding acute effects. However, there also exist other kind of guidelines. Some states or local municipal areas use guidelines based on possible weak field effects, like leukaemia among children growing up near power lines. An example of such a local area guideline could be that housing are not allowed in areas so close to power lines that the magnetic field is stronger than 0.2 μT.

A third class of guidelines / limits are technically based, and are often in some way or another connected to electromagnetic compatibility criteria (one piece of electrical equipment should not “pollute” its surroundings with electromagnetic fields so that other pieces of equipment is affected). One example of field limits of this category is the Swedish MPR / TCO guidelines used for classification of visual display units as “low radiation” units or not. These guidelines have had a tremendous influence on manufacturing of visual display units used in the computer users community. The visual display units today have much lower fields close by than they had before the MPR classification started about 1987, without a provable price increase. It is interesting to see that there has not been a similar development for video-monitors used during TV production and editing. Here it is common today with monitors with equally bad field characteristics as was common for visual display units for computer use well before the MPR development. It seems very odd, indeed, when some of the leading manufacturers make good low radiation visual display units for use in computing, while they have not done anything in order to reduce fields from video-monitors, even if the they have all the technology they need!

Acute effects at higher frequencies

Frequencies above 1 kHz will not be efficient in activating nerves (unless the fields are given in pulses with a low repetition frequency). Is the frequency increased to the MHz region or higher, the heat production may become a problem due to the increased electric current in biological tissue. Thus, the heat absorption is the key for understanding what is called an acute effect at radio frequency fields.

The heating effect depend on how much energy per time that is absorbed in the body tissue. Often the quantity “specific absorption rate” (SAR) is used in order to describe the absorption, and it is defined by:

SAR = Absorbed effect in a given amount of tissue / The mass of that tissue

SAR is given in watts per kilogram (W/kg).

We discriminate between whole body radiation and radiation only to localized parts of the body. The reason is that if only a portion of the body is heated by radio frequency radiation, the blood will partly transport away some of the heat to the rest of the body. Thus, it is normally possible to accept a higher SAR value for localized regions than for the whole body. An exception of this general consideration, is tissue with high water content and limited heat transfer to other parts of the body, especially the eye lens. This is particularly vulnerable for damage.

Experiments indicates that 30 min exposure for radio frequency radiation that produce a whole body SAR of 1-4 W/kg, results in a body temperature increase of less than 1 ^{o}C. A safety factor of 10 for occupational exposure leads to 0.4 W/kg as the basic guidelines for radio frequency radiation exposure. An additional safety factor of 5 is introduced in order to protect the general public, so that maximum whole-body SAR vale for this group is 0.08 W/kg.

It is not easy to measure SAR values. For practical reasons it is therefore common to rely on field measurements in air at places where the body might happen to be. Also for radio frequency fields, ICNIRP (International Commission on Non-Ionizing Radiation Protection) has issued guidelines guidelines for exposure, and some examples are as follows:

	10-400 MHz	*900 MHz (mobile telephone)*	
Magnetic field (H):			
	0.16 A/m	0.24 A/m	occupational exposure
	0.073 A/m	0.111 A/m	general public
Electric field:			
	61 V/m	90 V/m	occupational exposure
	28 V/m	41 V/m	general public
Plane wave power density:			
	10 W/m^2	23 W/m^2	occupational exposure
	2 W/m^2	4.5 W/m^2	general public

It could be noted that for mobile telephone users, the exposure is extremely localized to the head closest to the antenna. The SAR value that is used when evaluating mobile telephone use, is therefore based on a mean value for only 6 grams of tissue. Further details are given elsewhere in this book.

It might be of interest to note that radio and TV transmitting antennas may easily give a SAR value exceeding the guidelines if an operator is coming very close to the antenna (within a few meters). However, at areas accessible to the general public, the radiation is usually well below the guideline limits. The same apply for base stations used for mobile telephone communication.

Non-acute effects

What effects do electromagnetic fields have for fields considerably weaker than what is required for an acute effect? In the literature a high number of different effects are reported, but for weak fields the reproducibility among different laboratories are poor. Thus, in some studies it is found an increase in spontaneous abortion among women exposed for weak low frequency fields (of the order of 1 μT), while other studies fail to confirm this. Similarly for quite a few other effects as well. Even 20 years of active research have failed to give a consistent picture of the biological effects from weak, low-frequency electromagnetic fields.

Below we have listed some of the different biological effects that are reported the last couple decades, that may result after exposure to (low frequency) electromagnetic fields:

- Malformations/defects on animal and human fetuses
- Altered rate of embryonic development
- Increased occurrence of spontaneous abortion
- Increased occurrence of depressions and suicides
- More headache, problems with concentration
- Suppressed immune responses
- Higher occurrence of leukaemia and brain tumours among children growing up near power lines
- Higher occurrence of breast cancer among men and women
- Higher occurrence of other kind of cancer among various "electrical workers"
- Chromosomal damage
- Hypersensitivity among some people
- Skin problems
- Alteration in heart rate or heart-rate variability
- Reduced production of melatonin during night
- Altered circadian rhythm in men and animals/insects
- Altered sleep electrophysiology (monitored by EEG)
- Improved bone healing after fracture
- Improved regeneration of damaged nerve tissue in rats
- Altered ion concentration in blood for cattle on grazing land under power lines
- Onset of so-called "calcium-oscillations" in cells
- Alteration in c-myc expression and other examples of gene expressions
- Alteration in cell proliferation
- Alterations in receptor-mediated signalling pathways in cells
- Effects on cell-cell communication and gap junctions
- Increase in calcium efflux from the brain (on animals)
- Altered growth of plants (either the full plant or a part of it)

The list is by no means complete. For more details we refer to a recent review of possible health effects by a working group appointed by National Institute of Environmental Health Sciences of the National Institutes of Health (Portier and Wolfe, 1998, see list of references).

Among all the reported effects, the most important has been the following: In 1979 Wertheimer and Leeper found an elevated occurrence of leukaemia among children that had grown up close to power line (actually, distribution lines). The so-called relative risk was two to three times as high for these children as for other children. Since then a number of similar epidemiological studies have been performed, and in Figure 13 the "main finding" in most of these studies are presented.

Even if the different studies have many similarities, they are also in many respects very different. It is therefore difficult to compare the results. Some meta-analyses have been performed, but they have not so far added new insight. Leukaemia among children is a rare illness (only about 4 out of 100.000 children are hit by the illness every year), and only a few percent of the children grow up near power lines. Thus, the statistics is rather poor. This may lead to large fluctuations in the results depending on factors that one should think are of marginal importance. For example, in the Norwegian epidemiological study (J in Figure 13), the odds ratio (similar quantity as relative risk) for leukaemia among children was 0.3 if the analysis was based on the calculated time-weighted average of magnetic field exposure *from birth to diagnosis*. However, the odds ratio was 2.2 if the exposure for the calculated magnetic fields *the first four years of life* was the criterium for analysis. In the paper seven different kinds of analysis were presented, and it should be kept in mind that a figure like the one in Figure 13 will depend heavily on which results that are picked out from the total material available in the studies given.

Results like those presented in Figure 10-13 is interpreted differently by various people. Some count the number of studies that have given statistically significant increased (calculated) risk, and those studies that do not show such an increase. For the data in Figure 13, that means that about two studies showed statistical significant elevated risk, ten not ("Two studied showed an effect, ten did not show any effect."). Other people wander about the fact that most of the reported relative risks are above 1 (indicating increased risk). If the effect is *not* real, one should expect that the dots in the figure were distributed about equally above and below the relative risk equal to 1 line. (The results from studies of leukaemia and brain tumour among adults living close to power line, are very much distributed in that way.) This seemingly over-representation of Relative risk greater than 1 results in studies of children is taken as a possible indication that leukaemia (and also partly brain tumour) might occur more frequently among children growing up near power lines than among other children.

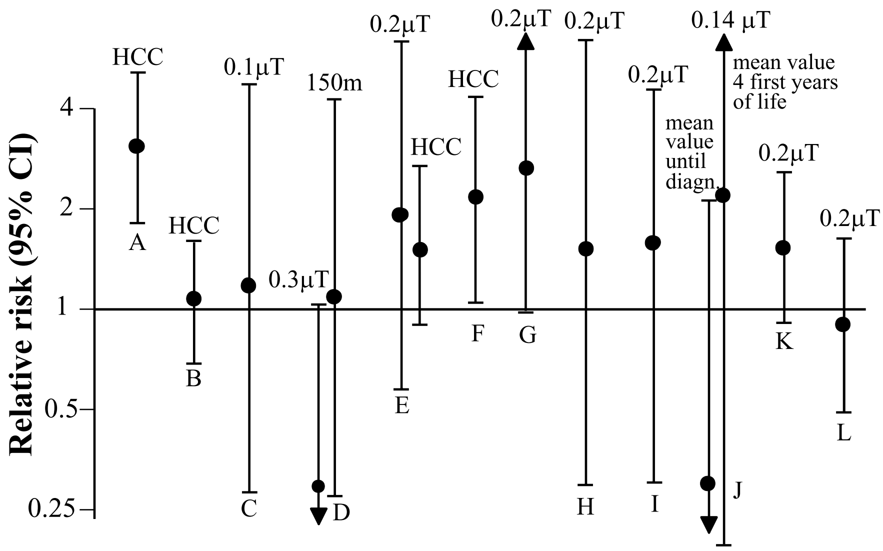

Figure 10-13. Results from most epidemiological studies on cancer (leukaemia) among children that have grown up close to power lines. The relative risks are given along with their 95 % confidence intervals. Risk above 1 indicates an elevated risk, below 1 a reduced risk. The criterion used in discriminating between "exposed" and "non-exposed" children are given for each study. The letter indicate the different studies as follows: A: Wertheimer and Leeper, 1979; B: Fulton et al., 1980; C: Myers et al., 1985; D: Tomenius, 1986; E: Savitz, 1988; F: London et al., 1991; G: Feychting and Ahlbom, 1993; H: Olsen et al., 1993; I: Verkasalo et al., 1993; J: Tynes and Holdorsen, 1996; K: Linet et al., 1997; L: Day et al., 1999 (Full references must be found elsewhere). For three studies two different outcomes are indicated (the two results from the Norwegian study J are discussed in the text).

There are a lot of uncertainties affiliated with this conclusion, and we are not going into most of them. However, a couple points should be mentioned. First of all, if the elevated occurrence of leukaemia is real, is it then connected to electric or magnetic field, or may be to quite another factor? Most investigators suppose that it is due to power frequency magnetic field, but we certainly do not know! Secondly, even if the characterization of magnetic field exposure has become much better in the latest studies than in the earliest ones, they all are based on an assumption that the "dose" is related to the "time weighted average" (TWA). That means, if one child is exposed to a 10 μT (RMS) field for 30 minutes a day, and very low field the rest of the day and night, this exposure would count the same as for a child that is constantly exposed to a 0.2 μT field (RMS). It is by no means obvious that such an assumption is valid, we simply do not know. If the time weighted average assumption is not valid, it is most likely that we have underestimated the relative risk rather than the opposite.

Leukaemia among children seems to be that particular finding that many people takes as the strongest evidence that weak low frequency electromagnetic fields may represent an unwanted health effect. A large number of various other studies may or may not indicate similar deleterious effects. Some years ago it was an intense debate on whether fields from a visual display terminal could lead to spontaneous abortion or deformations of fetuses. Both epidemiological studies and animal studies were carried out, and some results indicated that there were an effect, other did not find such an effect. Today most people seems to think that the effect, if it really is there, has to be very weak. Based on the available results, however, it is very difficult to draw a firm conclusion even on this subject.

There has been carried out epidemiological studies on breast cancer among both men and women. All thinkable kinds of cancer has been sought connected to different occupations. Electrical utility workers, train engine workers, workers in high voltage testing facilities etc., may have an elevated risk for some cancer or another. There are many indications, but no real "proof".

On the other hand, low frequency electromagnetic fields have also been used in attempts to cure the body. Magnet-therapy is claimed to work beneficial in man, especially in stimulating bone growth (often used after so-called "non-unions") and nerve regeneration. Some of the magnet-therapy use field patterns that actually induce currents in the body corresponding to the acute effect discussed above, some do not. A particular variant of magnet-therapy use static magnetic fields, based on inhomogeneity in the field.

Magnet-therapy is an umbrella covering a large variety of methods and actors. I think it is safe to claim that most people that offers magnet-therapy base their claims on very insufficient and far too little systematic and scientifically based experience. On the other hand, some part of the magnet-therapy business seems interesting, and several studies claims to have shown an effect even in so-called double blind experimental design. That is not necessarily a big surprise, since some of the reported effects may be explainable in terms of either effects similar to "acute effects" discussed above, or to inhomogeneities in the field, that add another interaction mechanism to what we have discussed so far.

As we have seen, there are no doubt that strong fields may lead to biological effects. What effect weak fields have, is a more open question. In spite of many years of research, it seems that we have not been able to conclude conclusively on this. Some particular biological effect may be rather well established, but it is difficult from those effect, often found in cell cultures or in animal systems, to conclude about any health effects. For this reason, people working in this field of research rely on their "gut feeling" when interpreting the different published studies. It becomes almost impossible to be completely objective, and some scientists interpret available data so that they are convinced that even weak low frequency electromagnetic fields may have not only an biological effect, but even an harmful effect. Other scientists interpret the very same available data differently. They think that the problems with inter-laboratory reproducibility indicates that the effects that are reported are all artifacts, and that weak fields do not have any biological effects, neither beneficial nor harmful. Most people are somewhere in between these two extremes, and struggle to make up ones judgements as well as possible. But only the most arrogant person will not admit that the uncertainty in this field of research is a great problem, at least intellectually.

10.7 Shielding

Shielding of low frequency electromagnetic fields is an art, and much more complex than shielding of ionizing radiation, light or infrared radiation. The efficiency of the shielding depends heavily on the frequency of the fields, whether it is the electric or the magnetic component that dominate, and on geometric and material factors.

A cage made of metal, properly connected to ground, often called a Faraday cage, is extremely efficient in shielding a static or extremely low frequency electric field. However, the shielding efficiency of the very same Faraday cage for static or extremely low frequency magnetic field, is about zero.

Low frequency magnetic field may be reduced markedly if the walls of the cage is made from thick, continuous sheets of metal with high conductivity. For 10-12 mm thick aluminium plates, carefully welded together, a 50 Hz magnetic field is typically reduced by 50-70%, depending on geometric factors.

The mechanism in this kind of shielding is the so-called «Eddy-currents»: Electric current induced in good conductors of large uninterrupted areas in the presence of a time-varying magnetic field. The induced currents produce a magnetic field that tends to reduce the original time-variable magnetic field (a principle often termed «Lenz law»).

It is also possible to shield static or ELF magnetic fields by magnetic active materials, like soft iron or various alloys. The magnetic material conduct the magnetic field lines through itself, leaving less field in the nearby regions. The efficiency here depends on the so-called relative magnetic permeability, and this parameter again depend on several factors like the choice of material and the magnetic field strength. Soft iron is quite efficient when shielding for a rather strong ELF magnetic field, but not as efficient when shielding from rather weak ELF fields like those found in houses near power lines etc. The reason for this is that the relative magnetic permeability of soft iron is relatively small (only in the order of 100) for a 1 μT 50 Hz (external) magnetic field, but in the order of 1000-3000 for a 500 μT 50 Hz external magnetic field (about 1 T internal magnetic flux density in the iron itself).

Alloys with a so-called "high initial relative magnetic permeability", like mu-metal (an alloy made from 75% nickel, 18% iron, 5% copper and 2% chromium), may have a relative magnetic permeability of about 50.000 for a 1 μT 50 Hz magnetic field. Thus, it can be rather efficient in shielding from relatively weak magnetic fields. A problem with mu-metal, however, is its high price and that it cannot be bent or formed without losing some of its magnetic properties. The material has to be heated and cooled down in a controlled way after bending etc. in order to restore its high initial magnetic permeability.

The mechanism behind shielding fields by magnetically active material is, as mentioned above, the material's ability to conduct magnetic field inside the metal, so that less field is found in the volume outside this material. But magnetic field lines always run in closed loops, so that at the end of a sheet of mu-metal, the magnetic field may be highly concentrated. Thus, if the mu-metal is used in an unfavourable way, it may lead to increased magnetic field on a particular place in space instead of a reduced field. Geometrical factors are highly relevant also for this kind of shielding.

In order to reduce very low frequency magnetic fields, the best strategy is to use a combination of several measures. The most important ones are:

1. Increased distance between the source and the place of interest.
2. Reduced distance between the two (three) cables that carry the «forward» and the «return» current.
3. Increased symmetry in cabling so that the magnetic field from the «forward» and the «return» current more efficiently cancel each other.
4. Introduction of shielding metal either based on «Eddy-currents» (thick aluminium) or on magnetic properties (often mu-metal or soft iron).
5. Active compensation.

The two first points are indirectly explained already in the sections above where we discussed sources of magnetic fields. The importance of these factors can be illustrated as follows:

In some countries heating cables in a concrete floor may be used for heating rooms during winter time. Several kinds of heating cables are commercially available. If the cable is a "one-lead" heating cable, it carries only current in one direction. If the cable is a "two-lead" cable, it contains two leads, closely packed together (but isolated from each other!), carrying equal, but oppositely directed currents. Heating cables are often laid in a "folded" pattern covering the floor, with a distance between the different loops of about 0.1-0.2 m (mean value often about 0.15 m). The magnetic field 0.5 m above the floor, for a current of 10 A, is then according to the equation given at page 8 (??), the magnetic field is about:

$$(0.2 * 10 * 0.15 / 0.5^2)\ \mu T = 1.2\ \mu T$$

for the one-lead cable. Here the distance between "forth" and "back" current is equal to the distance between two adjacent loops. For the two-lead cable, however, the distance between "back" and "forth" current leads is only a couple mm, since they are located within the very same cable. Thus, the field 0.5 m above the floor is about:

$$(0.2 * 10 * 0.002 / 0.5^2)\ \mu T = 0.016\ \mu T$$

In practice, the two leads within the same cable, are often twinned around each other, which reduces the field even more.

Thus, by a simple change in construction of the cable, from a one-lead cable to a two-lead cable, the magnetic field can be reduced by a factor of the order of one hundred! This illustrates the importance of cabling and construction. It also illustrates that it may be much more rewarding to reducing the field produced by a source than trying to reduce the field already present.

In the list above, active compensation was mentioned as a method for reducing low frequency fields. When applying active compensation, a new source of magnetic field are introduced that produce a magnetic field that has exactly the same frequency (and phase) as the magnetic field that we want to reduce. However, the compensating field must have a direction that is the opposite of the field we want to reduce (remember that electric and magnetic fields are vectors!). The total field is then brought close to zero, in principle at least. However, reduction of a static or ELF magnetic fields by active compensation can only be efficient for a limited volume in space. For that particular volume, the reduction can be very efficient.

Radio frequencies

As the frequency increases, the coupling between electric and magnetic field gets closer. A Faraday cage becomes less efficient in shielding the electric field component, but far more efficient in shielding the magnetic field component. For radio frequencies in the MHz range, a cage with solid metal walls is very efficient in shielding the fields or radio waves. However, if there are slits or holes in the walls that are of the same magnitude or larger than the calculated wavelength, the corresponding fields often finds its way through these slits/holes. But even this effect depend on geometrical factors like the polarization of the radio waves as compared to the direction of the slit/hole.

The magnetic response in various materials is a time-dependent property. For higher frequencies than a few hundred kilohertz (for some materials even for far less frequencies) the magnetic response cannot follow the rapid changes in the external magnetic field. The relative permeability is then reduced to near 1.0, and the material is not able to conduct the magnetic field very efficiently any more. Thus, for radio frequency fields, magnetic materials are seldom the right choice in reducing magnetic fields. Even if iron is used for example in a Faraday cage for radio frequency shielding, it is done so more because of its electrical conductivity and ease in construction rather than for its magnetic properties.

Active compensation is practically speaking not used for reductions in radio frequency fields.

Shielding in practice

People living in houses very close to high tension power lines often use a grounded metal net covering the roof (under the roof tiles) in order to reduce the power frequency *electric* field. This procedure might be highly efficient. On the other hand, shielding of the power frequency *magnetic* field is seldom carried out. The cost would be very high and the shielding efficiency rather poor.

Similarly, for a computer visual display unit (VDU), a grounded screen that consist of a slightly conductive film placed between two sheets of glass (or a similar construction), may reduce the electric field from the VDU quite efficiently, especially for the static electric field (not as efficiently for the line-frequency electric field). On the other hand, the screen have a rather minor effect in reducing the magnetic field. Today, most VDUs for computer use has a built in conductive layer at the front of the VDU. Thus, today extra filters have far less effect in reducing fields than they once had back in the 1980-ies, before «low radiation VDUs» came on the market.

Power frequency magnetic fields from an in-house transformer actually originates often from the high current cables in the secondary circuits, rather than from the transformer itself. One of the most efficient ways to reduce the fields from such sources, is to bring the cables carrying high currents further away from nearby rooms where people work. In addition, the cables of the three phases are often brought closer together, or even split in several cables and intertwined, in order to reduce the magnetic fields. Special cable constructions for such a use are commercially available, and they produce considerably less magnetic fields to the surroundings than ordinary cables.

In order to reduce the exposure to electric or magnetic fields from home appliances, an increase in distance is often the most efficient measure. By placing a clock radio twice as far from the pillow in a bed, the field values are often reduced by a factor between four and eight. Instead of putting the nose close to the front glass in a microwave oven during use, one could reduce the exposure considerably by watching the oven from a distance of e.g. 50 cm, or by limiting the time spent very close to the source.

We are all constantly exposed to radio frequency fields from radio and television transmitters and base-stations for the mobile telephone network. In most cases, the intensity of the incident radio waves pose no immediate problem because a safety distance is introduced from these transmitting antennas (and/or due to the narrow antenna radiation loop characteristics). The highest intensity people usually are exposed to in the radio frequency bands, are mobile telephones or cordless telephones used in homes or offices. In general it can be said that the closer the antenna is to the head, the higher is the intensity at the head, and also the absorbed energy per local tissue weight. Even so, people want their mobile telephone as small as possible, which often means a higher exposure level. An extra antenna may reduce the exposure considerably, but that is seldom used in practice. Some extra gadgets may be bought in order to reduce the absorbed energy in the head, but many of these do not work as the intention. Watch the information carefully if you want to buy one. The manufacturer must be able to prove that the gadget really reduce absorbed energy in the head for *identical output and input signals* between the mobile telephone and the base station. If not, the gadget may very well be a waste of money and lead to reduced battery life.

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