

Analysis of Modeling the Influence of Electromagnetic Fields Radiated by Industrial Static Converters and Impacts on Operators Using Maxwell's Equations

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Abstract

The study of Electromagnetic Compatibility is essential to ensure the harmonious operation of electronic equipment in a shared environment. The basic principles of Electromagnetic Compatibility focus on the ability of devices to withstand electromagnetic disturbances and not produce disturbances that could affect other systems. Imperceptible in most work situations, electromagnetic fields can, beyond certain thresholds, have effects on human health. The objective of the present article is focused on the modeling analysis of the influence of geometric parameters of industrial static converters radiated electromagnetic fields using Maxwell's equations. To do this we used the analytical formalism for calculating the electromagnetic field emitted by a filiform conductor, to model the electromagnetic radiation of this device in the spatio-temporal domain. The interactions of electromagnetic waves with human bodies are complex and depend on several factors linked to the characteristics of the incident wave. To model these interactions, we implemented the physical laws of electromagnetic wave propagation based on Maxwell's and bio-heat equations to obtain consistent results. These obtained models allowed us to evaluate the spatial profile of induced current and temperature of biological tissue during exposure to electromagnetic waves generated by this system. The simulation 2D results obtained from computer tools show that the temperature variation and current induced by the electromagnetic field can have a very significant influence on the life of biological tissue. The

paper provides a comprehensive analysis using advanced mathematical models to evaluate the influence of electromagnetic fields. The findings have direct implications for workplace safety, potentially influencing standards and regulations concerning electromagnetic exposure in industrial settings.

Keywords

Modeling, Electromagnetic Field, Power Converters, Geometric Parameters, Biological Tissue, Maxwell Equation, Bio-Heat Equation, Thermal Model

1. Introduction

The share of electronics in embedded systems (automobile, aeronautics, space, etc.) continues to grow. Supported by its strong integration, this electronic provides greater performance and makes it possible to offer solutions to the requirements, among other things, of safety and comfort. However, such rapid evolution requires taking into account any marginal phenomenon that could harm the environment. In the same way as thermal management or the management of mechanical constraints, electromagnetic disturbance has become a risk phenomenon of great importance for any power electronics system and also affects human health. The operation of a static converter is intrinsically polluting, the electrical quantities being highly variable due to their rapid switching, over very short durations ranging from 1 to 10 ns, with high amplitudes of the order of kilo Volt and kilo Ampere and frequencies up to 100 Hz to 1 MHz more than their amplitude. These are mainly the current and voltage gradients responsible for electromagnetic disturbances in the converter's environment. Indeed, all electromagnetic coupling phenomena operate proportionally to the variation of these quantities. This constitutes a serious Electromagnetic Compatibility (EMC) problem. Furthermore, the omnipresence of sources of electromagnetic fields in industrialized countries means that people residing in these countries are exposed to them daily, both in their domestic and professional environments [1] [2]. However, it is in the professional environment that these sources are the most frequent and also the most intense, such as industrial converters [3].

The potential risks for people exposed to interactions between electromagnetic fields and the human body are real and therefore require protective measures [3]. Exposure to these sources may be voluntary in the event of a medical diagnosis such as for example an NMR imager, hyperemia therapy, ablatherapy or involuntary mobile telephony, radio or television transmitters, household appliances, screens of computers, televisions, security systems in stores and airports, high voltage. lines, transformers, industrial converters, etc. [4]. Exposure to electromagnetic fields generates currents inside the body, and the corresponding absorption of energy in tissues leads to an increase in temperature [5]. The health effects generated are mainly a function of the coupling mechanism, the nature of the fields and the duration of exposure [6]. These phenomena are all

the more important as the intensity and/or frequency of the signal are high [3] [7]. In addition to the effects observed on biological functions and health, electromagnetic fields and waves also act on electronic devices [8]. It is therefore important when constructing these to ensure that their operation does not interfere with that of other devices or is not itself the victim of other field source devices. Avoid any form of electromagnetic compatibility [9]-[11].

Several epidemiological and experimental studies have been carried out on this subject and most of them have led to the establishment of biological effects that may result in risk to the long-term health of a living being [12]. Theoretical studies have also made it possible to estimate the doses of electromagnetic energy absorbed by animals and humans.

Modeling the influence of the geometric parametric of industrial static converters on the field radiated by the latter and the biological effects of these emissions being the objective of this article, it seems essential to us to describe the semi-analytical approach to the environment electromagnetic converter power circuits, the biological cell and the molecular structure of the plasma membrane to highlight the difficulties linked to their electrical characterization [13] and the modeling of the induced current in biological tissue. To do this, we took into account the analyses of some of the authors cited below to help us guide our work [1] [9] [12] [14] [15].

According to TBCarlos KONLACK and Roger TCHUIDJAN [2011] an evaluation of the power distribution induced by an electromagnetic wave in a spherical model of the brain allows us to say that [8], the quantity of energy received by the brain from electromagnetic waves is very high compared to that which emerges by radiation, and that almost all of the energy received is transformed into heat.

According to DV Land [3], microwave thermography techniques have been widely used in medical applications to monitor tissue temperature and detect electromagnetic fields in biological tissues. Since the temperature increases in the tissue resulting from the deposition of energy and is proportional to the square of the electric field in the tissue; the response to thermal radiation must have the same sample.

Various studies carried out on the subject have shown that electrical impulses induced by microwave electromagnetic waves can cause cell death. The mechanisms leading to this destruction may differ depending on the characteristics of the pulse, the number as well as the frequency of repetition [16] [17].

According to KH Schoenbach, S. Xiao, RP Joshi, JT Camp, T. Heeren, JF Kolb and SJ Beebe [2012] [18], the duration of the pulse is close to a nanosecond and the applied field is of the order of MV/cm. The death of illuminated cells is caused only by changes in the different electrical potentials of the different membranes. The study by JT Camp, Y. Jing, J. Zhuang, JF Kolb, SJ Beebe, J. Song, RP Joshi, S. Xiao and KH Schoenbach [2012] [18] shows that cell death is caused by electrical effects, but also by thermal effects.

A biological system irradiated by an electromagnetic wave is crossed by induced currents of high density [18]-[21]. The use of high frequencies, in the order of several tens of gigahertz and more, can cause non-thermal effects detrimental to the health of an exposed biological system. It depends on the frequency, and intensity of these waves and the duration of exposure to them.

Thus, the mathematical and numerical approach that we propose in our article is intended to be analytical, comparative and critical at the same time [12]. It is not only a matter of analyzing, but also of comparing the different theories of specialists in the field in order to draw useful lessons to achieve the objectives set.

Our work aims to complement and strengthen the veracity of some of the results already obtained. For our application, we will consider the particular case of a polluting AC/DC converter operating with a current of 1000A in interaction with a biological tissue characterized by blood and muscles. To do this we used the analytical formalism for calculating the electromagnetic field emitted by a filiform conductor, with a view to modeling the electromagnetic radiation of this device in the spatio-temporal domain.

The formatter will need to create these components, incorporating the applicable criteria that follow.

2. Study Method

To better understand the distribution of power at various points in a biological system and predict possible consequences on health, we will proceed with a mathematical and numerical analysis based on the analytical formalism of calculating the electromagnetic field emitted by a filiform conductor, with the aim to model the electromagnetic radiation of converter in the space-time domain. The interactions of electromagnetic waves with human bodies are complex and dependent on several factors linked to the characteristics of the incident wave, to model these interactions we implemented the bio-heat equation as the basis for the evaluation of the variation of temperature and current induced by the electromagnetic field in the biological tissue to obtain consistent results. The schematic diagram including the main stages of the research is as follows:

- Modeling of the electromagnetic field radiated by the industrial static converter based on the analytical formalism for calculating the electromagnetic field emitted by a filiform conductor.
- Resolution of the electromagnetic field-biological tissue coupling from theoretical models.
- Three-dimensional spatial modeling of the temperature profile based on the bio-heat equation.
- Numerical simulation.

There is some need for approximation in our study. Indeed, biological systems are quite complex due to their geometric shape and the inhomogeneity of their internal constitution. This is how we will assimilate for our study a biological

system to a dielectric characterized by three main parameters which are:

- The permittivity ϵ : it is linked to the capacity of the medium to be influenced by electric charges.
- Magnetic permeability μ : It reflects the influence of the magnetic field on the environment.
- Conductivity σ : It reflects the capacity of the medium to carry electrical charges.

3. Theoretical Models

3.1. Approach to the Electromagnetic Environment of Static Converters

Power electronics use power semiconductors in switch mode. This operation gives the converter very high efficiency; on the other hand, it gives rise to numerous electromagnetic disturbances due mainly to the rapid switching of semiconductors. The disturbances propagate towards the converter's power source and towards the load it supplies, a smaller part of this energy is radiated [22].

The use of electronic equipment is increasing in all fields of activity, whether consumer, industrial or military [23]. The technologies used in the design and development of digital equipment systems are based on three parameters:

- switching speed (microprocessor speed),
- the low energies used to switch from one state to another,
- the high level of component integration.

3.1.1. Types of Converters

The use of electronic equipment is increasing in all fields of activity, whether consumer, industrial or military [23]. The technologies used in the design and development of digital equipment systems are based on three parameters:

Static converters are electronic devices that convert one form of electrical energy into another form of electrical energy [22]. These devices are often used in electrical power systems to provide stable voltage, current, or electrical power to a load [23]. These are devices with electronic components capable of modifying the voltage and/or frequency of the electrical wave.

There are two types of voltage sources:

DC voltage sources characterized by the value V of the voltage.

Alternative voltage sources defined by the values of the effective voltage V and the frequency f .

Then we list the energy modulators making it possible to manage the energy necessary for controlling electrical systems:

- ✓ The dimmer which transforms fixed alternative energy into variable alternative energy.
- ✓ The uncontrolled rectifier which transforms fixed alternating energy into fixed continuous energy.
- ✓ The controlled rectifier which transforms fixed alternating energy into variable continuous energy.

- ✓ The assisted inverter which transforms DC energy into fixed AC energy.
- ✓ The autonomous inverter which transforms DC energy into variable AC energy.
- ✓ The chopper which transforms continuous energy into variable continuous energy.

Figure 1 shows the table of all static converters as described above.

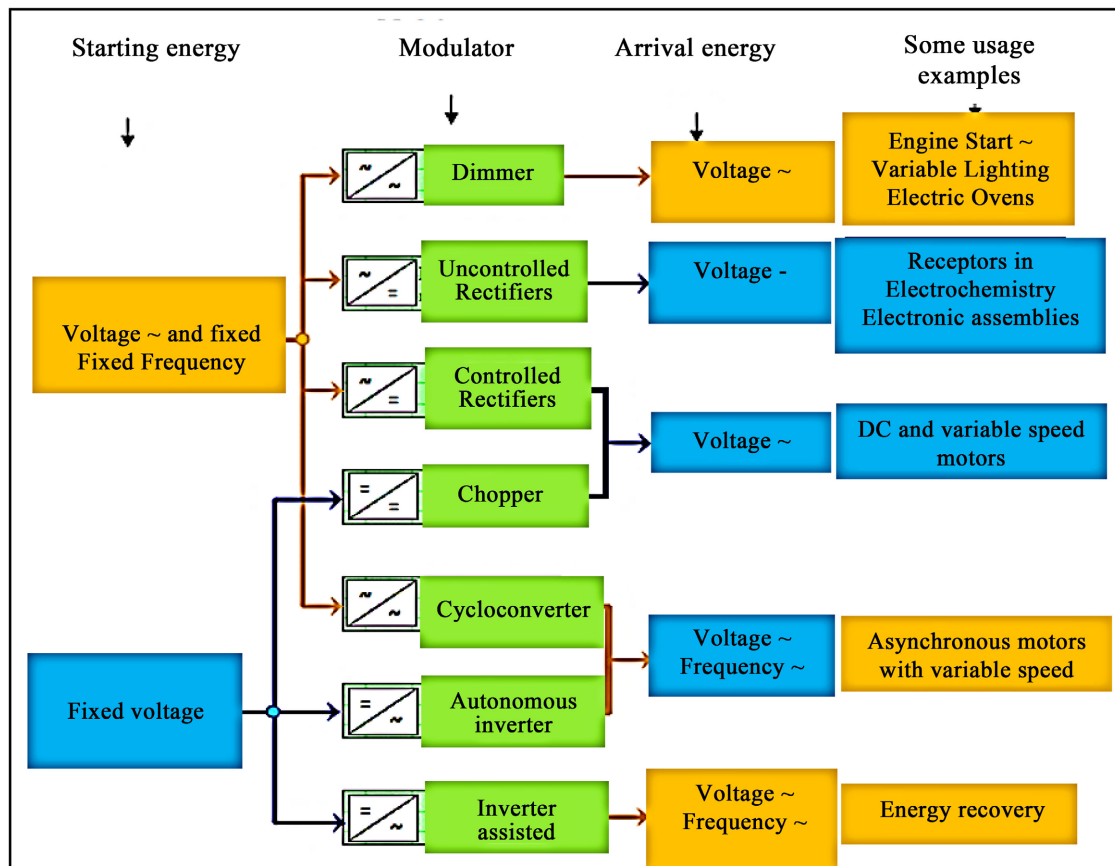


Figure 1. Table of different static converters [24].

3.1.2. Disturbances in Converters

The principle of a converter consists of establishing then periodically interrupting the source-load connection using the power switch. The latter must be able to be closed or opened at will in order to have an adjustable DC output voltage [25].

Disturbances in static converters can be caused by various factors, such as variations in supply voltage, variations in load, external electromagnetic disturbances, disturbances caused by transistor switching, etc. [25].

These disturbances can lead to problems such as output voltage or current fluctuations, power losses, electromagnetic interference, component failures, etc.

To reduce disturbances in static converters, it is important to consider several design factors, such as component selection, component layout, PCB design, grounding, etc. [26]. Appropriate filtering techniques can also be used to reduce

electromagnetic disturbances. Additionally, advanced control techniques can be used to minimize disturbances caused by transistor switching.

Finally, testing and verification must be carried out to ensure that the static converters meet the required specifications in terms of performance and electromagnetic compatibility.

Note that the main cause of producing disturbances is the rapid variation of voltages (dv/dt), currents (di/dt), magnetic fields (dH/dt) and electric fields (dE/dt). The most important consequence is the induction of parasitic voltages or currents in the devices (converters) under the influence of the disturbance. It can have the character of a source of voltage, current or energy depending on the nature of the physical phenomenon which produces it [27]. An electric wave is characterized by its frequency, voltage and intensity.

3.1.3. Emissions From Static Converters

Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers

The very principle of power electronics is to ensure the transformation of electrical energy by cutting at high frequencies (from 100 Hz to a few hundred kHz). Switching times are typically greater than 100 ns, while digital circuits dedicated to the signal have transition times often less than 5 ns. On the other hand, the voltages and currents involved which dictate the choice of power components lead to fairly similar voltage increases but to much higher current growth rates [28]-[32].

The di/dt will create brief voltage pulses across the parasitic inductances or connections and subsequently, disrupt by so-called common impedance coupling the sensitive circuits using the same conductors called power bus.

The dv/dt will also create very brief current pulses in the various parasitic capacitances (card to chassis coupling for example) and cause, as previously, disturbances in the control-command cards [30] [33] [34].

Depending on the frequencies there are 2 types of disturbances:

- LF: low frequencies.
- HF: high frequencies.

Low frequency disturbances the frequency range: $0 \leq \text{frequency} < 1$ to 5 MHz. Low frequency disturbances are found in installations mainly in conduit form (cables, etc.). Its duration is long (a few tens of ms). In some cases, the phenomenon can be permanent (harmonic). As for its conducted energy, it can be significant and results in the malfunction or even destruction of interconnected devices.

High frequency disturbances: frequency range: 30 MHz. High frequency disturbances are found in the installation in radiated form. Duration: the rise time of the pulse is less than 10 ns. The radiated energy is low and results in the malfunction of surrounding equipment.

Electronic energy conversion structures are ideally suited to illustrate the

mechanisms of conducted emissions and provide the basic building blocks for modeling these phenomena.

The very nature of their operation is in contradiction with the common sense rules that we seek to apply to limit inter- and intra-system interaction. CEM tends to show that it is necessary to limit rapid variations in electrical quantities (voltage, current) and electromagnetic (fields) while switching structures generate sudden variations, at least electrical, to manage the transfer of energy desired with lower losses.

3.1.4. Sources of Disturbances

To talk about the sources of disturbance in power electronics we choose, for example, energy conversion: cutting is done by power switches with semiconductor components. There are switches with controlled switching (MOSFET, IGBT, JFET) which require control and others with natural switching. It consists of identifying the problem in three parts: the sources of disturbance, the propagation paths or channels and the victim [34]. The sources of disturbances are the switching of power switches. These switchings are the cause of sudden variations in voltage (dv/dt) and current (di/dt) which give rise to electromagnetic disturbances.

The sources of electromagnetic disturbance can be characterized by [35]-[39]:

- Their origin: internal (maneuver), or external (lightning).
- Their temporal nature: permanent or transitory.
- Their frequency content:
 - ✓ *Low frequency*: due to radiation near lines and busbars, especially in the event of load imbalance.
 - ✓ *Medium frequency*: due to switching in the power electronics assemblies in the substation (hundreds of KHz), medium frequency signals transmitted permanently or occasionally for control purposes. Ex (carrying currents, and the corona effect in the conductive sections of the “lines and busbars” substation).
 - ✓ *High frequency*: due to transient waves which appear during the injection of a lightning wave.

3.1.5. Origin and Paths of Electromagnetic Disturbances

To understand the origin of electromagnetic disturbances, let's start by analyzing the spectral behavior of waveforms in power electronics.

Useful or parasitic electrical signals have two ways of propagating by conduction on a two-wire connection. We can therefore study the disturbances according to the two modes. Conducted and radiated disturbances have a common origin, they are linked to the spectral components of voltages and currents. The static converter, through its switching operation, produces sudden variations in voltage and current. These variations are the cause of parasites, called electromagnetic disturbances [35]-[39].

In an electric field, disturbances are mainly radiated by conductors subject to variations in potential.

In a magnetic field, the disturbances are radiated by the loops, the switching of the voltage generates common mode HF currents which we find in the parasitic components, the switching of the current creates differential mode disturbances.

3.1.6. Decomposition of an EMC Problem

Any electromagnetic interference situation involves three different elements as shown in **Figure 2**: a source of disturbance emission, a disturbance receiver (victim), and a coupling mechanism by which the disturbance reacts on the operation of the receiver.

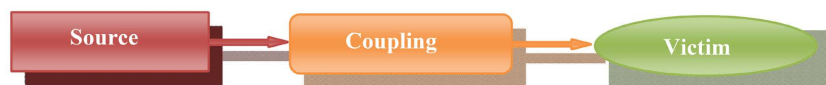


Figure 2. Decomposition of an EMC problem [35]-[39].

3.2. Electromagnetic Coupling

Coupling is the phenomenon of propagation of disturbances that occurs between the source and the victim. The coupling modes can be classified according to the type of disturbance and according to the propagation medium, by conduction (characterized by currents and potential differences), or by radiation (characterized by electric and magnetic fields) [35]-[37], this is illustrated by **Figure 3** below:

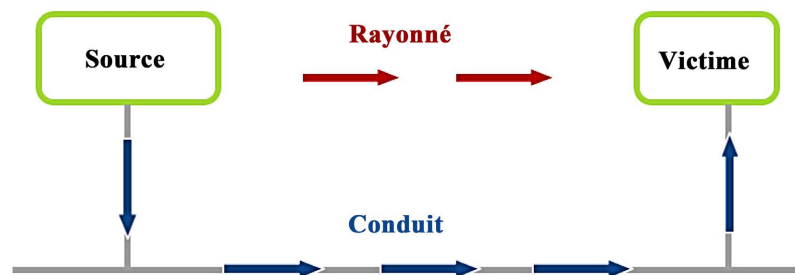


Figure 3. The coupling modes between the source of disturbance and the victim [35]-[37].

3.2.1. Coupling by Conduction

Conductive coupling occurs when the source of disturbance and the victim are connected together by a conductor. It is done in two modes illustrated by **Figure 4** and **Figure 5**:

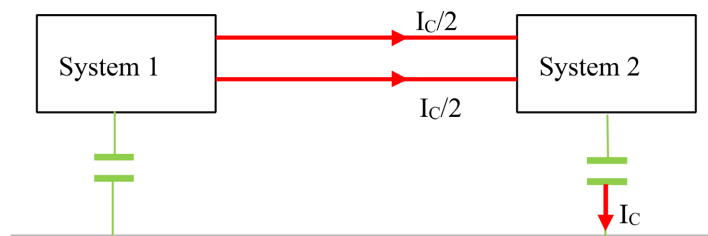


Figure 4. The common mode between two systems [35]-[37].

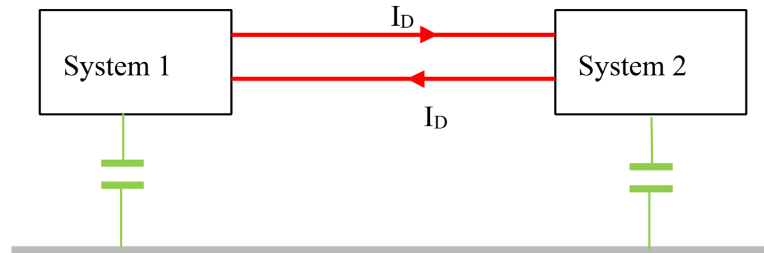


Figure 5. The differential mode between two systems [35]-[37].

The common mode: in common mode, signals propagate in the same direction on all conductors. Common mode currents return through ground. This mode represents 10% of cases. It is also called “parallel”, “longitudinal”, or “asymmetric” mode.

Differential mode: differential mode is the ideal mode of signal transmission which represents 90% of cases. In this mode, all current that enters the receiver returns to the source through a return wire. It is also called “series”, “normal”, or “symmetric” mode.

3.2.2. Coupling by Radiation (by Field)

We say coupling by radiation (field), if the propagation medium of a disturbance transmitted from the source to the receiver is space.

We know that the electromagnetic field radiated by a radiation source varies by the distance which separates the radiation source and the place where the field is observed, for this we distinguish two types of coupling by field [35]-[40]:

1) Near-field coupling

Near the source, the electromagnetic field depends on the characteristics of the source:

Coupling by electric field (capacitive):

The difference in potential between a conductor and its environment generates an electric field around the latter; the variation of this field injects a current into all nearby conductors. The cause of capacitive couplings is the parasitic capacitances formed by the presence of two conductors.

Coupling by magnetic field (inductive):

A current flowing in a wire generates a magnetic field. The variation of this field induces an electromotive force in the neighboring loops.

2) Far-field coupling

Beyond the near-field radiation zone, the so-called far-field radiation zone. In this region, the characteristics of the radiated electromagnetic field only depend on the properties of the medium in which the field propagates, and we say that we are dealing with coupling by electromagnetic field or by plane wave, so we must use the equations of Maxwell to calculate the amplitude of electromagnetic disturbances. Which means that the components of the electromagnetic field cannot be separated.

Figure 6 summarizes all the types of coupling.

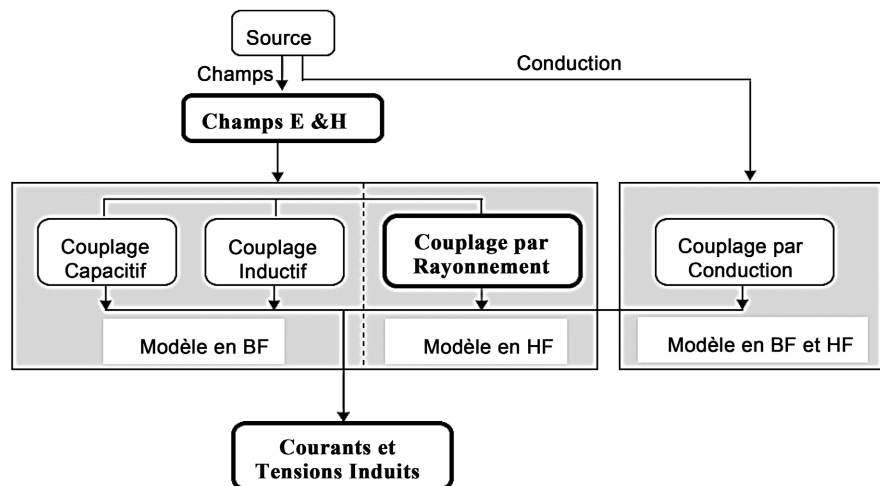


Figure 6. Coupling models [35]-[40].

3.3. Description of the Biological Cell

Since the effects of electromagnetic fields in a biological cell are the focus of this article, we believe it is essential to describe the biological cell and the molecular structure of the plasma membrane. The biological cell is the structural and functional unit of all living beings, it is characterized by its nucleus, its cytoplasm and its plasma membrane [21]. The cellular plasma membrane plays an essential role in the life of the cell, it delimits the cell and separates the cytoplasm from the external environment. It surrounds the cytosol (*i.e. the* liquid phase in which the cytoplasmic organelles bathe) and forms a very thin protective layer composed of lipid and protein molecules. It thus has a heterogeneous molecular structure allowing it to play a dual role: the phospholipids which are the essential constituents of its basic material, make it insulating, while the protein molecules which are dispersed, ensure the exchange between the cytoplasm and the extracellular environment [22].

The cell is the basic structural and functional unit of all living things. The cells are very small and very complex in organization. Knowledge of their structure, chemical composition and functioning (physiology) is very essential in biology and biomedical sciences. Studies on cellular functionality and behavior have been widely applied in many clinical and biomedical applications, such as diagnosing diseases and understanding their degree of progression, drug development, and cancer research [19] [23].

This is why knowledge of their components and their characteristics is important for the further development of our research and in particular for the study and modeling of human biological tissues exposed to microwave electromagnetic waves.

In the case of biological environments, energy absorption phenomena in tissues can be relatively complex and depend on numerous factors. They are mainly linked to the type of coupling between the emission source and the biological environment. Galvanic coupling corresponds to the case of physical contact be-

tween the source and the medium. This contact causes the circulation of an ohmic type current in the person's body. Depending on the intensity and frequency of the contact current, the consequences can lead to heating of the tissues, or even a burn [19] [23].

Radiated coupling includes three fundamental mechanisms by which electric and/or magnetic fields, of variable frequency over time, interact with biological media [19] [21] [23].

Coupling with low frequency electric fields: external electric fields induce, on the surface of the exposed body, a surface charge which causes, inside the body, the appearance of currents whose distribution depends on the conditions of exposure, body size and shape. The body as well as the position of the body in relation to the terrain [19] [21] [24] [25].

Coupling with low frequency magnetic fields [26] [27]: the physical interaction between magnetic fields of variable frequency and the human body creates induced electric fields and causes the flow of electric currents. The magnitude of the fields and the density of the induced current are proportional to the intensity and frequency of the magnetic field B , the radius of the current loop in the body, and the electrical conductivity of the exposed tissues.

It should be noted that exposure of the human body to low-frequency electric or magnetic fields generally results in only negligible energy absorption and no measurable temperature rise. In contrast, exposure to electromagnetic fields with a frequency greater than 100 kHz can cause energy absorption and a significant rise in temperature [21] [28]-[30]. In general, exposure to electromagnetic fields results in highly inhomogeneous energy deposition and distribution in the body that must be assessed by dosimetry [31]-[34]. Finally, it remains to underline the indirect consequences caused by exposure to electromagnetic fields of people with active medical implants (cardiac pacemaker, cardiac defibrillator, insulin pump, etc.) which result in malfunctions of the implanted equipment.

These different phenomena can be analyzed mathematically in detail using Maxwell's equations by defining each parameter and its role, some details of which are not given.

Then, we discussed the techniques most used to remedy the threats of two modes of conducted and radiated EM disturbances; filtering to protect against conducted disturbances and EM shielding against radiated.

Improving electromagnetic compatibility acts on the side of the sources by trying to reduce the disturbances they emit, and on the side of the victims by protecting them from external influences. We have seen that a source of disturbance reaches its victim through coupling. It is at this level that we must act. In order to protect equipment against conducted and radiated disturbances, we use EM filtering and shielding respectively.

3.3.1. Electrical Properties

From an electromagnetic point of view, biological media appear as materials at the same time [19] [21] [23] [41] [42]:

- ✓ Non-magnetic,
- ✓ Ionic conductors,
- ✓ Lossy dielectrics.

In general, biological tissues have a diamagnetic character. Certain substances such as ferritin, hemosiderin or methemoglobin with a paramagnetic nature are naturally present in the human body [41] [42]. However, the human body is still considered non-magnetic for the study of induced electromagnetic fields, and the magnetic permeability of biological tissues is therefore taken equal to that of a vacuum. Regarding electrical properties, given the chemical composition of biological tissues, the free charges capable of creating conduction currents are ions. These ions can move more or less freely under the effect of an electric field. They are subject to friction forces and stresses due to the structure of the tissues. Consequently, their mobility depends on the frequency of the source field. The presence of electric polar molecules of various sizes and also subject to friction, contributes to giving biological environments a lossy dielectric character. The human body therefore presents highly heterogeneous electrical properties at the microscopic (cellular structures) and macroscopic (organs) levels [41] [42]. The microscopic structure of a tissue can sometimes give it macroscopic anisotropic electrical properties: this is the case of muscles, for example, which are made up of cells that are very elongated in a single direction. In general, to characterize biological environments, we use the notions of conductivity (σ) and relative permittivity (ϵ_r) such that the density of electric current induced by the \mathbf{j} pulsating electric field ω is \mathbf{E} [41] [42]:

$$\mathbf{j} = (\sigma + j\omega\epsilon_0\epsilon_r)\mathbf{E} \quad (1)$$

where ϵ_0 is the electrical permittivity of the vacuum.

These properties are often derived from macroscopic measurements on a given tissue considered homogeneous (and sometimes anisotropic) [41]-[43] [44]. The conductivity thus defined includes the static conductivity of the medium as well as the effect of dielectric losses. Sometimes, the notions of complex conductivity (σ) or complex relative permittivity (ϵ_r) are used. The current density and the electric field are then given by the relations:

$$\mathbf{j} = \sigma\mathbf{E} = (\sigma' + j\sigma'')\mathbf{E} \quad (2)$$

$$\mathbf{j} = j\omega\epsilon_0\epsilon_r\mathbf{E} = j\omega(\epsilon_r' + j\epsilon_r'')\mathbf{E} \quad (3)$$

For most tissues [43] [44], it is not possible to carry out measurements allowing electrical characterization *in vivo*. It is often necessary to perform these *in vitro* measurements on tissue samples taken from deceased subjects. This very strong constraint poses the problem of conditioning the tissue to be studied. Indeed, the cellular structure can deteriorate rapidly after death, and the electrical properties can vary depending on many parameters that are difficult to control *in vitro* such as blood supply, hydration level or temperature.

This particular distribution of charges at the interfaces results in a very high impedance between the electrode and the biological environment for frequencies

below a few kHz. The spectroscopic study of this interface impedance shows that it can be modeled in the form [43]-[45]:

$$Z_i = K(j\omega)^{-\alpha} \quad (4)$$

avec $0 < \alpha < 1$

3.3.2. Methods for Macroscopic Electrical Characterization of Biological Media

The electrical characterization of biological media requires the use of a measuring device and a model allowing the extraction of conductivity and permittivity parameters. There are several measurement methods which differ depending on the frequencies studied [43]-[46]. For each method, there are different more or less complex models to represent the measuring device and the sample tested [46].

3.3.3. Models for Representing Frequency Variations of Conductivity and Permittivity

Different empirical models can be used to approximate the frequency variations of the electrical properties of biological media.

Debye Model

The complex permittivity is expressed in the form [43] [46] [47]:

$$\varepsilon_r = \varepsilon_{r\infty} - j \frac{\sigma}{\omega \varepsilon_0} + \sum_n \frac{\Delta \varepsilon_{rn}}{1 + j \frac{\omega}{\omega_n}} \quad (5)$$

where $\varepsilon_{r\infty}$ is the relative permittivity at infinite frequency, ω_n is the characteristic pulsation corresponding to relaxation n , σ is the conductivity at zero frequency and $\Delta \varepsilon_{rn}$ is the permittivity variation for relaxation n . This is the basic model for representing relaxation phenomena.

Cole Model Cole

This model introduces an additional parameter α_n characteristic of the frequency dispersion of each relaxation n [43] [46]-[49]:

$$\varepsilon_r = \varepsilon_{r\infty} - j \frac{\sigma}{\omega \varepsilon_0} + \sum_n \frac{\Delta \varepsilon_{rn}}{1 + \left(j \frac{\omega}{\omega_n} \right)^{1-\alpha_n}} \quad (6)$$

It is a simple model giving a good representation of the frequency behavior of the conductivity and permittivity of biological media, but it does not represent the physical phenomena at the origin of this behavior. It is used very frequently, notably by Gabriel. Generally, the Cole Cole model allows a better representation of the measured values than the Debye model [47].

3.3.4. Model Combining the Debye and Universal Dielectric Response Models

The universal dielectric response model represents the complex permittivity by a constant phase function of the form $(j\omega)^{n-1}$. The model combining the Debye and universal dielectric response models proposed by Raicu is of the type [50] [51]:

$$\varepsilon_r = \varepsilon_{r\infty} - j \frac{\sigma}{\omega \varepsilon_0} + \frac{\Delta \varepsilon_m}{\left((j\omega T)^\alpha + (j\omega T)^{1-\beta} \right)^\gamma} \quad (8)$$

Regardless of the model used, the different parameters are adjusted using optimization algorithms to correspond as precisely as possible to the values resulting from the measurements.

3.4. Modeling of Emissions Radiated by Industrial Static Converters

Starting from the wave equations are obtained from the Maxwell equations described previously. For the electric and magnetic fields in which we are interested, the wave equations, at a point \mathbf{r} and at time t , are given respectively by [52] [53]-[55]:

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r}, t) + \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \mathbf{E}(\mathbf{r}, t) = \mu_0 \frac{\partial^2}{\partial t^2} \mathbf{J}(\mathbf{r}, t) \quad (9)$$

$$\nabla \times \nabla \times \mathbf{H}(\mathbf{r}, t) + \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \mathbf{H}(\mathbf{r}, t) = \mu_0 \nabla \times \mathbf{J}(\mathbf{r}, t) \quad (10)$$

where \mathbf{E} is the electric field, \mathbf{H} is the magnetic field and μ_0 and ε_0 are the magnetic permeability and electric permittivity of air (vacuum), respectively. The wave equations are written as follows [55]:

$$\Delta \mathbf{E}(\mathbf{r}, t) - \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \mathbf{E}(\mathbf{r}, t) = \frac{1}{\varepsilon_0} \nabla \rho(\mathbf{r}, t) + \mu_0 \frac{\partial}{\partial t} \mathbf{J}(\mathbf{r}, t) \quad (11)$$

$$\nabla \times \nabla \times \mathbf{H}(\mathbf{r}, t) + \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \mathbf{H}(\mathbf{r}, t) = \nabla \times \mathbf{J}(\mathbf{r}, t) \quad (12)$$

The modeling of the contribution in radiated emissions from each discretization cell takes into account the currents in the structure, obtained by an appropriate method [55]. Firstly, a discretization cell is considered equivalent to a dipole. So, in this case, only one dimension, which is the length, is considered. To achieve this goal, two main approaches can be used for such a calculation: the quasi-steady state approximation and the infinitesimally small dipole approximation.

We know that the fields $\mathbf{E}(\mathbf{r}, t)$ and $\mathbf{H}(\mathbf{r}, t)$ can be written in terms of the vector potential \mathbf{A} and the scalar potential φ . The notion of potentials was used in order to simplify the resolution of Maxwell's equations. **Figure 7** below shows the structure of a discretized cell [55].

We demonstrate that, for a cell crossed by a current and whose section is very small compared to the length, the radiation will be considered equivalent to that generated by an electric dipole. Thus, the vector potential is given by:

$$\mathbf{A} = \frac{\mu_0}{4\pi} I \int_C \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{l}' \quad (13)$$

where I is the current passing through the cell and C is the length.

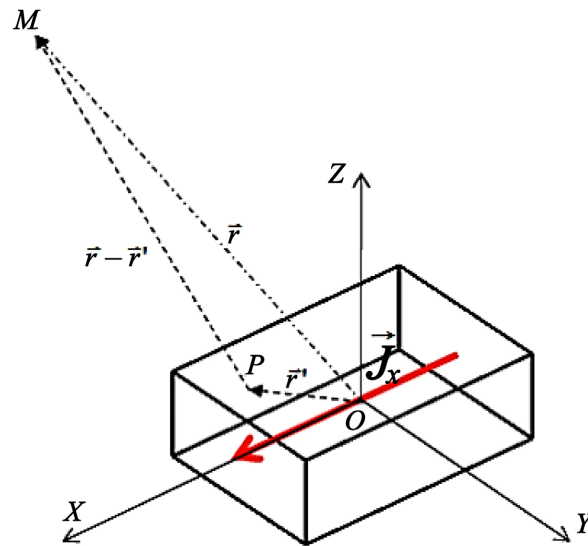


Figure 7. Discretization cell [53] [55].

The radiated emissions are perfectly defined by the magnetic field and the electric field. Using the Lorentz gauge, we can write the electric field as a function of the vector potential alone.

$$H = \frac{1}{\mu_0} \nabla \times A \tag{14}$$

$$E = \frac{1}{j\omega\epsilon_0\mu_0} \nabla \times \nabla \times A \tag{15}$$

We consider the discretization cell presented in Figure 9. The vector potential is given by:

$$A = \frac{\mu}{4\pi} j_\gamma \iiint_{V'} \frac{e^{-jk|r-r'|}}{|r-r'|} dv' \tag{16}$$

In our 1D case, we consider $\gamma = x$. The vector potential is written:

$$A_x = \frac{\mu}{4\pi} I_x \int_{-dx/2}^{dx/2} \frac{e^{-jk|r-r'|}}{|r-r'|} dx' \tag{17}$$

By applying the quasi-steady state approximation to Equation (17), we therefore find:

$$A_x = \frac{\mu}{4\pi} I_x e^{-jkr} \int_{-dx/2}^{dx/2} \frac{1}{\sqrt{x^2 + y^2 + z^2}} dx' \tag{18}$$

The calculation gives:

$$A_x = \frac{\mu}{4\pi} I_x e^{-jk} \log \left(\frac{x - \frac{dx}{2} + \sqrt{\left(x - \frac{dx}{2}\right)^2 + y^2 + z^2}}{x + \frac{dx}{2} + \sqrt{\left(x + \frac{dx}{2}\right)^2 + y^2 + z^2}} \right) \tag{19}$$

The infinitely small dipole approximation is widely used in electromagnetic

modeling and especially in the field of antennas. In this case, the length of the dipole is infinitesimally small compared to the wavelength. Typically, it is less than a tenth. Note also that the distance of the observation point from the origin of the dipole is an important parameter in this approximation. The vector potential is written:

$$A_x = \frac{\mu}{4\pi} I_x \frac{e^{-jkr}}{r} dx \tag{20}$$

In order to improve the calculation precision, we exploit the calculation approach based on the Maclaurin series. This approach is based on the fact that the length of the dipole is infinitely small compared to the wavelength. It resembles the infinitely small dipole approximation which is only a special case of it. Thus, we choose an order higher than the first order for calculation improvement.

By changing the variable ($\alpha = \frac{x'}{\lambda}$, $\eta = \frac{r}{\lambda}$ et $Q = \frac{x}{\lambda}$) in expression (17), we obtain the integral expression of the potential vector, considering Equation (21) below:

$$\frac{e^{-jk|r-r'|}}{|r-r'|} = \frac{e^{-jk\sqrt{(x-x')^2+y^2+z^2}}}{\sqrt{(x-x')^2+y^2+z^2}} \tag{21}$$

The new expression of the vector potential integrating the variable α is of the following form:

$$A_x = \frac{\mu}{4\pi} I_x \int_{-dx/2\lambda}^{dx/2\lambda} \frac{e^{-j2\pi\sqrt{\eta^2-2Q\alpha+\alpha^2}}}{\sqrt{\eta^2-2Q\alpha+\alpha^2}} d\alpha \tag{22}$$

Considering $\frac{e^{-j2\pi\sqrt{\eta^2-2Q\alpha+\alpha^2}}}{\sqrt{\eta^2-2Q\alpha+\alpha^2}} = f(\alpha)$, given that $\alpha \ll 1$ Taking into account

the dimensions of discretization cells are very small compared to the wavelength, the development of the function $f(\alpha)$ in the form of a Maclaurin series is in the following polynomial form:

$$f(\alpha) = f(0) + f'(0)\alpha + \frac{1}{2}f''(0)\alpha^2 + \frac{1}{6}f'''(0)\alpha^3 \tag{23}$$

Moreover, $f'(0) = f'''(0) = 0$ because in the calculation of the integral of the polynomial equivalent to f between $-dx/2\lambda$ and $dx/2\lambda$, terms of odd order, in particular those of the first and third order, are zero.

$$A(x, y, z) = \frac{\mu}{4\pi} I_x \left(\frac{1}{2} f(0) \frac{dx}{\lambda} + \frac{1}{24} f''(0) \frac{dx^3}{\lambda^3} \right) e_x \tag{24}$$

It is this last order which makes it possible to improve the precision. The component following ox of the vector potential is written, as in the case of the infinitely small dipole, as a function of the wavelength, of the length of the dipole. The expression of the vector potential is given by:

$$A_x = \frac{\mu}{4\pi} I_x e^{-jkr} dx \left(\left(\frac{1}{r} + \frac{1}{24r^3} \left(x^2 (jkr)^2 + (3x^2 - r^2)(1 + jkr) \right) \right) dx^2 \right) \tag{25}$$

Determining the radiated emissions of a cabling system involves two main steps: calculating the conducted emissions and deducting the radiated emissions. The first consists of determining for each discretization cell the current passing through it. Then, knowing both the geometry and the current value at each frequency, we use the analytical calculation approach to define the contribution of each of the discretization cells. The EM field at any point in space is the contribution of each cell and it is obtained by summing the different components of the magnetic and electric fields.

3.5. Modeling the Mechanism of Interaction of Electromagnetic Fields with Living Beings

To study the consequences of magnetic fields on living beings using Maxwell's equations, we can follow an approach based on the modeling of electromagnetic fields and their interaction with biological tissues. All electromagnetic phenomena can be described by Maxwell's equations. These equations make it possible to link the electromagnetic field to the sources which gave rise to it. In fact, these four equations are split into two groups of two equations: the first group reflects the intrinsic properties of the field (independently of the sources) and the second really provides information on its dependence on the sources [21].

To do this we have a few steps that we must follow to carry out this modeling:

- ✓ Problem identification: this point establishes the relationship of identifying sources of electromagnetic fields and the characteristics of the living being that we wish to study.
- ✓ Using Maxwell's equations: the equations are a set of four fundamental equations that describe the behavior of electric and magnetic fields.

The Maxwell equations to be implemented to model the coupling of electromagnetic fields-biological tissues are as follows:

- Maxwell-Gauss model expressing the electric field-biological tissue coupling:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad (26)$$

- Maxwell-Gaussian model expressing the conservation of the magnetic field:

$$\nabla \cdot \mathbf{B} = 0 \quad (27)$$

- Maxwell-Faraday model the unification between the electric field and the magnetic field:

$$\nabla \cdot \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (28)$$

- Maxwell-Ampère model expressing the magnetic field-biological tissue coupling:

$$\nabla \cdot \mathbf{B} = \mu_0 \left(\mathbf{j} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \quad (29)$$

3.5.1. Electromagnetic Field-Biological Tissue Interaction Model

Magnetic field-biological tissue model

Suppose we study human biological tissue exposed to a magnetic field radiated by industrial static converters located in a work environment. Solving equation 13 allows us to simplify the calculation of the magnetic field generated at a distance r illustrated in **Figure 10** as follows:

$$B_{(r)} = \frac{\mu_0 I}{2\pi r} \tag{30}$$

with:

μ_0 : the magnetic permeability of the vacuum is $4\pi \times 10^{-7}$ H/m;

I : Current intensity consumed by the converter in A;

r : the distance between the technician and the converter in m.

Figure 8 shows the interaction between the electromagnetic field and biological tissue.

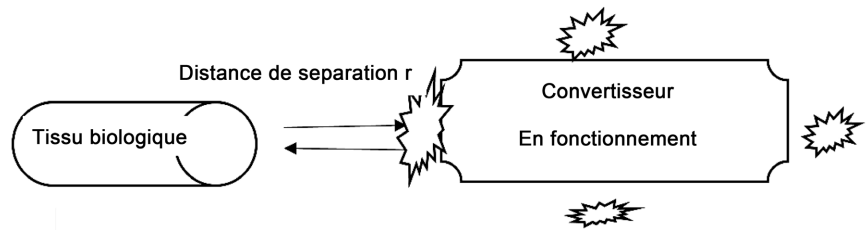


Figure 8. Interaction between the electromagnetic field and biological tissue.

The electromagnetic field generated around the converter induces a voltage in the biological tissue capable of raising its electrical potential in accordance with Faraday’s law:

$$e = -\frac{d\phi}{dt} \tag{31}$$

with ϕ is the magnetic flux through weber biological tissue (Wb).

If the magnetic field B varies with time, we can therefore write:

To fully understand, here is a global model to determine the e.m.f. in a cylinder (biological tissue):

$$\frac{d\Phi}{dt} = 2\pi f \Phi \tag{32}$$

Gold:

$$\Phi = \mathbf{B} \cdot \mathbf{A} \tag{33}$$

From where:

$$\frac{d\Phi}{dt} = 2\pi f \mathbf{B} \cdot \mathbf{A} \tag{34}$$

with: f the frequency in Hz.

A : biological surface area in m^2 .

Furthermore, surface area of biological A can be obtained via the following relation:

$$A = \pi r^2 \tag{35}$$

Injecting Equations (30) and (35) into expression (34), we find:

$$\frac{d\Phi}{dt} = 2\pi f \cdot \frac{\mu_0 I}{2\pi r} \cdot \pi r^2 \quad (36)$$

Gold:

$$e = \frac{d\Phi}{dt} \quad (37)$$

Let us equalize Equations (36) and (37), we therefore find:

$$e = \frac{d\Phi}{dt} = 2\pi f \cdot \frac{\mu_0 I}{2\pi r} \cdot \pi r^2 \quad (38)$$

This model determines the voltage induced by the magnetic field in biological tissue.

3.5.2. Model of Electric Field-Biological Tissue Interaction

To model and analyze the impact of electric fields on living beings, we made the hypothesis that human biological tissue is modeled as a continuous medium with specific dielectric and conductive properties.

We know well that, the continuity equation for electric charges in a conducting medium, the conservation of charge is described in the following form:

$$\nabla \cdot j = -\frac{\partial \rho}{\partial t} \quad (39)$$

where: j is the current density in A/m^3 and ρ is the charge density in C/m^3 .

Furthermore, the relationship between the electric field and the current density is given by Ohm's local law for a conducting medium is given by:

$$j = \sigma \cdot E \quad (40)$$

where E is the radiated electric field in V/m .

We inject the expression (40) into (39), we obtain:

$$\nabla \cdot (\sigma E) = -\frac{\partial \rho}{\partial t} \quad (41)$$

We know that the electric field derived from the scalar potential can be expressed by the following relation:

$$E = -\nabla \cdot \Phi \quad (42)$$

Let us introduce the electric potential into the Maxwell-Gauss equations for a dielectric medium, we obtain the following Poisson equations:

$$\nabla \cdot (\varepsilon \cdot \nabla \cdot \phi) = -\rho \quad (43)$$

By combining the Poisson equation with the relationship between the electric field and the current density, we arrive at the following final equations:

$$\nabla \cdot (\varepsilon_r \varepsilon_0 \nabla \phi) = -\rho + \nabla \cdot (\sigma \nabla \phi) \quad (44)$$

Equation (44) takes into account both the dielectric response and the conductivity of biological tissue. It also makes it possible to calculate the distribution of electric potential in tissues under the influence of an external electric field, which

is crucial for assessing the biological impact of electromagnetic fields.

3.5.3. Thermal Model of a Biological Tissue Under the Influence of the Electric Field

As a reminder, the greatest quantity of heat is evacuated from the biological environment by conduction. To implement the thermal model of biological tissue irradiated by the electric field, we consider that the biological environment is unidirectional and homogeneous. For this, the temperature propagation model in a biological environment is governed by the bio-heat equation.

$$\langle P \rangle = \rho \cdot C_{th} \cdot \frac{\partial T(x,t)}{\partial t} \quad (45)$$

with $\langle P \rangle$ the power flow in the biological tissue in Watt; C_{th} : Thermal capacity of the tissues in [W·s/°C] and $T(x,t)$: average increase in tissue temperature in °C.

Furthermore, the flow of incident power in biological tissue can be calculated using Poynting's theorem, Poynting's vector P is equal to the average power passing through the unit area of the wave plane, so the flux of P represents a power, in our case of a plane wave of direction Oz , the vector $P(z)$ has only one component $P(z)$ because almost all of the energy received by the biological tissue is transformed into heat, which allows us to write:

$$\langle P \rangle = \frac{1}{2} |\mathbf{E} \times \mathbf{H}| \quad (46)$$

Let us replace Equation (46) in (45), we therefore find:

$$\frac{1}{2} |\mathbf{E} \times \mathbf{H}| = \rho \cdot C_{th} \cdot \frac{\partial T(r,t)}{\partial t} \quad (47)$$

Let us multiply the expression (47) by $\frac{\partial r}{\partial t}$, we therefore find:

$$\frac{1}{2} |\mathbf{E} \times \mathbf{H}| = \rho \cdot C_{th} \cdot \frac{\partial r}{\partial t} \frac{\partial T(r,t)}{\partial r} \quad (48)$$

Now, $\frac{\partial r}{\partial t}$ represents the speed of temperature distribution in m/s and

$r = \sqrt{x^2 + y^2 + z^2}$ the position or space in m.

$$\gamma = \frac{\partial r}{\partial t} \quad (49)$$

For this purpose, expression (48) therefore becomes:

$$\frac{1}{2} |\mathbf{E} \times \mathbf{H}| = \rho \cdot C_{th} \cdot \gamma \cdot \frac{\partial T(r,t)}{\partial r} \quad (50)$$

The absorbed power density D (W/m³) in the biological medium transformed into heat is given by the following relationship:

$$D = -\frac{dP}{dr} = \frac{\sigma^2}{2} E^2 e^{-2\alpha r} \quad (51)$$

By introducing the density, we can also, from Equation (51), obtain the spe-

cific absorption rate (*SAR*) which is expressed in W/kg as follows:

$$DAS = \frac{D}{\rho} = \frac{\sigma}{\rho} \cdot |E|^2 \quad (52)$$

We can also write the following thermodynamic energy conservation equation:

$$\frac{1}{2} |\mathbf{E} \times \mathbf{H}| dr = \rho \cdot C_{th} \cdot \gamma \cdot d[\Delta T(r, t)] \quad (53)$$

We can infer the temperature variation in biological tissue as follows:

$$\Delta T(r, t) = \frac{1}{\rho \cdot C_{th} \cdot \gamma} \cdot \left[\frac{1}{2} |\mathbf{E} \times \mathbf{H}| \right] \cdot r \quad (53)$$

Poynting $\frac{1}{2} |\mathbf{E} \times \mathbf{H}|$ vector by the average power received by the biological tissue and the position r by $\sqrt{x^2 + y^2 + z^2}$:

$$\Delta T(r, t) = \frac{P_{moy} \cdot \gamma}{\rho \cdot C_{th} \cdot \sqrt{x^2 + y^2 + z^2}} \quad (54)$$

$\Delta T(r, t)$: Spatial distribution of temperature in °C.

P_{moy} : Average power received by the biological tissue in Watt.

3.5.4. Penetration Depth

When a material is exposed to an electromagnetic field, it is subject to a current density due to the movement of charges. Biological materials are not good conductors. Indeed, they conduct a current, however the losses can be significant, they cannot be described as lossless. This is due to the fact that the electromagnetic field only penetrates very superficially inside a conductor. The penetration depth is given by relation (55).

$$\delta = \frac{1}{\omega \sqrt{\frac{\epsilon \mu_0}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\epsilon \omega} \right)^2} - 1 \right]}} \quad (55)$$

4. Simulation

Results

Considering the electrical parameters of biological tissue presented in **Table 1** below, the frequency range from 0.01 to 100 Gigas Hertz [Ghz] of propagation of electromagnetic waves radiated by in human biological tissue, the model of the tissue under the effect of the electromagnetic field and the equations going from (1) to (54), the simulation results are presented in **Figures 9-12**. **Figure 10** and **Figure 13** the results obtained experimentally in the work of Rakotomananjara DF and Randriamantsoa PA [56]. Then, **Figure 11**, **Figure 12** below respectively show the results of the spatial profile of the temperature and the current induced in the biological tissue under the influence of the electromagnetic fields radiated by the industrial static converters in a professional environment.

Table 1. Skin permittivity parameters [56] [57].

Authors	ϵ_h	ϵ_l	τ	σ_s
Gandhi et Riazi	4	42	6.9 ps	1.4 S/m
Alekseev et Ziskin (forearm)	4	36.4	6.9 ps	1.4 S/m
Alekseev et Ziskin (hand)	4.52	31.7	6.9 ps	1.4 S/m

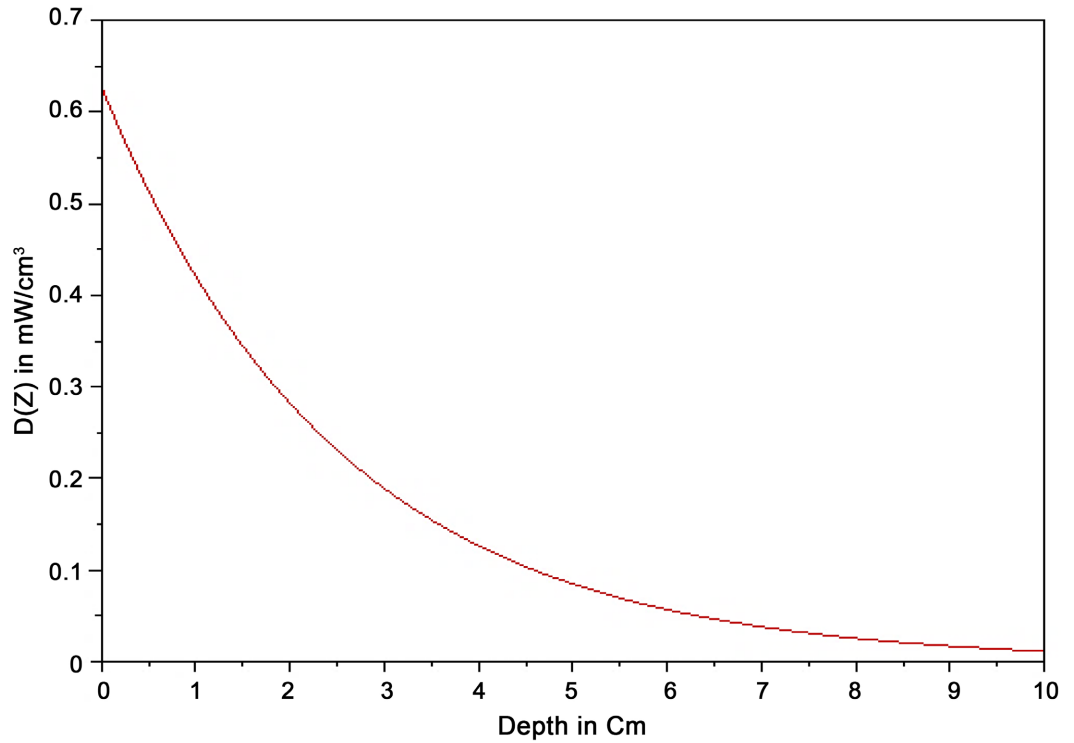


Figure 9. Trend curve of absorbed power density as a function of biological tissue thickness.

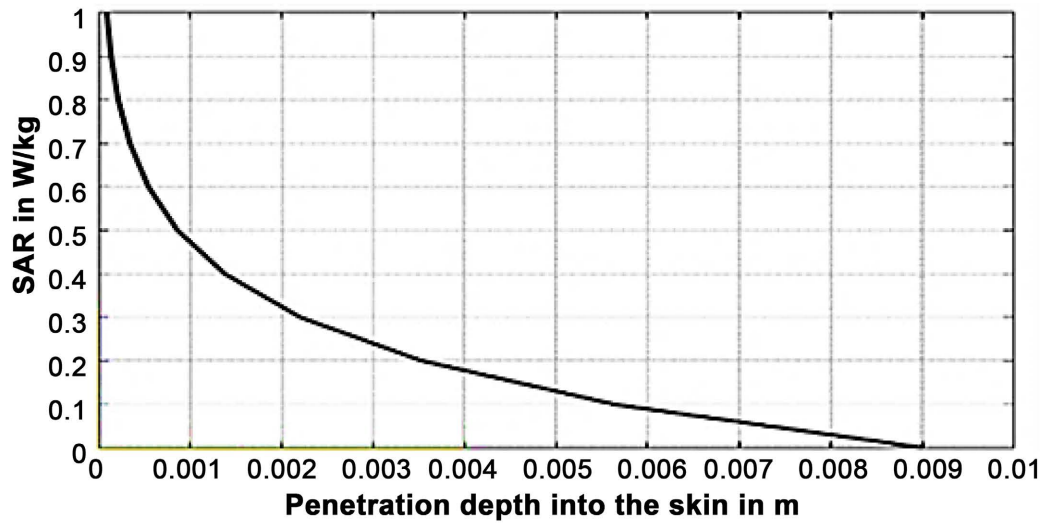


Figure 10. Trend of SAR attenuation in the skin: result published by Rakotomananjara DF and Randriamantsoa PA from [56] and [Research Laboratory in Telecommunications, Automation, Signals and Images] [37].

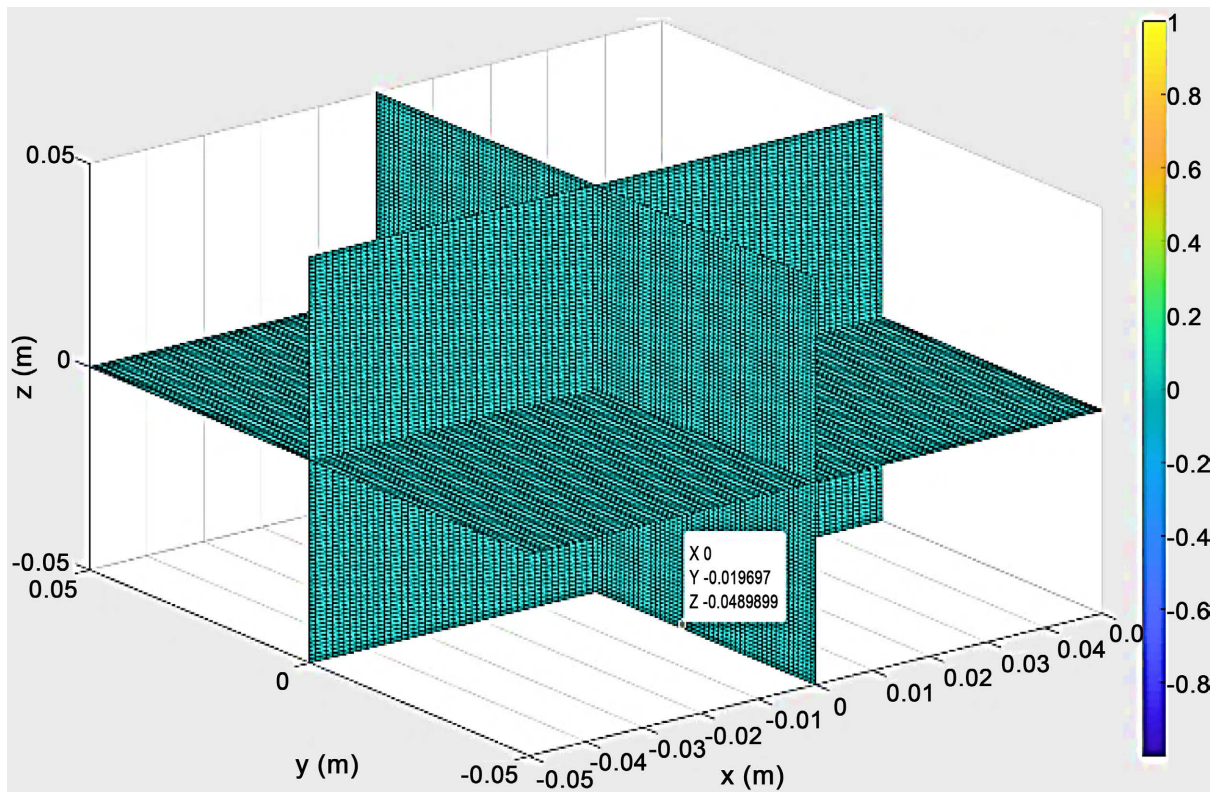


Figure 11. Temperature distribution in normal biological tissue.

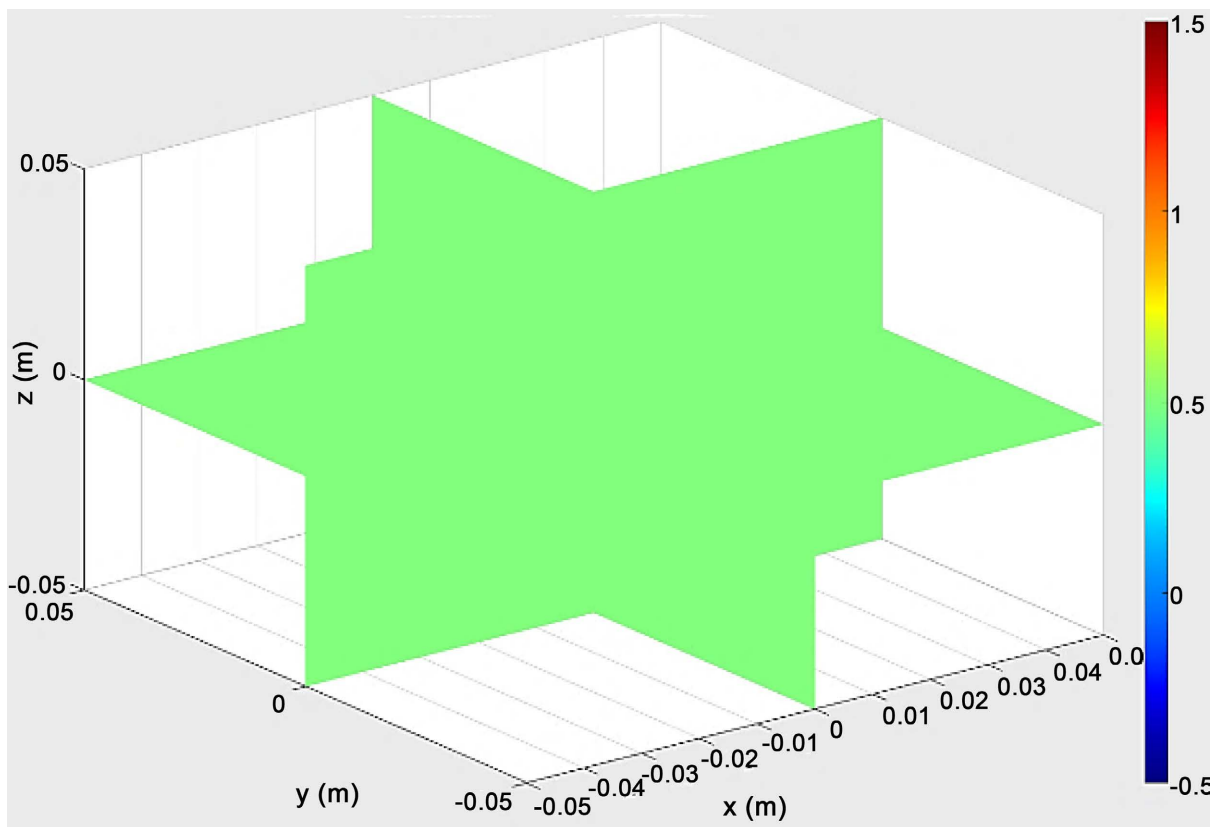


Figure 12. Simulation of current density distribution in biological tissue.

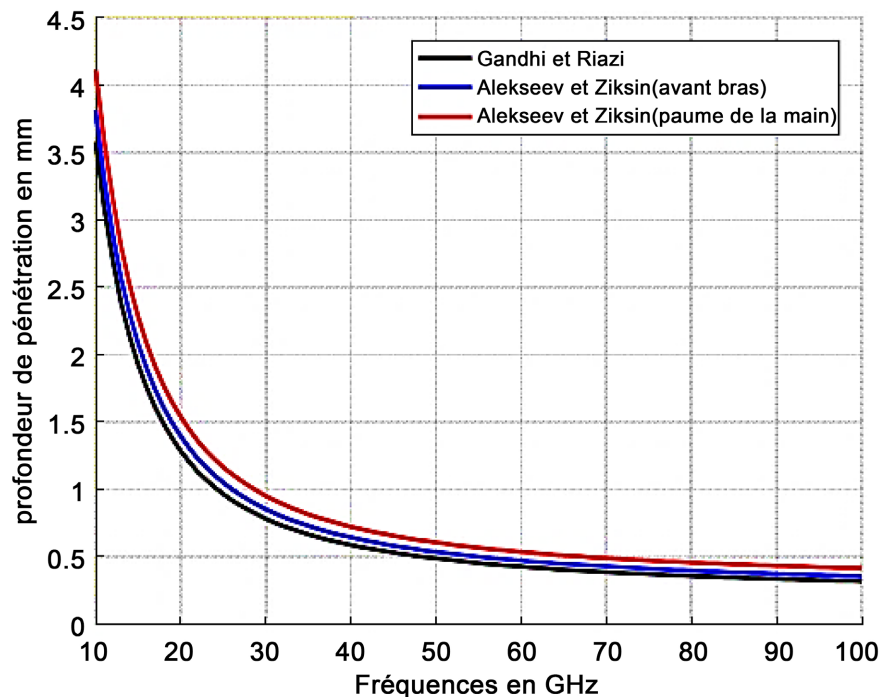


Figure 13. Simulation of Penetration Depth 10 to 100 GHz. Rakotomananjara DP and Randriamitantsoa PA [56].

5. Discussions

An evaluation of the power distribution induced by an electromagnetic wave in a spherical model of biological tissue allows us to say that the quantity of energy received by the tissue from electromagnetic waves is very high compared to that which emerges from it by radiation, and that almost all of the energy received is transformed into heat.

The curve in **Figure 9** shows that the absorbed energy is a function of the conductivity of the biological medium and decreases in the direction of propagation. Dosimetry consists of establishing the relationship between an electromagnetic field distribution in free space and the induced fields inside biological tissues or generally the human body. In other words it is the quantification of the energy in an environment exposed to an electromagnetic field by evaluating the specific absorption rate (SAR), the attenuation of the SAR in the skin, we clearly see that very little The energy is absorbed and most of it is absorbed into the epidermis (0.1 cm). These results can be compared to those obtained experimentally in the work of Rakotomananjara DP and Randriamitantsoa PA [2020] [56], in **Figure 10**.

Imperceptible in most work situations, electromagnetic fields can, beyond certain thresholds, have effects on human health. The interactions of electromagnetic waves with the human body are complex and depend on several factors linked to the characteristics of the incident wave (its frequency, intensity and polarization), of the tissue encountered (its geometry, its electromagnetic properties: dielectric permittivity and conductivity) and the type of coupling between

the field and the exposed body. The irradiating field generates currents inside the body, as well as energy absorption in the tissues. At a certain level of the irradiating field, these currents can cause heating of the target tissues and organs, this effect is well known under the name of thermal effects. And, **Figure 11** shows that the heating of the biological tissue as a function of the irradiation space will continue to increase and in a quasi-linear manner inversely proportional to the distance between the source and the biological tissue. This temperature is proportional to the speed of propagation of the radiated field and the power emitted by the source. Note that any stimulation of a cell, tissue or organism, whether by electromagnetic waves or by any other exciter of a given nature, can be accompanied by a normal adaptive response thereof: it is a biological effect. A biological effect can, however, endanger the normal functioning of an organism when its capacities for physiological responses in response to the action of the external agent are exceeded: a so-called health effect then occurs and health is hampered.

Figure 12 shows that the amplitude of the current induced in the human body is all the greater as the biological tissue is close to the emission source. According to Maxwell's equations associated with materials, a time-varying electric field induces an alternating current in the human body. We can therefore say that the higher the conductivity of a tissue, the less it opposes the passage of this current. This is why it is said that the passage of such a current can cause biological effects. INRS:

<https://www.inrs.fr/dms/inrs/GenerationPDF/accueil/risques/champs-electromagnetiques/Champs%20%C3%A9lectromagn%C3%A9tiques.pdf> classifies the effects of the current density induced in the human body according to the amplitude in mA/m²:

- ✓ Less than 10 mA/m²: no known health effects.
- ✓ From 10 to 100 mA/m²: visual and nervous effects, bone welding.
- ✓ From 100 to 1000 mA/m²: stimulation of excitable tissues.
- ✓ Greater than 1000 mA/m²: Fibrillation.

Finally, **Figure 13** proposed by [Rakotomananjara and Randriamitantsoa] shows that low frequency electromagnetic fields have strong penetration into biological tissue. This has proven consequences on the functionality of biological tissue.

Electromagnetic waves can cause several harmful effects on living beings that several studies have confirmed so far. These effects include childhood cancer, adult cancer, leukemia, brain cancer, and reproductive and developmental disorders.

6. Conclusions

In this article, we have chosen the modeling approach focused on a mathematical and numerical analysis based on the analytical formalism of calculation of the electromagnetic field emitted by a filiform conductor taking into account on

the one hand the physical phenomena of the propagation of a plane microwave electromagnetic wave and on the other hand the experimental values to model the electromagnetic radiation emitted by industrial static converters in the space domain.

The interactions of electromagnetic waves with human bodies are complex with consequences and dependent on several factors related to the characteristics of the incident wave. To achieve this, we have implemented a mathematical analysis through the bio-heat equation as a basis for the evaluation of the temperature variation and Maxwell's equations to quantify the current induced by the electromagnetic field in human biological tissues to obtain consistent results.

The document provides a comprehensive analysis using advanced mathematical models that evaluate the influence of electromagnetic fields on the operators of static converters.

The results have direct implications on the health of people working in the workplace potentially influencing the standards and regulations regarding exposure to electromagnetic waves in industrial environments. We should note that these electromagnetic waves can potentially affect human fertility such as sperm quality and energy absorption in the case of interactions of these electromagnetic waves with biological tissues of the human body although the results of research in this area are often contradictory and require further studies.

This research was focused on a particular type of conversion and interaction scenario. To generalize the results, including a wider range of converters and industrial parameters is very necessary.

A direct perspective of this study is the application of one of the methods we used to simulate the impact of electromagnetic waves on living beings living near relay antennas. Other electromagnetic parameters could be taken into account to develop an electrical model of biological tissue in a more complex form. The complete modeling of the brain, heart, and faith is a much broader perspective and can also be analyzed comprehensively from the MoM method.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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