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Attenuation in Transferred RF Power to a Biomedical Implant due to the Absorption of Biological Tissue

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Abstract**—**In a transcutanious inductive coupling of a biomedical implant, a new formula is given for the study of the Radio Frequency power attenuation by the biological tissue. The loss of the signal power is related to its interaction with the biological tissue and the composition of this one. A confrontation with the practical measurements done with a synthetic muscle into a Faraday cage, allowed a checking of the obtained theoretical results. The supply/data transfer systems used in the case of biomedical implants, can be well dimensioned by taking in account this type of power attenuation.

Keywords**—**Biological tissue, coupled coils, implanted device, power attenuation.

I. Introduction

IN the biomedical field, an optimal power transfer to the implanted devices is required, in order to ensure a sufficient supply/data transfer in spite of the attenuation due to the biological tissue absorption. A Radio-Frequency (RF) power transfer by a pair of coupled coils is generally used in this case [1], [8], [10].

The presence of various layers of biological tissue, gives a frequency selective attenuation of RF signal. So, it is important to well choose the transmission frequency of supply/data towards the implant. This choice can be guided by the study presented in this paper. An improvement of powering systems and data transmission systems, used in biomedical implants, can also be based on this study of power attenuation by biological tissue layers. In this context, more or less complex biological tissue models can be considered. Less complex biological tissue models can be considered.

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II. Electromagnetic Wave Interaction with Biological Tissue

In presence of an electromagnetic field, the biological tissue is considered as a medium with losses [2], [3], [4], [5], [6].

At frequency ω of complex electric field $\vec{\hat{E}}$ and complex magnetic excitation $\vec{\hat{H}}$, the Ampere law [7] is given by:

$$\overrightarrow{\mathrm{rot}}\,\vec{\hat{H}} = j\omega\hat{\varepsilon}\,\vec{\hat{E}} \tag{1}$$

The complex permittivity $\hat{\varepsilon}$ characterizes the biological tissue with conduction losses, and can be written in the following form [3], [5], [6]:

$$\hat{\varepsilon} = \varepsilon_0\left(\varepsilon' - j\varepsilon''\right) \tag{2}$$

where: $\varepsilon_0 = 8{,}8\cdot 10^{-12}$ F/m is the absolute permittivity, $\varepsilon' = \frac{\varepsilon}{\varepsilon_0}$ and $\varepsilon'' = \frac{\sigma}{\omega\varepsilon_0}$ are the relative permittivities with the conductivity σ and the dielectric permittivity ε of the biological tissue. ε' and ε'' are often indirectly measured by using RF impedance bridges and are provided into tables as function of the frequency [3], [5]. An example is given further in Table I.

A new approach is adopted here to evaluate the power attenuation caused by the presence of a biological tissue between the transmitter and receiver coupled coils. The magnetic field propagation in the biological tissue which is defined by its parameters of permittivity ε, conductivity σ and permeability of vacuum μ_0, is according to the magnetic wave equation, [7], using the Laplacian operator ∇^2 :

$$\frac{1}{\mu_0}\nabla^2\vec{\hat{B}} = \sigma\frac{\partial\vec{\hat{B}}}{\partial t} + \varepsilon\frac{\partial^2\vec{\hat{B}}}{\partial t^2} \tag{3}$$

For a sinusoïdal variation of magnetic field ($\vec{\hat{B}} = \vec{B}\,e^{j\omega t}$), equation (3) becomes :

$$\nabla^2\vec{\hat{B}} = j\omega\mu_0\left(\sigma + j\omega\varepsilon\right)\vec{\hat{B}} = \hat{\gamma}^2\,\vec{\hat{B}} \tag{4}$$

where $\hat{\gamma}\,(m^{-1}) = \alpha + j\beta$ is the propagation constant and α, β are attenuation and phase constants, respectively.

$$\alpha = \omega\sqrt{\frac{\mu_0\varepsilon}{2}\left(\sqrt{1+\mathrm{tg}^2\delta}-1\right)} \quad (5)$$

$$\beta = \omega\sqrt{\frac{\mu_0\varepsilon}{2}\left(\sqrt{1+\mathrm{tg}^2\delta}+1\right)} \quad (6)$$

The losses of the medium are represented by the tangent of loss [7].

$$\mathrm{tg}\,\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon} \quad (7)$$

Thus, for a propagation along OZ axis for example, the solution of (4) becomes:

$$\frac{d^2}{dz^2}\vec{\hat{B}} = \hat{\gamma}^2\,\vec{\hat{B}} \Rightarrow \vec{\hat{B}}(z) = \hat{B}_0\,e^{-\hat{\gamma} z}\,\vec{u}_z \quad (8)$$

The medium can also be characterized by its intrinsic impedance η defined by the ratio between the two fields of the electromagnetic wave propagating inside [7].

$$\hat{\eta}(\Omega) = \frac{\hat{E}}{\hat{H}} = \frac{j\omega\mu_0}{\hat{\gamma}} \Rightarrow \frac{\hat{E}}{\hat{B}} = \frac{\hat{\eta}}{\mu_0} \quad (9)$$

The complex intrinsic impedance can be written with real and imaginary parts, or module and phase parts.

$$\hat{\eta} = \frac{\omega\mu_0}{|\hat{\gamma}|^2}(\beta + j\alpha) = \frac{\omega\mu_0}{|\hat{\gamma}|}e^{\mathrm{arctg}\frac{\alpha}{\beta}} \quad (10)$$

The electromagnetic wave makes a partial reflection in contact with the skin. The transmission coefficient of the wave, propagating from medium 1 (ambient air) perpendicular to medium 2 (biological tissue), is defined by the ratio of the transmitted field to the incidental field. In terms of electric field, that becomes [7]:

$$\hat{T}_E = \frac{\hat{E}_2}{\hat{E}_1} = \frac{2\hat{\eta}_2}{\hat{\eta}_1 + \hat{\eta}_2} \quad (11)$$

According to (9) and (11), the transmission coefficient in terms of magnetic field, becomes:

$$\hat{T}_M = \frac{\hat{B}_2}{\hat{B}_1} = \frac{\hat{\eta}_1}{\hat{\eta}_2}\hat{T}_E = \frac{2\hat{\eta}_1}{\hat{\eta}_1 + \hat{\eta}_2} \quad (12)$$

By using (8), (11) and (12), the Poynting vector or average power density of the transmitted wave versus the incidental one, is:

$$\vec{S}_2(\mathrm{W/m^2}) = \frac{1}{2}\Re\left[\vec{\hat{E}}_2 \wedge \frac{\vec{\hat{B}}_2^*}{\mu_0}\right] =$$

$$\frac{1}{2}\Re\left[\left(\hat{T}_E\,\vec{\hat{E}}_1\,e^{-\hat{\gamma}_2 z}\right) \wedge \left(\hat{T}_M^*\,\frac{\vec{\hat{B}}_1^*}{\mu_0}e^{-\hat{\gamma}_2^* z}\right)\right]. \quad (13)$$

So,

$$\vec{S}_2(\mathrm{W/m^2}) = \vec{S}_1\,e^{-2\alpha_2 z}\,\Re\left[\hat{T}_E\,\hat{T}_M^*\right] \quad (14)$$

The star mark in these expressions, indicates conjugate part. By using (10), the attenuation coefficient of RF wave power due to biological tissue, is:

$$A_T = e^{-2\alpha_2 z}\,\Re\left[\hat{T}_E\,\hat{T}_M^*\right] = \frac{4\,e^{-2\alpha_2 z}\,\Re\left[\hat{\eta}_2\,\hat{\eta}_1^*\right]}{\left|\hat{\eta}_1 + \hat{\eta}_2\right|^2} \quad (15)$$

which becomes:

$$A_T = \frac{4\,e^{-2\alpha_2 z}\left(\alpha_1\alpha_2 + \beta_1\beta_2\right)}{\left|\hat{\gamma}_1 + \hat{\gamma}_2\right|^2} \quad (16)$$

III. Power Attenuation due to Biological Tissue

Propagation media 1 and 2, considered previously as air and biological tissue respectively, can represent two different layers of the same biological tissue. Fig. 1 shows an example of cochlear implant case [10], where the implanted coil is placed into the temporal bone and the biological tissue, essentially composed of skin and muscle, is intercalated between the two transfer coils.

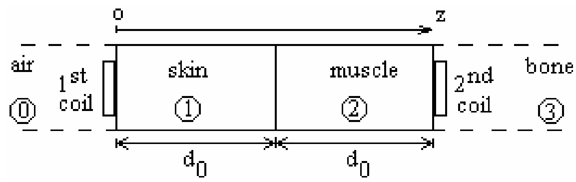

Fig. 1 Example of coils separation by biological tissue. The transmitter coil is on the skin and the receiver coil is into the bone. The coupled coils are separated successively by a same layer thickness of skin and muscle

By generalizing (16), related to the RF wave power attenuation in two tissue layers, factor A_T can be adapted to the tissue model with n superposed biological layers of thickness d_i:

$$A_T = \prod_{i=1}^{n}\frac{4\,e^{-2d_i\alpha_i}\left(\alpha_i\,\alpha_{i-1} + \beta_i\,\beta_{i-1}\right)}{\left(\alpha_i + \alpha_{i-1}\right)^2 + \left(\beta_i + \beta_{i-1}\right)^2} \quad (17)$$

The estimate of the relative permittivities ε' and ε'', at any frequency, can be deduced from Table I, [3], [5], by frequency extrapolation until 1 MHz. Second order polynomial representations of data in Table I, are used and are summarised in Table II for skin and muscle.

Also, the equation (7) reported in (5) and (6), allows the calculation of the attenuation and phase constants versus frequency, related to the biological tissue of Fig. 1 with layer thickness of d_0 = 1mm.

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TABLE I
DIELECTRIC CONSTANTS OF SOME TYPES OF BIOLOGICAL TISSUES

Tissues	T°	Dielectric constant ε'					Dielectric constant ε''					
		Frequency (MHz)					Frequency (MHz)					
		50	100	200	500	1000	10	50	100	200	500	1000
Skin	37°		65	57	47	44			140*	72	27	18*
Fat	37°	12*	10*	6*	5*	6*		17*	12	6*	2.2	2*
Blood	23°		75*	69*	68*				216*	100*	49*	
Muscle	37°	91*	74*	56	53*	50*	1100*	282*		90*	41	23

The dielectric constants are measured under specified frequencies and temperatures. Marked values with star are averages values.

TABLE II
POLYNOMIAL APPROXIMATION OF RELATIVE PERMITTIVITIES

	Polynomial estimation of ε'	Polynomial estimation of ε''
Skin	$\varepsilon'(f) = 2\cdot10^{-4}\cdot f^2 - 0.13\cdot f + 76.25$	$\varepsilon''(f) = 0.0024\cdot f^2 - 1.29\cdot f + 247.39$
Muscle	$\varepsilon'(f) = 18\cdot10^{-4}\cdot f^2 - 0.57\cdot f + 115.26$	$\varepsilon''(f) = 0.2\cdot f^2 - 30\cdot f + 1380$

The relative permittivities are expressed versus frequency.

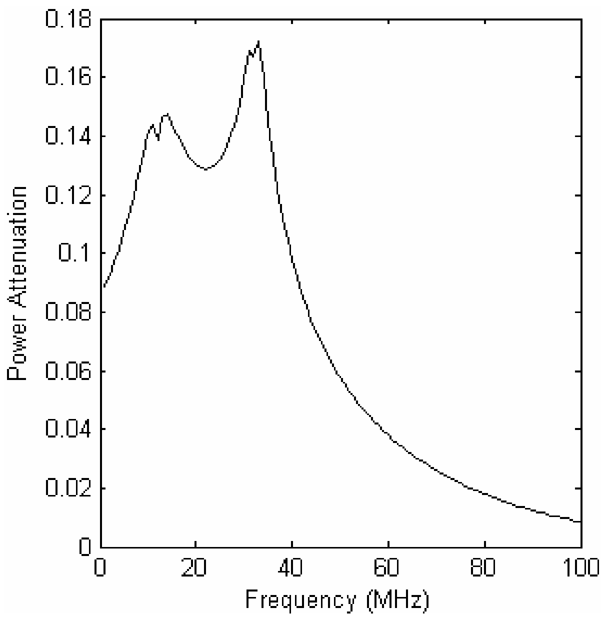

Fig. 2 Frequency response of power attenuation due to a biological tissue composed by 1mm layer of skin and 1mm layer of muscle. Attenuation between 9% and 17% is obtained below the frequency of 40 MHz

So in Fig. 2, the use of (17) allows the plotting of biological tissues absorption, related to Fig. 1, versus the frequency.

IV. CONFRONTATION WITH THE EXPERIMENT

An experimental bank, realized at Ensem-Cran of Nancy [2], [11], allows the practical study of a radio frequency energy transfer by magnetic coupling into a Faraday cage. In experience, a synthetic biological tissue with 4 cm of thickness is inserted between two coupled coils with diameters of 6.1cm and 1.8 cm. The characteristics of conductivity (σ = 0.42 $S\cdot m^{-1}$) and relative permittivity (ε' = 120) of this tissue are closer to those of the human muscle. The manipulation is done with incidental power of 10 W at 3 MHz. Measurements of transmitted power to a load of 2 kΩ are done, in presence or absence of tissue, under different misalignment states of transfer coils.

In absence of tissue and misalignment, the received power is 1130 mW. But with tissue and aligned coils, the received power is only 44 mW. Consequently, the power attenuation due only to tissue is $A_T = 0.039$ (measured value).

The model of tissue is reduced to a single biological layer, simulating the muscle, so the characteristics of both implied propagation mediums are given in Table III.

TABLE III
DIELECTRIC PROPERTIES OF THE AIR AND SYNTHETIC BIOLOGICAL TISSUE

Medium	α (Np/m)	β (rd/m)	η (Ω)
Air	0	0.06	377.9
Tissue	2.18	2.28	7.5

The three constants are calculated at frequency of 3 MHz.

Equation (16) is sufficient to evaluate the power attenuation due to this type of tissue, witch gives: $A_T = 0.045$ (calculated value). So, attenuations A_T due to the synthetic tissue alone are found close to approximately 87% between the practical and theoretical results. The power attenuation due to misalignment of the coupled coils versus their longitudinal inter distance, is evaluated by another equation [1].

In Fig. 3, the measured and calculated powers under simultaneous attenuations, by misalignment coils and synthetic tissue absorption, are compared. The powers are plotted versus the longitudinal distance between coils and parameterized by three different states of misalignment (shifted axis of coils: Δ in cm, rotation between coils: ψ in degrees). The curves with (0cm, 10°) and (0.5cm, 10°) misalignments are confounded in case of measure and also in case of calculation. A well agreement is noted in order of magnitude and decreasing form of power attenuations between the practical and theoretical results.

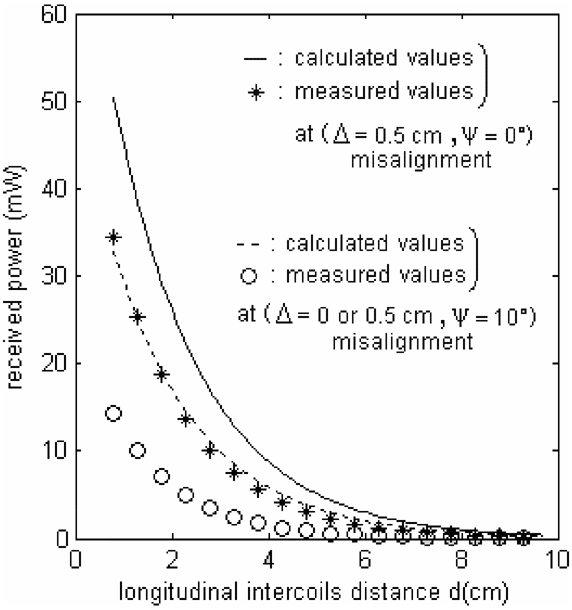

Fig. 3 Comparison of measured and calculated powers versus longitudinal inter-coils distance, in presence of biological tissue and different misalignment of transfer coils. Both of 0 and 0.5cm lateral misalignment with fixed 10° as angular misalignment, give confounded powers at measured curves. This is the same case in the calculated ones

The RF power attenuation due only to misalignments of the transfer coupled coils in absence of biological tissue, is presented and discussed in [1].

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