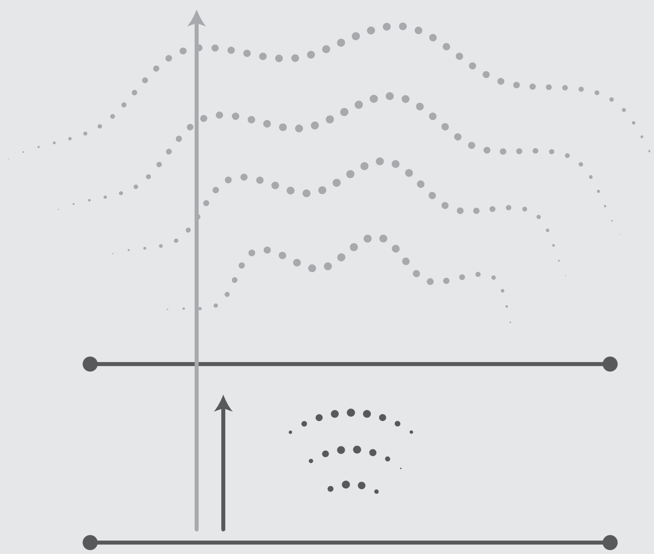

UNDERSTANDING LOW FREQUENCY NON-RADIATIVE POWER TRANSFER

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INTRODUCTION

In the past decade, the increased interest in wireless power transfer technology is evident both from the technical and consumer perspectives. Improved system efficiencies due to the emergence of resonant transfer of power have engendered the rapid increase of applications that are emerging for this technology. As a consequence of the increasing ubiquity of these applications and the electromagnetic radiations that might be emitted, more concerns are being raised on their environmental friendliness. This has led to increased studies on the impact of this technology on the biosphere, especially on humans.

Different technologies are usually summed up into the term, “wireless power transfer technologies” resulting in complexities and errors in studying their environmental and human impact. This is because the frequency of operation over a distance from the source varies considerably. Hence discussing the technology without separating them along this breakdown could be misleading. One goal of this write up is to examine a subset of this technology, the inductive wireless transfer technologies. The focus will be on their non-radiative characteristics with respect to distance from source and frequency. Such a discourse might bring clarity not only to engineers in the field and consumers of these wireless products, but might also help with the regulatory requirements for this technology and its applications.

In an inductive power transfer system, an alternating electromagnetic field due to an alternating current in a transmitting system of coils enables voltage to be induced in the receiving coil. This is based on Faraday’s law of electromagnetic induction. It is these electromagnetic fields in the vicinity of the power transfer system that raises the question of the radiation emitted by such systems; how they could be tested and/or limited. In order to examine the claim of non-radiative power transfer of this technology, a non-mathematical look at the solutions of Maxwell’s equations and some electromagnetic wave theory will facilitate the analysis.

1.0 EM ENERGY FLOW IN NEAR FIELDS, FAR FIELDS

1.1 Near Field Consideration

Any electromagnetic field source (point particle, dipole, antenna or coil) produces electromagnetic waves in surrounding media. The characteristics of these fields and how they interact with the media bring the differentiation as to the radiative (stored) and non-radiative components of electromagnetic waves or fields. These fields are usually separated into the near field and far field, by taking into consideration their distance from the source, but more importantly, because of the wave characteristics of the dominant waves in this region. These regional boundaries are usually described in terms of the wavelength of the field source. Therefore, the wavelength of an electromagnetic (EM) wave, which is related to its energy, describes its interaction with its surrounding media. For the purpose of this article, unless otherwise stated, the source of EM wave is considered a simple inductor as is used in wireless power technology. As shown in Fig.1, wavelengths of the EM field source (antenna) are used to portray the distances that are generally accepted to delimit the regions.

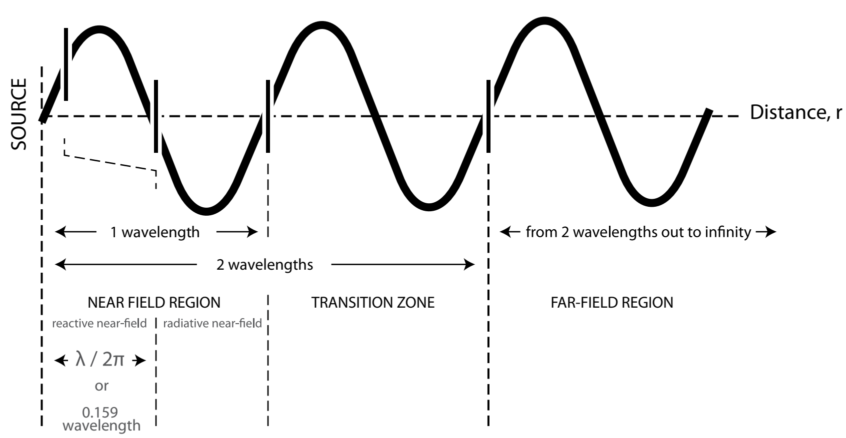

Fig. 1: Typical fields for EM sources showing region differentiation by wavelengths [1]

An ideal inductor source produces electric and magnetic (**E**-fields and **H**-fields) fields respectively, in its immediate vicinity. For energy conservation, the circuit drives power into the field and the field by induction drives power back into the source circuit and hence there is no loss of energy. This cyclic energy exchange during each half cycle ensures that the voltage (V) and current (I) of the circuit stay mutually orthogonal, resulting in the absence of a real component of the circuit impedance, hence **Z = jwL**, where L is the inductance of the circuit. Consequently this region is called the reactive near field. If another circuit with a load is introduced, both circuits will interact and exchange energy. In other words, the source circuit will conserve its energy until a load circuit is introduced into its vicinity. The source system will only transfer energy unto a load system when it is needed, i.e., it only 'reacts' to energy needs and does not radiate them when not needed [2]. It should be noted that the reactive near field (generally accepted 0.159 multiplied by wavelength of the EM source, as shown in Fig. 1) only exist when the source is turned on. In the more realistic systems, this reactive near field is composed of inductive, electrostatic, electric and magnetic fields along with some intrinsic but limited radiated energy (due to accelerated charges in inductor). These are all related in very complex relations, although the predominant fields are reactive. Because of the complex phase relationships between **E** and **H** in this near region, studying their individual characteristics in this near field is neither non-trivial nor very instructive. These fields generally decay with $1/r^2$, while the radiative components decay by $1/r$ (where r is the distance from the source) [1]. As a result, if we go further away from the source into the far field, the radiative fields become more prominent as the near reactive fields decay quickly. Furthermore, in this far field, **E** and **H** fields are necessarily perpendicular to each other.

Using Fig. 1 as a guide, it is instructive to compute the boundary differences at some frequencies used in power transfer technologies, to ascertain their maximum field strength and energy content distribution. As shown these boundaries fall at λ/2π, and beyond for the reactive field, radiative field and far field regions respectively. The near field boundaries are 0.5 m, 47.5 m and 477.5 m for 100MHz, 1MHz and 0.1 MHz, respectively. Thus, it can be said that the power transfer technologies below 1MHz will predominantly have non-radiative EM fields as their method of energy transfer given the ~50m 'buffer zone' which their near field provides, as the near field phenomena is strictly a short-range effect. This illustrates that most of the energy available in the eCoupled™ technology of Fulton Innovation is primarily inductive and non-radiative in essence.

1.2 Energy Flow Consideration

Another way of examining this issue is by the use of energy flow and intensity of EM fields. For electromagnetic fields produced by a dipole electric charge, the total energy density in free space,

$$\xi_{total} = \xi_{electric} + \xi_{magnetic} = \frac{1}{2}\left[\varepsilon_0 E^2 + \frac{B^2}{\mu_0}\right] \quad (1)$$

The flow of this energy is generally represented in the Poynting vector

$$\overline{S} = \frac{E\,x\,B}{\mu_0} \quad (2)$$

The magnitude and direction of the vector represents the energy intensity and the direction of flow of energy through a surface. Poynting's theorem then states that

$$\frac{\partial \xi_{total}}{\partial t} + \oint \overline{S}.dA + P_T = 0 \qquad (3)$$

Where ε_o is the permittivity of free space, μ_0 is the permeability of free space, ξ is the wave energy, $\overline{S}$ is the Poynting vector.

P_T is the work done in converting EM fields into other forms, and the first term represents the rate of increase in total field energy within the region. If there were no flow of field energy into or out of the surface, these two terms would add to zero by conservation of energy. The middle term must therefore represent the rate at which energy flows out through the surface. If we assume for simplicity that the oscillation of this charged dipole is harmonic, we can represent its dipole moment $p(t)=p_0 cos\omega t$. As discussed earlier, in the near field there is an exchange of energy between the dipole and the EM field every half cycle resulting in no net energy movement. These fields by definition (Biot-Savart law) fall off by $1/r^2$, so the Poynting vector (2) falls off by at least $1/r^4$ with distance from the source. It should be noted that the intrinsic oscillation of these near fields produces a weak 'induced' field with Poynting vector pointing outward, which constitutes the weak radiated field in the near field region. This falls off by $1/r$, and hence becomes more prominent in the far field.

Given that the **E** and **B** fields are proportional to the acceleration of the charges, it follows the second derivative of the dipole is

$$\frac{\partial^2 p}{dt^2} = \omega^2 p \qquad (4)$$

where p is the dipole moment and $\omega = 2\pi f$

This in turn suggests that the Poynting vector, being a product of **E** and **B** is proportional to ω^4, which shows that the amount of radiated power increases very rapidly with increase in frequency, and hence very little of the energy in the low frequency range is lost by radiation, as is the case with the radio and high frequencies [3].

2.0 EM FIELDS AND 'EVANESCENT' FIELDS IN POWER TRANSFER ANALYSIS

Given the inherent complexity and interaction of the EM fields which are present in power transfer technologies at low and high frequencies in the near and far fields, the analytic explanations for these interactions becomes very difficult when every single field type is being taken into account. One of the reasons being that the EM wave interactions change with distance from source, and get even more unpredictable the closer you get to the source. Solving Maxwell's equations for an EM source surrounded by homogenous isotropic media yield various fields that decay at different orders of $1/r$ away from the source as explained above. These fields can be written as a multipole mathematical series expansion in $1/r$ comprising of spherical harmonic and spherical Bessel functions representing axial and radial dependencies respectively [4]. This field expansion is then applied to the power leaving a sphere around the EM source. Total power is a product of the power density and the area of the sphere, such that

Power leaving area = Area x Power density = $4\pi r^2 . P_d = 4\pi (C1 + C2/r + C3/r^2 + C4/r^3 + \ldots)$. (5)

where P_d is the power density, and C_1-C_4 are expansion constants.

The first term is purely a constant. For this term, no matter what size you make the sphere, the same amount of power will flow through it. Mathematically, this shows that some power is carried away from the source. Therefore, the first term is due solely to the radiated field. Another thing to notice is that, as *r* gets very large, all the other terms will become negligible, leaving only the radiated term to be dominant in the far field, and at very close distances (small values of *r*), the non-constant terms will become much larger and the constant radiating term will become negligible. These non-constant terms taken together represent the power in the reactive field, and since it dominates at close distances it is called the near field [5].

The non-constant terms of this expansion can be attributed to the inductive and electrostatic fields which become significant as *r* reduces and we get closer to the source. In fact, as we get closer to the sources, this mathematical expansion breaks down due to the number of terms necessary to give an accurate description of the fields. Hence Eqn. 5 is then lumped into two terms, the first being the radiated field term, and the exponentially decaying fields lumped into another term called the **'evanescent fields'** (since their intensity decay with distance).

This grouping of the exponentially decaying components of the near field non-radiative EM field types are then mathematically examined as a single term called the evanescent fields, which is not in itself a physical entity, but a summation of the effects and characteristics of the various EM waves present near the source.

Such an approach, of using a cumulative 'evanescent field' in lieu of the electrostatic, radiative and inductive components of the near field is that which is adopted by Karalis, Soljacic and Joannopoulos of MIT in their papers on wireless power transfer [6][7], as it lends itself more to a mathematical, than to a physical analysis. Though this approach produces results consistent with experimental analysis, it obscures the physics and engenders misunderstanding, especially with the generic use of the term evanescent fields in various aspects of wave theory, and not specifically electromagnetics. A more comprehensive physical, mathematical and engineering analysis of the same concept was carried out by F.Z. Shen et al. [8], and yielded identical results. This latter approach was not only less convoluted, but provided more information on the electrical and magnetic concepts of strongly coupled non-radiative transfer.

In conclusion, the discussion above has tried to clarify the difference between radiative and non-radiative fields in the context of power transfer. It has sought to examine the effects of frequency on the levels of radiation in the near fields, and shown that using the low frequency range in power transfer technology produces negligible radiation as their near field regions mostly cover the region of function of these technologies. But going higher in frequency exacerbates the radiation emission due to the exponential dependence of radiated power on frequency.

References:

[1] '*Electromagnetic Radiation and How It Affects Your Instruments. Near Field vs. Far Field.*' www.osha.gov/SLTC/radiofrequencyradiation/electromagnetic_fieldmemo/electromagnetic.html#section_6

[2] Ron Schmitt, '*Understanding Electromagnetic Fields and Antenna Radiation Need No Math*' March 2000, www.ednmag.com.

[3] www.phy.duke.edu/~lee/P54/energy.pdf

[4] www.wikipedia.org

[5] http://ieeeb.okstate.edu/lecturenotes/EET4654%20Microwaves/Lecture%2010.pdf

[6] André Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, Marin Soljacic '*Wireless Power Transfer via Strongly Coupled Magnetic Resonances*' SCIENCE, Volume 317, 6 July 2007. www.sciencemag.org

[7] Aristeidis Karalis, J.D. Joannopoulos, Marin Soljacic '*Efficient Wireless Non-radiative Mid-range Energy Transfer*' Annals of Physics 323, (2008) 34-48.

[8] F.Z. Shen, W.Z. Cui, W. Ma, J.T. Huangfu, L.X. Ran '*Circuit Analysis of Wireless Power Transfer by 'Coupled Magnetic Resonance'*,' IET CCWMT 2009, Pg 602.

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Dr. Umenei joined Fulton Innovation in 2010 and is part of the research team tasked with improving wireless power design solutions while advancing eCoupled™ technology and extending its applications. He has over 16 published papers and conference presentations with two patents pending.