TESLA SKIN EFFECT MYTH

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Abstract.

We show for graduate and postgraduate students of Physics and Engineering that the electrical *skin effect* can only occurs in conductors. It is not observed in "poor" conductors like, for instance, human tissues. So, no Tesla skin effect take place in human bodies. It is a false theory, a myth. It is also pointed out when Tesla radiation is harmless for humans.

***Key words**: good and poor conductors; skin effect; Tesla radiation; human bodies.*

(I)Introduction

"An erroneous explanation for the absence of electric shock that has persisted among Tesla coil[1] hobbyists is that the high frequency currents travel superficially in the human body and thus do not penetrate to vital organs or nerves, due to an electromagnetic phenomenon called *skin effect*"[2] We show that this theory is false, a myth. This happens because radio frequency (**RF**) currents in "**poor conductors**" do not flow only close to its surfaces. They penetrate in the material up to a distance, called *skin depth*, which depends on the resistivity and permeability of the material as well as the frequency. In this paper is adopted the MKSA system.[2] In **Section 1** is shown the *skin effect* for alternating currents flowing in **conductors** in form of wires. In **Section 2** is shown that for "**poor conductors**" there is no *skin effect*. In **Section 3,** as the human tissue is a poor conductor, we can conclude that the skin effect cannot occur in human bodies and, consequently, in typical Tesla radiation experiments. In **Section 4** is seen the photo of Furukawa submitted to Tesla radiation and the estimation of the current which passes by his body.

(1). Skin Effect in Round Conductors.[3-5]

"Good" Conductors or, simply, "**conductors**" are materials with very low resistivity ρ like, for instance, Copper =1.7 10^{-8} Ωm, Au = 2.4 $10^{-8}\Omega$m, Pt = 10.6 10^{-8} Ωm and Al = 2.65 10^{-8} Ωm at T = 20^{o}C.

Charge carriers constituting the electric current in conductors are usually electrons driven by an electric field. The current I (see **Figure 1**) in a conductor produces a magnetic field in and around the conductor. When the intensity of current in a conductor changes, the magnetic field also changes. The change in the magnetic field, in turn, creates an electric field which opposes the change in current intensity. This opposing electric field is called “counter-electromotive force” (back EMF). The back EMF is strongest at the center of the conductor, forcing conducting electrons to the outside of the wire.

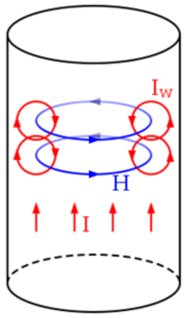


Figure 1. The current I flowing through a wire induces a magnetic field H. If the current increases, as in the figure, the resulting increase in H induces circulating "eddy currents" I_W [3] which partially cancel the current flow in the center and reinforce it near the skin.

Regardless of the driving force, the current density is found to be greatest close to the interior conductor's surface, with a reduced magnitude deeper in the conductor. The current density J(d) which describes the *skin effect* [2] is given by

$$J(d) = J_s \exp(-d/\delta_c) \qquad (1.1),$$

where J_s is the current density at the surface, δ the current *skin depth* and d is the depth **below** the surface of the conductor (see **Figure 2**). For frequencies $\omega < \rho_c\varepsilon_c$ we have $\delta_c \approx (2\rho_c/\omega\mu_c)^{1/2}$ where ρ_c and ε_c are, respectively, the resistivity and electrical permittivity of the conductor.

Figure 2.[3] Distribution of current flow in a cylindrical conductor(wire), shown in cross section. For alternating current, the current density decreases exponentially from the surface towards the inside. The skin depth, δ_c, is defined as the depth where the current density is just 1/e (~37%) of the value at the surface; it depends on the frequency ω and of the electrical and magnetic properties of the conductor(see Eq.1.1).

Over 98% of the current will flow within a layer 4 times the skin depth from the surface. This behavior is distinct from that of **direct current** which usually will be distributed evenly over the cross-section of the wire. For example, a 1MHz radio wave has a wavelength in vacuum λ_o ~ 300 m, whereas in copper, the wavelength is reduced to only about 0.5 mm with a phase velocity of only about 500 m/s. In good conductors, such as metals, all of those conditions are ensured at least up to microwave frequencies, justifying this formula's validity. For copper this would be true for frequencies much below 10^{18} Hz.

When the skin depth is not small with respect to the radius of the wire, current density J(r) at r may be described in terms of Bessel functions. The current density inside round wire, away from the influences of other fields, as function of distance r from the axis is given by: [3-5]

$$J(r) = (kI/2\pi R)J_o(kr)/J_1(kR) = J(R)\ \{J_o(kr)/J_1(kr)\} \qquad (1.2),$$

where $k = 2\pi/\lambda = \omega/c$, $\omega = 2\pi f$, r = distance from the axis of the wire, radius of the wiretotal current, Bessel function of the first kind, order 0 and Bessel function of the first kind, order 1(see **Figure 3**).

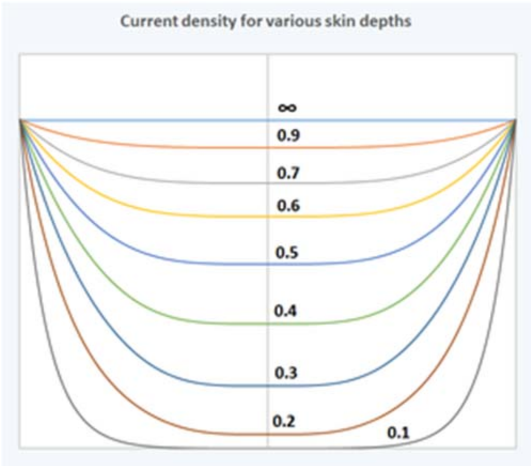


Figure 3. Current densities in round wire for various skin depths. Numbers shown on each curve are the ratio of skin depth to wire radius. The curve shown with the infinity sign is the zero frequency (DC) case. All curves are normalized so that the current density at the surface is the same. The horizontal axis is the position within the wire with the left and right extremes being the surface of the wire. The vertical axis is relative current density.[4,5]

(1.1)Resistance.

The most important effect of the skin effect on the impedance of a single wire is the increase of the wire's resistance, and consequent losses. The effective resistance can be estimated assuming that it is confined in a circular region with thickness δ_c. Thus, a long cylindrical conductor with length ℓ and a diameter *D* large compared to δ_c, would have a resistance R of a hollow tube with wall thickness δ_c carrying direct current given by

$$R \approx \ell\rho_c/\pi(D-\delta_c)\delta_c \approx \ell\rho_c/\pi D\delta_c \qquad (1.3).$$

A practical formula for the *skin depth* for frequencies ω much lower than $1/\rho_c\varepsilon_c$ is given by[2]

$$\delta_c = (2\rho_c/\omega\mu_c)^{1/2} \qquad (1.4),$$

where $\rho_c = 1/\sigma_c$ and μ_c are, the resistivity, conductivity and permeability of the medium. When f = 10 GHz, for instance, for Aluminum, Copper, Gold and Silver we have δ_c = 0.820, 0.652,0.753 and 0.634 μm, respectively.

(2)Skin Effect in Poor Conductors.

In a first approach, for common materials, one can assume that **conductors** have resistivity going from 10^{-8} Ωm up to 10^{-5} Ωm and that **poor conductors** have resistivity going from 10^{2} Ωm up to 10^{8} Ωm.[3,6,7]

We have not found in literature calculations about *skin effect* for **"poor conductors"** like that performed by Maxwell for round good conductors,[3,4] seen in **Section 1**. There are, however, many theoretical estimations and experimental results describing electric currents in poor conductors.[2,6,7]

The *skin depth* in a **conductor**, is given by $\delta_c = (2\rho_c/\omega\mu_c)^{1/2}$ which decreases with the increasing frequency ω, and that the *skin-depth* in a **"poor conductor"** is given by,[2] for $4\pi/\rho_{pc}\omega\varepsilon_{pc} \gg 1$,

$$\delta_{pc} \approx (2\rho_{pc})(\varepsilon_{pc}/\mu_{pc})^{1/2}, \qquad (2.1),$$

which is frequency independent, where ρ_{pc}, ε_{pc} and μ_{pc} are the resistivity, electric permittivity and magnetic permeability, respectively, of the poor conductor.[2]

For a conductor like, for example, Copper the skin depth δ_c decreases from 9220 μm at f = 50 Hz up to 2.06 μm at f = 1 Ghz. Giving rise, according to Section 1, to the so-called *skin-effect* in wires, by which an oscillating electromagnetic signal along the wire, is confined to an increasingly narrow layer δ_c.

On the other hand, for instance, for *bulk silicon* (undoped) which is a **poor conductor**, the skin depth is $\delta_{pc} \approx 40$ m[1] (measured at 100 kHz). It is observed that as the frequency is increased well into the MHz range, its skin depth never falls below the asymptotic value of 11m.[1] Since poor conductors have very large skin depth δ_{pc} no *skin-effect* can take place in these materials as occurs with round conductors.

(3)Human Tissues and the harmless currents.

Due to its high resistivity, human tissues are poor conductors.[7] Due to accurate measurements,[7] for Skeletal ρ = 171 Ωm, cardiac muscle = 175Ωm kidney 211 Ωm, liver 342 Ωm, lung 157 Ωm and spleen 342 Ωm. These precedent resistivity values have been found to be constant for frequencies measured between 100 Hz up to 10 MHz. It was verified that the skin depths for human tissues go roughly from 24 to 72 cm for frequencies in the range 0.1-1 MHz.[1]Since in the human body even the deepest tissues are closer than this to the surface, skin effect has little influence on the path of the current through the body. It tends to take the path of minimum to ground, and can easily pass through the core and another organs of the body.

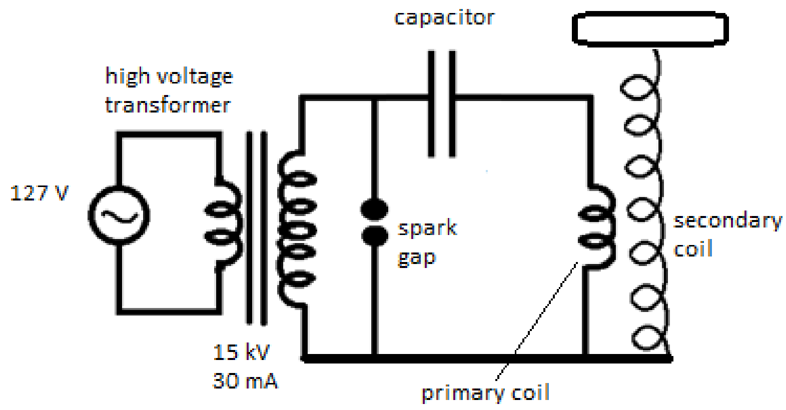
When high voltage *radio frequency* (RF) that is, bigger than 30 kHz when passed through the body they often do not cause the painful sensation and muscle contraction of electric shock, as lower frequency AC or DC currents do.[1,8] The nervous system is insensitive to currents with frequencies over 10 – 20 kHz.[1,8] As for RF no pain is felt, experimenters often assume Tesla currents as harmless. Teachers and hobbyists demonstrating small Tesla coils often impress their audience by touching the high voltage terminal or allowing the streamer arcs to pass through their body. If the arcs from the high voltage terminal strike the bare skin, they can cause deep-seated burns called *RF burns*. This is often avoided by allowing the arcs to strike a piece of metal held in the hand, or a thimble on a finger, instead. The current passes from the metal into the person's hand through a wide enough surface area to avoid causing burns. Often no sensation is felt, or just a warmth or tingling.

However, this does not mean **any** currents are harmless.[9] Even a small Tesla coil produces many times the electrical energy necessary to stop the heart if the **frequencies are smaller than 400 Hz**. In these conditions they are able to cause ventricular fibrillation. A minor maladjustments of the coil could result in electrocution. In reference [9] are presented detailed descriptions, in the general case, of the **electric shocks** effects in human body.

In the medical therapy called "longwave diathermy",[10] carefully controlled RF current frequencies was used for decades for deep tissue warming, including heating internal organs such as the lungs. Modern shortwave diathermy machines use a higher frequency of 27 MHz, which would have a correspondingly smaller skin depth, yet these frequencies are still able to penetrate deep body tissues.

(4)Tesla Coil in our Laboratory EWH (IFUSP).

Our Tesla Coin has a circuit shown below,



with the following characteristics:

- Input circuit transformer: V = 15 kV, I = 30 mA
- Number of turns of the secondary circuit coil: 950
- Oscillation frequency (resonance): ω = 250 kHz
- Output voltage: $V_o \sim 200$ kV

In the primary circuit, we use a saturated core transformer which has an output of 15 kV and a maximum current I = 30 mA. So, the maximum coil input power P_{max} would be P_{max} = 15 kV • 30 mA = 450 W.

In the secondary circuit, due to the energy conservation, the maximum current would be $I_{secondary} \sim P_{max} / V_o$= 450 W/ 200 kV ~ 2 mA.

Due to this cutoff transformation effect, the maximum current that would pass Furukawa´s body at the spark instant (see **Figure 4**) would be I_{max} ~2 mA.

Due to the low sensitivity of the human body to high frequency electrical currents, we practically do not feel the passage of electrical current through the body, as we can seen in the photo. This current surely penetrates deeply in the human body, as commented in **Section 3**, and probably passing through the heart.

Figure 4. Furukawa photo at the instant of the spark created by the Tesla Coil.

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