SKIN EFFECT and PROXIMITY EFFECT

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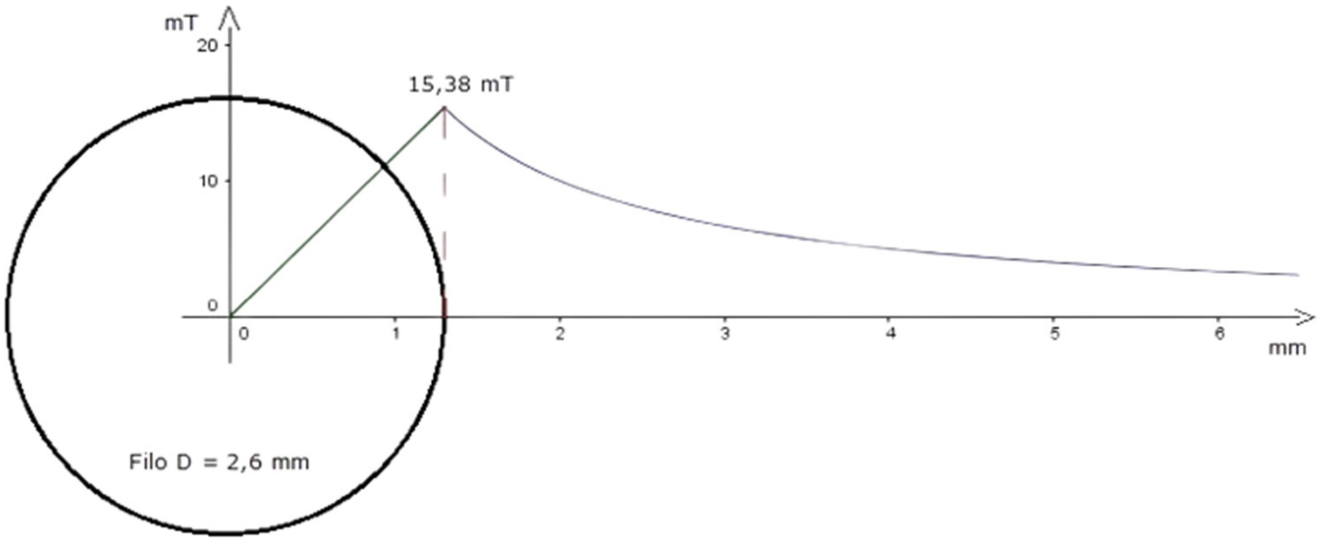
Magnetic Induction in Conductors

To understand the skin effect and proximity effect in wire conductors, it is necessary to know the distribution of the magnetic induction B that is created inside and outside the conductor when it carries current.
If we apply Ampère's law to a wire with a radius of r = 1.3 mm, through which a current of I = 1 A flows, we obtain the graph below.



Inside the conductor, the magnetic induction B increases as the distance from the center grows until reaching the edge of the wire (B = 15.38 mT). Outside the wire, on the other hand, it decreases with the inverse of the distance from the center.

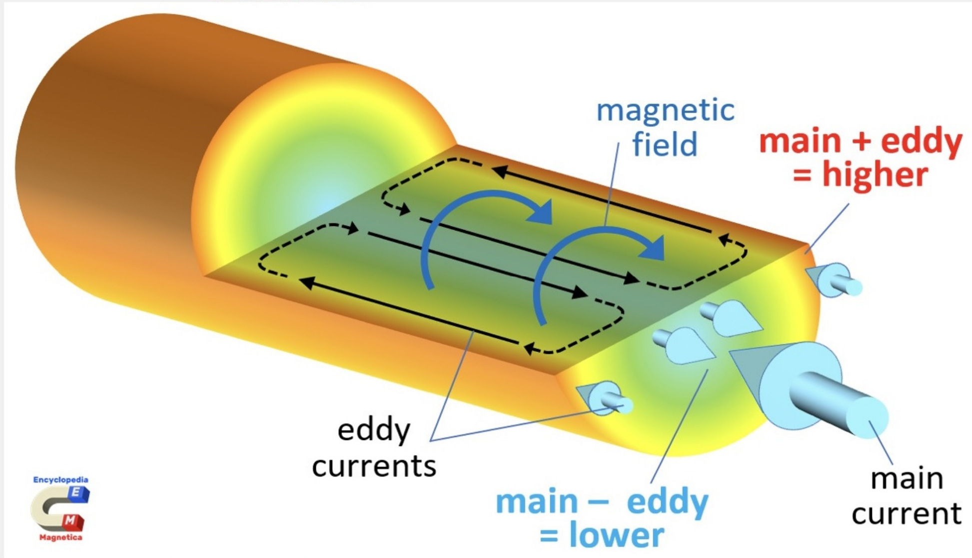
Skin effect

Inside the conductor (the wire), there is therefore a magnetic field that increases with the distance from the center, caused by the main current flowing through it. If the current is time-varying, for example, if it is sinusoidal, the induction B within the conductor will also be sinusoidal. However, if a conductor is immersed in a time-varying magnetic field, it induces an electromotive force (emf) that produces an eddy current

(called Foucault current), which, in turn, generates a magnetic field opposing the cause that generated it (Faraday's law, Neumann, Lenz). In the diagram, the induced current is represented by the black lines. The main current, therefore, experiences an induced current opposing its flow and towards the skin of the conductor at the center. Consequently, the current will move increasingly away from the center of the conductor to concentrate in the skin. This is the origin of the term "skin effect.

Mechanism of skin effect

Image taken from www.E-Magnetica.pl



S. Zurek, E-Magnetica.pl, CC-BY-4.0

Skin effect

Therefore, the current density increases in the vicinity of the surface layer of the conductor and exponentially decreases as one approaches the center of the conductor. The penetration depth (skin depth) is the distance from the edge d (delta) where the current has decreased by 37% (1/e).

The penetration depth (skin depth) δ depends on the square root of the frequency (f), the magnetic permeability (μ), and the conductivity (σ) of the conductor.

$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$

After appropriate simplifications, the resistance (R) of a conductor becomes:

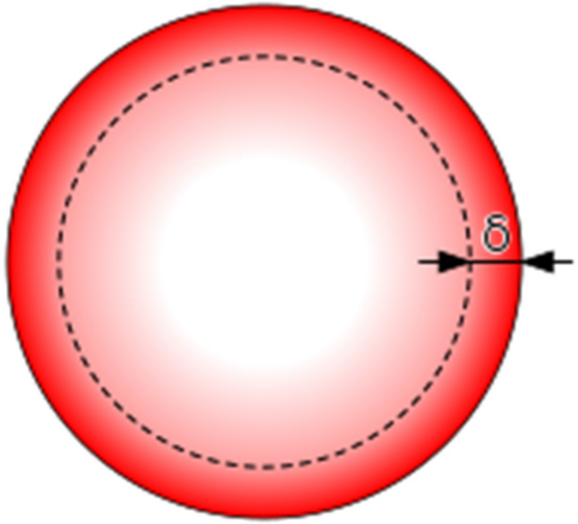
$R = 6{,}325 \cdot 10^{-4} \frac{l}{d} \sqrt{f \mu_r \rho}$ [Ω] Where f is in [Hz], ρ is in [nWm], l and d are in [m].

For cylindrical copper conductors (copper wires), this becomes:

$R = 8{,}304 \cdot 10^{-8} \frac{l}{d} \sqrt{f}$ [Ω] With *l* and *d* in the same unit of measurement.

The expression for resistance clearly indicates that resistance (R) increases with the length of the conductor (l) and the square root of the frequency (f), while it decreases with the diameter (d) of the conductor.

Image taken from https://en.wikipedia.org/



On https://e-magnetica.pl/doku.php/calculator/skin_depth there is an excellent calculator for d.

Skin effect

So much theory to draw inspiration for practical applications.

One of the ways to mitigate the increase in resistance of conductors due to the skin effect is to use **multi-strand** conductors (insulated from each other) twisted together to form a stranded cable (e.g., 7 strands). This technique is effective up to a few hundred kHz; beyond that, it behaves like a solid conductor without providing advantages. In fact, the central conductor is sometimes replaced with a steel wire to enhance tensile strength.

Another approach to reduce the increase in resistance is to use conductors with numerous individually insulated strands, known as **Litz** wires. However, these wires are effective only in the MF range up to about 3 MHz; beyond that, the skin effect becomes noticeable.

Yet another technique involves **silver-plating** copper conductors to encourage most of the current flow in a more conductive skin layer. The plating works until silver oxidizes into silver sulfide (black tarnish), which is a poor conductor. Copper conductors, on the other hand, develop a conductive oxide layer, so even when oxidized, they perform better than silver-plated conductors that have oxidized.

In conclusion, the most effective method to mitigate the skin effect is to increase the cross-sectional area of the copper conductor.

Proximity effect

Outside the conductor carrying current, the magnetic field lines extend circularly, also involving nearby conductors but decreasing with distance from the center of the conductor. Under sinusoidal current conditions, in nearby conductors, an electromotive force (emf) will be induced, producing a current vortex as in the previous case but within the adjacent conductor. In the diagram, the induced current in wire 1 is depicted with black lines.

If the currents in the two wires are in same direction, the main current flowing in conductor 1, near conductor 2, will experience an induced current opposing its flow and favoring it from the other side. Consequently, it will decrease on one side and increase on the other.

Therefore, the current in the conductors is influenced by the currents flowing in nearby conductors; for this reason, it is called the proximity effect.

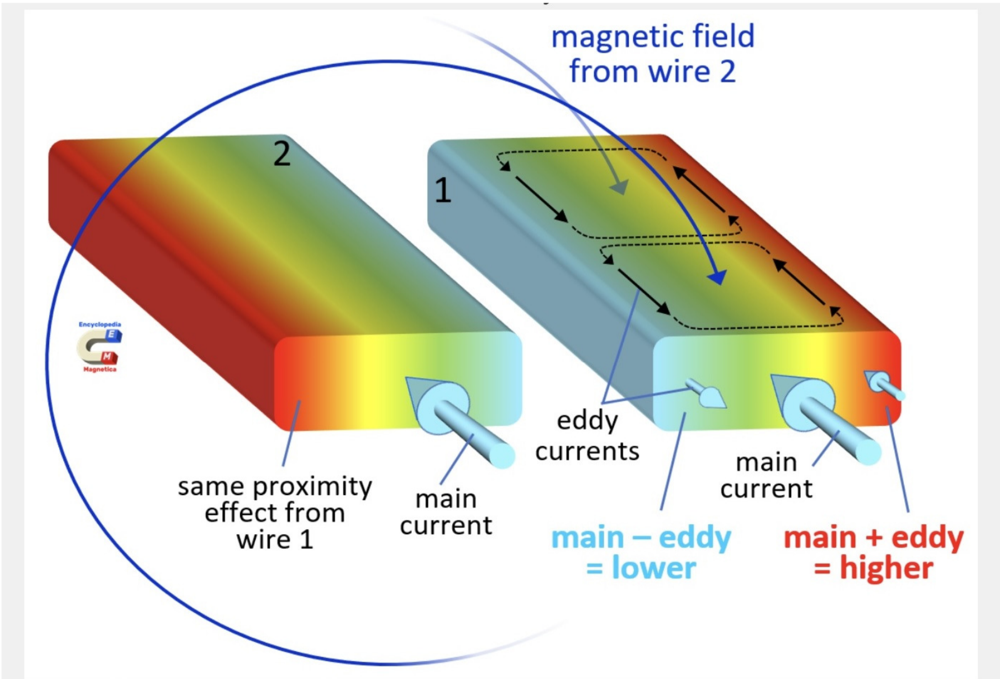


 Image taken from www.E-Magnetica.pl

Proximity effect

The proximity effect further reduces the cross-sectional area through which the current passes. The impact on the conductor's resistance is significant and considerably greater than that due to the skin effect.

There are not many remedies for this phenomenon, but let's see what can be done:

- Increase the separation between conductors: However, this is not always feasible.
- Avoid layering windings: yet, this is not always possible.
- Use conductors with a rectangular (flat) cross-section: this way, the perimeter of the conductor is larger than that of a circular one. However, this may not be readily available for amateur radio enthusiasts.
- Alternate, as much as possible, conductors carrying concurrent currents with those carrying opposing currents: This helps mitigate the proximity effect. This is the case with transformers, where primary and secondary turns alternate. However, in inductors and traps, it's not always achievable.

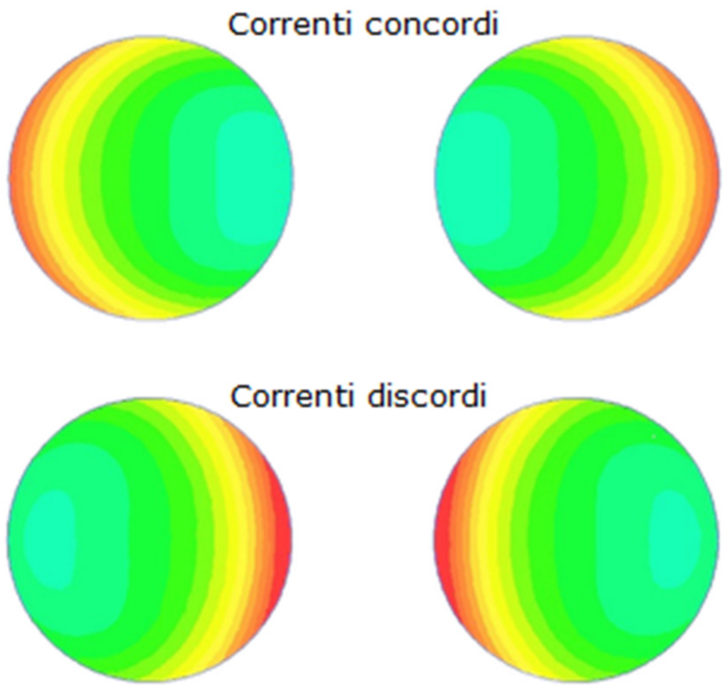


Image taken from www.E-Magnetica.pl

You can find an excellent calculator for determining the parameter of copper wires at https://e-magnetica.pl/doku.php/calculator/proximity_effect

Proximity effect

The proximity effect is measured by the parameter K, which expresses the ratio between the alternating resistance R_{ac} and the direct current resistance R_{dc}.

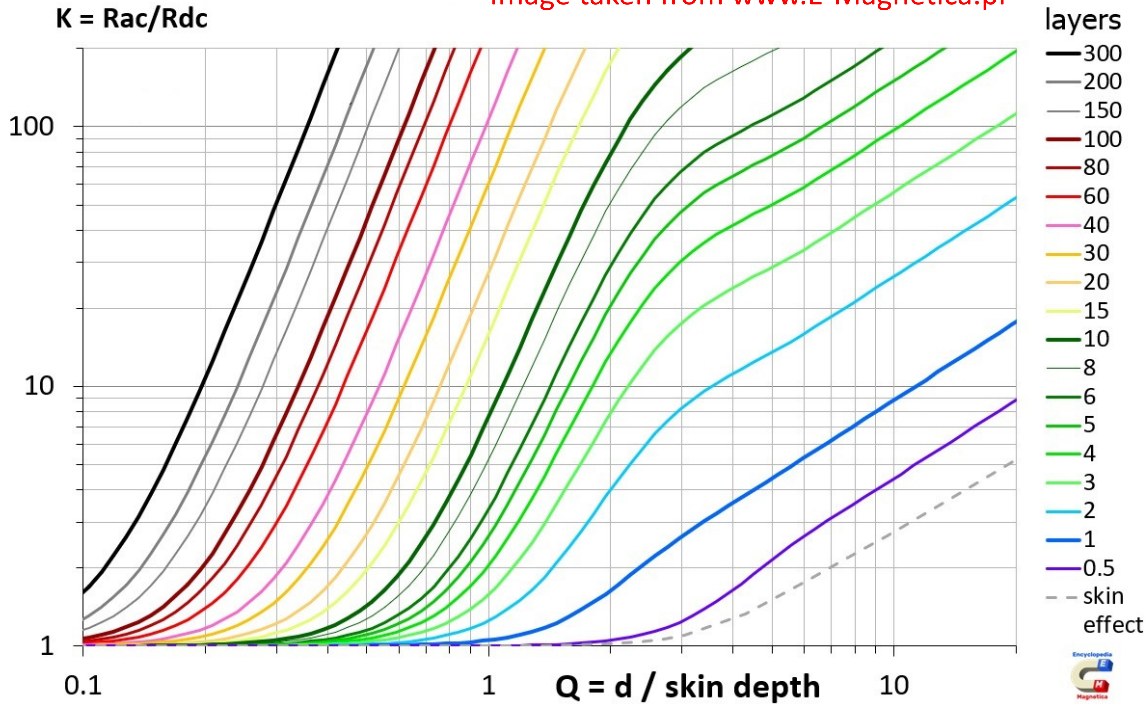
The image represents Dowell curves, where the x-axis shows the ratio between the wire diameter d and the skin depth δ, which, as mentioned, depends on the frequency.

The dashed gray line represents only the skin effect.

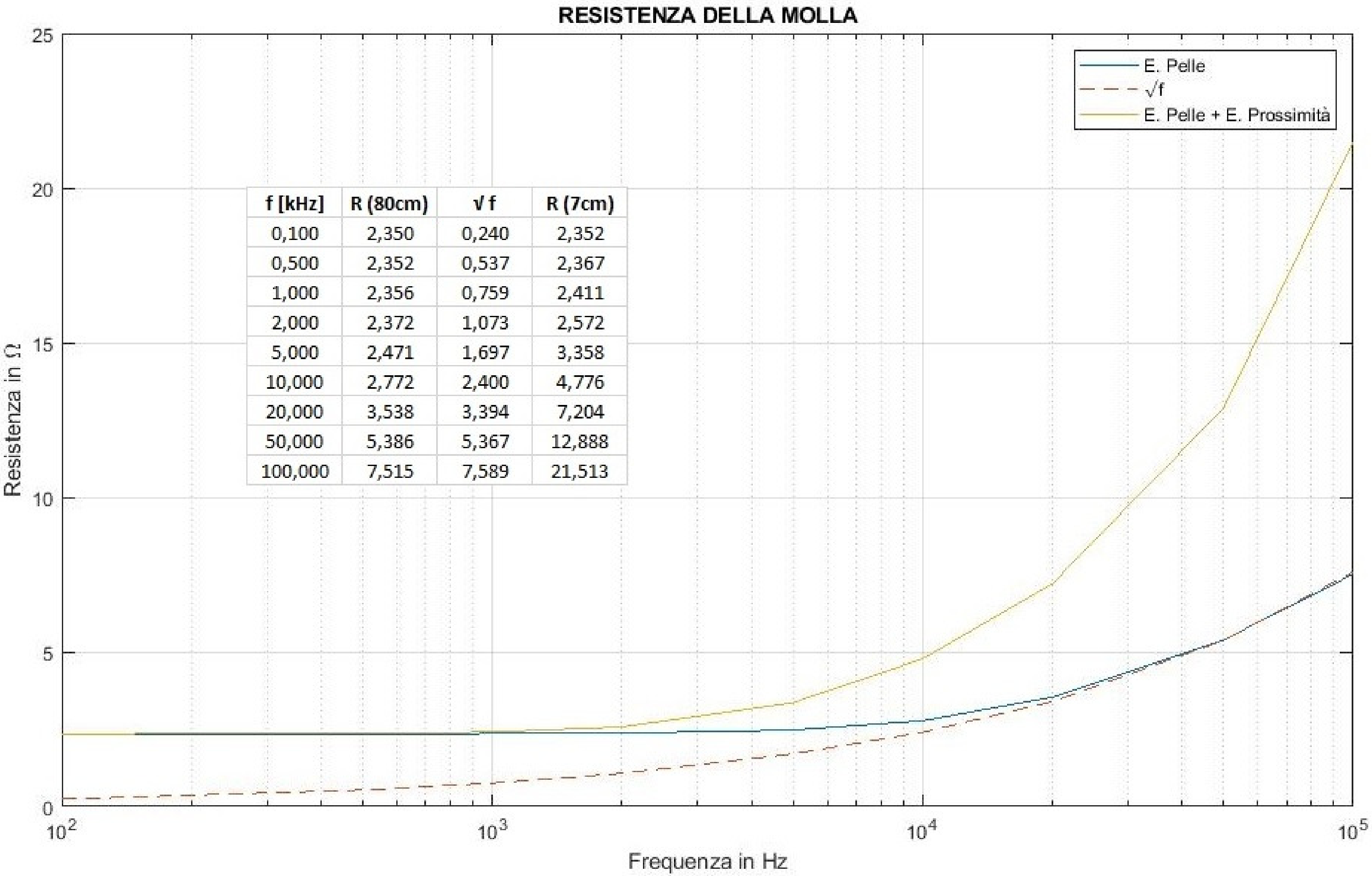
The violet line is obtained when alternating turns in the primary with those in the secondary.

The dark blue line represents winding on a single layer.

Image taken from www.E-Magnetica.pl



You can find an excellent calculator for determining the K parameter of copper wires at https://e-magnetica.pl/doku.php/calculator/proximity_effect_from_dowell_curves.



f [kHz]	R (80cm)	√ f	R (7cm)
0,100	2,350	0,240	2,352
0,500	2,352	0,537	2,367
1,000	2,356	0,759	2,411
2,000	2,372	1,073	2,572
5,000	2,471	1,697	3,358
10,000	2,772	2,400	4,776
20,000	3,538	3,394	7,204
50,000	5,386	5,367	12,888
100,000	7,515	7,589	21,513