High-Frequency Losses in Micro-Scaled Inductors and Transformers.

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Inductors and transformers are magnetic based components used in voltage converters in smartphones and computers [1]. Presently inductors and transformers are one of the largest components in the integrated circuits (IC) used to make these converters. As a result, they are in most cases fabricated as discrete components separate from the fabricated ICs. Increasing the frequency of operation permits scaling. In the case of a transformer this is because the core can transfer more power without reaching saturation and fewer turns are needed to achieve the same impedance. However, increasing the frequency of operation also increases AC power losses in the magnetic core and the conductive windings [2].

The winding loss includes both DC and AC resistance losses. At very high frequencies the AC resistance loss is much greater than the DC resistance loss and reduces the efficiency of the component. These loss mechanisms are much greater in scaled components compared to large scale inductors and transformers. The two major contributors to AC resistance are the skin effect and the proximity effect, both of which alter the current distribution of a current carrying conductor. Both effects are due to the presence of eddy currents in the conductor. The skin effect arises when the eddy currents cause the net current flowing through a conductor to reside in an area known as the skin depth near the surface of said conductor. The skin depth is a function of material parameters and the frequency of the applied waveform. A decrease in skin depth will increase the effective resistance of the winding. The proximity effect arises when the eddy currents generated by a changing magnetic field in a current carrying conductor alters the current distribution in an adjacent conductor. The proximity effect is a function of frequency, conductor geometry, winding arrangement and spacing [3].

Most micro-inductors and -transformers are fabricated to make their windings as wide as possible to reduce DC resistance loss whilst packing the windings close to each other to minimise the size of the component without much consideration to AC resistance losses. We have run initial simulations using finite element method, to evaluate winding resistance as functions of spacing and geometry for different waveform frequencies. These simulations will aid in developing empirical models for optimised winding configurations for a range of micro-inductor and -transformer designs with a reduced winding power loss.

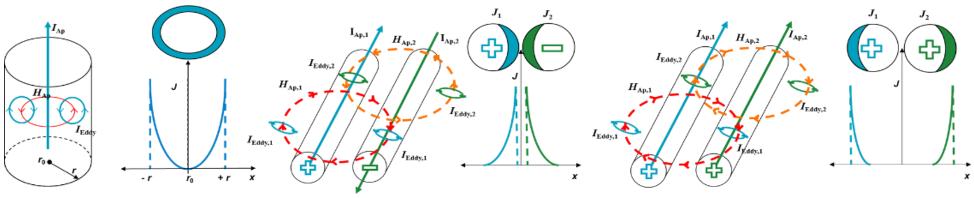

Figure 1: Visualization of skin and proximity effect in conductive winding(s)

[1] C. O Mathuna, et al, “Review of Integrated Magnetics for Power Supply on Chip (PwrSoC),” *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4799-4816, 2012.
[2] C. R. Sullivan et al, “Design of Microfabricated Transformers and Inductors for High-Frequency Power Conversion,” *IEEE Transactions on Power Electronics*, vol. 11, no. 2, pp. 228-238, 1996.
[3] M. K. Kazimierczuk, “Proximity Effect,” in *High-Frequency Magnetic Components*, West Sussex, Wiley, 2014, pp. 226-264.