Modeling and Analysis of the Planar Spiral Inductor
Including the Effect of Magnetic-Conductive
Electromagnetic Shields

Submitted to
Department of Electronic Engineering
in Partial Fulfillment of the Requirements
for the Degree of Master of Philosophy

by

SU, Yipeng

September 2008

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Abstract

The objective of this thesis is to analyze and model the planar spiral inductor including the effects of magnetic-conductive electromagnetic shields. The planar transmitter, planar receiver windings and the shielding structure constitute the main parts of the Contactless Energy Transmission Systems (CETS). Modeling such systems involves following issues: (i) the self-inductances of transmitters and receivers as well as the mutual inductance between them under arbitrary relative positions; (ii) the equivalent resistance of the windings at the operating frequency. The influence of the electromagnetic shield must be taken into consideration in both of them.

Firstly, a theory of inductance calculation is extended to determine the inductance of planar spiral windings shielded by double-layer planar EM shield consisting of a layer of soft magnetic material and a layer of conductive material. With the generalized equations, the inductance of the planar spiral windings with the effect of magnetic-conductive electromagnetic shield can be calculated accurately without using time-consuming finite-element method. The proposed equations can be applied to the cases of windings on a double-layer shielding substrate and of windings in a sandwich shielding structure. The optimal thickness of shielding materials also can be obtained easily. Therefore, the influence of the double-layer electromagnetic shields on the inductance of the planar spiral windings can be analyzed. Simulations and measurements have been carried out for several shielding plates with different permeability, conductivity and thickness. Both of the simulations and measurements of the winding inductance agree well with the extended theory.
Secondly, another extended formula is proposed to calculate the mutual inductance of two non-coaxial planar spiral windings sandwiched between two magnetic-conductive substrates. Recent developments of wireless battery charging platform have prompted the requirements to investigate the mutual inductance between a movable planar coil and the fixed planar coil on the charging platform. The wireless battery charging platform must allow the load to be placed anywhere on the charging surface. Therefore the relative position between the movable energy-receiving coil and the energy-transmitting coils on the charging platform should not be fixed. The proposed formula can be used to quickly determine the mutual coupling of two planar windings that can have arbitrary relative positions and distance between them. This new calculation tool provides a new and useful tool for calculating the mutual inductance of a movable planar coil and a fixed planar coil. The theory has been tested and compared with practical measurements and also finite-element analysis. The theoretical results agree very well with both practical measurements and finite-element results.

Finally, several major energy dissipation mechanisms in transmitting and receiving windings are addressed. The dominant factor of energy dissipation comes from the current flowing through the spiral inductor itself. They include both ohmic and eddy current loss. Eddy current manifest themselves as skin effect and proximity effect, which are highly dependent on the operation frequency and the inductor geometry. Therefore, some inductor design approaches for eddy current suppression are described, in order to minimize the power dissipations in the windings, maximize their quality factors, and thus improve the wireless power transfer efficiency.
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