

A New Testcase of TEAM Problem Family for Applications Having Both Solid and Stranded Conductors

Yanpu Zhao¹, Senior Member, IEEE, Xingxiong Yang¹, Yize Wei², Yaxin Li², Shenghu Liu², Qingxin Yang³, Shiyong Yang⁴, and Xian Zhang²

¹School of Electrical Engineering and Automation, Wuhan University, 430072, Wuhan, China, yanpu.zhao@whu.edu.cn

²The State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, 300132, Tianjin, China, zhangxian@hebut.edu.cn

³Tianjin University of Technology, 300384, Tianjin, China, qxyang@tjut.edu.cn

⁴College of Electrical Engineering, Zhejiang University, 310058, Zhejiang, China, eesyyang@zju.edu.cn

With the expanding application of wireless power transfer (WPT) technology, capacitive, hybrid, and self-resonant wireless charging methods have gained increasing attention. It is noteworthy that these WPT magnetic coupling structures often face numerical challenges due to the arbitrary connection between solid conductors (such as plates where induced eddy-currents can't be ignored) and stranded conductors (such as litz wires where the induced eddy-currents are negligible). To address this problem, which involves both solid and stranded conductors connected together and the possible capacitive effect between solid conductors, this paper proposes a benchmark test case and carried out the fabrication and measurement for the magnetic field values at given points first. Finite element field-circuit coupled formulation has been designed for this new need and to be implemented for validating the reliability of the finite element simulation results. Measurements are conducted for rigorously assess the accuracy of the oncoming numerical results.

Index Terms—Benchmark, numerical formulation, solid and stranded conductor, wireless power transfer.

I. INTRODUCTION

Due to the high flexibility and intelligence of wireless power transfer (WPT) technology, it has been widely applied in various fields such as consumer electronics, underwater autonomous vehicles, and electric vehicles [1]. With the in-depth research into the magnetic coupling structure of WPT, it has been noticed that there exists electric connection between solid conductors and stranded conductors in capacitive, hybrid, and self-resonant WPT systems [2]. Generally, there can be electric connections between the electrode plates, such as aluminum plates, and the litz wire coil terminals.

When it comes to such issues using finite element method for numerical modeling, sometimes the solid conductor is treated as an equipotential body for simulation studies [3]. However, when a solid conductor is connected to a stranded conductor, it is not guaranteed that the potential on the solid conductor will remain constant. As a result, further numerical calculations based on this assumption may lead to significant errors, especially for higher excitation frequencies. Therefore, by assuming the solid conductor to be an equipotential body is inappropriate and the relevant formulation should be designed to overcome the difficulties when there are solid conductors connected directly with stranded conductors.

As far as we know, there is no available commercial software tools can handle this kind of simulation. Therefore, a benchmark system having both solid and stranded conductors is proposed as a testcase for first measuring the potential or field at given points for validating the oncoming designed finite element formulation and the computational result.

II. BRIEF REVIEW OF CONDUCTOR MODELS

This paper presents the conductor model architecture and geometric dimensions of the proposed primary side of self-resonant WPT system, as illustrated in Fig. 1. In this system, the primary side achieve self-resonance through the series connection of coils (stranded conductors) and electrode plates (solid conductors). To increase the capacitance between the

electrode plates, a mica layer is added between them. In addition, the coil consists of 22 turns, and the material used for the coil is litz wire. In order to establish a more accurate electromagnetic field calculation benchmark, four measurement paths are defined, as shown in Fig. 2.

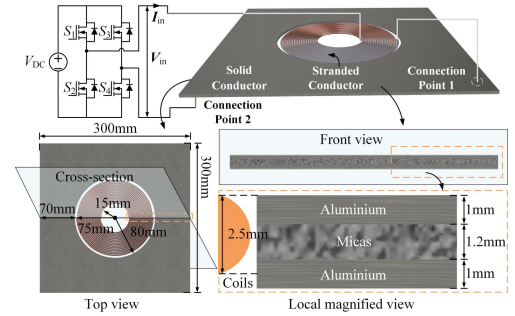


Fig. 1. Conductor models and the electric circuit connection.

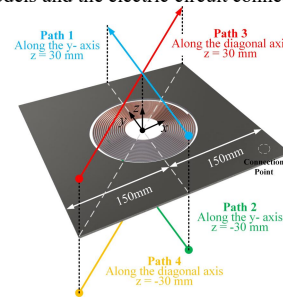


Fig. 2. Measurement path for the magnetic field.

III. EXPERIMENTAL SETUP AND RESULTS

As shown in Fig. 3, an experimental setup having composite solid and stranded conductors is constructed. Besides, the experimental parameters are listed in Table I. The measurement results of the magnetic flux density along the four measurement paths proposed in Section 2 are shown in Figs. 4 and 5. From Figs. 4 and 5, the magnetic field along the test path shows a distribution trend where the field is higher in the center and lower at the edges.

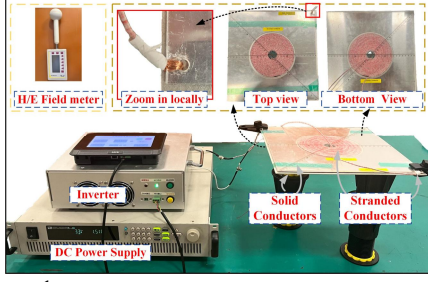


Fig. 3. Experimental system setup.

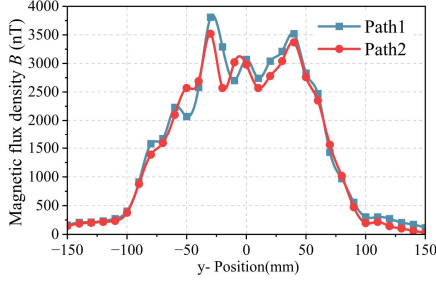


Fig. 4 Distributions of magnetic flux density along Path 1 and 2.

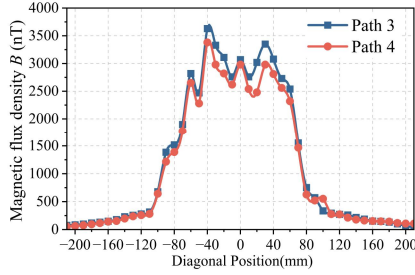


Fig. 5 Distributions of magnetic flux density along Path 3 and 4.

TABLE I
EXPERIMENTAL PARAMETERS

Parameters	Explanation	Value
f (kHz)	System operating frequency	903
L (μ H)	Primary coil inductance	31.2
C (nF)	Primary plate capacitance	1.25
V_{in} (V)	The RMS of ac voltage output by inverter	3.2
I_{in} (mA)	The RMS of ac current output by inverter	245

The cause of this phenomenon is the presence of eddy current magnetic fields on the electrode plate. As shown in Fig. 1, the difference in the vertical position of the coils causes the measurements of path 2 and 4 to generally be slightly lower than those of path 1 and 3.

IV. NUMERICAL METHODS

Regarding the numerical methods for this proposed benchmark problem, one has to take into account the stray capacitance between the solid conductor plates or the effect of the mica dielectric material, and also the coexistence of solid conductor and stranded conductor coils which are connected together in series to form the overall current path and establish the coupled electromagnetic fields. To address the capacitive effect, the authors have carried out research on addressing the stray capacitance in a previous study [4].

But for the electrically connected solid conductors and stranded conductors, which is not common to see to the best of

our knowledge, it is worthy of investigation and will be addressed in the full paper. A preliminary thought would be to both introduce an extra electric scalar potential variable V_s for the connection point of the upper solid plate conductor, and also the loop current i as the circuit unknowns. Then two more equations must be introduced to balance both unknowns, they are given below, where R is the resistance of the stranded coil, U is the input voltage source.

$$i = -\iint_s \sigma \left(\frac{\partial \vec{A}}{\partial t} + \nabla \varphi \right) \cdot d\vec{S}, \quad (1)$$

$$U = V_s + Ri + \frac{d\psi}{dt}. \quad (2)$$

The above equations need to be coupled with the potential variables, where $\vec{t}$ is the unit tangential vectors along the stranded coil mesh elements.

$$\begin{cases} \nabla \times (\nabla \times \vec{A}) + \sigma \left(\frac{\partial \vec{A}}{\partial t} + \nabla \varphi \right) + \varepsilon \frac{\partial \nabla \varphi}{\partial t} - \frac{\partial}{\partial t} \nabla p = i\vec{t} / S \\ \nabla \cdot \left(-\sigma \left(\frac{\partial \vec{A}}{\partial t} + \nabla \varphi \right) - \varepsilon \frac{\partial \nabla \varphi}{\partial t} \right) = 0 \\ \frac{\partial}{\partial t} (\nabla \cdot \vec{A}) = 0 \end{cases} \quad (3)$$

Equations (1)-(3) form the field-circuit coupling scheme regarding this benchmark testcase. The detailed numerical results will be presented in the full paper and extensive comparison with the experiment results will be also carried out.

V. CONCLUSION

For practical wireless power transfer (WPT) systems, the connection between solid and stranded conductors renders numerical difficulties. To this end, this work presents a benchmark case by measuring the magnetic field around the test rig to check the accuracy of finite element models that consider the interaction between solid conductors and stranded conductors. The aim is to better guide the design of WPT magnetic coupling systems and improve the system's utilization of near-field electromagnetic energy. Additionally, a novel finite element field-circuit coupled formulation is proposed, which will be implemented and validated against the presented benchmark case.

REFERENCES

- [1] Z. Zhang, H. Pang, A. Georgiadis, and C. Cecati, "Wireless power transfer—an overview," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1044-1058, Feb. 2019.
- [2] X. Zhang, G. Li, T. Chen, F. Wang, Q. Yang and W. Xu, "A High-Efficiency Underwater Hybrid Wireless Power Transfer System With Low Plate Voltage Stresses," *IEEE Trans. Power. Electron.*, vol. 39, no. 8, pp. 10546-10557, Aug. 2024.
- [3] T. Chen, C. Cheng, X. Zhang, G. Li, Y. Guo and C. C. Mi, "A Double-Sided LCL-Compensated Network for the Strongly Coupled CPT System With Minimum Plate Voltage Stresses," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 12, no. 4, pp. 4275-4287, Aug. 2024.
- [4] Y. Zhao and Z. Tang, "A Novel Gauged Potential Formulation for 3-D Electromagnetic Field Analysis Including Both Inductive and Capacitive Effects," *IEEE Transactions on Magnetics*, vol. 55, no. 6, pp. 1-5, Jun. 2019.