A Misalignment Tolerant Winding Pattern with Reduced AC Resistance for Inductive Power Transfer

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***Abstract*— Litz wire planar coils are widely used in inductive power transfer systems due to their low profile and high efficiency in medium-frequency operation. In high-frequency region, the AC resistance of Litz wire planar coils increases significantly, which leads to efficiency-drop and temperature-rise issues. Meanwhile, misalignment occurs during the daily operation and causes instable power supply. In this work, we propose a novel winding pattern for reducing AC resistance, thermal stress, and sensitivity to misalignment. According to the experimental results of the presented case study, the proposed winding pattern reduces the AC resistance maximally by 78% at 1 MHz, and 263% at 20 MHz compared to the conventional winding pattern under the same geometry and wire length. The misalignment tolerance is improved by 30% on x-axis direction, and 46% on y-axis direction.**

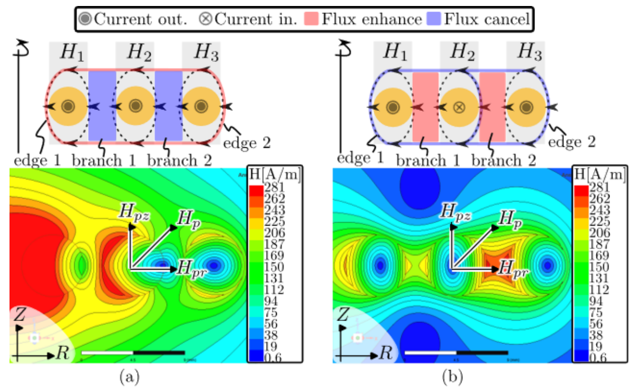
Keywords—AC resistance, misalignment tolerance, inductive power transfer

I. INTRODUCTION

In recent years, inductive power transfer (IPT) systems are gradually used in consumer electronics and bio-medical implant areas [1, 2]. However, the development of IPT systems in industrial applications is relatively slow due to challenges in misalignment sensitivity, efficiency and thermal dissipation.

In order to effectively tackle the above challenges, researchers proposed different aspects of methods in control, resonant tank structure and coil design [3]-[9]. A coil array structure is introduced in [9], which uses multiple coils to generate an uniform magnetic field to improve the misalignment tolerance. An interoperable coil is applied in [7] to improve misalignment tolerance. The double D coil is proposed in [4, 6], which increases the misalignment tolerance by enlarging the charging zone. One extra coil is placed in the center of the transmitter or receiver in [3, 8] to cancel the mutual inductance variation. However, these solutions require more material to construct the transmitter and receiver, which increases the material cost and AC resistance, and potentially induces thermal management problems for coils. In some volume-critical applications, e.g., bio-medical implants, enlarging the coil size is not feasible. To date, using Litz wire with a thinner strand is the main solution to reduce the coil AC resistance in high-frequency region. Due to the manufacturing difficulty, Litz wire with thinner strands is more expensive.

In this work, we propose a novel winding pattern to reduce the misalignment sensitivity, AC resistance, and thermal stress without increasing material cost, changing the Litz wire, or coil geometry.



	H_1[A/m]	H_2[A/m]	H_3[A/m]	P_{prox}[mW]	R_{prox}[mΩ]
Fig.(a)	277	169	119	10	4
Fig.(b)	119	125	129	5.3	3

(c)

Fig. 1. A three-turn Litz wire planar coil made with (a) conventional winding pattern, (b) proposed winding pattern, (c) magnetic field intensity and proximity-effect power loss comparison. (Simulation in ANSYS/Maxwell)

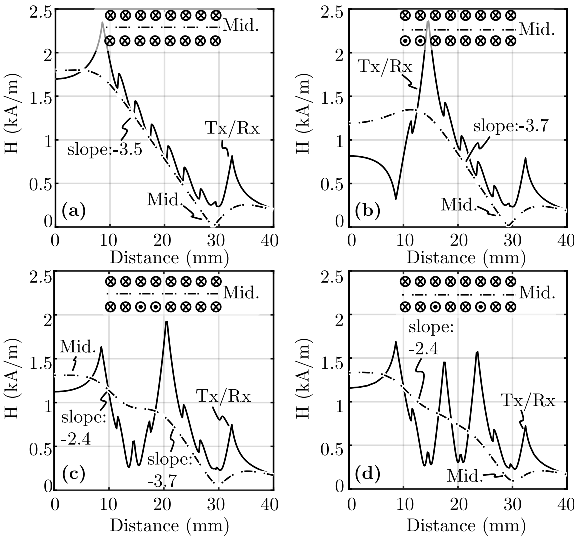
II. WINDING PATTERN OF PLANAR COILS

The comparison between the conventional winding pattern and the proposed winding pattern is presented in Fig. 1 with magnetic field intensity distribution. The conventional winding pattern connects each turn in series, and the current has the same direction between each turn. The magnetic flux is enhanced between each turn. The proposed winding pattern connects each turn in series, but the current direction is opposite between each turn. The magnetic flux is cancelled between each turn. The proximity-effect power loss is proportional to the magnetic field intensity surrounding the conductors [10].

$$P_{prox} = G_r H_e^2 \tag{1}$$

Where: H_e is the peak value of external magnetic field intensity, and G_r is an unitless factor given in [10].

Since the proposed winding pattern reduces the magnetic field intensity surrounding the conductor, the corresponding proximity-effect loss is lower than conventional winding pattern. In Fig. 1, the proximity-effect power loss for a three-turn Litz wire coil with conventional winding pattern is 10 mW. The proposed winding pattern reduces the proximity-effect power loss to 5.3 mW and the AC resistance is reduced by 1 mΩ. It corresponds to 47% proximity-effect loss reduction and 25% AC resistance reduction.



	(a)	(b)	(c)	(d)
High peak (kA/m)	1.8	1.34	1.31	1.33
Slope 1 (kA/m^2)	-3.5	-3.7	-2.4	-2.4
Slope 2 (kA/m^2)	-3.5	-3.7	-3.7	-2.6
Low peak (A/m)	0	0	63	100

(e)

Fig. 2. The magnetic field intensity of a 8 turn coil with (a) conventional winding pattern, (b) winding pattern 1, (c) winding pattern 2, (d) winding pattern 3, (e) comparison between different winding patterns.

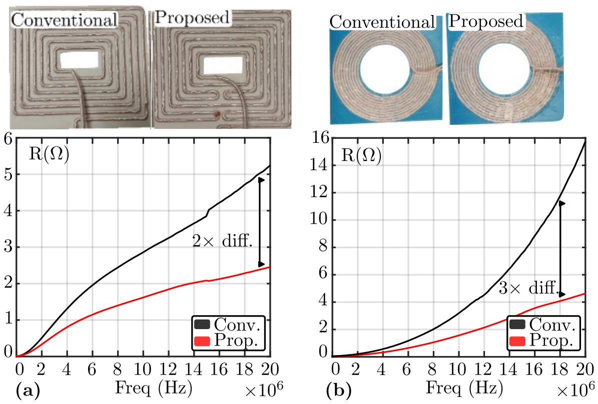
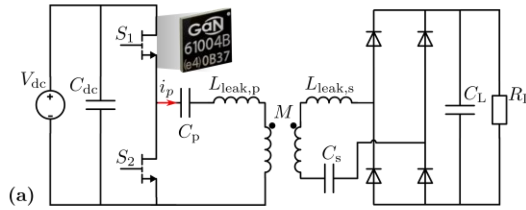
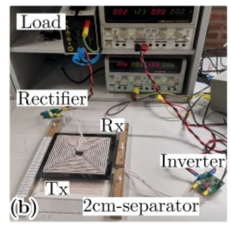


Fig. 3. AC resistance comparison between conventional winding pattern and proposed winding pattern for (a) 7-turn rectangular coil, (b) 10-turn circular coils.

The magnetic field intensity of an eight-turn coil with different winding patterns is compared in Fig. 2. In Fig. 2(a), the conventional winding pattern has the steepest magnetic field distribution. In Fig. 2(b), two opposite winding directions are added in the first and second turn, which creates a magnetic field intensity peak between the second and third turn. After the third turn, the magnetic field decreases rapidly. In Fig. 2(c), two opposite winding directions are added in the third and fourth turn, which create a magnetic field peak between the fourth and fifth turn. Since the opposite winding direction is in the middle of the coil, the magnitude of the magnetic field intensity is suppressed by the other turns. In Fig. 2(d), two opposite winding directions are added in the third and sixth turn, which create a quasi-uniform magnetic field distribution compared with other winding patterns. Since the turn-to-turn magnetic field intensity variation is reduced, the variation of the overlapped area between the transmitter and receiver is reduced. Therefore, the misalignment tolerance is improved.





(c)

Var.	Con.-Con.	Nov.-Con.
$L_{\mathrm{leak,p}}$ (μH)	8..03	3.19
C_{p} (nF)	14	41
$L_{\mathrm{leak,s}}$ (μH)	7.94	10.4
C_{s} (nF)	14	10
M(μH)	6.87	4.39
Tx. ESR (Ω)	0.27	0.16
Rx. ESR (Ω)	0.28	0.25
Freq (kHz)	500	500

Fig. 4. (a) Circuit topology of the 30W case study, (b) experiment setup, (c) resonant tank parameters.

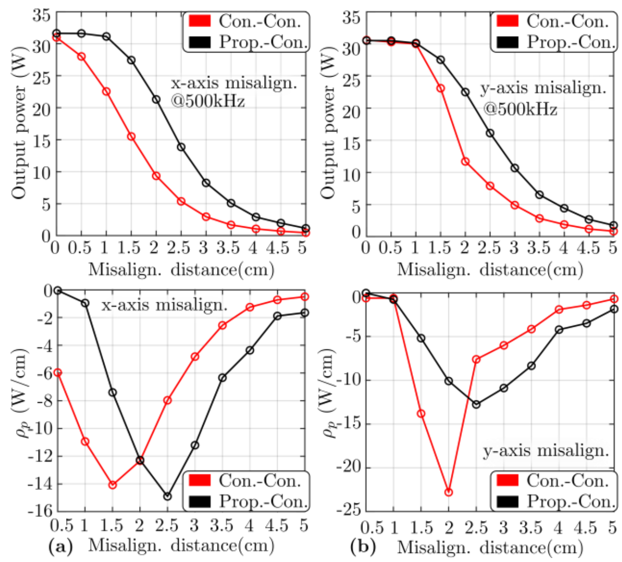


Fig. 5. The system output power and corresponding gradient with (a) x-axis misalignment and (b) y-axis misalignment.

III. Experimental Verification and Conclusion

The AC resistance of four Litz wire planar spiral coils are compared in Fig. 3, where the measurements are conducted by impedance analyser E4990A from 20Hz to 20MHz. For the seven-turn coil, the AC resistance is maximally reduced by 130% with the proposed winding pattern. For the 10-turn coil, the AC resistance is maximally reduced by 263% at 20MHz.

In order to validate the misalignment tolerance of the proposed winding pattern, a 30W demonstrator is designed and presented in Fig. 4. The misalignment test is conducted on x-axis and y-axis. The output power at different position is recorded with power analyser [11]. The output power gradient is calculated by:

$$\rho_p = \left.\frac{\partial P_{out}}{\partial x}\right|_{x=x_i,y_i} \quad (2)$$

where: P_{out}, ρ_p, x are output power and its gradient, and misalignment distance respectively. With the proposed winding pattern, the output power variation is maximally reduced by 30% on x-axis misalignment, and 46% on y-axis misalignment.

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