Methodology of Inductive Power Transfer Asymmetrical Coils Design for Space-Constrained Applications

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***Abstract*—For the coils design of the inductive power transfer (IPT) system, the coils for the received-side and the transmitter-side are usually designed symmetrical in order to obtain better coupling coefficient and for simplicity. Along with a growing number of space-constrained devices, such as drones and small automated guided vehicles (AGV), much more flexible designs of receiver coil, such as asymmetrical coil designs are of great interest. Nevertheless, since power transfer efficiency of the IPT system is highly correlated with the parameters of coils, it is challenging to convert symmetrical coils into asymmetrical coils while maintaining the power transfer efficiency and the load independent output. This paper proposes a design methodology of converting symmetrical coils into asymmetrical coils for series-series inductive power transfer (SSIPT) that keeps similar transfer efficiency and maintain the load independent current (LIC) output. The analysis of coils' parameters including the size and transfer distance is also taken into consideration, and the asymmetrical coil design flowchart is also introduced in this paper. Finally, a 30W experimental platform of the SSIPT system is built, and the experimental results verify the theoretical analysis and the practical feasibility of the proposed asymmetrical coil design.**

Keywords—Inductive power transfer (IPT), space-constrained applications, asymmetrical coils, transfer efficiency, load independent current output.

I. Introduction

Wireless power transfer (WPT) technique is widely used as a novel charging method for some recent products, such as electronic devices , electrical vehicles (EV) and drones, with the benefit of safety and convenience [1]-[4]. Inductive power transfer (IPT) is one of the important techniques of WPT and is common in the market since it provides high efficiency for near-field WPT applications that meet the requirements of the products. For IPT, the energy transmission is achieved by a magnetic field between two coils and the magnetic field is the medium that transfers the energy from one side to another side, generally composing of a transmitter coil and a receiver coil. Therefore, the design of the coils plays a significant impact on the charging process. A proper coil design can enhance the power transfer efficiency obviously. Besides, many electrical or electronics devices nowadays have a problem of the constrained space, such as, drones and small automated guided vehicles (AGV). However, if we are designing a symmetrical coil, the size of the transmitter coil will be limited by the receiver-side, thus resulting in degrading the transfer efficiency and the maximum transfer power. To further increase coil's power transferability, the size of transmitter coil should be designed to be larger than the receiver coil under the space-constrained situation, this comes up the asymmetric coil design.

It is well known that the coils design for IPT converter system is related with some key parameters, such as coupling coefficient, quality factor and mutual inductance, which obviously affect the characteristic of coils. The work in [5] demonstrated a systematic method to optimize coil design with minimize the value of quality factor. An optimum method in [6] with redesigning the structure of coils was proposed to improve the coupling coefficient, which is an important parameter of power transfer efficiency. However, most of the design equations in [5] and [6] assumed that the two coil are identical and coaxial (that is symmetrical). Thus, the design methodology in [5] and [6] is not applicable for asymmetrical coils design, especially for the complicated calculation method for mutual inductance. Also, the mutual inductance is sensitive to the coil distance, inner radius, outer radius, wire diameter and turns number of the coil. Due to the characteristics of series-series IPT (SSIPT) converter, the output current and power transfer efficiency closely depend on the mutual inductance as discussed in [7], which is complicated to design. Some studies utilized optimal coil's

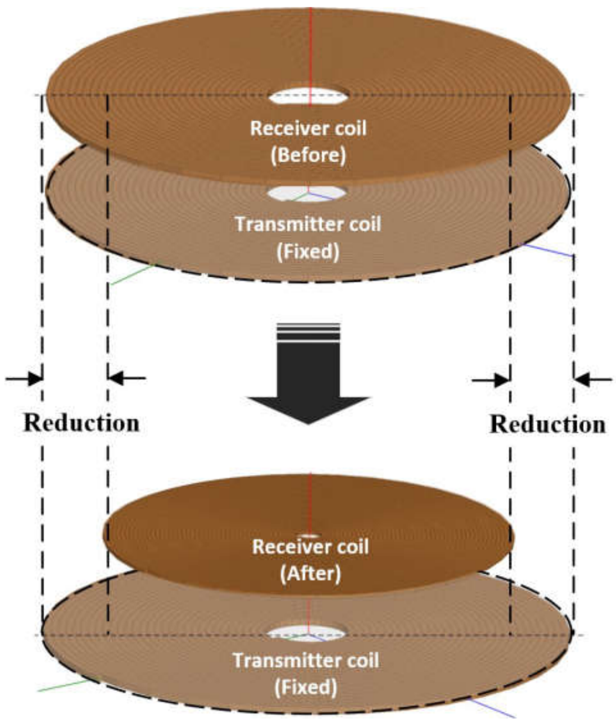

Fig. 1 Coil conversion from symmetrical to asymmetrical.

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turn number to optimize the power transfer efficiency [8]. All the transmitter-side turn number N_1 and receiver-side turn number N_2 were simulated by 3D finite-element-method (FEM) analysis to obtain the optimal N_1 and N_2, without any comprehensive mathematics analysis. But this simulation is very time-consuming.

Besides optimum design of coil's turn number, the coil structure is also important in the IPT system. Nowadays, many different types of coil structures have already been developed, such as circular pad, DD coupler, DDQ coupler, square coils, etc. [9]. To determine the effectivess of the coil structure, the coupling coefficient is an important parameter that can affect the system transfer efficiency [10]. The work in [11] shows that the coupling coefficients of the circular pad and DD coupler obtaining a higher value while the cost is lower compared with the rectangular coil and DDQ. In this paper, we focus on the circular pad because of its easy fabrication and less complicated structure. Based on the circular coils, this paper proposes a coil design methodology for the SSIPT converter, which applies an equivalent circular loop method to mathematically evaluate the mutual inductance of asymmetrical coils, in which the deduced equations are verified by both Maxwell simulation and experiment. Compared to the FEM simulation, this design method is faster and esaier to obtain an accurate mutual inductance value of asymmetrical coils. After obtaining the mutual inductance of an asymmetrical coil, a IPT transformer with symmetrical coil is designed to provide desired output power for conversion. This conversion is important such that it needs to convert the receiver side of symmetrical coil into a smaller size for space constrained application with the similar transfer efficiency and the constant output as shown in Fig. 1.

This paper mainly describes the conversion between symmetrical coil and asymmetrical coil, in order to fit for the design of an asymmetrical coil for small AGV. The rest of this paper is arranged as follows. Section II describes the SSIPT converter structure for the charging purpose and realizing load-independent current (LIC) output. In Section III, a step by step procedure to convert symmetrical coil to asymmetric coil for small AGV application is presented. In Section IV, the asymmetrical coils for a 1.35-A LIC SSIPT converter experimental system is built for experimental verification. Finally, Section V concludes this paper.

II. Series-Series Inductive Power Transfer (SSIPT) Converter

A. Structure of SSIPT Converter

The circuit diagram of the SSIPT converter [7] is shown in Fig. 2. V_I represents input DC source and V_O represents output voltage. V_p, I_p and V_s, I_s are the ac voltage and ac current in transmitter-side and receiver-side. Both input side and output side are paralleled with capacitors to filter out high frequency noise. For the SSIPT converter, it includes three main parts. Firstly, the inverter converts the DC source voltage into AC input voltage, which aims to generate alternating magnetic field through the coils to transfer the power from the transmitter-side to the receiver-side. There are two series connected capacitors in both coil sides for compensating their self-inductances and to improve the transfer efficiency. Finally, the receiver-side rectifier circuit convert the AC voltage into the DC output voltage in order to charge the battery. I_O and V_O are the charging current and output voltage for the battery.

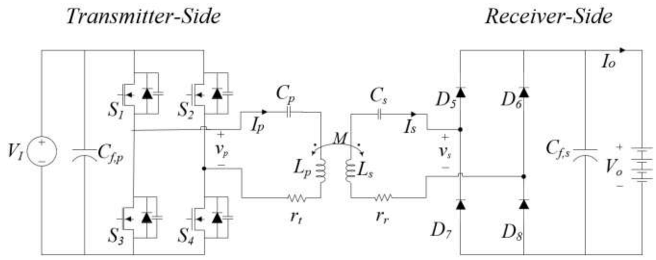


Fig. 2 Circuit configuration of a SSIPT compensated converter.

According to the charging profile for lithium-ion batteries, the constant current (CC) mode is the dominant for the whole charging profile, while SSIPT converter topology is widely applied for the CC charging mode.

For the SSIPT converter circuit as shown in Fig. 2, the capacitors C_P and C_S on the transmitter and receiver side respectively are the compensation capacitors. Their values can be calculated by equation (1).

$$\omega = \frac{1}{\sqrt{L_P C_P}} = \frac{1}{\sqrt{L_S C_S}} \tag{1}$$

Where $\omega = 2\pi f_{sw}$, f_{sw} is the operating frequency, L_P and L_S are the self-inductance sof the transmitter and receiver coils, respectively. Once the SSIPT converter operates at resonant frequency as (1), the load independent current output can be achieves, that is given by,

$$I_o = \frac{V_I}{\omega M} \tag{2}$$

III. Asymmetrical Coil Design of Space-Constrained Application

A. Design Parameters of Asymmetrical Coils

For the coil conversion of the SSIPT converter, the issue of the transfer efficiency under the constant output is of foremost concern. In the previous study [5], the corresponding transfer efficiency of the SSIPT converter can be expressed as,

$$\eta = \frac{\omega^2 M^2 R_L}{[(R_L + R_r)^2 + X_r^2]R_t + \omega^2 M^2 (R_L + R_r)} \tag{3}$$

Where M, R_L, R_r, X_r *and* r_t are the mutual inductance, load resistance, equivalent series resistance (ESR) and reactance of the receiver side coil, and ESR of the transmitter side coil, respectively. As the symmetrical coils are already designed to provide the desired output power, the transmitter-side coil size is fixed. And the load resistance is also varying during the charging process. Compared the symmetrical coils with the asymmetrical coils via (3), only two parameters are different, which are the mutual inductance and the ESR of the receiver -side coil. Therefore, if these two parameters or the effects of these two parameters cause similar impact to (3), the symmetrical and the asymmetrical coil design methods will obtain similar transfer efficiency. To achieve constant output power, the mutual inductance should be keep similar during the conversion. It is because under the condition that the coil distance and the input voltage remain unchanged, the similar mutual inductance ensures that the output current of the symmetrical coil and the asymmetrical coil are having the same value according to (2).

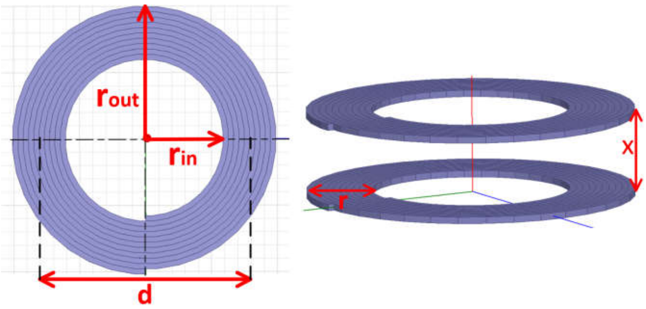


Fig. 3 Parameters in symmetrical coils design.

B. Mutual Inductance of Symmetrical and Asymmetrical Coils

Since the mutual inductance affects the output power and transfer efficiency directly, the design of mutual inductance is significant during the conversion. In [12], the mutual inductance of the symmetric circular pad coil on coaxial are derived as:

$$M=\frac{\mu_0}{4\pi}N^2 d\emptyset \tag{4}$$

$$\begin{aligned}\emptyset=\pi[&\left(1+\frac{3}{4}\xi^2+\frac{p^2}{24}-\frac{15}{64}\xi^4+\frac{7}{64}\xi^2p^2+\frac{11}{2880}p^4\ldots\right)\ln\frac{16}{\xi^2+p^2}\\&+\left(1+\frac{5}{8}\xi^2-\frac{161}{576}\xi^4+\frac{5}{8}\xi^2p^2\ldots\right)\frac{\xi^2}{p^2}\ln\frac{\xi^2+p^2}{\xi^2}-4(1\\&+\frac{2}{3}\xi^2-\frac{2}{5}\xi^2-\frac{2}{6}\xi^2p^2\ldots)\frac{\xi}{p}arctg\frac{p}{\xi}-1+\frac{37}{24}\xi^2+\frac{43}{144}p^2\\&-\frac{301}{360}\xi^4-\frac{\xi^2p^2}{720}+\frac{p^4}{75}+\cdots]\end{aligned} \tag{5}$$

Where μ_0 is the vacuum permeability, N is the turn number of coils. d is the average diameter. In (5), $p=r/d$ and $\xi=x/d$, where r represents the coil thickness, and x represents coils distance as shown in Fig. 3.

However, (4) is only suitable for calculating the mutual inductance of the symmetric coils. Regarding the calculation of the mutual inductance of asymmetrical coils. Generally, there are three calculation methods: Equivalent Circular Loop Method [12], Taylor Series [14] and Four Rectangle Theorem [12]. The Four Rectangle Theorem is only suitable for a small coil distance, which does not fit for our experiment with the coil distance larger than 40mm. In the contrast, the accuracy of the other two methods are improved with increasing coil distance. Although the Taylor Series is more accurate than the Equivalent Circular Loop Method, it consumes numerous calculation time. In this paper, the Equivalent Circular Loop Method is chosen because it can get a balance between the calculation time and accuracy.

The Equivalent Circular Loop Method divides one coil into two equivalent circular loops as shown in Fig. 4. The corresponding diameter d_a and location l can be calculated based on the below equations.

$$d_a=d\left(1+\frac{r^2}{6d^2}\right) \tag{6}$$

$$l=\sqrt{(a^2-r^2)/3} \tag{7}$$

Where d is the average diameter of coil, r is the coil thickness. a is the axial length of coil. d_a and l are used to define the diameter of the equivalent circular loops. The diameter of Loop 1 and Loop 2 are d_a+l and d_a-l,

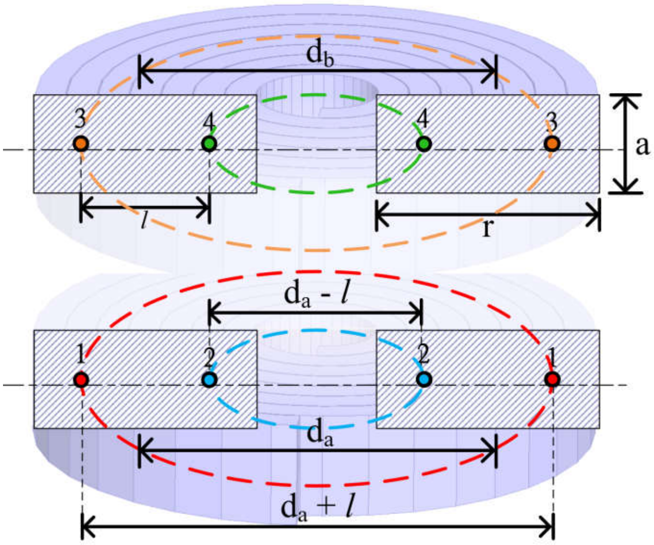


Fig. 4 Cross section of circular coil.

respectively. Based on this rule, the Loop 3 and Loop 4 of another coil can be deduced. Then, the mutual inductance of the asymmetrical coils can be expressed as:

$$M_{ab}=\frac{\mu_0}{4\pi}\sqrt{\frac{d_a}{2}\frac{d_b}{2}}F \tag{8}$$

$$M=\frac{N_1N_2}{4}(M_{13}+M_{14}+M_{23}+M_{24}) \tag{9}$$

In (8), M_{ab} represents the mutual inductance of two equivalent circular loops where the subscripts "*a*" and "*b*" indicate the sequence number of each equivalent circular loop. For example, M_{13} is the mutual inductance of Loop 1 and Loop 3. The variable F can be found in Table 5-5 of [12]. However, the mutual inductance of the transmitter coil and the receiver coil can be obtained by using (9). The N_1 and N_2 are the turn numbers of the transmitter coil and the receiver coil, respectively.

C. Design Flowchart and Coil Setting

The asymmetrical coil design flowchart is shown in Fig. 5. The symmetrical coils are designed based on the desired output power of the small AGV and charging distance (Step 1). In this experiment, with the 40mm coil distance and 30W output power, the inner and outer radius of circular pad coil r_{in} and r_{out} of the symmetrical coil are parametrically swept in finite-element simulation with single-lumped-turn winding method that can reduce the numerous simulation time [5]. However, based on (3) and (4), the transfer efficiency and mutual inductance of the symmetrical coils can be calculated accordingly as the reference value for comparison (Step 2).

After that, the asymmetrical coils design loop starts. Firstly, the diameter of the litz wire should be determined (Step 3). In the Step 3, since the transmitting coil is not altered throughout the conversion, it is difficult to reduce the receiver coil size while maintaining transfer efficiency by changing the r_{in} and r_{out} of receiver coil in certain wire diameter only. Therefore, before determining the wire diameter, it is necessary to realize the relationship among the self-inductance, the mutual inductance, ESR and the wire diameter in order to achieve the coil area reduction. In addition, the ESR of the coil can be obtained by

$$R_{coil} = 4p\frac{(r_{in}+r_{out})}{(r_{out}-r_{in})^2 k_p}N^3 \tag{10}$$

Where p is the resistivity of copper, r_{in} and r_{out} are the inner and outer radius of circular pad coil. N is the coil turn number. k_p is the packing factor of litz wire that is defined as the ratio of the entire copper cross-sectional area in the bundle to the area of the overall bundle [13], which depends on the wire diameter.

The wire diameter varies from 1mm to 4mm while the symmetrical coil size being kept the same are plotted in Fig. 6. It shows that the relationship among self-inductance, mutual inductance, ESR and wire diameter. The thicker wire obtains lower ESR, self-inductance and mutual inductance. It is because under the same symmetrical coil size, the greater the wire diameter, the fewer the number of turns that can be

TABLE I
DESIGN PARAMETER OF SYMMETRICAL AND ASYMMETRICAL COIL WITH 40MM COIL DISTANCE

Parameters	Coils	r_{inner} (mm)	r_{outer} (mm)	Turn Number N	Wire Diameter (mm)
Symetrical	Receiver and Transmitter	16	100	30	2.8
Asymmetrical	Receiver	5	75.4	44	1.6
	Transmitter	16	100	30	2.8

TABLE II
SELF-INDUCTANCE AND COMPENSATION CAPACITORS FOR BOTH SYMMETRICAL AND ASYMMETRICAL COILS

Parameters	*Symmetrical Coils*	*Asymmetrical Coils*
C_p	81.2nF	82.1nF
C_s	82.44nF	60.6nF
L_p	87.2μH	85.4μH
L_s	87.2μH	116.6μH

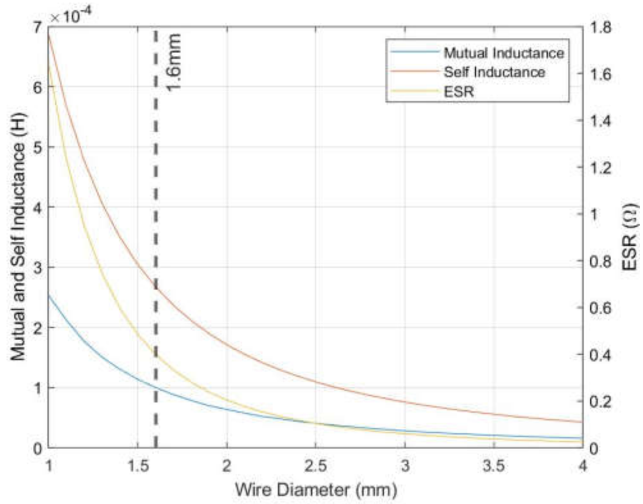


Fig. 6 The relationship among self-inductance, mutual inductance, ESR and wire diameter.

winded. From (4), the number of turns N decreases, the mutual inductance value will decrease. In general, the smaller ESR is beneficial for the transfer efficiency, but the decreasing of the mutual inductance will significantly reduce the transfer efficiency. Thus, there is a trade-off between lowering the ESR of the receiver coil and increasing the mutual inductance by varying the wire diameter. Moreover, it can be observed that once the thickness of the wire diameter is less than 1.6mm, the ESR will increase exponentially, this causes the effect of the ESR cannot be simply neglected in (3). Consequently, we chose 1.6mm as the wire diameter of the receiver side coil in this paper as it provides relatively high mutual inductance and low ESR.

After the wire diameter is chosen, the coil design program starts, which can automatically tune the inner radius r_{in}, the outer radius of circular pad r_{out} and the turn number N to generate all possible receiver coil design solutions (Step 4). To avoid the receiver coil's diameter over the requirement of the space constrained AGV (160mm*160mm), we set an upper boundary (160mm) of the outer diameter in the experiment. Also, the transfer efficiency and the mutual inductance of each design solution can be estimated by using (3) and (9), respectively. Finally, the comparison of the transfer efficiency and the mutual inductance between the symmetrical and asymmetrical coils will be carried out (Step

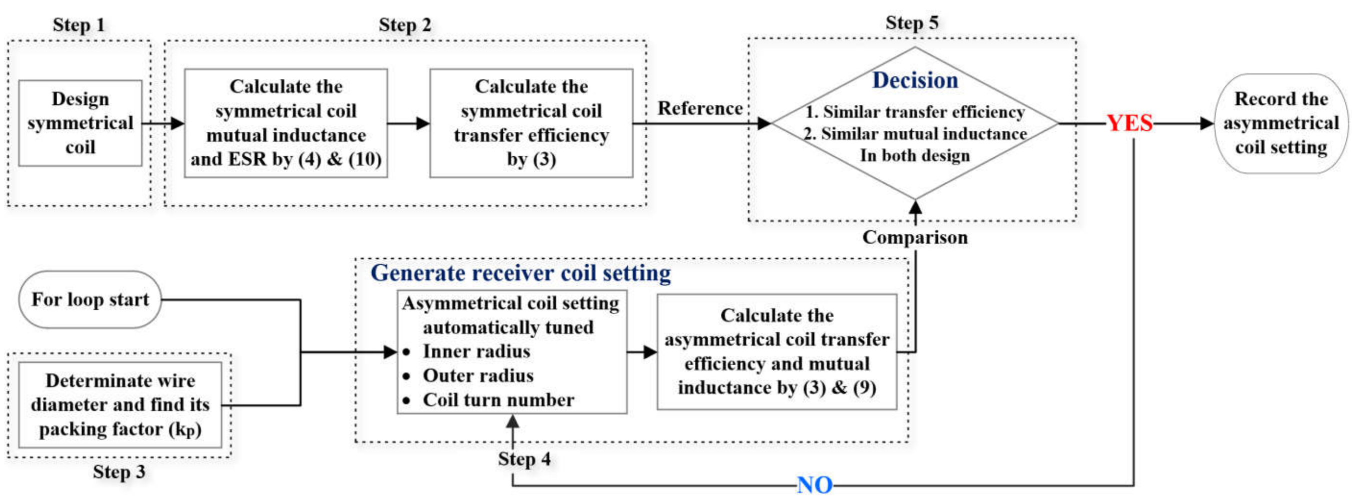


Fig. 5 Asymmetrical coil design flowchart.

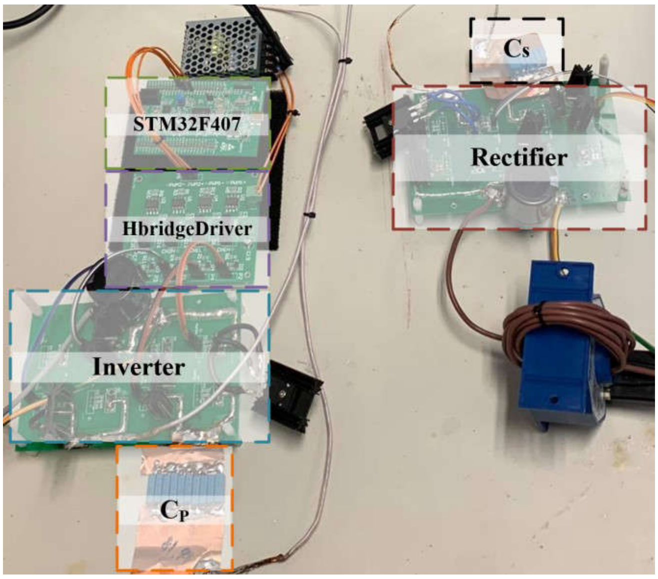


Fig. 7 Experimental platform of SSIPT converter circuit.

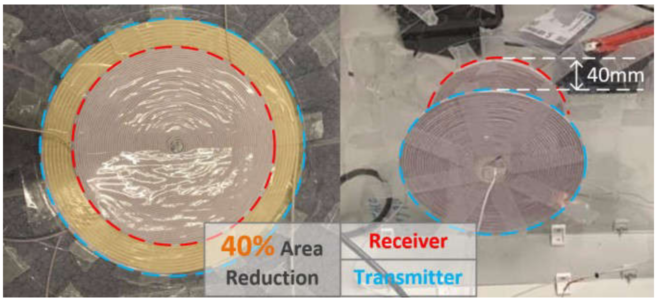


Fig. 8 Practical size of asymmetrical coil.

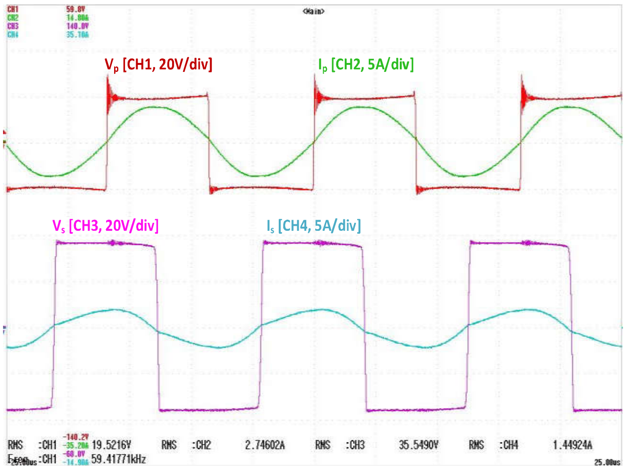
5). Finally, the smallest receiver coil size with the highest efficiency among all design solutions will be adopted. The designed receiver coil's parameters is shown in Table I.

IV. EXPERIMENTAL VERIFICATION

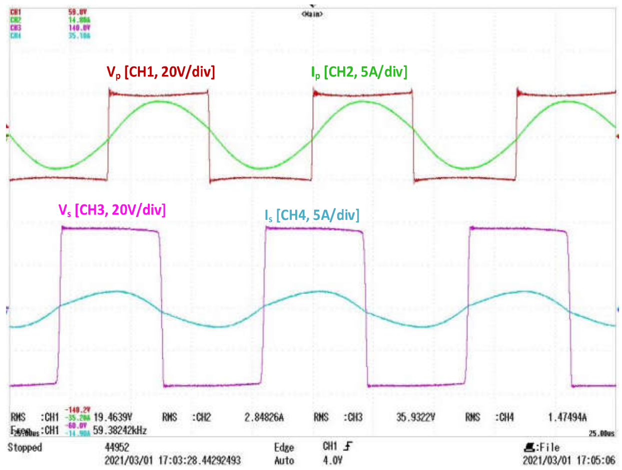
To verify the above analysis, a 30-W SSIPT converter experimental platform has been established as shown in Fig. 7. For the inverter, four MOSFET switches (S_1 to S_4) are driven by the H-bridge driver with operating frequency at 60 kHz. Those PWM signals are generated by the digital controller STM32F407VG. The self-inductance and compensation capacitors for both symmetrical and asymmetrical coils cases are given in Table II. At the receiver side, the rectifier is composed of four diodes for direct output voltage regulation. Fig. 8 shows the experimental coils with 40mm charging distance. In the experiment, the Yokogawa DL850EV Power Scope is used to record the experimental waveforms.

Fig. 9 shows the experimental waveforms of the transmitter-side ac voltage V_p and ac current I_p, and the receiver-sider ac voltage V_s and ac current I_s for both symmetrical and asymmetrical coil design of a SSIPT converter. And the I_p and I_s are nearly in phase with V_p and V_s, respectively, which demonstrate that the self-inductance of the coils are successfully resonant or compensated by the compensation capacitors.

To verify the LIC characteristic, the load resistance gradually increases from 15 Ω to 40 Ω in step of 1 Ω, Fig. 10 shows that the output current of both designs can maintain



(a)



(b)

Fig. 9 Waveforms of SSIPT converter for V_p, I_p, V_s, I_s in CC mode with loading resistance $R_L = 25\Omega$ with: (a) symmetrical coils, (b) asymmetrical coils.

around 1.35-A, which verifies the converter can significantly achieve LIC output. Fig. 11 shows that the efficiency of the symmetrical coil is slightly higher than the asymmetrical one, and their difference is less than 1% only. Compared with the conventional symmetrical coil design, the proposed asymmetrical design method can reduce up to 40% area, which is suitable for the space-constrained applications as shown in Fig. 8.

V. CONCLUSION

This paper proposed a coil design methodology for IPT converter for space-constrained applications. The design of the asymmetrical coils can keep the similar transfer efficiency and maintain the output characteristics simultaneously as the conventional symmetrical coils design. To verify the flexibility of the methodology, the SSIPT converter has been applied, the experimental results show that he LIC output can be maintained and the difference of the transfer efficiency between the symmetrical coils design and the asymmetrical coils design is less than 1%. Moreover, compared to the symmetrical coil, the proposed asymmetrical design methodology can save up to 40% of the coil area. This design is useful for space-constrained electric devices.

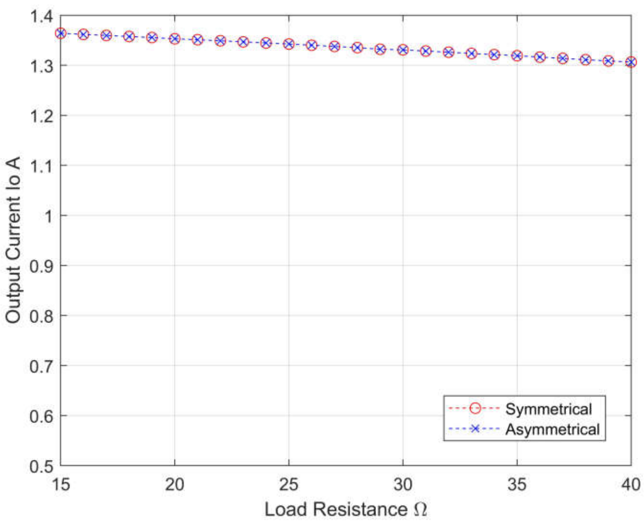


Fig. 10 Comparison of constant current charging between symmetrical coil and asymmetric coil for various load resistance R_L.

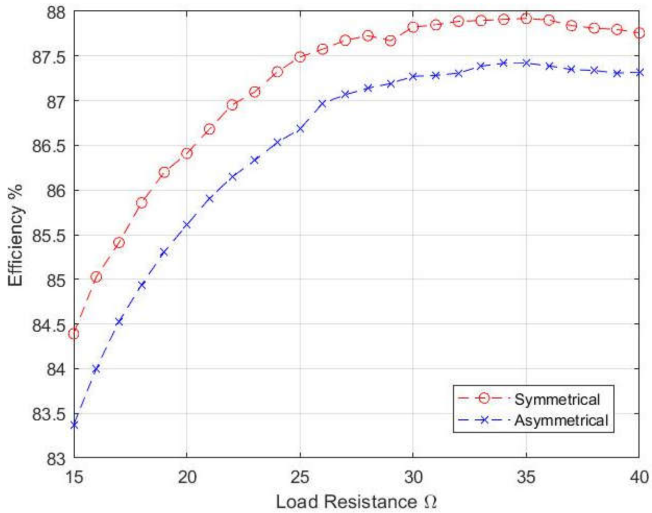


Fig. 11 Comparison of charging efficiency of SSIPT converter between symmetrical coil and asymmetrical coil for various load resistance R_L.

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