

Investigation of a GaN-based Bidirectional Wireless Power Converter using resonant inductive coupling

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Abstract— Two-way wireless power transfer (WPT) shows advantages to share energy via air without employing cable connection. This paper presents a study on a proposed GaN-based bidirectional wireless power converter for a battery to battery system using resonant inductive coupling technique. This power converter is built and tested that enables to wirelessly transfer power up to 45W at the frequency of 0.5Mhz. By varying the aligned distance, lateral and angular misalignment of coils, the influence of the relative positions to the self and mutual inductance of two coils as well as operation and efficiency of power converter has been thoroughly investigated and discussed.

Keywords—wireless power transfer, bidirectional power converter, energy sharing system, coils misalignment, power efficiency

I. INTRODUCTION

Wireless power transfer (WPT) technology has been developing rapidly in the past decade for many applications such as consumer appliances, biomedical implantable devices and electric vehicles (EVs) [1-3]. Due to convenience of no connection charging cable required and safety of no electrical contact, an increasing number of consumer electronics manufacturers show interest to the wireless charging technology and integrate it to their products [4, 5]. Huawei has freshly launched latest two-way wireless charging mobile phone that is able to reversely charging other Qi standard compatible handsets [6]. Although this applied technique has been reported to allow a small power transfer (2.5W) with low efficiency [7] and only works effectively in a very short distance like most existing commercial wireless chargers, this attempt still demonstrate the sign of growing demand from mass market on bidirectional wireless charging application for energy sharing. Therefore, the advanced bidirectional WPT technique must be developed in terms of an extended operational distance, higher power level and increased efficiency. In addition, thanks to the development of power semiconductor technology, gallium nitride (GaN) device is emerging as one of the next generation power devices to replace conventional Si-based counterparts in compact, high power density power conversion system due to its superb characteristics of high power handling capability with lower losses [8]. This offers opportunity to for wireless power consortium (WPC) to extend the existing Qi standard from low wireless power (5-15W) to medium power standard (up to

65W) for various consumer electronics (portable power tools, e-bikes, laptops e.g.) which enables to achieve more-compact and higher-efficiency power conversion [9].

In the wireless power transmission using resonant inductive coupling technique, the resonators are designed to compensate the loosely coupled coils with low coupling coefficient. Thus, the maximal power transfer from the transmitter to the receiver can be increased. The self-inductance and mutual inductance are related to the coupling coefficient, which is of significance to the maximum delivery power and achievable efficiency [10, 11]. In practical applications, the distance variation, lateral and angular misalignment of coils is often taken place that drastically affects both the self-inductance and mutual inductance. Although some research concerns focus on coil misalignment model for loosely coupled WPT to obtain the analytical models [12, 13], the accurate expression of mutual inductance using multi-layer coils and ferrite shielding layer is still difficult and not straightforward for application practitioners, since the complexity of analytical derivation on the produced magnetic field at different misalignment scenarios. Today, by means of using powerful 3D electromagnetic (EM) field solution software (Ansys e.g.), the parameters variation to relative space positions of coils can be accurately investigated that effectively provides useful information for system design.

This paper presents a bidirectional wireless charger using GaN devices that is able to deliver 45W power wirelessly in a battery to battery system such as laptop to laptop application. The relationship of various relative positions to self and mutual inductance variation of coils have been studied in 3D EM software and verified by equipment measurement. In addition, the operation of power converter has been validated by both simulation and experiments, and the influence to power transfer at varying coils distance with lateral and angular misalignment has been studied.

II. BIDIRECTIONAL WPT SYSTEM

Fig.1 shows the diagram of the proposed bidirectional WPT system that is able to operate in forward and backward power conversion mode. Full active bridges are employed at both sides that can be either operated as power transmitter using

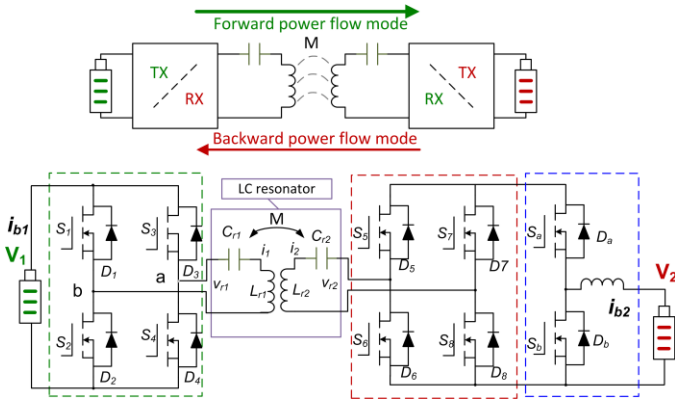


Fig.1 Diagram of the proposed bidirectional WPT system

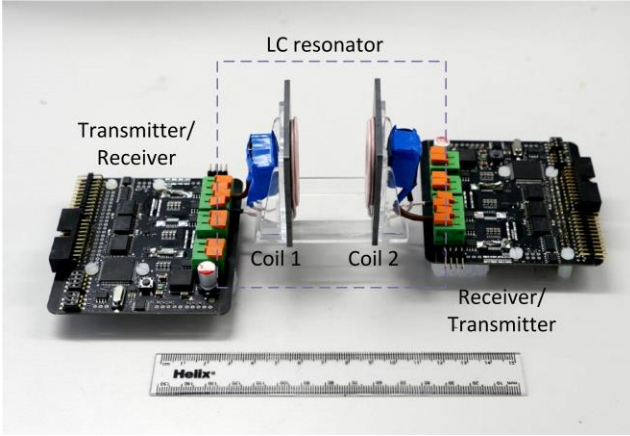


Fig.2 Photo of the prototype

switch bridges or it can work as power receiver using diode bridges. A cascaded bidirectional step up/down converter is used at one side for the applications to match lower voltage-level batteries. If the upper switch S_a is configured to be constantly on and lower switch S_b is in constant-off state, this converter operates as the dual active bridge converter with LC series-series (SS) compensation.

The photo of the prototype is presented in Fig.2 and the specification is given in Table 1. This prototype is designed to deliver the power up to 45W in battery to battery system at the switching frequency of 500 kHz.

Table 1 Specification of the prototype

Parameters	Values	Parameters	Values
Lr1, Lr2 (μH)	10	Cr1, Cr2 (nF)	10
Rcoils ($\text{m}\Omega$)	173	Rc ($\text{m}\Omega$)	40
Frequency(kHz)	500	Coupling coefficient k	0.05-1
V ₁ (V)	15-20	V ₂ (V)	7-15
R _{on} ($\text{m}\Omega$)	2.5	V _{diode} (V)	2
Output Power	0-45W	Efficiency	>60%
Distance variation	0-28mm	Lateral Misalignment	0-25mm
Angular Misalignment	0-60°		

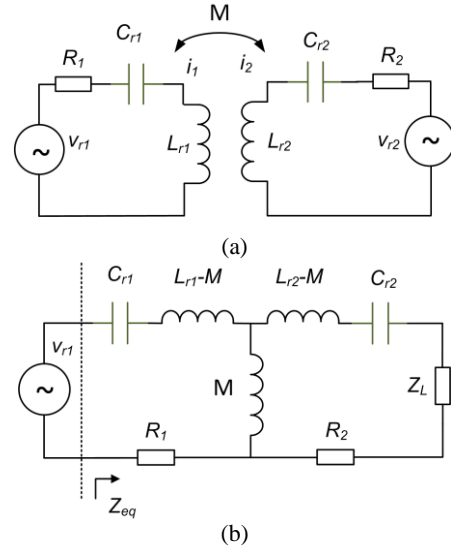


Fig.3 (a) circuit of two coils in inductive coupling
(b) T-type equivalent circuit

The circuit of two coils in inductive coupling and its T-type equivalent circuit are illustrated in Fig.3. The following equations can be obtained from Fig.3(a):

$$\begin{cases} V_{r1} = \left(R_1 + j\omega L_{r1} + \frac{1}{j\omega C_{r1}} \right) I_1 + j\omega M I_2 \\ V_{r2} = \left(R_2 + j\omega L_{r2} + \frac{1}{j\omega C_{r2}} \right) I_2 + j\omega M I_1 \end{cases} \quad (1)$$

where M is the mutual inductance, I_1 and I_2 are the transmitter and receiver side current, respectively. $R_1, R_2, L_{r1}, L_{r2}, C_{r1}, C_{r2}$ represent the resistance, inductance, and capacitance, respectively in the resonator at both sides.

From the transmitter side as shown in Fig.3(b), the input impedance can be represented as follows:

$$\begin{aligned} Z_{eq} &= R_1 + j(\omega L_{r1} - \frac{1}{\omega C_{r1}}) + \frac{(\omega M)^2}{j(\omega L_{r2} - \frac{1}{\omega C_{r2}}) + R_2 + Z_L} \\ &= V_{r1} / I_1 = \left| \frac{V_{r1}}{I_1} \right| \angle \varphi \end{aligned} \quad (2)$$

φ is the phase between input voltage and current. The real part and imaginary part of the equivalent input impedance Z_{eq} can be calculated as follows [14]:

$$\begin{cases} \text{Re}\{Z_{eq}\} = R_1 + \frac{(\omega M)^2 (Z_L + R_2)}{(Z_L + R_2)^2 + Z_{r2}^2} \\ \text{Im}\{Z_{eq}\} = Z_{r1} - \frac{(\omega M)^2 (Z_{r2})}{(Z_L + R_2)^2 + Z_{r2}^2} \end{cases} \quad (3)$$

where

$$\begin{cases} Z_{r1} = \omega L_{r1} - 1/\omega C_{r1} \\ Z_{r2} = \omega L_{r2} - 1/\omega C_{r2} \end{cases} \quad (4)$$

Assume that the converter is operated at the resonant frequency ω_0 , and the following equations are satisfied:

$$\omega_0 = \frac{1}{\sqrt{L_{r1}C_{r1}}} = \frac{1}{\sqrt{L_{r2}C_{r2}}} \quad (5)$$

Thus, $Z_{r1}=Z_{r2}=0$, and imaginary part of the Z_{eq} equals zero, in other words, there is no phase angle between the voltage and current of the resonator. By letting $R_1 = R_2 = 0$,

$$\begin{cases} U_{r1} = j\omega M I_2 \\ U_{r2} = j\omega M I_1 \end{cases} \quad (6)$$

Equation (6) indicates the converter is operated as the voltage controlled current source to the load. Using phase shift control method, the voltage at transmitter can be regulated to control the current at the receiver. When the phase shift angle is 180° , the equivalent amplitude of V_{r1} is regulated to V_1 . When the duty cycle of step up/down converter is D , the maximal charging current to the battery of the receiver is

$$I_{b2} = \frac{1}{D} \cdot \frac{1}{\sqrt{2}} \cdot |I_2| = \frac{1}{D} \cdot \frac{1}{\sqrt{2}} \cdot \frac{2\sqrt{2}}{\pi} \frac{V_1}{\omega M} = \frac{2V_1}{\pi\omega MD} \quad (7)$$

If the converter is operating at backward mode, the following equation of charging current can be obtained:

$$I_{b1} = \frac{2V_2}{\pi\omega M(1-D)} \quad (8)$$

It is noted that the charging currents are determined by the mutual inductance, duty cycle, switching frequency and the voltage of transmitter side. Equations (4)-(8) are valid when both of the transmitter and receiver are under resonance. From (3), it is evident that Z_{eq} relates to the self inductance and mutual inductance of the coils which are determined by their relative space positions. The next section is to investigate the influence of distance variation, lateral and angular misalignment to the self and mutual inductance in the proposed bidirectional WPT system.

III. INVESTIGATION OF COILS COUPLING

The coupling coefficient k of the coils are normally calculated by the following equation:

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (5)$$

However, the self-inductance (L_1, L_2) and mutual inductance of coils are relevant with many factors in terms of coils (materials, turns, wires, and radius etc), type and size of magnetic components, relative space positions of coils. Thus, to avoid deriving a complicated analytical expression of k in practical applications, 3D EM software is widely used to numerically compute the coupling factor.

In this study, two commercial coils for wireless charging system have been applied and their 3D model has been built using Ansys as shown in Fig.4 (a) and the relative positions of two coils have been investigated in aligned distance variation, lateral and angular misalignment as illustrated in Fig.4 (b).

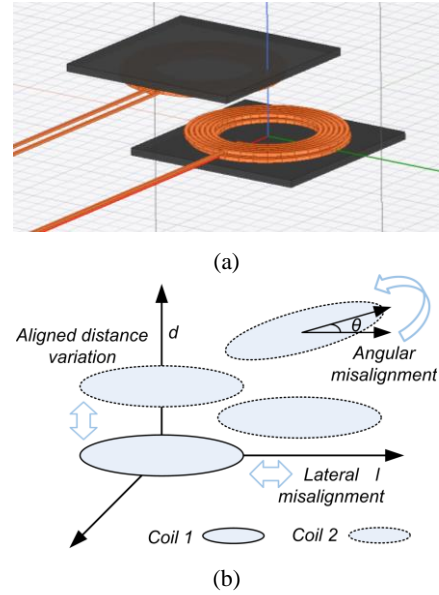


Fig.4 (a) Analysis of coils coupling coefficient using Ansys (b) relative positions of two coils (aligned distance variation, lateral and angular misalignment)

A. Variation of aligned coils' distance

To verify the effectiveness of the simulation results, we use RLC meter to measure the values for comparison and Fig.5 shows the comparison of measurement and simulation results. It can be seen that the measured self-inductance is changed over 35% from $16.2 \mu\text{H}$ (tightly coupled) to $10.6 \mu\text{H}$ (loosely coupled) with the increase of coils' distance, and the mutual inductance varies dramatically from $13.09 \mu\text{H}$ ($d=0$ mm) to $1.07 \mu\text{H}$ ($d=26\text{mm}$) Thus, the corresponding coupling coefficient is calculated from 0.81 to 0.1.

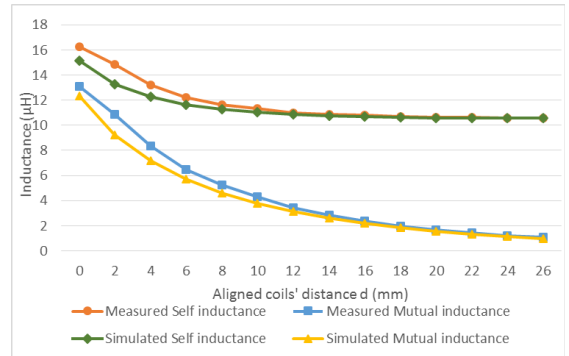
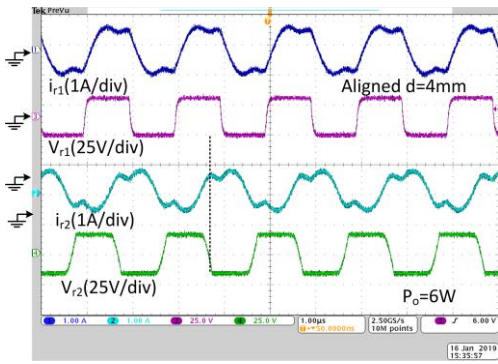
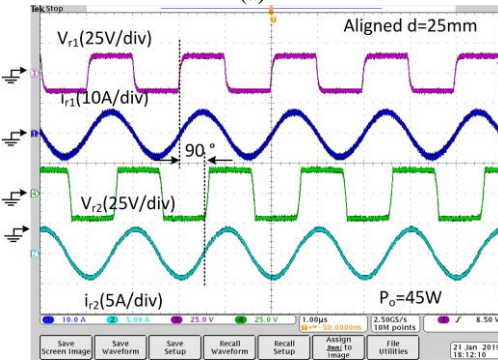


Fig.5 Comparison of self, mutual inductance coefficient in simulation and measurement by RLC meter when the coils are aligned with varying distance



(a)



(b)

Fig.6 Key operational waveforms at variation of aligned coils' distance (a) $d=4\text{mm}$ (b) $d=25\text{mm}$

Fig.6 presents the key operational waveforms of voltage and current of coils at both transmitter and receiver when the coil's distance d equals 4mm and 25mm respectively. When the coils' distance is near, the self inductance of the coils is larger than the value stated at the datasheet due to the tightly coupled condition, thus, the resonant frequency is shifted that results in the current waveform is not sinusoidal as shown in Fig.6 (a). With the increase of the distance, the self inductance is close to the rated value of $10\ \mu\text{H}$ that LC operates at the resonant frequency. Fig. 6 (b) demonstrates the phase relationship of voltage and current is almost consistent with the analysis under resonance according to (6).

B. Lateral misalignment

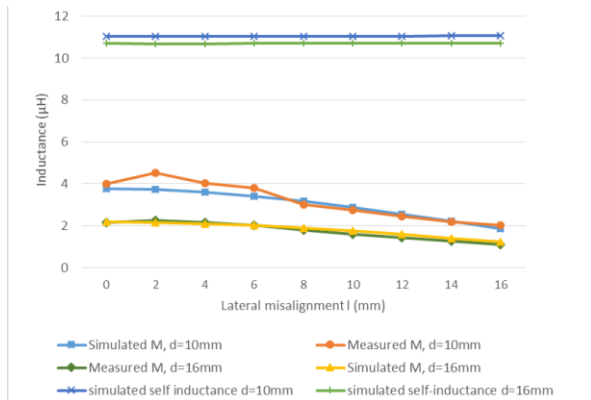


Fig.7 Self and mutual inductance at lateral misalignment (coils' distance $d=10\text{mm}$, 16mm respectively)

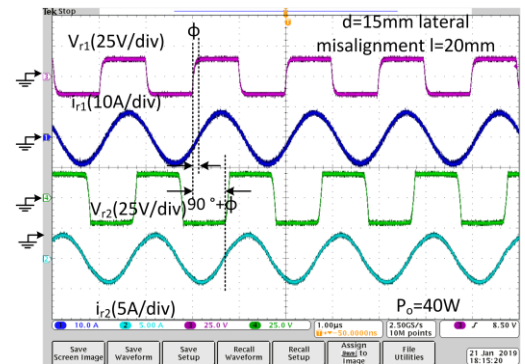


Fig.8 Key operational waveforms at lateral misalignment ($d=15\text{mm}$, $l=20\text{mm}$)

To investigate the influence of lateral misalignment to the mutual inductance, the coils' distance is set to 10mm and 16mm respectively and the lateral misalignment is varying from 0 to 16mm. It can be seen that the values of self-inductance are nearly constant at the variation of lateral misalignment, and the values are about $11\ \mu\text{H}$ when d equals 10mm. The mutual inductance approximately drops from $4\ \mu\text{H}$ to $2\ \mu\text{H}$ when d equals 10 mm, in contrast, the values are decreased from $2.2\ \mu\text{H}$ to $1.2\ \mu\text{H}$ when d equals 16mm. According to (3), the variation of L_{r1} , L_{r2} and M affects the practical circuit resonant frequency, making circuit mistuning at the switching frequency. Subsequently, the imaginary part of the Z_{eq} is not zero and there is a phase angle between input voltage and current that increase the reactive power and losses. Fig.8 shows an example of the influence of lateral misalignment to the waveforms and the power delivered to the receiver.

C. Angular misalignment

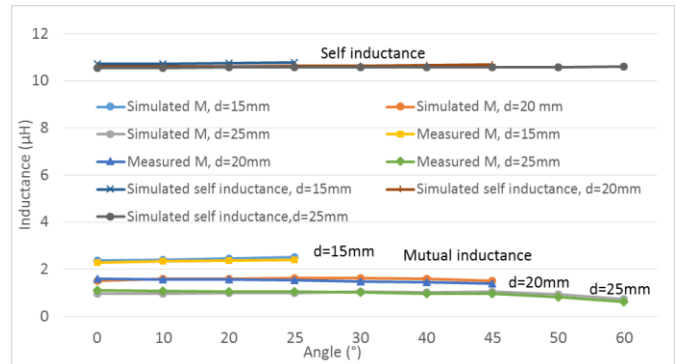


Fig.9 Self and mutual inductance at angular misalignment (coils' distance $d=15\text{mm}$, 20mm , 25mm respectively)

In order to study the effect of angular misalignment to self and mutual inductance of the coils, the distance of the aligned coils is set at 15mm, 20mm and 25mm respectively, and the tilt angles are changed according to the power and space limitation. Fig.9 illustrates the variation of self inductance and mutual inductance at different distance and tilt angles. It is shown that the self inductance changes very slightly at the given test conditions and the variation of mutual inductance is more relevant with the distance rather than the tilt angles.

IV. INVESTIGATE OF POWER TRANFER AND EFFICIENCY

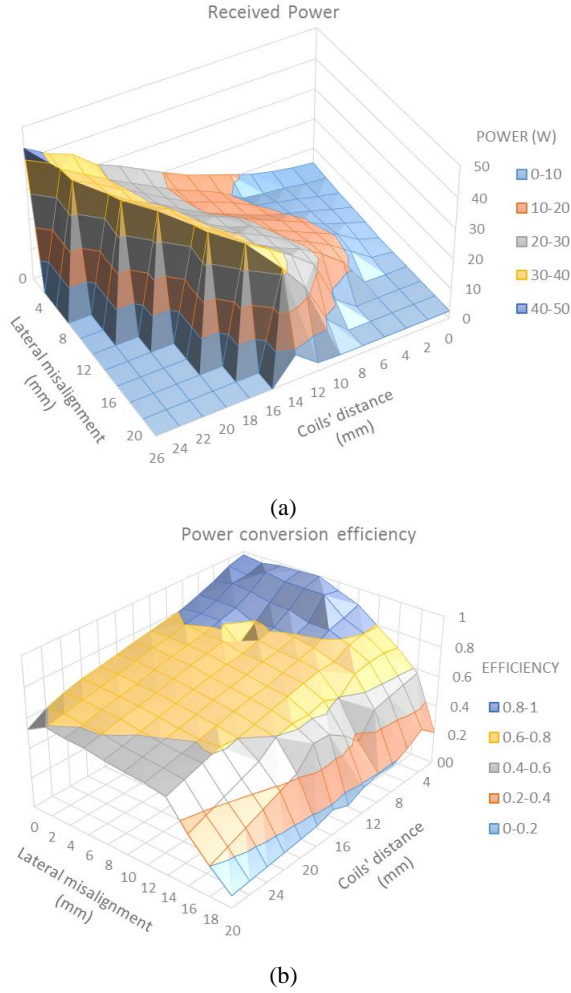


Fig.10 Influence of variation of coils' distance and lateral misalignment (a) Maximal received power (b) Measured power conversion efficiency

The maximal received power and the measured power conversion efficiency at different coils' distance and lateral misalignment are shown in Fig.10. It can be seen that the received power goes up to 45W with an increase of coils' distance; but the efficiency of the power converter falls accordingly. When the coils' distance is fixed, the increase of lateral misalignment makes a fairly rise of the received power due to the decrease of mutual inductance but it leads to a drop in efficiency. An obvious decrease of the efficiency can be observed when the lateral misalignment is increased over 16mm. In this scenario, a phase angle of voltage and current is increased due to the variation of self and mutual inductance as shown in Fig.8, which reduces the active power to the receiver.

Fig.11 presents comparison between the measured power converter efficiency and calculated efficiency using datasheet of components when the received power is varying. The conduction losses on the switches (E_{mos}), the diodes (E_{diode}) and the coils (E_{coil}) as well as the losses on capacitors (E_{cap}) are taken into account. The losses are calculated according to the specification of components as shown in Table 1.

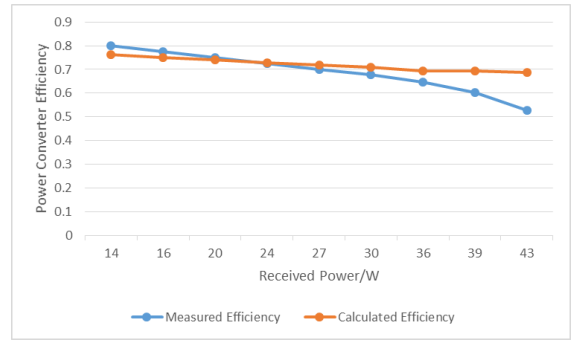


Fig.11 Comparison between the measured power conversion efficiency and calculated efficiency VS the received power

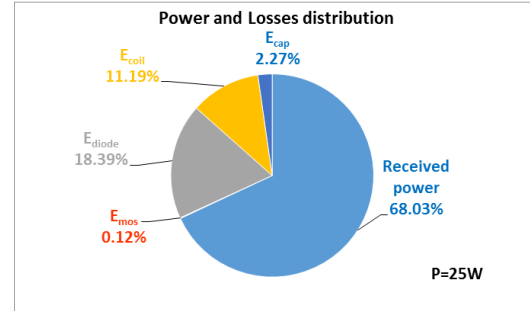


Fig.12 Power and losses distribution when the received power equals 25W at the aligned distance of coils is 20mm

When the aligned coils' distance is 20mm, the maximal received power equals 25W. A corresponding power and losses distribution is illustrated in Fig.12. It is shown that most of the losses are caused by the diodes and coils and GaN power switches only contribute slight portion of losses. This is because the body diodes of switches are employed that have large conduction voltage (about 2V). Moreover, the conduction resistance of the used GaN device is very small with only 2.5 m Ω and the switching losses of the power switches are ignored in the calculation due to soft switching transients under phase shift control. Thus, to improve the overall power conversion efficiency, low-voltage conduction Schottky diodes can be employed in parallel with switches or using synchronization control algorithm.

V. CONCLUSION

A bidirectional wireless charger using GaN devices for battery to battery application is studied in this paper. The influence of the position to the self and mutual inductance of the coils has been investigated using 3D EM simulation and equipment measurement. The results show that the variation of aligned distance has significant impact to the maximal power transfer and lateral misalignment has a remarkable effect to the power efficiency. In contrast, the variation of angular misalignment has a relatively smaller influence to the performance of power converter. In addition, the maximal power transfer and the power conversion efficiency has been analyzed. The overall efficiency of the prototype is between 60%-90% when the transferred power is about 5-45W.

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