Transformer with Adjustable Path-Core Type Inductance for Use in GaN-HEMT LLC Resonant Converter

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A novel magnetic structure for use in LLC resonant converters is proposed in this paper. It is known as a Path-core type Resonant Inductance Adjustable (PRIA) transformer, which is a type of transformer with adjustable resonant inductance. In the proposed transformer, the resonant inductance and magnetizing inductance can be designed separately; therefore, it becomes less challenging to realize the required resonant frequency. Moreover, the magnetizing inductance is not affected by any variation in the resonant inductance. The proposed PRIA transformer is found to improve the efficiency of the LLC converters. In this paper, the design of a resonant inductance of a PRIA transformer is presented. In addition, the application of PRIA transformers to a 1-MHz LLC resonant converter and 1 kW 1.4-MHz LLC resonant converter is presented.

Keywords: transformer, resonant converter, leakage inductance

1. Nomenclature

All the symbols which are used in this paper are listed below.

- $R_m$: the magnetic reluctance of the core
- $R_{cl}$: the magnetic reluctance of the main core’s center leg
- $R_{gm}$: the magnetic reluctance of the main core’s air gap
- $R_{path}$: the magnetic reluctance of the path-core
- $R_{lk}$: the leakage magnetic reluctance of the integrated transformer’s primary side
- $N_p$: the numbers of primary side coils
- $N_s$: the numbers of secondary side coils on the main core
- $N_{s2}$: the numbers of the secondary side coils on the path-core
- $L_{rp}$: the resonant inductance on the primary side
- $L_{rs}$: the resonant inductance on the secondary side
- $l_e$: the length of the effective magnetic path
- $l_{path}$: the length of the path-core
- $l_{gm}$: the length of the air gap on the main core’s center leg
- $l_{path}$: the length of the air gap between the main core and the path-core
- $l_{gpath}$: the length of the air gap between the main core’s side leg and the path-core
- $k$: coupling coefficient

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2. Introduction

Power supplies have become smaller and smaller since Si transistors appeared in the 1970s. The next generation, the High-electron-mobility Gallium Nitride (GaN HEMT) power transistors, allow high frequency operations from kHz-levels up to several MHz-levels. Normally, there are switching losses on power switching devices when they turn on or turn off. The switching losses will increase if the switching frequency increases in hard-switching models. After decades of improvement, however, LLC resonant converters have been proved to have the beneficial capability of soft switching operations. Moreover, high efficiency can be attained over the entire load range at high frequencies.(12) Also, some studies in (3), (4) have proved that LLC converters absolutely have the capability to handle high power output and wide output power range. LLC resonant converters have been adopted in many applications, such as ac-LED drive circuits(13), Advanced Technology Extended (ATX) power supplies(14) and onboard battery chargers for plug-in hybrid electric vehicles (PHEV)(15,16). It is not difficult to imagine that LLC resonant converters will eventually be applied in electric aircraft too.

Leakage inductance is playing an incredibly significant role in LLC resonant converters. For instance, many studies in the literature proposed topologies to utilize the transformer leakage inductance as a resonant inductance instead of using an external reactor coil in both single-phase(19) and three-phase topologies(15). Therefore, in many designs, the external resonant inductance, which is a reactor coil, becomes...
Path-Core Type Resonant Inductance Adjustable (PRIA) Transformer (Tengfei Ou et al.)

no longer necessary to allow for a further miniaturization of LLC resonant converters. However, the transformer leakage inductance, which acts as a resonant inductance in the circuit, may create excessive losses if it is not effectively used. Due to the above problem, there are studies that have proposed to design an optimized transformer adopted in LLC resonant converters. In (16), a custom transformer has been designed for LLC resonant converters by using a magnetic shunt to maximize the leakage inductance and be suitable in a 1-MHz LLC resonant converter. It has been successfully proved that a 280 V–380 V and 20 W–100 W half bridge LLC resonant converter was working with the new magnetic structure transformer which has a magnetic shunt. The magnetic shunt in the transformer was making a new magnetic flux path so that the leakage inductance of the transformer can be maximized. However, the leakage inductance, which is the resonant inductance, was not able to be adjusted easily with the magnetic structure in (16). Once the design is decided, it could be expensive and time consuming to redesign it again if a new value of resonant inductance is required. Inventing integrated transformers to be used in LLC resonant converters is an issue that many researchers have tried to give an answer in (17)–(20).

Those works inspired the idea to have an original magnetic structure which can adjust resonant inductance with the numbers of coils on a simple I-core as the path for the fluxes of resonant inductance, and without any effect on the value of the magnetizing inductance. The above idea has been proved successful in (21), and it has been proved that the PRIA structure can easily obtain higher values of resonant inductance in the integrated transformer with much fewer eddy current losses than traditional transformers, because the fluxes for creating resonant inductance are in the I-core. The value of the fluxes for creating resonant inductance can be controlled by adjusting the dimensions of the I-core.

The proposed PRIA structure can be used in a solar panel system which is shown in Fig. 1 to increase the efficiency of the isolated DC/DC converter, downsizing and reducing costs.

LLC resonant converters can handle high power output since there is an inductor $L_r$ resonant with a capacitor $C_r$ to achieve fewer switching losses. The topology of the prototype LLC resonant converter is shown in Fig. 2.

The magnetizing inductance $L_m$ is a component of transformer, $L_r$ is a component of coil in conventional LLC resonant converters. A lot of studies have achieved in integrating $L_r$ and $L_m$ as a transformer with using leakage inductance of transformer as $L_r$. The proposed magnetic structure is also one of them. The PRIA transformer can downsize the system, and the size difference is shown in Fig. 3.

There is much less space between the FET devices and transformers than in conventional LLC resonant converters and more costs could be saved compared with conventional LLC resonant converters using PRIA transformers.

The aforementioned reasons explain why integrated transformers are in the spotlight now, and integrated transformers have been adopted in many applications. However, the leakage fluxes between the primary side coils and secondary side coils were generated with conventional integrated transformers so that a lot of eddy current losses were generated. The proposed structure solve this problem and improve the efficiency of the transformer with LLC resonant converters.

2.1 Characteristics of Transformers for LLC Converters in Pervious Research

In the relevant literature, several design approaches were proposed for integrated transformers used in LLC resonant converters. The integrated transformers in (16), (19), (20) are shown in Table 1 to provide a comparison between the transformers. Each characteristic of the transformer is described as below.

(16): The leakage inductance can be adjusted with the magnetic shunt sheet. However, the magnetizing inductance will change when the leakage inductance is adjusted. Planer coils and a planer transformer were used, which also means that it could cost a lot of money and time to redesign when a new specification for the transformer is required.

(19): Two reactor coils for resonant inductance were combined with the transformer. The values for resonant inductance can be adjusted. Therefore, it can have a high-power output, but more core losses should be created than with an integrated transformer if they have the same power output. Moreover, the volume of the transformer should be the biggest one and the resonant frequency should be the lowest in (17)–(21).

(20): The leakage inductance can be adjusted with the
Table 1. Comparing characteristics of transformers that were used in LLC resonant converters (The number in [*] is the reference paper)

| Reference | Transformer Sharp | Magnetic Structure | Characteristics |
|-----------|-------------------|--------------------|-----------------|
| [16]      | Magnetic sheet    | Magnetic shunt (Planar core) | $L_r$ can be set with a magnetic shunt sheet |
| [19]      | 2 sets of EE core (Customize core) | $L_r$ is generated with air gap |
| [20]      | EE sharp transformer (Standard core) | $L_r$ cannot be designed |

| Reference | Transformer Sharp | Magnetic Structure | Characteristics |
|-----------|-------------------|--------------------|-----------------|
| [21]      | EE & I cores      | PRIA transformer (Standard core) | $L_r$ can be set |
|           | From A Side       | Easy calculation   | $L_r, L_m$, Independent |
|           | From B Side       |                    |                 |
|           | From C Side       |                    |                 |
|           | From D Side       |                    |                 |

where $L_r, C_r$ are the parameters of the resonant tank, $L_r$ is the resonant inductance and $C_r$ is the resonant capacitor. The values of $L_rC_r$ have to be decreased if a higher resonant frequency is desired. However, the values of $C_r$ are decided by the components which have standard values. In other words, it is not easy to exactly achieve the required capacitance value. In this case, $L_r$ is the only value that can be customized in the resonant tank.

In a normal transformer structure, the values of $L_r$ are affected by the self-inductance $L_p$. It can be expressed as follows:

$$L_r = L_p - L_m = L_p - kL_p = (1 - k) \cdot L_p \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd - 43 IEEJ Journal IA, Vol.11, No.1, 2022
where the $I$ is input current and $S$ is the cross-section respectively.

The impedance of the primary side’s coils and secondary side’s coils has the relationship,

$$Z_p = n^2 \cdot Z_s. \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (5)$$

where $n$ is the ratio of $N_p$ to $N_s$.

In this case, the input voltage is fixed, which means if the values of $N_p$ were decreased, since the input current will increase as a power multiple of 2, the values of $B$ will increase. It means there is a higher value of flux density $B$ in the transformer material.

Technically, when a smaller value of resonant inductance $L_r$ is designed to achieve a higher resonant frequency, more core losses should be produced normally.

### 3.2 Proposing Magnetic Structure

The PRIA magnetic structure transformer, which is proposed in this paper, can effectively improve the above situation. In terms of results, the values of resonant inductance are determined by the numbers of $N_p$ on the path-core and will not affect flux density $B$ which is designed in the main core.

A path-core (I core shape) was added between the primary side and the secondary side to allow the resonant transformer fluxes to flow in, from the main core. The PRIA transformer structure is shown in Fig. 4. The proposing structure combines with a EER28L-core and a I-core. Figure 4(a) is a 3D model created by FEMTET. And the Fig. 4(b) is the prototype made for experiments. In this case, the magnetic circuit of the PRIA transformer is shown in Fig. 5.

In order to design a resonant inductance with a PRIA transformer, the following equations have been used.

The magnetic reluctance of core $R_{gm}$, $R_{path}$, and air gap magnetic reluctance $R_{gpath}$ are,

$$R_{gm} = \frac{I_r}{\mu_0 \mu_i A_c}, \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (6)$$

$$R_{path} = \frac{I_{path}}{\mu_0 \mu_i A_{path}} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (7)$$

where the $A_c$ is the cross-sectional area of the main core and the $A_{path}$ is the cross-sectional area of the path-core.

$$R_{gpath} = \frac{I_{gpath}}{\mu_0 A_c} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (9)$$

### 3.3 Magnetizing Inductance

The primary side coils have two relationships with the secondary coils in the PRIA structure. These two relationships are shown in Fig. 6.

Therefore, when magnitude of $R_{gm}$ is ignored, then the magnetizing inductance can be approximately calculated as,

$$L_m = \frac{N_p^2}{R_m+R_{gm}+\frac{N_s^2}{2}+R_{gpath}+R_{path}} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (10)$$

The first term expresses the magnetizing inductance which is generated in the main core, and the second term expresses the magnetizing inductance which is generated between the center leg of main core and the path-core.

### 3.4 Resonant Inductance

The influence of the side legs with the PRIA structure to calculate the resonant inductance on the secondary side is ignored for the following reasons.

#### 3.4.1 Reason one

It is assumed that the inner windings (primary & secondary) are highly coupled, with no leakage, as the distance between the two windings is exceedingly small. The number of coils which wound the I-core influences $L_{r,\omega}$ due to the flux originating from these coils crossing in the I-core. The structure of the coils on the main core is shown in Fig. 7.

#### 3.4.2 Reason two

The large majority of fluxes which create resonant inductance are crossing into the I-core and the center legs of the main core. The length of the air gap between the main core and the path-core is shown in Fig. 8. The $I_{gpath}$ especially has less distance than $I_{r,\omega}$ in this case.

The resonant inductance which was designed exits on the secondary side in the PRIA structure so there is a relationship only between the secondary coils which are on the path-core and the main core when there is output current. The resonant fluxes are crossing the path-core to the side-legs of the EER core. This relationship is shown in Fig. 10.

Since they have the relationship in Fig. 9, the magnitude of $L_{r,\omega}$ can be calculated easily with equation (11). The resonant inductance was generated with the secondary coils and it only exists on the secondary side when there is output current with the PRIA structure.

$$L_{r,\omega} = \frac{(N_p+N_s)^2}{R_m+R_{gm}+R_{gpath}+R_{path}} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (11)$$

The magnitude of $L_{r,\omega}$ can be adjusted by the number of coils on the path-core and the magnitude of the $R_{path}$ or the $R_{gpath}$. The $R_{path}$ and the $R_{gpath}$ are expressed by (7) and (9). Then there are the relationships between the $R_{gpath}$, the $R_{path}$
The relationship of the primary coils with the secondary coils which are on the EER core.

The relationship of the primary coils with the secondary coils which are on the I-core.

(a) The relationship of the primary coils with the secondary coils which are on the EER core.

(b) The relationship of the primary coils with the secondary coils which are on the I-core.

Fig. 6. The relationships of the primary side with the secondary side

Fig. 7. Coil distribution on the main core

Fig. 9. The relationship of the secondary coils with the path-core

Fig. 10. The proposed transformer structure with adjustable $L_{r,\omega}$

and the I-core which is shown in Fig. 10.

Resonant inductance $L_r$ in the resonant tank should be transferred from $L_{r,\omega}$,

$$L_{r,\omega} = L_{r,\omega} \cdot \left( \frac{N_2}{N_s} \right)^2 \cdot \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS

Mainly $N_p$ determines $L_m$ and $B$. The value of $L_r$ can be set by $N_{s2}$, which is the number of coils on the path-core. Fine adjustments for resonant inductance that could also be achieved by adjusting the values of the $R_{path}$ or $R_{gpath}$ could be the best option.

4. Design Theory Evaluation

The specifications of the transformer which were used for designing the PRIA transformer are shown in Table 2.

In this section, the method of measurement is discussed and theoretical results and measurement results are confirmed.

An equivalent circuit of transformers is shown in Fig. 11. The magnitudes of magnetizing inductance and resonant inductance are measured with this equivalence during industrial
Table 2. The specifications of the transformer

| Simple        | Value |
|---------------|-------|
| Initial permeability $\mu_r$ | 1100  |
| $A_c$ [mm²]   | 81.4  |
| $A_{path}$ [mm²] | 37.45 |
| $L_c$ [mm]    | 33.8  |
| $l_{path}$ [mm] | 28.8  |
| $L_{ps}$ [mm] | 6.4   |
| $L_{spath}$ [mm] | 5.8   |
| $N_p$         | 7     |
| $N_s$         | 6     |

Fig. 11. Equivalent circuit of transformers

Process normally.

This method should be adapted when the magnitude of leakage inductance is much lower than the magnitude of magnetizing inductance as the condition. And consequently, when the magnitude of magnetizing inductance is not much larger than leakage inductance, the volume of leakage inductance is less than the real volume which exists on the transformer. One of the benefits of the proposing structure is that the leakage inductance exists on the secondary side, therefore, the volume of magnetizing inductance will not influence the magnitude of leakage inductance. The magnetizing inductance and leakage inductance were measured by the method which is shown in Fig. 11.

The yellow line is determined by equation (10). The red points are measurement results. The measurement results between the magnetizing inductance and $N_p$’s values are confirmed and shown in Fig. 12.

The magnetizing inductance can be set separately with resonant inductance with the PRIA structure. Theoretical results and measurement results between the resonant inductance and $N_s$’s values are confirmed and shown in Fig. 13. The yellow line is determined by equation (12). The red points are measurement results.

Since the resonant inductance could be calculated with equation (11), the resonant inductance could be calibrated by adjusting the distance between the main core and the path-core. At the beginning, when the transformer was designed, the distance which was between the main core and the path-core was kept as small as possible. However, it is impossible for the distance to be smaller than 5.8 mm because of the shape of the bobbin, which is shown in Fig. 4(b). Furthermore, the relationship between the resonant inductance and the distance has been confirmed and shown in Fig. 14.

The magnetizing inductance can be calculated with (10) and the resonant inductance can be calculated with (11) and (12). It is confirmed that the resonant inductance can be set with $N_s$’s values and the distance which was between the main core and the path-core in Fig. 13 and Fig. 14.

5. Experimental Evaluation

In this section, a 1-MHz resonant LLC converter and a 1.4-MHz resonant converter were designed to confirm the theory which was described in section 4 with experiments. The theoretical parameters which requested to be realized are shown in Table 3.

The experiment results of LLC resonant converters with the PRIA transformer are presented in Table 4.

Considering that some parasitic inductance exists on the PBC circuit board, the resonant inductance that were set with PRIA transformers were fewer than the requested values in
The theoretical values of $L_m$ and $L_r$, which were calculated from (10)–(12), were confirmed with experimental values. The advantages of the proposed magnetic structure, which is that the resonant inductance $L_r$ can be set by $N_{r2}$ and the magnetizing inductance $L_m$ can be set separately with $L_r$, were confirmed in this paper.

A 1-MHz LLC resonant converter and a design with a 1.4-MHz LLC resonant converter successfully worked with the proposed magnetic structure. The experiments proved that it is efficient to realize the required value of resonant frequency with the PRIA structure.

The analysis of the transformer losses results are being worked on at the moment. The core losses and the copper losses will be analyzed to show the advantages of the PRIA structure in the future soon.

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48 IEEJ Journal IA, Vol.11, No.1, 2022