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著者	Abe Seiya, Zaitsu Toshiyuki
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Solution of Triple Problems in Transformer Windings for Current Resonant Converter with High Power Density and Wide Input Voltage Range

Seiya Abe(1), Toshiyuki Zaitsu(2)
(1) Kyushu Institute of Technology, (2) Omron Corporation
(1) 2-4 Hibikino, Wakamatsu-ku, Kitakyushu, Japan
(2) 9-1 Kizugawadai, Kizugawa-city, Kyoto, Japan
Tel.: (1) +81 / (93) – 695.6235. (2) +81 / (774) – 74.2760.
Fax: (1) +81 / (93) – 695.6235. (2) +81 / (774) – 74.2004.
E-Mail: (1) s_abe@life.kyutech.ac.jp, (2) toshiyuki_zaitsu@omron.co.jp

Keywords

«Converter circuit», «DC power supply», «Design», «High power density systems», «Industrial application»

Abstract

The realization of wide input voltage and high power density on the conventional current resonant converter such as LLC converter remarkably increases transformer winding loss and its design difficulty. Therefore, it is difficult for the conventional LLC converter to satisfy both requirements.
In order to apply the LLC converter with both conditions, this paper investigates the mechanism of the transformer winding loss occurrence in the conventional LLC converter. Moreover, the solution for mentioned above problems is proposed which can removes the transformer design difficulty as well by only changing the resonant operation mode.

Introduction

A LLC converter is one of the most practical topology as soft-switching DC-DC converter without any auxiliary circuits, and it is widely used for consumer and industrial applications. This is because it has good performance for high-efficiency, small size, low noise and so on [1-4]. Moreover, the synchronous rectification technique of LLC converter has been introduced to the market in order to achieve higher efficiency. As a result, LLC converters become very popular in many applications [5-9].
On the other hand, from the view of the system configuration, a power factor correction (PFC) converter as a pre-regulator is generally used for LLC converter. Therefore, LLC converters are designed on premise that narrow input voltage range. Recently, LLC converters are expected for DC-DC converters without pre-regulator and smaller size such as battery applications. Hence, the wider input voltage range capability and higher power density are necessary to satisfy both requirements. However, as shown in Fig.1, those requirements cause a severe problem of huge transformer winding loss by three reasons as below.

1. Large cupper loss by finer winding.
2. Large magnetizing loss by small magnetizing inductance.
3. Large eddy current loss by wide air gap between transformer cores.

Those fatal drawbacks inhibit the realization of LLC converter with wide input voltage range and high power density.
This paper clarifies the mechanism of transformer loss occurrence in the conventional LLC converter. Moreover, LC series resonant mode (LC mode) operation is proposed in order to solve the transformer winding loss problems. The evaluation board is implemented with the specification of 200V-400V input voltage range and 10V/30A output to compare with LLC mode and LC mode operation.
As a result, the transformer winding loss is dramatically reduced with LC mode operation.

Triple problems of transformer windings loss

A LLC converter has no smoothing inductor at output side, and the resonant inductor is included in the integrated transformer as shown in Fig. 2. Therefore, the LLC converter can easily achieve small size. In the commercialized LLC converter, the transformer accounts for 20-30% as dominant portion of whole converter circuit. Therefore, miniaturization of transformer is the key technology to make high power density LLC converter.

In order to design optimally for wide input voltage and high power density, it is necessary to grasp the frequency characteristics of LLC converter in detail. The frequency characteristics of LLC converter are given by using well known FHA(Fundamental Harmonics Analysis) technique [11-16], and the output voltage is derived as following equation Eq. (1).-(4). Figure 3 shows a general frequency characteristic of the voltage conversion ratio. In the conventional LLC converters with the pre-regulator (narrow input voltage range), the gradual curve of frequency characteristic is accepted so that the converter works well near "fsr" series resonant frequency without any problems.

On the other hand, the realization of wide input voltage capability and high power density has big problems mentioned above with very steep frequency characteristic. In order to solve those issues, the mechanism of loss occurrence should be clarified.

$$V_o = \frac{V_{in}}{2n} \cdot \frac{1}{\sqrt{\left[1 + \frac{1}{L_n}\left(1 - \frac{f_{sr}^2}{f^2}\right)\right]^2 + \left[Q\left(\frac{f}{f_{sr}} - \frac{f_{sr}}{f}\right)\right]^2}} \tag{1}$$

$$L_n = \frac{L_m}{L_r} \tag{2}$$

$$f_{sr} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{3}$$

$$Q = \frac{\pi^2}{8n^2 R_L}\sqrt{\frac{L_r}{C_r}} \tag{4}$$

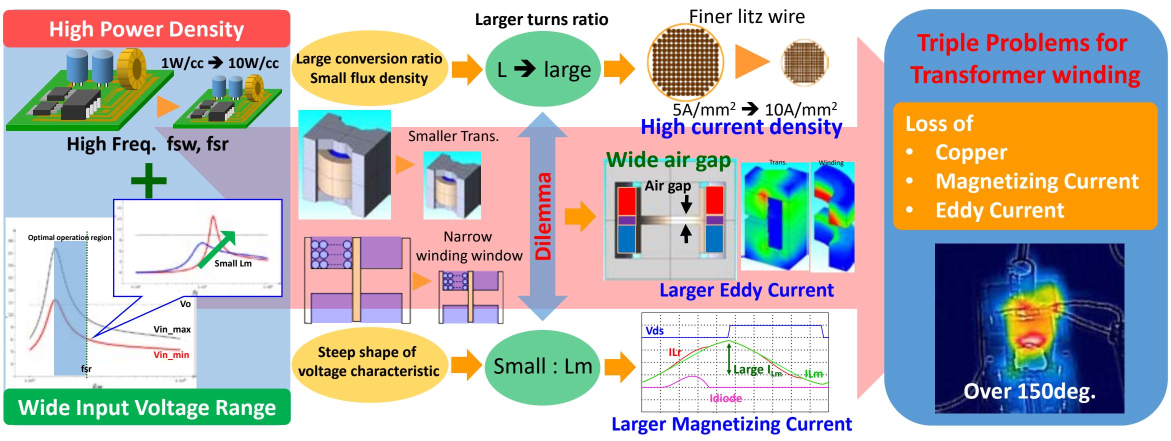


Fig. 1: Triple trouble for transformer windings in high power density and wide input voltage range.

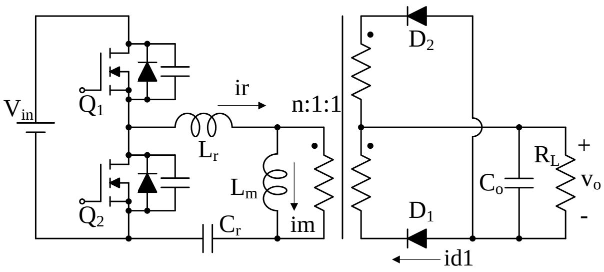


Fig. 2: Conventional LLC converter.

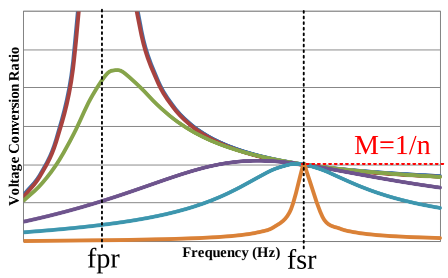


Fig. 3: Frequency characteristics of LLC converter.

Here, the transformer winding loss occurrence mechanism is discussed under the specification of Vin=200V-400V, Vo=10V, Io=30A, fsw=500kHz which is general specification for high voltage input battery application and low voltage output for electrical boards, and PC95PQ2625 (TDK) core is used for the transformer targeting 10W/cm3 power density converter.

A. Large cupper loss

If the transformer turns ratio is designed by using minimum input voltage Vin_min, the switching frequency "fsw" is higher than series resonant frequency "fsr" at maximum input voltage Vin_max, and the ZCS operation for secondary side diodes is not achieved as shown in Fig. 4. Therefore, the turns-ratio "nLLC" is decided by maximum output voltage Vin_max as shown in Eq. (5).
Meanwhile, in order to achieve high power density, the transformer size should be smaller, but this leads to small winding space.
Hence, large turns-ratio for wide input voltage range and the small size transformer for high power density lead to finer windings as shown in Fig.1. This results in larger copper loss.

$$n_{LLC} = \frac{V_{in\_max}}{2 \cdot V_o} \tag{5}$$

B. Large magnetizing loss

The LLC converters with narrow input voltage design does not reach to desired output voltage when the input voltage is low as shown in Fig. 5. In order to achieve the desired output voltage at the minimum input voltage Vin_min, the output voltage characteristic has to be steep shape [17, 18], and the small magnetizing inductance can make this steep shape as shown in Fig.5. However, this small magnetizing inductance results in a large magnetizing current loss.
Figure 6 shows the magnetizing current and magnetizing current loss against input voltage ratio (Vin_max/Vin_min) when the number of winding is n=22. When the input voltage ratio is "2.0", the magnetizing current is over 10A, and the magnetizing current loss reaches to 3.5W. When the input voltage ratio is "4.0", the magnetizing current is over 20A, and the magnetizing current loss reaches to 20W. In this way, the peak of magnetizing current linearly increases with the input voltage ratio.

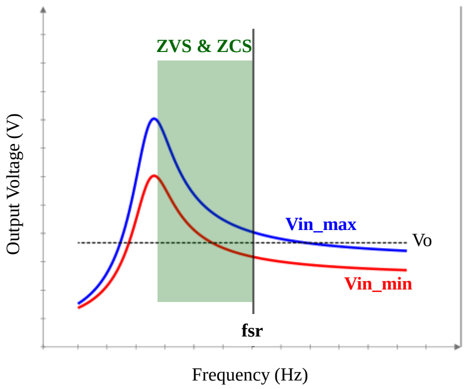
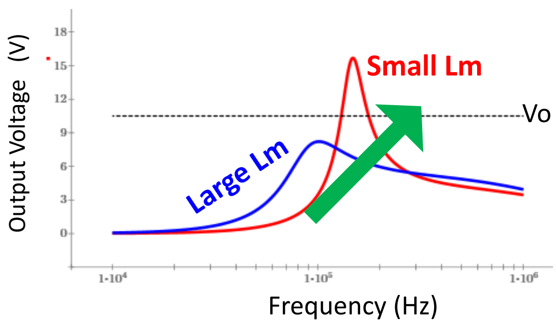


Fig. 4: Frequency characteristics for transformer turns-ratio design.



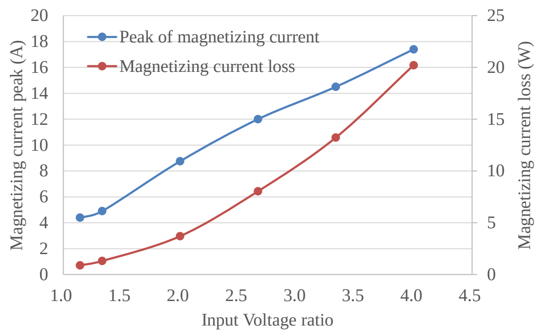


Fig. 5: Magnetizing inductance for steep shape. Fig. 6: Magnetizing current and loss vs. Vin ratio.

From these sections A and B, the following requirements for the transformer have been clarified.

1. The large turns-ratio is needed to satisfy ZVS & ZCS operation for all input voltage range, and the inductance of transformer becomes large.
2. The small magnetizing inductance is needed for steep voltage shape to achieve desired output voltage for all input voltage range.

These two conflicting requirements (large inductance or small magnetizing inductance) causes the inductance dilemma which leads to third big issue for transformer winding as eddy current loss.

C. Large eddy current loss

A wide air gap between the transformer cores can make small magnetizing inductance. However, the wide air gap leads to large leakage flux, and the large eddy current flows through the transformer windings. Therefore, the ac equivalent resistance of transformer winding becomes larger. Figure 7 shows the required magnetizing inductance air gap against the input voltage ratio. The required magnetizing inductance becomes smaller when the input voltage ratio is larger, and this leads to wider air gap. For example, around 3.5mm air gap is needed when the input voltage ratio is "2.0". Figure 8 shows the electromagnetic field simulation result with 3.5mm air gap as an example. The magnetic flux leaks from air gap, and the eddy current flows when the leakage magnetic flux interlinks transformer winding as shown in Fig. 8 (b). Moreover, the current concentration occurs, and the current density remarkably increases as shown in Fig. 8 (c).

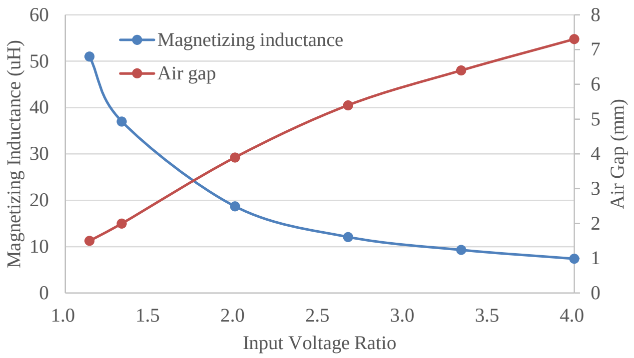
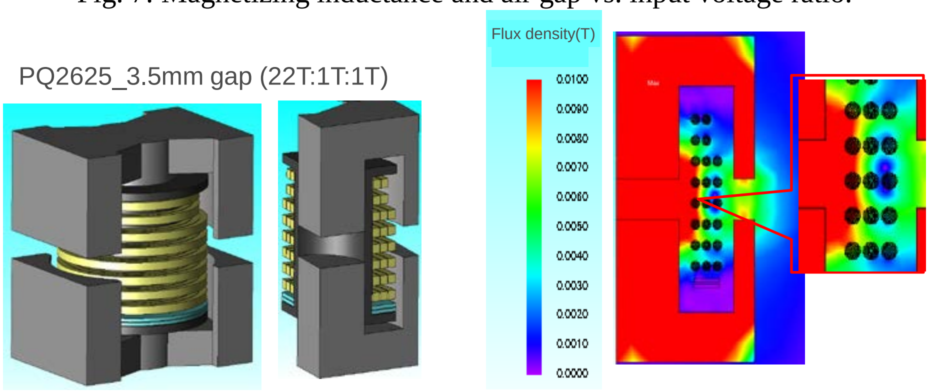
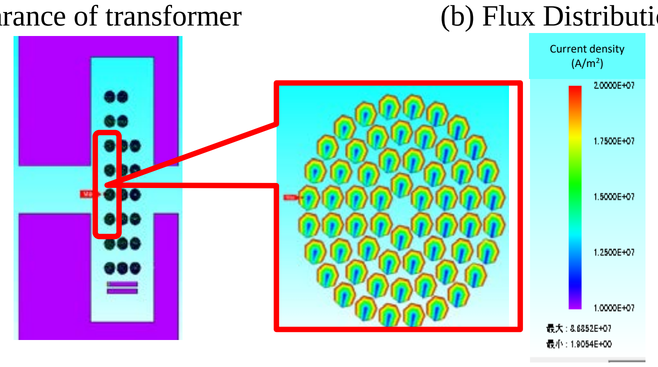


Fig. 7: Magnetizing inductance and air gap vs. input voltage ratio.



(a) Appearance of transformer (b) Flux Distribution



(c) Current Distribution

Fig. 8: Simulation result of transformer (LLC mode).

Solution of triple problems

In order to overcome triple loss problems of the transformer windings, following requirements are desired in the transformer.

1. Small turns-ratio "n" for small copper loss
2. Large magnetizing inductance for small magnetizing current loss
3. Narrow air gap for small eddy current loss

The solution for mentioned above problems can be figured out by only the operating mode change of LLC converter. It can improve dramatically not only transformer winding loss but also transformer design difficulty. This solution is very simple, because the operating mode (operating frequency range) changes to LC resonant mode (fsw>fsr) from LLC resonant mode (fsw<fsr) as shown in Fig. 9. In this case, there is no influence of magnetizing inductance. Therefore, larger magnetizing inductance is acceptable which can reduce not only the peak of magnetizing current but also the air gap between the transformer cores. This results in the low magnetizing current loss and eddy current loss. Also, the copper loss of transformer windings should be reduced due to the small transformer turns-ratio "nLC". Because "nLC" is decided by minimum input voltage in LC mode operation as shown in Eq. (6).

$$n_{LC} = \frac{V_{in\_min}}{2 \cdot V_o} \tag{6}$$

Figure 10 shows the electromagnetic field simulation result of LC mode operation without the air gap. The magnetic flux has not been hardly leak, so most of the eddy current do not flow as shown in Fig. 10 (b). Moreover, the current concentration does not occur, so that current density distribution became flat as shown in Fig. 10 (c).

Experimental verifications

In order to evaluate mentioned above discussions, the prototype evaluation board is implemented for both operation mode. Figure 11 shows picture of the prototype evaluation board. The purpose is the evaluation of the transformer temperature, so the power devices are installed on bottom side of the board for temperature isolation. Moreover, the power devices are forced-air cooling, and the transformer is natural-air cooling.

The circuit parameters and specifications are shown in Table 1. The test condition is set to Vin=200V, Vo=10V with operating frequency is around 500kHz for fairly comparison. As shown in Fig.12, in order to realize those condition, the series resonant frequency of LLC converter, fsr_LLC, is set to around 700kHz so that LLC converter can operate around 500kHz. And, the series resonant frequency of the proposed LC mode converter, fsr_LC, is set to around 250kHz so that it can operate around 500kHz as well to get Vo=10V. PC95PQ2625 (TDK) is used as the transformer core. The turns ratio n_LLC of the transformer is "22" for LLC mode converter, and the turns-ratio n_LC is "8" for LC mode converter, respectively.

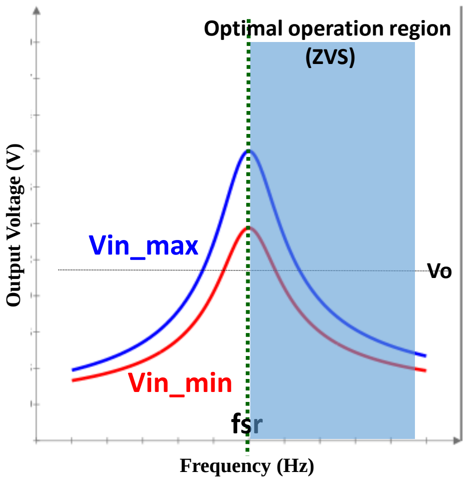
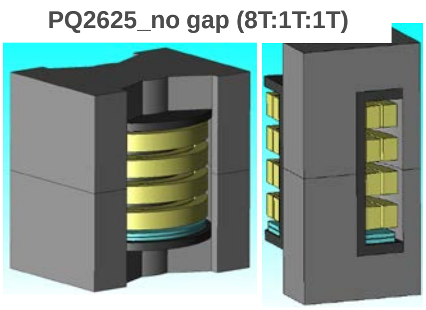


Fig. 9: Proposed operating condition of LLC converter.

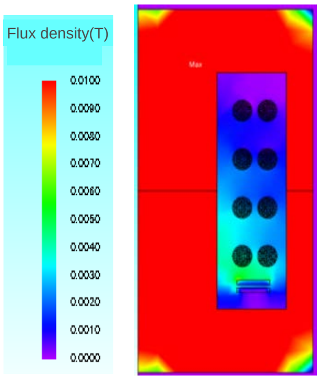
Figure 13 shows the experimental key waveforms of both operation modes. As shown in Fig. 13 (a) the peak to peak value of the resonant current is around 12A, and the resonant current ir is dominated by the magnetizing current im which is around 10Ap-p. On the other hand, the peak to peak of the resonant current is only around 4A in LC mode case as shown in Fig. 13 (b).

Figure 14 shows the temperature transition of the transformer winding. As shown in Fig. 14, the initial temperature is around 25deg in both cases, the winding temperature of LLC mode and LC mode settled down to around 176deg and 76deg at 10min, respectively. The transformer winding temperature is dramatically reduced in LC mode case, and the improvement of temperature rising is around 100deg.

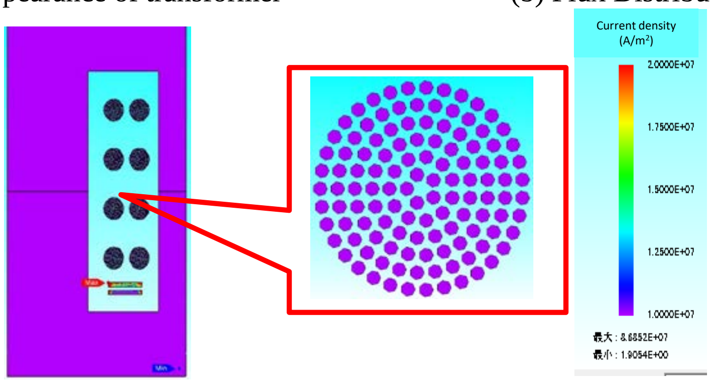
Figure 15 shows the temperature distribution at 10min. The transformer winding in LLC mode, the hot spot occurs around the air gap of core as shown in Fig.15 (a). Meanwhile, no hot spot is observed as shown in Fig. 15 (b)



(a) Appearance of transformer



(b) Flux Distribution



(c) Current Distribution

Fig. 10: Simulation result of transformer (LC mode).

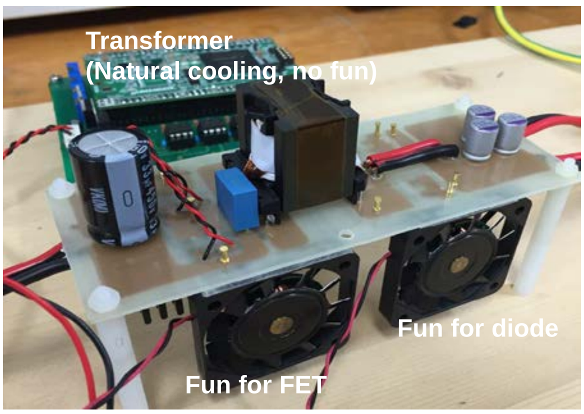


Fig. 11: Picture of evaluation board.

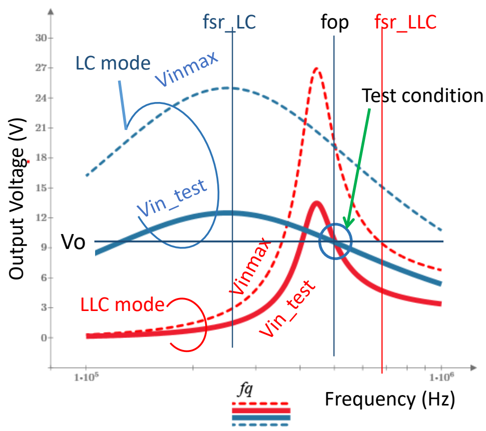
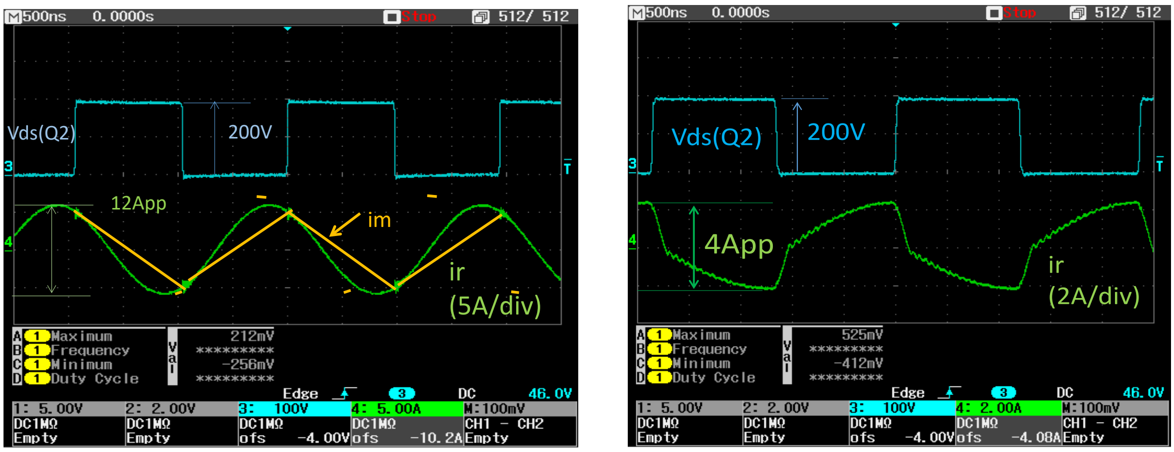


Fig. 12: Operating condition for both mode.

Table I: Circuit parameters and specifications

Description	Symbol	Value	
		LLC	LC
Input Voltage	Vin	200V	
Output Condition	Vo / Io	10V/15A	
Resonant Inductance	Lr	11uH	8.4uH
Magnetizing Inductance	Lm	18uH	-
Resonant Capacitor	Cr	4.7nF	47nF
Turns Ratio	n	22	8
Primary Winding	Litz wire	ϕ0.1*60	ϕ0.1*120
Secondary Winding	Cu plate	T:0.3mm W:2.5mm	
Air Gap		3.5mm	-
Resonant Frequency	fsr	700kHz	250kHz
Switching Frequency	fsw	510kHz	425kHz



(a) LLC mode (b) LC mode

Fig. 13: Experimental key waveforms

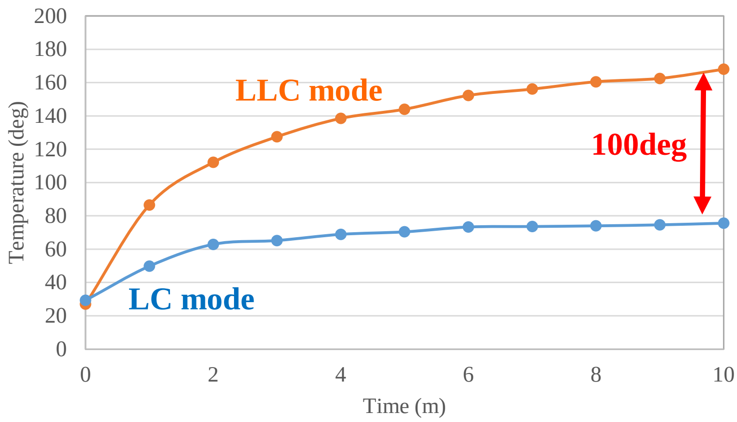
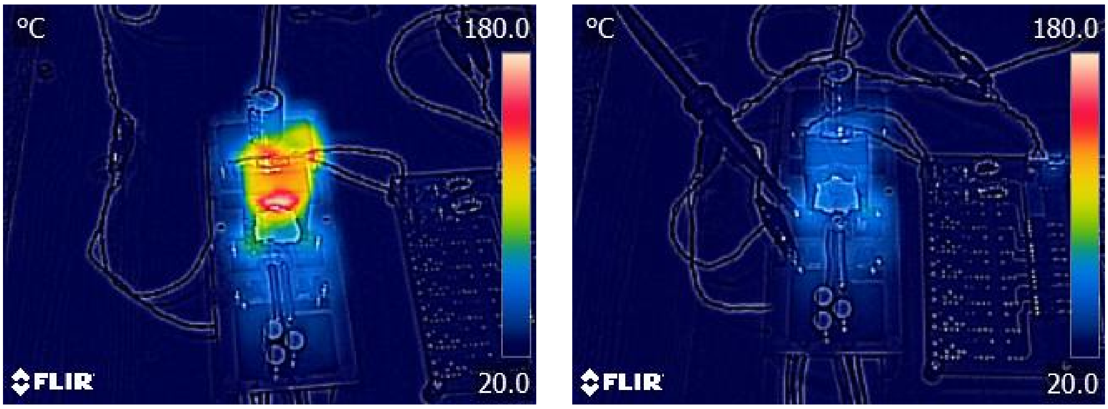


Fig. 14: Transformer winding temperature



(a) LLC mode (b) LC mode

Fig. 15: Temperature distribution after 15min.

Conclusion

This paper investigate the mechanism of transformer winding loss for LLC converter with wide input voltage range and high power density, and the solution for the loss problems is proposed. As a result, it is clarified that the mechanism of triple loss problems of transformer windings.

1st loss problem is a large copper loss for finer windings which is came from large turns ratio. In addition, narrow winding window has to be used for small transformer core.

2nd loss problem is a large magnetizing loss. Small magnetizing inductance is needed to achieve desired output voltage under wide input voltage ratio. This leads to large magnetizing current loss.

3rd loss problem is a large eddy current loss. In order to make the small magnetizing inductance, a large air gap between transformer cores is needed. This causes the leakage flux and eddy current generation, and the large eddy current loss occurs.

The solution for mentioned above problems is proposed. Only the operating mode change from LLC mode to LC series resonant operation mode could solve those issues simultaneously.

The evaluation board was implemented and the transformer winding temperature was compared. As a result, the transformer winding temperature was dramatically improved.

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