Transformer design difficulties of current resonant converter for high power density and wide input voltage range

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Abstract—A current resonant converter including wider input voltage range and higher power density is required for various applications. However, in our study, it has been found that the drastic increasing of the transformer winding loss becomes a severe problem. This paper clarifies the mechanism of transformer winding loss occurrence and proposes the different resonant mode operation which solves the problem of the huge transformer loss.

Keywords—Current resonant converter; High power density; Wide input voltage; Transformer loss

I. INTRODUCTION

A Current resonant converter such as LLC converter is one of the most popular topology as soft-switching DC-DC converter, and it is widely used for consumer and industrial applications because it has following good performance[1-4];

1. ZVS (Zero Voltage Switching) capability of primary side switches at turn on time.
2. ZCS (Zero Current Switching) capability of the secondary side diodes at turn off time.
3. The output voltage control capability by resonant frequency characteristic.
4. Small size by using integrated transformer.

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, a PFC (Power Factor Collection) converter as a pre-regulator is generally used for LLC converter in those applications. Therefore, LLC converters are expected for DC-DC converters without pre-regulator and smaller size. 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 copper 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 reduce the transformer loss. The evaluation board is implemented with the specification of 100V-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.

Fig. 1. Triple trouble for transformer windings
II. MECHANISM OF LARGE WINDING LOSS OCCURRENCE

Figure 2 shows a conventional LLC converter. There is no smoothing inductor at output side, and the resonant inductor is included in the integrated transformer. So, the LLC converter can achieve small size. On the other hand, the transformer is the most important element to decide the size of the LLC converter. In the commercialized LLC converter, the transformer accounts for 20-30% of converter circuit. Therefore, miniaturization of transformer is one of the most important technology to make high power density LLC converter.

In order to design optimal 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 output voltage, and the optimal operating region to achieving primary side ZVS and secondary side ZCS. In the conventional LLC converters, the frequency characteristic can accept the gradual curve due to narrow input voltage range with the pre-regulator as shown in Fig.3.

\[
V_o = \frac{V_{in}}{2n} \left[ \frac{1}{1 + \frac{1}{L_o} \left( \frac{f_{fs}}{f} \right)^2 + Q \left( \frac{f_{fs}}{f} - \frac{f_{fr}}{f} \right)^2} \right] \tag{1}
\]

\[
L_n = \frac{L_o}{L_r} \tag{2}
\]

\[
f_{sw} = \frac{1}{2\pi \sqrt{L_r C_r}} \tag{3}
\]

\[
Q = \frac{\pi^2}{8n^2 R_c} \sqrt{\frac{L_r}{C_r}} \tag{4}
\]

However, realization of wide input voltage range capability and high power density have some problems mentioned above. In order to solve those issues, the mechanism of loss occurrence should be clarified. Here, the transformer winding loss occurrence mechanism is discussed under the specification of Vin=100V-400V, Vo=10V, Io=30A, fsw=500kHz, and PC95PQ2625 (TDK) core is used for the transformer targeting 10W/cc power density converter.

A. Large copper loss

As shown in Eq (5), the turns-ratio “n” is decided by the output voltage value using Vin_max at frequency of “fsr”. Therefore, the large number of transformer turns-ratio “n” is needed to satisfy ZVS & ZCS operation for wide input voltage range.

\[
n_{LLC} = \frac{V_{in\, max}}{2V_o} \tag{5}
\]

On the other hand, the high switching frequency is needed in order to achieve the high power density. Hence, the small size transformer core for high power density and large turns-ratio for wide input voltage range lead to finer windings as shown in Fig.1. This results in larger copper loss.

B. Large magnetizing loss

As shown in Fig.3, general LLC converters with narrow input voltage design (Ln=5, Q=0.5) does not reach to desired output voltage when the input voltage is low. In order to achieve the desired output voltage at the minimum input voltage Vin_min, the output voltage characteristic has to be steep shape as shown in Fig.4 [17, 18], and the small magnetizing inductance achieves this steep shape. Figure 5 shows the Vo frequency characteristic of steep shape by small magnetizing inductance with Vin_max and Vin_min. However, this small inductance results in a large magnetizing current loss.
Figure 6 shows the magnetizing current and magnetizing current loss against input voltage ratio ($V_{\text{in\_max}}/V_{\text{in\_min}}$) when the number of winding is $n=22$. When the input voltage ratio is “4.0”, the magnetizing current loss reaches to 20W which is not acceptable.

C. Large eddy current loss

In order to realize small magnetizing inductance $L_m$, a wider air gap between the transformer cores is needed. 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 air gap against the input voltage ratio. Over 7mm air gap is needed when the input voltage ratio is “4.0”. Figure 8 shows the electromagnetic field simulation result with 1.2mm air gap as an example. It is found out the current concentration occurs by the influence of the eddy current.

III. SOLUTION OF TRIPLE PROBLEMS

In order to overcome mentioned above loss trouble of the transformer windings, following specifications 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 the problems mentioned above 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. Figure 9 shows the operating condition of proposed LC series resonant mode (LC mode) operation.

As shown in Fig. 3 and 5, the operation frequency is lower than series resonant frequency $f_{sr}$, and magnetizing current contributes to the output voltage. The triple problems occur in conventional LLC mode operation as mentioned above.

By changing the operation frequency higher than $f_{sr}$, this converter operates as LC mode as shown in Fig.9. In this case, there is no influence of magnetizing inductance.
Therefore, larger magnetizing inductance is acceptable which can reduce 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 turn-ratio “nLC”. Because “nLC” is decided by minimum input voltage in LC mode operation as shown in Eq. (6).

$$n_{LC} = \frac{V_{in\_min}}{2 \cdot V_o}$$  \hspace{1cm} (6)

IV. EXPERIMENTAL RESULTS

In order to evaluate mentioned above discussions, the prototype evaluation board is implemented for both of LLC and LC mode operation. The circuit parameters and specifications are shown in Table 1. The design specifications are Vin=200V-400V, Vo=10V and Io=30A for feasible construction.

In order to compare fairly for both converters, the test condition is set to Vin=200V, Vo=10V with operating frequency is around 500kHz. As shown in Fig.10, in order to realize those condition, the series resonant frequency of LLC converter, $f_{sr\_LLC}$, is set to around 700kHz so that LLC converter can operate around 500kHz. And, the series resonant frequency of the proposed LC mode converter, $f_{sr\_LC}$, 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. Figure 11 shows the key waveforms and the temperature distribution of conventional LLC mode design board.

### TABLE I. CIRCUIT PARAMETERS AND SPECIFICATIONS

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<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Input Voltage</td>
<td>Vin</td>
<td>200V</td>
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<tr>
<td>Output Condition</td>
<td>Vo / Io</td>
<td>10V/15A</td>
</tr>
<tr>
<td>Resonant Inductance</td>
<td>Lr</td>
<td>11uH</td>
</tr>
<tr>
<td>Magnetizing Inductance</td>
<td>Lm</td>
<td>18uH</td>
</tr>
<tr>
<td>Resonant Capacitor</td>
<td>Cr</td>
<td>4.7nF</td>
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<tr>
<td>Turns Ratio</td>
<td>n</td>
<td>22</td>
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<tr>
<td>Primary Winding</td>
<td>Litz wire</td>
<td>$\phi 0.1*60$</td>
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<tr>
<td>Secondary Winding</td>
<td>Cu plate</td>
<td>T:0.3mm W:2.5mm</td>
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<tr>
<td>Air Gap</td>
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<td>3.5mm</td>
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<tr>
<td>Resonant Frequency</td>
<td>fsr</td>
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</tr>
<tr>
<td>Switching Frequency</td>
<td>fsw</td>
<td>510kHz</td>
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Fig. 10. Operating condition for both mode.

FIGURE 11

(a) Key waveforms

(b) Transformer winding temperature

(c) Temperature distribution @15min

Fig. 11. Conventional LLC converter.
As shown in Fig. 11 (a) the resonant current $i_r$ is dominated by the magnetizing current $i_m$ which is around 12Ap-p. The winding temperature is increased to 176deg, especially the hot spot occurs around the air gap of core as shown in Fig. 11 (c).

Figure 12 shows the key waveforms and the temperature distribution of the proposed LC operation design board. As shown in Fig.12 (a) the resonant current $i_r$ is dramatically reduced to 4Ap-p, and the maximum temperature is reduced to around 76deg as well as shown in Fig.12 (b) and (c).

![Key waveforms](image1)

![Transformer winding temperature](image2)

![Temperature distribution](image3)

Fig. 12. Proposed LLC converter with LC mode operation.

V. CONCLUSIONS

This paper investigates the mechanism of transformer winding loss occurrence for LLC converter with high power density and wide input voltage range, and the solution for the loss problems is proposed. As a result, it is clarified that the mechanism of triple problems of transformer windings (magnetizing loss, eddy current loss, copper loss). The solution for the problems is figured out by only the operating mode change of LLC converter, which can dramatically improve not only transformer design difficulty but also transformer winding loss.

REFERENCES


