High Efficiency Step-down Flyback Converter using Coaxial Cable Coupled-Inductor

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Abstract

This paper proposes a high efficiency step-down flyback converter using coaxial-cable coupled-inductor which has a higher primary-secondary flux linkage than sandwich winding transformers do. The structure of the two-winding coaxial cable transformer is described and the coupling coefficient of the coaxial cable transformer and of a sandwich winding transformer is compared. Circuit model of the proposed transformer is also obtained from the frequency-response curves of the secondary short-circuited and of the secondary open-circuited. Finally, performance of the proposed transformer is validated by the experimental results from a 35W single-output flyback converter prototype. Also, the proposed two-winding coaxial transformer is extended to a multiple winding coaxial application. For the performance evaluation of the extended version, 35W multi-output hardware prototype of DC-DC flyback converter was tested as well.

Key words: High efficiency, coaxial winding, flyback converter, multi-output, coupled-inductor.

I. INTRODUCTION

Flyback converter is one of the most preferred topology in DC-DC power conversion applications because of the low cost by its relatively-simple circuit structure as well as the high reliability from the electrical isolation and etc. Recently, the flyback converter topology has been expanded to some new engineering fields such as a flyback inverter for power-conditioning systems in renewable energy sources, power conversion circuits for charge-balance in battery management system, and so on [1].

One of the most important factors in the power efficiency of flyback converters is the isolation transformer (coupled-inductor). Even though power loss in the main switch and diode are worth taking to consider, that of the transformer is one of the dominant factors in perspective of efficiency for flyback converters. In fact, reducing the leakage inductance of the transformer is extremely important to increase the efficiency of the flyback converter. Generally, conventional converters employ sandwich winding methods to reduce the flux leakage of the transformer. Fig. 1 shows an example of the sandwich winding structure [2]. Sandwich winding technique, however, has limits of the transformer’s coupling coefficient due to winding-to-winding distance in the winding layout of a half-primary, secondary, and the other half-primary stacking structure. Therefore, a totally-different winding method is necessary for the enhancement of the flux linkage between the windings in order to increase the efficiency of the flyback converter [3-15].

This paper proposes a coaxial-cable transformer which has higher degree of coupling coefficient than that of sandwich winding transformers. ‘Coaxial’ means that a couple of windings share the axis of the round-shaped conductors. From the geometry, the magnetic flux generated by the current conduction around the windings can almost perfectly be coupled each other. Using the core geometry, a flyback transformer as a coaxial-cabled-coupled-inductor can be made to operate as an ideal transformer does in perspective of the power electronics theory [16].

The remainder of this study is organized as follows. Section II presents the coupling measurement and circuit modeling of the coaxial cable transformer. Section III compares the experimental results of the 35W single-output hardware prototype with a coaxial cable and with a sandwich winding. Also, comparison of the experimental results of the 35W multi-output hardware prototype between a three-winding coaxial cable transformer and a three-winding sandwich transformer is presented in Section IV. Finally, the conclusion is given in Section V.

Fig. 1 An example of conventional sandwich winding layout. Primary winding ($N_p$) is sandwiched between other half-and-half layers ($N_h, N_o$) [2].
II. COAXIAL CABLE TRANSFORMER

Generally, transformer's coupling efficiency is influenced by the distance between the primary and secondary winding coils. So far, sandwich winding is considered as the main solution to make highly-coupled transformer. But the sandwich method has some limitation in increasing the magnetic flux linkage between primary and secondary winding due to the inherent layer-by-layer structure. Thus, this paper proposes an improved winding method to increase the degree of transformer's coupling. This section presents the parameter measurement details of the hardware device, and also suggests the circuit model of the coaxial transformer from the frequency response analysis [3].

A. Single-output coaxial cable transformer

Single-output coaxial-cabled transformer is made of a couple of a strand of high-voltage winding coils and a low-voltage winding coil which covers the high-voltage coils fully. From the structure, the high voltage side becomes inner conductor and the other is the outer, naturally. Then, the multiple strands of the high-voltage winding coils are connected in series at the extremity. Fig. 2 shows the cross-section of a coaxial cable. Since general step-down converters have the high voltage windings in primary side, the primary becomes inner conductors as shown in the figure.

The distributions of the magnetic flux amplitude and direction in both of a sandwich winding transformer and a coaxial winding one are calculated using Finite Element Method (FEM) analysis (COMSOL software), and the derivation results are shown in Fig. 3. ‘P’ means primary winding, ‘S’ means secondary one, and the arrow refers to the flux. In Fig. 3(a), the secondary fluxes around the coil are not shared with the primary. On the other hand, in Fig. 3(b), all the secondary fluxes encircle the primary winding, which contributes to the higher flux linkage. The proximity between the two coils also contributes to the high coupling coefficient. However, due to the proximity, it also increases the interwinding parasitic capacitances which lead to a low dynamic response when a transient happens.

Fig. 4 shows the realized sandwich winding transformer and coaxial cable. Sandwich winding transformer is made of enameled wires, primary 210 turns and secondary 35 turns. PC40 ferrite core (TDK Co.) is used, because the sandwich winding typically has an optimized coupling coefficient with bobbin-equipped ferrite magnetic core. On the other hand, coaxial cable transformer utilized CH270125 toroidal core as the worst case which is hard to make high inter-winding flux coupling for the same operating condition.

To compare the coupling coefficient, a two-winding transformer was implemented with each winding method. Calculation of the coupling is done with the following equations [17]:

\[
k_{12} = \frac{\sqrt{L_1 L_2}}{L_1 + L_2 - L_{opp}} = \frac{L_{add} - L_{opp}}{L_1 + L_2}
\]

where \(k_{12}\) is constant of primary-secondary coupling, \(L_1\) is primary inductance, \(L_2\) is secondary inductance, \(L_{add}\) is series-adding inductance and \(L_{opp}\) is series-opposing inductance.

Coupling coefficient of the transformer is measured with eq. (1). The sandwich winding transformer is 0.9897505 and the coaxial cable transformer is 0.9999448. From the results, coaxial cable transformer has a superior flux linkage performance to that of the sandwich winding transformer.

Fig. 2. Cross section of the coaxial cable

(a) Sandwich winding          (b) coaxial cable

Fig. 3 Magnetic field simulation using COMSOL for checking the magnetic flux distribution of a sandwich and a coaxial cable transformer (P: primary winding, S: secondary).

(a) Sandwich winding          (b) coaxial cable

Fig. 4 Sandwich and coaxial cable transformer
B. Transformer modeling

Fig. 5 shows an example of commonly-used model for the proposed two-winding transformer. On the primary side, the winding resistance is represented by $R_p$, the leakage inductance by $L_{lk1}$, magnetizing inductance by $L_m$, and winding capacitance by $C_m$. The secondary winding resistance is $R_s$, and the leakage inductance is $L_{lk2}$. The modeling process is depending on the primary-side impedance measurements with the open-circuited secondary and the short-circuited secondary [18-19]. Network analyzer HP4194 was used for the impedance measurements of the coaxial transformer. The frequency-response range is from 100Hz to 40MHz. Fig. 6 shows both of the two primary impedance curves under the condition of the secondary-opened and the short-circuited. From the comparison of the circuit model with secondary-open curve (especially with magnitude) shown in Fig. 6(a), information on the primary resistance, magnetizing inductance, and winding capacitance are obtained.

In first, we measured magnitude and phase of the primary impedance under two operating frequencies such as:

$$|Z_{\text{open}}| = 33.4\Omega (1.02\text{kHz}), 99.6\Omega (1.06\text{kHz})$$

In this region, since the winding resistance $R_p$ and the magnetizing inductance $L_m$ works dominantly on the impedance parameter, the parameters are calculated as follows:

$$R_p = 885\text{m}\Omega$$
$$L_m = 5.2\text{mH}.$$  

Also, the resonant frequency is:

$$f_{r1} = \frac{1}{2\pi\sqrt{L_mC_m}} = 161.131\text{kHz} \quad (2)$$

From the data, winding capacitance can be calculated as:

$$C_m = 0.19\text{nF}.$$  

The second series-resonant frequency is:

$$f_{r2} = \frac{1}{2\pi\sqrt{L_{lk1}C_m}} = 21.675\text{MHz}. \quad (3)$$

Then, the leakage inductance is:

$$L_{lk1} = 0.287\mu\text{H}.$$  

Likewise, the other parameters can be calculated from the short-circuited measurement. Fig. 6(b) shows the measurement results. The curves contain total resistance of the primary and the reflected-secondary one in low frequency region. At frequencies above 10 kHz, the impedance rises due to the leakage inductor impedance. However, for more accurate parameter derivation, we need to separate out the real and imaginary parts to consider each of the contribution of these elements.

In first, we measure magnitude and phase of the primary impedance under two operating frequencies such as:

$$|Z_{\text{short}}| = 13.64\Omega (297.35\text{kHz}), 42.59\Omega (1.01\text{MHz}). \quad (4)$$

In this region, since the total winding resistance and the reflected leakage inductance work dominantly on the impedance graph, the parameters are calculated as follows:

$$R_s = 45\text{m}\Omega$$
$$L_{lk2}/N^2 = 5.652\mu\text{H}.$$  

Therefore, the secondary inductance is:

$$L_{lk2} = 0.157\mu\text{H}.$$
These equivalent circuit parameters describe the main characteristics of the transformer efficiently. For example, the resistances have a critical effect on the power efficiency. Also, the leakage inductances cause voltage spikes on the switching devices, which is essentially considered to select the device part number or to design an effective snubber circuit. From the circuit model, we can perform not only an analysis to understand the operating principles, but also to derive the design guidelines for various converter topologies employing this coaxial-winding transformer. The main parameters of the coaxial transformer are summarized in Table I.

<table>
<thead>
<tr>
<th>TABLE I. KEY PARAMETER OF COAXIAL TRANSFORMER</th>
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<tr>
<td>Symbol</td>
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<tr>
<td>Lm</td>
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<td>L_{k1}</td>
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<td>L_{k2}</td>
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<td>C_m</td>
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III. SINGLE-OUTPUT FLYBACK CONVERTER

A. Leakage inductance

Fig. 7 shows the circuit diagram of a single-output flyback converter used for hardware verification in this paper. Ideally, the flux linkage of the coupled-inductor is perfect and the leakage inductances on both sides are insignificant to the main operation. However, since the coupled-inductor contains an air gap between the cores for the flux storage, some flux leakage occurs between the cores or between the windings in practical. The leakage is modeled as an inductance, located in series with the ideally-transforming part on both of the primary and secondary sides.

The leakage inductance becomes a main reason for severe voltage spikes on the main switch as well as for the electromagnetic interference with the stored energy in the magnetic device. These spikes increase the voltage stress of the main switch, and ultimately decrease the efficiency when the turn-on resistance increases. For these reasons, flyback converter has been modified to several topological variations through an addition of some peripheral circuits such as clamping or snubber circuit. However, the fundamental solution is to reduce the leakage inductance even under the significant flux storage operation with a large air gap. This paper applies the coaxial winding method to obtain the ideal operation of the flyback converter through realization of the minimized leakage inductance [20-21].

B. Experimental result

<table>
<thead>
<tr>
<th>TABLE II. KEY PARAMETERS OF FLYBACK CONVERTER</th>
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<tbody>
<tr>
<td>Symbol</td>
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<tr>
<td>--------</td>
</tr>
<tr>
<td>V_{in}</td>
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<tr>
<td>V_{out}</td>
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<tr>
<td>P_{out}</td>
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<tr>
<td>f_s</td>
</tr>
<tr>
<td>Q</td>
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<tr>
<td>N_p</td>
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<tr>
<td>N_s</td>
</tr>
<tr>
<td>D</td>
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<tr>
<td>R</td>
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</table>

The abbreviated units are: V_{DC} = DC volt, W = watt, kHz = kilo Hertz, mH = milli-henry, Ω = ohm

In order to evaluate the performance of the proposed scheme, a 35W hardware prototype of the flyback converter has been implemented. The implemented component data concerning the hardware prototype are listed in the Table II and a picture of the single-output prototype is presented in Fig. 8. Two channel power analyzer (2802 Xitron Technologies) is used to measure the efficiency of the converter.

Fig. 9 shows the waveforms of the PWM gate signal and the MOSFET’s drain-source voltage without a snubber when a conventional sandwich winding coupled-inductor is applied. On the other hand, fig. 10 shows the waveforms of the PWM signal and the MOSFET’s drain-source using the proposed coaxial cable coupled-inductor under the same condition. From the figures, it can be seen that the ringing of the MOSFET’s drain-source voltage of the proposed flyback converter employing coaxial inductor has been improved significantly from 250V to 100V, which is almost 60% reduction. The experiment presents good agreement with the analysis and modeling results shown in previous sections.
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Fig. 9 Waveforms of the hardware experiment using sandwich winding transformer (Top: PWM gating, Bottom: drain-source voltage of main switch).

Fig. 10 Waveforms of the hardware experiment using coaxial cable transformer (Top: PWM gating, Bottom: drain-source voltage of main switch).

(a) Conventional flyback converter

(b) Proposed flyback converter

Fig. 11 Experimental results of the single-output flyback converter according to the variation of the input voltage.

Fig. 12 Comparison of thermal distributions of the hardware prototypes ($V_{in}=140$ V, full load).
(a) Thermal distribution of the conventional flyback converter
(b) Thermal distribution of the proposed flyback converter

Fig. 11 shows the measured efficiency of the hardware prototype according to the input voltage variation. Proposed coaxial method maintains high efficiency level greater than 83% in every condition of the input voltage range and with 89% maximum, while the conventional one presents less than 80% around the extreme conversion ratios even with snubbing operation for optimization of the efficiency. From the experimental results, it can be seen that the ideal coupling of the coaxial version has a benefit of higher conversion efficiency.

For more detailed analysis, temperature distributions on the hardware prototypes were measured and presented in Fig. 12. In the experiment, the conventional-type transformer flyback converter and the proposed coaxial-winding transformer flyback converter were investigated. The surface temperatures of the components were measured by Thermal Imaging Camera (DM-60, Zhejiang Dali Technology Co., Ltd). The infrared thermography system mainly consists of a camera and a software converting recorded information to the temperature signal [22-23].

Fig. 12(a) and 12(b) shows the temperature distribution of the two converters with the same operating condition such as $140$V input voltage at full load. The experiment was done at the ambient temperature. When you look at the thermal images, the spots of heat sources such as the diode, winding and core of the coupled-inductor and the main switch are shown in dark yellow color and outlined rectangular with numbers 1, 2, 3, and 4, respectively. The numbers shown in the right upper section of the picture are the steady-state operating temperatures measured at each of the rectangular area. The experimental results show that the diode temperature is not significantly different from each other, which means that the absolute loss-relieving portion at the diode is insignificant. On the contrary, the temperature of the main switch and the coupled-inductor in the conventional converter rises up to 34.0°C and to 74.4°C (See Fig. 12(a)), while in the proposed case, the temperature rises to 31.3°C and to 29.8°C (See Fig. 12(b)). This loss reduction significantly contributes to the efficiency improvement of the proposed converter.
From the experimental results, it is concluded that the proposed scheme is effective to improve the conversion efficiency, and relieving the step-down flyback DC–DC converter from the severe power stress on the main power-stream components.

IV. MULTI-OUTPUT FLYBACK CONVERTER

A. Multiple winding coaxial transformer

Fig. 13 shows the circuit diagram of a multiple output flyback converter used for hardware verification in this paper. Multiple output converter is generally composed of a multi-winding transformer for easy implementation, simple structure, and the low cost. In this paper, it can be supposed to extend the single output application of coaxial winding to the multiple output structure.

There can be several structure variations for the realization of the multi-winding coupled-inductor using coaxial concept. One of them is made of high-voltage side winding coils and of two or more low-side winding coils which cover high-voltage side winding coils. Another version is that one of the low-side wires is surrounded by multiple strands of high-side wires. Fig. 14 shows the cross-section of three winding coaxial cable used for hardware verification of a multi-output flyback converter [24-26].

Three winding transformer has two coupling constant, $k_{12}$ is coupling between the primary winding and the secondary winding, and $k_{13}$ is coupling between the primary winding and the tertiary winding (also see Fig. 13).

B. Experimental results

35W hardware prototype of the flyback converter has been implemented to verify the higher efficiency of the coaxial cable transformer. The implemented component data concerning the prototype are listed in the Table II and picture of the multi-output hardware prototype is presented in Fig. 16. The same two channel power analyzer is used to measure the efficiency of the converter.
TABLE III. KEY PARAMETERS OF FLYBACK CONVERTER

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter (part number)</th>
<th>Spec.</th>
</tr>
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<tbody>
<tr>
<td>( V_{in} )</td>
<td>Input voltage</td>
<td>40 – 300 VDC</td>
</tr>
<tr>
<td>( V_{o,1} )</td>
<td>Output voltage</td>
<td>15 VDC</td>
</tr>
<tr>
<td>( V_{o,2} )</td>
<td>Output voltage</td>
<td>15 VDC</td>
</tr>
<tr>
<td>( P_{out} )</td>
<td>Total output power</td>
<td>35W</td>
</tr>
<tr>
<td>( f_s )</td>
<td>Switching frequency</td>
<td>60kHz</td>
</tr>
<tr>
<td>Q</td>
<td>Main switch (IXFX48N60P)</td>
<td>600V, 48A</td>
</tr>
<tr>
<td>( N_P )</td>
<td>Primary winding</td>
<td>228 turns</td>
</tr>
<tr>
<td>( N_T )</td>
<td>Secondary winding</td>
<td>38 turns</td>
</tr>
<tr>
<td>( N_T )</td>
<td>Tertiary winding</td>
<td>38 turns</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>Secondary diode (B10100)</td>
<td>100V, 10A</td>
</tr>
<tr>
<td>( D_2 )</td>
<td>Tertiary diode (B10100)</td>
<td>100V, 10A</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>Secondary load resistance</td>
<td>6.3Ω</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>Tertiary load resistance</td>
<td>6.3Ω</td>
</tr>
</tbody>
</table>

The abbreviated units are: VDC = DC volt, W = watt, kHz = kilo Hertz, mH = milli-henry, Ω = ohm

Fig. 17 shows the waveforms of the PWM gate signal and the MOSFET’s drain-source voltage without snubber using sandwich winding transformer. Fig. 18 shows the waveforms of the PWM gate signal and the MOSFET’s drain-source voltage without snubber using coaxial cable transformer. The ringing of the MOSFET’s drain-source voltage has been improved significantly when the coaxial cable transformer is applied. From the results, it can be seen that the coaxial winding method can be applied to multi-winding coupled-inductors successfully.

Fig. 19 shows the overall efficiency of the converter according to the input voltage variation. From the experimental result, multi output coaxial cable transformer also has higher efficiency than the conventional sandwich prototype in every condition of the input voltage variation as the single-output result shows.

V. CONCLUSIONS

In this paper, flyback converter using coaxial-cable transformer for step-down off-line converter has been proposed. Coupling coefficient of the coaxial cable transformer was measured and presented to be equal to an ideal value, greater than 99.9%. For more detailed analysis, circuit modeling of the coaxial transformer was done with the help of frequency response curve obtained with secondary open-circuited and secondary short-circuited. 35W single-output and multi-output hardware prototype were tested, under continuous conduction mode with 60 kHz switching frequency. The experimental results verify that the voltage spikes of the drain-source voltage and the power conversion efficiency is superior with the proposed scheme to those of the conventional one by 60% and 10%, respectively. Also, the thermal distribution of the conventional and proposed hardware prototype has been given.

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