Coupling Coefficient Improvement and Electromagnetic Induced Noise Reduction using Short-Circuited Winding for Loosely Coupled Inductor

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A loosely coupled inductor for interleaved power converters has attracted interest for downsizing magnetic components. Although the loosely coupled inductor is usually designed by adjusting the coupling coefficient in order to meet the design specifications, the coupling coefficient is saturated by the fringing fluxes in the central leg and the external leakage fluxes in the case of the EE or EI magnetic core structures. It is a matter of concern that these fluxes are causes of electromagnetic induced noise and reduction in the downsizing performance. To solve this problem, this paper proposes a short-circuited winding for the coupled inductor in order to reduce the external leakage flux in the windings. The effectiveness of the coupled inductor with a short-circuit ring is evaluated with experimental tests.

Keywords: loosely coupled inductor, external leakage flux, electromagnetic shield, short-circuited winding

1. Introduction

Interleaved converters with a loosely coupled inductor have attracted interest due to its high power density and low-cost of the magnetic components. However, the conventional coupled inductor that uses magnetic cores such as EE or EI shapes presents the following three problems. 1) There are external leakage fluxes in the windings, and these fluxes affect the other components as electromagnetic induced noise if the winding is located near the other components. Although there is a solution where the inductor can be arranged far from the other components, the power-density packaging is compromised. 2) Additional winding losses due to fringing flux near the air-gap occur by a long air-gap in the central leg. 3) If the coupling coefficient is saturated by these leakage fluxes, the designer has to insert an air-gap into the outer legs. However, this solution makes the mutual inductance be decreased, and the magnetizing current of transformer be increased. As a result, the power conversion efficiency may be decreased. On the other hand, the reduction in downsizing performance of the coupled inductor is also concern. This is because the leakage inductance which is proportional to the DC fluxes has to be increased when the inductor current ripple of the circuit specifications is satisfied. To solve this problem, EIE core structure, designed to suppress fringing flux, has already been proposed in⁽¹⁾. However, this core structure needs three parts of magnetic cores to configure the EIE structure. In order to realize an easy manufacture, this paper proposes a Short-Circuited Winding (SCW) approach for the coupled inductor. This SCW approach is effective for reducing the external leakage flux which is one of the causes of the electromagnetic induced noise to other components. The effectiveness of this method is discussed from experimental viewpoints as well.

2. Short-circuited Winding Approach for a Loosely Coupled Inductor

The interleaved boost converter with coupled inductor is

Fig. 1. Interleaved converter with a loosely coupled inductor

Fig. 2. Coupled inductor covered by a short-circuited winding

shown in Fig. 1(a). The magnetic core structure of the conventional loosely coupled inductor is shown in Fig. 1(b). In the coupled inductor, there are several fluxes such as the external leakage flux of the windings and the fringing flux at the air-gap and the magnetizing flux between each winding. The saturation of the coupling coefficient is caused by the fringing flux and the external leakage flux in the case of the EE core structure. As a solution method for reducing the external leakage flux, this paper proposes a coupled inductor using the SCW. The aim of the SCW is to surround the magnetic core, see Fig. 2. The internal fluxes, including the fringing flux and the magnetizing flux, do not affect the SCW because the total interlinkage fluxes do not change. However, only the external leakage fluxes have effect inducing currents into the SCW. Therefore, the external leakage fluxes are canceled by the induced current. Consequently, the high coupling coefficient by the short-air gap length and the effect of the electromagnetic shield for the external leakage flux can be obtained.

3. Experimental Results

To show the effectiveness of the SCW for the coupled inductor, an experimental evaluation was carried out. The evaluation circuit parameters and the magnetic parameters are

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Table 1. Circuit parameters of the interleaved boost converter

Input voltage	V_i	140V
Output voltage	V_o	390V
Switching frequency	f_s	100kHz
Inductor ripple current	I_{Lpp}	1.5A
Output power	P_o	700W

Table 2. Magnetic parameters

Magnetic core		PC40EER49-Z(TDK)	
Number of winding turns	N	44 turns	
Maximum flux density	$B_{\max}$	250mT	
Designed values			
Mutual inductance	M	4.4mH	
Leakage inductances	L_{lk1}, L_{lk2}	138μH	
Measured values			
Proposed loosely coupled inductor with a short circuited winding			
Mutual inductance	M	4.5mH	
Leakage inductances	L_{lk1}, L_{lk2}	139μH, 140μH	
Air-gap length in the central leg	4.1mm		
Conventional coupled inductor without a short circuited winding			
Mutual inductance	M	4.5mH	
Leakage inductances	L_{lk1}, L_{lk2}	150μH, 148μH(Saturation)	
Air-gap length in the central leg	22.2 mm

Fig. 3. Appearance of the prototypes of coupled inductor

Fig. 4. Experimental waveforms

shown in Tables 1 and 2, respectively. The circuit parameters are assumed for a boost PFC converter. The inductor ripple current and the flux density are designed at 1.5 A and 250 mT. To obtain these designed parameters, a design method that satisfies both the inductor current ripple and the flux density is applied⁽¹⁾. The design value and the measured value using the SCW and a conventional inductor are shown in Table 2. In addition, the appearances of the prototype of coupled inductors are shown in Fig. 3. As seen in this table and figure, the air-gap length of the loosely coupled inductor with SCW can be reduced in comparison with the conventional loosely coupled inductor. Therefore, this SCW approach contributes to improve the coupling coefficient. Additionally, the leakage inductance of the conventional coupled inductor is saturated around 150 μH. These values are different from the designed value of 140 μH. Therefore, the conventional loosely coupled inductor cannot obtain any leakage inductance with high mutual inductance.

Figures 4(a) and (b) show the experimental waveforms under the conditions of Table 1. From (a), (b), the proposed method fulfills the designed inductor ripple current, however the conventional coupled inductor could not realize the design specification because of the external leakage flux. Figure 5 shows the power conversion efficiency when

Fig. 5. Power conversion efficiency when changing short-circuited winding

Fig. 6. Experimental waveforms including induced current

the structure of the SCW is changed from Litz wire to thin-film winding. The reasons why Litz wire or thin-film winding are applied to the SCW is to reduce the AC resistance R_{ac} in the SCW and to improve the power conversion efficiency. From Fig. 5, the power conversion efficiency is improved if the number of winding turns for the SCW is increased. The power losses in the SCW are shown as follows:

$$P_{loss} = R_{ac} \cdot i_{ind_rms}^2 \dots \dots \dots (1)$$

where R_{ac} is the AC resistance of the SCW; and i_{ind_rms} is the RMS value of the induced current in the SCW. By applying SCW, the power conversion efficiency decreases due to the winding losses of the SCW. However, if the number of winding turns is increased, the induced current can be reduced as shown in Fig. 6. Therefore, the power conversion efficiency is improved in comparison with the few winding turns. If the AC resistance is close to the DC resistance of the SCW using Litz wire or thin-film winding, increment in the winding turns of the SCW is effective for realizing the improving power conversion efficiency of the converter and keeping the electromagnetic shielding effect even if R_{ac} is increased by the winding length.

4. Conclusion

This paper proposed the SCW for the loosely coupled inductor, and described some attractive features. As a future work, we will analyze the characteristic analysis of the short-circuited winding in detailed, and we will search the effective way to use the induced current for efficiency improvement. Furthermore, we will analyze the proposed method for high frequency applications using GaNFETs and SiC-MOSFET in order to suppress noise phenomena.

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References

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