Novel Clamp Diode to Mitigate the Voltage Oscillation of Low Voltage Rectifier Diodes in Asymmetric Half-Bridge Converter

Minsu Lee[1], Dongmin Choi[1], Jongyoon Chae[2], Kyunghwa Park[3], and Gun-Woo Moon[1]
[1] KAIST, Republic of Korea
[2] Hyundai Motor Company, Republic of Korea
[3] Defense Agency for Technology and Quality, Republic of Korea

***Abstract*-- This paper proposes a novel clamp diode for the asymmetric half-bridge (AHB) converter. The proposed clamp diode is connected between the rectifiers and the output capacitor, and the voltage oscillation of the rectifier diodes with the low voltage is clamped to the output voltage. Meanwhile, the proposed clamp diode has no additional inductance between it and the rectifier diode. Therefore, no additional resonance occurs in the rectifier diodes, and the voltage oscillations are completely clamped to the output voltage. Consequently, by utilizing the proposed clamp diode in the AHB converter, the conduction loss can be reduced by applying rectifier diodes that have lower voltage stress compared to the conventional. Therefore, the proposed converter structure is suitable for achieving high efficiency. The practicability of the proposed converter was validated using 300W prototypes operating under input conditions of 360-400V and output conditions of 48V.**

***Index Terms*-- Asymmetric Half-Bridge Converter, Clamp Diode, DC/DC Converter, Voltage Oscillation.**

I. Introduction

A clamp diode is a structure used in the broad field of electronic engineering, and it operates to maintain the voltage of a specific node within a circuit within a specified range. These clamp diodes are similarly applied in the field of power conversion converters [1]-[2], and they mitigate the voltage oscillations of the rectifier diodes.

The voltage oscillation of the rectifier diodes is caused by resonance between the leakage inductor and the junction capacitor of the rectifier diode when the rectifier diode no longer conducts, and the voltage rises rapidly. At this time, the clamp diodes remove this voltage oscillation occurring at a specific node in the converter and operate to mitigate the oscillation occurring in rectifier diodes even without affecting the fundamental operation of the converter. Therefore, they allow using the low voltage diode for rectifier diodes and reduce the conduction losses.

Among various converters, the asymmetric half-bridge converter (AHB) converter is one of the representative topologies in low-to-medium power applications [3]-[5]. However, AHB converters also have several factors that reduce efficiency, including the voltage oscillation issue of the rectifier diodes, and several studies have been conducted to solve those efficiency problems [6]-[15]. Whereas, all of these advanced studies change the basic operating characteristics of the AHB converter. Therefore, further detailed validation is necessary to employ these advanced converters.

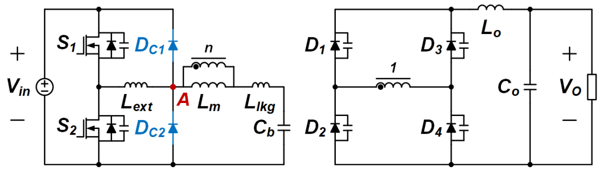


Fig. 1. AHB converter with conventional clamp diodes D_{C1} and D_{C2}.

Meanwhile, the clamp diodes are also applied to this AHB converter, as shown in Fig. 1, and they reduce the voltage oscillation without altering the essential operation of the AHB converter [2]. Within the AHB converter, clamp diodes D_{C1} and D_{C2} are placed between the external series inductor L_{ext} and the transformer, and they are connected to input voltage V_{in} and ground, respectively. The upper clamp diode D_{C1} suppresses the voltage oscillation of the rectifier diodes D_2 and D_3 to which a relatively high voltage is applied, and the lower clamp diode D_{C2} suppresses the voltage oscillation of the rectifier diodes D_1 and D_4 to which a relatively low voltage is applied.

Each clamp diode only conducts at the specific time when the voltage oscillation arises and significantly mitigates the voltage oscillations of the rectifier diodes without affecting the operation of the AHB converter. Therefore, when the clamp diode is applied, the operational characteristics of the AHB converter do not change from the conventional AHB converter, such as voltage gain and control parameters, unlike the case of applying advanced structure in [6]-[15]. Accordingly, it can be applied to applications that apply the conventional AHB without additional analysis. However, there is the transformer internal leakage inductor L_{lkg} between the clamp diode and the rectifier diode. Therefore, the voltage oscillation is not completely eliminated, and the conventional clamp diodes still have a limit in suppressing voltage oscillation.

This article proposes a new clamp diode for the AHB converter that clamps the voltage oscillation of rectifier diodes, which have a low voltage, without additional voltage oscillation. The AHB converter with the proposed clamp diode is shown in Fig. 2. The proposed AHB converter uses the same upper clamp diode D_{C1}, and replaces only the lower side clamp diode D_{C2} with the

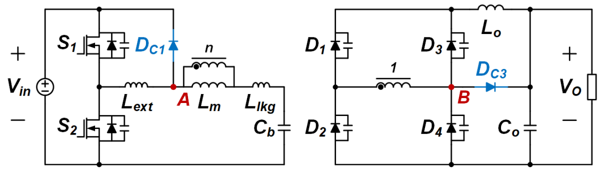


Fig. 2. AHB converter with D_{C1} and proposed clamp diode D_{C3}.

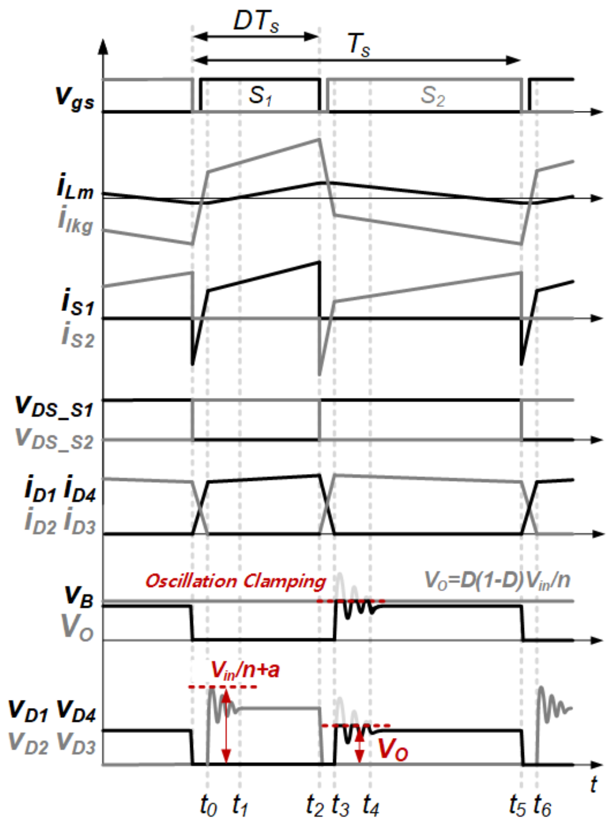


Fig. 3. Key waveforms of the proposed converter.

secondary side clamp diode D_{C3}. The clamp diode D_{C3} is connected from the cathode of D_4, which has a low voltage among the low-side rectifier diodes, to the output voltage, and it clamps the voltage oscillation of D_1 and D_4 to output voltage in entire operation conditions. Meanwhile, no additional voltage oscillation occurs because there is no leakage inductor between the rectifier diodes and the proposed clamp diode. Therefore, the proposed clamp diode can completely replace the conventional clamp diode D_{C2} and performs better.

II. Operational Principle

the key waveforms and operational circuits of the proposed converter are depicted in Fig. 3 and Fig. 4. The operation of the proposed converter is divided into a total of 6 modes, and the conducting path and main waveforms of each mode are shown in Fig. 3 and Fig. 4. To analyze the operation of the proposed converter simply, the following assumptions are made.

1) The rectifier diodes are ideal, excluding the junction capacitor, and the power MOSFETs are also ideal, excluding their body diodes and parasitic capacitors.
2) The clamp diodes D_{C1} and D_{C3} are ideal diodes.

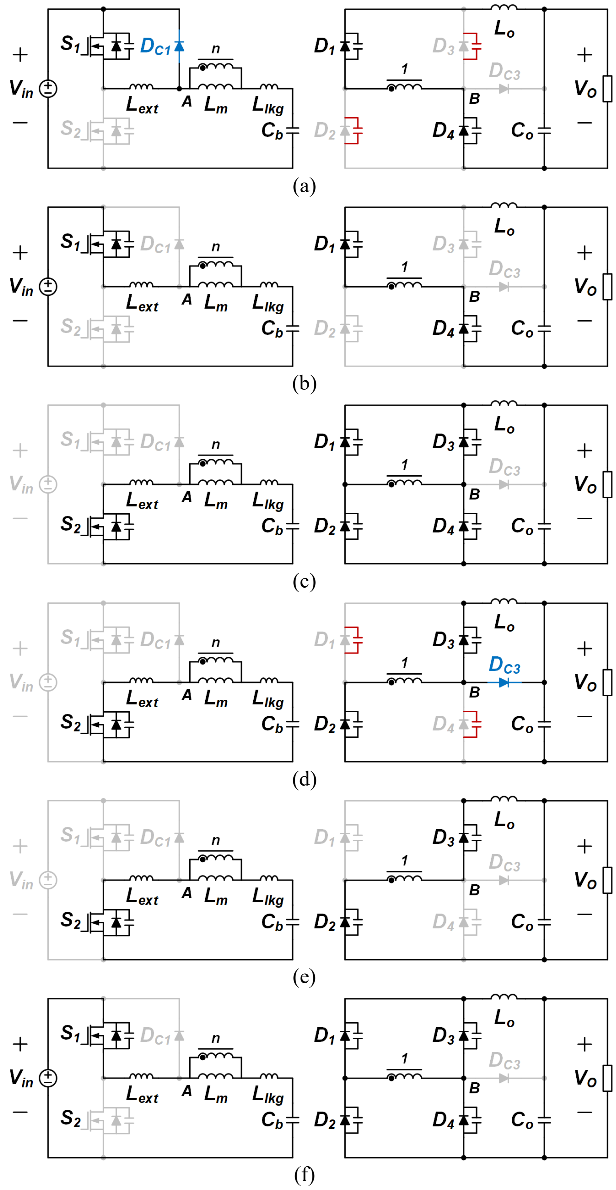


Fig. 4. AHB converter with proposed clamp diode. (a) Mode 1 (t_0-t_1). (b) Mode 2 (t_1-t_2). (c) Mode 3 (t_2-t_3). (d) Mode 4 (t_3-t_4). (e) Mode 5 (t_4-t_5). (f) Mode 6 (t_5-t_6).

3) The time that the drain-source voltage transition after switching is neglected.
4) There is no stray inductance in the pattern.
5) The blocking capacitance C_b is large enough to assume that it is a voltage source.
6) The magnetizing inductance L_m is large enough than the leakage inductance L_{lkg} and external inductor L_{ext}.

Mode 1 [$t_0 - t_1$, Fig. 3(a)]: Mode 1 starts when the diode commutation is complete, and power is delivered through paths of D_1 and D_4. In this mode, resonance occurs between L_{lkg}+L_{ext} and the junction capacitor C_j of diodes D_2 and D_3. Due to this resonance, at the moment the node A voltage V_A becomes higher than the input voltage V_{in}, D_{C1} momentarily conducts and clamps V_A.

However, L_{lkg} is located between the A node and the rectifier diodes, and the current energy of L_{lkg} is not removed through D_{C1} and remains. Thus, a resonant voltage still occurs across the rectifier diode.

Mode 2 [$t_1 - t_2$, Fig. 3(b)]: Mode 2 starts when the resonance is completely damped and D_{C1} is no longer conducting. This mode is still a period in which power is delivered through the paths of D_1 and D_4. Consequently, the operation of the proposed converter in the period of t_0-t_2 (mode 1 and mode 2) is exactly the same as the powering period of the conventional AHB converter except for the instantaneous conduction of the clamp diode.

Mode 3 [$t_2 - t_3$, Fig. 3(c)]: Mode 3 starts when the switch S_1 is off. The drain-source voltage v_{DS} of S_1 and S_2 is rapidly converted at the start of this mode, and current flows through the body diode of S_2 at the beginning. Therefore, the blocking capacitor voltage V_{Cb} is applied to primary side inductors, and the primary side current i_{lkg} rapidly decreases. This decreasing current is projected onto the secondary side and causes commutation between the rectifier diodes.

When the dead time ends during diode commutation, S_2 is turned on. However, the operation is almost the same, and the only difference is that the current flowing through the body diode of S_2 flows through its channel.

Mode 4 [$t_3 - t_4$, Fig. 3(d)]: Mode 4 starts the moment diode commutation ends. Unlike the previous mode, when all the rectifier diodes are conducting, in this mode, only D_2 and D_3 are conducting, and power is transferred through their path. In this mode, similar to mode 1, resonance occurs between L_{lkg}+L_{ext} and C_j of D_1 and D_4. As resonance occurs, when the voltage of node B v_B becomes greater than V_O, D_{C3} momentarily conducts and clamps the voltage. Therefore, the maximum voltage of v_B is limited to V_O.

Meanwhile, there is no additional inductance between the cathodes of D_1 and D_4 and node B. Therefore, unlike the operation of D_{C1} in mode 1, in the clamping operation of D_{C3}, there is no current energy source that causes a residual resonance of more than V_O in D_1 and D_4, and additional resonance does not occur. This is a great advantage of the proposed clamp diode.

Mode 5 [$t_4 - t_5$, Fig. 3(e)]: Mode 5 starts when the resonance is damped enough and D_{C3} is no longer conducting, similar to mode 2. In this mode, power is still delivered through the path of D_2 and D_3. Therefore, this mode operates the same as mode 4 except that D_{C3} is instantaneously on. Consequently, the operation of the proposed converter in the period of t_3-t_5 (mode 4 and mode 5) is the same as the powering period of the conventional AHB converter except for the instantaneous conduction of D_{C3}.

Mode 6 [$t_5 - t_6$, Fig. 3(f)]: Mode 6 starts when the switch S_2 is off. The drain-source voltage v_{DS} of S_1 and S_2 is rapidly converted at the start of this mode, and current flows through the body diode of S_1 at the beginning. In this mode, the voltage of V_{in}-V_{Cb} is applied to the primary side inductors, rapidly increasing the i_{lkg}. Therefore, like mode 3, this increasing current is projected to the secondary side and causes the commutation between the rectifier diodes. When the diode commutation is completed, mode 6 is terminated, and the operation of mode 1 to mode 6 is repeated.

In mode analysis of the entire period, the proposed structure works the same as the conventional AHB converter except that the clamp diode conducts when resonance occurs. Consequently, the operational characteristics of the proposed converter are almost unchanged from those of the AHB converter, and the basis of the proposed converter design, such as voltage gain and small signal characteristics, and so on, is unchanged from the design of the conventional AHB converter, except for the voltage stress of the rectifier diodes. Therefore, there are no additional design considerations, which is the most substantial advantage of the proposed clamp diode.

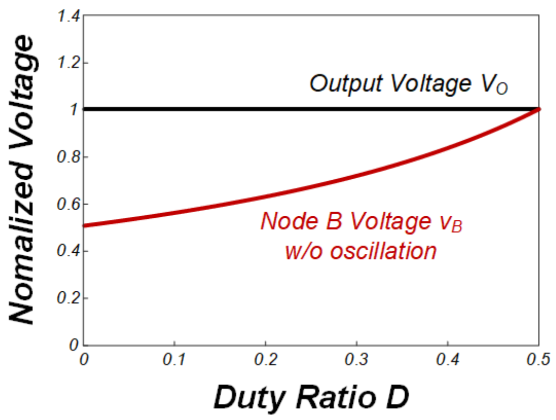


Fig. 5. v_B and V_O according to D in the AHB converter.

III. Characteristics of Proposed Converter

A. Voltage Conditions of Operation for Clamp Diode

For the proposed clamp diode D_{C3} to operate as a clamp diode as intended, a specific voltage precondition must be satisfied. Specifically, when there is no oscillation, v_B, where the anode of D_{C3} is connected, should always be lower than the output voltage V_O where the cathode is connected. When this voltage condition is not achieved, D_{C3} conducts even in the nominal operating conditions of the AHB converter, not at the moment of voltage oscillation. Therefore, D_{C3} completely changes the operation of the AHB converter and loses its characteristics as a clamp diode any more.

Meanwhile, v_B is always higher than V_O under the entire operating conditions of the AHB converter, and it can be known through the equations for each voltage as follows:

$$V_O = \frac{2D(1-D)V_{in}}{n} \tag{1}$$

$$v_{B,w/o\ oscil} = \frac{DV_{in}}{n} = \frac{V_O}{2(1-D)} \tag{2}$$

where n is turn ratio which is (number of turns on the primary side)/(number of turns on the secondary side) and D is duty ratio.

Fig. 5 shows the normalized voltage graph according to D when V_O is set at a fixed value of 1 as a control variable. As can be seen in the graph, v_B always has a lower value than V_O as the duty changes, and even under the condition of D=0.5 which v_B has the maximum value, it is the same as V_O.

Therefore, the proposed clamp diode D_{C3} is always open when voltage oscillation does not occur under entire

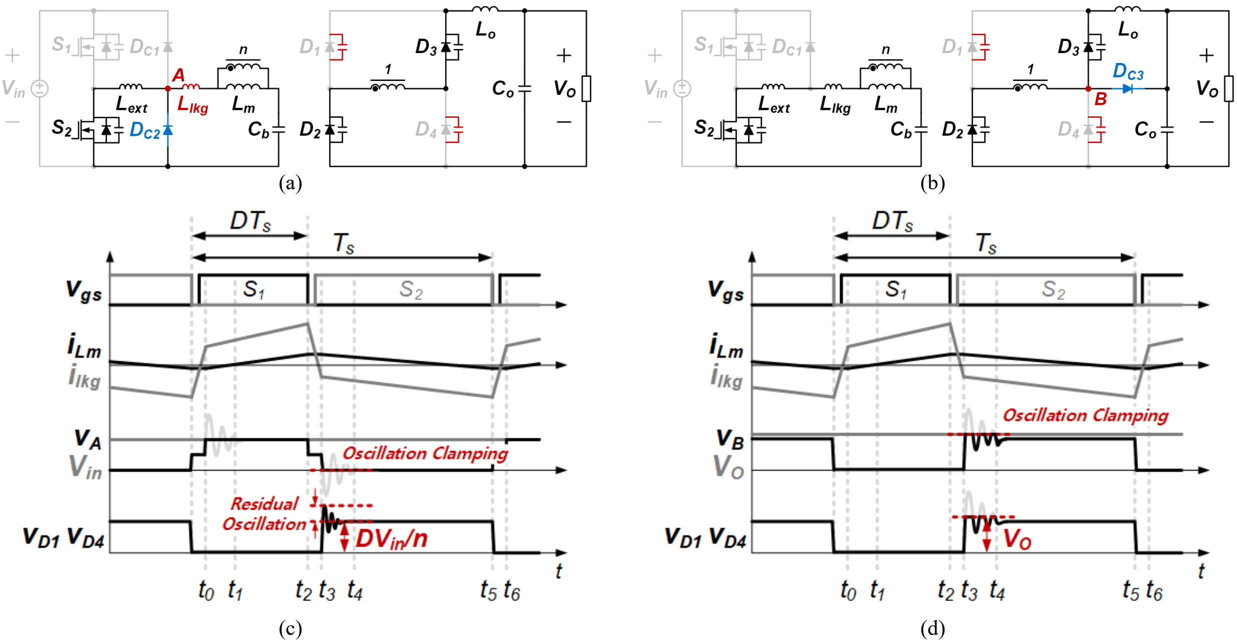


Fig. 6. Difference between the conventional clamp diode D_{C2} and the proposed clamp diode D_{C3}. (a) Circuit diagram of the AHB converter applying D_{C2}. (b) Circuit diagram of the AHB converter applying D_{C3}. (c) Key waveform of the AHB converter applying D_{C2}. (d) Key waveform of the AHB converter applying D_{C3}.

operating conditions, and is temporarily conducted momentarily when voltage oscillation occurs and clamps the voltage.

B. Difference between Conventional and Proposed Clamp Diode

As mentioned in the operational principle in chapter 2, the proposed clamp diode D_{C3} has the same principle as the conventional clamp diode D_{C2}. However, since the location of the clamp diode is different, the amount of clamping the voltage is different. Fig. 6 shows the conventional clamp diode for clamping the rectifier diodes D_1 and D_4, which have a lower voltage, and the circuit diagrams during the operation of the proposed clamp diode.

As shown in Fig. 6(a), the conventional clamp diode completely clamps V_A when the voltage of D_1 and D_4 oscillates. However, an internal leakage inductor L_{lkg} located between node A and the rectifier diodes, and resonance energy remaining in L_{lkg} cannot be removed through D_{C2}. Accordingly, this appears as the residual resonance of the rectifier diode, as shown in Fig. 6(c).

However, the proposed clamp diode, as shown in Fig. 6(b) directly clamps the voltage of node B, that is, the voltage of cathodes of D_1 and D_4. Therefore, unlike conventional clamp diode, residual resonance does not occur, and voltage oscillation exceeding V_O is eliminated as shown in Fig. 6(d).

In the case of applying each clamp diode, each voltage of the rectifier diodes, while accounting for voltage oscillation, are as follows [1]-[2]:

$$v_{D1,conv} = \left(\frac{DV_{in}}{n}\right) \times \left(1 + \sqrt{\frac{L_{lkg}}{L_{lkg} + L_{lkp}}} \sin \omega t\right) \tag{3}$$

$$v_{D1,prop} = V_O \tag{4}$$

The rectifier diode voltage applying the conventional clamp diode has a square root term due to residual resonance, whereas that with the proposed clamp diode is fixed to V_O, and there is no additional oscillation.

Meanwhile, since the center voltage in each case has different values of DV_{in}/n and V_O, the direct comparison may seem difficult. However, for the high-efficiency design of the AHB converter, the AHB converter should be designed so that the maximum operating duty operates close to 0.5, and referring to Fig. 5, in the case of D=0.5, DV_{in}/n is equal to V_O.

Rectifier diodes should be selected considering the worst case of voltage stress. When the conventional clamp diode is applied, the center voltage of resonance is V_O in the worst case(D=0.5), and additional resonance occurs as much as the square root term based on the center voltage as shown in (3). However, the proposed clamp diode always clamps the voltage of the rectifier diode to V_O.

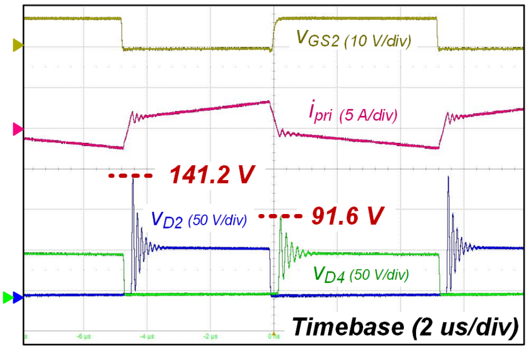
Consequently, when designing the AHB converter for high efficiency (with a maximum duty of D=0.5), the proposed clamp diode is superior to the conventional clamp diode in terms of clamping performance, and rectifier diodes with low voltage stress can be applied.

IV. Experimental Results

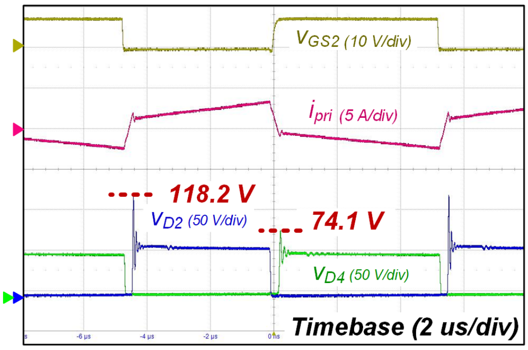
To validate the practicability of the proposed converter, 300W prototypes under 360-400 V input and 48 V output conditions are designed with the components stated in Table I and tested. Unlike conventional clamp diodes D_{C2}, the proposed clamp diode uses ES1B, which has low voltage and low current, to clamp D_1 and D_4 with a low voltage. In addition, to mitigate the voltage oscillations of D_2 and D_3, upper-side conventional clamp diode D_{C1} is

TABLE I
DESIGNED COMPONENTS OF PROTOTYPES

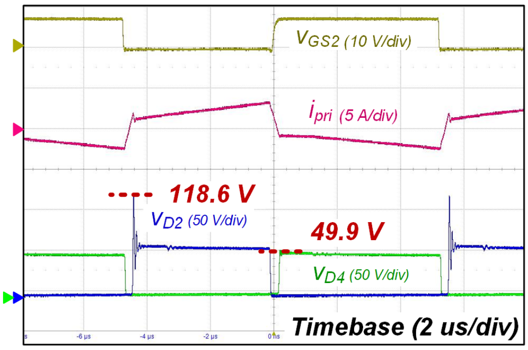
		AHB Converter without Clamp Diode	AHB Converter with D_{C1} and D_{C2}	AHB Converter with D_{C1} and Proposed Clamp Diode D_{C3}
Switching Frequency		100 kHz		
Primary Switch		IPP60R280P7 (650 V, 22 A, 280 mΩ, $C_{oss(er)}$=27 pF)		
Transformer		PQ2625 (390 μH, 27 : 8 turns, L_{lkg} = 7.2 μH)		
External Inductor		RM6 (6 μH, 8 turns)		
Rectifier Diode	Oscillation Comparison	D_2 & D_3: MBR40250G (250V, 0.86V_F) / D_1 & D_4: MBR20100CT (100V, 0.80 V_F)		
	Efficiency Comparison	MBR40250G (250V, 0.86 V_F) MBR20100CT (100V, 0.80 V_F)	MBR40250G (250V, 0.86 V_F) MBR1080CT (80V, 0.75 V_F)	MBR40250G (250V, 0.86V_F) MBR1060CT (60V, 0.65 V_F)
Clamp Diode		-	D_{C1}&D_{C2}: ES1J [2ea] (600 V, 1 A, 1.25 V_F)	D_{C1}: ES1J (600 V, 1 A, 1.25 V_F) D_{C3}: ES1B (100 V, 1 A, 0.95 V_F)
Output Inductor		CH234125 (190 μH, 43 turns)		



(a)



(b)



(c)

Fig. 7. Experimental result. (a) AHB converter without clamp diodes. (b) AHB converter with conventional clamp diodes D_{C1} and D_{C2} (c) AHB converter with D_{C1} and the proposed clamp diode D_{C3}.

applied.

In order to compare the voltage oscillations of the rectifier diodes under the condition with the same junction capacitor, oscillation comparison experiments are conducted by applying the same rectifier diodes. Fig. 7 shows the oscillation comparison of experimental waveforms of prototypes under 360 V input and full load conditions. In the case of the conventional clamp diode, it can be seen that the voltage of D_4 is reduced from 91.6 V to 74.1 V, but it can be confirmed that the voltage oscillation still occurs due to the effect of L_{lkg}.

However, in the case of the proposed clamp diode, it can be seen that almost all voltage oscillations occurring above the output voltage are removed. Accordingly, it can be confirmed that the voltage is clamped to 49.9 V, which is a smaller voltage than when the conventional clamp diode is applied. Therefore, the AHB converter with the D_{C3} can utilize a diode with a smaller voltage stress for D_1 and D_4, which will reduce conduction loss and increases efficiency.

Therefore, considering the maximum voltage stress of each rectifier diode, an efficiency comparison experiment is conducted by applying different rectifier diodes stated in table 1, and the results are shown in Fig. 8. The AHB converter with the proposed clamp diode has the same losses as the conventional AHB converters, and the conduction losses by D_1 and D_4 can be reduced. Therefore, it can achieve high efficiency under entire load conditions. Therefore, even though the proposed clamp diode has a smaller voltage rating, it has better clamping performance than the conventional clamp diode.

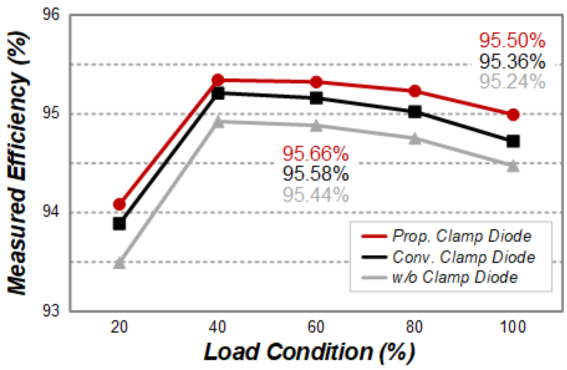


Fig. 8. Measured Efficiencies.

V. Conclusion

This paper proposes a novel clamp diode for the AHB converter that clamps the voltage oscillation of rectifier diodes, which have a low voltage. Unlike the conventional clamp diode, the proposed clamp diode can mitigate the voltage of the rectifier diode without creating any extra oscillation. Therefore, the AHB converter applying the proposed clamp diode can reduce conduction loss by applying rectifier diodes with lower voltage stress than conventional ones. Consequently, the proposed clamp diode can further improve the performance of various applications using the AHB converter.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.2021R1A5A1031868).

References

[1] R. Redl, N. O. Sokal, and L. Balogh, “A novel soft-switching full-bridge dc/dc converter: Analysis, design considerations, and experimental results at 1.5 kW, 100 kHz,” *IEEE Trans. Power Electron.*, vol. 6, no. 3, pp. 408-418, Jul. 1991.

[2] M. L. Heldwein, A. F. de Souza, and I. Barbi, “A primary side clamping circuit applied to the ZVS-PWM asymmetrical half-bridge converter,” i*n Proc. Power Electron. Spec. Conf*., 2000, pp. 199–204.

[3] R. Oruganti, P. C. Heng, J. T. K. Guan, and L. A. Choy, “Softswitched DC/DC converter with PWM control,” *IEEE Trans. Power Electron.*, vol. 13, no. 1, pp. 102-114, Jan. 1998.

[4] K. M. Cho, W. S. Oh, K. W. Lee, and G. W. Moon, “A new half bridge converter for the personal computer power supply,” *in Proc. IEEE Power Electron. Spec. Conf*., Aug. 2008, vol. 28, no. 5, pp. 986–991.

[5] M. Arias, M. F. Diaz, J. E. R. Cadierno, D. G. Lamar, and J. Sebastian, “Digital implementation of the feedforward loop of the asymmetrical half bridge converter for LED lighting applications,” *IEEE J. Emerg. Sel. Topics Power Electron*., vol. 3, no. 3, pp. 2539–2550, Sep. 2015.

[6] H. Mao, J. A. Qahouq, S. Luo, and I. Batarseh, “Zero-Voltage Switching Half-Bridge DC-DC Converter With Modified PWM Control Method,” *IEEE Trans. Power Electron*., vol. 19, no. 4, pp. 947-958, Jul. 2004.

[7] M. Arias, D. G. Lamar, F. F. Linera, D. Balocco, A. Aguissa Diallo and J. Sebastián, “Design of a soft-switching asymmetrical half-bridge converter as second stage of an LED driver for street lighting application,” *IEEE Trans. Power Electron*., vol. 27, no. 3, pp. 1608–1621, Mar. 2012.

[8] I. O. Lee and G. W. Moon, “A New Asymmetrical Half-Bridge Converter With Zero DC-Offset Current in Transformer,” *IEEE Trans. Power Electron*., vol. 28, no. 5, pp. 2297-2306, May. 2013.

[9] Y. S. Lai, Z. J. Su, and W. S. Chen, “New hybrid control technique to improve light load efficiency while meeting the holdup time requirement for two-stage server power,” *IEEE Trans. Power Electron*., vol. 29, no. 9, pp. 4763–4775, Sep. 2014.

[10] J. B. Lee, K. B. Park, J. K. Kim, H. S. Youn, and G. W. Moon, “A new center-tapped half-bridge zeta converter with small transformer dc-offset current and low voltage stress,” *IEEE Trans. Power Electron*., vol. 30, no. 12, pp. 6593–6603, Dec. 2015.

[11] S. Chakraborty and S. Chattopadhyay, “An improved asymmetric half bridge converter with zero DC-offset of magnetizing current,” in Proc. *IEEE Appl. Power Electron. Conf. Expo*., Mar. 2015, vol. 28, no. 5, pp. 1–8.

[12] J. I. Baek, J. K. Kim, J. B. Lee, H. S. Youn, and G.-W. Moon, “Integrated asymmetrical half-bridge zeta (AHBZ) converter for DC/DC stage of LED driver with wide output voltage range and low output current,” *IEEE Trans. Ind. Electron*., vol. 62, no. 12, pp. 7489–7498, Dec. 2015.

[13] J. K. Han, J. W. Kim and G. W. Moon, “A High-Efficiency Asymmetrical Half-Bridge Converter With Integrated Boost Converter in Secondary Rectifier,” *IEEE Trans. Power Electron*., vol. 32, no. 11, pp. 8237-8242, Nov. 2017.

[14] J. K. Han, J. W. Kim, B. H. Lee, J. S. Lai, and G. W. Moon, “High Efficiency asymmetrical half-bridge converter with a new coupled inductor rectifier (CIR),” *IEEE Trans. Power Electron*., vol. 34, no. 12, pp. 11541–11552, Dec. 2019

[15] J. Bae, J. S. Kim, M. Lee, J. K. Han, and G. W. Moon, “High-Efficiency Asymmetrical Half-Bridge Converter with Linear Voltage Gain,” *IEEE Trans. Power Electron*., vol. 37, no. 12, pp. 14850-14861, Dec. 2022.