Reduction Method of Recovery Current in a Bi-directional Chopper

Yusuke Fujita* Satoshi Miyawaki* Jun-ichi Itoh*

*Nagaoka University of Technology

Abstract:- This paper demonstrate a circuit to suppress the loss of recovery that occur in switching devices. The test circuit has structure that the body diode of a switching device does not flow a freewheeling current. Recovery current is not generated by a freewheeling current that flow through SiC-SBD. The two small inductors in the test circuit are coupled and compared. The experimental results confirmed that the test circuit achieves to suppress the loss of recovery in compared with the conventional circuit.

Keywords : Bi-directional chopper , Non-isolated , Recovery current , Coupled inductor

1. Introduction

Recently, non-isolated bi-directional DC/DC converters are actively researched. Compact size and high efficiency of DC/DC converters are desired for interconnecting with battery which is mounted in the EV and HEV [1-3]. The chopper circuit is useful for bi-directional power conversion due to simple structure of the circuit. However, the losses incurred in the body diode of the switching devices are matters [4].

This paper demonstrates a structure of a chopper circuit, which consists of two choppers. SiC - Schottky Barrier diode (SBD) and small inductors is added to the conventional chopper circuit. The test circuit can suppress the recovery loss due to by using SiC-SBD with superior characteristic freewheeling current. Therefore, the recovery current does not flow through the body diode of switching devices. As a result, it is possible to suppress the conduction loss of the body diode. In addition, the current paths can be varied by using the coupled inductors.

This paper discusses that which the structure of the suppression inductor is the best, a positive coupled, negative coupled or non-coupled .

2. Structure of circuit and operating principle

Fig. 1 shows the bi-directional test circuit which consist of step-down chopper and a boost-chopper. The test circuit has two characteristic structures; 1) The diodes are connected in series to each switching devices of the bi-directional chopper and 2) The inductor is connected to each of the connecting point of the switching device and the diode [5]. This structure can prevent a freewheeling current that flows through the body diode of the switching devices. A freewheeling current flows into the SiC-SBD with superior characteristic of switching time. The body diode of the switching device is not superior characteristic of switching time. Therefore, the conduction losses and the recovery losses of the diodes can be suppressed in comparison with the conventional circuit.

Fig. 2 shows the typical waveforms of the test circuit. In the buck chopper operation, there are five operating modes in one switching period of the test circuit.

Fig. 3 shows the current-flow path of test circuit for each mode. I_{load} is current that flows through L. The operating modes are described as follows.

1) Mode 1 : Fig. 3 (a) shows the current-flow path in the mode 1. In this mode, S_1 is turned on. S_2, D_1 and D_2 are turned off. Power of V_{DC} is transferred to the output. Further, L_1 and L store the magnetic energy from the input side.

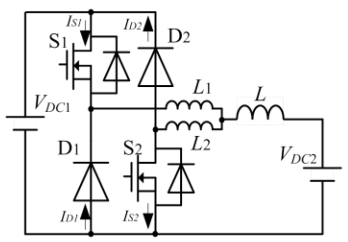

Fig. 1. Test circuit using two choppers.

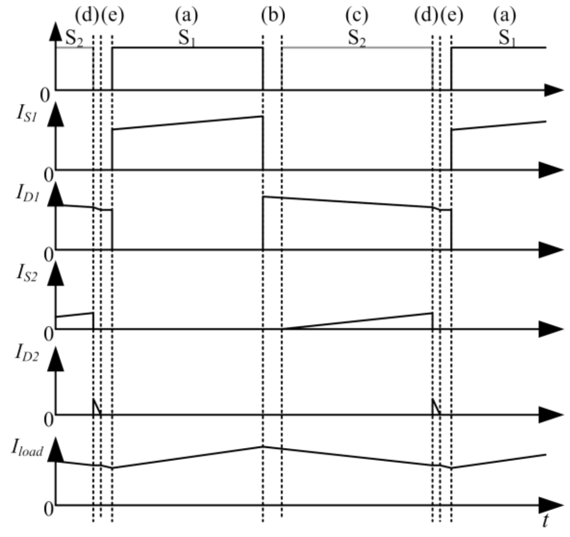

Fig. 2. Typical waveforms of the test circuit in a buck chopper operation.

2) Mode 2 : Fig. 3 (b) shows the current-flow path in the mode 2. In this mode, S_1 is turned off. S_2 and D_2 are turned off. A back electromotive force is induced in L_1 and L. As a result, a current keeps to flow in the same direction. Thus, a current flows through L_1, L, R, and D_1.

3) Mode 3 : Fig. 3(c) shows the current-flow path in the mode 3. In this mode, S_2 is turned on. S_1 and D_2 are turned off. D_1 is still on because a current keeps to flow through L_1. When S_2 is turned on, some of the current that has flew through L_1 flows through L_2. The current of L_2 is smaller compared with current of L_1. It should be noted that if the on-state voltage of S_2 is lower than that of D_1, the current flows in S_2. As a result, the conduction loss can be reduced in this circuit.

4) Mode 4 : Fig. 3(d) shows the current-flow path in the mode 4. In this mode, both of S_1 and S_2 are turned off. The current of L_2 flows through D_2, V_{DC} and D_1.

5) Mode 5 : Fig. 3(e) shows the current-flow path in the mode 5.

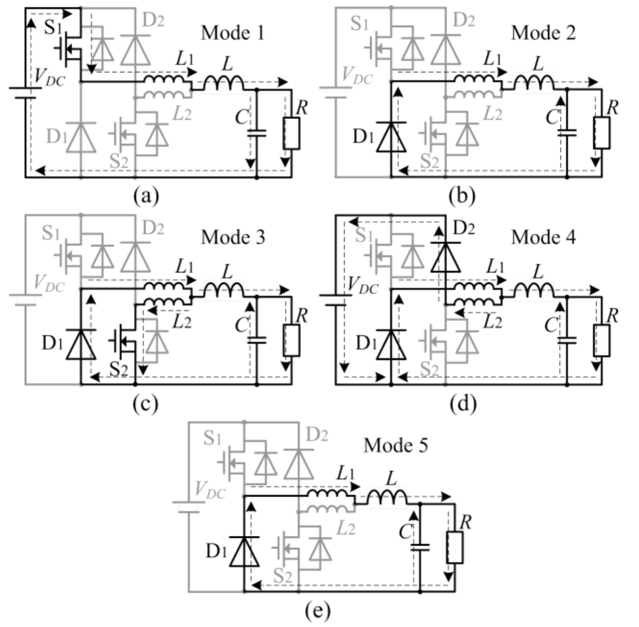

Fig. 3. Current flowing paths of test circuit at buck chopper operation.

(a)Non coupling (b)Positive coupling (c)Negative coupling

Fig. 4. The coupling direction of the inductors.

In this mode, S_1, S_2 and L_2 are turned off. This mode is the same as the mode2.

When the condition is changed from the mode 5 to the mode 1, the current flow D_1 in the test circuit. As a result, in case of D is SBD, the recovery current is not induced in the test circuit. In the conventional circuit, D is the body diode of S_2. Therefore, recovery current occurs in the conventional circuit

3. Coupled small inductors

The two inductors, L_1, L_2 can be magnetically coupled. In case of L_1 and L_2 are magnetically coupled, current flowing paths are different from the Fig. 3.

Fig. 4 shows the three kinds of the coupled inductor. Fig.4 (a) shows non-coupled inductors. Fig. 4 (b) shows positive coupled inductor which a mutual inductance M is positive Fig. 4 (c) shows negative coupled inductor which M is negative.

Fig. 5 shows the typical waveforms and Fig.6 shows the current-flow path of test circuit when the positive coupled inductor.

Fig. 7 shows the typical waveforms and Fig. 8 shows the current-flow path of test circuit when the negative coupled inductor.

In the buck chopper operation when the positive coupled inductor, there are five operating modes in one switching period. The operating modes are described as follows.

1) Mode 1 : Fig. 6(a) shows the current-flow path in the mode 1. In this mode, S_1 is turned on. S_2 and D_1 are turned off. The power of V_{DC} is transferred to the output. Further, both of L_1 and L store the magnetic energy. Furthermore, a back electromotive force is generated in L_2 because L_1 and L_2 are magnetically coupled. As a result, the current flows through D_2 to S_1.

2) Mode 2 : Fig. 6(b) shows the current-flow path in the mode 2.

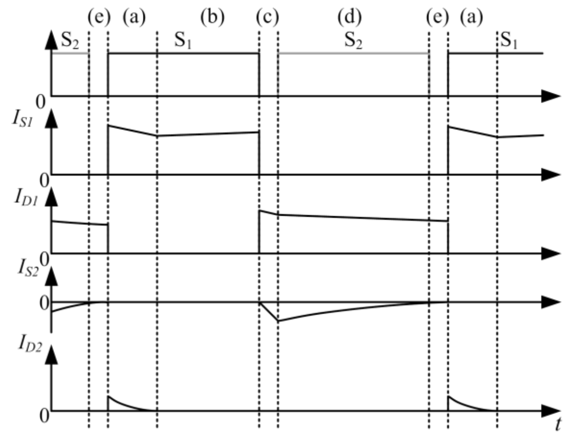

Fig. 5. Typical waveforms of the test circuit with the positive coupled inductor at buck chopper operation.

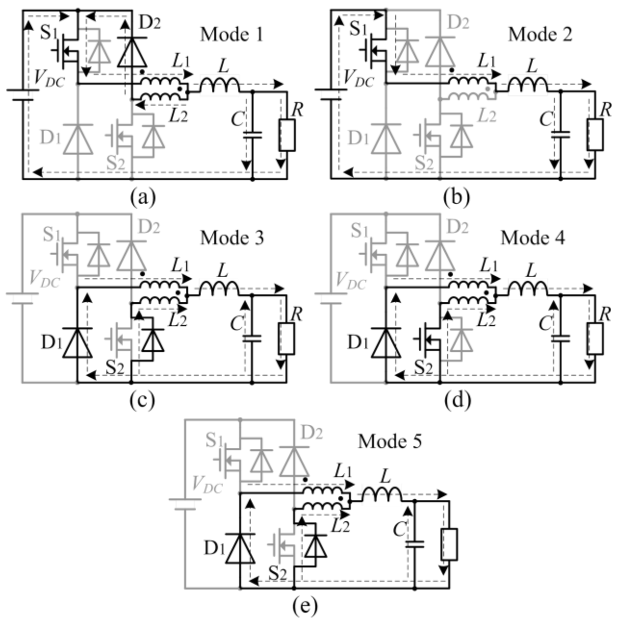

Fig. 6. Current flowing paths of test circuit with positive coupled inductor at buck chopper operation.

In this mode, S_1 keeps turn on. The current of L_1 is the steady state. Therefore, the back electromotive force is not generated in L_2. As a result, the current does not flow through L_2.

3) Mode 3 : Fig. 6(c) shows the current-flow path in the mode 3. In this mode, S_1 is turned off. The current of L_1 keeps to flow in the same direction due to the back electromotive force. Therefore, D_1 is turned on. Then the current of L_1 decreases. Therefore the back electromotive force is generated in L_1 and L_2. As a result, the current flows from the L_1 and L_2 to the L. Therefore, the current flows through the body diode of S_2.

4) Mode 4 : Fig. 6(d) shows the current-flow path in the mode 4. In this mode, S_2 is turned on. The current flows through the same paths of the mode 3. However, the current flow through on resistance instead of the body diode of S_2. The current of L_2 gradually decreases.

5) Mode 5 : Fig. 6(e) shows the current-flow path in the mode 5. In this mode, S_2 is turned off. The current flows through the same paths of the mode 3. The current of L_2 becomes almost zero.

In the buck chopper operation when the negative coupled

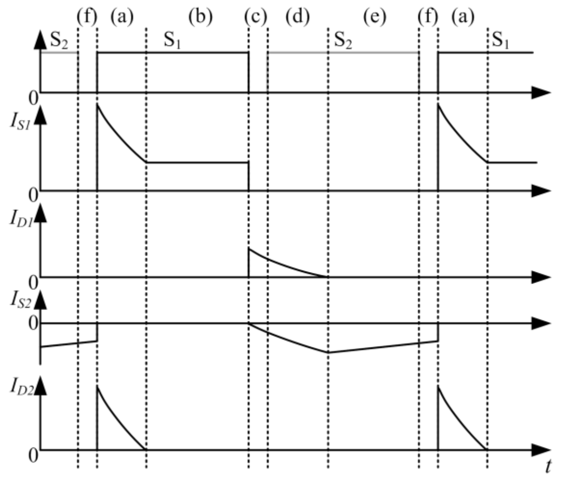

Fig. 7. Typical waveforms of the test circuit with negative coupled inductor at buck chopper operation.

inductors, there are six operating mode in one switching period. The operating modes are described as follows.

1) Mode 1 : Fig. 8(a) shows the current-flow path in the mode 1. In this mode, S_1 is turned on. S_2 and D_1 are turned off. The power of V_{DC} is transferred to the output. Further, L_1 and L store the magnetic energy. Furthermore the back electromotive force is generated in L_2 because L_1 and L_2 are magnetically coupled. As a result, the current flows through D_2 to S_1. This behavior is the same as the mode when the positive coupled inductors. However, larger current is generated. This cause is that the inductance of L_2 is increased by the mutual inductance.
2) Mode 2 : Fig. 8(b) shows the current-flow path in mode 2. In this mode, S_1 keeps turn on. The current of L_1 is the steady state. Therefore, the back electromotive force does not occur to the L_2. As a result, the current does not flow through L_2.
3) Mode 3 : Fig. 8(c) shows the current-flow path in the mode 3. In this mode, S_1 is turned off. The current of L_1 keeps to flow in the same direction due to the back electromotive force. Therefore, D_1 is turned on. In addition, the current of L_1 decreases. Therefore the back electromotive force is generated in L_1 and L_2. As a result, the current flows through the L_1 and L_2 to the load. Therefore, the current flows through the body diode of S_2.
4) Mode 4 : Fig. 8(d) shows the current-flow path in the mode 4. In this mode, S_2 is turned on. The current flows through the same paths of the mode 3. However, the current flow through on-resistance instead of the body diode of S_2. The current of L_2 gradually increases.
5) Mode 5 : Fig. 8(e) shows the current-flow path in the mode 5. In this mode, all of the stored energy of L_1 is discharged. As a result, the current of D_1 becomes zero. However, the current keeps to flow through S_2 to L_2.
6) Mode 6 : Fig. 8(f) shows the current-flow path in the mode 6. In this mode, S_2 is turned off. The current keeps to flow in the same direction. Therefore, the current flows through the body diode of S_2.

In the case that these coupled inductor is used, the advantage of the test circuit that "the current does not flow thorough the body diode of switching device" diminish due to couple with the small inductors.

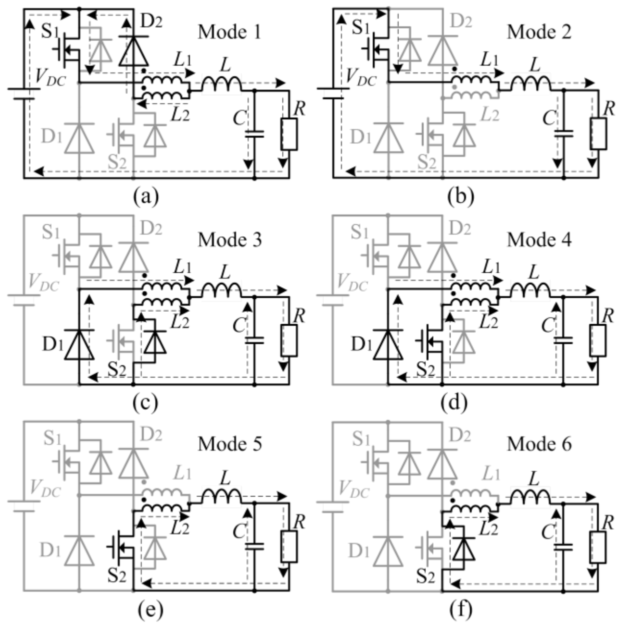

Fig. 8. Current flowing paths of test circuit with negative coupled inductor at buck chopper operation.

Table 1. Experimental parameters.

Input voltage	50 (V)	Duty	50 (%)
Switching frequency	300 (kHz)	Dead time	120 (ns)
MOSFET	H5N2508DS	Diodes	IDH06SG60C
L	270 (μH)	*C*	100 (μF)
R	33.6 (Ω)		

Table 2. Parameters of inductors.

	L_1[μH]	L_2[μH]	M[μH]
Non coupling (as shown in Fig. 4(a))	12.4	12.6	-
Positive coupling (as shown in Fig. 4(b))	12.2	12.2	11.1
Negative coupling (as shown in Fig. 4(c))	11.5	12.0	-10.6

4. Experimental results

The validity of the test circuit was confirmed by experiments. The waveforms are compared between the conventional circuit and the test circuit. The conventional buck chopper is operated by connecting the midpoint of the switching device and the diode in the test circuit. Table 1 shows the experimental parameters. Table 2 shows the parameters of small inductors and the coupled inductor.

Fig. 9 shows the experimental result of the conventional buck chopper circuit when S_1 is turned on. In this condition, the recovery current is generated in the body diode of S_2 because of a reverse voltage. The theoretical value of the reverse recovery time di_f/dt is 100A/μs. This value is given from the data sheet of the MOSFET which is used in the experiments. From Fig. 9, it is confirmed a forward current of S_2 is 0.8A and the reverse recovery time is 16ns. Therefore, measured reverse recovery time is 50 A/μs that is twice the theoretical value. This reason is that an increasing of the current is slowly because the switching device is closely connected to the inductor.

Fig. 10 shows the experimental result of the test circuit at the buck chopper operation. From Fig. 10, it is confirmed the recovery current does not occur. However, the high frequency oscillation occurs when S_1 is turned on. The cause of this oscillation is a

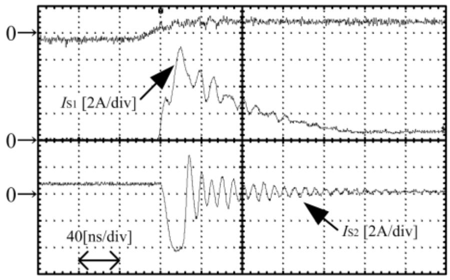

Fig. 9. Experimental result of conventional circuit.

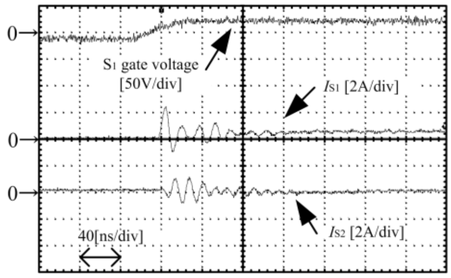

Fig. 10. Experimental result of test circuit at buck chopper operation.

resonance with the parasitic capacitance of the switch and wiring inductance of the circuit. This cause is proved by calculating the frequency with parameters of the circuit.

Fig. 11 shows the experimental result of the current of S_1 and D_1 in the condition that is the same as Fig. 10. The resonance occurs in the current of D_1 when the current path is changed from D_1 to S_1. However, the peak value of the resonance current of the test circuit is small compared with the conventional circuit. Therefore, the loss can be reduced. The experimental results confirmed that the test circuit could suppress the recovery current.

Fig. 12 and Fig. 13 shows the experimental results of the test circuit with a positive coupled inductor at the buck chopper operation. In use of a positive coupled inductor, the experimental result is similar to the result that the non-coupled inductor is used. In addition, the current that flows through the body diode of S_2 is lower than the conventional circuit. Therefore, the recovery current does not occur as shown in Fig. 13. From these experimental results, in the positive coupled inductor, the test circuit can suppress the recovery current as with the case that the non-coupled inductor is used. Therefore, the volume of the inductor can be reduced compared with the case that the non-coupled inductor is used.

Fig. 14 shows the experimental result of the test circuit with the negative coupled inductor at the buck chopper operation. In the negative coupled inductor, the current of S_1 is so large. Therefore, the current could achieve the maximum rated current of the device. The experimental result confirmed that the test circuit with the negative coupled inductor is not suitable.

5. Conclusion

In order to suppress the recovery current the body diode of switching devices, the test circuit is demonstrated at the bi-directional chopper by experiments. The experimental result confirmed the basic operation of the test circuit. In addition, it confirmed the test circuit can suppress the recovery current compared with the conventional circuit. Further, the volume of the inductor can be reduced by using the positive coupled inductor.

In future work, the optimum design of inductors will be discussed.

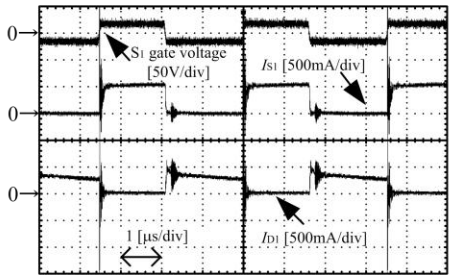

Fig. 11. Experimental result of the test circuit at buck chopper operation.

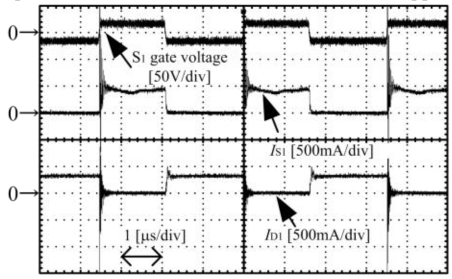

Fig. 12. Experimental result of the test circuit with positive coupled inductor at buck chopper operation.

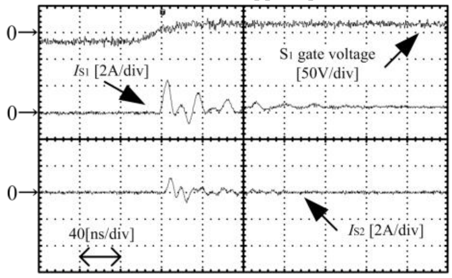

Fig. 13. Experimental result of test circuit with positive coupled inductor at buck chopper operation.

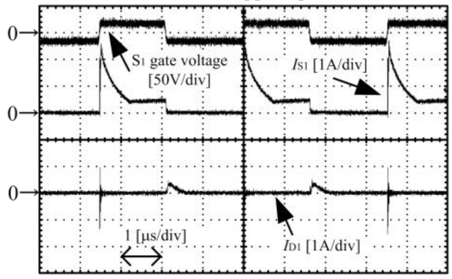

Fig. 14. Experimental result of the test circuit with negative coupled inductor at buck chopper operation.

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