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A New Three Winding Coupled Inductor - Assisted High Frequency Boost Chopper Type DC-DC Power Converter with a High Voltage Conversion Ratio

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ABSTRACT

In this paper, a novel circuit topology of a three-winding coupling inductor – assisting a high-frequency PWM boost chopper type DC-DC power converter with a high boost voltage conversion ratio and low switch voltage stress is proposed for the new energy interfaced DC power conditioner in solar photovoltaic and fuel cell generation systems. The operating principle in a steady state is described by using its equivalent circuits under the practical condition of energy processing of a lossless capacitive snubber. The newly-proposed power MOSFET boost chopper type DC-DC power converter with the three-winding coupled inductor type transformer and a single lossless capacitor snubber is built and tested for an output power of 500W. Utilizing the lower voltage and internal resistance power MOSFET switch in the proposed PWM boost chopper type DC-DC power converter can reduce the conduction losses of the active power switch compared to the conventional model. Therefore, the total actual power conversion efficiency under a condition of the nominal rated output power is estimated to be 81.1%, which is 3.7% higher than the conventional PWM boost chopper DC power conversion circuit topology.

Keywords: Boost chopper, DC-DC power converter, low voltage and large current power MOSFETs, new energy related power conditioner, automotive power DC feeding supply.

1. Introduction

In recent years, industrial requirements for small capacity UPS of telecommunication and information plants, automotive 36V/42V DC power supplies and new energy related DC feeding power conditioners (including solar photovoltaic cells and fuel cell-based generating systems) are becoming greater and greater [1-3]. From this technological background, the latest developments of the boost type PWM chopper fed DC-DC power converter circuit topology using power MOSFETs or IGBTs (which includes the high DC boost voltage conversion ratio in addition to the lowered switch peak voltage stress characteristics due to the spike voltage surge) are particularly required for low voltage large current DC feeding power supply sides in solar PV arrays, fuel cells,

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super capacitors and new battery types [4]-[5].

In this paper, an advanced boost chopper type DC-DC power converter with a high boost voltage conversion ratio and low switch voltage stress characteristics that incorporates a three winding coupled inductor configuration and a lossless snubbing capacitor is proposed. Its circuit description and operating principle in a steady state are described and compared with the conventional boost type PWM chopper-fed DC-DC power converter. It is actually proven in the feasible experiment that total actual efficiency of this power converter is improved compared to that of the two winding coupled inductor assisted conventional boost chopper type DC-DC power converter.

2. Circuit Configuration of Proposed Boost Converter

The newly-proposed boost PWM chopper type DC-DC power converter is schematically illustrated in Fig. 1 for a new energy related DC feeding power conditioner. The coupled inductors composed of two windings in addition to an auxiliary winding with a turn ratio of 1:n:m are incorporated in order to achieve a high boost DC voltage conversion and voltage clamp characteristics due to the diodes; D_{cmp1}, D_{cmp2}, the clamping snubber capacitor C_{cmp} and an auxiliary tertiary winding; m of the three-winding coupled inductor with one magnetic integrated circuit connected in parallel with single main active power switch SW; power MOSFET as well as the lossless capacitor snubber with the blocking diode; D_{cmp1}. Observing this circuit configuration, due to the leakage inductances of the three winding coupled inductors, the surge voltage or voltage spike generated across the active power switch SW can be clamped to its peak voltage stress which is much lower than the output voltage V_{out}. Moreover, only passive snubber circuit components; D_{cmp1}, D_{cmp2}, C_{cmp} and the tertiary winding inductor in addition to the two winding inductors are utilized in the voltage clamping circuit including the snubber capacitor. This shows that the control circuit implementation does not need to be modified in circuit structure when compared with that of the conventional boost chopper type DC-DC power converter with two winding coupled inductors.

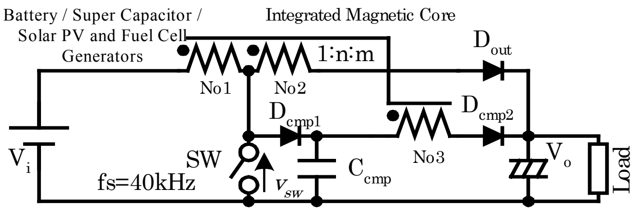

Fig. 1 The proposed high frequency PWM boost chopper type DC-DC power converter circuit with three winding coupled inductors

3. Convert Circuit Operation

The typical voltage and current waveforms are mainly depicted in Fig.2. The equivalent circuits of five operation modes are also illustrated in Fig. 3 in order to explain the operating principle.

Mode 0: The active power switch SW is in a conduction state and the magnetic energy is stored into inductor No.1 from the input voltage V_i.

Mode 1: The switch SW is turned off by its gate voltage signal pattern and the voltage v_{sw} across the active power switch SW increases linearly.

Mode 2: The voltage clamping diode (D_{cmp1}) turns on immediately and the current of the active power switch SW flows through the voltage clamping capacitor C_{cmp}.

The voltage clamping capacitor C_{cmp} operates as the lossless capacitive snubber during the turn off transition of the active power switch SW which can suppress its voltage spike surge. The switch voltage is then clamped to the voltage clamping capacitor (C_{cmp}) voltage and *dv/dt* value is suppressed by the capacitive snubber. The voltage across C_{cmp} can be determined by the auxiliary tertiary winding m of the three-winding coupled inductor windings.

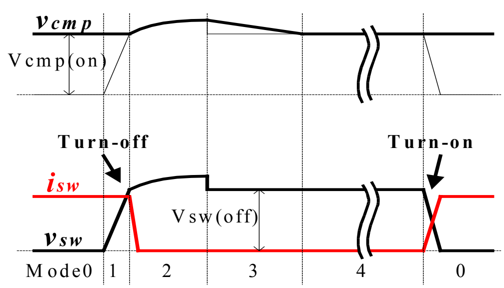

Fig. 2 Typical voltage and current operating waveforms for the operating modes

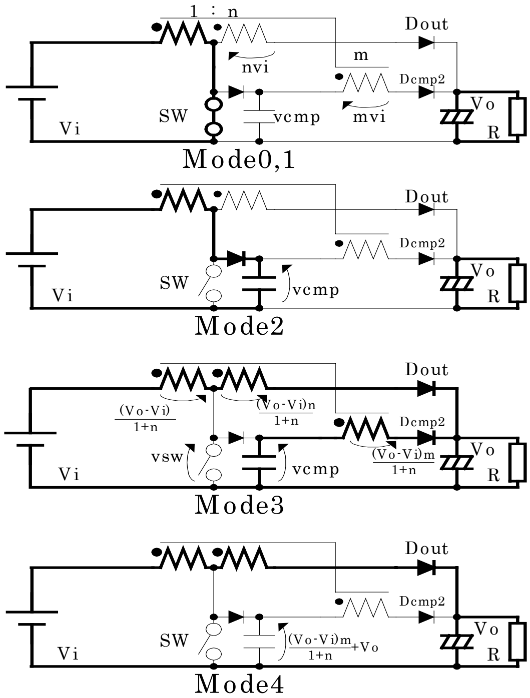

Fig. 3 Operating mode transitions and equivalent circuits

Mode 3: In this operating mode, the diode denoted as D_{cmp1} turns off under reverse biased condition. The energy stored in the capacitor C_{cmp} is partially discharged to the output load stage through the auxiliary tertiary winding m and the diode D_{cmp2}.

Mode 4: The diode denoted as D_{cmp2} turns off naturally and the voltage clamping capacitor C_{cmp} stops discharging. At the end of this operating mode, the active power switch SW turns on and the circuit operation of this converter moves to Mode 0.

4. Experimental Results and Discussions

4.1 Measured waveforms

The working principle and the steady state operating characteristics of the proposed boost chopper type DC-DC power converter using power MOSFET are verified by a 500W-40kHz experimental breadboard setup using a low voltage and a large current power MOSFET (FS30SM-05 x4). A power MOSFET with the voltage rating (250V) is utilized in order to compare with the conventional boost chopper type DC-DC power converter topology. The design specifications and circuit parameters of this boost chopper type DC-DC power converter shown in Fig.1 are as follows;

Input battery voltage V_i = 12V (Li battery), Output average voltage V_{out} = 180V, Chopper switching frequency;100 KHz, Three-winding coupled inductor device with only one magnetic core: Ferrite core PQ50, turns ratio: 7 : 35(n) : 33(m), Clamping snubber capacitor C_{cmp} = 4μF, Clamping diodes D_{cmp1}, D_{cmp2}: FML-23S and main Blocking diode D_{out}: FML-23S.

The switching voltage and current operating waveforms of the conventional boost chopper type DC-DC power converter without the clamping circuit including the auxiliary tertiary winding of the coupled inductors is shown in Fig. 4. The observed switching voltage and current operating waveforms of the proposed boost chopper type DC-DC power converter with the three-winding coupled inductors and the clamping diode-capacitor snubber circuit is represented in Fig. 5.

As can be seen, the peak voltage across the active power switch SW in Fig. 4 is 140V. However, in Fig. 5, the peak voltage across the active power switch is clamped to 48V, proving that the proposed clamping passive snubber circuit with the auxiliary tertiary winding is more effective in keeping the switch voltage lower than the output load voltage.

4.2 Performance Evaluations

The comparative actual efficiency characteristics of the proposed and conventional boost chopper type DC-DC power converter circuits without the clamping snubber circuit and with the proposed clamping power snubber circuit are depicted in Fig. 6.

The actual efficiency of the proposed boost chopper type DC-DC power converter circuit with the coupled inductors assisted by the clamping passive snubber circuit is shown to be sufficiently improved over the conventional DC-DC converter circuit. At the operating range of the full load, the improved effect on the actual efficiency becomes more and more remarkable. At the rated output power designed for the proposed boost chopper type DC-DC power converter circuit in the experiment, the actual efficiency has been increased from 77.4% with the conventional boost chopper type DC-DC power converter circuit to 81.1% showing a 3.7% improvement.

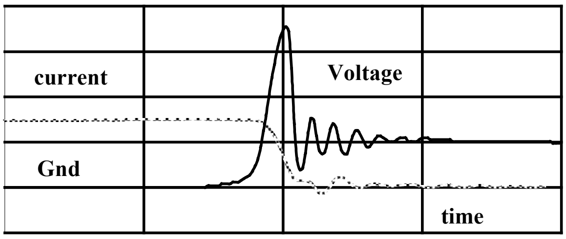

Fig 4 Switching voltage waveforms of the conventional converter without the clamp circuit

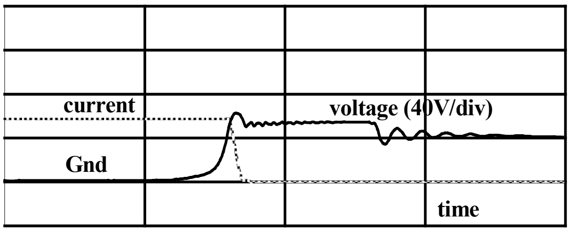

Fig 5 Switching voltage and current waveforms of the proposed DC-DC power converter circuit

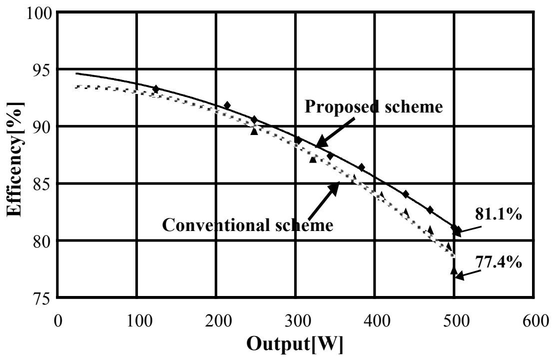

Fig. 6 Comparative actual efficiency vs. output power characteristics

5. Conclusions

In this paper, an advanced topology of a three winding coupled inductor and a lossless capacitive snubber-assisted boost PWM chopper type DC-DC power converter with a high voltage conversion ratio and low voltage peak stress was proposed originally for a new energy related power conditioner such as solar photovoltaic and fuel cell power generations. From experimental results, the proposed boost chopper type DC-DC power converter circuit could efficiently work with high efficiency performances and switch peak voltage suppressed with a comparatively lowered voltage rating. The actual efficiency and the reduced switch voltage of the proposed DC-DC power converter with a simple auxiliary voltage clamping lossless snubber capacitor circuit including an auxiliary tertiary winding coupled inductor, could be improved when compared with the conventional boost chopper type DC-DC power converter circuit without an auxiliary clamping snubber circuit.

References

[1] T. F. Wu, S. A. Liang, "A Systematic Approach to Developing Single Stage Soft Switching PWM Converters", *IEEE Transactions on Power Electronics*, Vol. 16, No. 5, pp. 581-593, September 2001.

[2] K. M. Smith, K. M. Smedley, "Engineering Design of Lossless Passive Soft Switching Methods for PWM Converters – Part I; With Minimum Voltage Stress Circuit Cells", *IEEE Transactions on Power Electronics*, Vol. 16, No. 3, pp. 336-344, May 2001.

[3] Y. Xi, P. K. Jain, Y. F. Liu, R. Orr, "A Self Core Reset and Zero Voltage Switching Forward Converter Topology", *IEEE Transactions on Power Electronics*, Vol. 15, No. 6, pp. 1192-1203, November 2000.

[4] C. Y. Inaba, Y. Konishi, H. Iyomori, and M. Nakaoka "Performance Evaluations of Coupled Inductor-Assisted High Frequency PWM Chopper Type DC-DC Converters", *28th Annual Proceedings of IEEE IECON 2002*, Vol. 1, pp. 43-48, November 2002.

[5] K. Hirachi, M. Yamanaka, K. Kajiyama, S. Isokane: "Circuit Configuration of Bidirectional DC-DC Converter Specific for Small Scale Load Leveling System", Proceedings of IEEJ PCC Osaka, pp. 603-609, April 2002.

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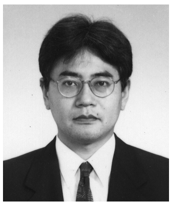

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