

Comparison of Active-Clamp and ZVT Techniques Applied to Tapped-Inductor DC-DC Converter with Low Voltage and Large Current

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Abstract

This paper compares three kinds of soft-switching circuits from viewpoints of surge suppression, load characteristic, and power efficiency for a tapped-inductor buck converter with low voltage and high current. As a result, these soft-switching techniques have achieved much higher efficiency of 80% when compared with a hard-switching buck converter for the output condition of 1V and 20A.

Key word: tapped-inductor, active-clamp, ZVT

1. Introduction

In recent LSI technologies, the power supply voltage has become much lower than the conventional one. In order to produce a lower voltage of 1 volt by the conventional DC-DC converter, its duty ratio is made much smaller. However, the small duty ratio results in the decrease in power efficiency. In order to achieve a large voltage-conversion ratio, a forward converter with a big turns ratio of transformer windings can be considered, but two magnetic components of transformer and inductor are needed. Many years ago, DC-DC converters with a tapped inductor which has two functions of voltage conversion and filter inductor were examined[1-3]. We have proposed the usage of the tapped-inductor buck converter to maintain a medium duty ratio even for the lower output voltage[4,5]. However, this tapped inductor has a leakage inductance, and a big surge voltage is generated across the switch during its turn-off time. Therefore, to suppress the surge voltage, some soft-switching techniques are required. So far, two typical soft-switching techniques have been developed, i.e. an active-clamp type[6,7] and a Zero-Voltage Transition (ZVT) type[8].

In this paper, three kinds of soft-switching circuits are examined and compared from viewpoints of surge suppression, load characteristic, and power efficiency when using the tapped-inductor buck converter under the output condition of 1V and 20A. As a result, it is experimentally confirmed that these soft-switching techniques are effective for surge suppression and efficiency improvement.

2. Circuit topology and operation

Figure 1 shows a tapped-inductor type buck converter. This circuit utilizes the tapped inductor as a filter inductor and a transformer where the voltage conversion ratio can be arbitrary determined through the design of its winding turns ratio.

Next, the basic circuit operation is explained. While the main switch S1 is ON, the tapped inductor becomes the inductance with number of turns of N_1+N_2 and is excited by voltage $V_{in}-V_o$. On the other hand, while the main switch S1 is OFF and the synchronous rectifying switch S2 is ON, this tapped inductor becomes the inductance with number of turns of N_2 and is excited by voltage V_o . Assuming the magnetic flux balance of the tapped inductor in the continuous-conduction mode and neglecting internal resistance, the relation of input and output voltages is expressed with the following equation:

$$V_o = \frac{D}{D + \frac{N_1 + N_2}{N_2}(1-D)} V_{in} \quad (1)$$

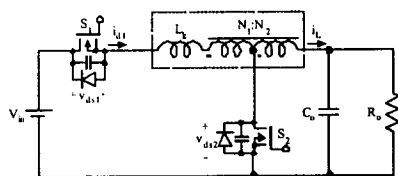


Fig. 1. Tapped-inductor type buck converter.

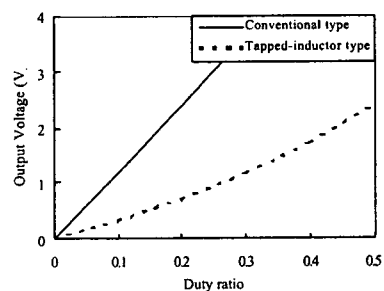


Fig. 2. Control characteristics of conventional type and tapped-inductor type

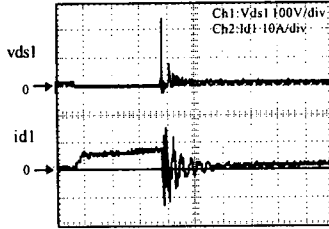


Fig.3. Waveforms associated with main switch in case of conventional type.

This equation shows that the output voltage can be chosen arbitrary by designing the winding turns ratio of the tapped inductor and the duty ratio of the main switch. As seen from the result shown in Fig.2, where the control characteristics of the conventional and the tapped-inductor buck converters are compared, an extremely small duty ratio is required to obtain a low output voltage in the conventional buck converter, and the small duty ratio results in the power efficiency decrease. On the other hand, in case of the tapped-inductor converter with an appropriate ratio of the winding turns, a low voltage can be obtained for a medium duty ratio around 0.5, and it can maintain the high efficiency.

However, this tapped inductor has a big difficulty. It is due to the leakage inductance associated with the tapped inductor, and a big surge voltage of several hundred volts is generated across the switch during its turn-off time as shown in Fig.3. In order to suppress the surge voltage, some soft-switching techniques are required. So far, two typical soft-switching techniques have been developed, i.e. an active-clamp type and a Zero-Voltage Transition (ZVT) type.

In the next section, three kinds of soft-switching circuits are illustrated and their operations are described.

3. Circuit topology and operation for surge absorption

a) Active-Clamp Type

The tapped-inductor buck converter with an active-clamp circuit is shown in Fig.4, where the active-clamp circuit is composed of a clamp switch S3 and a clamp capacitor Ca. In this circuit, a synchronous rectifier switch S2 is also used to decrease the power loss under the condition of a low voltage and high current.

In this case, this active-clamp circuit absorbs the energy stored in the leakage inductance Lk, and reduces the surge voltage across the main switch. Furthermore, this absorbed energy is recovered to the output side and is also used to achieve the Zero-Voltage Switching(ZVS) of the main switch.

One switching period is divided into six states as shown by the key waveforms in Fig.5. Figure 6 shows the experimental

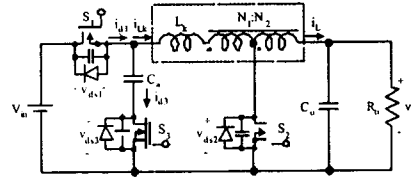


Fig.4. Active-clamp type tapped-inductor buck converter with synchronous rectifier.

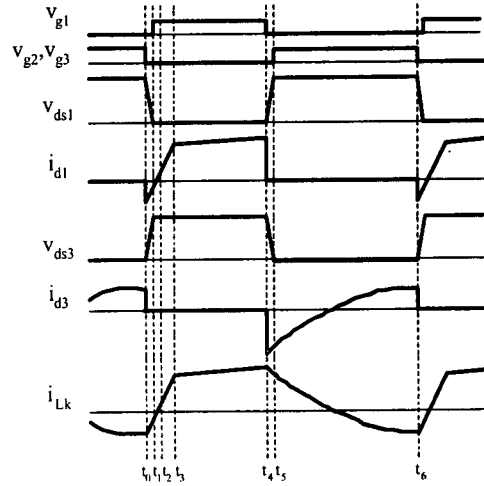


Fig.5. Key waveforms of active-clamp type.

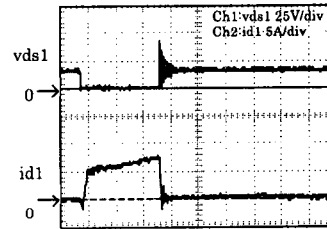


Fig.6. Experimental waveforms associated with main switch in case of active-clamp type.

waveforms of voltage and current associated with the main switch S1. As seen from these waveforms, the ZVS operation was confirmed, but the voltage clamping during turn-off time was not complete due to parasitic inductances in the wire and ESL in the clamp capacitor.

b) ZVT Type (1)

When ZVT is applied to the tapped-inductor buck converter, a few circuit topologies can be considered. Firstly, a topology shown in Fig.7 is examined. In this case, the stored energy in the leakage inductance Lk is absorbed in the snubber capacitor C during turn-off time of the main switch, and then by turning on the auxiliary switch S3 just before turning on the main switch, the absorbed energy is transferred to an auxiliary small-size transformer, and then is recovered to the output side. One switching period is divided into eleven states as shown by the key waveforms in Fig.8. Equivalent circuits

corresponding to these states are shown in Fig.9. The simplified explanation for the operation in each state is as follows:

At first, when the auxiliary switch S3 is turned on just before turning on the main switch S1. The current flows from the snubber capacitor C through transformer's primary winding, switch S3, secondary winding, and diode D, and then the stored energy in snubber capacitor is transferred to the transformer Tr (State 3). After all the energy in the snubber capacitor moves to the auxiliary transformer, the current flows through the body diode of the main switch. Turn on the main switch during this interval (State 4), and Zero-Voltage Switching of the main switch S1 is achieved. Next, when the auxiliary switch S3 is turned off, the stored energy in the auxiliary transformer is transferred to the output side (State 5).

Consequently, the surge energy due to the transformer leakage inductance is recovered, and the higher efficiency is achieved.

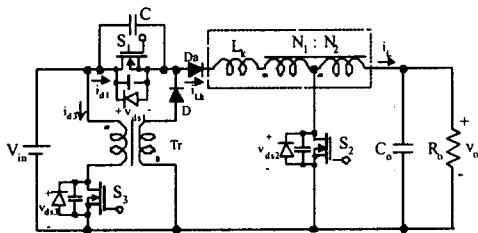


Fig.7. ZVT type 1 tapped-inductor buck converter with synchronous rectifier.

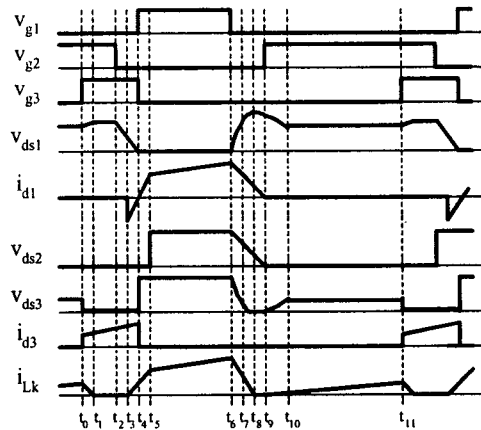


Fig.8. Key waveform of ZVT type 1.

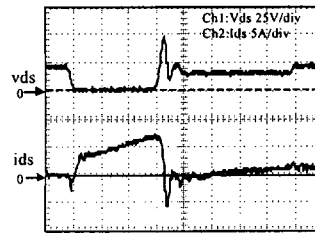


Fig.10. Waveforms associated with main switch in case of ZVT type 1.

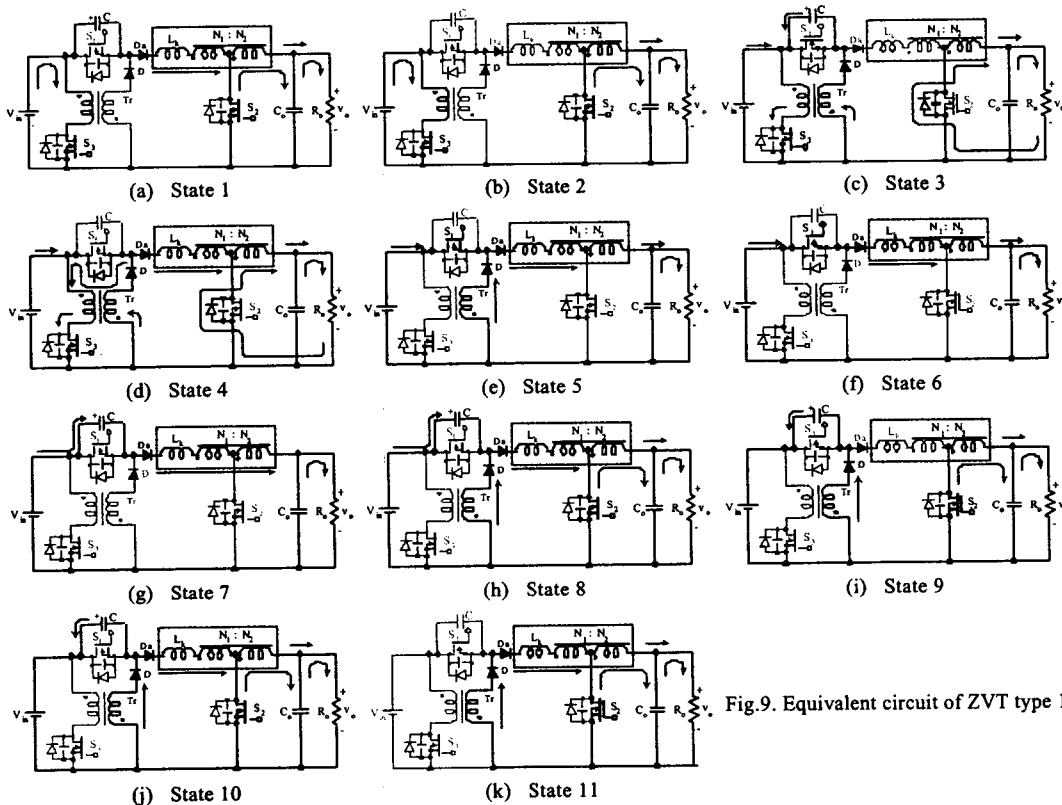


Fig.9. Equivalent circuit of ZVT type 1.

Figure 10 shows the experimental waveforms of voltage and current associated with the main switch S1. In this case, the ZVS operation of the main switch has been confirmed, though a voltage oscillation for a short period is not suppressed.

b) ZVT Type (2)

Consider another ZVT topology shown in Fig.11, where an auxiliary transformer is not needed. The absorbed energy in the snubber capacitor is transferred through the tapped inductor to the output side. One switching period of this converter is divided into six states as shown by the key waveforms in Fig.12.

Figure 13 shows the experimental waveforms of voltage and current associated with the main switch S1. In the original circuit without diode Da, a high-frequency oscillation occurs across the main switch as shown in Fig. 13, and it is due to the

resonant circuit composed of Lk and C. In order to remove this oscillation, diode Da is inserted in series. As a result, the oscillation was removed as shown in Fig.14. On the other hand, the clamped voltage was twice higher than the previous one.

4. Experimental comparison of total characteristics

Three types of soft-switching circuits mentioned above are compared concerning the steady-state characteristics.

Firstly, the load characteristic is compared in Fig.15 in case of no voltage regulation. Secondly, the power efficiency is compared in Fig.16. In these figures, the tapped-inductor

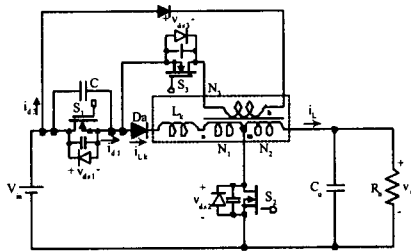


Fig.11. ZVT type 2 tapped-inductor buck converter with synchronous rectifier.

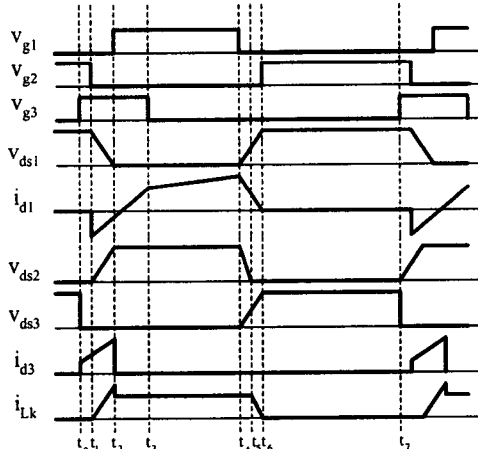


Fig.12. Key waveform of ZVT type 2.

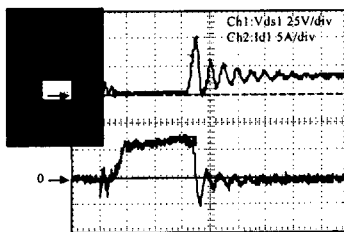


Fig.13. Waveforms associated with main switch in case of ZVT type 2.

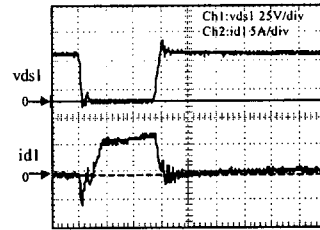


Fig.14. Waveforms associated with main switch in case of ZVT type 2 with diode Da.

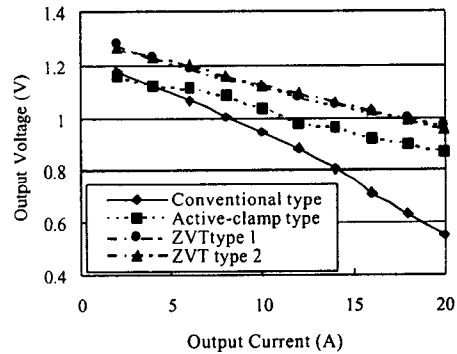


Fig.15. Load characteristics.

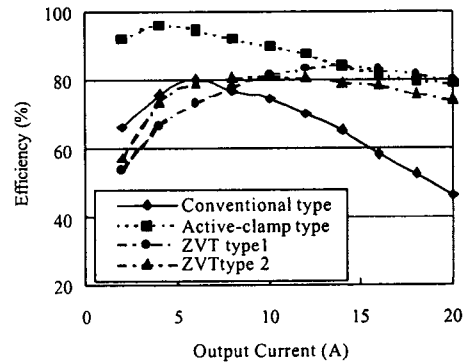


Fig.16. Efficiency characteristics.

converter without any soft-switching circuit is also compared, where a high-voltage MOSFET was used to operate under a big surge voltage and it resulted in the efficiency decrease at heavier load current.

As seen from these results, it is evident that the soft-switching techniques are very effective for efficiency improvement of the tapped-inductor buck converter. Among them, the active-clamp type looks a little superior to the others, and has achieved a high efficiency of 92% under the output condition of 1.1V and 4A for the input voltage of 12V. Even for the heavier load current of 20A, a high efficiency of 80% has been achieved.

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