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

Keywords: 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 1volt 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]. Rrecently, the usage of the tapped-inductor buck converter to maintain a medium duty ratio even for the lower output voltage has been proposed[4-6]

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[7,8] and a Zero-Voltage Transition (ZVT) type[9]

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

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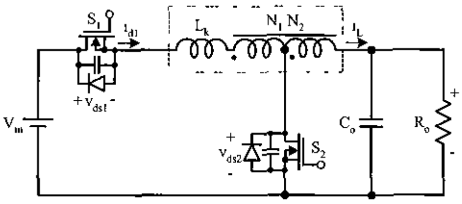


Fig 1 Tapped-inductor type buck converter

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 N1+N2 and is excited by voltage Vin-Vo 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 N2 and is excited by voltage Vo 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:

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

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,

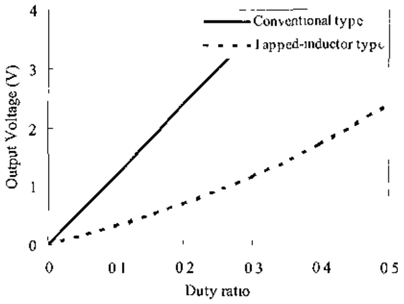


Fig 2 Control characteristics of conventional type and tapped-inductor type

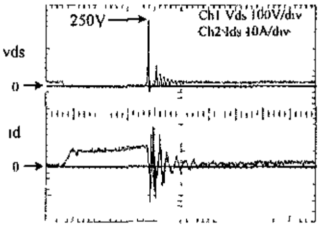


Fig 3 Waveforms associated with main switch in case of conventional type

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

3.1 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 waveforms of voltage and current associated

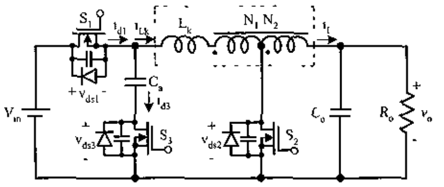


Fig 4. Active-clamp type tapped-inductor buck converter with synchronous rectifier

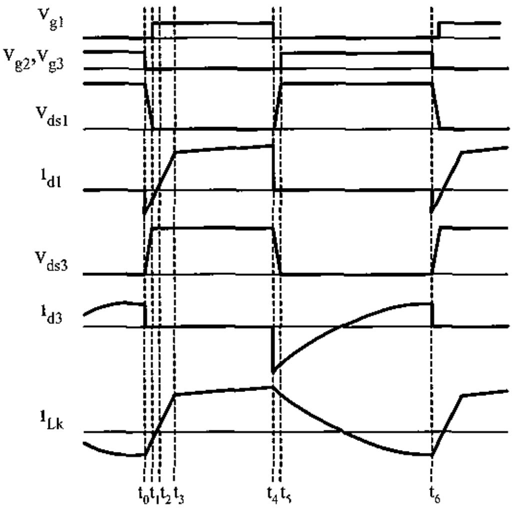


Fig 5 Key waveforms of active-clamp type

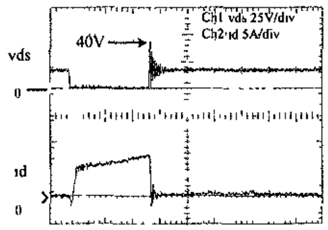


Fig 6 Experimental waveforms associated with main switch in case of active-clamp type

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.

3.2 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:

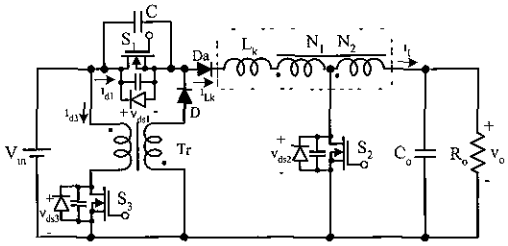


Fig 7 ZVT type 1 tapped-inductor buck converter with synchronous rectifier

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).

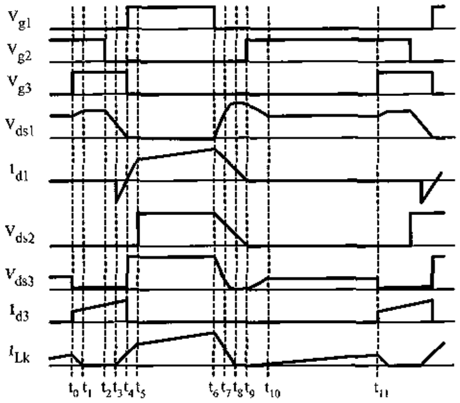
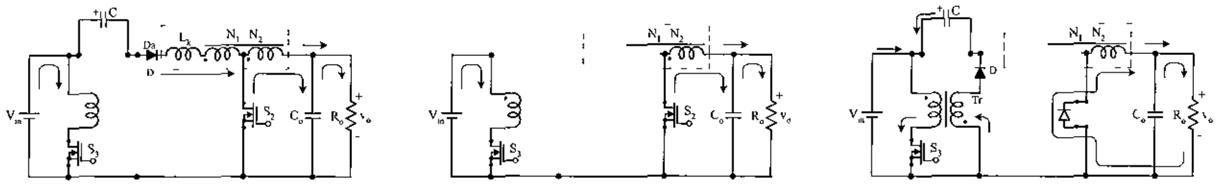
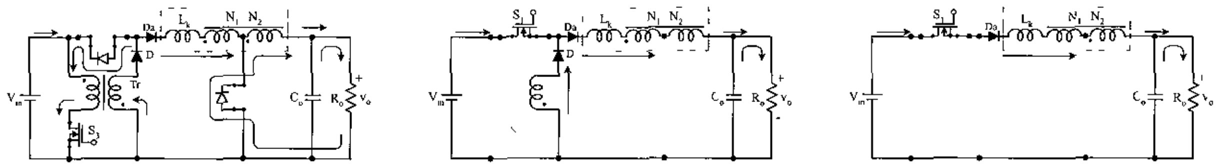


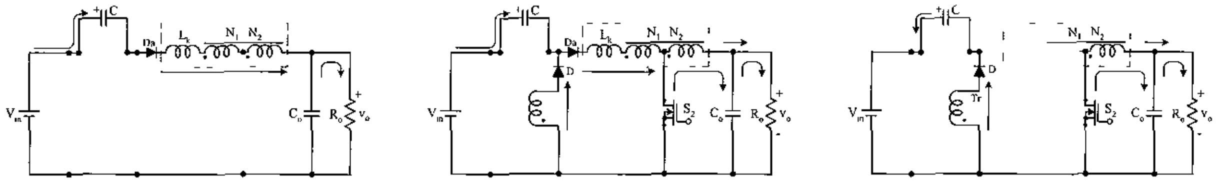
Fig 8 Key waveforms of ZVT type 1



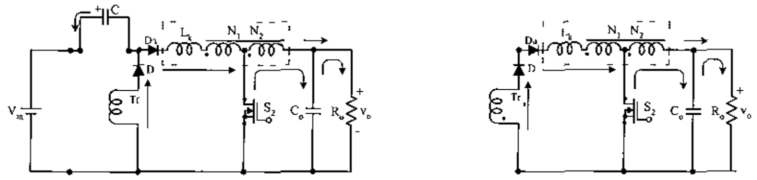
(a) State 1 (b) State 2 (c) State 3



(d) State 4 (e) State 5 (f) State 6



(g) State 7 (h) State 8 (i) State 9



(j) State 10 (k) State 11

Fig 9 Equivalent circuit of ZVT type 1

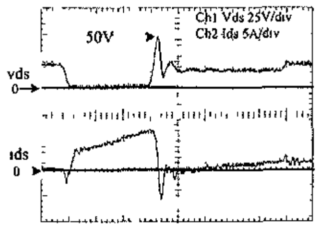


Fig 10 Experimental waveforms associated with main switch in case of ZVT type 1

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

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.

3.3 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.

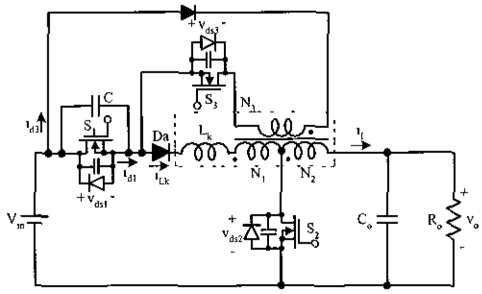


Fig 11 ZVT type 2 tapped-inductor buck converter with synchronous rectifier

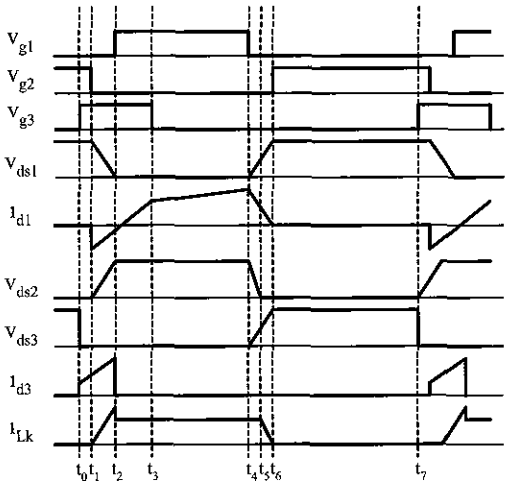


Fig 12 Key waveforms of ZVT type 2

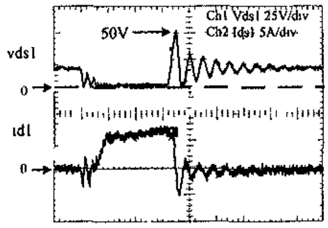


Fig 13 Experimental waveforms associated with main switch in case of ZVT type 2

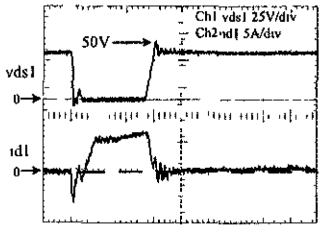


Fig 14 Experimental waveforms associated with main switch in case of ZVT type 2 with diode Da

4. Experimental comparison of total characteristics

Three types of soft-switching circuits mentioned above were examined in the experiment The experimental values used for circuit parameters are shown below

The common conditions are as follows:
Switching frequency · 100kHz,
Input voltage : 12V,
Output condition . 1V/20A,
Tapped-inductor N1:N2=3 1,
Leakage inductance 100nH,
Output capacitor · 660μF,
a) Active-clamp type:
Clamp capacitor 30μF,
b) ZVT type (1)
Sunbber capacitor 15nF,
c) ZVT type (2).
Sunbber capacitor . 15nF,

The surge voltages across the main switch have been already shown in Figs 6, 10, and 14. From these results, the surge voltage was the most suppressed in case of the active-clamp method However, a high-frequency ringing remained due to parasitic inductances included in some devices and wires.

Next, the comparison of steady-state characteristics is discussed Firstly, the load characteristics with the feedback regulation are compared in Fig 15. Secondly, the power-efficiency characteristics are compared in Fig 16. In these figures, the tapped-inductor 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 all the soft-switching techniques are very effective for efficiency improvement of the tapped-inductor buck converter, and that the efficiency was improved by a factor of 30% under the full-load condition of 20A.

Comparing three types of soft-switching techniques, the active-clamp type looks a little superior to the others, and has achieved the maximum efficiency of 87% under the output condition of 1V / 10A for the input voltage of 12V.

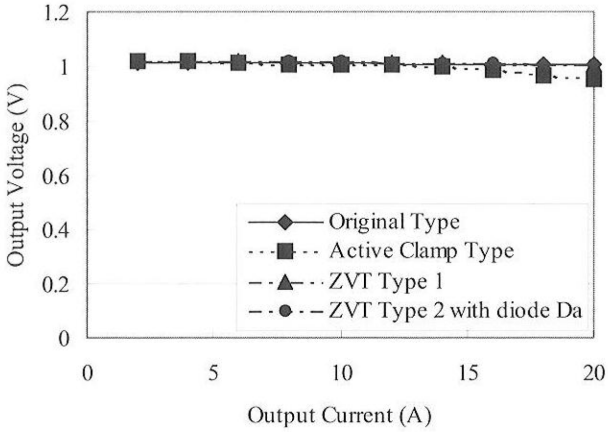


Fig. 15. Load characteristics.

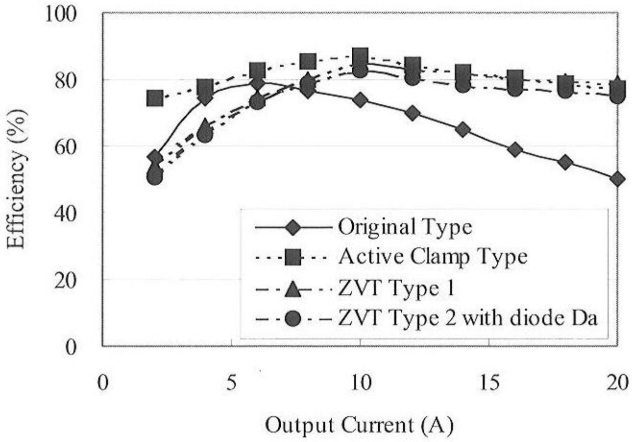


Fig. 16. Efficiency characteristics.

5. Conclusions

Three types of soft-switching techniques for a tapped-inductor buck converter have been examined experimentally.

As a result, the following conclusions were obtained:

(1) All types of soft-switching techniques are very effective for surge voltage suppression and power-efficiency improvement.

(2) Among three types, the active-clamp type looks a little superior to the others from the viewpoint of power efficiency, but a high-frequency voltage ringing remains at the turnoff instant due to some parasitic inductances.

(3) The total evaluation needs the circuit simplicity including also driving circuits for high-side switches as well as the power efficiency.

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