An Improved Modulation Strategy on Boost Soft-Switching Converter

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Abstract: In order to improve the modulation strategy of zero-voltage zero-current transition boost converter, an improved modulation strategy was put forward in this paper. The main switch can only achieve zero-current turn-on under traditional modulation strategy. However, the change to the turn-on time of main switch can make the main switch achieve zero-voltage zero-current turn-on, and the change to the turn-off time of auxiliary switch can realize the zero-voltage zero-current turn-off of auxiliary switch in advance as well. The simulation results verify the correctness of improvement.

Key words: Modulation strategy, boost converter, zero-voltage zero-current turn-off.

1. Introduction

Whether electric appliances and electronic devices have broad market is related to their performance, size, cost and power consumption [1], [2]. But transformers, inductors, and capacitors can hardly meet the need of volume and weight in practical engineering application. With the increase of switch frequency, the voltage and current cannot be zero at the same time, leading to generate overlapping region [3], [4], when the switch is turned on (or turned off). The switch working in hard-switching state produce switch loss. The introduction of soft-switching technology can eliminate the power loss of switch completely by adding small inductors, capacitors and other components in the circuit, whose principle is the resonance between the inductor and capacitor [5], [6].

Zero transition PWM circuit, including zero-current transition PWM circuit and zero-voltage transition PWM circuit [7], [8], is applied extensively in different circuits. There are two methods to improve circuit working efficiency [9], the first method is to improve the modulation strategy, another method is to improve the circuit working efficiency. This study is based on the second method. In paper [10], a zero-current zero-voltage transition PWM boost converter was put forward, which was formed by the application of zero transition circuit into boost converter and whose main switch can achieve zero-current turn-on under traditional modulation strategy. The change to the modulation strategy can make main switch achieve zero-voltage zero-current turn-on and auxiliary switch achieve zero-voltage zero-current turn-off in advance.

2. Boost Soft-Switching Converter Working Principle and Mode Analysis

2.1. Boost Soft-Switching Converter Circuit Working Principle

The boost soft-switching converter in Fig. 1 is the circuit proposed in paper [9], which contains zero-current transition PWM circuit within the dotted line. The zero-current transition PWM circuit is applied into boost circuit, which can get zero-current turn-on and zero-voltage turn-off of main switch S_1 and zero-current turn-on and zero-current zero-voltage turn-off of auxiliary switch S_2 . The input inductor is split into two split inductors L_1 、 L_2 , while the resonant branch consist of two diodes D_1 、 D_3 , resonant inductors L_1 、 L_2 、 L_3 , resonant capacitor C_1 and auxiliary switch S_2 with anti-parallel diode.

Fig. 1. Boost soft-switching converter.

2.2. Mode Analysis

The electronic devices in the circuit can be regarded ideally, the photovoltaic arrays are considered as ideal voltage source as well. Resonant inductors $L1$ and $L2$ are two split inductors of main inductor of boost converter, with a value of $L/2$, meanwhile, the value of resonant inductor s $L1$ and $L2$ are far more than resonant inductor $L3$, therefore, the resonant inductors $L3$ is neglected, the circuit has seven circuit working modes:

2.2.1 Working mode 1 $[t_0, t_1]$

Fig. 2 shows the equivalent circuit of mode 1, the voltage of resonant capacitor C_1 reach to its peak value U_0 before t_0 . At t_0 , the auxiliary switch achieve zero-current turn-on. After t_0 , the current i_{S2} flowing through auxiliary switch S_2 increase nonlinearly and the current flowing through resonant inductor L_1 increase linearly, while the current i_{L2} flowing through resonant inductor L_2 decrease linearly and the voltage of resonant capacitor C_1 decrease nonlinearly. All the parameters change as following:

$$u_{L1} = u_{C1} - u_0 \quad (1)$$

$$u_{L1} = L_1 \frac{di_{L1}}{dt} \quad (2)$$

$$i_{L1} = C_0 \frac{du_{C0}}{dt} + \frac{u_0}{R_1} \quad (3)$$

The followings can be obtained from the formulas (1)、(2)、(3):

$$\frac{di_{L1}}{dt} = \frac{2u_{L1}}{L} \quad (4)$$

$$\frac{du_{C0}}{dt} = \frac{1}{C_0} i_{L1} - \frac{u_{C0}}{R_1 C_0} \quad (5)$$

Fig. 2. Boost soft-switching converter.

2.2.2 Working mode 2 $[t_1, t_2]$

At t_1 , the main switch S_1 achieve zero- current turn-on. After t_1 , the current i_{S1} flowing through main switch S_1 increase linearly and the diode D_4 cut off. The resonant capacitor C_1 continues to discharge to inductors L_1 and L_2 , the current i_{L1} flowing through resonant inductor L_1 increase linearly, while the current i_{L2} flowing through resonant inductor L_2 decrease slowly. The voltage of resonant capacitor C_1 decrease nonlinearly till t_2 , at which the voltage u_{C1} of resonant capacitor C_1 reach to zero and the current i_{S1} flowing through main switch S_1 reach its maximum. The variation of some parameters change as following formulas:

$$L_2 \frac{di_{L2}}{dt} + L_1 \frac{di_{L1}}{dt} = E_1 \quad (6)$$

$$\frac{du_{C0}}{dt} = \frac{1}{C_0} i_{L1} - \frac{u_{C0}}{R_1 C_0} \quad (7)$$

 Fig. 3. Working mode 2 $[t_1, t_2]$.

2.2.3 Working mode 3 $[t_2]$

The voltage u_{C1} of resonant capacitor C_1 become zero at t_2 , the diode D_1 is on conduction.

 Fig. 4. Working mode 3 $[t_2]$.

2.2.4 Working mode 4(t_2, t_3):

After t_2 , resonant inductor L_1 start to charge to resonant capacitor C_1 , the voltage between diode and resonant capacitor C_1 is zero. According to Kirchhoff laws, the current i_{S1} flowing through main switch S_1 decrease rapidly, while the current i_{S2} flowing through auxiliary switch S_2 decrease gradually. In addition, the current of resonant inductor L_1 keep constant, the current flowing through resonant inductor L_2 increase until t_3 , when the current of two resonant inductors are same, the circuit turns into next working mode.

Fig. 5. Working mode 4(t_2, t_3).

2.2.5 Working mode 5[t_3, t_4]

At t_3 , the current i_{L2} flowing through resonant inductor L_2 equals the current i_{L1} flowing through resonant inductor L_1 , the diodes D_1 and D_2 cut off, so the current i_{S2} of auxiliary switch S_2 become zero. After t_3 , the current of resonant inductors L_1 and L_2 increase gradually.

Fig. 6. Working mode 5[t_3, t_4].

2.2.6 Working mode 6[t_4, t_5]

At t_4 , the current flowing through main switch S_1 reach its maximum value, but the current flowing through auxiliary switch S_2 become zero, which achieve zero-current turn-off, and the main switch turn off. After t_4 , the diode D_1 is on conduction. The resonance among resonant inductors L_1 , L_2 and resonant capacitor C_1 make the voltage u_{C1} of resonant capacitor C_1 increase gradually and the current of resonant inductors L_1 , L_2 decrease slowly till t_5 , when the voltage u_{C1} of resonant capacitor C_1 reach its peak value U_0 . All the parameters change as following:

$$\frac{di_{L1}}{dt} = -\frac{1}{L}u_0 + \frac{E_1}{L} \quad (10)$$

$$\frac{du_0}{dt} = -\frac{1}{C_0}i_{L1} - \frac{1}{C_0R_1}u_0 \quad (11)$$

Fig. 7. Working mode 6 $[t_4, t_5]$.

2.2.7 Working mode 7 $[t_5, t_6]$

At t_5 , the voltage u_{C1} of resonant capacitor C_1 become maximum, resonant capacitor C_1 and direct power supply charge to resonant inductors L_1 and L_2 until t_6 . The circuit is equivalent to boost converter, releasing energy in this process. and the circuit turn into next working cycle.

Fig. 8. Working mode 6 $[t_5, t_6]$.

3. Traditional Modulation Strategy

The main switch S_1 can only achieve zero-current turn-on at t_1 from mode 3, but both of the current and the voltage of main switch S_1 are zero, so it can achieve zero-current zero-voltage turn-on at t_2 . The current and voltage of auxiliary switch S_2 are zero at t_3 from mode 5, so it can achieve zero-current zero-voltage turn-off. Fig. 9 illustrates traditional modulation strategy, whose solid arrow indicates the turn-on time of main switch and the turn-off time of auxiliary switch needed to improve. Furthermore, the dotted line shows the direction needed to change.

Fig. 9. Traditional modulation strategy.

4. Improved Modulation Strategy

The main switch S_1 in Fig. 9 can only achieve zero-current turn-on at t_1 , however, the improved modulation strategy in Fig. 10, whose turn-on time of main switch S_1 is moved to the right along the abscissa, can make main switch S_1 achieve zero-current zero-voltage turn-on. The auxiliary switch S_2 in Fig. 9 can turn off at t_4 , while the turn-off time of auxiliary switch S_2 in Fig. 10 moves from t_4 to t_3 , with zero-current zero-voltage turn-off. The improved modes are as following:

Fig. 10. Improved modulation strategy.

4.1. Working Mode 3 $[t_2]$:

As the voltage u_{C1} of resonant capacitor C_1 is zero and the diode D_1 is on conduction, the voltage between

diode D_1 and resonant capacitor C_1 is zero, meanwhile, the current flowing through the main switch S_1 is zero, so it is easily for the main switch S_1 to achieve zero-current zero-voltage turn-on.

Fig. 11. Working mode 3[t_2].

4.2. Working Mode 5[t_3, t_4]

At t_3 , the current flowing through resonant inductor L_2 equals the current flowing through resonant inductor L_1 , so the current of auxiliary switch S_2 is zero according to Kirchhoff laws.

In addition, the current flowing through resonant inductor L_1 stay constant from t_2 to t_3 , leading to the voltage of auxiliary switch S_2 become zero, therefore, the auxiliary switch S_2 can achieve zero-current zero-voltage turn-off. After t_3 , the circuit is equivalent to energy storage process of boost.

Fig. 12. Working mode 3[t_3, t_4].

5. Simulation Verification

5.1. Parameter Settings

Table 1 is the parameter settings of circuit, whose resonant inductors L_1 and L_2 are equivalent.

Table 1. Parameter Settings

Input Voltage E_1	200V	Resonant Inductor L_3	0.8mH
Output Voltage u_0	400V	Resonant Capacitor C_1	0.33uF
Resonant Inductors L_1 、 L_2	10mH	Frequency f_k	25kHz

5.2. Parameter Settings

Fig. 13 illustrates main switch and auxiliary switch driving signals of primary circuit, the voltage V_{P1} and the current I_1 of main switch, the main switch S_1 can only achieve zero-current turn-on.

Fig. 14 illustrates main switch and auxiliary switch driving signals of improved circuit, the voltage V_{P1} and the current I_1 of main switch, the main switch S_1 can achieve zero-current zero-voltage turn-on at t_2 .

Fig. 15 shows main switch and auxiliary switch driving signals of primary circuit, the voltage V_{P2} and the current I_2 of auxiliary switch, the auxiliary switch S_2 can achieve zero-current zero-voltage turn-off at t_4 .

Fig. 16 shows main switch and auxiliary switch driving signals of improved circuit, the voltage V_{P2} and the current I_2 of auxiliary switch. Compared to Fig. 15, the auxiliary switch S_2 in Fig. 16 can achieve zero-current zero-voltage turn-off before t_4 .

Fig. 13. Driving signals of primary circuit and the voltage and current of main switch.

Fig. 14. Driving signals of improved circuit and the voltage and current of main switch.

Fig. 15. Driving signals of primary circuit and the voltage and current of auxiliary switch.

Fig. 16. Driving signals of improved circuit and the voltage and current of auxiliary switch.

Compare Fig. 13 with Fig. 14, it is obvious that the energy stored in resonant capacitor C_1 is transferred to resonant inductor completely at t_2 . The voltage between diode D_1 and resonant capacitor C_1 is zero, while the current flowing through main switch S_1 is zero. Therefore, it is easily for the main switch S_1 achieve zero-current zero-voltage turn-on. Compare Fig. 14 with Fig. 15, it is apparent that the auxiliary switch S_2 achieve zero-current zero-voltage turn-off at t_3 under the improved driving signals of main switch and auxiliary switch.

At t_3 , the current of resonant inductor L_2 is equivalent to the current of resonant inductor L_1 and the current flowing through auxiliary switch S_2 is zero. As the current flowing through resonant inductor L_1

stay constant from t_2 to t_3 , so the voltage of auxiliary switch S_2 is zero, which can achieve zero-current zero-voltage turn-off at t_3 .

6. Conclusion

According to the analysis above, the improved modulation strategy based upon zero-voltage zero-current transition boost converter can make main switch achieve zero-voltage zero-current turn-on. However, the change to the turn-on time of main switch can make the main switch achieve zero-voltage zero-current turn-on, and the change to the turn-off time of auxiliary switch can realize the zero-voltage zero-current turn-off of auxiliary switch in advance as well. The change to the open time and close time can reduce the power loss of switches in chopper circuit. The simulation results verify the correctness of improvement. The way to change the modulation strategy can be applied to chopper circuit.

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Papers:

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