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DC boost converter with buck buffer

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Abstract: For a conventional high-power active power factor correction (APFC) boost converter, its output capacitor needs to be precharged, which means that two power switches of the main circuit and the control circuit are needed to be respectively turned on and turned off in a fixed order. After the main circuit switch is turned on, it is necessary to wait for precharging before turning on the control circuit power switch. Once an inadvertent operation is performed, an overcurrent phenomenon from the output capacitor will occur. In this study, the buck circuit is used as the pre-stage snubber circuit, which can directly supply power to the circuit without precharging the output capacitor. As a result, potential safety hazard caused by the overcurrent due to the capacitor and the charging maloperation during the start-up stage can be avoided. Theoretical analysis and simulation experiment show that the DC boost converter with buck buffer can maintain the peak value of the main circuit within the safe range when the device boot does not precharge the output capacitor, and thus the safety and stable operation of the DC boost converter are ensured.

Key words: active power factor correction (APFC); boost converter; precharging; power switch; overcurrent; buck buffer

0 Introduction

Active power factor correction (APFC) technology is an effective method to suppress harmonic current and improve power factor[1-3]. Boost circuit is usually used in the conventional high-power APFC boost converter to increase the inductor current when the output capacitor is started without precharging[4]. Controlling the conduct time of the switch transistor cannot control the size of the input current. In such case, both inductance stored energy and current increase constantly. After several cycles of turning on and turning off the switch, the current turns into a large shock current. If nothing is done, overcurrent will happen in the main circuit and worst of all the equipment is damaged[5].

This problem will occur because the output capacitor is not precharged before the device boots[6]. In response to this problem, the traditional solution is to first turn on and turn off the two power switches of the main circuit and the control circuit respectively in a fixed order, then wait for precharging after turning on the main circuit switch, and finally turn off the control circuit switch[7]. This method depends on manual operation. Once maloperation occurrs, i. e. the two power switches of the main circuit and the control circuit are turned on in reverse order, and the time for the precharging is not enough, the instantaneous current of the main circuit will be out of the safe range. In Ref. [8], a single-stage boost bridge active power correction converter based on active clamp is proposed. This circuit of the active clamp circuit can absorb overvoltage produced in the converter circuit. However, when the voltage of the circuit to the output capacitance is low, the energy stored in the inductor is close to saturation after several cycles of turning on and turning off of the switch tube. As a result, the released current breaks through the output capacitance, which causes damage to the equipment. All of the above methods may cause a fire and pose a threat to personal and property safety. In general, the DC input uses a battery as a power source. In medium and high voltage battery applications, electric vehicle power battery is a common example. And power safety, power controllability and equipment intelligence are major considerations[9]. Since the switching process of traditional professional APFC boost converter requires professional operation, further consideration is needed to increase its versatility and safety, so as

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to avoid the safety hazard that caused by the operation[10].

To avoid the overcurrent generated by precharging the output capacitor in the conventional high-power APFC boost converter, based on the characteristics of the buck circuit, we design a DC boost converter with buck buffer, which can boot device at any time. Overcurrent phenomenon during the whole work process is avoided and the safety of the device is improved even though the output capacitor is not precharged. Theoretical analysis and simulation experiments show that the designed converter can greatly reduce the instantaneous current and make the converter work stably.

1 Hardware structure

The hardware structure of buck and boost converters is a cascade connection, so that the output capacitor voltage can gradually rise from zero to the target voltage without a precharging process. The circuit configuration of a DC boost converter with a buck buffer is shown in Fig. 1. Simultaneous control of M_1 and M_2 can make the front buffer output and the final output of the circuit rise slowly to achieve the purpose of protecting the circuit.

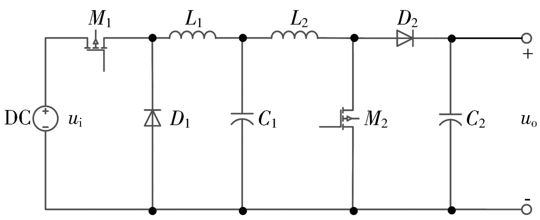

Fig. 1 Circuit structure of DC boost converter with buck buffer

2 Theoretical derivation

The core part of the DC boost converter is the boost circuit, as shown in Fig. 2.

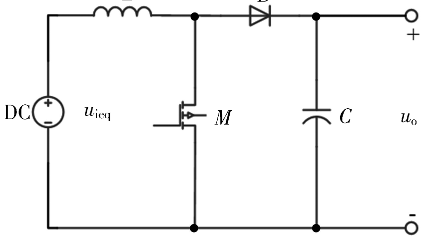

Fig. 2 Schematic diagram of boost circuit

When the circuit starts to work and $u_{\text{ieq}} \geqslant u_{\text{o}}$, it can be concluded that M is disconnected according to the proportional integral (PI) control principle[11-12]. Before the current is reversed, the equivalent circuit of Fig. 2 is shown in Fig. 3. The voltage and current equations in boost circuit are expressed as

$$\begin{cases} u_{\text{ieq}} = u_L + u_{\text{o}}, \\ u_{\text{ieq}} = L\dfrac{\mathrm{d}i}{\mathrm{d}t} + u_{\text{o}}, \\ i = C\dfrac{\mathrm{d}u_{\text{o}}}{\mathrm{d}t}, \end{cases} \tag{1}$$

and the simplified expression of Eq. (1) is given as

$$u_{\text{ieq}} = u_{\text{o}} + LC\frac{\mathrm{d}^2 u_{\text{o}}}{\mathrm{d}t^2}, \tag{2}$$

where u_{ieq} is the equivalent input voltage; u_L is the voltage of the equivalent inductance of L; u_{o} is the output voltage; L is the equivalent inductance; and C is the equivalent capacitance.

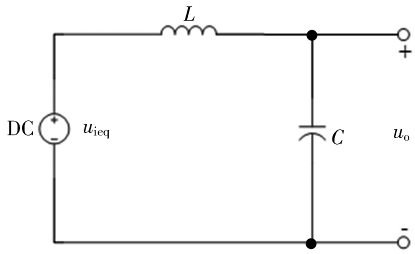

Fig. 3 Equivalent circuit of initial state of boost circuit

When u_{ieq1} is the real part of u_{ieq}, assuming that $u_{\text{ieq1}} \neq 0$, we can get

$$u_{\text{o}} = u_{\text{ieq1}} - u_{\text{ieq1}}\cos\frac{t}{\sqrt{LC}}, \tag{3}$$

$$i = u_{\text{ieq1}}\sqrt{\frac{C}{L}}\sin\frac{t}{\sqrt{LC}}. \tag{4}$$

Meanwhile, assuming that u_{ieq} is a positive proportional function of time t, and the proportional coefficient is k, when $u_{\text{ieq}}=kt$, we can obtain

$$kt = u_o + LC\frac{\mathrm{d}^2 u_o}{\mathrm{d}t^2}. \tag{5}$$

According to Eqs. (2) and (5), we can obtain

$$u_{\text{o}} = k\left(t - \sqrt{LC}\sin\frac{t}{\sqrt{LC}}\right), \tag{6}$$

$$i = kC\left(1 - \cos\frac{t}{\sqrt{LC}}\right). \tag{7}$$

Combining Eqs. (4) and (7), when $u_{\text{ieq1}} \neq 0$, the maximum current can be deduced as

$$i_{\max} = u_{\text{ieq1}}\sqrt{\frac{C}{L}}, \tag{8}$$

where u_{ieq1} is the real part of u_{ieq}.

Combining Eqs. (4) and (7), when $u_{ieq}=kt$, $t\leqslant\frac{\pi\sqrt{LC}}{2}$ and $i\geq 0$, the maximum current can be deduced as

$$i_{max1}=kC,\tag{9}$$

where k is the proportional coefficient.

From Ref. [13], we can obtain that the order of magnitude of capacitor in the boost circuit is μF, and the that of inductance is μH.

Eqs. (8) and (9) show that the instantaneous current i_{max} and i_{max1} and equivalent voltage u_{ieq} in the boost circuit are of the same order of magnitude, while instantaneous current i_{max1} in the circuit structure of the DC boost converter with buck buffer is 10^{-6} order of magnitude. By comparing the current with buck buffer and the current without buck buffer, the instantaneous current i_{max1} of the DC boost converter circuit with buck buffer is less than the instantaneous current i_{max} of the boost circuit. Therefore, the circuit structure of the DC boost converter with buck buffer can reduce the instantaneous current, and the peak current of the main circuit will not exceed the safe range when the device boots.

3 System model

3.1 Generation algorithm of switch control signal

In Fig. 1, the buck circuit serves as the power structure of the boost circuit and performs PI control on M_1 and M_2.

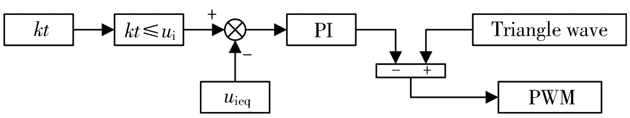

Fig. 4 Algorithm of control signal of M_1

The buck circuit provides a power supply to the boost circuit in Eq. (5) and the boost circuit can use the power supply to perform a DC boost conversion without precharging. The block diagram of the control signal generation algorithm of M_1 is shown in Fig. 4, and the block diagram of the control signal generation algorithm of M_2 is shown in Fig. 5. In Fig. 5, s is the output voltage rising slope, u_o is the reference value of steady-state output target voltage, and i_{L2} is the current flowing through the inductor L_2.

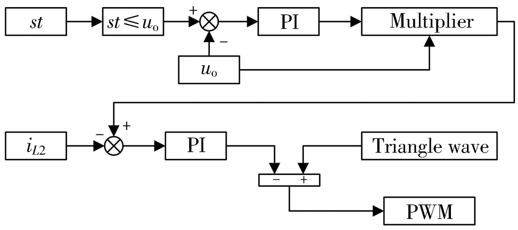

Fig. 5 Algorithm of control signal of M_2

The control signal of M_1 is generated by the PI voltage loop. Specifically, the voltage reference value is needed to be gradually increased from 0 V to the input voltage. The control signal of M_2 is generated by the double loop of PI voltage and current. This voltage reference value gradually rises from 0 V to the final target voltage. Since the equivalent input and output initial states of the boost converter are both zero as well as there is no abrupt change, the precharging is actually performed simultaneously in the working process. Therefore, no special precharging process is required, which ensures that there is no overcurrent in the circuit.

The mathematical model of PID control is expressed as

$$u(t)=K_p\left[e(t)+\frac{1}{T_i}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}\right],\tag{10}$$

where K_p is the proportional coefficient, T_i is the integral time constant, and T_d is the differential time constant.

The transfer function of PID is expressed as

$$D(s)=\frac{U(s)}{E(s)}=K_p\left(1+\frac{1}{T_i}+T_d s\right).\tag{11}$$

In Matlab/Simulink, it is impossible to process the continuous output signal like analog PID. So, the analog PID algorithm is needed to be discretized. This discretization processing is as follows: Taking k as the sampling serial number, T as the sampling period, and kT as the discrete sampling continuous time, by discretization, the integral is replaced by the summation and the differential is replaced by the incremental form, which are expressed as

$$\begin{cases} t\approx kT \quad k=(0,1,2,\cdots), \\ \int_0^t e(t)dt\approx T\sum_{j=0}^{k}e(jT)=T\sum_{j=0}^{k}e_j, \\ \frac{de(t)}{dt}\approx\frac{e(kT)-e[(k-1)T]}{T}=\frac{e_k-e_{k-1}}{T}. \end{cases}\tag{12}$$

In conclusion, we can obtain

$$u_k=K_p\left[e_k+\frac{T}{T_i}\sum_{j=0}^{k}e_j+\frac{T_d}{T}(e_k-e_{k-1})\right],\tag{13}$$

where e_k is the simplified $e(kT)$ in Eq. (13).

In this study, as the controlled objects are more complicated and the mathematical model is difficult to establish, the PID regulator is designed by Ziegle and Nichols in the process of system design and debug. This method is used to achieve the "quarter-decay" response, that is, the designed regulator makes the overshoot of the closed loop step response of the system adjacent to the next cycle decrease to about 25% of the previous cycle. Suitable for low gain, stable gain and high gain systems, the oscillation is divergent. In the second method of Ziegler-Nichols, continuous oscillation is used to set the parameters. At the beginning, only the proportional correction is performed. The system firstly works with a low gain value and then slowly increases the gain until the closed-loop system outputs equal amplitude oscillation. The oscillation period T_o and the proportional gain K_o are recorded, and the PID parameters are obtained by

$$K_p = 0.45K_o,\ K_i = \frac{1.2K_p}{T_o} = \frac{0.54K_o}{T_o}. \quad (14)$$

3.2 Software control process

The design described in this paper does not require precharging of the output capacitor, and can turn on or turn off the main circuit and the control circuit switches at the same time. A relay is connected between the switch and M_1 for program control protection of the power supply and the circuit. In order to make the equipment operation normal and efficient, software control process is shown in Fig. 6, where u_1 and u_2 are the upper and lower limits of the voltage, respectively, and u_{ref} is the reference value of equivalent input voltage, which is the maximum allowable error of u_{ieq}, and u_{ref} is Δu.

To control the program, firstly, system initialization is performed, making sure that the input voltage u_i is within the upper and lower limits of the voltage to allow the power supply to successfully initialize the system. Secondly, turn on the relay and the program control switch, making sure that the input voltage u_i is within the voltage range during the charging and discharging process. Finally, perform PI control on M_1 and M_2. When the difference between the equivalent input voltage u_{ieq} and the reference value of the equivalent input voltage u_{ref} are greater than the maximum allowed error Δu, turn off the relay and end the program.

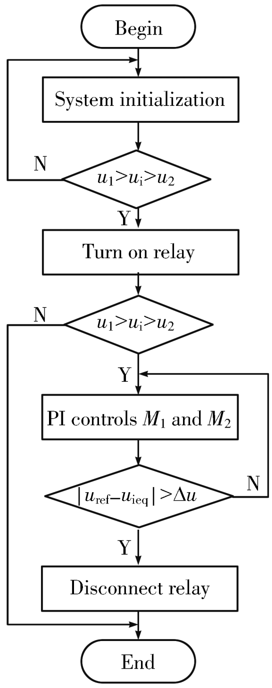

Fig. 6 Software control process

3.3 DC boost converter circuit model with buck buffer

The circuit model of the DC boost converter with buck buffer is built by Matlab/Simulink toolbox, as shown in Fig. 7.

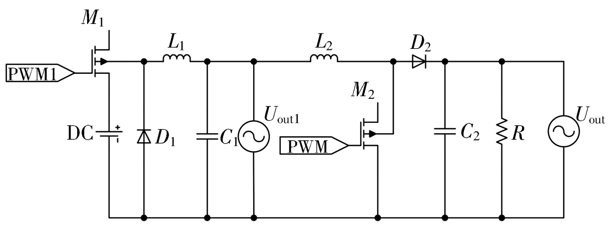

Fig. 7 Circuit model of a DC boost converter with buck buffer

In Fig. 7, the PWM waveform is generated by the program to turn on and turn off the switch tube. According to the control signal generation algorithm of the buck circuit shown in Fig. 4, the PWM driving model of the buck circuit is established, as shown in Fig. 8. The control signal generation algorithm of the boost circuit is shown in Fig. 5, the PWM driving model of the boost circuit is established, as shown in Fig. 9. According to Eq. (14), the parameters of discrete PID controller1 in Fig. 8 are $K_p = 0.2$ and $K_i = 2$. The parameters of discrete PID controller2 in Fig. 9 are $K_p = 0.0135$ and $K_i = 0.704$. The parameters of discrete PID controller3 are $K_p = 0.702$ and $K_i = 1.46$.

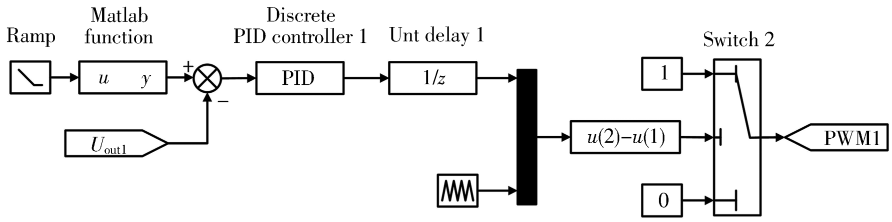

Fig. 8 PWM driving model of buck circuit

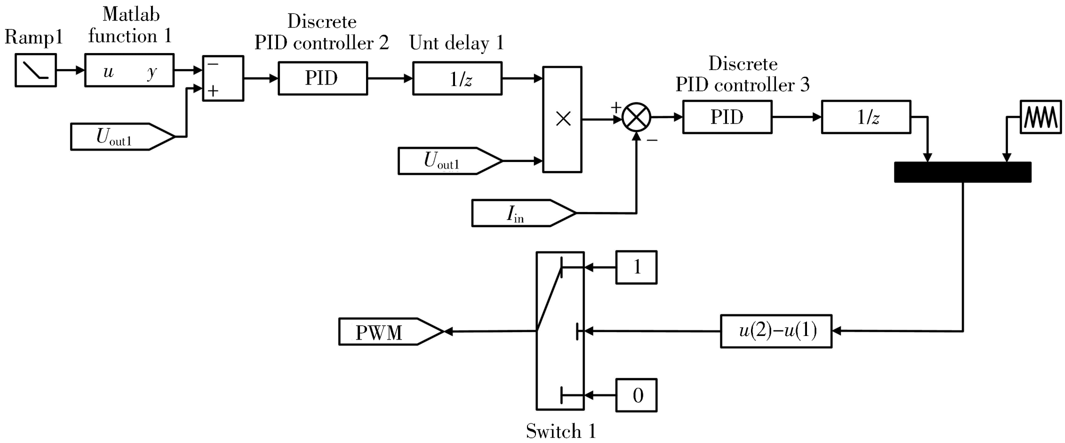

Fig. 9 PWM driving model of boost circuit

4 Simulation

In order to verify the designed converter, the simulation experiments are carried out with Matlab/Simulink. The power supply is a 240 V battery and the voltage is boosted to 380 V. The inductance of the circuit is 750 μH and the capacitance is 4 230 μF. The thyristor uses G40N60UFD IGBT with rated voltage of 600 V, rated working current of 40 A, maximum working current of 60 A and maximum forward instantaneous current of 160 A. The diode is DSE160-06, whose rated voltage, rated operating current, maximum operating current and the maximum forward instantaneous current are 600 V, 30 A, 60 A and 160 A, respectively. This circuit is subjected to a simulation experiment with a load of 3 000 W, $k=1\ 500$, and $s=1\ 700$. In order to illustrate the safety impact of precharging the output capacitor on the circuit in the conventional high-power APFC boost converter, the DC boost converter without buck buffer is simulated by Matlab/Simulink, and inputs when precharging is performed are 0 V, 50 V, 100 V, 150 V and 200 V, respectively. The current waveform is shown in Fig. 10.

When the precharging of the DC boost converter without buck buffer are 0 V, 50 V, 100 V, 150 V and 200 V, the maximum input current is shown in Table 1.

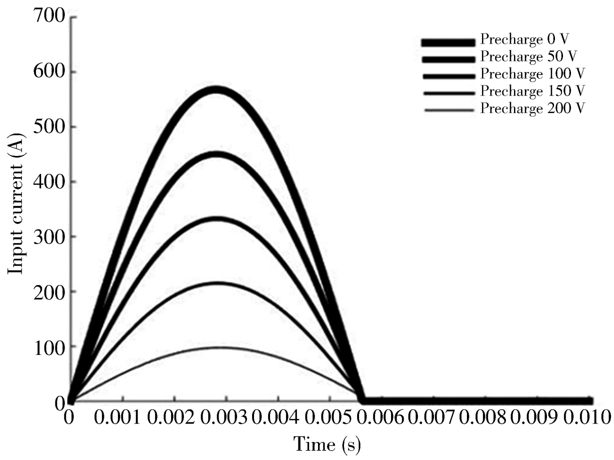

Fig. 10 Waveforms of input currents at precharged 0 V, 50 V, 100 V, 150 V and 200 V, respectively

Table 1 Maximum input current of DC boost converter without buck buffer

Precharge voltage(V)	0	50	100	150	200
Maximum value of current (A)	568.2	450.4	332.7	215.1	97.4

The DC boost converter with buck buffer is simulated by Matlab/Simulink. If the boost converter without buck buffer is mistakenly operated, the output capacitor will not be charged. The input current waveform is shown in Fig. 11 and local amplification figure is shown in Fig. 12.

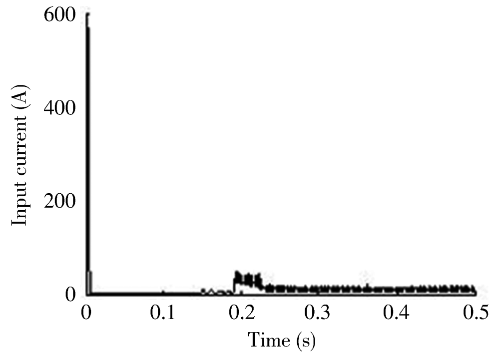

Fig. 11 Input current waveform

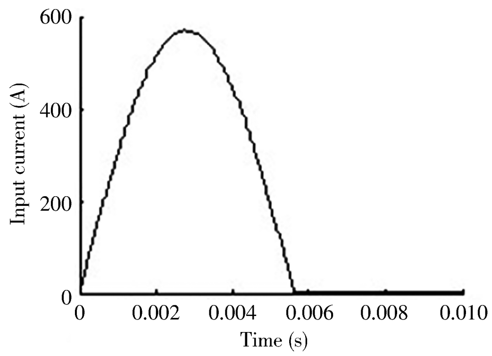

Fig. 12 A partial enlargement of input current waveform

The buffer current waveform of the DC-boost converter with buck buffer is shown in Fig. 13, where the input current waveform in the boost circuit is shown in Fig. 14.

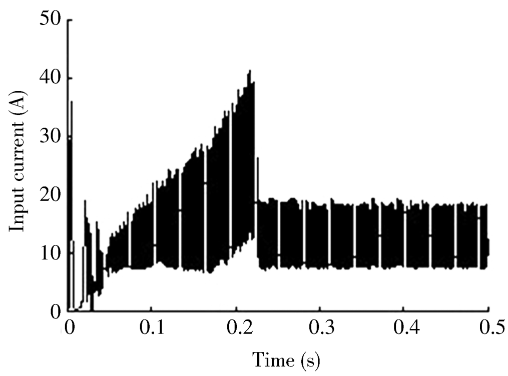

Fig. 13 Buffer current waveform of a DC boost converter with buck buffer

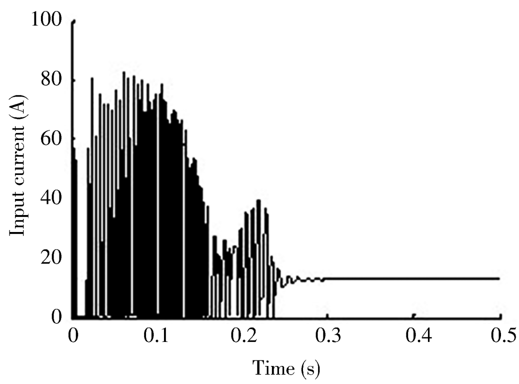

Fig. 14 Waveform ofinput current in boost circuit

Table 2 shows the data of the maximum input current and the maximum value of the buffer current for the DC boost converter without buck buffer and the DC boost converter with buck buffer.

Table 2 Maximum input current of DC boost converter

Current value	DC boost converter without buck buffer	DC boost converter with buck buffer
Input current maximum(A)	568.2	42.3
Buffer current maximum(A)	Non-existence	81.8

In order to verify the stability of the DC boost converter with buck buffer, the DC power supply voltage is changed. When the DC power supply voltage is 100 V, the input current waveform is shown in Fig. 15. When the power supply voltage is 150 V, the input current waveform is shown in Fig. 16.

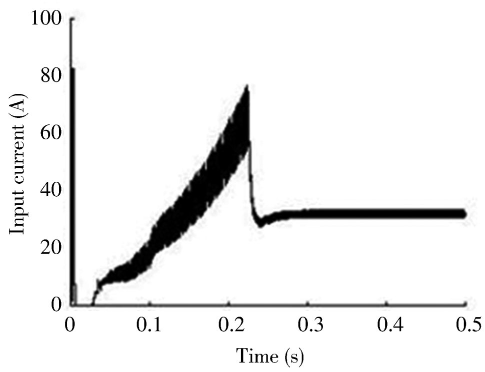

Fig. 15 Waveform of input current when power supply is 100 V

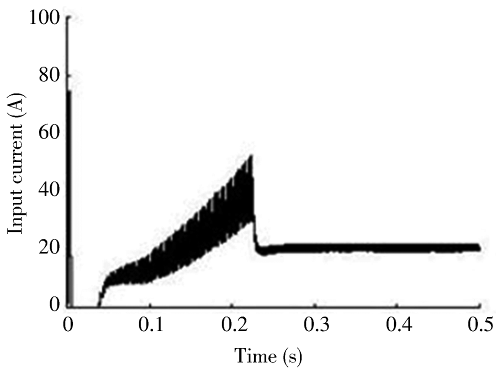

Fig. 16 Waveform of input current when power supply is 150 V

From the simulation experiments, when the precharging of the DC boost converter without buck buffer is not completed, the maximum input current is shown in Table 1. It can be concluded that the current is greater than the maximum operating current of the thyristor, diode and capacitor, which makes the circuit unsafe. The maximum input current of the DC boost converter without buck buffer and the DC boost converter with buck buffer are compared and the data are shown in Table 2. The maximum current of the DC boost converter with buck buffer is 81. 8 A and the maximum input current is 42. 3 A, which is less than the maximum operating current of the thyristors, diodes, and capacitors.

5 Conclusions

This paper presents a DC boost converter with buck buffer is proposed, which provides a buffered equivalent power supply for the post-stage boost circuit. Theoretical calculations and experimental simulations show that the designed DC boost converter with buck buffer not only can greatly reduce the instantaneous current to avoid overcurrent, but also can provide good stability for different input supply voltages to ensure the safety of the DC boost circuit.

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带 buck 缓冲的直流升压变换器

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摘　要： 常规的大功率有源功率因数修正（Active power factor correction，APFC）升压变换中对输出电容需要进行预充电来避免过流现象，因此主电路和控制电路的电源开关需按固定顺序分别闭合和断开，在闭合主电路开关后需要等待预充电，最后才闭合控制电路电源开关，一旦操作过程中出现误操作，输出电容就会产生过流现象。本文采用 buck 电路作为前级缓冲电路，无需对输出电容进行预充电就可以直接对电路供电，从而避免电容与充电误操作带来的启动阶段电路过流引起的安全隐患。对带 buck 缓冲的直流升压变换器模型进行理论分析和仿真实验可知，带 buck 缓冲的直流升压变换器在不对输出电容预充电的情况下，可以使设备启动时主电路电流峰值不超出安全范围，从而确保直流升压变换器安全稳定的工作。

关键词： 有源功率因数校正；升压变换；预充电；电源开关；过流；buck 缓冲

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