Novel Buck-Mode Three-Level AC Direct Converter

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***Abstract*—A novel buck-mode three-level AC/AC converter is proposed. Effectively to solve the problem such as switch voltage stress and harmonic interference of the two-level AC-AC converter existed in the field of large capacity transform, The inverter has the advantages such as simple topology, bidirectional power flow, two-stage power conversions, high frequency electrical isolation, three-level voltage across the output filter, strong load adaptability and so on. The converter could convert the alternating current with instability distortion to the steady sine alternating current with same frequency, this paper has studied the topology, high frequency switching process, and the feedback control strategy of instantaneous voltage value of this converter, also the diagram formed by the driving signal is given. At last, the correctness and advancement of this Buck-Mode Three-level converter are verified through simulation tests.**

***Index Terms*—three-level, buck-mode, electrical isolation, AC/AC converter**

I. INTRODUCTION

AC/AC converter is a kind of converter device which utilizes power semiconductor devices, convert the alternating current with instability distortion to the steady sine alternating current with same frequency for AC load. Due to insufficient of grid capacity, especially the performance and quality issues of distribution and a variety of power transmission equipment, makes the terminal quality of power supply system has been seriously affected. Use of these devices is to ensure and improve the quality of AC power, especially AC voltage stabilizer and UPS [1], They have become the essential AC power supply system terminal device, not only can improve the overall quality of power supply, but also have the ability to protect the load on the power supply system and help users perform management functions, Therefore, AC voltage stabilizer has become an important part in AC power systems[2], [3].

This paper presents a novel buck-mode three-level direct AC/AC converter, effectively reduces the voltage across the switch stress, reduces harmonic interference, good output waveform quality, has broad application prospects in high power conversion occasions. This paper analyzes the topology of the circuit, high-frequency switching process, set up circuit mode and the feedback control strategy of instantaneous voltage value. The feasibility and correctness of the converter are fully verified through simulation tests [4], [5].

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II. INVERTER TOPOLOGY

The circuit topology of the novel buck-mode three-level AC/AC converter is shown in Fig. 1.

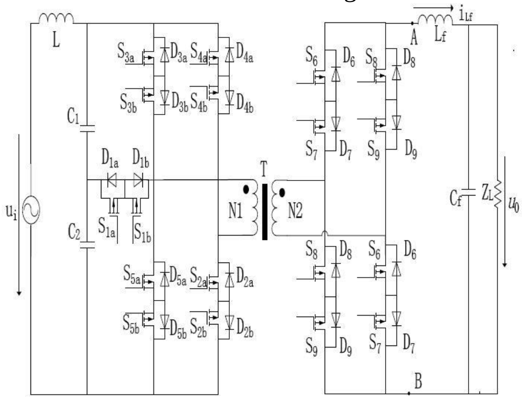

Figure 1. Buck-mode three-level AC/AC converter

The converter is made up of input voltage source, input filter, three-level transformation, high frequency storage transformer, output cycloconverter and load. The converter could convert the alternating current with instability distortion to the steady sine alternating current with same frequency, has the advantages of simple structure, high power density and two-stage power conversions. This three-level transformation composed of one or more two-way control modules can change the input voltage into three output levels. The introduction of two sub-circuit voltage capacitors used as the clamping voltage sources, can be regarded as infinite, in order to ensure that the voltage across the capacitors are constant when in the process of charging and discharging [6].

III. OPERATION PRINCIPLE

Before analyzing the principle, we do some assumptions:

1) All components, including, diodes, switches, inductors and capacitors are regarded as ideal devices, and also internal resistance of power source is equal to zero.

2) Select the same specifications of C_1 and C_2, make C_1=C_2.

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There are four switch-modes of the buck-mode converter. To take u_o>0, i_{Lf}>0 as an example for analysis, there are six switch mode, the driving signal waveforms is shown in Fig. 2.

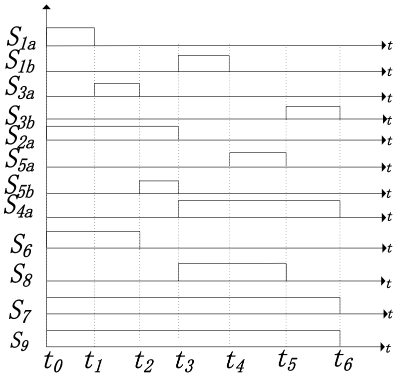


Figure 2. Driving signal waveforms of the power switches

A. Switch Mode 1 [t_0~t_1]

At the time of t_0, Switch S_{1a}, S_{2a}, S_6 will be turned on, Switch S_7, S_9 are turned on too, at this moment, the voltage of the primary *N1* winding of the transformer is:

$$u_{N1} = \frac{1}{2} u_i \tag{1}$$

The voltage in front of the output filter is:

$$u_{AB} = \frac{N2}{N1} \cdot \frac{1}{2} u_i \tag{2}$$

B. Switch Mode 2 [t_1~t_2]

At the time of t_1, Switch S_{3a}, S_{2a}, S_6 will be turned on, Switch S_7, S_9 are keeping turning on, at this moment, the voltage of the primary *N1* winding of the transformer is:

$$u_{N1} = u_i \tag{3}$$

The voltage in front of the output filter is:

$$u_{AB} = \frac{N2}{N1} \cdot u_i \tag{4}$$

C. Switch Mode 3 [t_2~t_3]

At the time of t_2, Switch S_{1a}, S_{3a}, S_6 will be turned off, Switch S_{2a}, S_{5b}, S_7, S_9 are keeping turning on, at this moment, the voltage of the primary *N1* winding of the transformer is:

$$u_{N1} = 0 \tag{5}$$

The voltage in front of the output filter is:

$$u_{AB} = 0 \tag{6}$$

The filtering inductance current i_{Lf} circulates through S_7, S_9, D_6, D_8.

D. Switch Mode 4 [t_3~t_4]

At the time of t_3, Switch S_{4a}, S_{1b}, S_8 will be turned on, Switch S_7, S_9 are turned on too, at this moment, the voltage of the primary *N1* winding of the transformer is:

$$u_{N1} = -\frac{1}{2} u_i \tag{7}$$

The voltage in front of the output filter is:

$$u_{AB} = \frac{N2}{N1} \cdot \frac{1}{2} u_i \tag{8}$$

E. Switch Mode 5 [t_4~t_5]

At the time of t_4, Switch S_{4a}, S_{5a}, S_8 will be turned on, Switch S_7, S_9 are keeping turning on, at this moment, the voltage of the primary *N1* winding of the transformer is:

$$u_{N1} = -u_i \tag{9}$$

The voltage in front of the output filter is:

$$u_{AB} = \frac{N2}{N1} \cdot u_i \tag{10}$$

F. Switch Mode 6 [t_5~t_6]

At the time of t_5, Switch S_{5a}, S_{4a}, S_8 will be turned off, Switch S_{4a}, S_{3b}, S_7, S_9 are keeping turning on, at this moment, the voltage of the primary *N*1 winding of the transformer is:

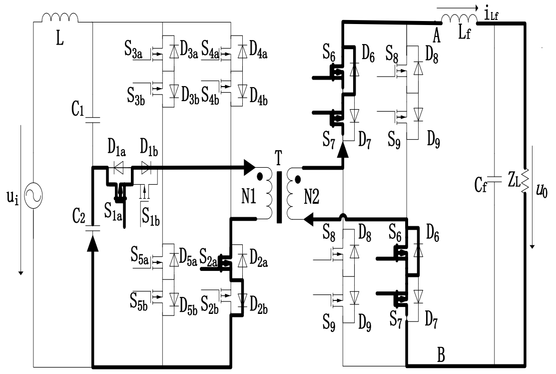
$$u_{N1} = 0 \tag{11}$$

The voltage in front of the output filter is:

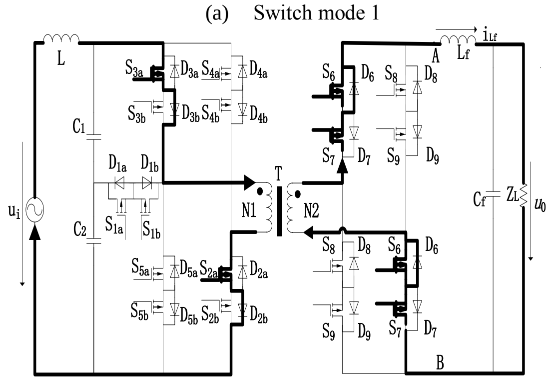
$$u_{AB} = 0 \tag{12}$$

The filtering inductance current i_{Lf} circulates through S_7, S_9, D_6, D_8.

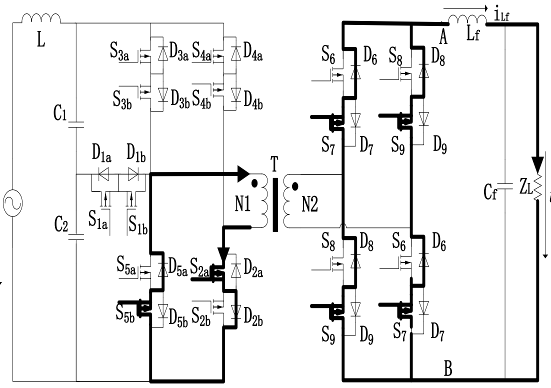
According to the voltage and current of the primary winding of the transformer, in a high frequency switching cycle, there are six switch-modes in a high-frequency switching cycle [7], [8]. Operation modes are shown in Fig. 3. Then we can get the relationship between voltage of the primary winding of the transformer u_{N1} and voltage in front of the output filter u_{AB} in every operation mode, as shown in Table I.



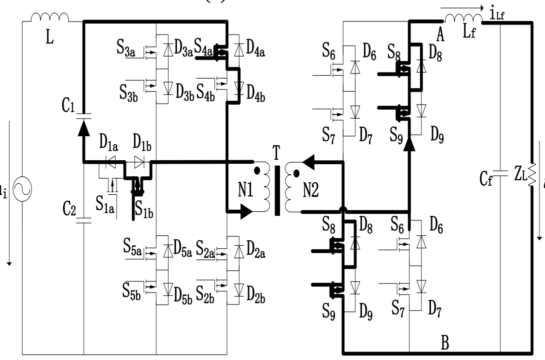
(a) Switch mode 1



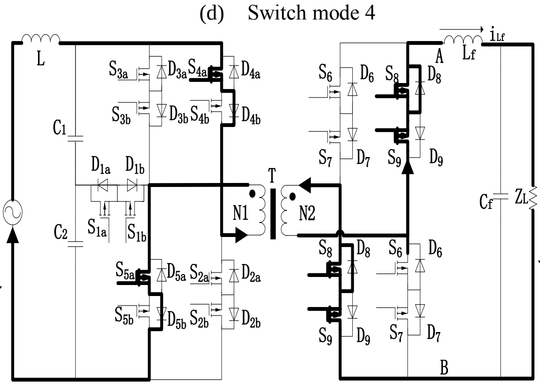
(b) Switch mode 2



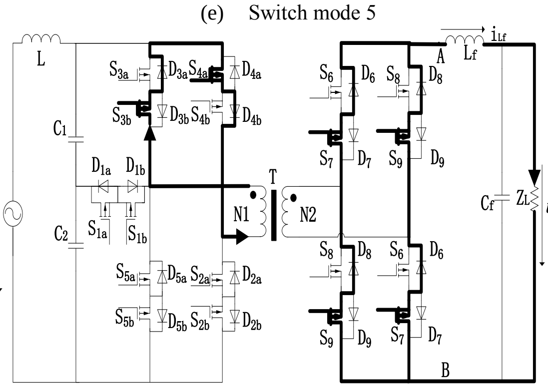
(c) Switch mode 3



(d) Switch mode 4



(e) Switch mode 5



(f) Switch mode 6

Figure 3. The switching states when $u_o>0$, $i_{Lf}>0$

TABLE I. OUTPUT VOLTAGE AND STATES OF THE SWITCHES

Mode	U_{N1} level	U_{AB} level	ON	OFF
A	+1/2	+1/2	S_{1a},S_{2a} ,S_6,S_7,S_9	others
B	+1	+1	S_{3a},S_{2a},S_6,S_7,S_9	others
C	+0	+0	S_{2a} ,S_{5b},S_7,S_9	others
D	-1/2	+1/2	S_{4a},S_{1b},S_8,S_7,S_9	others
E	-1	+1	S_{4a},S_{5a} ,S_8,S_7,S_9	others
F	-0	+0	S_{4a} , S_{3b},S_7,S_9	others

Above is the operation of $u_0>0$, when $u_0<0$, adjust the working condition of cycloconverter. In the end, filter front-end output voltage u_{AB} can get 0, $\pm 1/2u_i$, $\pm$ u_i these five level.

IV. CONTROL STRATEGY

According to the control requirements of the converter, a novel buck-mode three-level AC/AC converter take single close-loop SPWM control strategy based on the feedback scheme of instantaneous voltage value. Comparing the output feedback voltage with the reference voltage, the error voltage u_e is obtained. Through the absolute value circuit we can get $|u_e|$. Then $|u_e|$ is compared with the two sawtooth waves, we can get two SPWM waveforms. Frequency divide SPWM pulse signal, with logic circuit, achieve multiple outputs driving signals [9], [10].

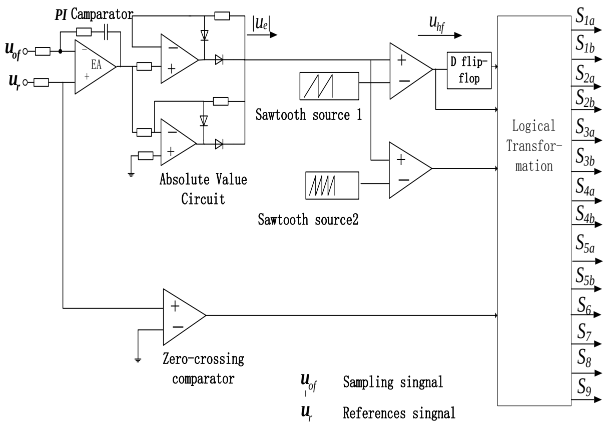


Figure 4. Principle figure of control circuit

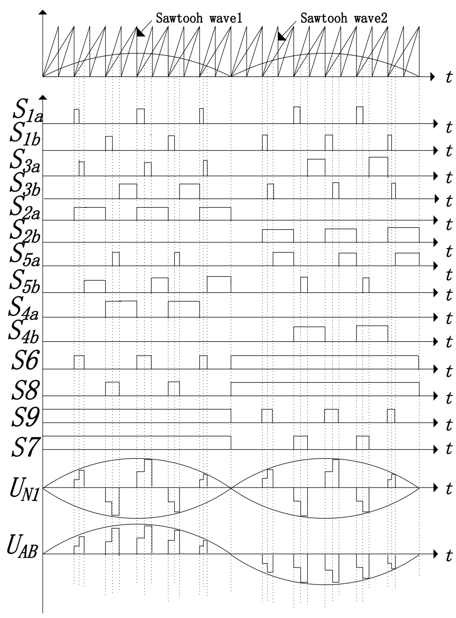


Figure 5. Control principle waveform

The principle figure of control circuit is shown in Fig. 4, Comparison between the sampling signal u_{of} of the sinusoidal output AC voltage u_o and the sinusoidal reference signal u_r(synchronous with the input power voltage), flowing through the *PI* regulator, absolute value circuit, the error signal $|u_e|$ can be obtained. Each power switch driving signal can be obtained through a series of logical transformations of the PWM signal u_{hf}, which is the comparison between the absolute value of error signal and the two unipolar sawtooth waves [11], [12].

Comparing between the sampling signal u_{of} of the sinusoidal output AC voltage u_o with the sinusoidal reference signal $u_{r,}$ flowing through the *PI* comparator, absolute value circuit, can obtain the error signal $|u_e|$, the detail of Control principle waveform caused by comparison between $|u_e|$ and the two unipolar sawtooth waves is shown in Fig. 5 [13].

For the resistive loads, the directions of the voltage and the current are the same. But such as inductive and capacitive loads, voltage and current will lead or lag with each other, and then load will transfer energy to the power supply. Therefore, the corresponding feedback channel must be provided on both sides of the transformer [14].

V. Parameter Calculation

When the converter work steady, and the output filter inductor current is continuous within a switching cycle, the small-signal equivalent circuit shown in Fig. 6.

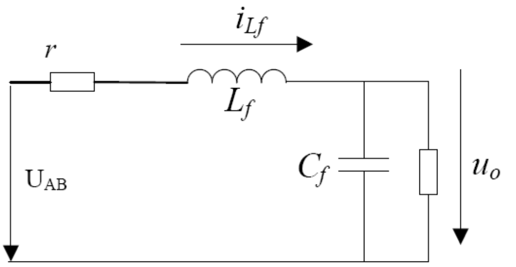


Figure 6. Small-signal equivalent circuit

As high-frequency switching frequency f_s is set much larger than the cutoff frequency of the filter output and the input, the output frequency of the voltage, therefore, in a switching period T_s, input voltage u_i and u_o are regarded as a constant amount. Establish a relationship between u_i and u_o with the state space averaging method. Take u_0>0, i_{Lf}>0 as example, D_2 is the duty cycle of S_{2a}, D_1 is the duty cycle of S_{1a}:

A. Switch Mode 1 [t_0~t_1]

$$L_f \frac{di_{Lf}}{dt} = -ri_{Lf} + \frac{u_i}{2}\frac{N2}{N1} - u_0 \tag{13}$$

$$C_f \frac{du_o}{dt} = i_{Lf} - \frac{u_0}{R_L} \tag{14}$$

B. Switch Mode 2 [t_1~t_2]

$$L_f \frac{di_{Lf}}{dt} = -ri_{Lf} + u_i \frac{N2}{N1} - u_0 \tag{15}$$

$$C_f \frac{du_o}{dt} = i_{Lf} - \frac{u_0}{R_L} \tag{16}$$

C. Switch Mode 3 [t_2~t_3]

$$L_f \frac{di_{Lf}}{dt} = -ri_{Lf} - u_0 \tag{17}$$

$$C_f \frac{du_o}{dt} = i_{Lf} - \frac{u_0}{R_L} \tag{18}$$

The formula (14), (15) multiplied by D_1, plus formula (15), (16) multiplied by (D_2-D_1), plus formula (17), (18) by (1-D_2), make di_{Lf}/d_t =0、du_o/dt =0, Can get a stable value of state variables:

$$U_0 = U_i \frac{N2}{N1}\frac{D_1+D_2}{2}\frac{R_L}{r+R_L} \tag{19}$$

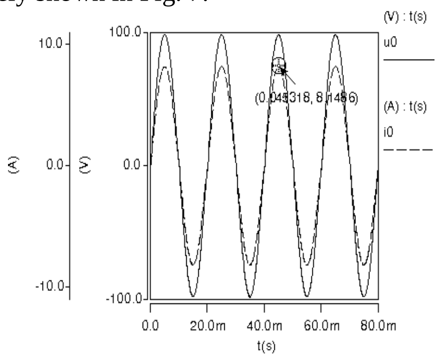
$$I_{Lf} = U_i \frac{N2}{N1}\frac{D_1+D_2}{2}\frac{1}{r+R_L} \tag{20}$$

In the Ideal situation and the CCM mode, the external characteristic of the converter is:

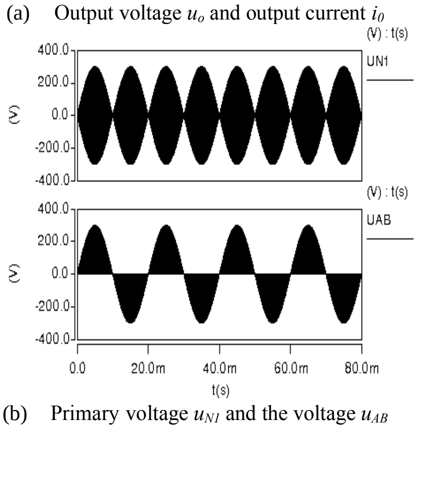
$$U_0 = U_i \frac{N2}{N1}\frac{D_1+D_2}{2} \tag{21}$$

VI. Test Results

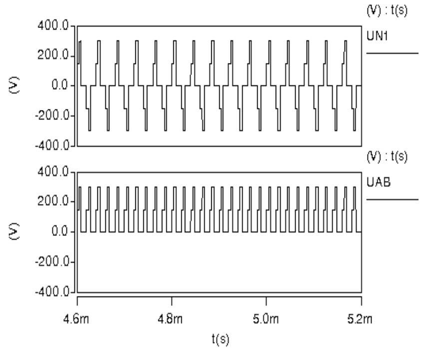
According to the schematic of the AC-AC converter, take resistive load as example, verify the correctness of the topology by simulation. The simulation parameters: input voltage u_i=300VAC±10% (50Hz), output voltage u_0=100V AC (50Hz) switching frequency f_s=50KHz, maximum duty cycle D_{max}=0.5, turn ratio of the transformer $N1$:$N2$=1:1, input filtering inductance L=20 μH, input capacitance C_1=C_2=30 μF, output filtering capacitance C_f=30 μF, output filtering inductance L_f=650 μH, rated load R_L=12Ω. Test waveforms are respectively shown in Fig. 7.



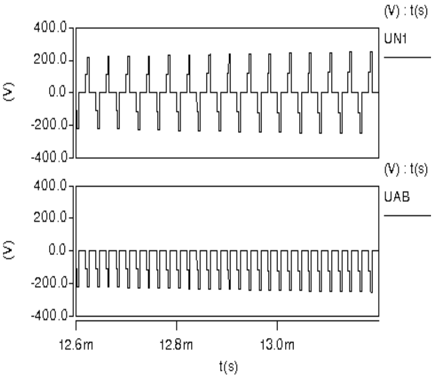
(a) Output voltage u_o and output current i_0



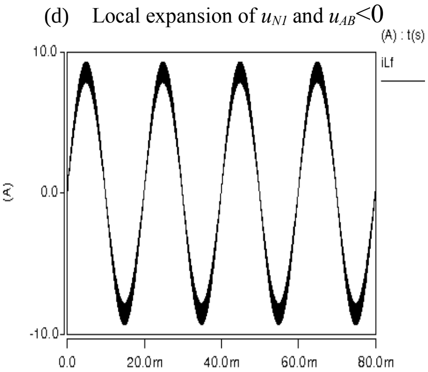
(b) Primary voltage u_{N1} and the voltage u_{AB}



(c) Local expansion of $u_{N1}$and u_{AB}>0



(d) Local expansion of u_{N1} and u_{AB}<0



(e) Output filtering inductance current i_{Lf}

Figure 7. Test waveforms

The output voltage u_0 and current i_0 is shown in Fig. 7(a), The output voltage of the filter front-end u_{AB} and the transformer primary side voltage u_{N1} is shown in Fig. 7(b), Local expansion figure of u_{N1} and u_{AB}>0 is shown in Fig. 7(c), Local expansion figure of u_{N1} and u_{AB}<0 is shown in Fig. 7(d), the voltage of filter inductor is shown in Fig. 7(e).

VII. CONCLUSIONS

Based on the analysis and simulation results above, we can make the following conclusions:

1) The proposed converter which can transfer one unregulated sinusoidal voltage into another regulated constant frequency sinusoidal voltage, owes such advantages like simple topology, high frequency electrical isolation, good load adapting ability and good line current waveform

2) Three-level transformation unit is introduced, comparing with traditional two-level inverter, this novel inverter has the advantages of the power swtiches have lower voltage stress , reducing the size of filter capacitor and inductor and high efficiency transformation .

3) The simulation results prove the correctness of the topology. Its high efficiency and reliability make it very suitable for the high input voltage situation. So it will have good development prospects.

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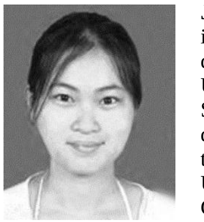

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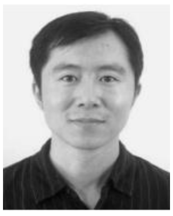

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