A Novel High Frequency Isolated Full-Bridge Three-Level AC/AC Converter

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Abstract—In order to solve the problems existed in the field of high power applications such as voltage stresses and harmonic interferences of the two-level AC/AC converter. A new kind of high frequency isolated full-bridge three-level AC/AC direct converter is proposed. The converter has many advantages such as two-stage power conversions, simple topology and, low voltage stresses. The topology of circuit, operational principle and six kinds of operational strategy are deeply analyzed. The control method of SPWM, which is based on instantaneous voltage value feedback, is used to respond fast to the change of input and output voltage. The control method of converter driving signal, which is from the comparing of four carrier waves and error magnification signal, is summarized. The circuit is simulated by saber and the result indicates that the wave of the converter is improved; however the harmonic and voltage stresses are reduced.

Index Terms—high frequency link, three-level, AC/AC, SABER

I. INTRODUCTION

Multi-level power conversion is a new technology which can meet high voltage and power. Devices of low grade can convert high power which widens the range for power and electronic technology to use in the field of high power and voltage [1]. Supported by the fast development of high-power semi-conductors over recent years, multilevel converters have emerged and enable better line-side behavior than current converter topologies[2]-[4]. AC/AC converter is power semiconductor device which can convert a certain frequency and amplitude of AC into the same or another frequency and amplitude of AC. AC/AC converter with multi-level can widen the usage in high voltage and power and improve the quality of waveform. [5]

In this paper, traditional full-bridge two-level AC / AC converter has been improved. A new kind of high-frequency isolated full-bridge three-level AC /AC converter is proposed, which can produce better wave of three-level voltage at front-end of output filter. The power converter voltage stresses are reduced so that it can be used in the field of high power and voltage applications.

II. CIRCUIT TOPOLOGY OF THE INVERTER

The circuit topology of the high-frequency isolated full-bridge three-level AC/AC converter is shown in Fig. 1. The circuit topology is made up of input alternating voltage source, input filter inductance, divider capacitance, three-level cycle-inverter, high frequency transformer, output cycle-inverter, output filter and output alternating load, which can turn the unstable alternating current into the sinusoidal stable alternating current with same frequency. This three-level cycle-inverter is composed of one or more two-way control modules, which can change the input voltage into three output levels. The basic constituent unit includes a four-quadrant power switch and a four-quadrant clamp power switch, each power tube is paralleled with the corresponding parasitic diode. Basic component in series with each other unit can reduce the voltage stress. Two capacitors are used as the clamping voltage sources. Five kinds of level, which are $U_i$, $U_i/2$, 0, -$U_i/2$, -$U_i$, can be got at the both sides of the transformer and three kinds of level, which are $U_i$, $U_i/2$, 0, can be got at the front-end of filter.

Figure 1. Isolated full-bridge three-level AC/AC converter

The units of $S1$, $S2$, $S3$, $S4$, $S7$, $S8$ are four-quadrant power switches, $S5$ is four-quadrant clamping power switches in Fig. 1. $L_i$ is the input filtering inductance, $L_f$ is the output filtering inductance, $C_f$ is the output filtering capacitor. Low frequency alternating voltage can be turned into high frequency pulsant voltage by input cycle-inverter when power is transmitted to load from electric fence. High frequency pulsant current can be demodulated by output cycle-inverter and low frequency alternating voltage can be got through output filter. Output cycle-inverter works in the state of modulation and input cycle-inverter works in the state of demodulation when power is reversed to electric fence from load. [6]
III. STEADY-STATE ANALYSIS AND EXTERNAL CHARACTERISTICS

A. Operational Modal Analysis

In order to simplify the description of the circuit operation, we make the assumption:

1. All components, including switches, diodes, inductors and capacitors are thought to be ideal devices, and also internal resistance of power source is equal to zero.
2. Select the same specifications of $D1$ $D7$, $C1$, $C2$, $C1=C2$, $N2=N3$.

In a high-frequency switching cycle, there are six switch-modes of the converter. To use $U_o>0$, $i_{ls}>0$ as an example for analysis, the driving signal waveforms is shown in Fig. 3. When in normal working process, power switches will be turned on or off in the set order, thus realizing the circulation working modes of $A$-$B$-$A$-$C$-$D$-$E$-$D$-$F$-$A$.

Switch mode $[t_0~t_1]$ and $[t_2~t_3]$ Fig. 3(a).

Switch $S_4$, $S_5$ and $S_6$ will be turned on at the time of $t_0$ or $t_2$. Then, primary current $i_{N1}$ circulates through $C_1$, $S_{5a}$, $S_{5b}$, $S_{4a}$, $S_{4b}$, while the filtering inductance current $i_{Lf}$ circulates through $S_{6a}$, $S_{6b}$. At this moment, the current through the secondary transformer is increasing quickly. The voltage of the primary winding of the transformer is $U_{N1}$:

$$U_{N1} = U_i / 2$$  \hspace{1cm} (1)

The voltage in front of the output filter is $U_{AB}$:

$$U_{AB} = U_{N2} = \frac{N_2}{N_1} U_{N1} = \frac{N_2}{2N_1} U_i$$  \hspace{1cm} (2)

Switch mode $[t_1~t_2]$ Fig. 3(b).

Switch units $S_1$ is turned on at the time of $t_2$, while $S_4$ is turned off and $S_5$, $S_6$ remain turned on. Then primary
current $i_{N1}$ circulates through $S_{1a}$, $S_{1b}$, $S_{4a}$, $S_{4b}$ while the filtering inductance current $i_{Lf}$ circulates through $S_{6a}$, $S_{6b}$. At this moment, the current through the secondary transformer continues to increase. The voltage of the primary winding of the transformer is $U_{N1}$:

$$U_{N1} = U_i$$  \hspace{1cm} (3)

The voltage in front of the output filter is $U_{AB}$:

$$U_{AB} = U_{N2} = \frac{N_2}{N_1} U_{N1} = \frac{N_2}{N_1} U_i$$  \hspace{1cm} (4)

Switch mode C \{ $t_3 \sim t_4$ \} Fig. 3(c).

Switch units $S_3$, $S_7$ is turned on at the time of $t_3$, while $S_4$ is turned off and $S_5$, $S_6$ remain turned on. Then primary current $i_{N1}$ circulates through $S_{4a}$, $S_{4b}$, $S_{5a}$, $S_{5b}$, and achieve the positive maximum. The filtering inductance current $i_{Lf}$ circulates through $S_6$, $S_7$. But the current through $S_{4a}$, $S_{4b}$ will continue to decrease until zero while current flowing through $S_{7a}$, $S_{7b}$ will continue to increase, thus realizing the exchange between the power switch units $S_6$ and $S_7$. At this time, the voltage of the primary winding of the transformer is zero, the front voltage $U_{AB}$ of output filter is also zero by calculation and verification, which also avoids the circulation phenomenon at the overlapping period of the cycloconverter.

Switch mode D \{ $t_4 \sim t_5$, $t_6 \sim t_7$ \} Fig. 3(d).

Switch units $S_2$, $S_3$ is turned on at the time of $t_4$ or $t_6$, while $S_3$, $S_5$, $S_4$ is turned off and $S_7$ remain turned on. Then, primary current $i_{N1}$ from positive to negative, circulates through $S_{2a}$, $S_{2b}$, $S_{4a}$, $S_{4b}$, $C_2$. At this point commutation has ended, while the filtering inductance current $i_{Lf}$ flows through switch units $S_{7a}$, $S_{7b}$ at the same time. The current flowing through the secondary side of the transformer will continue by negative growth. The voltage of the primary winding of the transformer is $U_{N1}$:

$$U_{N1} = -\frac{U_i}{2}$$  \hspace{1cm} (5)

The voltage in front of the output filter is $U_{AB}$:

$$U_{AB} = U_{N2} = -\frac{N_2}{N_1} U_{N1} = -\frac{N_2}{2N_1} U_i$$  \hspace{1cm} (6)

Switch mode E \{ $t_5 \sim t_6$ \} Fig. 3(e).

Switch units $S_7$ is turned on at the time of $t_5$, $S_2$, $S_7$ remain turned on. Then primary current $i_{N1}$ circulates through $S_{2a}$, $S_{2b}$, $S_{4a}$, $S_{4b}$, while the filtering inductance current $i_{Lf}$ flows through switch units $S_{7a}$, $S_{7b}$. In this case the transformer primary current is negative and continues to increase. The voltage of the primary winding of the transformer is $U_{N1}$:

$$U_{N1} = -U_i$$  \hspace{1cm} (7)

The voltage in front of the output filter is $U_{AB}$:

$$U_{AB} = U_{N3} = -\frac{N_2}{N_1} U_{N1} = \frac{N_2}{N_1} U_i$$  \hspace{1cm} (8)

Switch mode F \{ $t_6 \sim t_7$ \} Fig. 3(f).

Switch units $S_1$, $S_8$ is turned on at the time of $t_6$, $S_2$, $S_7$ remain turned on. Then, primary current $i_{N1}$ circulates through $S_{2a}$, $S_{2b}$, $S_{4a}$, $S_{4b}$, and achieve the maximum negative positive, while the filtering inductance current $i_{Lf}$ flows through switch units $S_{8a}$, $S_8$. But the current that circulates through $S_{8a}$, $S_{8b}$ will continue to decrease until zero, while the current that circulates through $S_{4a}$, $S_{4b}$ will continue to increase, thus realizing the exchanging between the power switch units $S_8$ and $S_7$. At this time, the voltage of the primary winding of the transformer and the voltage in front of the output filter are zero.

B. The Expression of Output Voltage and Filter Inductor Current Expression

From the above analysis, when the converter is operating at steady state and the output inductor current is in CCM mode, there are three equivalent circuits in a switching cycle, which is shown in Fig. 4. The parameter $r$ is the equivalent resistance denoting the winding resistance of the transformer, leakage reactance and parasitic resistance of the filter.

\[
\begin{align*}
\text{(a)} & \quad \frac{N_1}{N_1} U_i, \quad \text{Cf} = R_f \\frac{U_a}{U_i} \\
\text{(b)} & \quad \frac{N_2}{N_1} U_i, \quad \text{Cf} = R_f \\frac{U_a}{U_i} \\
\text{(c)} & \quad \frac{N_3}{N_3} U_i, \quad \text{Cf} = R_f \\frac{U_a}{U_i}
\end{align*}
\]

Figure 4. Three equivalent circuit in a switching cycle

$U_o$ can be regarded as steady value as the switch frequency is much higher than cut-off frequency of voltage. The state transformer of equivalent circuit in Fig. 4(a) is:

\[
L_f \frac{di_{Lf}}{dt} = -ri_{Lf} + \frac{N_2}{N_1} - u_o
\]

\[
C_f \frac{du}{dt} = i_{Lf} - \frac{u}{R_f}
\]

The state transformer of equivalent circuit in Fig. 4(b) is:
The state transformer of equivalent circuit in Fig. 4(c) is:

\[
L_f \frac{di_f}{dt} = -ri_f + u_i \frac{N_2}{2N_1} - u_o 
\]

(11)

\[
C_f \frac{du}{dt} = i_f - \frac{u_o}{R_e} 
\]

(12)

The state transformer of equivalent circuit in Fig. 4(c) is:

\[
L_f \frac{di_f}{dt} = -ri_f - u_o 
\]

(13)

\[
C_f \frac{du}{dt} = i_f - \frac{u_o}{R_e} 
\]

(14)

Eq. (11) and (12) multiplied by 2D1 plus (9), (10) multiplied by D2 plus (13), (14) multiplied by (1-2D1-D2), assumption \( \frac{di}{dt} = 0 \), \( \frac{du}{dt} = 0 \), the steady-state value of State variables is:

\[
u_o = \frac{N_2}{N_1}u_i(D_1 + D_2) \frac{R_e}{R_e + r} 
\]

(15)

\[
i_{sf} = \frac{N_2}{N_1}u_i(D_1 + D_2) \frac{1}{R_e + r} 
\]

(16)

When in ideal state and CCM mode, the external characteristic of transformer is:

\[
u_o \approx \frac{N_2}{N_1}u_i(D_1 + D_2) \frac{R_e}{R_e + r} 
\]

(17)

The load current \( I_o \) is:

\[
I_o = \frac{1}{2} [i_{sf}(t_1) + i_{sf}(t_2)] \bullet (D_1 + D_2) + \frac{1}{2} i_{sf}(t_1)(1 - D_1 - D_2) 
\]

(18)

Assumption \( D_2 = 0.2 \), the load current \( I_g \):

\[
I_g = \frac{N_2}{N_1}u_i \frac{T_f}{L_f} (-2D_1 + 1) + \frac{1}{10} 
\]

(19)

When \( D_1 = 0.125 \), \( I_g \) take the maximum:

\[
I_{g_{\text{max}}} = \frac{11}{80} \frac{N_2}{N_1} \frac{T_f}{L_f} u_i 
\]

(20)

When in ideal state and CRM mode, the external characteristic of transformer is:

\[
I_g = \frac{80}{11} I_{g_{\text{max}}} (-2D_1 + 1) + \frac{1}{10} 
\]

(21)

When in DCM mode, the output load current \( I_o \) is:

\[
I_o = \frac{80}{11} I_{g_{\text{max}}} \left[ \frac{0.6D_1^2 - 3D_1^3 + 0.17D_1 + 0.16}{D_1 + D_2} \right] 
\]

(22)

When in ideal state and DCM mode, the external characteristic of transformer is:

\[
N_i u_o = \frac{N_i u_i}{11I_f} \frac{80I_{g_{\text{max}}}}{D_1 + D_2} \left[ \frac{0.6D_1^2 - 3D_1^3 + 0.17D_1 + 0.16}{D_1 + D_2} \right] 
\]

(23)

IV. CONTROL CIRCUIT DESIGNING

Feedback control scheme of instantaneous voltage value is adopted in the high-frequency isolated full-bridge three-level AC/AC direct converter [1]. 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 the four sawtooth waves compare with the voltage \( |U_e| \) respectively. The four sawtooth waves is shown in Fig. 5. Comparison with sawtooth waves, the signal of SPWM1, SPWM2, SPWM3 SPWM4 are obtained. The four SPWM waves obtained a series of logical transformation can get the drive signal power switch.

In order to control the switch on and off to produce a three-level voltage step wave, you need to master power switch duty cycle is divided into three parts. Four waves of SPWM can be got by comparing sawtooth waves in Fig. 5 with \( |U_e| \). It is shown in Fig. 6. Frequency of sw1 and sw3 are same and three times larger than sw2 and sw4. Amplitude of saw-tooth waves is more than three times larger than the amplitude of sine wave.

V. SIMULINK

High frequency isolated full-bridge three-level AC/AC direct converter, transient voltage feedback control strategy, CCM mode. Normalized capacity \( S = 1\text{KVA} \), input voltage \( U_i = 220\text{V} \pm 10\% (50\text{Hz}) \), power factor of the load \( \cos \phi = 0.75\sim 0.75 \), switching frequency \( f_s = 50\text{KHz} \), turn ratio of the transformer \( N_1 : N_2 : N_3 = 1:2:2 \), input filtering inductance \( L_1 = 20\mu \text{H} \), input capacitance \( C_i = C_s = 30\mu \text{F} \), output
filtering capacitance $C_f = 8 \mu F$, output filtering inductance $L_f = 650 \mu H$, rated resistive load $R_e = 12.1 \Omega$; RC series capacitive load $R_c = 9.1 \Omega$, $C = 0.4 \mu F$, RL series inductive load $R_L = 9.1 \Omega$, $L = 25.49 mH$.

Voltage and current from resistive load are shown in Fig. 7(a). Voltage and current from capacitive load are shown in Fig. 7(b). Voltage and current from inductive load are shown in Fig. 7(c). Voltage waveform at both sides of transformer and front-end of filter are shown in Fig. 8.

The result of simulation indicates that waveform of voltage and current from full-bridge three-level AC/AC converter is much better with less harmonic and ripples. The output filter inductance and size of the filter are much smaller. Main power switch tube voltage stresses are decreased by $u_i/2$.

VI. CONCLUSION

A new kind of high frequency isolated full-bridge three-level AC/AC direct converter is proposed. The topology of circuit, operational principle and process, characteristic of transformer are deeply analyzed. Control strategy which is based on voltage instant value is designed on it. The simulation is based on SABER and the result proves:

(1) High frequency electrical isolation, two-stage power conversion, bidirection power flow are all advantages of the converter. Three-level wave can be got at the front-end of filter. Switch tube voltage stresses can be reduced. Voltage harmonic can be decreased. It can be used in the field of high power and voltage applications.

(2) Comparing with the traditional multilevel converter, this converter has the advantage of simple structure and high frequency electrical isolation.

(3) The ability of transformer to carry load is strong. Output voltage waveforms from resistive load, capacitive load and inductive load are stable and quality.

REFERENCES


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