Electrolytic Capacitor Ripple Current Analysis of SPWM NPC Three-Level Inverter

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***Abstract*—Neutral point clamped (NPC) three level inverter is widely used in high voltage and high power applications. The capacitance of DC bus plays an important role in the inverter. The DC capacitor current and neutral point current affect the lifetime of the electrolytic capacitor. The equivalent circuit model of electrolytic capacitor and the analytical expression of ripple current are analyzed in this paper. Finally, the validity of the expression is verified with simulation in MATLAB/Simulink.**

Keywords—three-level inverter;Pulse Width Modulation (PWM); electrolytic capacitor; ripple current; reliability

I. INTRODUCTION

Electrolytic capacitors have been widely used in power electronics system because of the features of large capacitance, small size, high-voltage, and low-cost. An electrolytic capacitor provides a low impedance path for the ac current and acts as a constant voltage source in the power converters. Unfortunately, it is reported that the electrolytic capacitors are responsible for the failure of power electronics system in 60% of the cases[1]. In order to ensure the DC voltage stability of the converter, the DC-Link capacitor is connected at the DC side to absorb the high amplitude pulsating current. But the DC bus ripple current can cause capacitance heating, and the neutral point current can cause unbalance voltage between two capacitor banks.

In this paper, the NPC three-level inverter is studied, and the failure mechanism and equivalent circuit model of electrolytic capacitor are introduced. The capacitive current (i_{DC}) and neutral point current (i_{NP}) of DC bus under Sinusoidal Pulse Width Modulation(SPWM) mode are analyzed. All simulations have been developed with the Matlab SimPowerSystems Blockset.

II. FAILURE MECHANISM OF ALUMINUM ELECTROLYTIC CAPACITOR

The DC side capacitor plays an important role in the NPC three-level inverter. The two capacitor parts having a voltage regulation divide the DC side voltage into three levels. The capacitor can also balance the instantaneous power difference between the input source and output load, and minimize voltage variation in the DC link. In some applications, they are also used to provide sufficient energy during the hold-up time. Therefore, the capacitor is critical for the NPC three level inverter.

The aluminum electrolytic capacitor is composed of a capacitor core, a protective structure and a lead out terminal, where in the most important component is the capacitor core, and the structure is shown in Fig. 1.

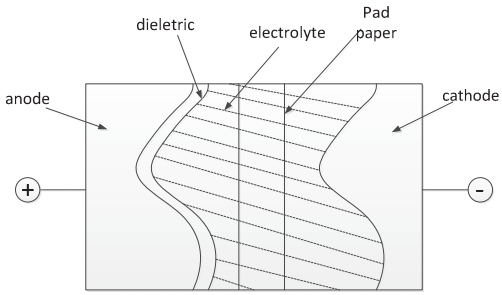

Fig. 1. Structure diagram of aluminum electrolytic capacitor core

According to the physical structure, a simplified equivalent circuit of the aluminum electrolytic capacitor can be obtained, as shown in Fig. 2. Where C is the capacitance component, R_C is the series equivalent resistance of the capacitor, R_L is the leakage resistance of the capacitor, R_D and C_D are the parasitic resistance and parasitic capacitance of the capacitor, ESL is equivalent series inductance.

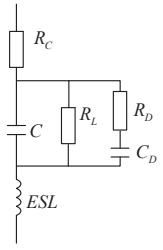

Fig. 2. Simplified equivalent circuit of aluminum electrolytic capacitor

In practice, the electrolytic capacitor in use will experience, continuous evaporation of electrolyte, and the key lifetime parameters of electrolytic capacitor (electrostatic capacity, equivalent series resistance and leakage current) and appearance will change. The evaporation rate of the electrolyte increases with the increase of the capacitance temperature, which leads to the increase of the equivalent resistance of the capacitor and the decrease of the capacitance. The temperature

of the capacitor plays an important role in the failure of the aluminum electrolytic capacitor. However the temperature of the capacitor is affected by the ambient temperature and the rise of internal temperature caused by the ripple current of the capacitor body. Power losses are a function of the capacitor current and its series equivalent resistance. Power losses will cause heating within the capacitor are defined as in(1).

$$Q = I^2 Rt \tag{1}$$

Where Q is power losses, I is ripple current, R is equivalent series resistance and t is the time of ripple current flowing through capacitor.

In the NPC three-level converter, the neutral point current i_{NP}, which leads to lower transmission power capacitor on the DC bus imbalance, is caused by neutral point voltage fluctuation. So the voltage between the two capacitors is imbalanced, which certainly reduces the reliability of capacitor.

III. ANALYTIC EXPRESSION OF RIPPLE CURRENT

A. Analytical formula of DC bus ripple current

Ripple current is the alternating current flowing through a capacitor, which causes capacitor to heat up. The maximum allowable ripple current of capacitor is affected by environment temperature, capacitor surface temperature, radiating area, loss angle, AC frequency and so on.The main circuit of a three-phase,three-level NPC inverter is show in Fig. 3. Each of the IGBT and the freewheeling diode module is considered as a switch, which accepts the corresponding phase current and flows through the half bridge arm of the inverter. The sum of phase currents of inverter leg is represented by i_1 .The DC component in the current i_1 is supplied by the DC power supply, while the AC component is supplied by the DC side capacitor.

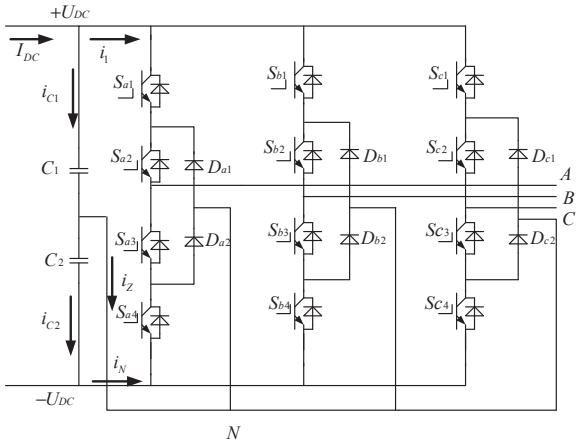

Fig. 3. Topology of NPC three-level converter

The schematic diagram of the carrier and modulation wave signals of NPC three-level converter is show in Fig. 4,the carrier phase modulation is adopted in the modulation mode. Fig. 4 shows the intervals, or sectors, in which the three reference voltage signs are constant.

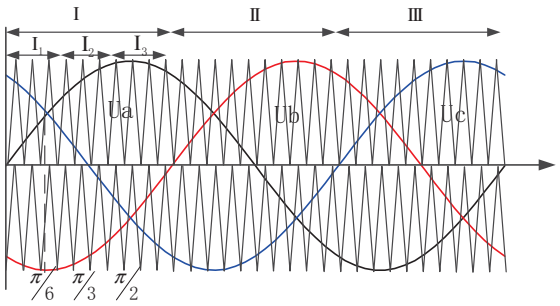

Fig. 4. Traditional carrier sinusoidal PWM modulation

This paper is based on the following two assumption:(a).the output currents are sinusoidal, and the DC-link voltage is constant; and (b).sinusoidal output currents imply that the switching frequency ripple content of the phase current is negligible. On the basis of the above two assumptions, the three-phase output current of the inverter can be considered as (2):

$$\begin{cases} i_A = I_N \sin(\theta - \phi) \\ i_B = I_N \sin(\theta - \frac{2}{3}\pi - \phi) \\ i_C = I_N \sin(\theta + \frac{2}{3}\pi - \phi) \end{cases} \tag{2}$$

In (2), I_N is the load current amplitude, and ϕ is the load power factor angle.

The DC side input current i_1 is the total current flowing through the switch, which can be calculated as (3) and expressed as the output current and the switching state of the switch.

$$i_1 = S_{Ta1} \cdot i_A + S_{Tb1} \cdot i_B + S_{Tc1} \cdot i_C \tag{3}$$

Here, S_{Ta1} , S_{Tb1} , and S_{Tc1} are switching functions, with 1 for turn-on and0 for turn off.

As shown in Fig. 4, the reference modulate signal is symmetrical, and the magnitude and variation of the input current are exactly the same within the $2/3\pi$ range. The difference is in the switch status of each bridge arm. The reference voltage is divided into three intervals as shown in Fig.4, and only the average and effective values of i_1 in the interval I are calculated. For interval I of interval I_1 ,the following rules are made: all switches S_{Ta1} , S_{Tb1} and S_{Tc1} are switched off during T_0 ; Only switch S_{Ta1} is switched on during the T_1 period;during T_2 ,the switches S_{Ta1} and S_{Tc1} are switched on. The duty cycle can be calculated as in (4)~(6).

$$T_0 = \frac{T_S}{2}[1 - M\sin(\theta + \frac{2}{3}\pi)] \tag{4}$$

$$T_1 = \frac{T_S}{2} M[\sin(\theta + \frac{2}{3}\pi) - \sin(\theta)] \tag{5}$$

$$T_2 = \frac{T_S}{2}[1+M\sin(\theta)] \tag{6}$$

Where M is the modulation index and θ is reference voltage phase angle.

During the T_1 period, only the switch S_{Ta1} is turned on so that the current flows through i_a ;during T_2, the switches S_{Ta1} and S_{Tc1} are opened, so the current flows through i_a and i_c. The average and RMS values of i_1 in a switching cycle are expressed in(7) and (8) :

$$\begin{aligned} i_{1,avg,I_1}(\theta) &= \frac{1}{T}\int_0^T i_1(\theta)d\theta \\ &= \frac{1}{T_S}[i_c T_1 + (i_a + i_c)\ T_2] \\ &= \frac{1}{T_S}(i_c T_1 - i_b T_2) \end{aligned} \tag{7}$$

$$\begin{aligned} i^2_{1,rms,I_1}(\theta) &= \frac{1}{T}\int_0^T i^2_{1,rms}(\theta)d\theta \\ &= i_c^2 \cdot T_1 + i_b^2 \cdot T_2 \end{aligned} \tag{8}$$

The average and RMS values in the interval Ⅰ are expressed in (9)~(10):

$$I_{DC} = I_{1,avg} = \frac{3}{4}MI_N\cos\phi \tag{9}$$

$$I_{1,rms} = I_N\sqrt{\frac{\sqrt{3}M}{4\pi}[\frac{1}{4}+\cos^2(\phi)]} \tag{10}$$

The DC side input current i_1 contains two parts: the average component and the ripple component. If the DC side capacitor is large enough, the ripple component of i_1 is all absorbed by the capacitor, when the ripple of the power input is negligible. As can be seen from the diagram, according to Kirchhoff's current law, the ripple current flowing through the DC bus capacitor is calculated as in(11):

$$i_{C1} = i_{DC} - i_1 \tag{11}$$

The RMS value of the DC side capacitor current I_{C1} can be expressed as (12):

$$\begin{aligned} I_{C1,\ rms} &= \sqrt{I_{DC}^2 - I_{1,rms}^2} \\ &= I_N\sqrt{\frac{M}{2}[\frac{\sqrt{3}}{2\pi}+(\frac{2\sqrt{3}}{\pi}-\frac{9}{8}M)\cos^2(\phi)]} \end{aligned} \tag{12}$$

It can be seen from the (12), in three-level NPC inverter, there is no relation between the ripple current of the electrolytic capacitor and the switching frequency. Therefore, the increase of the switching frequency can't reduce the ripple current of electrolytic capacitor.

Fig. 5 is a relation among ripple current unitary value of capacitor and power factor and modulation degree of the NPC three level inverter. We can see that the ripple current of the input DC side capacitor is determined by the converter operation parameters. When the power factor is 1,the ripple current is maximum at modulation index $M = 0.612$.

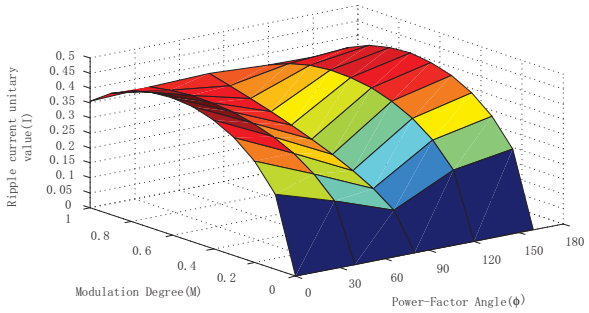

Fig. 5. Ripple current unitary value of capacitor of NPC three level inverter

B. *Analytic formula of neutral point current*

In the literature [6], the NPC i_{NP} of the three-level converter is studied in detail under the condition that the modulation mode is SPWM. The frequency of the i_{NP} waveform is three times of the modulation wave frequency, and it produces an unbalanced voltage between the two capacitor banks, thus reducing the reliability of the capacitor. When the modulation system is used, the instantaneous expression of the three harmonics can be express as in(13):

$$i_{NP}(t)|_{3\omega_{base}} = 0.74\hat{i}_{phase}\cos 3\omega_{base}t \tag{13}$$

The $\hat{i}_{phase}$ is the peak of the phase current of the inverter.

In practical application, the calculation of i_{NP} can be calculated as in (14):

$$i_{NP}(t) = i_N(t) - i_P(t) \tag{14}$$

Where, $i_P(t)$ is the instantaneous current flowing through the capacitor C_1 and $i_N(t)$ is the instantaneous current flowing through the capacitor C_2.

Ⅳ. SIMULATION ANALYSIS

The simulation model of the NPC three-level inverter is built in the environment of MATLAB/Simulink, The simulation parameters are shown in Table Ⅰ.

TABLE I. SIMULATION PARAMETER OF THREE LEVEL INVERTER

DC side voltage	U_{DC}	$100V$
Capacitance	$C_1 = C_2$	$4400\mu F$
Load impedance	$(R + jX)$	$10+j0.001$
DC side inductance	$L_1 = L_2$	$0.001H$

Fig. 6 is the ripple current flowing through the capacitor under SPWM modulation and its FFT analysis spectrum.

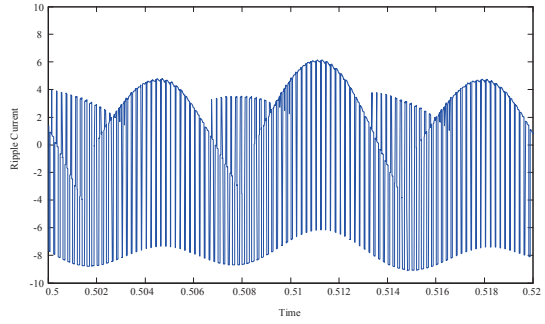

Fig. 6. The ripple current of capacitor and its FFT analysis spectrum diagram under SPWM modulation: (a) ripple current (b) FFT analysis spectrogram

It can be seen from Fig.6 that the harmonic component of capacitance ripple current is concentrated near the third harmonic, and the third harmonic has the highest amplitude. The ripple current fluctuates between-8~+6 amperes .This will affect the heating of the capacitors banks and reduce the life of the capacitor.

In order to achieve similar study with SPWM modulation technology, a model based on the comparison of the modulation signal of a phase with two carrier signals is developed [7]. Fig. 7 is the waveform and harmonic analysis of the neutral point current.

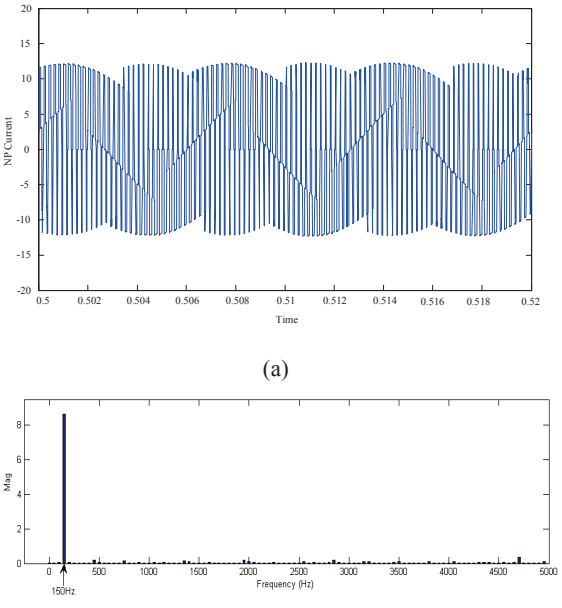

Fig. 7. Neutral point current and its FFT analysis spectrum under SPWM modulation: (a) neutral point current (b) FFT analysis spectrogram

It can be seen from Fig. 7 that the frequency of i_{NP} is three times of the modulation wave frequency, and the amplitude of the third harmonic component is $0.74\hat{i}_{phase}$. The neutral point current amplitude fluctuates between-12~+12 amperes.

From Fig. 6 and Fig. 7 ,the ripple current of the DC-bus capacitors of the NPC three-level inverter has the next harmonic component:

1.Zero frequency, due to possible unbalances in the voltage of the two banks of capacitors.

2. High frequency ripple of i_{DC} ,due to commutation frequency, and

3.Three times the frequency of the modulation signals due to i_{NP} ,called low frequency ripple.This current generates the voltage unbalance between the two banks of DC-bus capacitors.

In the NPC three level inverter, the capacitor ripple current i_{DC} affects the heating of the capacitor, and the neutral point current i_{NP} will produce unbalanced voltage between the two capacitor banks of the DC bus. The DC-link applications can be classified into high ripple current ones and low ripple current ones. The ripple current capability of the three types of capacitors is approximately proportional to their capacitance value as show in Fig. 8.From Fig. 8, we can conclude that the high ripple current will reduced the reliability of the capacitor.

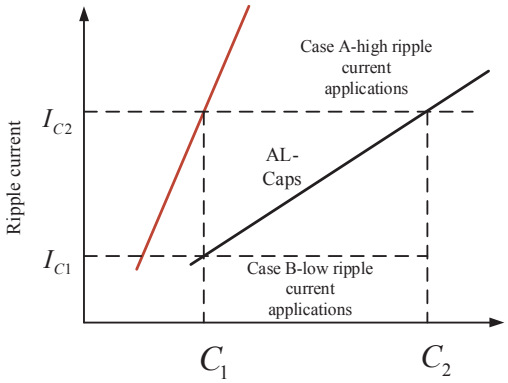

Fig. 8. Capacitance requirement of low ripple current applications and high ripple current applications

Ⅴ. CONCLUSIONS

In this paper, the structure and equivalent circuit of electrolytic capacitor are analyzed firstly, and then the mathematical expressions of the capacitor ripple current and the neutral point current are obtained by analyzing the mathematical model of NPC three-level ripple current. A MATLAB graphical has been implemented to calculate this current ripple in a fast and simple way. Finally, the validity of the expression is verified by simulation. The mathematical model presented in this paper reflects the influence of operating parameters on ripple current and neutral point current. It has been verified that the 150Hz current ripple obtained in the simulations agrees with the ripple obtained by calculations for the same working conditions. It can also be applied to the calculation of the temperature rise of electrolytic

capacitors in NPC three-level inverter and provides reference for the selection of electrolytic capacitors.

ACKNOWLEDGMENT

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