Ripple Current Analysis of Three-level Inverter based on SVPWM and Design of LCL Filter

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Abstract: - Three-level gird-connected converter is used more and more widely in renewable energy generation system. At the same time LCL filter is also widely utilized in order to achieve lower current harmonic. However, current research about LCL filter is mostly aimed at two-level inverter. The study involving multi-level inverter is much less. When using space vector pulse width modulation, Current transient process near the current peak value of three-level inverter in one switching period is analyzed. And the lower limit of arm side inductance is obtained through the study of maximum ripple current. After that, based on LCL filter model for high order harmonic, the impact on ripple inhibition and resonant frequency caused by different filter parameters and scale factor is analyzed, Which provides a basis for design of LCL output filter parameters. Finally, calculations are made. Both the simulation and experiment results verify the validity of the proposed Design method.

Key-Words: - three-level inverter, SVPWM, LCL filter, harmonic, ripple.

1 Introduction

Along with the popularization and application of new energy sources such as photo-voltaic, wind energy and so on, the grid-connected inverter is getting more and more attention [1-3]. Inverter using three-level topology can be used to output high capacity and high quality power with relatively small capacity switching device. due to its high stress levels, low du/dt and low harmonic content of output waveform, the three level inverter has become a new research hot spot [4-6]. In the selection of the output filter, because the three-level grid-connected inverter is usually used in a large capacity, considering the size of the filter, the cost and other issues, LCL filter is usually selected. A lot of papers introduce the design of LCL filter based on two-level inverter. However the study involving multi-level inverter is much less. Inverter using multi-level topology can derive more voltage vector, which makes it difficult to design the parameters of the output LCL filter. So, it is necessary to study how to design LCL filters for multi-level inverter [7]. For three level grid connected inverter LCL filter, the design of its grid side inductance, filter capacitor and damping resistor are basically the same as the two level LCL filter. The distinctive difference is the design of the bridge side inductance, because the impact of the current ripple is different between two-level and three- level inverter.

In this paper, with the three level voltage inverter using space vector pulse width modulation (SVPWM) as the study object, the ripple current of the inductor current in a switching period is analyzed. Based on the traditional LCL filter parameter design and considering of stability, the influence the harmonic content and resonant frequency caused by scale factor and capacitance parameter is analyzed, and the design scheme of output LCL filter for three level inverter is proposed. Finally, the Matlab simulation model is established, and a set of experimental platform based on DSP-CPLD is built, which verifies the correctness of the proposed method, which has high value of application.

2 System Topology

Among all multi level topologies, three-level neutral-point-clamped (NPC) inverter is the most widely used at present. The grid connected system comprises a NPC inverter and a low-pass output LCL filter as shown in Fig.1.

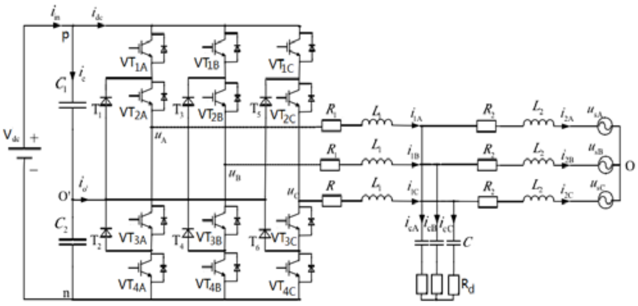


Fig.1. System topology of grid-connected three level.

Each leg of the NPC inverter consists of four power switches (IGBT), four freewheeling diodes and two clamping diodes that limit the voltage excursions across each device to half the input dc-bus voltage. For three-level NPC inverter, each bridge leg has three different switching states. For example, the switching state of phase A is shown in Table 1.

Table 1. Switching States of Three-Level Inverter

State	VT_{1A}	VT_{2A}	VT_{3A}	VT_{4A}	u_A
P	on	on	off	off	$V_{dc}/2$
O	off	on	on	off	0
N	off	off	on	on	$-V_{dc}/2$

Considering three-phase, the total switching states consist of 3^3=27 different states. According to the magnitude value, these 27 switching states of the three-level inverter indicating each state with the combination of P, N and O states are classified by four voltage vectors: one zero vector , six small vector whose length is $V_{dc}/3$, six middle vector whose length is $\sqrt{3}V_{dc}/3$, and six large vector whose length is $2V_{dc}/3$, as shown in Fig.2. The zero vectors have three switching states (PPP, OOO and NNN). Each of the six small vectors has two switching states and each of the middle vectors and the large vectors has one state respectively.

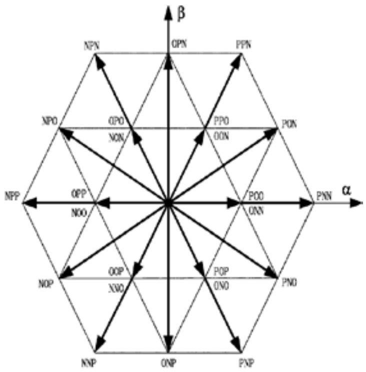


Fig.2. Space Voltage Vector With Their Switching States for Three-level Inverter.

The space vector diagram is divided into six triangle sections by six large voltage vectors. If we start from the large voltage vector PNN, the whole region can be defined as sectors I, II… and VI every 60 degrees. And each sector is divided into four sub triangles as shown in Fig.3.

3 Ripple Current Analysis

The main idea of SVPWM is to find out which sector and sub triangle the target reference vector V_{ref} falls into, and then, form the target reference vector by its three nearest voltage vectors according to voltage-second balance principle[8].

When the SVPWM method is used, the range of the DC side voltage is needed. The switch device voltage stress and the loss of the system will be increased if voltage of DC side is too high. On the contrary, too low DC side voltage will lead to the failure of current tracking. Considering the power grid fluctuations, linear control range and other factors, the calculation of the DC side voltage is as follows [9]:

$$V_{dc} \approx \frac{3}{\sqrt{2}} E_m \tag{1}$$

Where E_m denotes the peak phase voltage of grid.

Under steady state condition, when the current reaches the peak value, the ripple current is most serious. So the current transient process in a switching period at the current peak is the key points of ripple analysis. In order to simplify the analysis, assume that inverter is controlled by unit power factor, when the current reaches the peak value, the power grid voltage reaches its peak value too, the rate of current and voltage is zero at the same time. At this time, E_m lies on the α-axis and the fitting of the reference voltage vector is shown in Fig. 3.

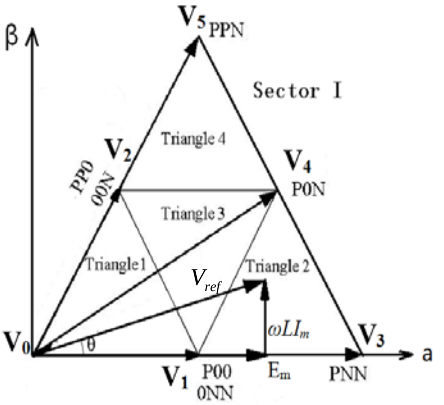


Fig.3. Fitting of Reference Voltage Vector.

In sector I, when the reference vector is in the region of triangle 2 as shown in Fig. 3, according to the three vector nearest principle , the small vector V_1, the middle vector V_3 and the large vector V_4 can be selected as basic vectors in order to synthesize reference vector. Assume T_1, T_3, and T_4 to be the operating time of vector V_1, V_3 and V_4 respectively, T_s to be the time of a switching cycle, there is:

$$T_1 + T_3 + T_4 = T_S \tag{2}$$

In order to get a better harmonic elimination effect, the seven segments pulse width modulation is adopted, which started with the small negative vector OON, counter clockwise passes through PNN, PON, reaches to the small positive vector POO, and then returns back clockwise. In this process the transient state of the ripple current is shown in Fig. 4 [10].

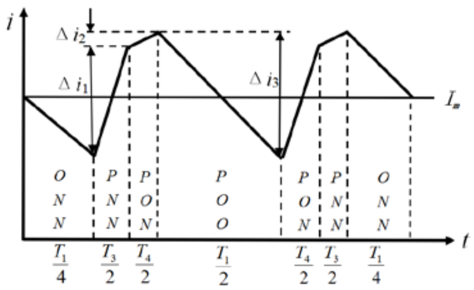


Fig.4. Transient State of Ripple Current Near Current Peak.

In the vicinity of the peak current, the maximum ripple current is concerned, the most serious situation occurs when the operating time of V_4 is zero. At this time, Δi_1 is equal to Δi_3, the following equations could be attained:

$$|V_1| - E_m = \frac{V_{dc}}{3} - E_m = -L_1 \frac{2\Delta i_3}{T_1} \tag{3}$$

$$|V_3| - E_m = \frac{2V_{dc}}{3} - E_m = L_1 \frac{2\Delta i_1}{T_3} \tag{4}$$

Make T_4=0, there is:

$$T_1 + T_3 = T_S \tag{5}$$

$$\Delta i_1 = \Delta i_3 = \Delta i_{\max} \tag{6}$$

Combine Formula (3) ~ (6), the following equation could be attained:

$$\Delta i_{\max} = \frac{T_s}{6L_1 V_{dc}}(3E_m - V_{dc})(2V_{dc} - 3E_m) \tag{7}$$

The value obtained in formula(7) should meet the requirements of the maximum ripple current, which often take 10% of the rating current peak value[11]. Make $\Delta i_{\max}$=0.1I_m and substitute into equation (7), there is:

$$L_1 \ge \frac{5T_s}{3I_m V_{dc}}(3E_m - V_{dc})(2V_{dc} - 3E_m) \tag{8}$$

According to above equation, the bridge side inductance can be determined, which usually takes the lower limit.

4 Design of LCL Filter for Three-Level Grid-Connected Inverter

4.1 Mathematical Model of LCL Filter

Since the output of inverter adopting SVPWM does not contain low order harmonics, the power grid voltage is equivalent to a short circuit when higher harmonics are concerned only. Thus, the single phase equivalent circuit of the LCL filter can be obtained as shown in Fig. 5.

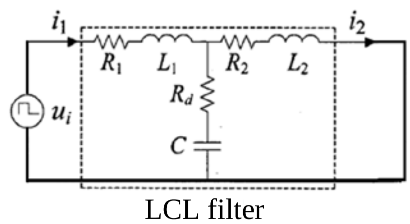


Fig.5. Single Phase Equivalent Circuit of High Order Harmonic.

The equivalent resistance R_1 and R_2 are usually small, if the resistance is ignored, we can get the LCL filter's transfer function from voltage of the bridge side to the current of the grid side [12]:

$$G(s) = \frac{I_2(s)}{U_1(s)} = \frac{R_d Cs + 1}{L_1 L_2 Cs^3 + (L_1 + L_2) R_d Cs^2 + (L_1 + L_2)s} \tag{9}$$

When R_d is ignored, there is:

$$G(s) = \frac{1}{L_1 L_2 Cs^3 + (L_1 + L_2)s} \tag{10}$$

Therefore, the filtering effect of specific frequency harmonic can be expressed as:

$$G(jw) = \frac{1}{-jL_1 L_2 Cw^3 + jw(L_1 + L_2)} \tag{11}$$

4.2 Design of Bridge Side Inductor

According to the formula (8), we can determine the inductance of the bridge side. Under steady state conditions, the ability of active power output is considered, the total inductance of the three level grid connected inverter under the unity power factor should be satisfied [13]:

$$L_1 + L_2 \le \frac{\sqrt{M^2 V_{dc}^{\ 2} - E_m^{\ 2}}}{2\pi f I_m} \quad (12)$$

Where, M is the modulation coefficient, take it as $\sqrt{3}/3$ when using SVPWM; f is the fundamental frequency of the power grid.

4.3 Impact of Scale Factor and Capacitance

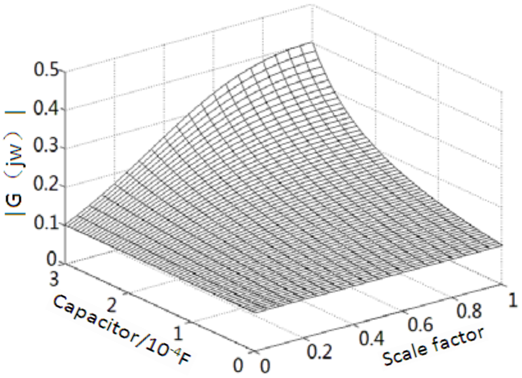
Define the scale factor as $\lambda=L_2/L_1$, the resonant frequency of system is computed as follows:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1 L_2 C}} = \frac{1}{2\pi}\sqrt{\frac{1+\lambda}{\lambda L_1 C}} \quad (13)$$

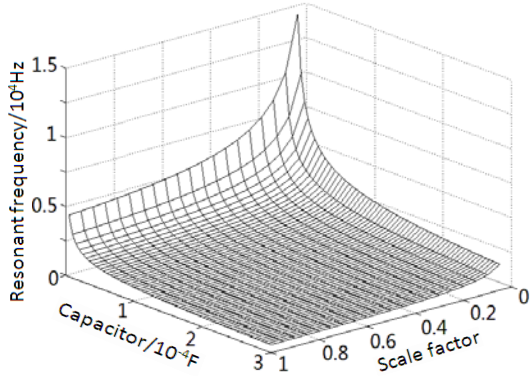
In consideration of the ripple current of the inverter bridge is decided by L_1 mainly, and higher ripple current will lead to larger loss of switching and loss on the inductor. Therefore, the inductance of the bridge side is usually greater than the power grid side, so the value of scale factor is lower than 1.

According to the formula (11) and (13), influence on filter effect and resonant frequency caused by the scale factor and capacitance can be investigated respectively, as shown in Fig 6.

The filtering effect of specific harmonic affected by different scale factor and capacitance is shown in Fig. 6(a). When total inductance is certain, the resonant frequency affected by different scale factor and capacitance is shown in Fig. 6(b). Fig. 6(a) shows that with the increasing of capacitance, the amplitude of harmonic is getting much higher. For the same capacitance, higher scale factor lead to higher current harmonic amplitude. From Fig. 6(b), it can be seen that if the capacitance or scale factor is increased, the resonant frequency becomes lower, which means better filtering effect of high order harmonic can be achieved. When the filter capacitance is between 30~300uF and the scale factor is between 0.2~1, the resonant frequency is more gentle. Considering that with the increasing of capacitance and scale factor, the harmonic content would be increased, so the capacitance and scale factor should be selected closed to the lower bound as far as possible.



(a)relationship between |G(jw)| and λ,C



(b)relationship between resonant frequency and λ,C

Fig.6. Impact on Filter Effect and Resonant Frequency Caused By λ and C.

The filter capacitor in LCL filter is mainly used to meet the requirement of high frequency current decay rate. But greater the capacitance is, the more reactive power is produced, which leads to the larger fundamental reactive current and lower power factor. Thus, the current capacity of inverter is limited equivalently. In addition, the size of AC capacitor with large capacitance is big and expensive. Generally, the reactive power produced by the capacitor of LCL filter must not exceed 5% of the rating active power[14]:

$$C \le \frac{5\% P_n}{6\pi f E_n^{\ 2}} \quad (14)$$

Where P_n for rating active power; E_n for the rating phase voltage of the grid side.

In addition, the introduction of the capacitor branch is to provide a low resistance path for the high frequency components, the grid side inductance and filter capacitor constitute a parallel circuit on the switching ripple content. In order to ensure the shunt effect, the capacitor impedance must be much less than the inductor impedance of grid side.

The proportion relationship exists between the impedance of capacitor and inductor is generally taken as 20% [12]. So the lower bound of the filter capacitance can be determined.

$$C \geq \frac{5}{4\pi^2 f_s^2 L_2} \tag{15}$$

Where f_s is switching frequency.

After the initial LCL parameters are determined, it is necessary to check the resonant frequency. Too high or too low resonant frequency of the LCL filter should be avoid. The resonant frequency of the LCL filter should be better 10 times greater than the grid frequency, and less than half of the switching frequency.

4.4 Design of Damping Resistance

After the checking of the resonant frequency, the design of the damping resistance can be carried out. Through the bode diagram analysis of the transfer function based on formula (9), an conclusion was made, that is, increasing damping resistor can enhance the damping coefficient and system stability. With the increasing of the damping resistor, the resonant peak value decreases. When the damping resistance is 0.3~0.4 times of capacitor impedance, effect of the resonance peak suppression is satisfying. If we keep on increasing damping resistance, more damping loss would be afforded. So the calculation of the damping resistance can be determined by the following formula:

$$R_d = (0.3 \sim 0.4) X_C = (0.3 \sim 0.4) \frac{1}{2\pi f_{res} C} \tag{16}$$

5 Calculation, Simulation and Experiment

5.1 Calculation

In order to demonstrate the design method of LCL filter proposed in this paper, taking a 50kW three-level inverter based on SVPWM as example, which is connected with grid through transformer. Parameters are as follows:

Table 2. Parameters Categories

Parameters	**Value**
Grid line voltage(RMS)	380 V
Load rate	50 KW
Transformer voltage ratio	380V / 315V
DC bus, V_d	600 V
Utility frequency, f	50 Hz
Sampling frequency	12.5 kHz
Switching frequency, f_s	12.5 kHz
Current peak, I_m	130 A

The calculation procedures are as follows:

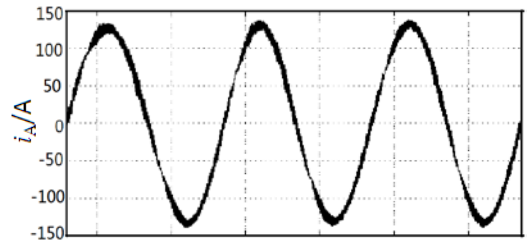
(1) According to formula (12), the total inductance must not exceed 5.7mH. According to formula (8), the inductance of the bridge side should be greater than 0.25mH. So the inductance of the bridge side is selected to be 0.3mH.

(2) Choose the scale factor to be 0.2, therefore the inductance of the grid side is 0.06mH. According to formula (14), the capacitance should be less than 80.97uF, and must be greater than 9.01uF on the basis of formula (15). So the initial selection of capacitance is 40uF.

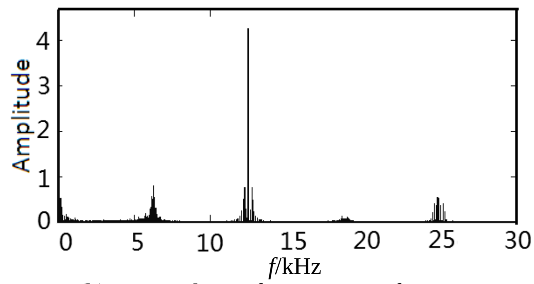
(3) When the initial LCL parameters are settled, the resonance frequency of the LCL filter is 3558 Hz obtained by formula (13), which satisfies the requirement of the checking condition. And then, it can be calculated that the damping resistance is 0.34Ω according to formula (14).

5.2 Simulation

In order to verify the correctness of the filter parameters design, a simulation model based on Matlab/Simulink is established. Total harmonic distortion (THD) is shown in Fig. 7. In Fig. 7(a), it can be found that the current ripple is most serious when the current reach to its peak value. After a fast Fourier transform, the spectrum is investigated, as shown in Fig. 7(b). It can be seen that harmonics are mainly concentrated at the switching frequency, and THD is 4.81%.



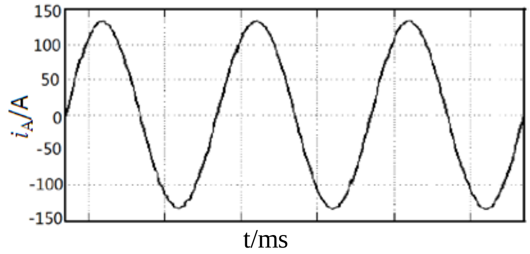
(a) A-phase arm side current waveform



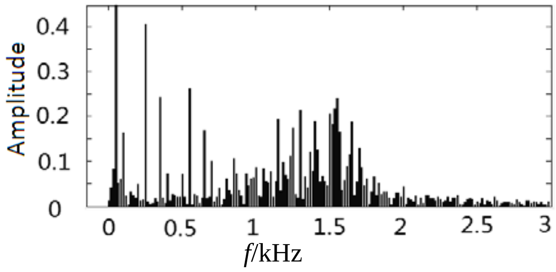
(b) FFT analysis of current waveform

Fig.7. Arm Side Current Waveform and Its FFT Analysis of A-phase

Simulation results of the grid side current after LCL filtering are shown in Fig. 8. The THD of the grid side current is 0.71%, which has good filtering effect. It can be seen from Fig. 8(b) that the harmonic contents are mainly located in frequency below 2.5kHz, which shows that the LCL filter can filter out high order harmonics successfully.



(a) A-phase grid side current waveform



(b) FFT analysis of current waveform

Fig.8. Grid Side Current Waveform and Its FFT Analysis of A-phase.

5.3 Experiment

In order to go a step further to verify the correctness of the design method, a set of experimental platform based on DSP-CPLD as the control core is set up, as shown in Fig 9.

Fig.9. Experimental Devices.

Waveform of grid side phase current under steady state as shown in Fig. 10. And with a power quality analyzer, it can be measured that the THD is 1.87%, which means that the three level inverter system meet the requirements of the power grid.

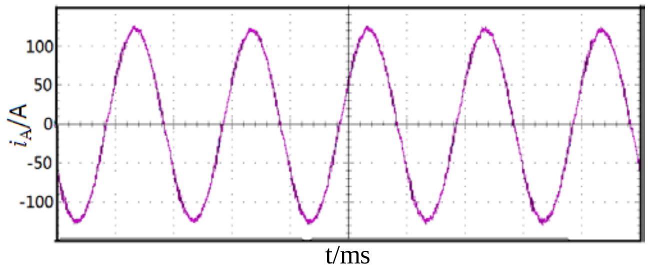


Fig.10. Steady-state Waveform.

6 Conclusion

In this paper, the ripple current of three level grid connected inverter adopting SVPWM is analyzed. The lower limit of the inductance of the bridge side is settled by investigating the current transient process. Based on the LCL output filter model for high order harmonic, the impact on ripple inhibition and resonant frequency caused by different the filter parameters and the scale factor is analyzed. And this provides a basis for design of LCL output filter parameters.

Finally, calculations are made to demonstrate the design. Both the simulation and experiment research are also realized. The THD of the grid-tied current is rather small and the quality of the waveform is quite good, which verify the validity of the proposed method.

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