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ANALYSIS AND DESIGN OF AN LCL FILTER FOR THE NINELEVEL GRID-CONNECTED INVERTER

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ABSTRACT-A neutral-point-clamped (NPC) nine-level inverter is used more and more in the grid-connected power generation system. In order to achieve the lower current harmonic, an LCL filter is widely utilized due to its superior filtering performance. Passive and active damping control are studied to solve the resonant problem appearing in an LCL filter, active damping control overcomes the weakness of power loss existing in the passive damping method, thus it gradually becomes one of research focus. According to the feature of the NPC Nine -level grid-connected inverter and active damping method based on feedback control of the capacitor current, design method of the LCL filter is thoroughly discussed in this paper, simulation and experimental results show that the filter design method is right.

Keywords- LCL Filter, Parameter Design, Active Damping Control, NPC Nine-level Grid-connected Inverter

I. INTRODUCTION

Compared with the two-level inverter, NPC ninelevelinverter has high voltage range, small du/dt and low output current harmonics, therefore it develops fast in the high power grid-connected field [1]. Current harmonics generated by a PWM strategy for the grid-connected inverters is filtered usually by ac filters. An LCL filter may use smaller inductance to achieve the same filtering effect relative to L and LC filter, so it is paid extensive attention. But the LCL filter is a three order system, in which the resonant gridconnected control strategy to bring about the instable operation state. The passive damping control is analyzed in detail in [2], passive damping control strategy is simple and can solve the instable problem caused by the resonant peak well, but there is power loss especially in the high power system. An active damping strategy using capacitor current feedback control strategies [4,5,6]. Besides the grid-connected control strategy, design of an LCL filter is another important factor influencing the filtering performance. Most parameter design methods of an LCL filter presented in the past references are based on two-level inverters [7]. And parameter design for NPC three-level inverters is quite less. In [8] the gridconnected inverter is supposed to be Y form, in which the neutral point of the reference midpoint of the inverter, and then each phase may be analyzed and calculated alone. However, the above assumption is not rational in the actual renewable energy power generation system. In a word, most of the algorithms focus on design of the filtering inductance, but the design of filtering capacitance is only limited simply by the consumption of reactive power, no specific design method is given. In this paper, filtering inductance design directed at the NPC nine-level inverter is studied, and filtering capacitor considering the characteristic of active damping strategy based on the capacitor current

II. ANALYSIS AND DESIGN OF AN LCL FILTER

High performance grid-connected inverters are provided with high efficiency, high power quality, low THD, high reliability, and simple topology. Fig.1 shows the main circuit and control diagram of a three-phase transformer-based grid connected inverter with current control. The transformer T is used to isolate the grid from the inverter and restrain harmonic components flowing into the grid. Powerloss are composed of power devices loss in the nine inverter-legs including IGBTs and diodes, loss in the filter inductance Lf and loss in the transformer T. They are divided into uncontrollable and controllable losses. Main

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circuit of the three-phase three-level grid-connected PV generation system with an LCL filter is shown in Fig.1.

The input stage is a PV array. C1, C2 are the dc-link filtering capacitors.
The threelevel inverter is composed of S1-S12 and six NPC diodes, and is connected with the grid through theLCL filter Assuming that three-phase grid voltages are symmetric, the single-phase equivalent circuit of an LCL filter is shown in Fig.2.

Transfer functionsolves the power loss caused by the passive damping control, and only proportional control is utilized forthe inner current loop, it's easy to ensure the system stability, so it becomes one of the most popular between output current and input voltage is deduced according to Fig.

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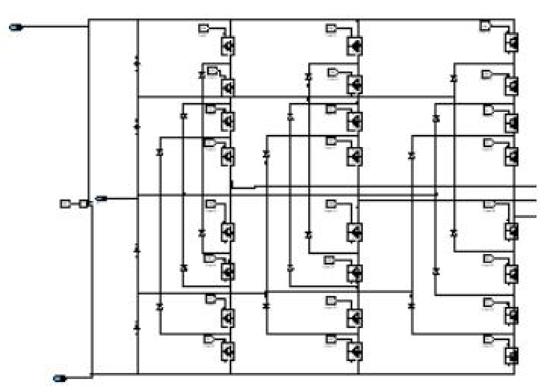

Fig.1 Main circuit of the three-phase nine -level grid-connected PV generation, system with an LCL filter

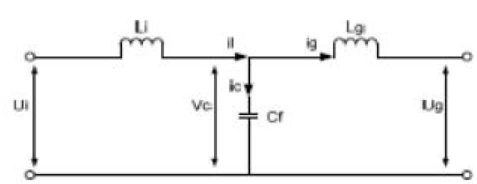

Fig 2. Equivalent circuit of a single phase LCL filter

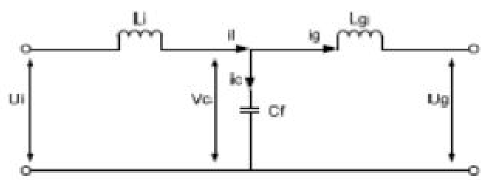

Fig 2. Equivalent circuit of a single phase LCL filter

$$\frac{I_g(s)}{U_i(s)} = \frac{1}{L_g L_i C_f s^3 + (L_g + L_i)s} \quad (1)$$

Therefore, filtering effect of specific harmonic is expressed

By

$$H_{LCL}(j\omega) = \frac{1}{-jL_i L_g C_f \omega^3 + j\omega(L_i + L_g)} \quad (2).$$

where, represents angular frequency of specific harmonic.

A. Design of Total Filtering Inductance LT

For the NPC three-level inverter, the voltage of filtering inductor of each phase is decided by switching states of three phases, there exists strong coupling relationship among three phases. If coupling relationships among phases and all switching states are taken into consideration, the analysis becomes very complex. Therefore, only the worst possible case is analyzed.

$$S_{a/b/c} = \begin{cases} 0.5 & \text{turn-on of upper two switches on the same arm} \\ 0 & \text{turn-on of middle two switches on the same arm} \\ -0.5 & \text{turn-on of downer two switches on the same arm} \end{cases} \quad (3).$$

So the reference midpoint voltage is

$$U_N = \frac{U_{dc}}{3}(S_a + S_b + S_c) \quad (4).$$

Where, *U*dc is the dc-link voltage.

Take the positive half cycle of phase a as an example, the equivalent circuit is shown in Fig.3, due to less influence of filtering capacitor on inductance voltage, filtering capacitor is neglected.

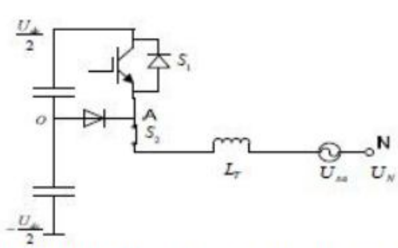

FIG3. Equivalent circuit of phase a when the voltage is positive

Inductance voltage has multilevel change in each switching period, but the state change is limited to 0.5 for each phase. Considering the most serious situation, i.e., Sa changes from 0.5 to 0, Sb and Sc change from -0.5 to 0, the voltage relationship is shown in Fig.4 according to Fig.3.

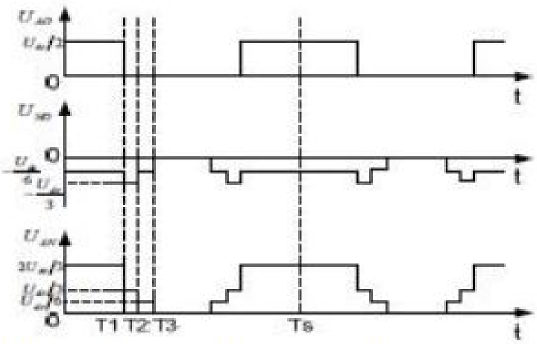

Fig 4 Voltage sketch related to a phase voltage

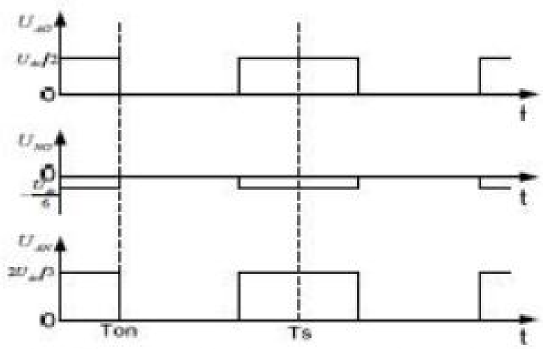

Fig 5 Simplified voltage sketch related to a phase voltage

In Fig.4, Sa changes from 0.5 to 0 at T1, Sb and Sc change from -0.5 to 0 at T2 and T3 respectively.

The moments of T1, T2 and T3 change with different modulation index, when T1, T2 and T3 are extremely close to be equal, the most serious situation happens. Suppose that the turn-on time in one switching period is Ton, the turn-off time is Toff=Ts-Ton.

Thus Fig.4 is simplified to Fig.5, and the relationship between voltage and current ripple is shown in Fig.6.

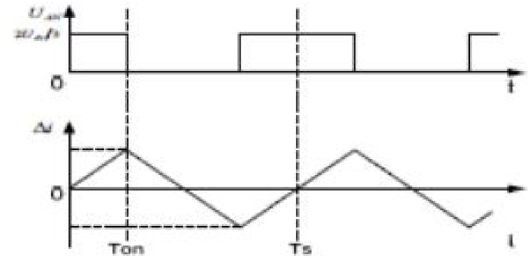

Fig 6 Relationship between the voltage and current ripple

According to Fig.3, while S1 turns on:

$$U_{dc} = L_T\frac{\Delta i}{T_{on}} + U_{sa} + U_N = L_T\frac{\Delta i}{T_{on}} + U_{sa} + \frac{U_{dc}}{3}(0.5+S_{b1}+S_{c1}) \quad (5)$$

When S1 turns off :

$$\frac{U_{dc}}{2} = -L_T\frac{\Delta i}{T_{off}} + U_{sa} + U_N = -L_T\frac{\Delta i}{T_{off}} + U_{sa} + \frac{U_{dc}}{3}(0.5+S_{b2}+S_{c2}) \quad (6)$$

where, LT is total inductance, i is current ripple of phase a. Sb1、Sb2、Sc1、Sc2 represent switching states of phase a and b before and after Ton. When current ripple is maximum, the following equation is satisfied.B. Inductance Ratio at the Inverter Side and Grid SideThe filtering effect of an LCL filter is not only decided by the capacitance and inductance values, but also associated with the ratio of two inductors. With fixed total inductance LT, of inductance ratio and capacitance value on filtering effect for specific harmonic according to (2) is achieved, as shown in Fig.7. The total inductance is 8mH, inductance ratio changes in the ranges of 0-10, the capacitor Cf changes from 0 to 100μF. It is easy to see from Fig.7 that the filtering effect is best at λ=Li/Lg=1 when the total filter capacitance and inductance are fixed, and the effect is similar when λ changes within the scopes of 0.2-5.Because the inverter-side current ripple is mainly decided by the inverter-side inductance Li, Li should be greater under the condition of the similar filtering effect in

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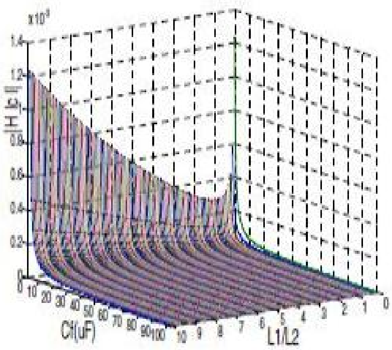

Fig 7 Filtering effect with different inductors

order to reduce the inverter switching noise and power loss, in general is selected as 2-5, if the resonant frequency is taken into account, may be chosen as 3-5.

C. Design of Filtering Capacitor

Filtering capacitor is generally designed when its consumption reactive power should be no more than 5% of the rated power, so a capacitance range is given by (13).

$$C_f \leq \frac{0.05P_n}{6\pi f_g U_{ph}^2} \qquad (13)$$

where, *f*g is the grid frequency.

But capacitor current is essential for active damping control strategy based on capacitor current feedback, so both sampling rationality and reactive current should be considered. It is seen from Fig.8 that while the inductance ratio is constant, the bigger the filtering capacitance is, the better the filtering effect is. But after filtering capacitance reaches to a certain value, with the increase of the capacitance, filtering effect changes less, however reactive current of the inverter side increases too, it will lead to the greater switching current and power loss of the inverter, in the meanwhile, the filter voltage drop increases, it may cause the output current distortion. It is necessary for active damping control strategy based on capacitor current feedback to sample the corresponding current, resonant frequency of the filter is significant which is expressed by (14).

$$C_f \leq \frac{0.05P_n}{6\pi f_g U_{ph}^2} \qquad (13)$$

where, *f*g is the grid frequency.

According to (12) and (14), influence of thecapacitance on resonant frequency with constant total inductance LT and fixed is shown in Fig.8 shows that resonant frequency fres of an LCL filter decreases along with the increase of filtering capacitance. In practical control system, relationship between sampling frequency fsamp and switching frequency fsw generally is given by (15).

$$\omega_{res} = \sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \qquad (14)$$

According to (12) and (14), influence of the capacitance on resonant frequency with constant total inductance *L*T and fixed is shown in Fig.8 shows that resonant frequency *f*res of an LCL filter decreases along with the increase of filtering capacitance. In practical control system, relationship between sampling frequency *f*samp and switching frequency *f*sw generally is given by (15).

$$f_{samp} = f_{sw}/h \quad h = 1,2,3... \qquad (15)$$

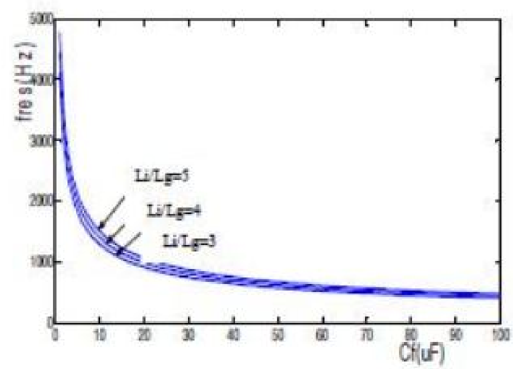

Fig 8 Freq/Cs

$$10f_g < f_{res} < f_{sw}/5 \qquad (16)$$

According to (14) and (16), equation (17) is obtained.

$$\frac{25L_T}{\omega_{sw}^2 L_i L_g} < C_f < \frac{L_T}{100\omega_g^2 L_i L_g} \qquad (17$$

where, *sw* is the switching angular frequency.

In a word, filtering capacitor is calculated on the basis of (13) and (17).

same while the inverter-side current has more harmonics

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III. SIMULATION AND EXPERIMENTAL RESULTS

According to the previous analysis, a 2kW simulation system is built with PSIM, using active damping control strategy based on capacitor current feedback in dq rotating coordination system. System structure is shown in Fig.1. Main parameters are given as follows:

Rated power: 2kW;
Dc-link voltage: 400V;
Grid phase voltage: 110V/ 50Hz;
Rated output current: 6A;
Switching frequency: 10kHz.

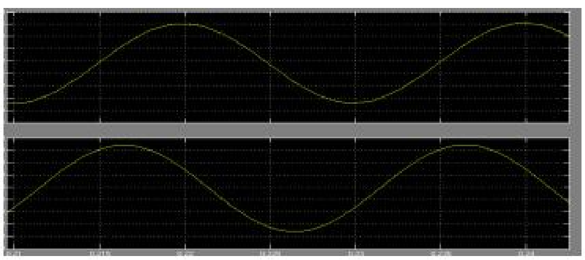

Fig.9 Simulation results with different inductance ratio

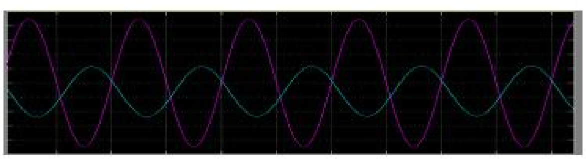

Fig.10 Experimental result without any damping control

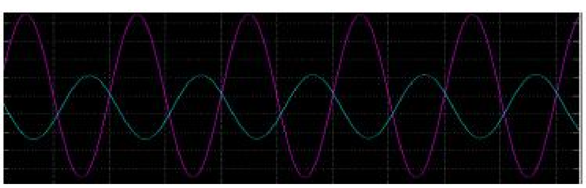

Fig 11. Grid voltage and grid-connected current

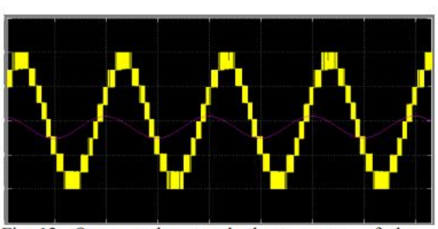

Fig 12. Output voltage and phase current of the inverter side

under the condition of λ =1relative to λ = 3. A 2kW prototype based on MCU XE164 is built. The same control strategy and parameters as those of the simulation are used. Fig.10 shows experimental results with traditional current control, neither passive damping control nor active damping control strategy has been used, where, 62.5% of the rated power is carried out in order to avoid damaging the inverter system. It is known from Fig.10 that highfrequency oscillation occurs in the gridside current, it means that the system is instable. Fig.11 is the experimental result with active damping control based on capacitor current feedback. Fig.11 (a) shows that grid-connected current is sinusoidal and there is no resonant phenomenon. Fig.11 (b) shows output voltage and current of the inverter side, it is seen from Fig.11 (b) that output voltage has three levels and the current ripple of the inverter side gets the better restriction because the inverter side inductance is bigger.

IV. CONCLUSION

Parameter design of an LCL filter based on the NPC ninelevel inverter and inductor current ripple is analyzed in detail in this paper. Filtering capacitor parameter based on active damping control strategy is designed too. Simulation and experimental results verify that the design method is feasible, good filtering effect has been achieved.

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