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단상 계통연계 태양광 인버터용 L-C-L 필터 설계 및 분석

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Study and Design of L-C-L Filter for Single-Phase Grid-Connected PV Inverter

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Abstract - Nowadays, the LCL-filter type becomes an attractive grid interfacing for grid-connected Voltage Source Inverter (VSI). LCL-filter can render the current harmonics attenuation around the switching frequency by using smaller inductance than L-filter. This paper presents a study about the LCL-filter design for single-phase grid-connected inverter in Photovoltaic (PV) system. According to the expected current ripple, the inductances of the filter can be determined. Based on the absorbed reactive power on capacitor, the capacitance can be calculated. Due to the theoretical analysis, a LCL-filter based single phase grid connected inverter control system are simulated. The studied simulation results are given to validate the theoretical analysis.

1. INTRODUCTION

To eliminate the current harmonics around the switching frequency and comply with the standards (i.e IEEE 1547.1), the inverter for renewable energy source requires an output low-pass filter to interface with the grid. However, in high power grid-connected inverter, the filter design is hard to satisfy the trade-off when considering the switching loss/efficiency and fundamental voltage drop.

Comparison with L- and LC-filter, the LCL-filter produces better attenuation of inverter switching harmonics even with small values of L and C. However, the three-order LCL-filter design needs to consider various constraints, such as the resonance phenomenon, the current ripple through inductors, the total impedance of the filter, the current harmonics attenuation at switching frequency and the reactive power absorbed by capacitor, etc.

A simple design rule is presented but it does not discuss about the voltage drop [1]. In [2], although the detail of voltage drop, power loss, damping resistance and resonant frequency are presented , it is too complex and not directly mentioned about the total inductance. Furthermore, LCL-filter has significant phase lag at turn round frequency, results in trouble of instability [3-5].

In this paper, a study about the LCL-filter design is summarized. Based on these investigations, the implementation principles are discussed, and their effectiveness are shown theoretically. Simulation results are shown to confirm the effectiveness of LCL-design process.

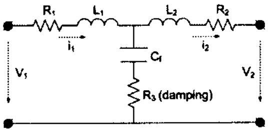

Fig.1 LCL-filter equivalent circuit diagram

2. LCL-FILTER PRINCIPLE ANALYSIS

The LCL-filter equivalent circuit diagram is shown in Fig.1, where V_1 is the inverter output voltage, V_2 is the grid voltage, L_1 and L_2 are the filter inverter- and grid-side inductor corresponding with equivalent resistor R_1 and R_2, respectively. A damping resistor R_3 is in series with capacitor C_f.

As equivalent resistance R_1 and R_2 are small enough to be ignored, the transfer function from the input V_1 to output I_2 of LCL-filter can be deduced as (1):

$$G(s)=\frac{i_2(s)}{V_1(s)}=\frac{C_fR_3s+1}{L_1L_2C_fs^3+(L_1+L_2)C_fR_3s^2+(L_1+L_2)s} \tag{1}$$

The determinations of three unknown parameters L_1, L_2 and C_f, will be discussed in the next sections.

2.1 Current ripple

The inductor determines the ripple in the inductor current and reduces the low frequency harmonic components. To simplify the analysis, assuming that the system has unity power factor and the bipolar Pulse Width Modulation (PWM) is adopted. Then the occurred maximum current ripple at the phase current zero-crossing can be deduced:

$$I_{ripplemax}=\frac{V_{dc}}{2Lf_s} \tag{2}$$

where

Iripplemax is maximum ripple current; V_{dc} is the dc-link voltage; L is the total filter inductance; f_s is the switching frequency.

Typically, Δ_{ripple} can be chosen as 5%~25% of rated current. The smaller the ripple current, the lower the IGBT switching and conduction losses, but the larger the inductor, resulting in larger coil and core losses.

2.2 Filter inductances

As mentioned in the previous section, from equation (2), we can get the value of the total filter inductance as following:

$$L = \frac{V_{dc}}{2 I_{ripplemax} f_s} \tag{3}$$

With inserted filter capacitor, the total inductance L is split into two parts: inverter-side L_1 and grid-side inductor L_2 with the following relationship:

$$L_1 = aL_2 \quad \text{with } a \geq 1 \tag{4}$$

The inductance ratio can be calculated by using the switching harmonic current attenuation ratio [6].

2.3 Filter capacitor

The filter capacitor Cf can be determined by considering the reactive power absorbed in C_f as following:

$$C_f = \frac{Q_{re}}{\omega_0 V_{rated}^2} = \frac{\alpha P_{rated}}{\omega_0 V_{rated}^2} \tag{5}$$

where

Q_{re} is the reactive power absorbed by filter capacitor; P_{rated} is the total rated power; α is the power ratio (<5%); ω_0 is grid frequency; V_{rated} is the rated grid voltage.

The more capacitance, the more reactive power flowing into capacitor, the more current demand from L and switches and the ripple on the inductor current will tend to increase. Hence the efficiency will be low. But the capacitance cannot be too small because a large inductance causes a high voltage drops across the inductor L_1.

2.4 Resonance frequency

The LCL-filter is constructed by a parallel resonance circuit, which resonance frequency is:

$$\omega_c = \frac{1}{\sqrt{(L_1 \parallel L_2) C_f}} \tag{6}$$

In filter design, one must avoid ω_c overlaps harmonic source in the circuit.

2.5 Passive damping resistor

The LCL-filter can contain a damping resistor to avoid the resonance phenomenon. The resistance should be one third of the impedance of the filter capacitor:

$$R_3 = \frac{1}{3\omega_c C_f} \tag{7}$$

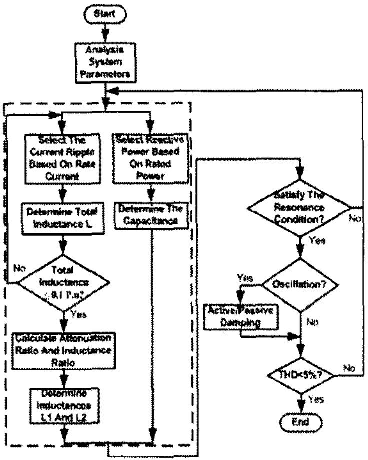

Fig.2 LCL-filter design

3. LCL-FILTER DESIGN PROCEDURE

The main LCL-filter design steps are summarized in Fig.2. There are some limits on the parameter values such as: - The total inductance should be less than 0.1 p.u to limit the AC voltage drop during operation. Otherwise, a higher DC-link voltage will be required, this results in higher switching losses.; - The capacitance is limited by the power factor (normally <5%); - The resonance frequency should be in range: $10\omega_o \leq \omega_c \leq \frac{1}{2}\omega_{sw}$ to avoid resonance problems; - The damping element losses cannot be high as to reduce efficiency.

4. LCL-FILTER BASED SINGLE-PHASE GRID-CONNECTED PV INVERTER

The filter design procedure for our single-phase grid-connected VSI control system, as shown in Fig.3, is described, where rated power P_{rated}=3kW, rated RMS line-to-line voltage is V_{rated}=220V, dc-link voltage V_{dc}=400V, switching frequency f_{sw}=10kHz and the rated current I_{rated}=6A.

Adopting $\Delta_{ripple} = 25\%$ and $Q_{re} = 2.5\% P_{rated}$, we can calculate the filter inductances L1=10.8(mH), L_2=2.53(mH), the filter capacitance C_f=4.11(μF), the resonance frequency f_c=1.733(kHz) and the damping resistance R_3=7.4(Ω).

The frequency response of LCL-filter is shown in Fig.4. The bandwidth of the closed-loop system when using LCL-filter will be the same as that of the L-filter below ω_c. With damping resistor, the system is stable, the resonance phenomenon is almost eliminated and the phase

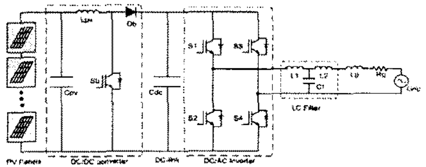

Fig.3 Single-phase grid-connected PV inverter system

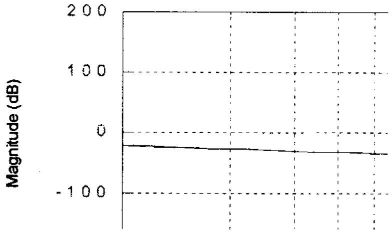

Fig.4 LCL-filter frequency response

lag is about 220^0. Increase resistance can depress the resonant peak but tends to reduce the attenuation. The stability of closed-loop control is ensured with control algorithm.

5. SIMULATION

To verify the feasibility of the LCL-filter design, a simulation using Matlab/Simulink as depicted in Fig.5 is carried out. The inductor L_1 and L_2 currents are shown in Fig.6 and Fig.7 with their frequency spectrums, respectively. It can be seen that the resonance phenomenon is almost avoided by adding the damping resistor. For comparison purpose, the L-filter is used (with the inductance $L=L_1+L_2$) and its results are shown in Fig.8. The final output response of L-filter still contains more ripple than that of LCL-filter and has a higher THD.

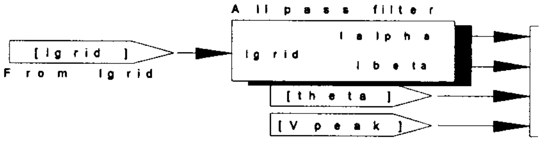

Fig.5 LCL-filter based single-phase grid-connected PV inverter

6. CONCLUSIONS

In this paper, a study on the LCL filter design for single-phase grid-connected inverter is described. The filter design considers on the constraints of parameter determinations and the overall process can be done by step-by-step equations solving. The design procedure ensures that the parasitics of the filter components are kept as low as possible.

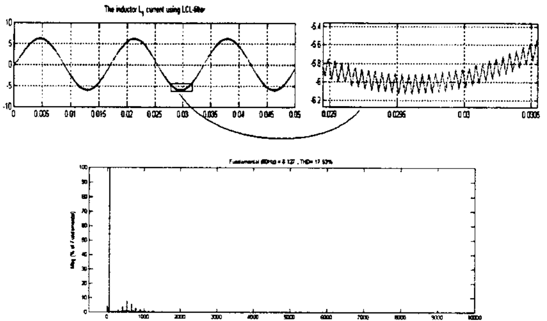

Fig.6 Inductor L_1 current and FFT analysis

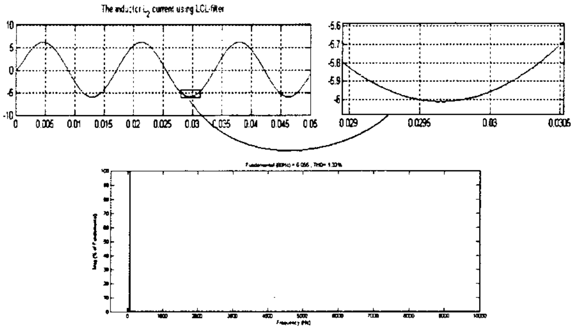

Fig.7 Inductor L_2 current and FFT analysis

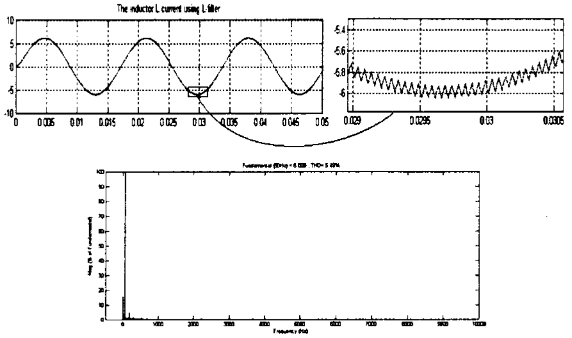

Fig.8 Inductor current and FFT analysis

Finally, the simulation results in the effectiveness of the LCL-filter in term of harmonic rejection. The methodology used in this paper can be extended to three-phase and applied to such distributed generation application as microturbine, fuel cell, wind power, etc.

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