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Design Method for the LCL Filters of Three-phase Voltage Source PWM Rectifiers

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Abstract

A new design method for the LCL filters of three-phase voltage source PWM rectifiers is presented in this paper. Based on the single-phase harmonic equivalent model, the harmonic voltage of the rectifier side is calculated to design the LCL filter parameters by an iterative algorithm, in which the resonance frequency f_{res} and the ratio r between the grid-side inductance and the rectifier-side inductance are selected as known constants. The design criteria and process are introduced and the influence on the design result by the value of the resonance frequency f_{res}, ratio r is analyzed. Finally an example (600V, 500kW) is tested by simulation and experiment to verify the validity of the new design method.

Key words: Damping resistance, Harmonic analysis, LCL filter, Resonance frequency, Three-phase voltage source rectifier

I. Introduction

Due to its controllable dc voltage and adjustable power factor, the three-phase voltage source rectifier (VSR) has been widely employed in solar and wind power generation systems [1], [2]. A single L type filter is the simplest filter between a PWM rectifier and the grid, and it offers sufficient attenuation of the switching ripple currents caused by pulse width modulation (PWM). However, in medium- and high-power applications, the switching frequency is relatively low, so a larger filter inductance is required to reduce the current harmonic around the switching frequency and to satisfy the harmonic standard of the grid current. This results in the following problems: 1) decreasing the system dynamic performance; 2) raising the limited dc voltage; 3) increasing the cost and the size of the inductance.

An attractive solution to overcome these problems is to use an LCL filter [3],[4]. The higher harmonic attenuation permits the inductance value of an LCL filter to be much less than that of a single L type filter. However, the design of an LCL filter is a complex procedure and an irrational design may cause distortion of the grid current and worsen the rectifier performance. Design procedures for the LCL filter parameters have been explored in the literature. A design procedure where the maximum converter current ripple determines the filter inductance and capacitor was proposed in Ref. [3]. It showed that many of the parameters such as the overall filter size and the ripple current in different filter components were involved in the selection of the LCL filter parameters. M. Liserre presented a step-by-step design procedure and criteria for the parameter selection of an LCL filter together with consideration of the control of rectifier [5],[6]. The design consideration of an LCL filter and the damping filter design was presented in [7], which is based on the filter attenuation factor for the grid current harmonic at the switching frequency. Kamran Jalili pointed out that the design of an LCL filter should be based on the limitation of the grid harmonic currents, which is related to the switching frequency and he proposed an iterative algorithms using a Thevenin circuit to calculate the LCL parameters [8]. This iteration idea is adopted in this paper. A design method which sets the attenuation coefficient of rectifier side harmonic current and then calculates the LCL parameters based on the harmonic voltage of space vector pulse width modulation (SVPWM) was presented in [9]. However, the influence of this coefficient selection on the design results was not analyzed.

The design criterion for the LCL filter parameters is analyzed in this paper. A new design method for an LCL filter is reported with a design example (600V, 500kW). Both simulation and experiment results are presented to verify the validity of this method.

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II. PRINCIPLE OF THE PARAMETER DESIGN FOR LCL FILTERS

A. Single phase equivalent model of a three- phase VSR

The power circuit of a three-phase voltage source PWM rectifier based on an LCL filter is depicted in Fig.1, where T_1~T_6 are the IGBT modules, L_g is the grid side inductance, L_r is the rectifier side inductance, the damping resistor R_d connects the filter capacitor C_f in series to avoid resonance, C is the dc bus capacitor, R_g and R_r are the equivalent resistors of the inductance, U_{dc} is the dc voltage, e_{sx} and i_{gx} are the grid voltage and current (x=a, b, c), u_{rx} and i_{rx} are the voltage and current of the rectifier ac side, and u_{Cf} and i_{Cfx} are the voltage and current of the filter capacitor. The reference direction of the current is shown in Fig.1.

An equivalent single-phase model of the system is shown in Fig.2 (a), in which the rectifier ac side is equivalent to the controlled voltage source and the equivalent resistors R_g and R_r are neglected. Fig.2 (b) is a single-phase harmonic equivalent model, where h is the order of the harmonic, the rectifier ac side is equivalent to a harmonic generator and the grid can be considered as a short circuit with the assumption that the grid is an ideal voltage source. The design method proposed in this paper is based on these two models.

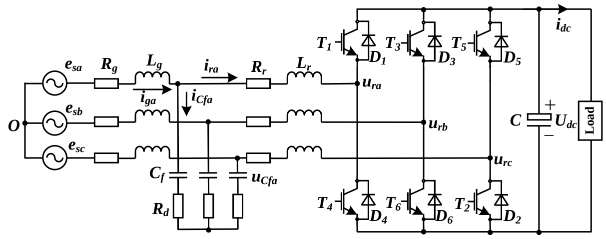
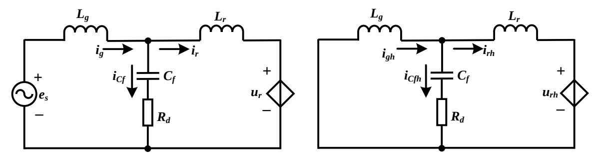


Fig. 1. Power circuit of three-phase voltage source PWM rectifier based on LCL filter.



(a) (b)

Fig. 2. The equivalent single-phase model.

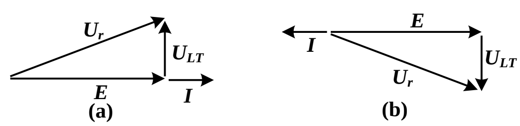


Fig. 3. Steady voltage, current vector diagram of three-phase voltage source rectifier.

B. Design criteria for the LCL filter parameters

1) Filter capacitance:

The capacitance of the filter capacitor is limited by the requirement of the power factor at its rated power (generally less than 5%) and is related to the positions of the current and voltage sensors in the control system. If there is no capacitor branch, there is only one possible position for the grid voltage and current sensors, which are for sensing the grid voltage and rectifier current. The VSR system manifests the resistive characteristic when the rectifier current is controlled with the same phase as the grid voltage. The system fundamental impedance is:

$$Z_{\mathrm{b}} = 3E_s^2 / P_{oe} \tag{1}$$

where E_s is the grid phase rms voltage and P_{oe} is the active power in the rated condition.

The positions of voltage and current sensors have four cases with an LCL filter. The most common case is for sensing the grid voltage and controlling the rectifier current. In this case, the ratio between the system reactive and active power is:

$$|Q/P| = Z_b / X_c = \omega_b Z_b C_f \tag{2}$$

It can be deduced that:

$$C_f = \frac{\tan\varphi P_{oe}}{3E_s^2\omega_b} \tag{3}$$

where φ is the power factor angle. Equation (3) indicates that the capacitance of the filter capacitor is in reverse proportion to the power factor.

2) Grid side and rectifier side inductances:

The impact of the filter capacitor can be neglected in the grid frequency. As a result, the LCL filter can be modeled as an L_T filter, L_T=L_g+L_r. The total inductance L_T is restricted by the current and voltage vector relation in the VSR. Fig.3 (a) and (b) show the voltage and current vector diagrams of the VSR in the steady state of the power factor rectifying and inverting modes, where **I**, $\mathbf{U_r}$, **E**, $\mathbf{U_{LT}}$ are the VSR ac side fundamental current, the voltage, the grid voltage, and the inductance voltage drop, respectively. The maximum fundamental voltage which the rectifier ac side can output is fixed by the constant dc voltage. In other words, the vector relations reflect the restrain of the total inductance value, as expressed in (4):)

$$L_T \le \frac{\sqrt{(MU_{dc})^2 - E_{sm}^2}}{\omega_1 I_m} \tag{4}$$

where, I_m and E_{sm} are the fundamental magnitude of the current and grid voltage, and M is the modulation depth of the PWM. For SVPWM M=0.577 and for sine pulse width modulation (SPWM) M=0.5.

3) Resonance frequency:

The resonance frequency f_{res} should be in a range as shown in (5):

$$10 f_1 < f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_g + L_r}{L_g L_r C_f}} < \frac{1}{2} f_{sw} \quad (5)$$

where f_1 is the grid fundamental frequency and f_{sw} is the switching frequency.

4) Damping resistance:

The resonance of the LCL filter can be effectively damped by connecting a resistor in series with the filter capacitor. The losses can be easily calculated as:

$$P_{loss} = 3 \cdot R_d \cdot \sum_h \left| i_{gh} - i_{rh} \right|^2 \quad (6)$$

The main harmonics in (6) are near the switching frequency and its multiples. The decreased resistance of the damping resistor decreases the losses but it also reduces its effectiveness. An appropriate damping resistance is set at 1/3 the resonance frequency capacitance ($1/\omega_{res}C_f$) [6].

III. DESIGN METHOD FOR THE LCL FILTER

The ratio between the grid side inductance and the rectifier side inductance is defined as $r=L_g/L_r$. By using (5), the filter capacitance can be expressed as:

$$C_f = \frac{(r+1)}{(2\pi f_{res})^2 r L_r} \quad (7)$$

According to Fig. 2(b), by neglecting the damping resistor R_g, the grid harmonic current is related to the rectifier harmonic current:

$$\frac{i_{gh}}{i_{rh}} = \frac{1}{1 - L_g C_f \omega_h^2} \quad (8)$$

where ω_h is the h order radian frequency, $\omega_h=2\pi f_h=2\pi h f_1$.

The harmonic current attenuation factor σ between the grid and rectifier side can be transformed as a function of the ratio r and the resonance frequency f_{res} by using (7) and (8):

$$\sigma = \frac{i_{gh}}{i_{rh}} = \frac{1}{1-(r+1)\cdot(\frac{hf_1}{f_{res}})^2} = \frac{k^2}{k^2 - r - 1} \quad (9)$$

where $k=f_{res}/hf_1$.

For the h order harmonic voltage:

$$j\omega_h L_r i_{rh} + j\omega_h L_g i_{gh} + u_{rh} = 0 \quad (10)$$

The grid and rectifier inductances can be deduced from (9) and (10)

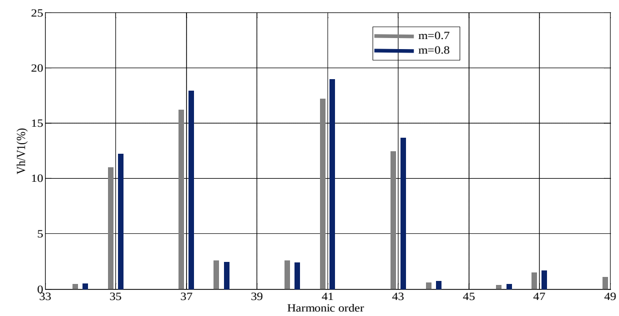


Fig. 4. Harmonic spectrum for AC side of three-phase VSR by SVPWM (f_{sw}=1.95kHz).

$$L_r = \left| \frac{U_{rh} k^2}{\omega_h I_{gh,\max}(k^2 - r - 1 + rk^2)} \right| \quad (11)$$

$$L_g = rL_r = \left| \frac{U_{rh} r k^2}{\omega_h I_{gh,\max}(k^2 - r - 1 + rk^2)} \right| \quad (12)$$

$$L_T = L_g + L_r = \left| \frac{U_{rh} k^2}{\omega_h I_{gh,\max}(k^2 - 1)} \right| \quad (13)$$

The current harmonic limit in the percentage of the rated current amplitude is illustrated by IEEE-519-1992[0]. In (11), $I_{gh,max}$ is the maximum rms current of the h order harmonic according to IEEE-519, and U_{rh} is the rectifier ac side phase rms voltage of the h order harmonic. (13) indicates that the total inductance L_T is determined by the resonance frequency f_{res} with the definite harmonic voltage U_{rh}.

For the SVPWM method, the main harmonic voltage in the spectrum of the rectifier ac side is of the (m_f±2) order in which the m_f is the carrier to the fundamental ratio, $m_f = f_{sw}/f_1$ and its magnitude is related to the modulation depth [11]. The harmonic voltage can be calculated by the double Fourier series method. The harmonic voltage spectrum with a different modulation depth is depicted in Fig.4 as the switching frequency is 1.95kHz [12].

Under the no load condition, the fundamental phase rms voltage of the rectifier ac side is equal to that of the grid. The no load modulation depth M_0 is:

$$M_0 = \frac{\sqrt{6} E_s}{U_{dc}} \quad (14)$$

Under the nominal condition, the fundamental phase rms voltage of the rectifier ac side is:

$$\begin{aligned} U_{r1,n} &= \sqrt{E_s^2 + (\omega_1 L_g I_{g1,n})^2 + (\omega_1 L_r I_{r1,n})^2} \\ &= \sqrt{[(1-\frac{1}{rk_1^2})E_s]^2 + [\omega_1 L_g I_{g1,n}(1+\frac{1}{r}-\frac{r+1}{rk_1^2})]^2} \end{aligned} \quad (15)$$

where $I_{g1,n}$ and $I_{r1,n}$ are the nominal rms currents of the grid

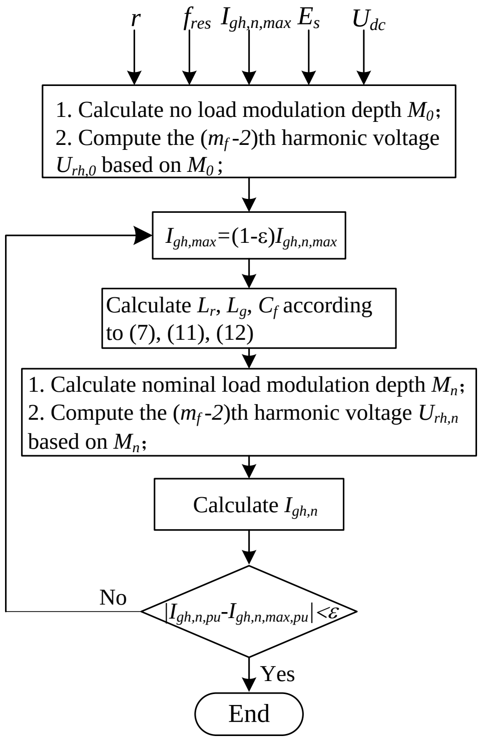


Fig. 5. Flow chart for design method of LCL filter.

and rectifier, $k_1=f_{res}/f_1$.

The nominal load modulation depth M_n is:

$$M_n = \frac{\sqrt{6}\sqrt{[(1-\frac{1}{rk_1^2})E_s]^2+[\omega_1 L_g I_{g,n}(1+\frac{1}{r}-\frac{r+1}{rk_1^2})]^2}}{U_{dc}} \tag{16}$$

The h order harmonic rms current can be calculated with the LCL filter parameter:

$$I_{gh,n} = \left|\frac{U_{rh,n}k^2}{\omega_h L_r(k^2-r-1+rk^2)}\right| \tag{17}$$

$$I_{rh,n} = \left|\frac{U_{rh,n}(k^2-r-1)}{\omega_h L_r(k^2-r-1+rk^2)}\right| \tag{18}$$

However, the nominal load modulation depth M_n can not be computed with an unknown LCL filter parameter. As a result, an iterative algorithm is adopted, where the resonance frequency f_{res} and the ratio r are treated as constants. Based on a no load modulation depth M_0, the (m_f −2)th harmonic voltage is computed, so that the LCL filter parameters L_r, L_g and C_f can be calculated according to (7), (11) and (12). With the calculated parameters, the nominal load modulation depth M_n is obtained by (16), as is the harmonic voltage $U_{rh,n}$. The iterative algorithm is terminated if the calculated harmonic rms current $I_{gh,n}$ from (17) satisfies inequality (19), otherwise $I_{gh,max}$ is modified to repeat the above process.

$$\left|I_{gh,n,pu} - I_{gh,n,\max\ pu}\right| < \varepsilon \tag{19}$$

TABLE I

SYSTEM PARAMETERS FOR THREE-PHASE VSR

P_{oe}	500[kW]
E_s	346.4[V]
f_1	50[Hz]
U_{dc}	1100[V]
Power factor, $cos\varphi$	>0.98
f_{sw}	1.95[kHz]
Modulation	SVPWM

where $I_{gh,n,pu} = \frac{I_{gh,n}}{I_{g1,n}}$, $I_{gh,n,\max,pu} = \frac{I_{gh,n,\max}}{I_{g1,n}}$, ε is the error tolerance.

A flow chart of the design method for the LCL filter parameters is shown in Fig. 5.

IV. AN EXAMPLE OF THE DESIGN METHOD WITH A 500KW VSR

A. System Parameters

A design example of an LCL filter for a 500kW three-phase VSR using above-mentioned method is clarified in this section. TABLE I lists the system parameters.

B. Design procedure

According to the analysis in section II.B, the parameters of the LCL filter should be satisfy the following conditions:

1) Filter capacitance:

$$C_f < \frac{\tan\varphi P_{oe}}{3E_s^2\omega_b} = 898uF$$

2) Total inductance:

For the SVPWM, M=0.577.

$$L_T \le 1.88mH$$

3) Resonance frequency f_{res}:

The resonance frequency should be in the range of:

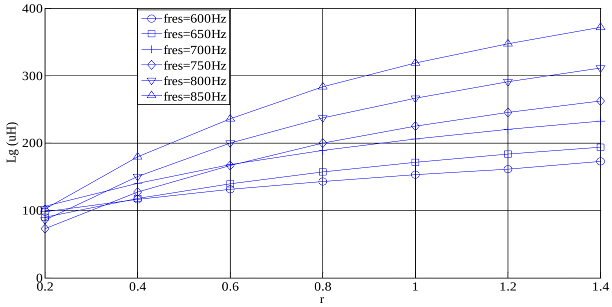
$$500Hz < f_{res} < 975Hz$$

4) Design of the LCL filter parameters:

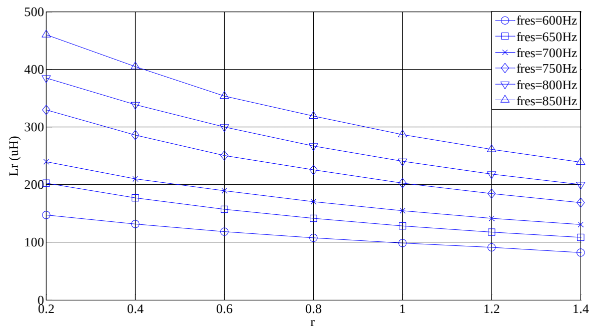
According to the IEEE-519 standard, the desired grid harmonic rms current over the 35^{th} order as a percent of the rated fundamental component is 0.3%. In the parameter design procedure, the tolerance ε is set to 0.005%.

Fig.6 shows the design results of the LCL filter parameters for various values of r and f_{res}, which indicates that:

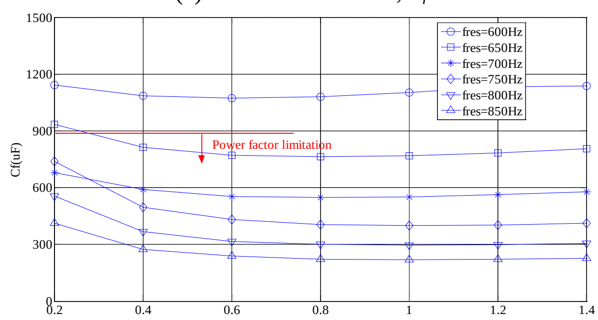
a) With an increasing resonance frequency, the total inductance increases and the filter capacitance decreases. When the resonance frequency is f_{res}=600Hz, the designed capacitance is limited by the desired power factor. There are



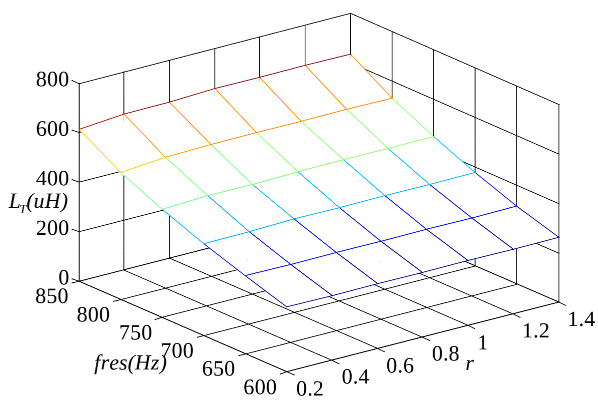
(a) Grid side inductance, L_g



(b) Rectifier inductance, L_r



(c) Filter capacitor, C_f



(d)Total inductance, L_T

Fig. 6. Design results of LCL filter for various r, f_{res}, E_s=346.4V, U_{dc}=1100V, f_{sw}=1.95kHz, P_{oe}=500kW

several optimization criteria for the selection of the LCL filter parameters such as the minimum volume, the minimum weight and the minimum filter stored energy. For the high-power VSR, a decrease of the total inductance can minimize the system volume and reduce the system cost effectively. This is due to the fact that the magnetic

TABLE II

DESIGN RESULTS OF LCL FILTER WITH F_{RES}=700HZ

r	0.4	0.52	0.8	1	1.2	1.4
L_g[uH]	106.6	129.2	168.0	188.9	206.1	220.4
L_r[uH]	266.6	248.5	209.9	188.9	171.8	157.5
C_f[uF]	678.8	608.1	554.0	547.2	551.7	562.8

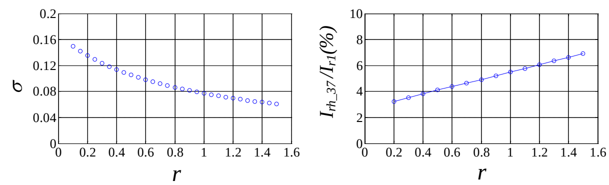


Fig. 7. Variation of attenuation factor and amplitude of the rectifier side current harmonic with different r.

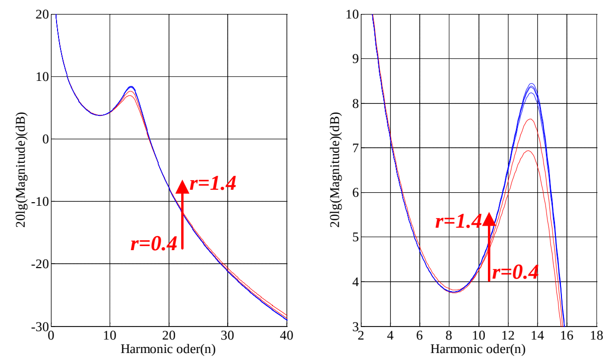


Fig .8. Frequency response of LCL filter with different values of r, L_T=380uH, C_f=600uF, R_d=0.1.

components are normally heavy and costly and the capacitor size does not have much impact on the system size. In consideration of this point, the criterion for the LCL filter parameter selection is using a larger filter capacitance to minimize the total inductance L_T based on the desired power factor. As a result, the resonance frequency is selected as 700Hz for this system and the calculated total inductance is L_T≈380uH.

b) When the ratio r changes, the total inductance remains almost constant for an invariable resonance frequency. This point can be utilized under the condition of using the leakage inductance of the isolation transformer as the grid side inductance and the rectifier side inductance can be calculated by the ratio r. The designed LCL filter parameters are listed in TABLE II.

However, the ratio r is decided by the losses of the damping resistor, the attenuation factor and other aspects. Fig.7 shows the variation of the attenuation factor and the amplitude of the rectifier side current harmonic with different values of the ratio r. This indicates that the attenuation factor decreases and the amplitude of the rectifier side (m_f-2) order current harmonic increases with an increasing r. On the one hand, the aim to attenuate the rectifier side current ripple as much as possible needs a smaller value of σ, which means a larger ratio r should be chosen. On the other hand, a larger value of the ratio r leads to increasing of the rectifier side harmonic current near the switching frequency, which increases the switching losses of the power device. From (6), the damping losses also increase because the grid side current harmonic remains almost constant with different designed LCL filter values. Fig.7 also indicates that when r>1, its effect on the attenuation factor is decreased but the power device loss and damping loss are increased. Therefore, an appropriate selection region for the ratio r is (0, 1).

5) Damping resistance:

According to the data listed in Table 2 and considering the convenience of commercial manufacturing, the final designed LCL filter parameters are C_f=600uF and L_T=380uH, and the resonance frequency capacitance is:

$$X_{\mathrm{Cf}} = 1/(2\pi f_{\mathrm{res}} C_{\mathrm{f}}) \approx 0.378\Omega$$

Therefore, the damping resistance is set as 0.1Ω.

Considering the whole LCL filter, the transfer function is:

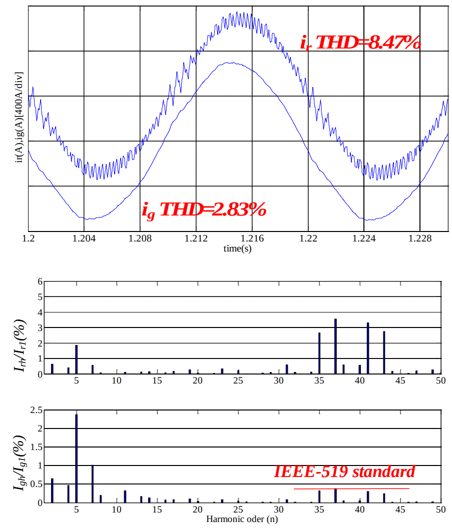
$$\frac{I_g(s)}{U_r(s)} = -\frac{R_d C_f s + 1}{L_r L_g C_f s^3 + (L_r + L_g) R_d C_f s^2 + (L_r + L_g)s} \quad (20)$$

Fig. 8 shows the frequency response of an LCL filter with different values of r, which indicates that with an increased ratio r, the attenuation of the high order harmonic (above 20th) components by the LCL filter are the same, but for those of the lower order harmonic (below 17th) components, it shows the opposite characteristic. The 2^{th}~9^{th} harmonic components are amplified and those of the 10^{th}~16^{th} harmonic are attenuated with an increasing ratio r, which can be seen in the simulation results. In this paper, the ratio r is selected as 0.52.

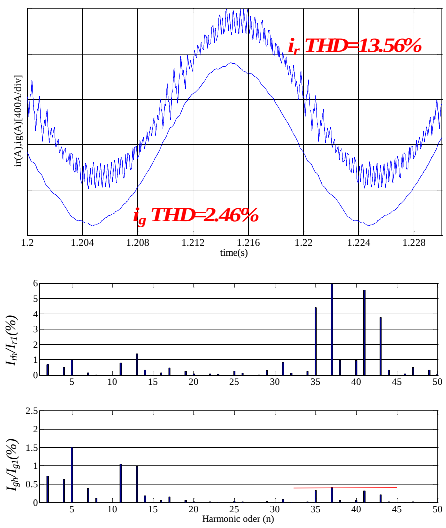
V. Simulation and Experiment

Based on the above analysis and design, the effectiveness of the designed method is first verified through simulation results. Fig.9 shows the simulation results of the grid side, the rectifier side currents and the corresponding harmonic spectra with different values of r. It can be seen that the total harmonic distortion (THD) of the rectifier side current increases with the decreasing of r. However, the high-order harmonic components of the grid current still meet the IEEE-519 standard.

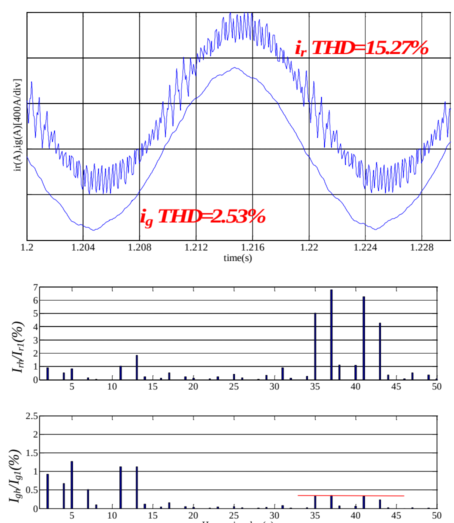
The effectiveness of the design method is further verified by experimental results. A 500kW VSR prototype is manufactured, in which the control core is based on a TMS320F28335 digital signal processor (DSP) and the LCL filter parameters are the same as those in Fig. 8 (a).



(a) L_g=130uH, L_r=250uH, C_f=600uF, r=0.52



(b) L_g =190uH, L_r =190uH, C_f =600uF, r =1



(c) L_g =210uH, L_r =170uH, C_f =600uF, r =1.2

Fig. 9. Simulation analysis of grid side, rectifier side currents and the corresponding harmonic spectra.

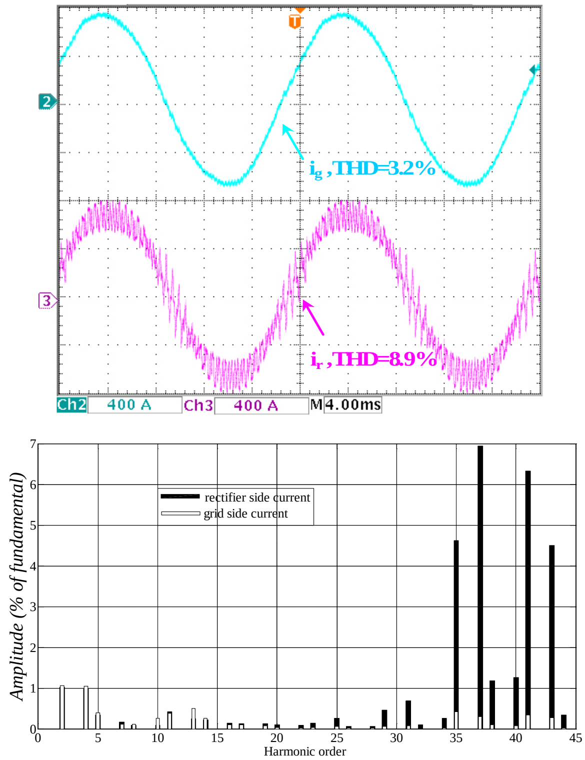


Fig. 10. Experiment waveform of grid side, rectifier side current (400A/div) and the corresponding harmonic spectra at rated condition.

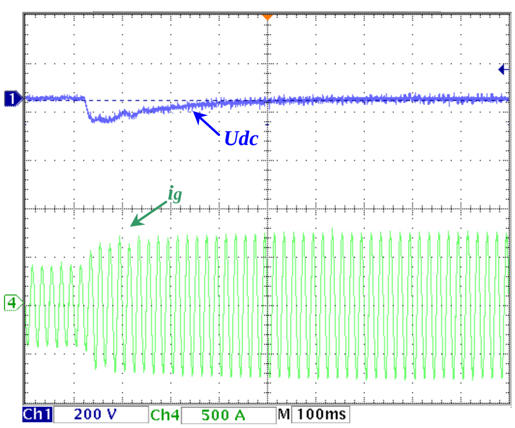


Fig. 11. Measured grid currents (500A/div) and dc voltage (200 V/div) for a step change from 50% to 100% rated load.

Fig.10 shows the experiment waveforms of the grid side, the rectifier side current and the corresponding harmonic spectra at the rated condition. TABLE III compares the higher order harmonic factor of the rectifier side and the grid side current at the rated condition. The higher order harmonic current near the switching frequency is attenuated effectively by the designed LCL filter parameters, the 37th harmonic factor decreases from 6.94% to 0.314%, the THD of the rectifier side and the grid side current are 8.9% and 3.2% and the power factor in the rated condition is 0.99. These results

TABLE III

COMPARISON OF HIGHER ORDER HARMONIC FACTOR OF RECTIFIER SIDE, GRID SIDE CURRENT AT RATED CONDITION

Harmonic order	35	37	38	40	41	43
Rectifier side(%)	4.61	6.94	1.18	1.26	6.32	4.49
Grid side (%)	0.31	0.31	0.1	0.08	0.29	0.28

are consistent with the simulation.

Finally, the dynamic response of the system has been tested by step changing the load from 50% to 100% of the rated power, as shown in Fig. 11.

VI. CONCLUSIONS

A new design method for the LCL filter of three-phase voltage source PWM rectifiers is presented in this paper. The criteria of the LCL parameter choices and the design procedure are illustrated in detail with a design example (600V, 500kW). Both simulation and experiment results indicate that 1) The total inductance is determined by the resonance frequency of the LCL filter; 2) When the ratio r changes, the total inductance remains almost constant for an invariable resonance frequency; 3) The designed capacitance of the filter capacitor is restricted by the desired power factor, which limits the selection of the resonance frequency.

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