Reference Current Regulation for Inverter with Virtual Resistor Damping Control

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***Abstract*—Inverter with output *LCL* filter is widely used in power system. It has better switching frequency harmonic suppression effect, meanwhile it has resonance problem. Virtual resistor damping can suppress the resonance, but it affects the current control character, particularly for harmonic current. This paper develops the detailed models of the inverter with virtual resistor damping for output harmonic current control. Based on the analysis of current control loop with virtual resistor, the transfer function of current loop is obtained. Moreover, with the optimal value of virtual resistor, the performance of inverter is similar to 2nd order low pass filter. To control the output current equals to reference current, reference regulation method is proposed. At last, simulation and experimental results verify the correctness of theatrical analysis and effectiveness of the method.**

Keywords—LCL inverter; virtual resistor damping; reference regulation; 2nd order low pass filter(LPF)

I. INTRODUCTION

The grid connected converter with pulse-width modulation control will cause switching and multiple switching frequency harmonics [1],[2]. In order to attenuate those harmonics, an effective filter is needed. Compared with the *L* filter, the *LCL* filter is a more attractive solution [3],[4]. However, it brings some challenges in practical application, particularly the resonance problem. Fortunately, this unstable problem can be resolved by applying existing damping techniques, such as adding a real resistor in series with the filter capacitor [5], splitting the filter capacitor to reduce the system order [6], feeding back converter-side current [7] or capacitor current [8], estimating capacitor voltage [9] for control purposes.

Harmonic pollution is one of the main problems of power system. IEEE standard 519 clearly states that harmonic currents should be limited. DG converters not only have the primary purpose of real power generation, but also have the potential to improve power quality and system stability [10],[11]. In [12],[13], the DG converters are controlled to compensate the harmonic current generated by nonlinear load. For the load harmonic current compensation, not only the fundamental current but also the harmonic current must be controlled accurately. For the harmonic control, both the magnitude and phase need be taken into account.

But the previous research of virtual resistor damping is mainly suppress the transient harmonic excitation and stabilize the output fundamental component, the virtual resistor value is not strictly required. For different virtual resistor control method, the inverter will perform as different models [14],[15]. It means when consider the output harmonic current control, like active power filter application, the virtual resistor's influence need to be researched carefully. It is the further exploration of the traditional active damping method.

This paper focus on the control strategy to enhance the output harmonic current control capability of the inverter with *LCL* filter. In the section II, the model of the inverter with virtual resister damping control is established. In the section III, Norton's equivalent model of inverter and the reduced order model of current transfer function are established. And the optimal virtual resistor value is investigated. Based on the inverter 2^{nd}-order LPF model, the reference current regulation method is proposed. Finally, in the section IV, simulation and experimental results validate the correctness and effectiveness of the proposed method.

II. MODELLING OF LCL INVERTER WITH VIRTUAL RESISTOR DAMPING CONTROL

For the inverter with output *LCL* filter, virtual resistor damping control is often used to suppress the resonance. For inverter-sider current control, the schematic diagram of an inverter is presented in Fig. 1, where the upper part is the main circuit configuration and the lower part is the digital control diagram.

In Fig.1, for the *LCL* filter, L_1 and R_1 are the converter-side filter inductance and its parasitic resistance, respectively. L_2

and R_2 are the grid-side inductance and its parasitic resistance, respectively. C_f is the filter capacitor. The pulse-width modulation (PWM) reference voltage is obtained as:

$$V_{\mathrm{PWM}}^{*}(s)=V_{\mathrm{C}}(s)+K_{\mathrm{p}}(s)(I_{\mathrm{ref}}(s)-I_{\mathrm{AD}}^{\mathrm{ref}}(s)-I_{\mathrm{L}}(s)) \qquad (1)$$

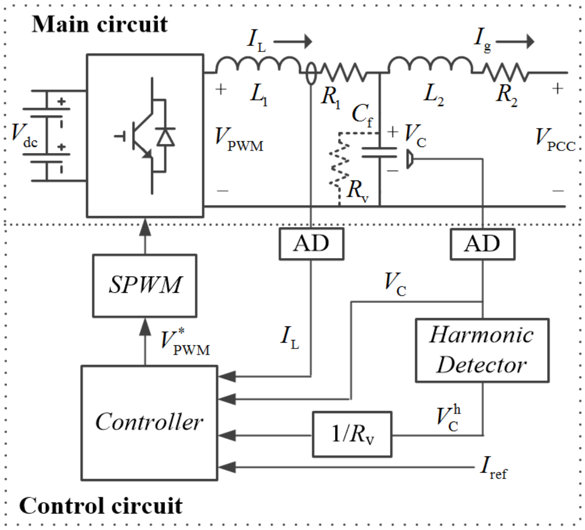


Fig.1 Schematic diagram of inverter with virtual resistor damping control

Compare to PR (Proportional-Resonant) or PI (proportional -Integral) controller, the single P (proportional) controller can make the impedance characteristics of the inverter valid in the continuous frequency range and better linearity. Moreover, P controller is easy realized. So in this paper, the current control loop only use the P controller.

In (1), the $I_{\mathrm{ref}}(s)$ and $I_{\mathrm{L}}(s)$ are reference current and the measured converter-side current, respectively. $K_{\mathrm{p}}(s)$ is the proportion of current controller, and V_{c}(s) is the measured capacitor voltage. $I_{\mathrm{AD}}^{\mathrm{ref}}$(s) is the harmonic damping current, and it can be described as：

$$I_{\mathrm{AD}}^{\mathrm{ref}}(s)=V_{\mathrm{C}}^{\mathrm{h}}(s)/R_{\mathrm{v}}(s) \qquad (2)$$

In (2), the $R_{\mathrm{v}}(s)$ is the resistance of the virtual resistor. It's a dimensionless constant value, and equals to the resistance value of capacitor parallel virtual resistor.

The transfer functions of *LCL* filter plant are obtained as follow:

$$I_{\mathrm{L}}(s)=H_1(s)V_{\mathrm{PWM}}(s)+H_2(s)V_{\mathrm{PCC}}(s) \qquad (3)$$

$$I_{\mathrm{g}}(s)=H_3(s)V_{\mathrm{PWM}}(s)+H_4(s)V_{\mathrm{PCC}}(s) \qquad (4)$$

$$V_{\mathrm{C}}(s)=H_5(s)V_{\mathrm{PWM}}(s)+H_6(s)V_{\mathrm{PCC}}(s) \qquad (5)$$

Where V_{PWM}(s) and V_{PCC}(s) are the converter output voltage and PCC voltage, respectively, and I_{g}(s) is the output current. The transfer functions $H_1(s)$–$H_6(s)$ are determined by filter parameters and shown as follow:

$$H_1(s)=(L_2C_fs^2+R_2C_fs+1)/[L_1L_2C_fs^3+(R_2L_1+R_1L_2)C_fs^2+(L_1+L_2+C_fR_1R_2)s+R_1+R_2] \qquad (6)$$

$$H_2(s)=-1/[L_1L_2C_fs^3+(R_2L_1+R_1L_2)C_fs^2+(L_1+L_2+C_fR_1R_2)s+R_1+R_2] \qquad (7)$$

$$H_3(s)=1/[L_1L_2C_fs^3+(R_2L_1+R_1L_2)C_fs^2+(L_1+L_2+C_fR_1R_2)s+R_1+R_2] \qquad (8)$$

$$H_4(s)=-(L_1C_fs^2+R_1C_fs+1)/[L_1L_2C_fs^3+(R_2L_1+R_1L_2)C_fs^2+(L_1+L_2+C_fR_1R_2)s+R_1+R_2] \qquad (9)$$

$$H_5(s)=(L_2s+R_2)/[L_1L_2C_fs^3+(R_2L_1+R_1L_2)C_fs^2+(L_1+L_2+C_fR_1R_2)s+R_1+R_2] \qquad (10)$$

$$H_6(s)=(L_1s+R_1)/[L_1L_2C_fs^3+(R_2L_1+R_1L_2)C_fs^2+(L_1+L_2+C_fR_1R_2)s+R_1+R_2] \qquad (11)$$

Ignoring the time delay of the PWM voltage modulation ($V_{\mathrm{PWM}}(s)=V_{\mathrm{PWM}}^{*}(s)$), the closed-loop behavior of the inverter can be obtained into (12) by substituting (1) and (3)-(5).

$$I_{\mathrm{g}}(s)=G_{\mathrm{T}}^{\mathrm{ad}}(s)I_{\mathrm{ref}}(s)-Y_{\mathrm{eq}}^{\mathrm{ad}}(s)V_{\mathrm{PCC}}(s) \qquad (12)$$

In (12), the coefficients $G_{\mathrm{T}}^{\mathrm{ad}}$ (s) and $-Y_{\mathrm{eq}}^{\mathrm{ad}}$ (s) describe the output current responses to the reference current and the PCC voltage, respectively. The detailed expressions of the ratio are described as follows:

$$G_{\mathrm{T}}^{\mathrm{ad}}(s)=\frac{K_{\mathrm{p}}(s)H_3(s)}{1-H_5(s)(1-\frac{K_{\mathrm{p}}(s)}{R_{\mathrm{v}}(s)})+K_{\mathrm{p}}(s)H_1(s)} \qquad (13)$$

$$Y_{\mathrm{eq}}^{\mathrm{ad}}(s)=\frac{K_{\mathrm{p}}(s)H_2(s)H_3(s)-H_3(s)H_6(s)(1-\frac{K_{\mathrm{p}}(s)}{R_{\mathrm{v}}(s)})}{1-H_5(s)(1-\frac{K_{\mathrm{p}}(s)}{R_{\mathrm{v}}(s)})+K_{\mathrm{p}}(s)H_1(s)}-H_4(s) \qquad (14)$$

III. REFERENCE REGULATE OF THE OUTPUT CURRENT

In this section, the Norton's equivalent model of the inverter with virtual resistor damping is established and the influence of R_{v} value on the harmonic current control is analyzed. Then the reference regulation method is proposed to deal with this influence.

A. Research of iptimal virtual resistor value

Equation (12) means the inverter with virtual resistor damping control can be considered as a current source $G_{\mathrm{T}}^{\mathrm{ad}}I_{\mathrm{ref}}$ and its parallel admittance $Y_{\mathrm{eq}}^{\mathrm{ad}}$.

Fig.2 shows the Norton's equivalent model of inverter.

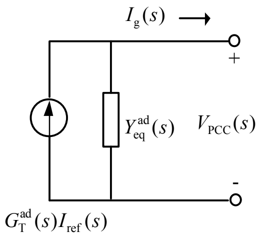


Fig. 2. Norton’s equivalent circuit model

Here G_T^{ad} is the coefficient between the output current I_g and reference current I_{ref}. With parameters listed in Table I, the bode plot of G_T^{ad} is shown in Fig.3.

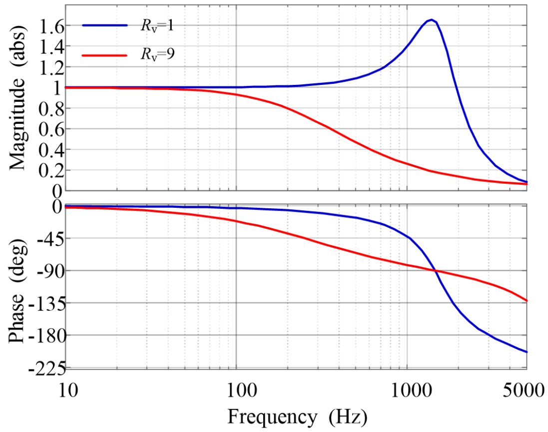


Fig.3 Bode plot of G_T^{ad} with different R_v value

From Fig.3, different R_v value relates to different damping effect. For harmonic current, before 1.5 kHz, lager R_v value means output current amplification, while smaller R_v value means output current reduction. When G_T^{ad} is not equal to unit, the output current I_g will not equal to reference current I_{ref}. Both of them make the performance of harmonic current control not good.

Ignoring the parasitic resistance, the G_T^{ad} is 3-order function. Simplified expression of (13) is shown as follow:

$$G_T^{ad}(s)=\frac{K_P}{L_1L_2Cs^3+K_PL_2Cs^2+(L_1+K_PL_2/R_v)s+K_P} \tag{15}$$

Consider that the coefficient of s^3 is very small, so it is omitted in the analysis. The rest expression is similar to a 2nd order low pass filter, as (16):

$$\hat{G}_T^{ad}(s)\approx\frac{1/L_2C}{s^2+(L_1+K_PL_2/R_v)/(K_PL_2C)s+1/L_2C} \tag{16}$$

The characteristic equations of the low pass filter (16) are:

$$\sqrt{1/L_2C}=\omega_n \tag{17}$$

$$(L_1+K_PL_2/R_v)/(K_PL_2C)=2\times\delta\times\omega_n \tag{18}$$

Here ω_n is cutoff frequency and δ is quality factor.

There is no overshoot when the quality factor δ equals to 0.707. Then from (17) and (18), the optimal value of damping resistor R_v is obtained, R_v=4.5. With the optimal R_v, bode plot of G_T^{ad} is shown in the Fig.4.

It can be seem that, with the optimal virtual resistor, in the low frequency range (<1kHz) the transfer function of $\hat{G}_T^{ad}$ is very similar to 2nd-order low-pass filter. The inverter with optimal virtual resistor damping control, can be equivalent to a low-pass filter.

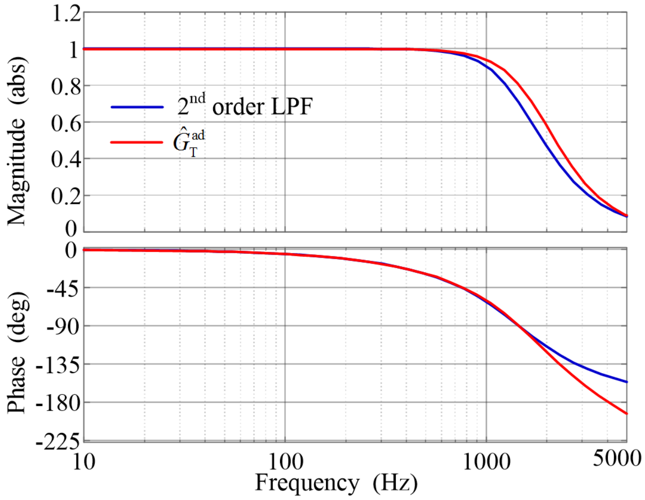


Fig.4 Bode plot of $\hat{G}_T^{ad}$ and LPF

B. *Reference current regulation method*

To guarantee the output current control performance, the reference current regulation method is proposed. Fig.5 shown the diagram of the reference regulation loop.

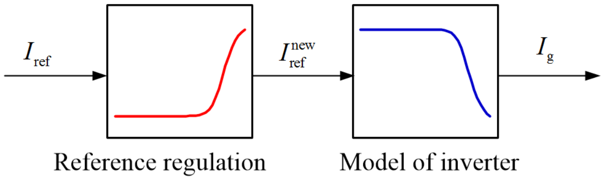


Fig.5 Reference current regulation loop

The mean idea is multiplying the reference current by $1/G_T^{ad}$. The new reference current is as follow:

$$I_{ref}^{new}(s)=\frac{I_{ref}(s)}{G_T^{ad}(s)} \tag{19}$$

Then the output current becomes as:

$$\begin{aligned}I_g(s)&=G_T^{ad}(s)I_{ref}^{new}(s)-Y_{eq}^{ad}(s)V_{PCC}(s)\\&=I_{ref}(s)-Y_{eq}^{ad}(s)V_{PCC}(s)\end{aligned} \tag{20}$$

From (20), ignore the disturbance of V_{PCC}, the inverter output current is just equal to the reference current.

As shown in Fig.5, the reference regulation loop is a phase-lead compensation. $1/G_T^{ad}$ is with third derivative, calculation is very complex and difficult. However, consider that the model of inverter with optimal virtual resistor is very similar to a 2nd order low pass filter. The transfer function of the reference regulation loop can be simplified as $1/\hat{G}_T^{ad}$.

Fig.6 shows the new coefficient of the output current responses to the reference current. Compare with the bode plot of $\hat{G}_T^{ad}$ in Fig.4, it can be see that, after reference regulation the output current is just equal to the reference current, both in the magnitude and phase below 1kHz.

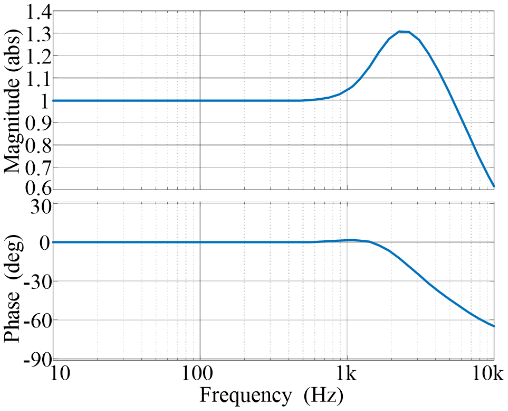


Fig.6 Coefficient of the output current responses to the reference current with reference regulation

It means the performance of current control is enhanced and the load harmonic current compensation effect is guaranteed.

TABLE I. Parameters of the System

symbol	value	symbol	value
L_1/mH	0.6	R_{grid}/Ω	0.01
R_1/Ω	0.01	V_{dc}/V	600
L_2/mH	0.6	V_{grid}/V	220
R_2/Ω	0.004	f_{grid} /Hz	50
C_f/μF	20	K_p	30
L_{grid}/mH	0.1	f_s/kHz	20

IV. SIMULATION AND EXPERIMENTAL RESULTS

To verify the correctness of theoretical analysis about the optimal virtual resistor and effectiveness of the proposed control method, simulation and experiment are implemented. The same parameters are selected in both simulation and experiment, as listed in Table I.

A. Simulation Results

The simulation is implemented via PSIM. Fig. 7 shows the circuit diagram. To analyze the harmonic current control performance, only the harmonic components are considered. Non-linear load is replaced by ideal harmonic current sources.

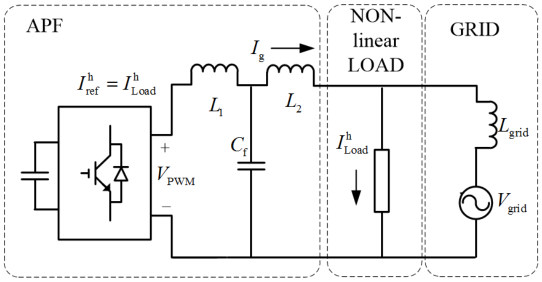


Fig.7 Circuit diagram of the simulation

The load current is shown in Fig.8. When without active power filtering, this current is all flowing into grid.

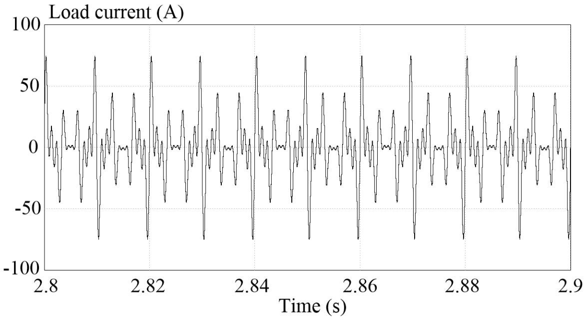
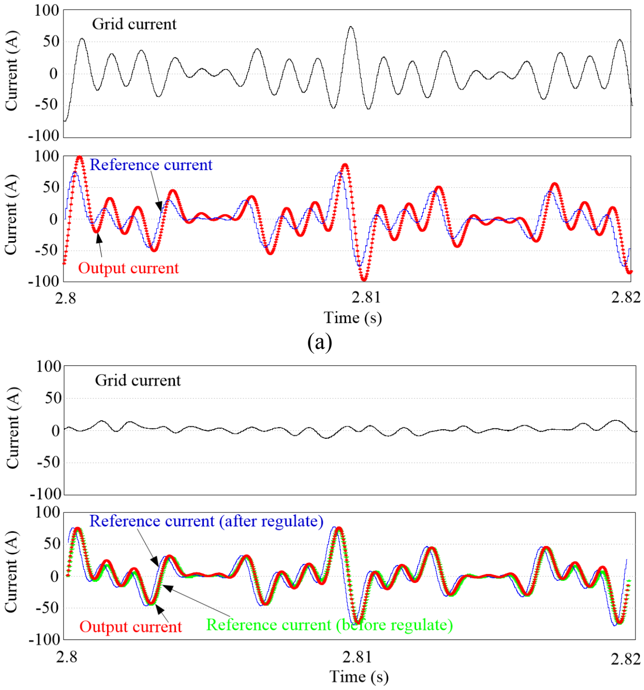


Fig.8 Load current in the simulation

The inverter works in active power filter (APF) mode. The load current contains 5th, 7th, 11th, 13th, 17th and 19th (6n±1) harmonic. Fig.9 and Table II is the simulation results.



(a)

(b)

Fig.9 Simulation results. (a) only with optimal damping; (b) with optimal damping and reference regulation.

TABLE II. FFT results of simulation

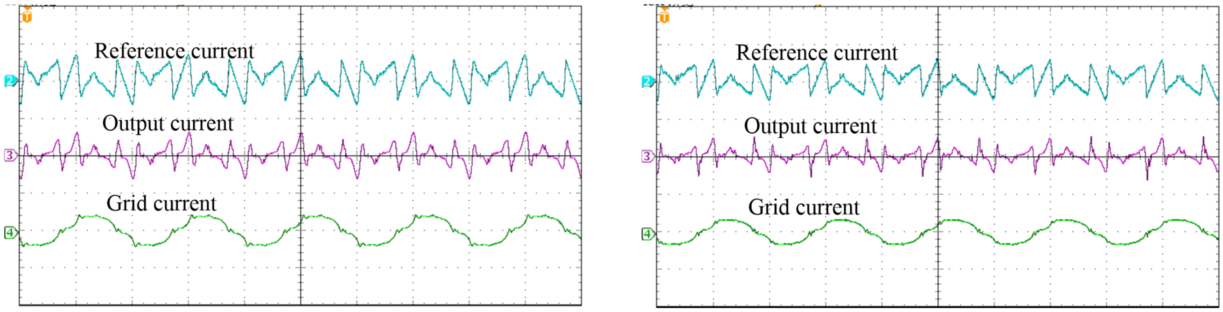
Control method	Variable	Frequency					
		250Hz	**350Hz**	**550Hz**	**650Hz**	**850Hz**	**950Hz**
Optimal virtual damping only	Grid current(A)	5.0∠-107	6.9∠-109	10.9∠-115	12.8∠-118	16.8∠-124	19.3∠-128
	Reference current(A)	15.0∠-2	15.0∠-3	15.0∠-5	15.0∠-5	15.0∠-7	14.9∠-8
	Output current(A)	14.4∠-19	14.3∠-27	14.4∠-43	14.5∠-51	14.9∠-68	15.5∠-78
Optimal damping and reference regulation	Grid current (A)	0.9∠-135	1.1∠-136	1.1∠-128	0.8∠-125	0.7∠28	2.1∠24
	Reference current(before regulation)(A)	15.0∠-2	15.0∠-3	15.0∠-5	15.0∠-5	15.0∠-7	14.9∠-8
	Reference current(after regulation)(A)	15.0∠12	15.0∠17	15.2∠27	15.3∠34	15.4∠45	15.7∠51
	Output current (A)	14.4∠-3	14.2∠-3	14.4∠-6	14.6∠-6	15.6∠-8	15.6∠-8

From the result in Fig.9 (a), the output current is lagging reference current obviously. The bad performance of harmonic current control results in poor harmonic current compensation effect. It contains lots of harmonic component in the grid current. While with the reference regulation, in Fig.9 (b) the new reference current (reference current after regulation) is ahead of load current (reference current before regulation). Through the phase-lag loop of the inverter, the output current is just equal to load current. As results, the harmonic current in the grid is reduced much.

B. Experimental Resultss

The experiment is under the laboratory conditions. In the experiment, non-linear load is a diode rectifier. The harmonic current of the rectifier is detected and used as reference current of the APF. DSP (Digital Signal Processor, TI TMS320F2812) is utilized as the micro-controller. The switching frequency and sampling frequency are both 20 kHz.

Fig.10 give the experimental results of reference current, output current and grid current. Table III is the corresponding FFT results.



(a) (b)

Fig.10 Experimental results. (a) only with optimal damping; (b) with optimal damping and reference regulation.

TABLE III. FFT results of simulation

Control method	Variable	Frequency					
		250Hz	**350Hz**	**550Hz**	**650Hz**	**850Hz**	**950Hz**
Optimal virtual damping only	Grid current (A)	1.12∠-107	0.62∠-109	0.80∠-115	0.45∠-118	0.58∠-124	0.30∠-128
	Load current (A)	2.88∠45.7	1.19∠123.0	1.01∠128.3	0.49∠209.1	0.46∠207.6	0.23∠-67.5
	Output current(A)	2.71∠15.7	1.07∠83.8	0.9∠77.4	0.46∠149.2	0.42∠122.4	0.16∠-159.2
Optimal damping and reference regulation	Grid current (A)	0.39∠-135	0.23∠-136	0.23∠-128	0.17∠-125	0.13∠28	0.12∠24
	Load current (A)	2.8∠52.4	1.33∠134.5	1.06∠143.4	0.65∠227.5	0.56∠228.9	0.35∠-38.5
	Output current(A)	2.72∠46.1	1.28∠125.7	0.98∠134.6	0.59∠215.3	0.48∠211.9	0.24∠-58.2

The major harmonics of the diode rectifier is below 1 kHz and the harmonic order are 6n±1. When only with optimal damping, the current filtering performance is not good. At 850Hz and 950Hz, after active power filtering, grid harmonic current is even larger than the load harmonic current. While with optimal damping and reference regulation, the harmonic components in grid current is reduced obviously.

V. CONCLUSIONS

Virtual resistor damping control is widely used, but it will affect the current control characteristic, particularly for the harmonic components. The transfer function of output current responses to the reference current can be simplify to 2^{nd} order low-pass filter. Meanwhile, the optimal virtual resistor value can be evaluated by appropriate quality factor of the second-order low-pass filter.

By regulating the reference current, the phase-lag effect of the inverter can be compensated. The reciprocal of the LPF transfer function is selected as the channel coefficients of the current reference regulation loop. With the current reference regulation control, the output harmonic current is controlled more accurate.

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