The Application Research of Proportional Resonance Control in APF Ripple Voltage Control

Yang Jian-feng, Wu Ting, Chen Jia-xing
College of Automation & Electrical Engineering, Lanzhou Jiao Tong University,
Lanzhou, 730070, CHINA Email:13919207702@163.com

Abstract: For the existence of the dc side active power filter ripple voltage will directly affect the selection of dc side capacitor value problems, in order to improve the control precision and reduce the dc side voltage ripple as the goal, a kind of dc side APF ripple voltage proportional resonant (Proportional Resonance, PR) control method is put forward, using an improved $i_p - i_q$ harmonic detection method at the same time. Improved $i_p - i_q$ harmonic detection method is instead of low pass filter with integral delay gain module, increase the precision of harmonic filter and improve the system control precision. PR control method is used to join the resonant link, which makes PR controller in tracking the current instruction and can eliminate the steady-state error, thus reducing the ripple voltage, and solving the problem of the selection of the dc side capacitor in the actual engineering application. At last, a simulation experiment is done to verify the principle above.

Keyword: Active power filter, dc side ripple voltage, proportional resonance control, improved $i_p - i_q$ harmonic method

1 Introduction

In fact, the operational principle of the active power filter is that by detecting the load side harmonic current, the compensation current harmonic current which has equal amplitude and opposite phase with harmonic current is directly injected to the grid. By using the compensation current to offset the harmonic current, the current in the power network as a standard sine wave can be ensured [1-3]. Tracking and compensating current control in the APF performance is directly related to the effect of harmonic compensation, so the compensation current tracking control is the core of APF system. Common compensation current tracking control methods have hysteresis control, PI control, deadbeat control and so on [4-6]. PI control has the characteristics of simple algorithm and high reliability, but the conventional PI control for AC reference signal is difficult to achieve the ideal control effect. Due to the proportional resonant controller gain is infinite at the resonant frequency, it can make the sine signals with the same frequency and resonant frequency is zero steady-state error control. Due to the gain of the proportional resonant controller is infinite at the resonance frequency, it can make the sinusoidal signal which is same with the resonance frequency in frequency to realize zero steady-state error control. Therefore, the use of proportional resonant controller can focus on specific harmonic compensation [7].

In this paper, firstly the produce of APF dc side voltage ripple is reasoned and computed in detail. The ripple voltage is produced by the impact of compensation current harmonics. In order to eliminate the dc side ripple voltage, a proportional resonant controller is used in this paper. By using this controller, the influence of the steady-state error can be eliminated and compensation effect is better when compensating current. At the same time, the use of the improved harmonic detection method can reduce the influence of error in harmonic detection for harmonic and reduce the voltage ripple further.

2 The Analysis of APF DC Side Ripple Voltage

In the structure of the APF system in the power supply voltage can be expressed as follows [9-12]:

$$\begin{aligned} u_a &= \sqrt{2}U_s \sin\left(\omega_0 t + \varphi_u\right) \\ u_b &= \sqrt{2}U_s \sin\left(\omega_0 t + \varphi_u - 120^\circ\right) \\ u_c &= \sqrt{2}U_s \sin\left(\omega_0 t + \varphi_u + 120^\circ\right) \end{aligned} \quad (1)$$

Among them, $\omega_0 = 2\pi f_0$; f_0 : the fundamental frequency; φ_u :power supply phase.

The power loss in the general power converter is very small, we can be ignored, so it will produce the AC side and DC side power balance, i.e.:

$$P_{DC} = P_{AC} \quad (2)$$

Wherein, P_{DC} represents the instantaneous power absorbed from the capacitor at DC side of APF, P_{AC} on behalf of the AC side instantaneous power supply system APF, equation (2) can also be written:

$$-\frac{dw_{DC}}{dt} = -\frac{d}{dt}\left(\frac{1}{2}Cu^2{}_{DC}\right) = u_a i_{ak} + u_b i_{bk} + u_c i_{ck} \quad (3)$$

Where: C is APF the DC side capacitor; u_{DC} is the capacitor voltage; i_{ak} , i_{bk} and i_{ck} is the output K current of APF, They can also be expressed as:

$$\begin{aligned} i_{ak} &= \sqrt{2}I_k \sin\left(k\omega_0 t + \varphi_{ik}\right) \\ i_{bk} &= \sqrt{2}I_k \sin\left(k\omega_0 t + \varphi_{ik} - 120^\circ\right) \\ i_{ck} &= \sqrt{2}I_k \sin\left(k\omega_0 t + \varphi_{ik} + 120^\circ\right) \end{aligned} \quad (4)$$

Equation (3) can be rewritten:

$$\begin{aligned} &-\frac{d}{dt}\left(\frac{1}{2}Cu^2{}_{DC}\right) \\ &= u_a i_{ak} + u_b i_{bk} + u_c i_{ck} \\ &= 3U_s I_k \cos\left[2\pi\left(k-1\right) f_0 t - \varphi_u + \varphi_{ik}\right] \end{aligned} \quad (5)$$

Combined equation (2), (3) and(5), we found that when APF was injected into the K harmonics current to the system, if the P_{DC} is positive, the capacitor voltage u_{DC} is reduced; However, if P_{DC} is negative, the capacitor voltage u_{DC} is increasing, so the voltage ripple formation.

Considering that in half the time P_{DC} is positive, u_{DC} will be reduced to $u_{DC\max}$ from $u_{DC\min}$. According to the law of conservation of energy, we have:

$$\int_{\tau}^{\tau + 1/2(k-1)f_0} P_{AC}\,dt = \frac{1}{2}C\left(U^2{}_{DC\max} - U^2{}_{DC\min}\right) \quad (6)$$

The equation (6) can be rewritten:

$$\begin{aligned} &\int_{\tau}^{\tau + 1/2(k-1)f_0} P_{AC}\,dt \\ &= \int_{\tau}^{\tau + 1/2(k-1)f_0} 3U_s I_k \cos\left[2\pi\left(k-1\right) f_0 t - \varphi_u + \varphi_{ik}\right] dt \\ &= \frac{3U_s I_k}{\pi\left(k-1\right) f_0} \end{aligned} \quad (7)$$

The right of equation (6) can be rewritten:

$$\begin{aligned} &\frac{1}{2}C\left(U^2{}_{DC\max} - U^2{}_{DC\min}\right) \\ &= \frac{1}{2}C\left(U_{DC\max} - U_{DC\min}\right)\left(U_{DC\max} + U_{DC\min}\right) \\ &= 2CU_{DC\_ref}\Delta_k \end{aligned} \quad (8)$$

Wherein, U_{DC_ref} is the DC capacitor given voltage value, in most cases it can be assumed as:

$$U_{DC\_ref} = \frac{U_{DC\max} + U_{DC\min}}{2} \quad (9)$$

Wherein, Δ_k is the amplitude of the DC voltage ripple caused by the K harmonics, can be defined as:

$$\Delta_k = \frac{U_{DC\max} - U_{DC\min}}{2} \tag{10}$$

It is obtained from the equation (6)-(8) we derive:

$$\Delta_k = \frac{3U_s I_k}{2\pi(k-1) f_0 U_{DC\_ref} C} \tag{11}$$

Voltage ripple in fact change over time, we can also infer its function through time. So in any instantaneous voltage ripple can be expressed as:

$$\delta_k = u_{DC} - U_{DC\_ref} \tag{12}$$

Putting equations (12) into equation (2) and(3) considered together , can be obtained:

$$\frac{d\left[C\left(U_{DC\_ref} + \delta_k\right)^2 / 2\right]}{dt} = -P_{AC} \tag{13}$$

Usually, compared with U_{DC_ref} , δ_k is small, the equations (14) did not bring obvious error and enough ignore the high harmonics, so it will lead to:

$$\delta_k = \frac{3U_s I_k}{2\pi(k-1) f_0 U_{DC\_ref}} * \sin\left[2\pi(k-1) f_0 t - \Psi_u + \Psi_{ik}\right] \tag{14}$$

Equation (15) gives the instantaneous value of the capacitor voltage ripple caused by the K harmonic current. Based on this result, we can infer that all harmonics caused the accumulation of the voltage ripple. In the APF design process, the voltage ripple through capacitor usually depends on the actual application that is one of the most important performance indicators. If not eliminated, it is difficult to determine the value of APF DC side capacitor. In order to control the ripple voltage, harmonic detection method is improved and the proportional resonant controller is used.

3 Improved Harmonic Method

The traditional $i_p - i_q$ harmonic detection method based on the theory of instantaneous reactive power uses the PLL that generates a sine signal $\sin\omega t$ and cosine signal $\cos\omega t$ which has similar phase with A phase voltage e_a . According to the above theory i_p and i_q can be calculated[13,14]. The DC components ($\bar{i}_p$ and $\bar{i}_q$) are obtained after the LPF filter. The fundamental positive sequence component i_{af}, i_{bf}, i_{cf} can be obtained through inverse transform. The phase of the harmonic current component i_{ah}, i_{bh}, i_{ch} can be obtained through the current i_a, i_b, i_c subtracts i_{af}, i_{bf}, i_{cf} . The schematic diagram shown in figure 1.

In order to increase and improve system voltage ripple caused by harmonic filtering is not clean, improved $i_p - i_q$ harmonic detection method is used. This method using a integral delay gain module to replace the traditional low pass filter. Improved the block diagram shown in figure 2.

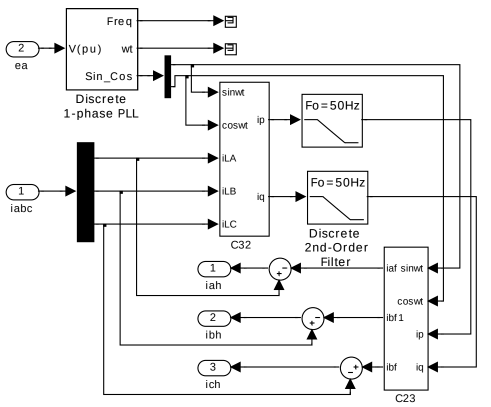


Fig.1 Schematic diagram

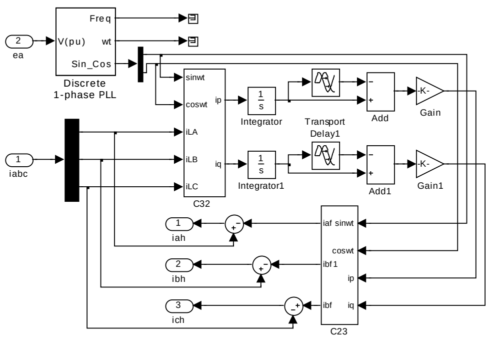


Fig.2 Improved simulation module

The improved method is found by calculation that it will shorten the entire operating cycle to 1/6 of the power cycle, that is, this method only use T / 6 cycle to complete the entire process of filtering. Compared with the traditional harmonic detection method . This method improved the increased harmonic flow caused by time delay during the operation process. This further improved the error be generated in the harmonic detection and the harmonic reduced [15,16].

4 APF DC Ripple Voltage PR Control Analysis and Realization

4.1 PR CONTROL ANALYSIS

The PR controller is also called the proportional resonant controller and consisted by a proportional link and resonant link, and no static error control for sinusoidal signal can be achieved. At present the PR controller has got widespread application and research in the filter and converter. Control characteristic of PR controller is elaborated just only from the current tracking characteristic [17-19]:

$$G_{PR}\left(s\right)=K_p+\frac{K_i s}{s^2+\omega_0^2} \tag{15}$$

Among them, K_p is the time constant of proportionality, K_i is the integration time constant, ω_0 is resonance frequency. In the proportional resonant controller, the proportional gain is used to adjust the gain for the entire frequency signal, at the same time the resonance gain provides the desired gain for a particular frequency. The simulation diagram of the transfer function is shown in figure 3.

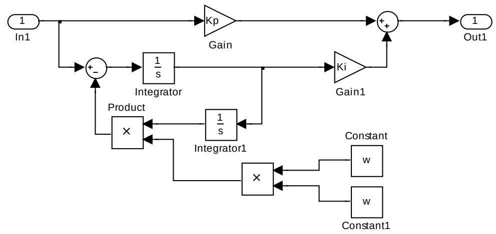


Fig.3 The simulation diagram of transfer function

K_i is used to change the band width, a low K_i can produce narrow frequency band, a high K_i can generate wide band. When K_p is increased, the PR controller increased until the resonant frequency increased to a peak value. In additional, when the value of K_p increased, the phase amplitude decreased. In this case, the harmonic impedance increased and may lead to a low harmonic component.

4.2 PR CONTROLLER TO REALIZE DC RIPPLE VOLTAGE OF APF

In equation (15), unlike there is a high gain at zero frequency under the PI controller, the PR controller provides a high gain AC system frequency (resonant frequency) to ensure zero steady-state error when regulating the sinusoidal signal. The amplitude-frequency characteristic of PR controller is as follow:

$$A\left(\omega\right)=\sqrt{K_p^{\,2}+\left(\frac{K_i\omega}{\omega_0^2-\omega^2}\right)^2} \tag{16}$$

Through the analysis, it is easy to obtain the voltage loop equation of AC side active power filter:

$$\begin{cases} u_a=u_{sa}-l\dfrac{di_{ca}}{dt}-i_{sa}R \\ u_b=u_{sb}-l\dfrac{di_{cb}}{dt}-i_{sb}R \\ u_c=u_{sc}-l\dfrac{di_{cc}}{dt}-i_{sc}R \end{cases} \tag{17}$$

When using the PR controller of DC ripple voltage control equation is as follows:

$$u_k = -\left(K_p + \frac{K_i s}{s^2 + \omega_0^2}\right)(i_h - i_c) + u_{sk} \quad (18)$$

Wherein, $k = a, b, c$, i_h is harmonic current, i_c is compensation current. Control system structure of active power filter shown in figure 4[20-21] .

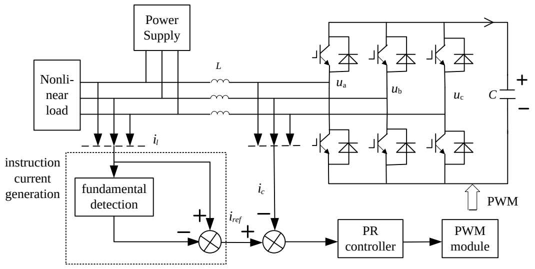


Fig.4 The control system structure diagram of APF

Control system of active power filter is double closed loop control structure, which is comprised with an outer voltage loop and an inner current loop control. In order to achieve the desired uniform grid side power factor control, frequency and phase of the supply side voltage are required the same with sinusoidal voltage. Obviously, a precise phase locked loop is necessary for the detection of supply side voltage, and in order to realize the better synchronous control of the supply side current.

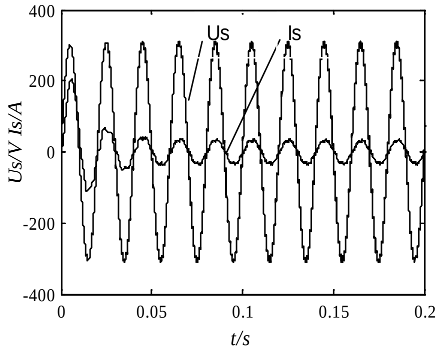
5 Simulation Analysis and Experimental Validation

In order to verify the rationality of the above method, using MATLAB/SIMULINK to do the simulation, the simulation parameters are shown in table 1.

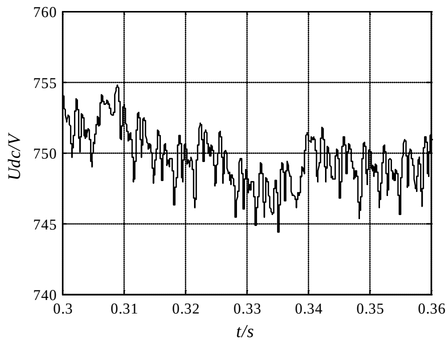
Tab.1 Simulation parameters of system

Name	Parameters
System power supply	380V/50HZ
Grid side load	30Ω,10mH
AC resistance	0.02Ω,2mH
DC capacitor	6800uF
Given voltage value	600V

The $i_p - i_q$ harmonic detection and improved $i_p - i_q$ harmonic detection method based on instantaneous reactive power theory are employed as detection algorithm, the traditional PI control and proportional resonant control are used as the controller, hysteresis control is adopted as PWM control strategy, the simulation results are shown in figure 5 to figure 8.



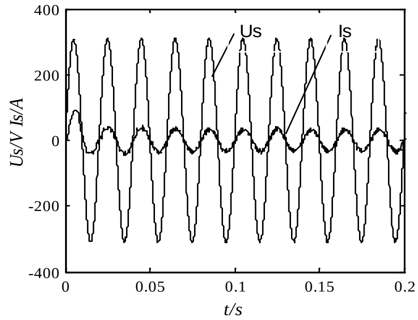
(a) The power supply voltage waveform and current waveform



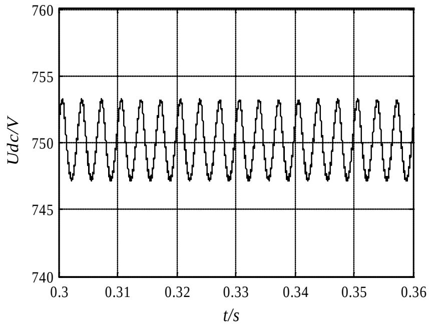
(b) Through the capacitor voltage ripple

Fig.5 $i_p - i_q$ harmonic test simulation results

Figure 5 shows the voltage waveform and current waveform of phase A and the corresponding voltage ripple through the capacitance under the $i_p - i_q$ harmonic detection method and the traditional PI controller. Figure 6 shows the voltage waveform and current waveform of phase A and the corresponding voltage ripple through the capacitance under the improved $i_p - i_q$ harmonic detection method and the traditional PI controller.



(a) The power supply voltage waveform and current waveform

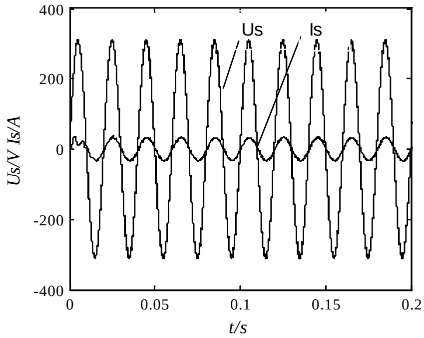


(b) Through the capacitor voltage ripple

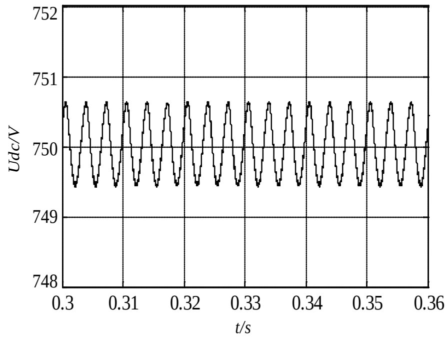
Fig.6 Improved $i_p - i_q$ harmonic test simulation

Compared figure 5 with figure 6 can be seen that the burr of source current is reduced, current shock in 0.01s is reduced from 200A to 80A. Variation range of voltage ripple is from 745V to 755V. But in figure 5 the change of ripple is excursive and instability and jump too fast. Compared to figure 6, ripple transformation range decreases, but also can change according to the regular trend. By contrast, the change range of ripple in figure6 is smaller, and can change according to a regular trend.

Figure 7 shows the voltage waveform and current waveform of phase A and the corresponding ripple voltage under the improved $i_p - i_q$ harmonic detection method and the PR controller. Compared with Fig. 6 can be seen that the current of supply side is almost no burr and the current shock in 0.01s. The variation range of DC side voltage ripple is reduced from 745V-755V to 749V-751V, voltage ripple is obviously reduced.



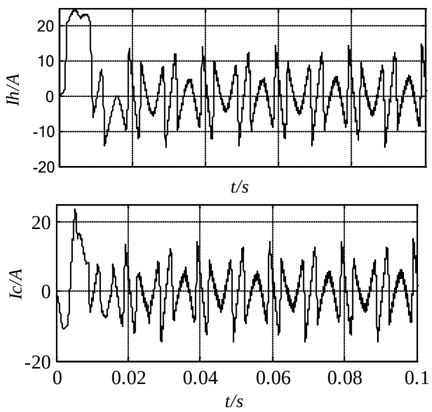
(a) Power supply voltage waveform and current waveform



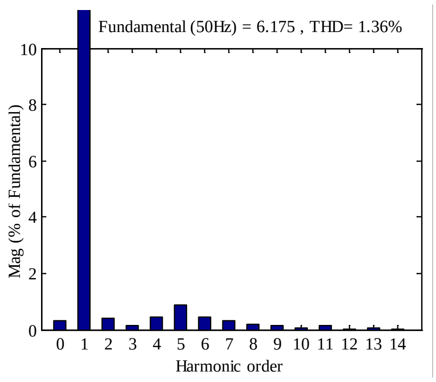
(b) Through the capacitor voltage ripple

Fig.7 The simulation results of the two methods

Contrast figures of FFT analysis under the improved $i_p - i_q$ harmonic detection method and the PR controller between harmonic current and compensation current and source current are shown by figure 8.



(a) Harmonic current and the compensation current waveform

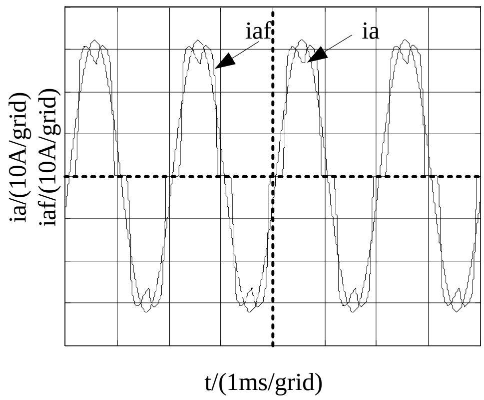


(b) Analysis of current FFT current after compensation

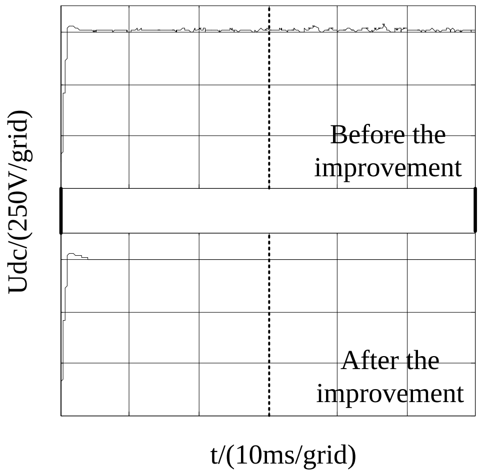
Fig.8 The analysis of simulation results

From the analysis of simulation results in figure 8 can be seen that the amplitude of the compensation current is the same with harmonic current, but in the opposite direction, so the compensation current can compensate harmonic current. After the compensation the total harmonic distortion of source current felled down to 1.36%. The simulation results show that the improved harmonic detection method and the proportional resonant control can reduce the harmonic current in varying degrees, so the impact of harmonic current on the capacitor's voltage of DC side and the ripple voltage are both reduced.

The experiment is based on 380V/66KVA APF prototype. Experimental conditions： Three-phase AC voltage is 380V/50Hz，the IGBT switching frequency is 6.4 kHz, nonlinear load resistance is 30Ω, inductance value is 10mH, inverter dc side capacitor value is 6800uF, DC side given voltage value is 750V. The control part adopts PR control method, harmonic detection algorithm based on improved $i_p - i_q$ harmonic detection method, the current tracking control is hysteresis pulse width modulation method.



(a) Supply current and fundamental current



(b) The DC side voltage

Fig.9 Experimental waveforms

Figure 9 (a) is the waveform of source power current and fundamental current. Figure 9 (b) is the experimental waveform of improved harmonic detection algorithm and a proportional controller. From the figure that the dc side capacitor voltage ripple is significantly reduced and reached a given voltage value 750V. So the effect verify the rationality of the use of these two methods.

6 Conclusion

Using an improved $i_p - i_q$ harmonic detection method for harmonic detection and put forward the proportional resonant controller to complete the ripple voltage control of DC side. Simulation results show that the improved $i_p - i_q$ harmonic detection method can reduce the influence of harmonics on the DC side ripple voltage, at the same time, the use of proportional resonant controller makes the steady state error caused by harmonics eliminated, and the control of DC side voltage ripple is further strengthened. The experimental results verified that the improved $i_p - i_q$ harmonic detection method and proportional resonant controller of the article proposed was effective to improve the voltage ripple, so its application in the practical engineering can play a better role

ACKNOWLEDGEMENTS

This project was supported by the Nature Science Foundation of Gansu Province (No. 1308RJYA044) and Scientific Research Project in Gansu Province Department of Education (2014-045).
Email address:13919207702@163.com or 752310464@qq.com

REFERENCES

[1] Liu Weiwei, Ding Honfa, Duan Xianzhong. Selective harmonic current control strategy in active power filters. Proceedings of the CSEE, vol. 31, no. 27, pp. 14-20, 2011.

[2] Garlapati, S. ,Gupta, R. Shunt active power filter as front end converter for DC loads Power Electronics (IICPE), pp. 1- 6, 2012.

[3] Fang Hong juan. A Study on the DC Voltage Control Techniques of Cascaded Multilevel APF. International Power Electronics and Motion Control Conference, pp. 2-5, 2012.

[4] Grino, R. Cardoner, R. Costa-Castello. Digital Repetitive Control of a Three-Phase Four- Wire Shunt Active Filter. Industrial Electronics, IEEE Transactions on, vol. 57, no. 3, pp. 1495-1503, 2007.

[5] Wang Jianxun, Liu Huijin, Han Fengshou, Wang Zhanlei. When a hybrid approach for inter-frequency harmonics Monitoring. Power System Technology, vol. 36, no. 10, pp. 229-234, 2012.

[6] Briz F, Garcia P, Degner M W,et al . Dynamic behavior of current controllers for selective harmonic compensation in three-phase active power filters. IEEE Transactions on Industry Applications, vol. 49, no. 3, pp. 1411-1420, 2013.

[7] Thelukuntla, C.S.; Veerachary. M., Resonant controller based single phase Z-source inverter with LCL-filter. Power Electronics, Drives and Energy Systems (PEDES) & 2010 Power India, 2010 Joint International Conference on , vol., no., pp.1,6, 20-23 Dec. 2010.

[8] Hanju Cha; Trung-Kien Vu; Jae-Eon Kim. Design and control of Proportional-Resonant controller based Photovoltaic power conditioning system. Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE , vol., no., pp.2198,2205, 20-24 Sept. 2009.

[9] Fujun Ma, An Luo. Voltage ripple analysis of simplified active power compensator for negative sequence and reactive power compensation. IET Power Electron, pp. 2582–2594, 2014.

[10] Munduate, A., Garin, I., Figueres, E., Garcera, G. Analytical study of the DC link capacitors voltage ripple in three level Neutral Point Clamped Inverters. Power Electronics, Electrical Drives, Automation and Motion, pp.552-555, 2006.

[11] Lajos Török, Laszlo Mathe, Stig Munk-Nielsen. Voltage ripple compensation for grid connected electronic power supply using small

DC link capacitor. International Journal of Electrical Power & Energy Systems, vol. 38, no. 2, pp. 607-611, 2014.

[12] U. Ayhan, and A. M. Hava. Analysis and characterization of DC Bus ripple current of two-level inverters using the equivalent centered harmonic approach. in Proc. IEEE Energy Conversion Congress Exposition, pp. 3830-3837 , 2011.

[13] Naimish Zaveri,Ajitsinh Chudasama. Control strategies for harmonic mitigation and power factor correction using shunt active filter under various source voltage conditions. International Journal of Electrical Power & Energy Systems, vol. 42, no. 1, pp. 661-671, 2012.

[14] H.Dogan,R.Akkaya.A. Simple Control Scheme for Single-Phase Shunt Active Power Filter with Fuzzy Logic Based DC Bus Voltage Controller. Lecture Notes in Engineering and Computer Science, pp. 1505-1509, 2009.

[15] Gu He-rong, Wang De-yu, Shen Hong, Zhao Wei, Guo Xiao-qiang. Technology Research of Three-phase Four-leg Inverter Control. Power System Protection and Control, vol. 39, no.24, pp. 41-46, 2011.

[16] Ghoshal, A., John V.. Anti-windup Schemes for Proportional Integral and Proportional Resonant Controller. National Power Electronics Conference, 10 - 13th June of 2010.

[17] Prasad, C.R.; Narayanan, G., Proportional resonant controller based circulating power setup for thermal testing of multilevel inverter. Industrial and Information Systems (ICIIS), 2012 7th IEEE International Conference on , vol., no., pp.1,6, 6-9 Aug. 2012.

[18] Q. Geng, C. L. Xia, Y. Yan, W. Chen. Direct power control in constant switching frequency for PWM rectifier under unbalanced grid voltage conditions. Proceedings of the Chinese Society of Electrical Engineering, vol. 30, no.36, pp. 79-85, 2010.

[19] Hongbo Li, Kai Zhan g, and Hui Zhao. Active DC-Link Power Filter for Single Phase PWM Rectifiers. 8th International Conference on Power Electronics, 2011.

[20] Ma Lin, Jin Xin-ming, Tang Fen. Analysis fed before three-phase grid-resonant inverter proportional pressure control and network. Transactions of China Electro technical Society, vol. 27, no.8, pp. 56-63, 2012.

[21] Briz F, Garcia P, Degner M W,et al. Dynamic behavior of current controllers for selective harmonic compensation in three-phase active power filters. IEEE Transactions on Industry Applications, vol. 49, no.3, pp. 1411-1420, 2013.