International Journal of Control and Automation
Vol. 8, No. 9 (2015), pp. 275-290
http://dx.doi.org/10.14257/ijca.2015.8.9.27

An Efficient Control System of Shunt Active Power Filter in Three-Phase Four-Wire Power System

Lei Wang[1], Lei Zhang[2], Xiaoyan Wen[3], Jian Zheng[4] and Chuncheng Liao[5]

[1,2,3,4]*School of Electricity and Information Engineering, Beijing University of Civil Engineering and Architecture, Beijing*
[5]*Management, Beijing Normal University, Beijing*
zhanglei@bucea.edu.cn

Abstract

On the basis of the three-phase four-wire shunt active power filter (APF), this paper discusses the control system. In order to produce compensation current faster, it takes the fusion of FFT and p-q method to detect the harmonic current, and adopt dual-DSP hardware structure based on MCBSP to realize signal processing. At the same time, this paper presents a three- closed-loop control system to keep the accuracy. Then, we build some MATLAB models for the control system to verify the validity of this system. At last, we did an experiment to realize the communication between the dual-DSP.

Keywords: *Active power filter, Closed-loop control system, FFT, Dual-DSP, MCBSP, MATLAB Simulation*

1. Introduction

Electrical power quality has been, in recent years, an important and growing problem because of the proliferation of nonlinear loads such as power electronic converters in typical power distribution systems [1-2]. Particularly, voltage harmonics and power distribution equipment problems result from current harmonics produced by nonlinear loads. Many researchers have put forward approaches to solve the problem [3].

The traditional approach of eliminating the harmonics is adopting LC passive filter, which exhibits impedance lower than the source impedance at a tuned harmonic frequency to reduce the harmonic currents flowing into the source. On the other side, passive LC filters have inevitable disadvantages, such as large size, resonance, fixed compensation characteristics, and so on [4]. Their performance is dependent on the variation in the power system impedance. They can do little if the load is supplied by a stiff power source and overloading of the filter is possible. Because of the probable resonance between the system impedance and the passive filter, the design of the latter must be rigorous system studies taking all possible filter and supply system parameter changes into consideration. Besides, passive filters suffer from bulkiness and mistuning problems.

Shunt active filters proposed and studied for about 3 decades are connected in parallel to the power distribution [5]. Since then, theories and applications of active power filters have become more and more popular and have attracted much attention, especially after instantaneous reactive power theory was proposed and used as the basis of the calculation of compensation current. Shunt active filter adopting such a configuration can enable power system with inductive load to be free from harmonic currents by injecting the compensating current into the power system to make the source current into sinusoid shape. In this case, the shunt active filter serves as a current source [6].

The basic principle is to detect harmonic component result from load, with the help of a converter device to produce a compensation current which has the same frequency,

ISSN: 2005-4297 IJCA

reversing phase compared with harmonic current, and make the grid current into an ideal standard sine waveform.

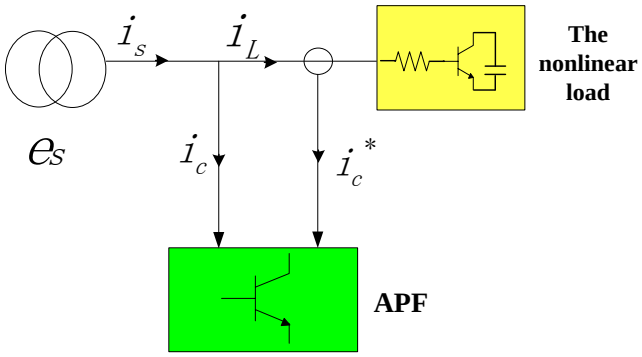


Figure 1. Schematic of Control System of APF

In Fig.1 the load current i_L contains harmonic current i_{Lh} and Fundamental current i_{Lf}. After the harmonic current i_{Lh} is calculated by harmonic detecting method, compensation current instruction i_c^* can be derived by reversing the phase of i_{Lh}. Control signals generated by the control circuit, after driving isolation, control the main circuit to get **Error! Reference source not found.**, which is the same as i_c^*.

By the principle of KCL：

$$i_s = i_L + i_c \tag{1}$$

$$i_L = i_{Lh} + i_{Lf} \tag{2}$$

$$i_c = -i_{Lh} \quad \textbf{Error! Reference source not found.} \tag{3}$$

Using (2) and (3) results in

$$i_s = i_{Lh} + i_c + i_{Lf} = i_{Lf} \tag{4}$$

As shown Fig.1, the lateral load harmonic current component can be compensated, and it will only be the fundamental frequency component in power systems, so as to achieve the purpose of suppressing harmonic current.

Compared to conventional analog and microprocessor based methods the DSP based solution provides a flexible and efficient method to control the APF [7-9]. But with the progress of technology and performance requirements, the monolithic DSP system cannot meet the requirements of the design on account of the large data throughput. So we introduce the dual-DSP [10] system. In recent years, the APF research mainly focus on improving the responding speed of control system [8]. Much work has been done in the area of active filter control [1,7, 8]. Nevertheless, it seems that, as a conclusion, the main point is the need for high-gain current control loops [7-12]. Perhaps, the easiest way to obtain them is to use some kind of hysteresis controller [13-15]. However, this controller has the disadvantage of a varying switching frequency, which produces a continuous harmonic spectrum. This problem is not present in fixed-frequency pulse width modulated schemes that have their high-frequency content around switching frequency harmonics. The instantaneous power theory (p–q theory) has been used successfully to control active power filters for three-phase systems [16, 17]. This instantaneous theory is valid for steady and transient states and for generic voltage and current waveforms. It analyze the powers in an unbalanced system, including the zero-sequence instantaneous power, By using the concepts of symmetrical components together with the new theory [18, 19].

In this paper, In order to produce compensation current faster, it takes the fusion of FFT and p-q method to detect the harmonic current, and adopt dual-DSP hardware structure based to realize signal processing. At the same time, this paper presents a three-closed-loop control system to keep the accuracy. This paper is organized as follows. Section II introduces the control system of APF, the control objectives. Section III shows the harmonic detection method. Section IV describes the three closed-loops system. Section V describes the communication between dual-DSP. Section VI presents the experimental and results. Finally, Section VII summarizes the results of this paper.

2. Control System for APF

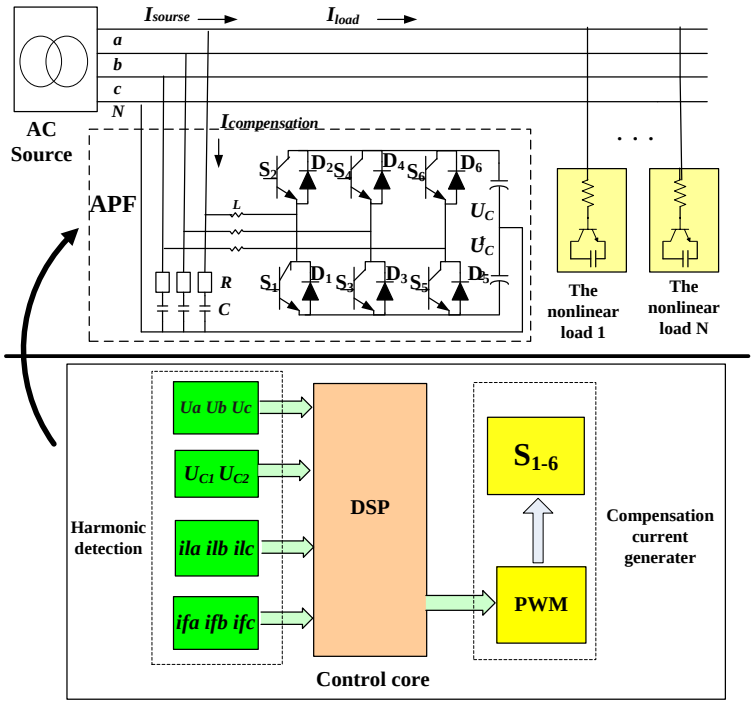


Figure 2. Three-phase Four-wire Source with Nonlinear Load and Shunt Active Power Filter

As shown in Figure 2, it is the main structure of three-phase four-wire source with nonlinear load and shunt active power filter. The APF is placed between the power source and the nonlinear load. The main circuit is three-phase voltage type current transformer, Dc side shunt two large capacitance, IGBT and clamp diode compose a bridge arm current transformer, Parallel inductance is placed in filter branch, the inductance main plays a role of booster when the power switch tube by the work in the state of rectifier; when the power switch tube working a state of the inverter, due to form a stable current, the ac inductor have the effect of smoothing current. The APF include three function parts:

1. Harmonic detection

To detect the harmonic generated by nonlinear load, APF should detect three kind of parameters: AC power source is the reference standard to eliminate the harmonic, which is 380 V and 50 Hz; DC side capacitor is the energy source of active power filter harmonic, we should keep it in a constant value, which is 1000V; harmonic current is a important parameter we should detect, in this paper, the harmonic frequency of compensation current f_c can be resulted from (5).

$$f_c = f_b \times c_1 \tag{5}$$

$$f = f_c \times c_2 \tag{6}$$

In this paper, c_1= 50 which is the highest harmonic; c_2=4 times; f_b is 50Hz, so we can get that:

$$f_c = 50 \times 50\text{Hz} = 2.5\text{kHz}$$

According to the sampling theory, this kind of harmonic sampling frequency *f*:

$$f \geq 4 \times 2.5\text{kHz} = 10\text{kHz}$$

The sampling frequency is 1 MHz in this paper, in order to ensure the accuracy of the experiment.

2. Harmonic current generator

In order to make the compensation current generated satisfy the need of active power filter, in this paper, the double closed-loop control was designed to generate compensation current. The current inner loop is for high-speed sampling, to make compensation current value stable with instruction on the size of the compensation current in a short time; the out current loop is slower, in order to make the whole outputting compensation current waveform is the same as the instruction current waveform.

The function of active power filter is to keep power supply side current and power supply voltage in same or close to the sine wave. Under the condition of the steady state, for a system without the loss of active power filter, the power provided must be equal to the consumption the load of power, Therefore, the average voltage of inverter DC capacitance will remain to a certain value. When the power imbalance, such as load changes, Inverter DC capacitance will provide power difference between the source and load, this will lead to the change of current (DC) of the average voltage. Voltage closed control is used to control the fluctuation of DC side voltage.

3. Control core

This part mainly describes the communication between the controllers, and we adopt double DSP based on MCBSP to realize communication to meet the demand of speed. The communication speed between the dual DSP is designed 1 MHz and 16-bit.

3. Harmonic Current Detection Method

There are several detection methods, and each has their own characteristics, which main divided into three categories, namely the method based on frequency analysis, based on the time-domain analysis method, and the method based on modern control theory.

3.1. The Method of p-q

This theory broke through the traditional power definition on the basis of the average, defining the instantaneous reactive power, the instantaneous active power amount of instantaneous power, etc. Systematically, Therefore, it not only used in the sine wave, but also suitable for nonsine wave and any other transition. But it will have a delay when detecting harmonic current, the most important thing is that it cannot detect specific frequency harmonic current [20]. As shown in Figure 3, at first, the three phase current i_a, i_b, i_c of power grid are transformed through the section of 3/2 transformation, get the current component i_α, i_β in the coordinates of α β, and then get the instantaneous active power and reactive power p and q through the p q transformation , then get the fundamental component $\overline{p}$ $\overline{q}$ through the low pass filter (LPF), Then after inverse transform to get the fundamental of three-phase current, get the harmonic current by subtracting the original load current.

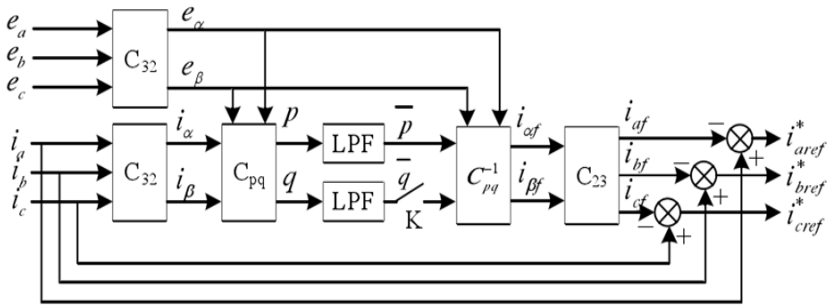


Figure 3. p-q Harmonic Detection Principle Diagram

3.2. The Method of FFT

This method is to put the analog signal sampling frequency, according to certain frequency through discrete by sampling retainer, collecting a series of points into a certain sequence length. Get these points through the fast Fourier transform, analyze the data points every harmonic characteristics which including phase and amplitude, through the inverse transform can we accurately get current command signal of the compensated signal. This method, little affected by external environment factors, can be achieved for specific harmonics detection. But, result in large amount of calculation due to the FFT transformation calculation [21]. If consider FFT method we must pay attention to the sampling points.

3.3. Simulation for FFT

Fig.4 to Fig.8 are the fast Fourier analysis results in the end. The following is FFT transform effect comparison for different sampling frequency and sampling points .If the sampling frequency is 1200Hz, through observing different sampling points, the treatment effect is as following:

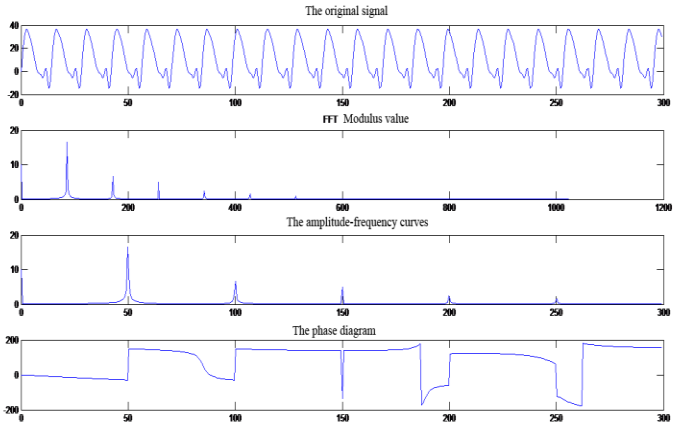


Figure 4. N = 1024 Original Signal and FFT Spectrum Image After Processing

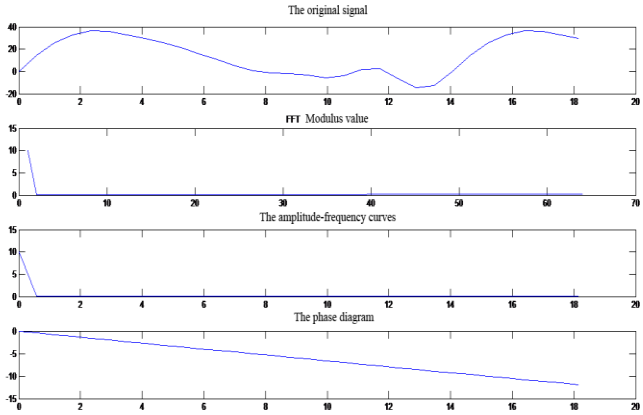


Figure 5. N=128 Raw Signal and after Treatment with FFT Spectrum

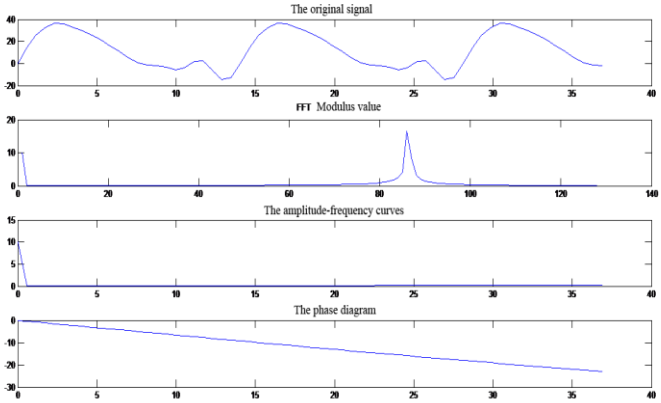


Figure 6. N =128 Original Signal and FFT Spectrum Image after Processing

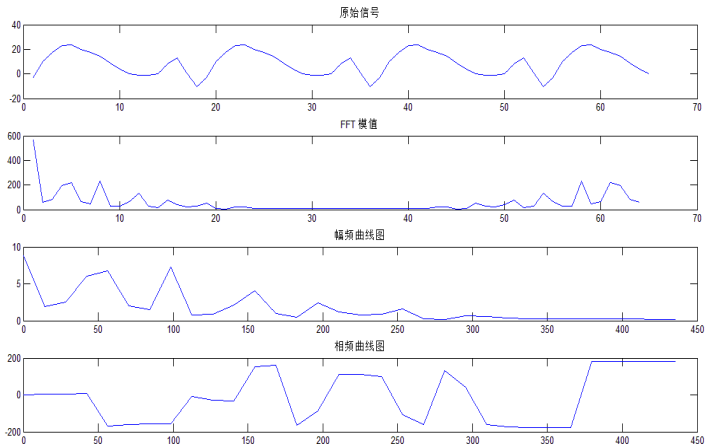


Figure 7. N=64 Raw Signal and after Treatment with FFT Spectrum

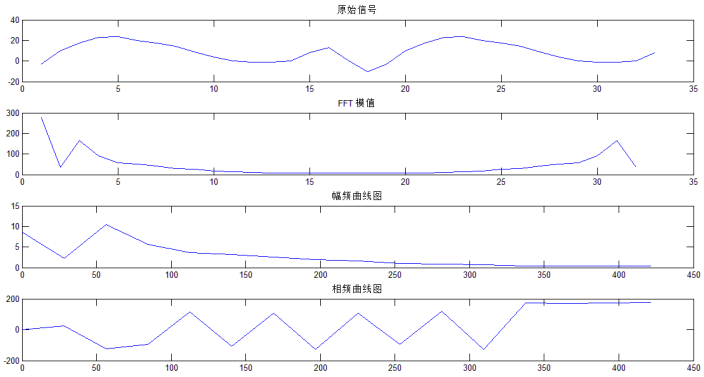


Figure 8. N=32 Raw Signal and after Treatment with FFT Spectrum

Can be seen from the FFT analysis results contrast, for the same signal and same sampling frequency , the smaller the sampling points, the less accurate the FFT analysis. As shown in Fig.4 when N=1024, amplitude-frequency curve is sharp, and with fewer sample points the curve becomes smooth, even the phenomenon of harmonics appears. AS shown in Fig.8, three and higher times harmonics can't be detected, that illustrates the sampling points has a great influence on the result of FFT analysis, and using this method for harmonic detection, the sampling points number must be big enough to achieve the accuracy.

4. The Implement of Three Closed-loops

4.1. Current Control Loop

1. The Inner Loop of Current Control

The inner loop of compensation current control refers to the compensation instructions in the form of current after harmonic detecting and calculating, and then compare with harmonic compensation currents generated by the SVPWM. To let compensation harmonic and instructions generated by harmonic are equal anytime, to get compensation harmonic which is accurately equaled amplitude and opposite phase with the compensation harmonic in the grid . With the demand of APF, the compensation current should track the harmonic current quickly, so the switching frequency the higher the better. In this paper we adopt IGBT that can meet our demand.

2. The outer Loop of Current Control

We know that APF compensation current is generated by the IGBT controlled by SVPWM. But the instruction of compensation current we need and actually harmonic compensation current may be different. So we need to use a control method to make the actual output of the compensation current to be equal to its command. The so-called outer loop means that the actually generated harmonic compensation compared with the harmonic detecting from power grid. The harmonics actual generated and the harmonic detecting from power grid must be equal amplitude, opposite phase. In this way can we effectively offset harmonic current in the power grid and the filtering effect will be obtained. As shown in Fig.9, it is the implement of current closed-loops.

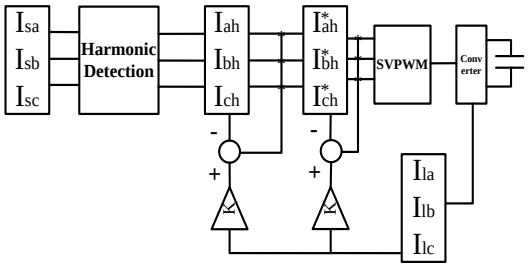


Figure 9. Compensation Current Control Loop

4.2. DC Voltage Closed- loop Control

The basic cause of the DC side voltage fluctuation is the fluctuations between AC power and active power filter compensation current energy. This paper used PI controller to maintain DC side capacitor voltage to the required level.

DC side capacitor is the energy source of active power filter harmonic. In order to guarantee the effective harmonic generated by active power filter to make its voltage constant and the capacitor voltage higher than the grid voltage to feedback energy to the grid. As shown in Fig.10, which contains these following several parts:

Command voltage calculation: Get the actual values of DC voltage, and take it into the PI regulator after comparing with the reference voltage, then the PI regulator will output corresponding results.

Voltage and phase detection: Collect the voltage and phase angle of phase A, and then through PLL to provide a reference phase.

The AC voltage transformation: AC three-phase voltage was taken into orthogonal value under coordinates by the 3/2 transformation, to overlay with the phase and PI - control references.

Instruction current generation: The instructions current is converted switch signal by the 3/2 transformation, the SVPWM will output the IGBT on-off signal and then output to the circuit.

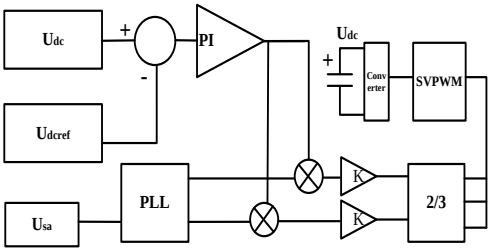


Figure 10. DC Voltage Control Loop

4.3 Simulation of Control System

Fig.11 is MATLAB simulation diagram of the whole control system [23], the main function is to keep the DC side voltage to a certain value, to make it as appropriate for the use of rectifier voltage sources. In the whole simulation, the 'v_detection' module is used to detect the value of voltage, the model under the 'v_detection' module is used to detect the value of current, then through the way of d-q, the voltage is changed in the formal of current and then they will produce the instruction current through the'2d_closed-loop'module, be sent to the SVPWM generator through action of inverter by the module'a2d-svpwm' to generate the compensation current we need.

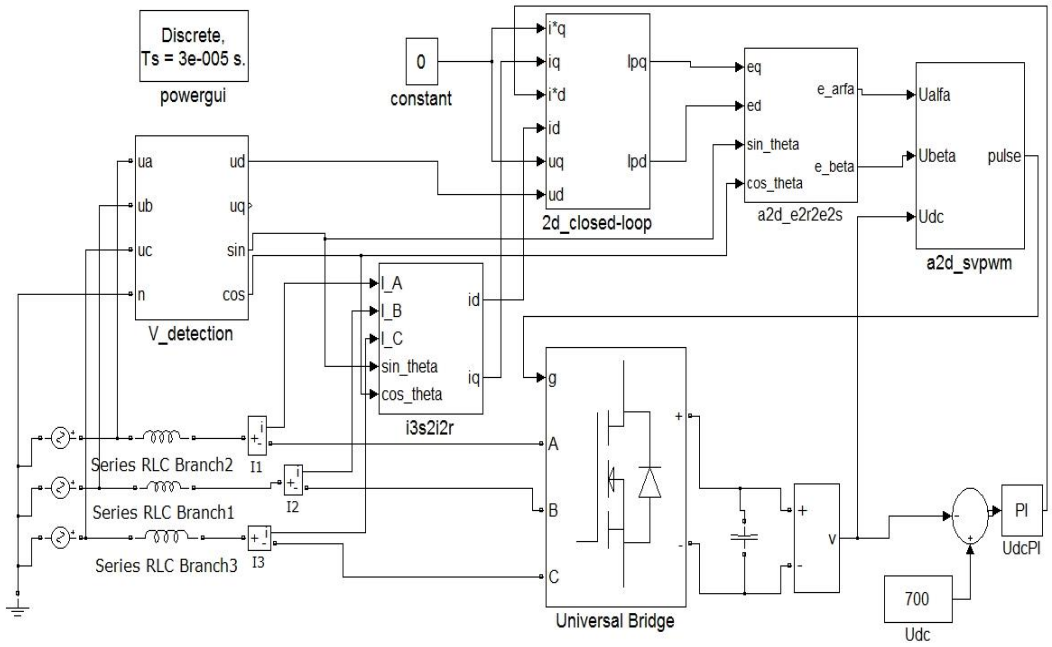


Figure 11. MATLAB Simulation Diagram of the Whole Control System

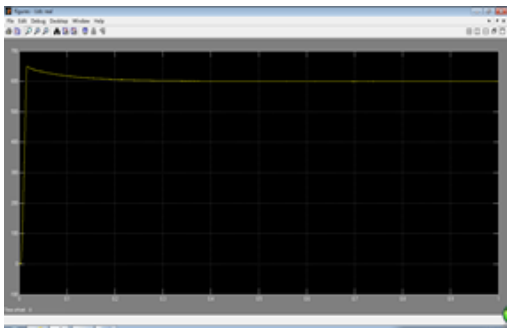


Figure 12.The Simulation Results of the DC Side Voltage

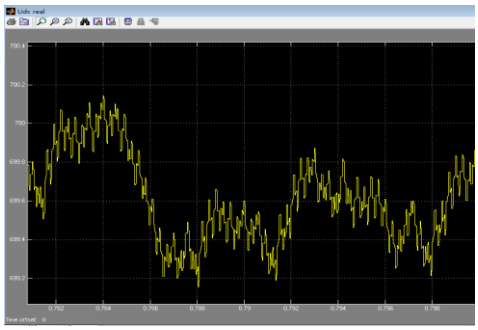


Figure 13.The Simulation Results of the DC Side Voltage

Figure 12 for the DC side voltage through the PI regulator has reached the process of voltage stability. The peak is the amount of overshoot (MP) regulated in PI. Its computation formula is:

$$M_p = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{7}$$

ζ is the damping ratio, the M_P only related to the ζ, With the increasing of ζ, the M_P will monotonous decrease.

So, when ζ equal to 1, M_P will equal to 0, the system has no overshoot, in the critical damping state, outputting voltage from the DC side of the PI regulator will reach a constant value.

From Figure 13 we can get the control precision. In this experiment we give a reference voltage which is 700V, as shown in Figure 11, from Figure 13, we can get:

$$V_{max} = 700.2\text{V} \tag{8}$$

$$V_{min} = 699.2\text{V} \tag{9}$$

Using (8) and (9), results in:

$$E_{max} = \frac{V_{min} - V}{V} = 0.11\%$$

The maximum error is about 0.11%. This error can meet the demands of our experiment, and under this condition we can carry out other experiments.

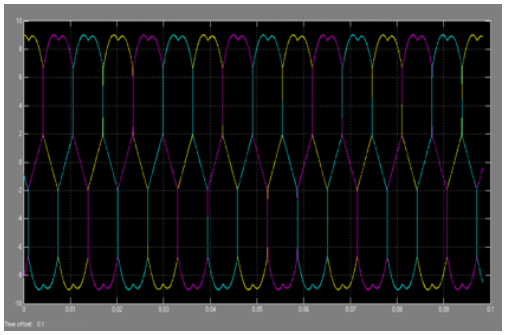


Figure 14. Lateral Load Current

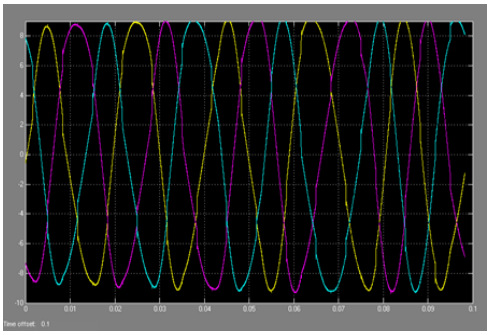


Figure 15.The Grid Current

As shown in Figure 14, The lateral load current waveform distortion is serious, is not sinusoidal current because of the existence of the harmonic current. But As shown in Figure 15, the grid side current is relatively stable, agreed with sine waveform which achieves the compensation, after compensating of APF.

5. Dual-DSP Communication in the Side of Control Board

5.1. Double DSP

In this system, the monolithic DSP system cannot meet the requirements of the design on account of the large data throughput. As a result, the study of high-speed communication between DSP is particularly important. Double DSP based on MCBSP to realize communication to meet the demand of speed.

The functions of control system are divided into two parts, including main controller (MC) and field controller (FC). By using dual-DSP allocation of functions, the MC-DSP is responsible for

(1) Collecting real-time data of network parameters, analyzing and extracting harmonic current and generating current compensation instructions;

(2) Collecting real-time data of the compensation current, compared with the current instruction, after PI correction for the first current loop control;

(3) Collecting DC capacitor voltage, analyzing and correcting through an integrated command current compensation to stabilize the DC voltage control;

(4) Checking failure when interrupted, and controlling circuit breakers, contactors, fans, lights and other switch input and output status.

The FC-DSP is responsible for

(1) Detecting real-time compensation current, and controlling the second current loop.

(2) Receiving the compensation instruction generated by the MC-Controller, dealing with the corresponding sine pulse signal conversion, driving three-phase full-bridge, generating the compensation current, and effectively inhibiting the load harmonics.

As is shown in Figure 16, the TMS320C28x family of processors has a multi-channel buffered serial port (MCBSP) for two-machine communication, complete power management, output analog voltage 1.8V, 3.3V and two digital 1.8V, 3.3V.

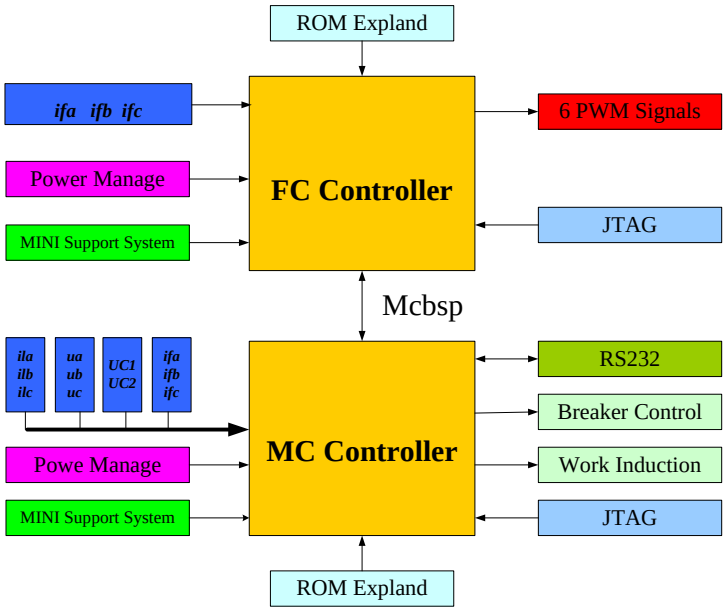


Figure 16. Control System Functions Assigned

5.2. DSP based on MCBSP

In this paper, dual-DSP control circuit uses two DSPs, which are responsible for their own assigned tasks. MC controller is mainly responsible for compensating command current computing tasks; FC controller is mainly responsible for deriving the IGBT driving signal. Control system requires quick dynamic compensation. It is necessary to control the data transfer at the most short time. High-speed dual-DSP communication experiment is to test dual-DSP based MCBSP working from the master device's on high-speed communication. MCBSP clock stop mode, mainly from the device to provide environmental work in the SPI protocol. When MCBSP is configured as clock stop mode, receive and transmit communications constitute a synchronous manner. In this case, the transmit clock signal to provide a serial clock signal from the device transmits the frame synchronization signal from the enable signal devices. Receiving a clock signal and a frame synchronization signal in the DSP receiver connected to the corresponding internal transmission signal does not work. The characteristics of this mode of communication are to achieve duplex synchronous communication, and data transmission is controlled by the clock signal. At that time, the data transfer starts when the clock signal is issued, data transmission is terminated when the clock signal is stopped, and at the same time, enabling the controller to reduce the amount of processing tasks to improve their overall performance. In this paper, set CLKSTP=10b, CLKXP =0, CLKRP=0.The Signal timing of Pin is shown in Fig.17: (a) the falling edge of the clock signal means the arrival of a data transmission. A frame signal may include a specific plurality of clock signal, which

is valid only on the falling edge. To save timer resources, the timer interrupt is generated after 4us timer and turn MCBSP transmit interrupt, six frames of data transmission, in which each frame of data transfer is completed within 1us. Frame data format is shown in Figure 17 (b).These can be adjusted as necessary. Six data includes three current compensation instructions, and the other three data used to verify.

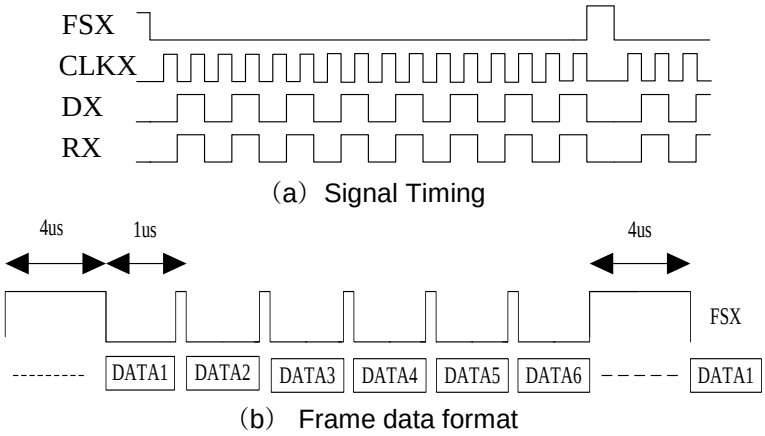


Figure 17.Timing and Fame Data

Based on this experiment, the DSP working as the main receiver is designed for the verification, which means that the data in the received frame by subtracting the first frame of the fourth data, the received data by subtracting the fifth frame of the second frame data, and the received data by subtracting the third frame of the sixth frame data are given a value of 100 for verification judgments. If the condition is true, the received data is correct and effective. If the received data is not accurate, FC-Controller discards and notifies MC-Controller to send again.

6. Experiment and Result

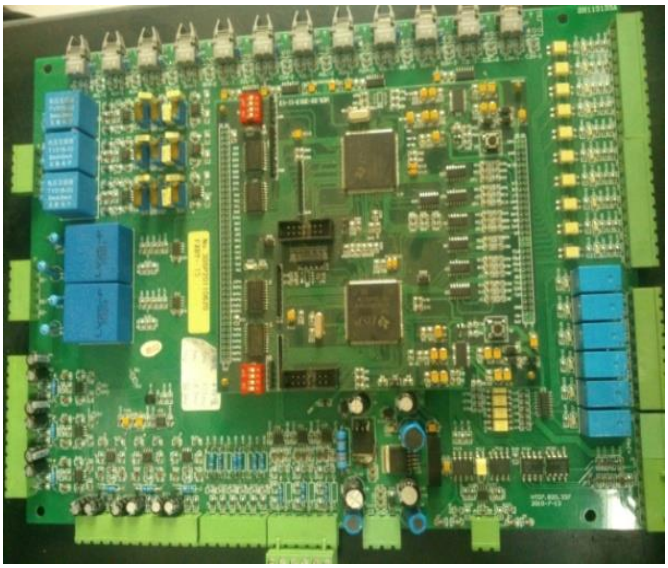
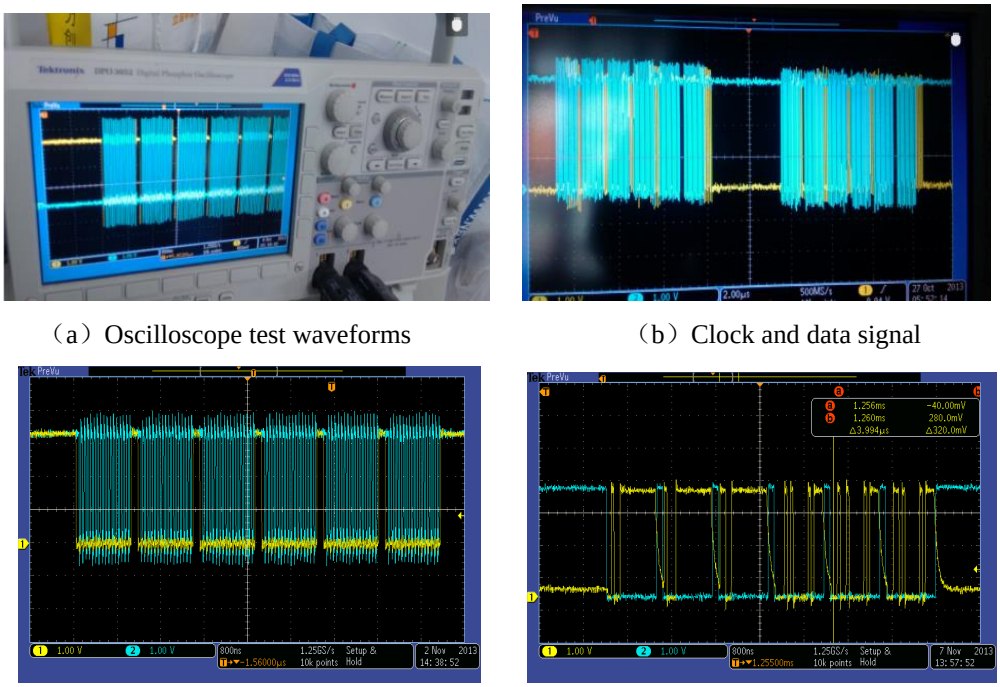


Figure 18. Control Board of APF

As shown in Figure 18, the control board of APF, the top DSP is the field controller, and the bottom one is the main controller. Experimental test data waveform is shown in Figure 15.



（a）Oscilloscope test waveforms　（b）Clock and data signal

（c）Clock and frame sync signal　（d）Data and frame sync signal

Figure 19. Communication Waveform

Experiment results show that the SPI master-slave device based on MCBSP can achieve the dual-DSP communication with the simple hardware circuit design and logical structure, and the real-time analysis of the data operated by MC-Controller is passed to FC-Controller. Figure 19(c) and (d) reflects the communication timing and fame data. We design different transmission frequencies to transmit data statistical accuracy and record 10000 transmit data. Figure 19 reflects the correct transmission rate trends over the transmission rate. Data show that when using 15MHz transmission accuracy rate for the first time brought to 100.

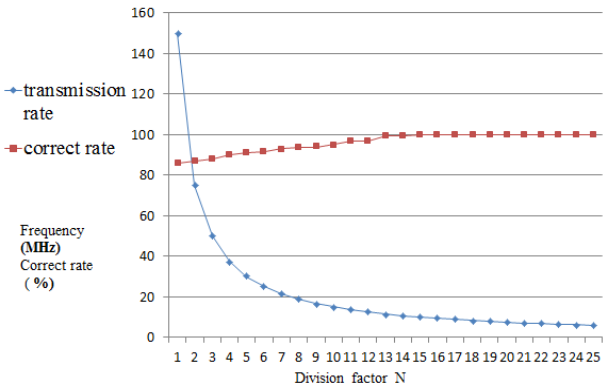


Figure 20. Correct Rate and Transmission Rate

To ensure the accuracy of the received data, MC-Controller sample rate generator clock is 15 MHz with data latency 1bit; FC-Controller sample rate generator clock is 150 MHz with data latency 0bit. By sending data to any of the six on master device and receiving data to any of the six on slave device, it is to check and determine whether the receiver is accurate, and accuracy of the data is expressed by signal LED. At the same time, crawling the LED test points waveform to verify whether the data is accurate. Considering the real-

time and ensuring the accuracy of data transmission, communication speed between the dual DSP is designed 1 MHz and 16-bit.

7. Conclusion

Through simulation, we can get that the closed-loop voltage control can maintain the stability of the DC side voltage; Three current closed-loops control make us compensate the harmonic current accurately; The fusion of FFT and p-q method are better when we adopt double DSP, but we must pay attention to the sampling points. Through the experiment, we can demonstrate that the double DSP based on MCBSP can quickly realize the communication between each other.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant No. 61473027), sponsored by Ministry of Housing and Urban-Rural Development of The People's Republic of China, Project's "The Research of Power Quality Monitoring and Energy Saving for Intelligent Building with Multiple Equipment" (2012-K1-42); also sponsored by BUCEA Urban Rural Construction and Management Industry Research Development Collaboration Post Graduate Training Centre (cxy2014175).

References

[1] H. Akagi, "New trends in active filters for power conditioning", IEEE Trans. Ind. Appl., vol. 32, no. 6, **(1996)**, pp. 1312–1322.
[2] W. F. Zou and L. Zhang, "An Active Power Filter Controller Based on dual-DSPs in Low-Voltage Power System", Applied Mechanics and Materials, **(2013)**, p. 1.
[3] M. I. M. Montero and F. B. González, "Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems", IEEE Transactions on Power Delivery, vol. 22, no. 1, **(2007)**, pp. 229-236.
[4] H. Fujita and H. A. Akagi, "Practical approach to harmonic compensation in power systems-series connection of passive and active filters", IEEE Trans. Ind. Appl., vol. 27, no. 6, pp. 1020-1025.
[5] Z. Wang, Q. Wang, W. Yao and J. Liu, "A series active power filter adopting hybrid control approach", IEEE Transaction on Power Electronics, vol. 16, no. 3, **(2001)**, pp. 301-310.
[6] F. Zhuo, J. Yang and Z. Wang, "Main circuit structure and control of the active power filter for three-phase four-wire system", Advanced Technology of Electrical Engineering and Energy, vol. 19, no. 2, **(2000)**, pp. 1-6.
[7] M. Aredes and K. Heumann, "Three-Phase Four-Wire Shunt Active Filter Control Strategies", IEEE Transactions on Power Delivery, vol. 12, no. 2, **(1997)**, pp. 311-318.
[8] S. Buso, L. Malesani and P. Mattavelli, "Comparison of current control techniques for active filters applications", IEEE Trans. Ind. Electron., vol. 45, no. 5, **(1998)**, pp. 722–729.
[9] P. Mattavelli, "A closed-loop selective harmonic compensation for active filters", IEEE Trans. Ind. Appl., vol. 37, no. 1, **(2001)**, pp. 81–89.
[10] P. Jintakosonwit, H. Fujita and H. Akagi, "Control and performance of a fully-digital-controlled shunt active filter for installation on a power distribution system", IEEE Trans. Power Electron., vol. 17, no. 1, **(2002)**, pp. 132–140.
[11] S. Fukuda and R. Imamura, "Application of a sinusoidal internal model to current control of three-phase utility-interface converters", IEEE Trans. Ind. Electron., vol. 52, no. 2, **(2005)**, pp. 420–426.
[12] H. Komurcugil and O. Kukrer, "A new control strategy for single-phase shunt active power filters using a Lyapunov function", IEEE Trans. Ind. Electron., vol. 53, no. 1, **(2006)**, pp. 305–312.
[13] I. Etxeberria-Otadui, A. L. D. Heredia, H. Gaztanaga, S. Bacha and M. Reyero, "A single synchronous frame hybrid (ssfh) multi frequency controller for power active filters, IEEE Trans. Ind. Electron., vol. 53, no. 5, **(2006)**, pp. 1640–1648.
[14] M. I. M. Montero and F. B. González, "Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems", IEEE Transactions on Power Delivery, vol. 22, no. 1, **(2007)**, pp. 229-236.
[15] R. Griñó and R. C. Castelló, "Digital Repetitive Control of a Three-Phase Four-Wire Shunt Active Filter", IEEE Transactions on Power Delivery, vol. 54, no. 3, **(2007)**, pp. 1495-1503.
[16] H. Akagi, Y. Kanazawa and A. Nabae, "Instantaneous reactive power compensator comprising switching devices without energy storage components", IEEE Trans. Ind. Appl., vol. IA-20, no. 3, **(1984)**, pp. 625–630.

[17] H. Akagi, A. Nabae and S. Atoh, "Control strategy of active power filter using multiple voltage-source PWM converters", IEEE Trans. Ind. Appl., vol. IA-22, no. 3, **(1986)**, pp. 460–465.
[18] E. H. Watanabe, R. M. Stephan and M. Aredes, "New concepts of instantaneous active and reactive powers in electrical systems with generic loads", IEEE Trans. Power Delivery, vol. 8, **(1993)**, pp. 697–703.
[19] M. Aredes and E. H. Watanabe, "New control algorithms for series and shunt three-phase four-wire active power filters", IEEE Trans. Power Delivery, vol. 10, **(1995)**, pp. 1649–1656.
[20] N. R. Raju, S. S. Venkata and V. V. Sastry, "The use of decoupled converters to optimize the power electronics of shunt and series AC system controllers", IEEE Trans on Power Delivery, vol. 12, no. 2, **(1997)**, pp. 895-900.
[21] R. Griñó, R. C. Castelló and E. Fossas, "Digital control of a single phase shunt active filter", Proc. 34th IEEE Power Electron. Spec. Conf., **(2003)**; Acapulco, Mexico.
[22] C. Rech, H. Pinheiro, H. Grundling, H. Hey and J. Pinheiro, "Analysis and design of a repetitive predictive-PID controller for PWM inverters, Proc. 32nd Annu. IEEE PESC, **(2001)**.
[23] M. Djarallah, "Energy Transfer Mechanism for a Grid-connected Residential PV System Within the Matlab/Simulink Environment".